AN EXPERIMENTAL ANALYSIS OF OPERATING CONDITIONS IN COLD ROLL-FORMING

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APRIL 1990

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SUMMARY

A detailed literature survey confirmed cold roll-forming to be a complex and little understood process. In spite of its growing value, the process remains largely un-automated with few principles used in set-up of the rolling mill.

This work concentrates on experimental investigations of operating conditions in order to gain a scientific understanding of the process. The operating conditions are; inter-pass distance, roll load, roll speed, horizontal roll alignment .

Fifty tests have been carried out under varied operating conditions, measuring section quality and longitudinal straining to give a picture of bending. A channel section was chosen for its simplicity and compatibility with previous work. Quality measurements were taken in terms of vertical bow, twist and cross-sectional geometric accuracy, and a complete method of classifying quality has been devised. The longitudinal strain profile was recorded, by the use of strain gauges attached to the strip surface at five locations.

Parameter control is shown to be important in allowing consistency in section quality. At present rolling mills are constructed with large tolerances on operating conditions. By reduction of the variability in parameters, section consistency is maintained and mill down-time is reduced. Roll load, alignment and differential roll speed are all shown to affect quality, and can be used to control quality.

Set-up time is reduced by improving the design of the mill so that parameter values can be measured and set, without the need for judgment by eye. Values of parameters can be guided by models of the process, although elements of experience are still unavoidable.

Despite increased parameter control, section quality is variable, if only due to variability in strip material properties. Parameters must therefore be changed during rolling. Ideally this can take place by closed-loop feedback control. Future work lies in overcoming the problems connected with this control.

KEYWORDS : COLD ROLL-FORMING

OPERATING CONDITIONS

SECTION QUALITY

EXPERIMENTAL ANALYSIS

DOWN-TIME

Dedicated to my parents

and I.S.A.

ACKNOWLEDGEMENTS

I would like to thank the numerous people who have helped me complete this research, especially all the machine setters in the Precision Division of Hadley's Sections and the Aston University students and staff. Particularly, I would like to acknowledge the help of;

Dr D.A. Milner, Supervisor until December 1988, for continuing advice.

Dr I.M. Cole, Supervisor.

Mr G. Deeley, Technical Director, Hadley's Sections Plc, who helped to arrange much of the experimental work in the factory.

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GLOSSARY OF ABBREVIATIONS

NC	Numerically Controlled
CNC	Computer Numerically Controlled
CR	Cold Rolled
CRF	Cold Roll-Forming
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacture

PAPERS PUBLISHED

In the course of the research, three relevant papers have been published. This thesis contains information from those papers. The papers are ;

J. Fewtrell, D.A.Milner
"Some Aspects of Operating Conditions in Cold Roll-Forming" Advances in Manufacturing Technology III. Proceedings of the Fourth National Conference on Production Research. Sheffield City Polytechnic. Sept 1988. pp 502-507. Published by Kogan Press.

J. Fewtrell, D.A.Milner
"An Experimental Study of Operating Conditions in Cold Roll-Forming" The Tenth International Conference on Production Research. Nottingham. Aug 1989. Published by Taylor and Francis.

J. Fewtrell, D.A.Milner
"An Experimental Study of Operating Conditions in Cold Roll-Forming" Advances in Manufacturing Technology IV. Proceedings of the Fifth National Conference on Production Research. Huddersfield Polytechnic. Sept 1989. pp 61-66. Published by Kogan Press

CHAPTER 1

INTRODUCTION

1.1 A HISTORY OF COLD ROLL-FORMING

The importance of Cold Roll-Forming (CRF) continues to grow with the increasing needs for lightweight, strong, low cost, attractive construction products. Just as stone was replaced by timber in the early 19th century; timber is being replaced by cold-rolled metals today. In North America, it has been estimated that more metal is roll-formed each year than is produced by die-casting, extrusion, closed die forging and powder metallurgy combined (56).

The use of relatively thin elements in structures was first realised in the early 19th century with the development of plate girders and tubular bridges. The plate components of these were not thin by today's standards, but they represented in their time a very real attempt at making use of the high structural efficiency of thin structures, as opposed to thick or massive structural forms (31).

The most important development towards thin metal structures was the introduction of mild steel during the latter part of the 19th century. This led to the manufacture of large thin plates of a strong ductile material which could be connected to other components by riveting or bolting and enabled established practice in wrought iron tubular structures and deep web beams to be consolidated and extended. A whole new field of structures on both large and small scale was brought about, and except for the introduction of high strength materials and welded connections, it still provides much of the present day basis of the field of thin structures.

With the development of the aeroplane in the early 20th century came an overriding need for as light a structural form as possible. This was usually achieved by using thin metal sheets to which stiffeners (stringers) were riveted. These stiffeners were usually of extruded aluminium channel, "Z" or "H" section (16).

Much of the early theoretical and empirical analysis of the behaviour of light gauge structures as we know it today followed the development of this structural form. Because of the weight-saving offered, the application to aircraft was mainly in aluminium, but the principles evolved are equally applicable to steel. As with much structural development, theoretical analysis tended to follow practical application, and the use of cold-rolled sections is no exception.

The next stage in the development of cold formed steel structural elements came in the automobile industry. During the First World War, techniques were developed whereby body sections of cars and lorries etc. could be produced by bending or shaping light gauge sheet in the cold state continuously along its length. These techniques were then applied to the production of window frames and similar non-structural elements of buildings. From this, and with the experience being gained in the aircraft industry, it was a short step to the production of thin steel shapes which could be used structurally in building. The age of cold formed structural steel elements was born.

Because of the shortage of steel during the Second World War the advantages of saving weight were obvious and the use of thin-walled sections was consolidated. Roll forming technology spread widely, the number of lines in operation greatly increased and other operations such as piercing, curving, and welding were added to lines. In Europe and other parts of the world the increasing prosperity of the late sixties and seventies created a favourable atmosphere for mass-produced roll formed products. New markets for cold roll-formed products are continually being found, however acceptance of metal products in some sections of industry such as building has been slow because of the traditionally conservative, masonary-orientated costumers [56].

Surprisingly, the importance of cold roll-forming has not led to a large amount of published research in the area [42]. Only recently have computer-aided design (CAD) techniques been applied. Both theoretical and experimental investigations of the process are in their early stages, well behind the stages reached in rolling, or drawing for example.

Traditionally, the areas of roll design and mill setting have relied on individual experience and judgment. The lack of guides, whether it be rules, formulae or accurate instrumentation has caused cold roll-forming to be an unpredictable and little understood process. Down-times of mills are extremely high, often over 50%, as the result of long set-up times and frequent stoppages due to errors in section quality. The potential for savings through the application of scientific research is great, and is demonstrated in this work.

1.2. AIMS OF THE RESEARCH

Diagram 1.1 shows the interaction of the three main areas of this research.

1. Experimental study.
2. Theoretical study.
3. Mill design study.

The overall aim is to improve the utilisation of cold roll-forming mills economically.

This research makes an experimental investigation of cold roll-forming from the most fundamental cases in order to achieve a base from which to work. Past work has been largely concentrated on specific rolling jobs. The conclusions drawn from such tests can only be applied to that particular case and so are of limited use. By taking a fundamental approach, more of the information gained is applicable to a range of specific cases. Starting with a very simple case allows a natural starting point for the experimental and theoretical study of the process. The work has been structured as follows;

Background Work

1. A study of cold roll-forming and the parameters of the process.
2. A literature survey to find the position of research and expose the need for research.
3. Definition of the specific area of research.

Experimental Work

4. Development of a rolling mill for experimentation.
5. Experimental study of the effect of parameters on output quality.

Theoretical Work

6. Evaluation of existing mathematical models.

Mill Design Work

7. Development of systems for increased machine utilisation.

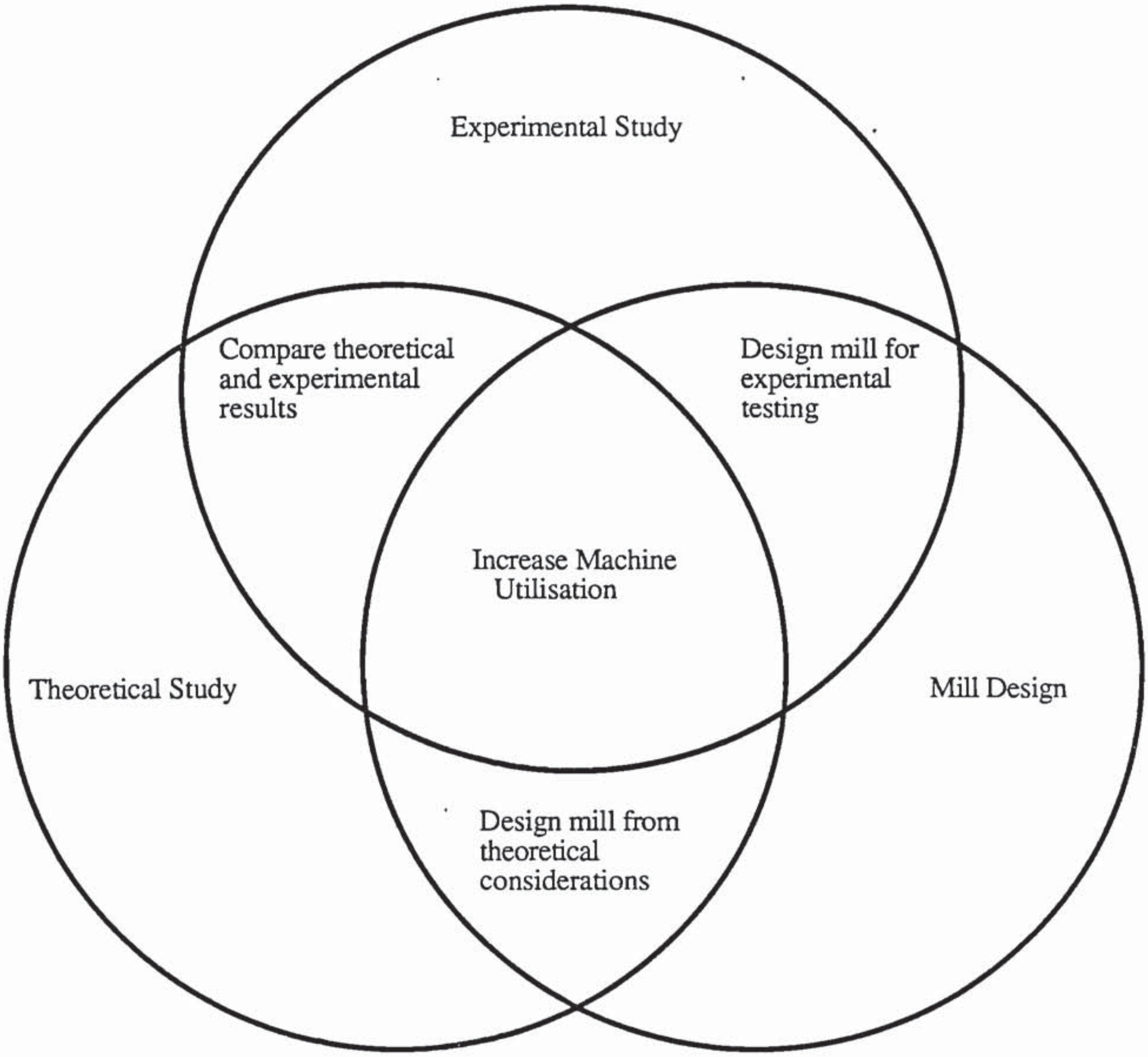


DIAGRAM 1.1 VENN DIAGRAM SHOWING THE AREAS OF RESEARCH WORK

CHAPTER 2

REVIEW OF COLD ROLL-FORMING

2.1 INTRODUCTION

Cold roll-forming can be defined as; "A continuous process of progressively bending metals in a straight line, without changing the material thickness, using successive sets of rotating tools". In practical cases however, there is thinning of the material at bends, and small deviations in alignment of the rolls.

The process provides a very useful sheet metal forming process, capable of the consistent and accurate production of a wide range of profiles in a wide range of ferrous and non-ferrous materials with little restriction in length (1,2,6,9).

A section is produced by the progressive bending of flat strip. Form is imparted to the metal, stage by stage, using successive sets of rotating tools called rolls, or form rolls. Diagram 2.1 shows a view of the strip entering the roll gap between a pair of rolls, and leaving with the roll form. Rolls are paired top and bottom with the option of side rolls on the left and right. The side rolls are rolls with vertical axes, which are used for producing vertical or near vertical legs in a section. This group of rolls is called a roll pass, roll stage, or roll station.

To form a completed section, the strip is fed through a series of roll passes. Generally, the more complex the section, the more passes are required. Rolls are designed to allow a smooth, progressive flow of metal from one pass to the next and unlike many other forming processes, cold roll-forming is not severe.

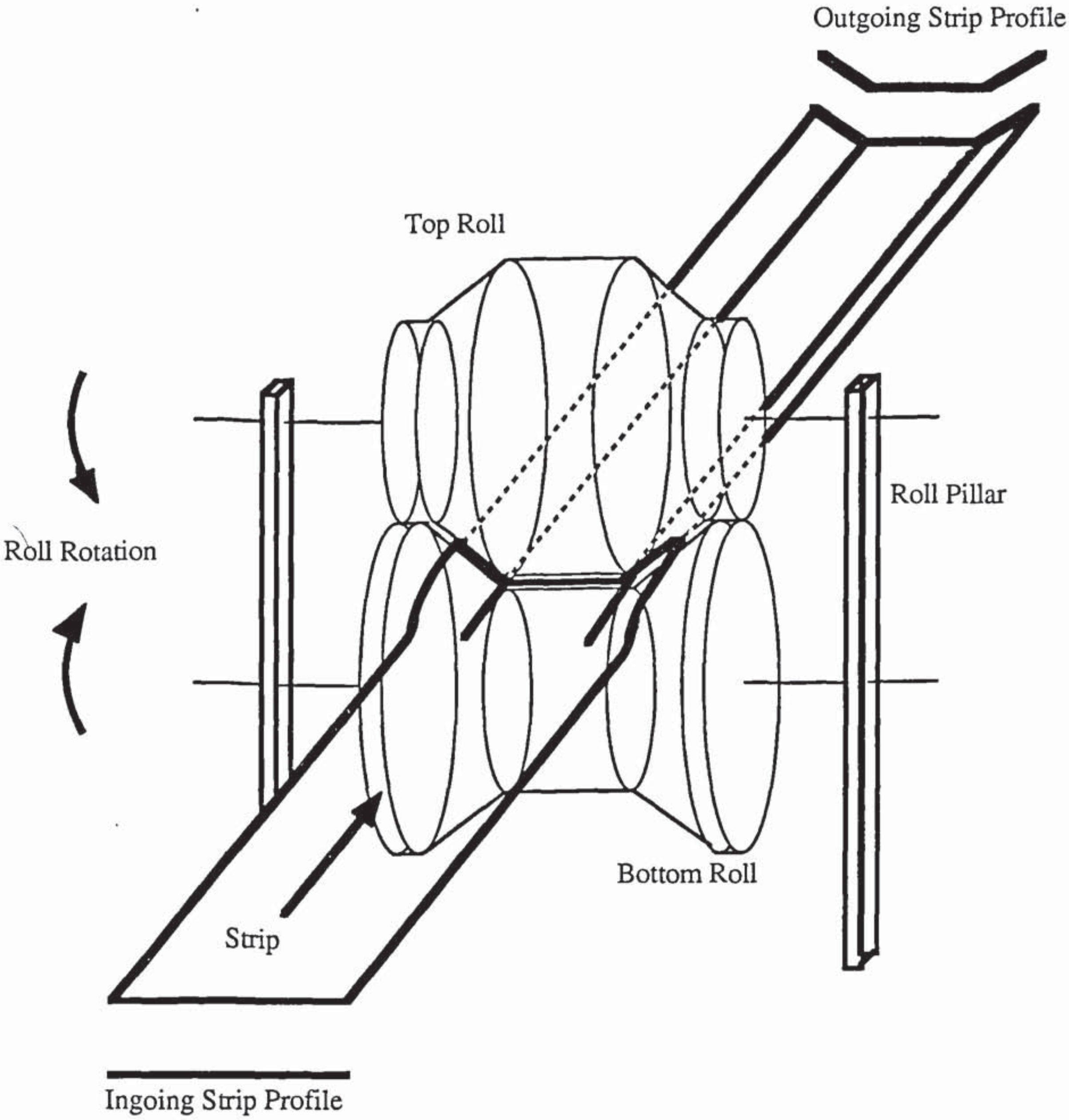
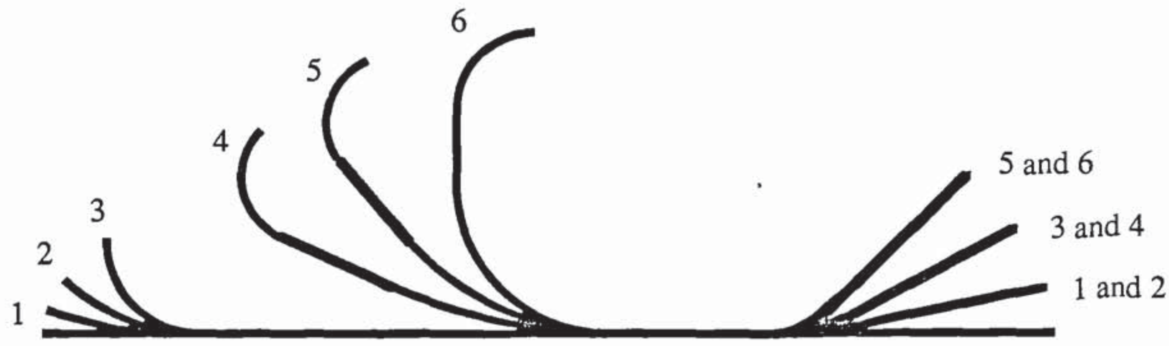


DIAGRAM 2.1 FORMING THROUGH A SINGLE PASS

The cross-sections of the strip at each pass can be drawn superimposed with a nominal neutral axis to give a pictorial representation of the bending. Such diagrams, first described by Vanderploeg (3,6,7,8), are called flower patterns, and have been a useful tool in roll design. Diagram 2.2 shows a flower pattern for a section produced in six passes.

The rolling mill is the carriage for the roll passes. It provides the necessary fixtures to position the rolls and to drive them. The power is used in rotating the rolls and in driving the strip through the mill.

Section profiles at each roll pass



The numbers indicate the pass number

DIAGRAM 2.2 A FLOWER PATTERN

2.2 THE RANGE OF COLD ROLL-FORMED PRODUCTS.

A very wide range of sections can be produced by cold roll-forming. Diagram 2.3 shows a selection. Generally, all metals that can be formed by other common forming processes can be successfully cold roll-formed. This allows roll formers to take advantage of hot and cold finished carbon steel, stainless steel, aluminium and its alloys, copper, brass, bronze and zinc[24,22,9].

The gentle action of the process allows polished, anodised, pre-painted and plastic-coated material to be formed without scuffing. Such material is often used for decorative purposes. Also dissimilar strips of metal can be rolled back to back to form a composite with multiple properties, such as corrosion resistance with strength [16].

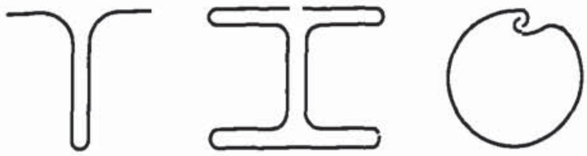
The majority of sections for structural loading applications are "Zs", channels, and angles. These three are the simplest members of three families of sections which contain many relations. Lips and ribs are often incorporated into standard sections to improve loading characteristics in particular applications [3,7,8,31].

Other popular cold roll-formed sections are the different trough-shaped elements which are now widely used for roof decking and wall cladding on many industrial buildings [15]. These are usually provided as pre-galvanised or plastic coated, and need minimal maintenance throughout their working life [73].

Generally only the simpler sections are used structurally. The dimensional and cross-sectional properties of a typical range of sections are given in British Standard BS. 2994 [168].

Fixtures can be added to a roll-forming machine that will form the workpiece into a ring or hoop. Bending shoes or roller-type benders mounted on the machine produce the desired curvature after the cross-sectional shape has been formed. Wheel rims for cars are a typical example of this type of product [24].

Common shapes



"T" beam "I" beam Seamed tube

Basic "Z" Added lips Added lips and ribs

Family of "Z" sections

DIAGRAM 2.3 SHAPES OF SECTIONS PRODUCED BY COLD ROLL-FORMING

Auxiliary operations allow a further range of pierced and perforated products, together with seamed tubes. These operations were formerly too slow to be economic [24,72], but interest is increasing as can be seen by the new papers from Japan in these areas (153,165,166).

2.3 ALTERNATIVES TO COLD ROLL-FORMING

Press-braking offers the greatest competition to cold roll-forming in forming sheet steel to the same shape. However the press-brake is not as versatile in terms of the section it can produce, and is usually suitable for limited quantity production runs (24,31). For forming lengths of 3000 ft and over, cold roll-forming is much cheaper (9).

Cold roll-forming mills become increasingly economic with larger production runs. The pressure of competition has however forced the process further to small batch runs, with the growing needs for reduced set-up times.

Increasingly, cold roll-formed products are in competition with drawn or extruded sections due to the widening of the roll-formed product range. For example welded tubes can now be rolled, competing in the market-place with those that were formerly produced by drawing alone.

In general, if cold roll-forming can be used in shaping products, conversion costs will be low(6).

2.4 THE OUTPUT OF COLD ROLL-FORMING MILLS

Angel (5) in 1949 stated that mills could roll up to 100 m/h of strip. Much later (including the present time), other authors (31,47,72) stated similar maximum speeds of rolling as the norm. As a figure of material output, maximum rolling speed is misleading since it does not take into account the down-times of the mill, and so does not reflect the true output over a long period.

The actual output for rolling mills however, has also remained static, with mills needing to roll batches of over 2000 m of strip at over 600 m/h to remain economic (31,47). This situation cannot remain for much longer with ever increasing needs for flexibility and higher levels of competition.

2.5 ROLLING MILLS

2.5.1 TYPES OF MILL

Mills used for cold roll-forming are of many types. They are available with shaft diameters from 25 to 380 mm, and with width capacities of up to 1.5 m. The number of roll passes can be from one to forty depending on the maximum requirements (24). Most of these machines are built for interchangeability, so a mill can be set up with differing numbers of passes depending on the section demands.

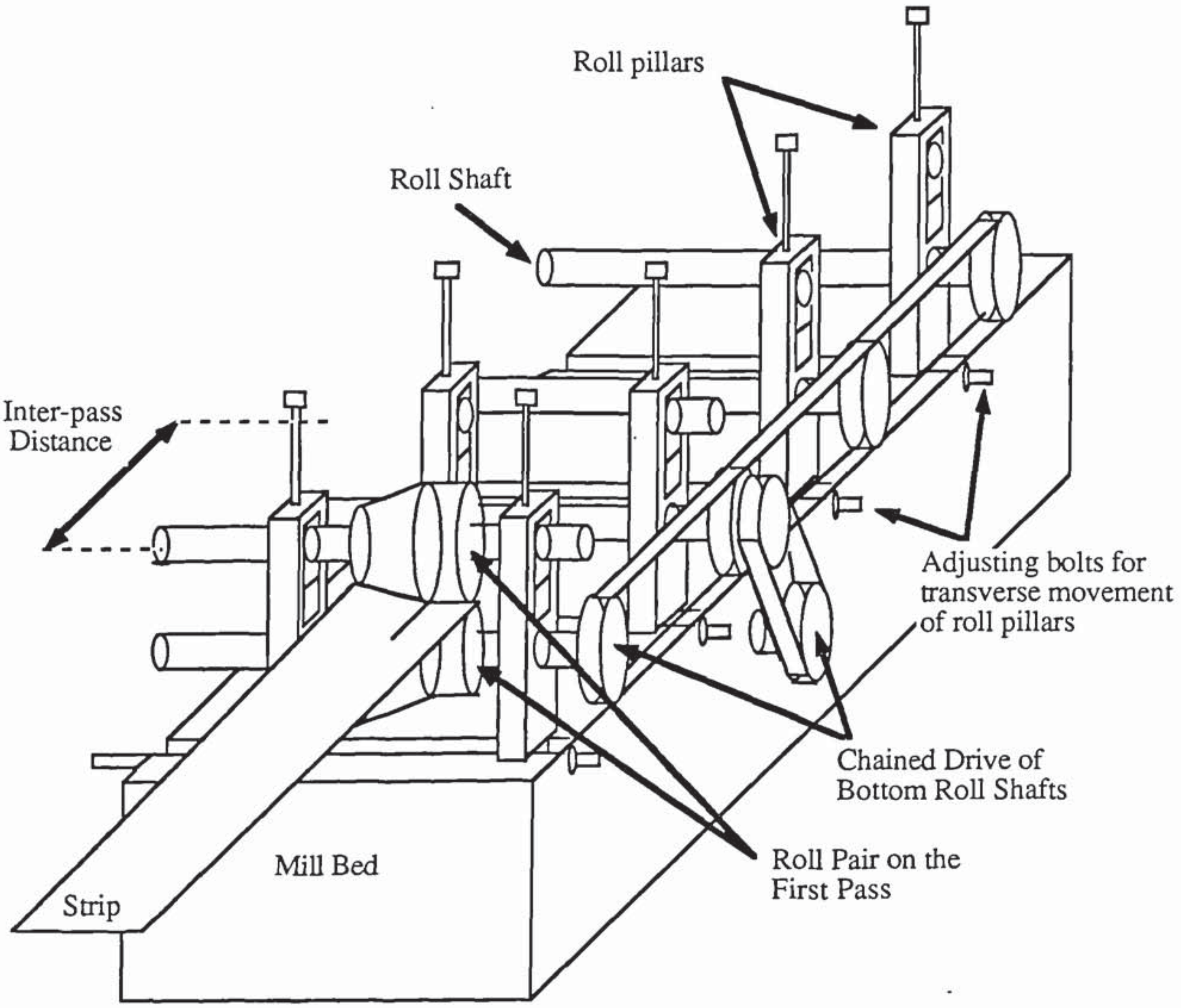
Rolling mills generally fall into two categories. Inboard mills have housings which support both ends of the roll shafts. If the roll shafts are supported at one end only (in a cantilever fashion), the mill is an outboard mill. Outboard (overhung) mills are typically used for thinner material than inboard (24,72). They lack rigidity with roll shafts of 25 to 50 mm limiting their use to rolling mild steel strip of less than 50 mm wide, and under 1 mm thick (to as low as 0.13 mm). However their open design allows fast set-up and changeover times.

Inboard mills are capable of rolling 19 mm mild steel and the widest sections. They are rigid, but slow to set up. One of the roll pillars must be removed to allow the interchange of rolls at a roll pass.

2.5.2 THE DRIVE SYSTEM

The mill includes a drive system usually powered by a 1.5 to 150 kW electric motor. Star and delta configurations are both used. The motor connects to the roll shafts by chain and sprockets, continuous gear trains, or individual gears. Commonly, only the bottom roll is driven, the top roll being left free to idle, thus avoidsing scuffing of the strip. For 22 kW drives and higher, a clutch is used, and often a brake to prevent 'coasting' is fitted (72). Speed control can be electric, e.g. a "Danfoss" power controller, or mechanical, e.g. variation of sprocket sizes. During rolling, the roll speed is rarely altered by the operator. Individually driven shafts are not available on commercial machines.

Diagram 2.4 shows the main parts of an outboard rolling mill with chained drive.



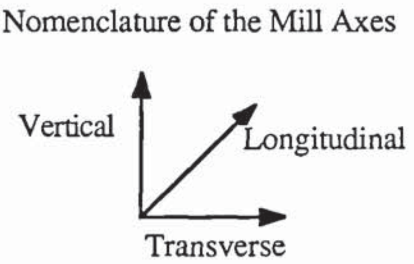


DIAGRAM 2.4 OUTBOARD COLD ROLL-FORMING MILL

2.5.3 ROLL STATIONS

There are various configurations of roll pillars depending on the roll configuration. They locate and lock the roll shafts (and hence the rolls) in the required position. For a simple top and bottom roll arrangement, two vertical pillars are used. Diagram 2.5 shows this arrangement. The bearing block is moved up or down by rotating the pillar bolt. Such adjustment is made to allow the rolls to be slid onto the shafts unobstructed, and also to apply pressure to the strip during rolling.

The whole roll station, consisting of a roll pair, shafts and pillars, is clamped to the mill bed. On some mills, each station can be aligned relative to its neighbours in the transverse plain by loosening the clamps and using adjusting bolts on each side of the pillars.

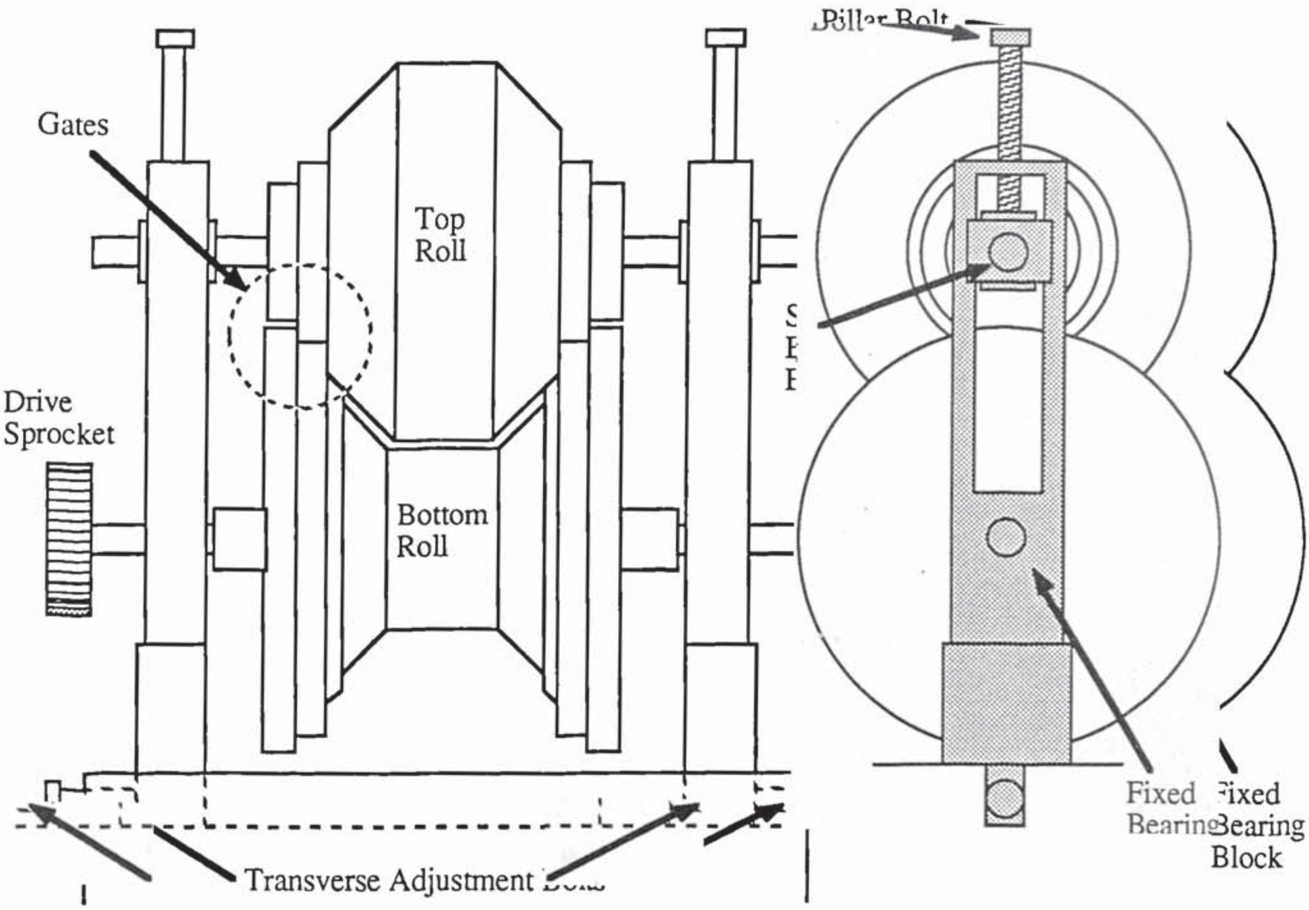


DIAGRAM 2.5 A ROLL STATION, ROLL PILLARS AND ROLLS

Few mills allow an adjustment of the distance between roll stations (inter-pass distance) in the longitudinal or vertical direction. The inter-pass distances are restricted normally to the position of the clamps machined as part of the mill bed, the distance between successive clamps being constant.

2.5.4 AUXILIARY EQUIPMENT

In addition to the rolling mill, there are several other pieces of equipment that are usually required for the production operation. These include stock reels, materials handling machines, lubrication systems, welding equipment, cut-off machines, piercers and notchers, guides and straightening equipment.

The cut-off, piercing and notching equipment is of special interest because it often determines the maximum line speed [72,10,24]. Presses for these operations are most frequently mechanical, but sometimes pneumatic and, in rare cases, hydraulic. Due to the continuous nature of cold roll-forming, flying die techniques are used. Flying dies are so called because they accelerate to the speed of the moving strip. Once synchronised with the material, the stroke is performed "on the fly". The flying die press function is actuated through various types of length sensing and press triggering mechanisms. Frequently these functions are microprocessor controlled.

Precut lengths of strip can be rolled, however such sections tend to result in flare of the leading and trailing part ends, and are not suitable for short section lengths.

Welding equipment also affects the maximum line speed, whereas the other parts which make up auxiliary equipment have effects over the set-up time and other down-times. Generally, these pieces of equipment are particular to the rolling company and vary diversely [9,10,24,31,72].

2.5.5 LUBRICATION

Roll-formers need to have a good knowledge of lubricant properties. Inappropriate choice of lubricants can cause many problems such as sectional distortion due to differential friction, surface defects such as white rust, staining, blushing, blistering and peeling and the need for auxiliary degreasing operations; thus many sections are rolled without lubricant.

Lubricants are used to reduce sectional distortion due to heat, and to give a better surface finish by reducing scuffing and by "flushing" away debris from between the rolls.

Additionally they can reduce wear and prolong tool life.

Ivaska (61) produced a tabulated guide to the type of lubricant suitable for specific metals, and investigated the most common lubrication problems.

2.6 ROLL PRODUCTION

2.6.1 INTRODUCTION

Errors in roll production can lead to;

1. Scrapping rolls
2. Remachining rolls
3. Increased set-up times
4. Reduction of roll life
5. Instability and unreliability leading to frequent stopping and resetting of the mill
6. High levels of scrap strip

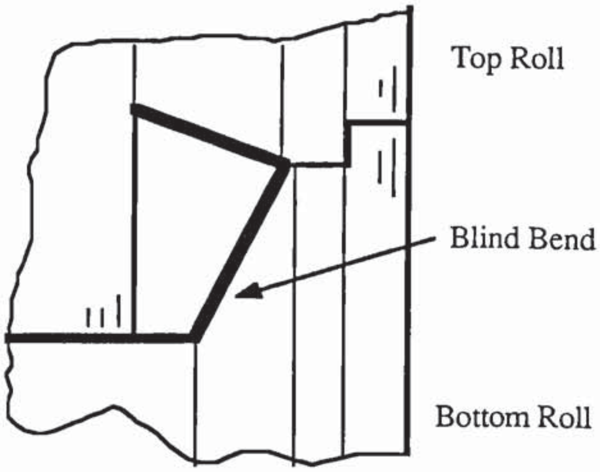
Accurate roll production is thus of great importance to roll-formers. The conventional approach is described as follows;

Roll production incorporates four main elements;

1. Section redesign for manufacture.
2. Flower pattern design.
3. Roll design.
4. Roll manufacturing

2.6.2 SECTION REDESIGN FOR MANUFACTURE

Purchasers of roll-formed sections define certain geometric criteria for the profile. Others are left undefined and are free to be changed by roll designers, to aid the ease of manufacture. Certain features in sections are difficult to produce. It is therefore useful if the roll designer and section designer can work together in producing a section, with the required properties, that can be manufactured easily.



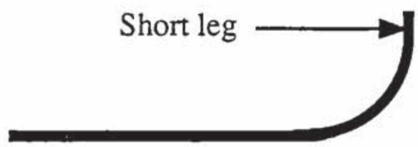


DIAGRAM 2.6A. BLIND BEND

DIAGRAM 2.6B. SHORT LEG LENGTH

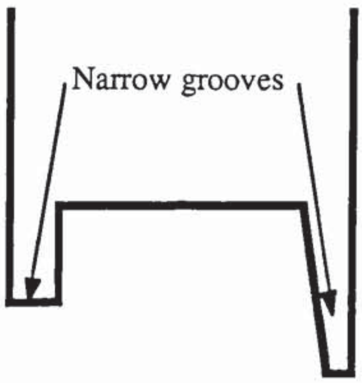


DIAGRAM 2.6C. EXAMPLE OF SECTION CONTAINING NARROW GROOVES

Design features to be avoided in sections are ;

1. Large radii. Springback increases as the ratio of radius to thickness increases. The minimum ratio can be found in tables.
2. Blind bends (Diagram 2.6A). These occur where the section profile is not followed by the roll profile due to geometric constraints.
3. Short leg lengths (Diagram 2.6B).
4. Deep narrow slots (Diagram 2.6C).

Such features cause production difficulties which are usually evident in the inaccuracy of the rolled section profiles.

2.6.3 FLOWER PATTERN DESIGN

Flower pattern design can be split into four main areas.

1. Orientation of section
2. Sequencing of bends
3. Amount of bending at each stage
4. Means of forming bends

2.6.3.1 ORIENTATION OF SECTION

Any section orientation is determined by a number of (often conflicting) considerations, careless orientation may result in tooling, production or quality problems. As with many other aspects of roll forming, section orientation is often a compromise, some of the factors influencing the designer's final decision are described as follows.

Whenever a bend is not formed by both a male and a female roll it is termed a blind bend or fresh air bend, such bends often result in sectional inaccuracy and are thus to be avoided if at all possible. Careful orientation can reduce fresh air bending. (Diagram 2.6A illustrates fresh air bending).

Springback (elastic recovery) is a common problem in roll forming, and there are several methods for overcoming it. Where springback is likely to be a problem, careful section orientation will allow the use of side rolls to "overbend" a leg.

The section orientation will be influenced by the preferred vertical centre line, a theoretical line the position of which relative to the centre of the machine does not change. Where mention is made of the left hand side or right hand side of a section this refers to the position relative to the section centre line. The vertical centre line is itself often a compromise, the main criteria for choosing it being balancing horizontal forces each side of the guide line allowing metal movement by forming rather than drawing, and choosing a vertical centre line which passes through the deepest part of the section.

The surface finish of pre-finished material can be damaged by careless orientation. The pre-finished material should be orientated so as to minimise "rubbing velocity " (the relative roll velocity between opposite surfaces) and also, if possible, to aid operator inspection. Staining may occur on sections if coolant trapping is possible, this may be minimised by careful orientation of a section.

Auxiliary operations such as notching, piercing, embossing and welding can obviously dictate a section orientation. Cut-off tooling should also be considered since, by careful orientation, it may be possible to eliminate additional de-burring operations by altering the position of the burr.

2.6.3.2 SEQUENCING OF BENDS

The order in which the designer chooses to form the bends is termed the sequencing of the bends. In very simple sections, such as channels and angles, there is no choice in the sequencing (since there is only one bend); in complex sections there are a very large number of possibilities.

Ideally, designers work from the centre line outwards in sequencing, which means that a bend once formed is never subject to further deformation. However, a designer must consider a large number of often conflicting factors when sequencing bends. Hence it is often not possible to work from the centre line outwards since often there are good reasons to form by other sequences, e.g. to avoid fresh air bending or to reduce metal movement or to avoid excessively large bending moments.

Fresh air bending refers to bending where only one roll is in contact with the active bend, such as in diagram 2.6A. It is sometimes impossible to eliminate fresh air bending in a section but, by careful sequencing of bends, it can be minimised. Careful sequencing can also reduce the amount of metal movement between passes, when required.

2.6.3.3 AMOUNT OF BENDING AT EACH STAGE

Whilst there are a number of techniques to aid the designer in deciding how much forming to perform, there is no single generally accepted method.

It is common to adopt standard sequences of bends for forming legs. While such standards are quick and simple, they take no account of sectional properties, material properties or mill properties, and cannot be considered ideal.

2.6.3.4 MEANS OF FORMING BENDS

Having decided on the sequencing and magnitude of the bends, it is necessary to think of the means of forming of bends. In general, the only parameter within the designer's control is the inside radius of the bend (although it is also possible to control the shape of the bends).

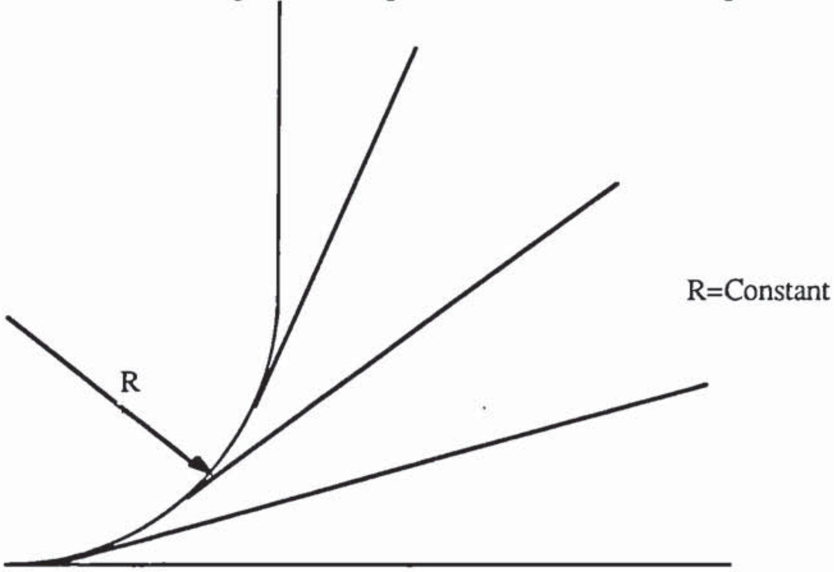


DIAGRAM 2.7A. CONSTANT INSIDE RADIUS METHOD OF FORMING BENDS

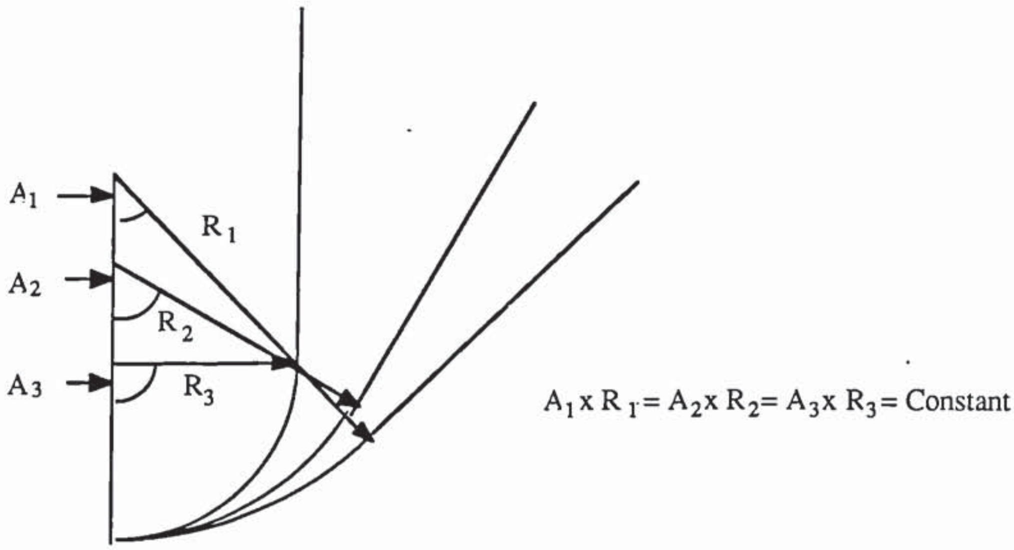


DIAGRAM 2.7B. CONSTANT ELEMENT LENGTH METHOD OF FORMING BENDS

The two most common methods of forming bends are the constant inside radius method and the constant element length method (Diagram 2.7A and 2.7B). Each method has its advantages; the constant inside radius method reduces springback and distributes deformation evenly between passes, whereas the constant element length method reduces wear on the rolls and reduces the likelihood of "trapping" of metal.

The designer should decide which method is the most suitable for each job. In practice it is likely that individual designers use one method or the other,and become skilled in minimising the disadvantages.

2.6.4 ROLL DESIGN

The roll profile is mainly dictated by the flower pattern, however there are additional features which require design consideration at the roll design stage.

In order to form near-vertical legs, and to perform the minimum amount of fresh air bending, side rolls may be used. However on many mills where side rolls are used, the pass cannot be used to "drive" the metal. Therefore, whilst side rolls are often indispensable, the designer must be very careful when deciding on their use.

In order that "drive" will always occur, the distance between the driving surfaces must be less than or equal to the minimum permissible metal thickness. Since it is undesirable to have contact on non-drive surfaces, the distance between non-drive surfaces must be adjusted to be greater than or equal to the maximum metal thickness .

The diameter of each roll must also be decided at this stage. The radius at the midpoint (in the transverse axis) of the bottom roll is referred to as the "pass height", whilst the radius of the bottom roll plus the strip thickness plus the radius of the top roll, is referred to as the "centre-to-centre distance". Use of large roll diameters often result in deformation being evenly distributed between passes and reduces the differential surface velocity between different parts of deep sections. However, large diameter rolls are expensive to manufacture and can result in production and setting difficulties. By altering the pass heights, it is possible to create "uphill" or "downhill" on a section; some designers like to arrange the pass heights so as to keep the vertical coordinate of the centroid of the section constant, whilst others prefer constant pass heights (47).

2.6.5 ROLLS AND ROLL MANUFACTURING.

Rolls are made from various steels depending on their application. Low-carbon steels or grey iron, turned and polished, are used for undemanding low production runs. They machine easily and are relatively inexpensive. For more demanding sections, low-alloy tool steel (such as O1 or L6) or high-carbon, high-chromium tool steel (such as D2) are used, all hardened to Rockwell C 60 to 63 and sometimes chromium plated. These are more expensive in material and machining cost, but can form sharp angles in sections of thicker strip and have longer life (up to 1500 km of strip for low-alloy steels and over this for high-carbon high-chromium steels, between regrinds). Chromium plating is sometimes necessary where surface finish requirements are high. Plated rolls scratch less than un-plated and pick up fewer impurities(6,24,68).

Other roll materials are occasionally used in special circumstances, e.g. soft bronze and nylon rolls have been used in rolling coated materials (24,68).

In conventional roll manufacturing, there are three usual ways of transferring the roll design data to the machinist;

1. A detailed roll drawing can be produced, which the machinist must study and translate into the necessary cutting actions. This is a slow, complex and consequently error-prone method of production, requiring a high level of machining skill, suited for "one-off" cases.

2. A solid template of the roll profile is milled, and used in conjunction with a copy lathe to manufacture the roll. This is a more reliable method, but templates are expensive and slow to produce, and a copy lathe is required.

3. A compromise is by the use of a wire template and a simplified roll drawing (which defines that information which is not contained in the wire template). The method relies on machining skill, but the templates can be used as a checking profile.

Rolls need to be machined to high accuracy to be efficient tools. The geometries of roll profiles may be highly complex, and errors in machining are costly in terms of scrap and lost production time. For these reasons, Computer Numerically Controlled (CNC) lathes are being found suitable for roll production (76-106), replacing conventional methods.

Rolls have a hollow bore to allow the roll shaft to run through. Both shaft and bore have keyways so they can be locked together (See photograph P5 and P6). The form of the rolls includes the surfaces that contact the strip and also other surfaces called gates that lock the top and bottom and side rolls in the vertical and transverse direction, relative to each other. Diagram 2.5 illustrates these surfaces for top and bottom rolls.

The roll drawing defines the gating (Diagram 2.5). The type and size of gates depends on the scale and orientation of the section but, in general, are not critical to the forming of the section.

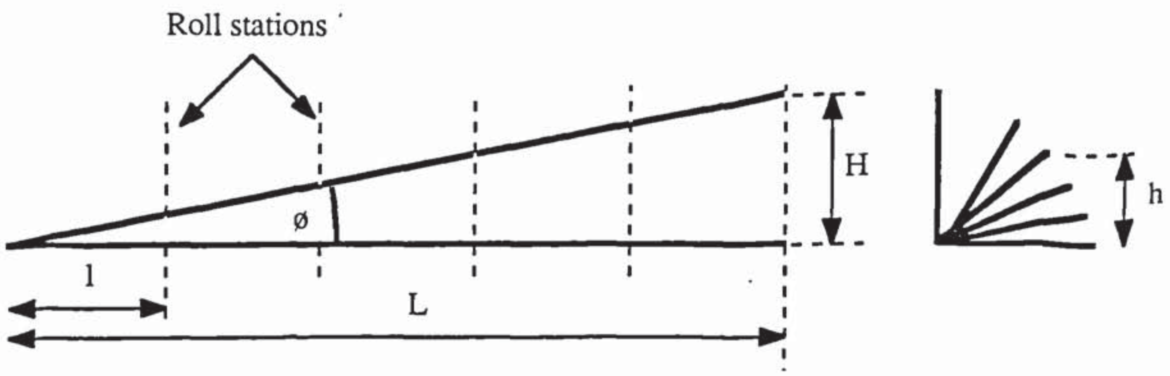
2.6.6 PRINCIPLES OF ROLL PRODUCTION

Conventional roll production relies heavily on roll designers skill in decision making. There are many considerations, as have been described, but few rules. It is the roll designer's work to find a solution which avoids most of the causes of production difficulty. Through experience, the relative importance of certain considerations in certain cases becomes learned. A good roll designer is therefore a valuable asset.

The roll designer will usually be confronted with a section that is the same or similar to a section that has been rolled previously. By referring back to past successes, suitable designs can be suggested with a high level of confidence in the quality of the output.

In design of totally new sections, roll designers must rely wholly on their experience and judgment. For this reason roll designing has come to be considered a "black art". Cadney (42) estimated that roll designers used 80% experience and judgment, and 20% science in designing rolls. Certainly many sources (e.g. Cadney [42], Bhattacharyya [160,127,120], Jimma and Ona [102,1146,157]) have concluded roll design to be an area of art rather than science and, as result, it is an area of uncertainty and error.

The science behind cold roll-forming has developed slowly. Angel [5] is generally acknowledged as the first to attempt to produce a useful formula for roll-formers. His work gave the "forming angle" formula for use in calculating the number of roll stations. The principle was based on keeping the amount of incremental bending equal at each pass, and for the bending to be kept below a set maximum. Formulae were derived by considerations of geometry in a simple channel section and, as such, were only applicable to these sections. Diagram 2.8 illustrates the formula. Angel suggested the forming angle ø should be 1.25°.



L=Cot ø x H   Where ø = forming angle
h = height of any given pass
H= height of bend
l = horizontal centre distance
L = forming length

DIAGRAM 2.8 THE FORMING ANGLE METHOD OF CALCULATION

Strip width calculations are used to estimate the raw material width required, and also to determine the material needed to form a bend for the one of the two main types of bending. The calculations are really no more than applied trigonometry. For a curved element of inside radius up to 2t (t being material thickness) then;

$$w = a(r - t/3)$$

Where;

w is the strip width

a is the angle to which the metal is bent in radians

For sharp bends r is omitted so

$$w = a(t/3)$$

If the material is less ductile than mild steel, then t/2 is substituted for t/3.

Several authors have questioned the validity of the forming angle theory, primarily since it infers that increasing the pass length always allows correspondingly more bending to be performed. Sarantidis (143) argued that, since from experimental work he observed that virtually all the forming took place in the region of the rolls, the pass length was irrelevant. Cadney (42) observed that the forming angle theory took no account of the discontinuous metal movement, and that the experimental work on which the theory was based was probably unrepresentative.

Also in 1981 Cadney (42) commented; "Specifying the number of roll stations for a bend is remarkably difficult to do in any way other than by taking individual cases. Generalisation is difficult and unreliable using what is optimistically termed 'current theory', of which the sum total seems to be the forming angle. In my experience the number of stages can vary between two and nine for a 90° bend, depending on material type, thickness and whether there is already a profile on the material edge".

Wright (72) writing in 1987 also brought attention to the lack of theory in interviewing roll-formers e.g. "There is better equipment better tools, and hopefully the engineers have learned a few tricks, but I haven't seen any drastic developments", and "they haven't found a way to make a computer think like a good tool designer". These comments highlight the slow acceptance of scientific principles into cold roll-forming.

Work in Japan (122,125) and New Zealand (117,120,127) have produced various mathematical models to aid roll design, that are claimed to be accurate (see Chapter 3). This has however had minimal affect on the Industry's trust in experienced roll designers in this country.

2.7 MILL SETTING

2.7.1 INTRODUCTION

There are different setting up procedures for different mills. However, in the conventional approach for setting an outboard mill, the mill setters work follows the following order;

1. The back roll pillar is put onto the mill and roll shafts inserted.
2. The rolls, spacers, keys etc., for the first pass are slid onto the pillar shafts.
3. Strip is fed usually from a guide until its leading edge is just before the first pass.
4. The rolls are moved transversely until they align with the material from the guide.
5. The strip is pushed through the first roll.
6. The roll station is locked down.
7. The pillar bolts are tightened down.
8. The material is inched forward until it appears protruding from the pass.
9. The material profile is examined by comparison with a wire template for geometric accuracy, and also any faults in surface finish, twisting, buckling etc. are checked.
10. If there is a fault, adjustments are made to the roll alignment and roll pillar pressure and the material is inched a little further, the previous profile being cut off with a saw to reveal the new one.
11. If there appears to be a large error in alignment the material may be reversed out of the pass. On reversing, new corners are formed in the section by the side of those formed when "inching" forward. This helps the setter judge how far to adjust the roll alignment. The process from 3 is then repeated.
12. The process from 1 to 11 is repeated for the next rolls until all the roll passes h /e been set correctly.

The roll setting time is unpredictable and, as for roll designing, dependent on experience and judgment. Roll setters have a number of variables they can adjust to achieve a section of acceptable quality. These variables are called the Operating Conditions (Operating Variables or

Operating Parameters).

For the mill described, the operating conditions are;

1. Roll Load (or roll pressure).
2. Roll Alignment (transverse).
3. Rolling Speed.
4. Inter-pass Distance (incremental; dictated by the position of machined slots in the mill)
5. Lubrication (not normally chosen by the setter)

Further operating conditions are available on some mills, such as vertical roll height and angle of rotation of the whole final pass about the longitudinal axis. Inter-pass distance may also be continuously adjustable.

There may be cases where mill setters cannot achieve the desired section quality and the roll design will have to be changed, new rolls machined and the mill set up again.

Mill setters also have a second function, which is to maintain the required section quality during rolling. If the section quality falls to an unacceptable level, the mill is stopped and adjustments made to the operating conditions (normally roll load, and roll alignment) in an attempt to remedy the fault. As such, the setter forms a part of a manual feedback system. The actions of mill setters can worsen the situation, and in some cases the mills have to be reset from scratch.

Errors made in mill setting have as much importance to down-time and high costs as errors in roll design. Such errors can lead to;

1. Damage to rolls, and reduced roll life due to poor roll alignment and excessive roll loads.
2. Unnecessary rejection or remachining of rolls.
3. Over-correction or under-correction of operating conditions causing excessive down-times.
4. High levels of scrap.

It is through a combination of good roll production and good mill setting that high quality sections are maintained.

2.7.2 PRINCIPLES OF MILL SETTING.

The literature survey revealed that there was very little work published on mill setting. That which did exist showed that there were few new principles for mill setters, and those developed had only been implemented in isolated companies within the last ten years.

At Hadley's Sections in Smethwick, a successfully competitive cold roll-forming company, mill setting remains an art. In general, roll loads are measured by feel and chosen through experience; alignments are judged by eye; inter-pass distances, roll speed and lubrication are chosen through experience alone.

In essence, there are no rule-based principles applied in conventional mill setting.

2.8 PRODUCTION LIMITATIONS IN CONVENTIONAL COLD ROLL-FORMING

2.8.1 INTRODUCTION

Cold roll forming is a process of low machine utilisation, average levels being 20-30% (56) (Machine utilisation is regarded as the ratio of actual output per year to theoretical output of running the line constantly at full speed, one shift per day for one year). The low levels are due to very high down-times. In improving the output of a process, research is often directed at increasing the speed. However, in the case of cold roll-forming, there are larger possible gains in reducing down-time. The causes of down-time are;

1. Setting up
2. Strip down
3. Length change
4. Waiting for information
5. Faulty rolls
6. Defective tool
8. Machine fault
9. Tool trials

10. Reject material
11. Material shortage
12. Meal break
13. Down-time without reason
14. No work
15. No labour

Specific to cold roll-forming, down-times are associated with roll design and mill setting. To remain competitive cold roll-formers must minimise these areas associated with low productivity and high costs. The importance of fast, accurate roll setting and good roll design is of obvious importance to roll formers. However, the lack of scientific knowledge in this area indicates that Industry has not been willing to invest in research and development. Cadney [42] described the cold roll-forming industry as "stagnant", reflecting complacency and a fear of no immediate returns from research. Britain's industries have frequently declined due to lack of investment in long-term research and development. Halmos [56] observed that roll forming mills have an average life of 20-25 years, and so no sudden changes in the industry would be expected. However, he further predicted that to remain competitive into the 1990's, roll-formers would have to invest in new technology, research and development.

2.8.2 SUMMARY OF APPARENT PRODUCTION LIMITATIONS

1. Rolling mill utilisation is low.
2. Roll production and mill setting are unpredictable and error-prone.
3. Errors in roll production and mill setting are costly in lost production and wastage of material.
4. Roll production and mill setting are areas of high skill, take lengthy training, and are time-consuming.

2.8.3 SUMMARY OF UNDERLYING PRODUCTION LIMITATIONS

1. Roll production and mill setting are both based on the reliance on past experience and are hence unpredictable.
2. Mill setting is based on remedial action not on the cause.

3. There are few guidelines (rules, formulae) for roll designers and mill setters.

4. There are no methods of predicting quality of sections prior to production of the rolls.

5. There are no methods of predicting quality from the changes made by mill setters.

CHAPTER 3

COMPUTER AIDS IN COLD ROLL-FORMING

3.1 INTRODUCTION

The increase in competition, economic pressure, and the growth of technology, have caused an increase in the amount of research and development work in cold roll-forming. The limitations discussed in chapter 2 have been acknowledged as reasons of low productivity and have been made the subject of investigations. As a result there has been an increase in the understanding of the process, which has led to improved production techniques.

This chapter describes the work which has taken place in applying the computer to cold roll-forming techniques.

3.2 CAD / CAM

3.2.1 INTRODUCTION

The applicability of computers to roll design and manufacturing was appreciated early by roll formers. As a result there are working CAD / CAM systems in use today. The abilities of the computer to carry out large numbers of calculations rapidly, to store and recall information, produce detailed graphics and allow easy editing, have all been exploited.

The extent to which CAD / CAM has been tailored to fit the needs of roll formers is varied. Two approaches have been taken. First, general CAD / CAM packages have been purchased, and the applicable features used. This has allowed roll formers to get systems operating quickly, with good product support. Secondly, CAD / CAM systems have been designed by roll formers for their specific needs. Although taking longer to set up, these systems are better suited to the company requirements, and do not have redundant features.

Initially CAD systems were devised to relieve roll designers of much of the work in tedious calculations and complex roll drawings. Step by step growth in computer aids then led to changes in the manufacturing of rolls. Use of NC lathes was realised to give great reductions in machining time, and improved roll accuracy. These lathes could be programmed with digital information produced directly from the CAD systems, to give CAD / CAM systems.

3.2.2 A REVIEW OF CAD / CAM SYSTEMS.

Various descriptions of working CAD / CAM systems for form rolls have been published. The following list names the systems, and gives their origin;

1.	MTIRA	U.K. (76,80,83,86,87,88,89,104)
2.	METFORM	U.K. (95)
3.	ROLLSEC	U.K. and Sweden (85,99)
4.	ROLL DATA	U.S.A. (81,82)
5.	GIFFORD-HILL	U.S.A. (77,78,79)
6.	INDUSTRIE SECCO	Italy (96)
7.	DELTA ENGINEERING	Canada (100)
8.	JOHN LYSAGHT	Australia (84,94,97)
9.	ASTON UNIVERSITY	U.K. (92,93)

The above systems, although different from each other, have common features and essentially perform the same function. By running through the Aston University system as an example,. these features are described.

The CAD software comprises five parts;

1. Finished section programme
2. Flower pattern programme
3. Template programme
4. Roll design programme
5. Roll editor programme

The CAM software is a post-processor programme.

Each programme has input and output files. The software reads the input files to create the output. Input files can be typed in as data, or are produced as output from a preceding programme. All the files are saved and can be re-run when required. Parts of the software can read files to produce graphics on plotters or computer screens, or coded instructions for other pieces of hardware.

3.2.2.1 THE FINISHED SECTION PROGRAMME

The finished section programme, defines the finished section numerically, produces the finished section drawing, and calculates the strip length.

The shape is defined by the user considering the section as numbered linear and circular elements. The linear elements are described by length and thickness, and the circular by inside radius of curvature angle of bend and thickness.

The programme plots the section given this information, and allows title block details to be added to the drawing, (diagram 3.1).

The strip length is calculated by adding up the strip lengths of the elements. For linear elements the strip length is the element length. For circular elements, the strip length is calculated as the product of the angle of bending and the radius to a neutral axis, called the mean radius.

$$R_m = R + kt$$

Where R_m = mean radius

R = inside radius

k = a constant called the bend factor

t = strip thickness

There are several authors (10,24,25,33) who have produced tables for determining the bend factor. Normally the values vary from 0.33 for formable materials, to 0.5 for less formable materials.

3.2.2.2 THE FLOWER PATTERN PROGRAMME

Flower patterns remain as important in CAD roll design as they do in manual roll design.

The flower pattern is defined by choosing elements to be bent at each stage, and then by giving the amount of bending at those stages.

The software draws the flower pattern with each stage on the same origin, or on separate origins, or both (diagram 3.2). This gives the designer a visualisation of the design. Other systems allow the centroid of the section to form the constant position in the flower pattern.

Most of the systems allow the choice of constant element length or constant inside radius (described in chapter 2) in definition of curved elements.

3.2.2.3 THE TEMPLATE PROGRAMME

Templates are not required when using NC lathes. However, templates can still be used to check the profile quality of formed sections and, if necessary, used when machining with conventional lathes. The programme produces a drawing of the profile on the screen (diagram 3.3), and a 10 times scale plot on paper. Using a shadowgraph, a 10 times scale shadow of section profiles at each pass can be projected over the plot as a visual check for geometric accuracy.

DIAGRAM 3.1 SECTION DESIGN DRAWING

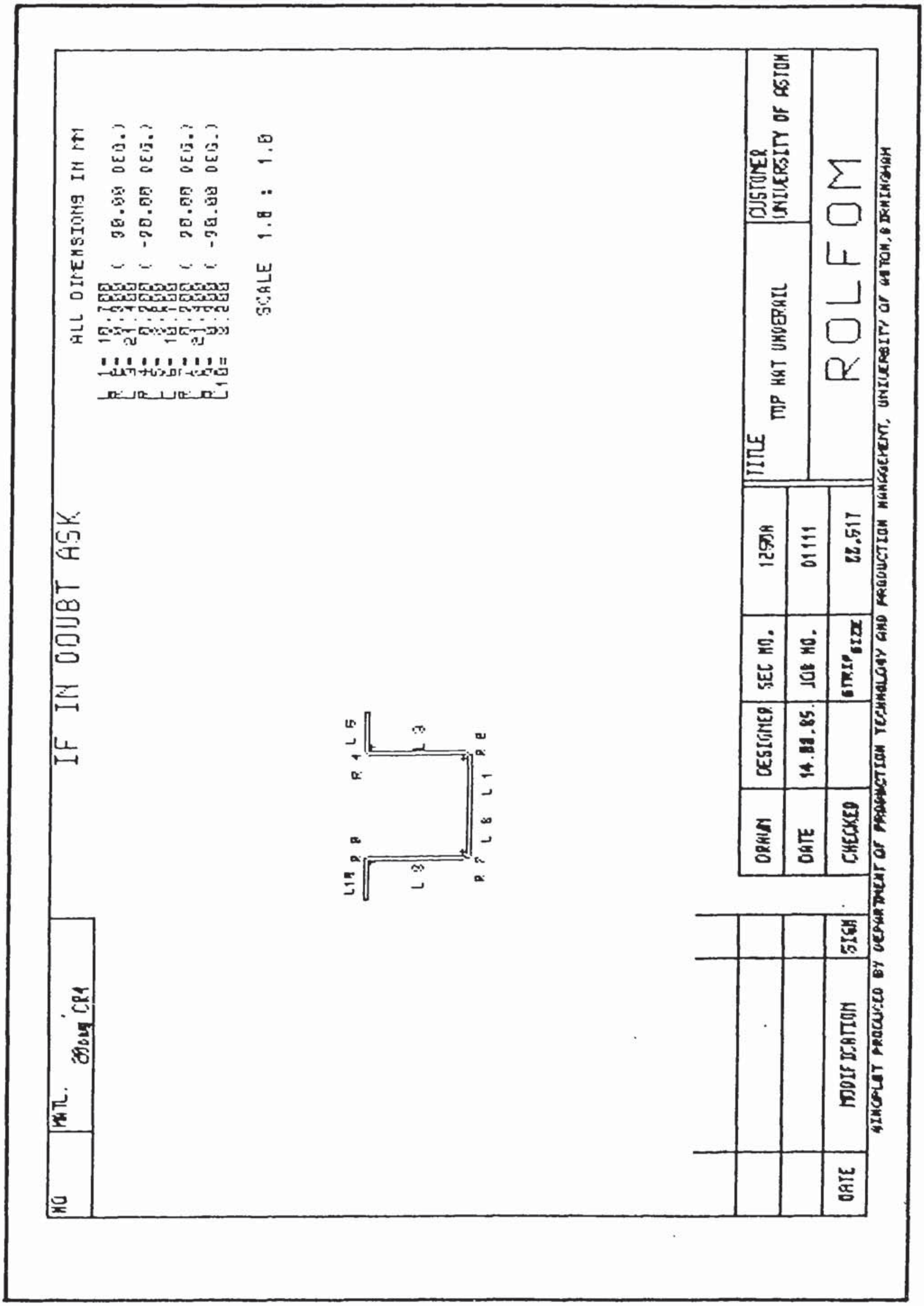
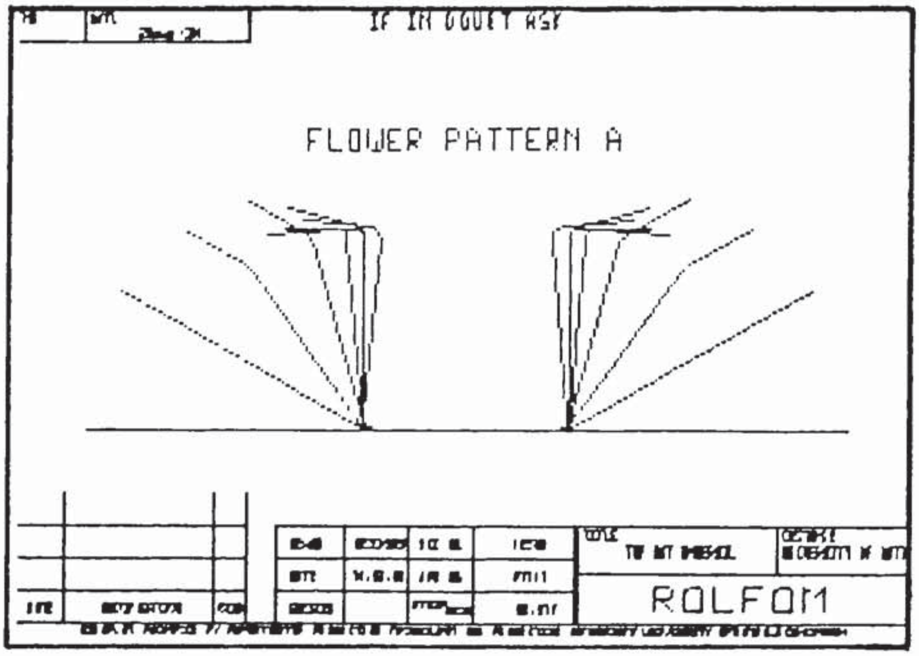


DIAGRAM 3.2 DRAWINGS OF FLOWER PATTERNS IN TWO CONFIGURATIONS



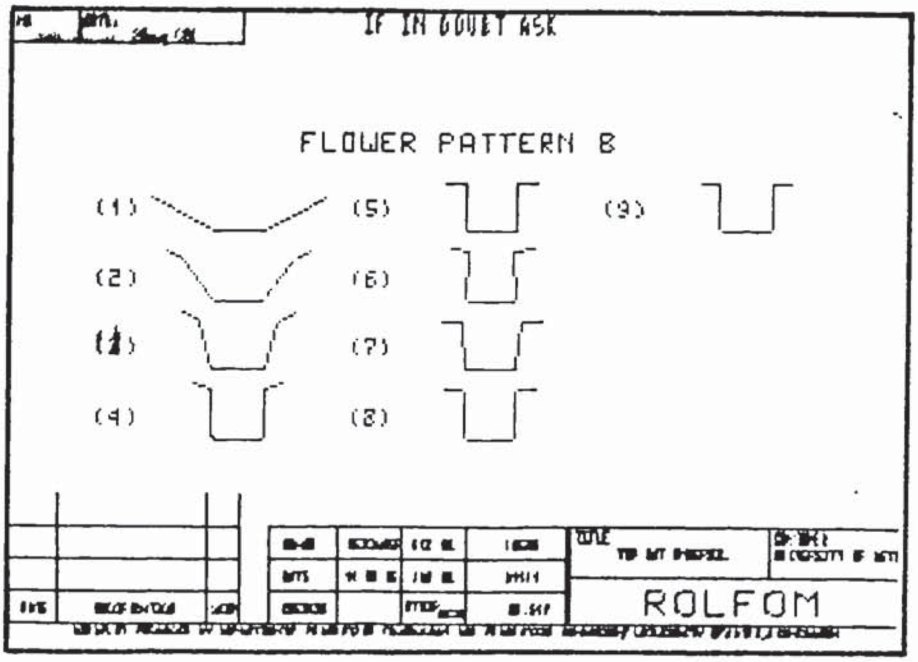
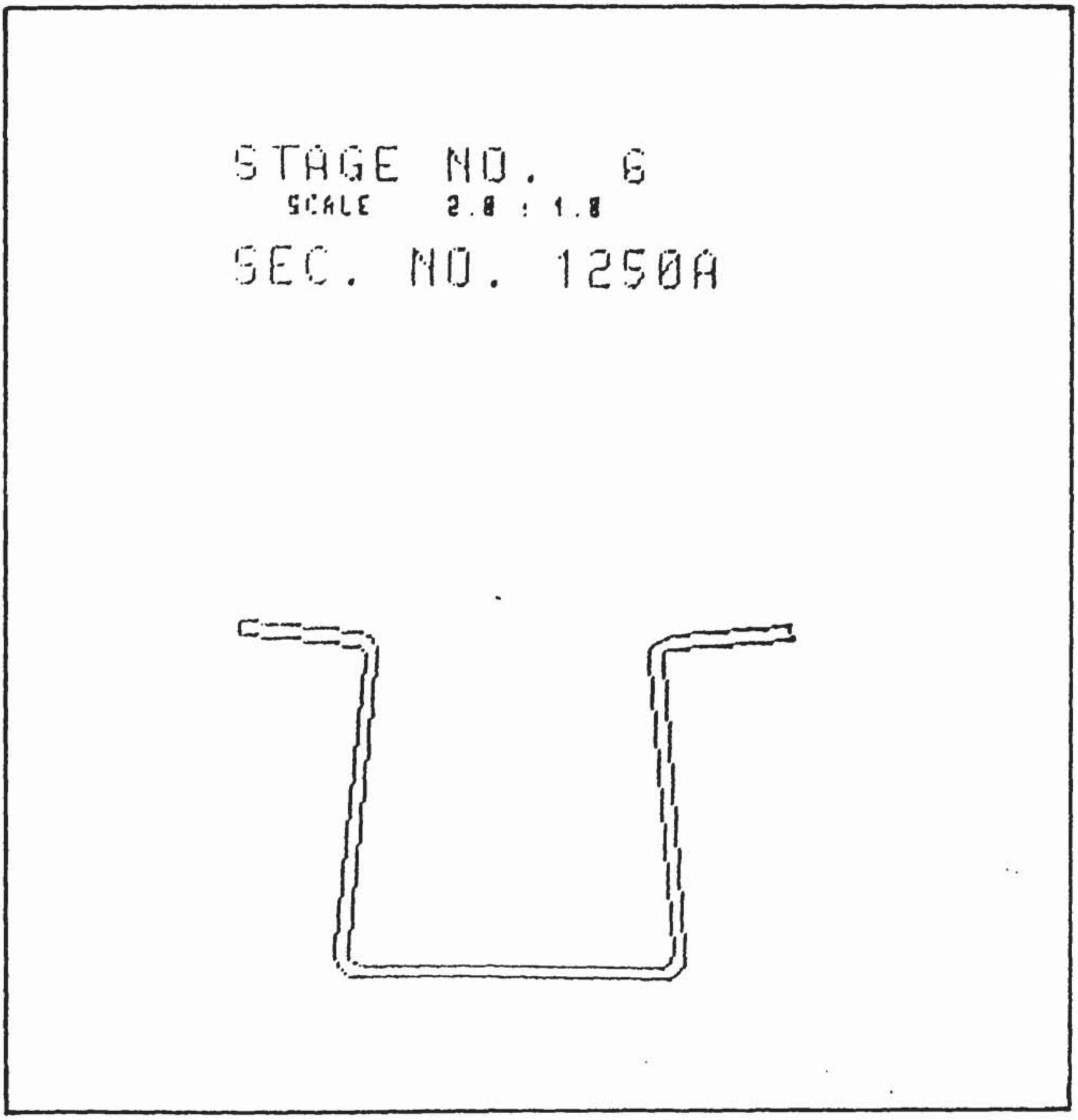


DIAGRAM 3.3 TEMPLATE DRAWING OF PASS 6.



3.2.2.4 THE ROLL DESIGN PROGRAMME

Five groups of data input make up the roll design programme

1. Pass height and roll centre-to-centre distance
2. Strip tolerance
3. Pinch difference
4. Side roll definition
5. Extension contour and gate definition

Pass height and centre-to-centre distance can be input as two values defining all the stages, or as separate values of each, for each pass.

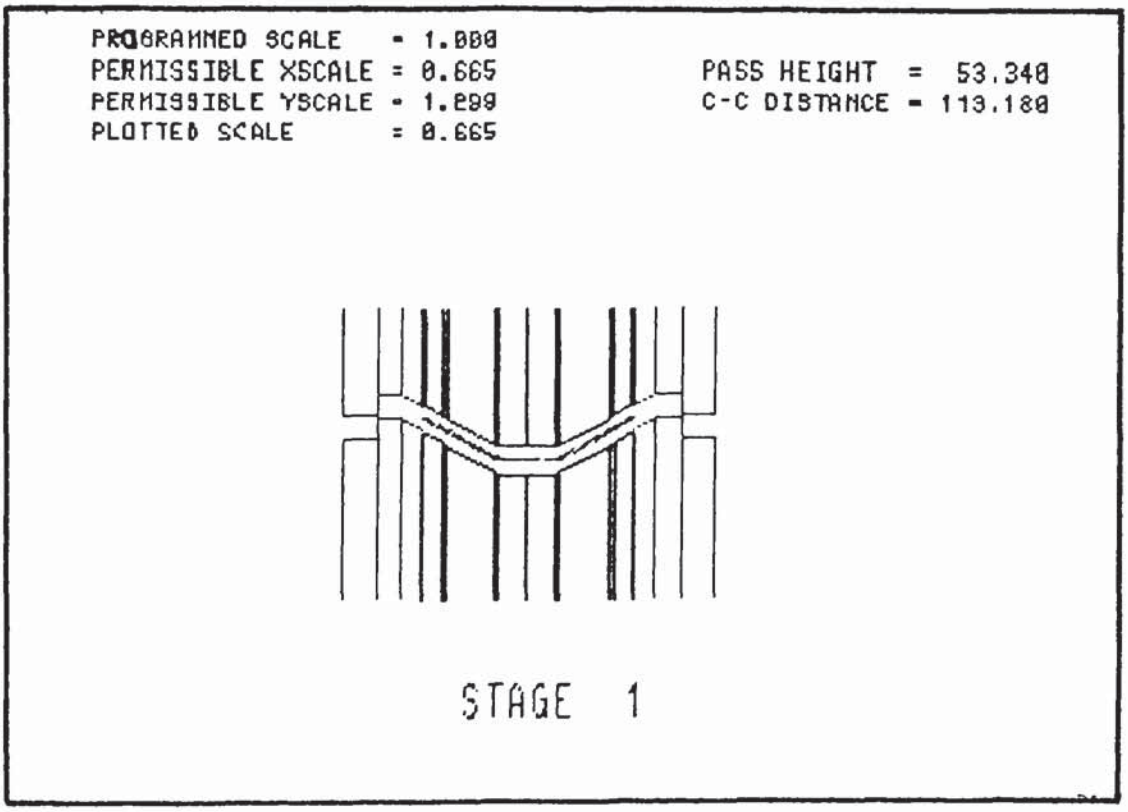
Strip tolerance allows for the possible variation in nominal strip width in the roll design. When the strip width is shorter than the maximum width, there will be a tendency for the material to move to one side of the roll gap during rolling. This causes the end elements of the profile to differ from the template drawing but is not a cause for rejection of the strip.

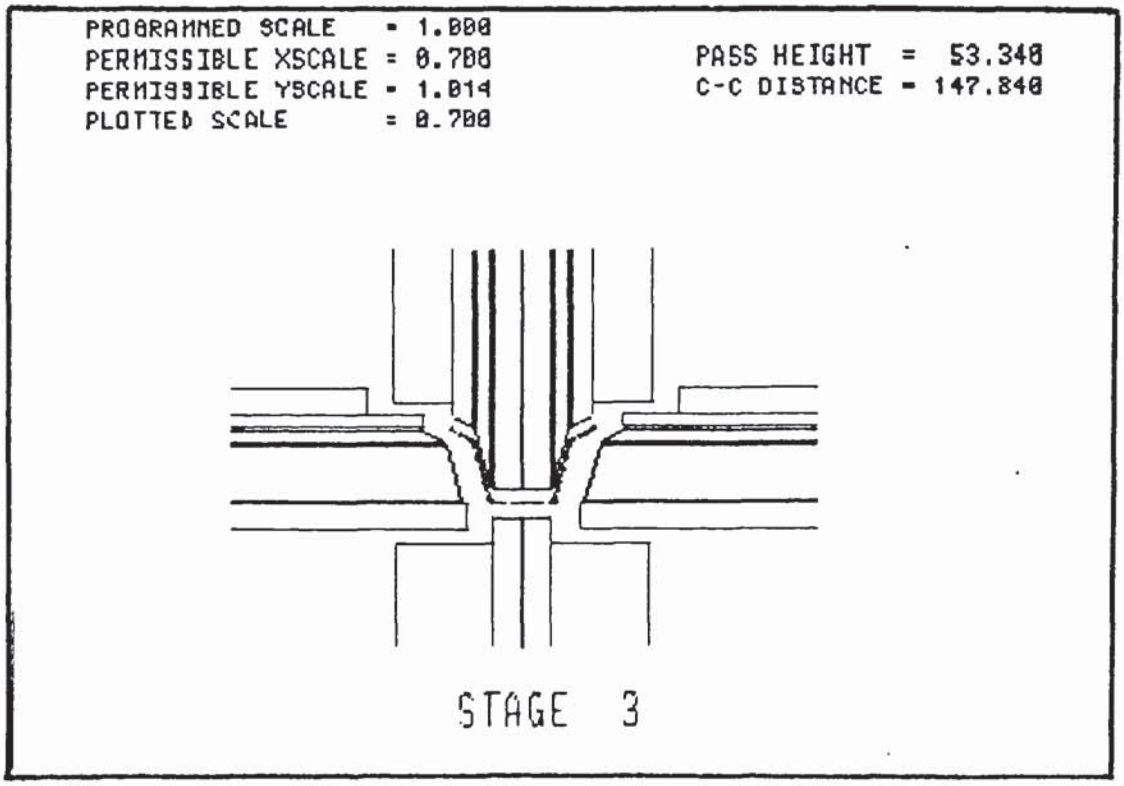
The pinch difference defines the clearance between the rolls and the strip. When rolls are given no clearance or a negative clearance they grip the strip. This is desirable on the drive surface where the rolls run at the same linear speed (where possible normally chosen as the deepest part of the section running parallel with the transverse axis). On certain surfaces there must be clearance to allow for the difference in surface speed of the rolls. If there was drive on these surfaces there could be strip distortion and scuffing.

Side rolls are chosen when considered necessary to form near vertical legs. In the CAD system the designer defines at which stages the side rolls are to be used, the element of the section to be formed by the side roll, and the side roll diameter.

Gates and extension contours are defined by lengths in the transverse and vertical directions, coupled with lengths which form continuations of elements of the roll that contact the strip.

DIAGRAM 3.4 ROLL DRAWINGS FOR THE FIRST AND THIRD PASSES





3.2.2.5 THE ROLL EDITOR PROGRAMME

The roll editor programme is used to make modifications to the roll design. For example sharp corners can be replaced by smooth radii to aid machining. Most systems have included this feature, which allows great flexibility in design. A complete editor programme allows elements to be inserted, deleted and replaced, and sharp corners blended to a radius.

The areas that need to be edited can be enlarged on the screen to show the detail and, once altered, the roll profile is displayed with the new changes.

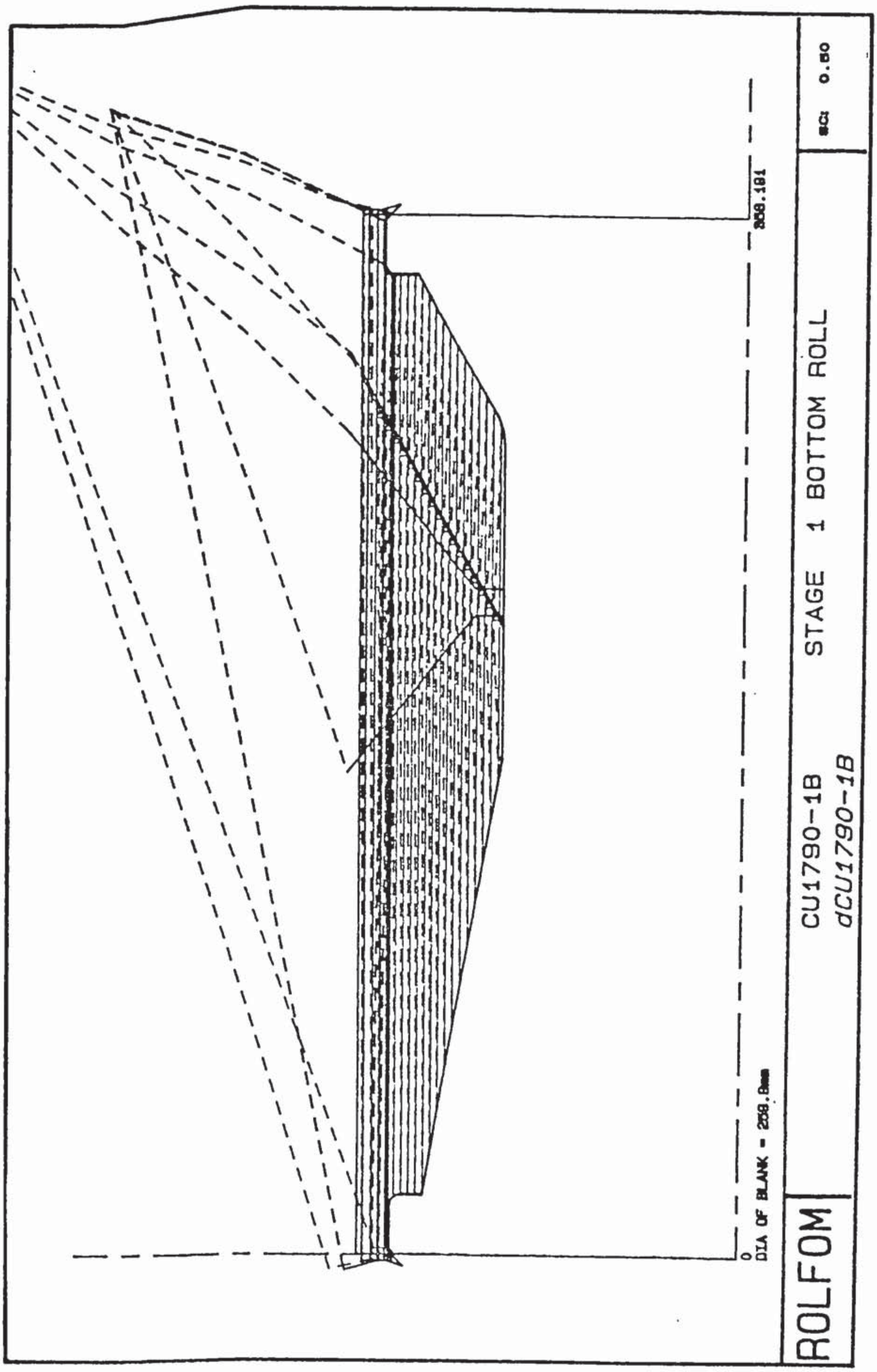
3.2.2.6 THE CAM PROGRAMMES

A numerical file representing the roll profile is produced by the roll editor programme. The CAM software reads this information together with other inputs and produces an output tape of cutting commands for NC machines. The output in some of the systems is formatted to be compatible with standard NC tape preparation packages such as A.P.T. Others have written their own translators to prepare the tapes.

The roll designer must input data regarding the cutting tools. There is a tool library stored in the programme that gives the definition of the cutting tools number, position, type and geometry. A particular tool is chosen to cut a certain part of the roll. For instance, a left hand roughing tool is used to cut a cycle of incremented depth cuts, running from left to right. Areas of the roll cannot be cut by this single tool, so other cutting tools are used for pocketing, grooving and finishing cycles. A clearance is specified for the roughing cuts, so that the finishing cuts remove a small quantity of material in producing the final roll dimensions. Machining speeds, feeds and depths of cut are all given by the designer for each cycle.

The CAM system is interactive, that is,the roll and the paths of the tools are displayed on the screen after the input of tool data for each cycle. Thus the designer has a picture of the cutter movements that will take place on the lathe. This helps to show areas that have been missed by the cutting tools and allows experimentation with different tool cycles to achieve a good solution, before any machining has taken place (diagram 3.5).

DIAGRAM 3.5 CUTTER MOVEMENTS PLOT



The CAD programme produces a cutter location file, i.e. a numerical description of all the cutter movements. This file is machine independent. To convert this file to the form required by a particular NC machine, a post processor programme is used, which is specific to that machine.

3.2.3 ADVANTAGES.

The advantages offered by CAD / CAM systems to cold roll-forming are great, as indicated by the following list.

1. Lead times are reduced, due to the automation of many of the routine calculations and peripheral tasks to design.

2. There are fewer errors in the calculations made by a tested system, than in doing them by hand. High costs are incurred by such errors in roll design (described in chapter 2). Also higher levels of mathematics can be tackled by computers, to give more sophisticated methods of calculating strip length, thus increasing the accuracy.

3. Roll design has been improved by the reduction of the number of peripheral roll design tasks allowing greater concentration on design alone. Also alterations to designs are easily made, so several possible designs can be run through on the computer relatively quickly, in order to find a good solution.

4. All the input and output files can be stored on disks or tape and so can easily be retrieved if rolls need to be made again to the same design. Files can be sorted into a database store. This allows a faster, smaller and more flexible information retrieval system than using paper drawings and documents.

5. The need for highly skilled machining is eliminated by the CAM system. There is no slow, error-prone interpretation of templates or complex roll drawings.

3.2.4 LIMITATIONS

CAD / CAM systems require a large investment in computer hardware, software and NC machines. For roll formers to convert to such systems, there must usually be major rearrangements in areas of production technology and production management. It is therefore likely that many small companies will not have the confidence or finance to commit themselves to these changes.

At present, the systems use a range of computers (from mainframes to micros) depending on the complexity of the programmes, size of data files, and number of work stations. Increase in technology should allow these systems to be run on smaller, cheaper computers in the future.

Although much of the roll designers work has been reduced or eliminated by these systems, roll design choices have been made no less reliant on experience and judgment. Roll designers must still decide on the information to give the computer that defines the flower pattern and all the other necessary details. The computer has allowed that information to be quickly transformed into machined rolls, but has not aided the decision-making of the designer.

CHAPTER 4

THEORY

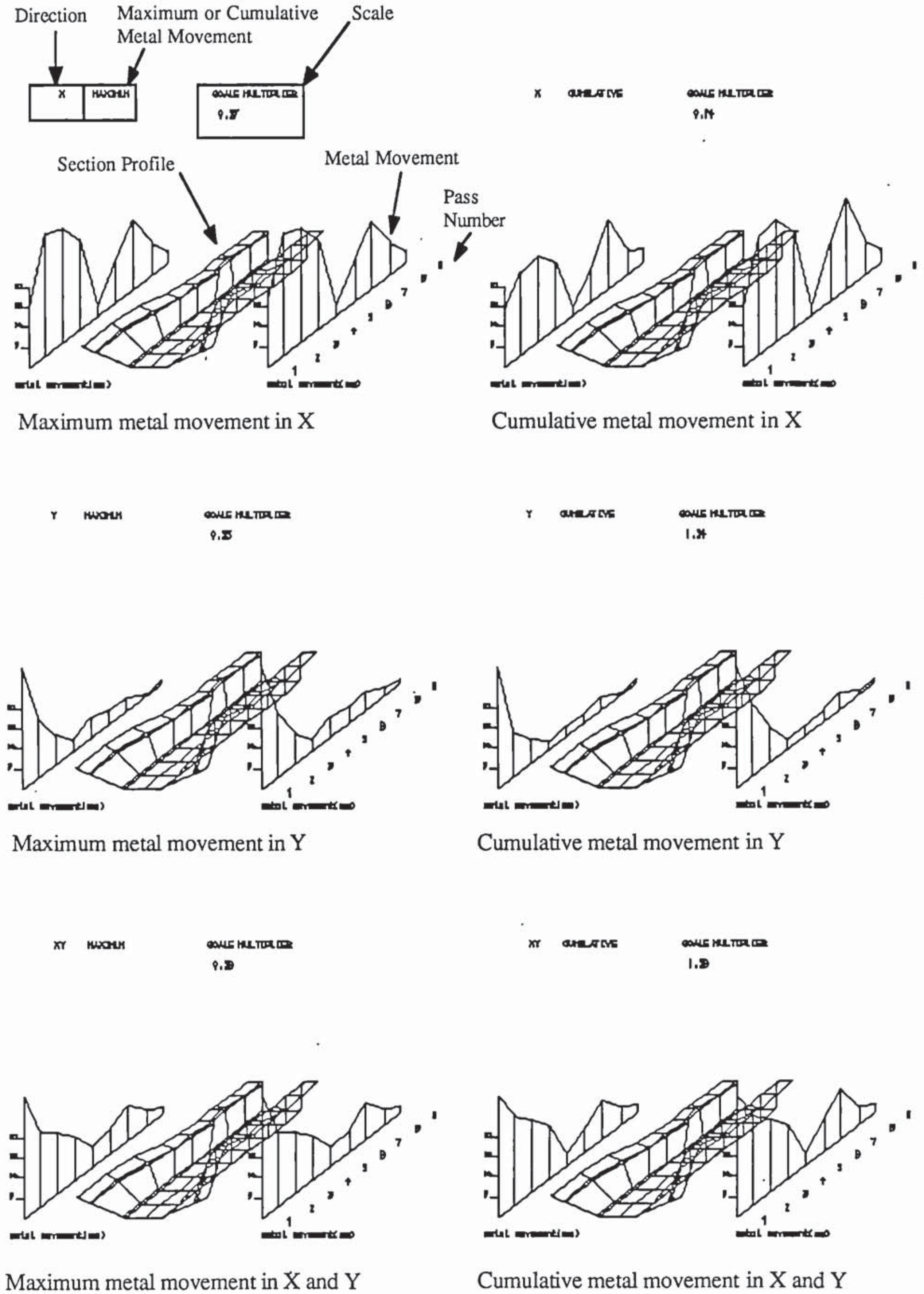
4.1 INTRODUCTION

The reliance on experience, skill and judgment in areas of cold roll-forming, can be reduced by the following three tools;

1. Visualisation models
2. Rules
3. Mathematical models

Visualisation models are used as pictorial representations of the forming process. The flower pattern is a two-dimensional example of this kind of tool. A picture of the forming helps to show the flow of material and indicates regions of uneven bending or too severe bending. CAD solid modelling packages are well suited to this type of application, and can be extended into three dimensions.

Graph 4.1 shows a three dimensional wire frame visualisation aid, which was written as part of the Aston University CAD package. Options allow the amount of bending at each pass to be displayed graphically for the left and right sides of the section, and for the bending in the X and Y planes to be shown combined or separately. Bending is measured in terms of metal movement, i.e. the distance each element moves (in X and Y) relative to the preceding pass. The element movements can be summed, or the maximum individual value selected, for each pass. In this type of model, the skill in interpretation of the graph becomes the key to its value.



GRAPH 4.1 WIRE FRAME VISUALISATION MODEL (ASTON UNIVERSITY)

Rules already exist in roll design as described in chapter 2, e.g. "blind bends should be avoided". Although not precise, such rules do give a guide in certain areas of roll forming, and can be easily understood.

Mathematical modelling of processes allows predictions of output variables to be made from given input values via formulae. The modelling can be done "on paper" without needing the process to be run. This offers considerable advantages over judging variable behaviour from experience. For example, in roll design, formulae should ideally relate changes made by the designer to the final section quality. The formulae should model the actual changes that take place as the result of changes in design. In that way, the section quality can be predicted from the designer's choices, prior to rolling. All the experience of the roll designer is made redundant, since the choices that give the best quality from the model would be used in practice. Optimum roll designs could be found from the particular model input parameters, and rolls produced with certainty of high quality.

However, to produce the ideal formulae, every parameter affecting the section quality would have to be taken into account. This is not practically possible or necessary. In modelling of other forming processes, approximations have be made by using the most important parameters. In many cases these models are accurate enough to be of great use.

In modelling processes, there is a rough balance between complexity and accuracy. However there is a point where increasing the model complexity is unnecessary. That is when:-

1. There is not enough processing power to solve complex equations.
2. There are too lengthy calculations (uneconomic).
3. There are insoluble equations.
4. There is negligible resulting increase in accuracy.

A useful computer-aided mathematical modelling technique is finite-element analysis. The deformed shape, stress and strain values, and many other outputs may be calculated and displayed both graphically and numerically, making this a combination of a mathematical and visualisation model. The processing power of computers has allowed finite element analysis to become one of the most commonly used tools in structural design, stress / strain, heat transfer and deformation problems. Accuracy of the model can be very high, however interpretation of results, and correct input of data, require a good understanding of the technique.

In cold roll-forming, mathematical modelling is a new application. It is not necessarily possible that a complete model (the ideal solution) can be achieved. However, parts of the roll forming process may be capable of being modelled in order to reduce some of the problems in design and manufacture.

To produce a model of a process, relations between input and output parameters are deduced either empirically, theoretically or as a mixture of both (semi-empirically).

4.2 PUBLISHED WORK

4.2.1 INTRODUCTION

All the workers concerned with theoretical work have attempted to predict the shape of the strip from given parameters, highlighting the awareness of roll-formers to the importance of replacing experience with analysis.

The work has concentrated on modelling longitudinal stress and strain in the strip from the input parameters. Models of stress and strain allow strip geometry and rolling power to be derived, giving the advantages to roll design and rolling described in section 4.1.

4.2.2 BACKGROUND THEORY

To understand some of the descriptions of theoretical work it is necessary to describe the background theory of straining.

When a tensile load (L) is applied to a metal specimen as in diagram 4.1, there is an elongation (dl) in the direction shown. The metal is stretched from its original length (l_0) to its length under load (l).

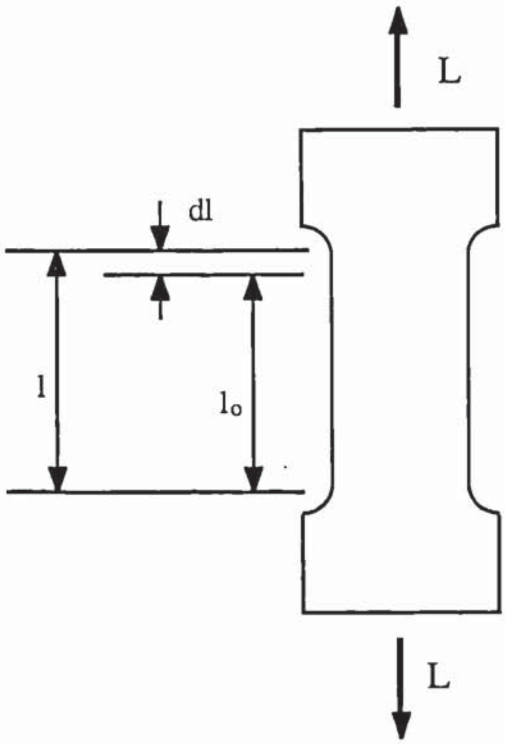


DIAGRAM 4.1 SPECIMEN UNDER TENSILE LOADING

$$\text{Nominal Strain } e_n = \frac{dl}{l_0}$$

$$\text{Nominal Stress } \sigma_n = \frac{L}{A_0} \quad (1)$$

Where A_0 is the original cross-sectional area of the specimen

The nominal load-extension graph for mild steel is as in diagram 4.2. The plot shows that there is a straight line portion to the graph. This represents the pure elastic region of the strain, where stress divided by strain is a constant (E), called Young's Modulus. If the load is released at any point in this proportional region the stress returns to zero. The Yield Point B marks the end of the pure elastic strain, and the start of the plastic region.

Beyond the yield point the specimen continues to extend with a gradual non-linear increase in stress, up to a maximum at point D. With further extension there is an increase in stress, and reduction of load, as the specimen starts to neck and ultimately fails at point E.

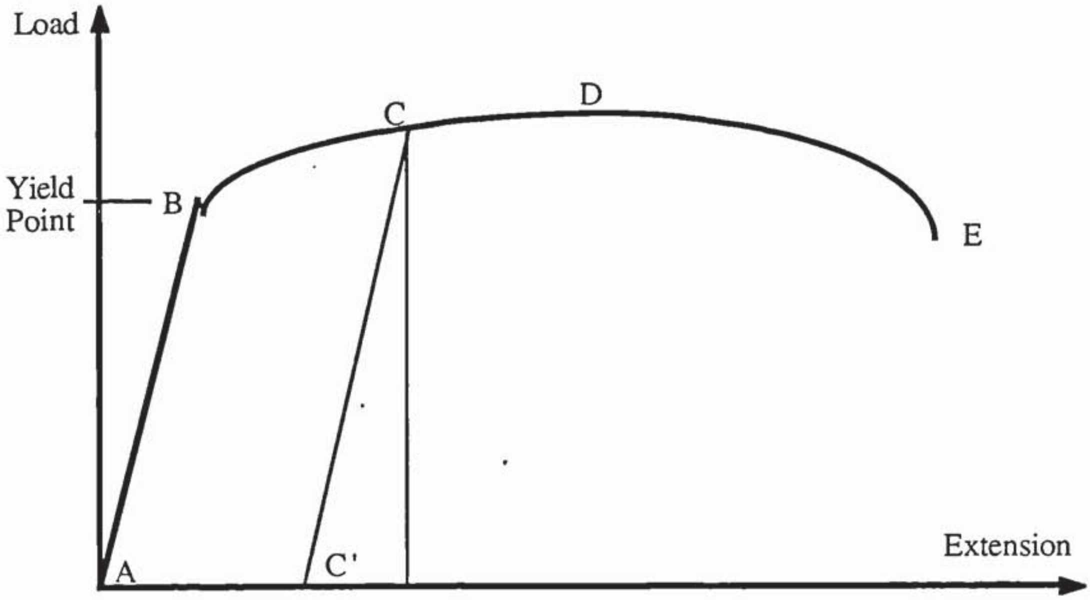


DIAGRAM 4.2 LOAD-EXTENSION CURVE FOR MILD STEEL

Point C marks a point past yielding. If the load is released at this point the strain does not return to zero, but returns with elastic character to point C'. The total strain is made of two parts, the elastic and the plastic. So;

$$e = e_e + e_p \qquad (2)$$

The ratio of the two parts is important, in cold roll-forming, to the formation of the finished section shapes. At section corners, a high plastic-to-elastic ratio reduces springback. It is desirable therefore to achieve maximum plastic deformation in these regions.

If the load was re-applied to the specimen, the starting point of the graph would be C'. The new graph would be the same shape as the original, only with shifted origin, from A to C'. Also the yield stress would be higher. This effect of increasing the yield point, by straining into the plastic region, is called strain (or work) hardening.

The nominal stress is defined as the load divided by the original area. A better definition of stress is the load divided by the current area, and is called the true stress. Diagram 4.3. shows the true stress-strain curve.

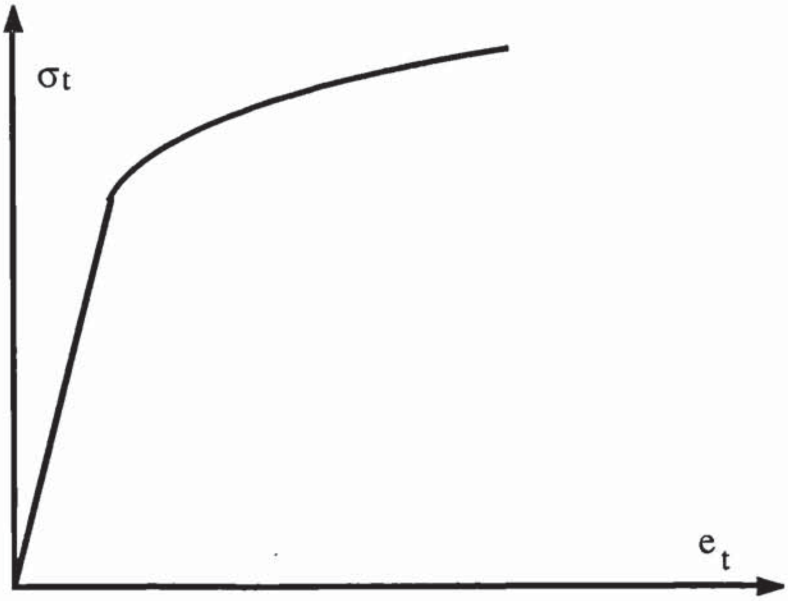


DIAGRAM 4.3 TRUE STRESS-STRAIN CURVE

Assuming elastic incompressibility there is volume constancy, so in a strip of length (l);

$$A_0 l_0 = Al \quad \text{and true stress} \quad \sigma_t = \frac{L}{A} \quad \text{so} \quad \sigma_t = \frac{Ll}{A_0 l_0} \qquad (3).$$

Similarly the specimen length changes under load, so a better description of straining is the sum of the incremental strains from the original length to the final length. So;

$$\text{True Strain} \quad \varepsilon_t = \int_{l_0}^{l} \frac{dl}{l} = \ln\left(\frac{l}{l_0}\right) \qquad (4)$$

Note that the main difference between the two stress-strain graphs, is that the true strain increases right up until failure. For small strains the two graphs are very similar. The plot of true stress against true strain may be modelled by the equation;

$$\sigma_t = A\varepsilon_t^n \qquad (5)$$

Where A and n are constants determined experimentally relating to the material properties.

This empirical equation is one of the simplest of attempts to model the stress-strain curve. Commonly the stress-strain relation is simplified to ease mathematical modelling. The graphs 4.4 A-D show these idealisations.

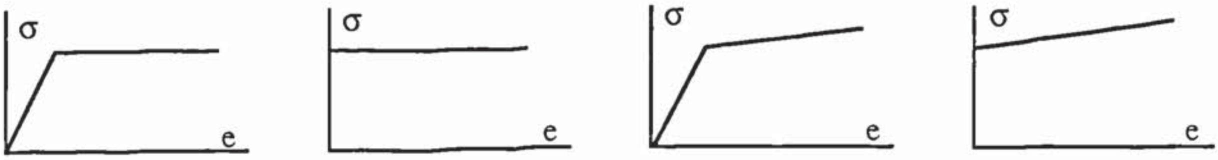


DIAGRAM 4.4A DIAGRAM 4.4B DIAGRAM 4.4C DIAGRAM 4.4D.

(A) Elastic perfectly plastic

(B) Rigid perfectly plastic

(C) Elastic work hardening

(D) Rigid work hardening

DIAGRAM 4.4 IDEALISED STRESS-STRAIN RELATIONSHIPS

The stress-strain relationships discussed so far have been uni-axial, one dimensional. In cold roll-forming there are two theoretical states of stress, two dimensional and three dimensional. The two dimensional case occurs in the regions of the strip between passes (Diagram 4.5), that is plane stress, with the stress across the thickness assumed to be zero.

The three dimensional case occurs in the roll gap, where the roll pressure applies the third dimension of stress through the strip thickness (Diagram 4.5). Three dimensional modelling of stress is extremely complex in this case, although roll pressure is known to have a significant effect on section quality. Most theoretical studies assume plane stress in this region as a simplification.

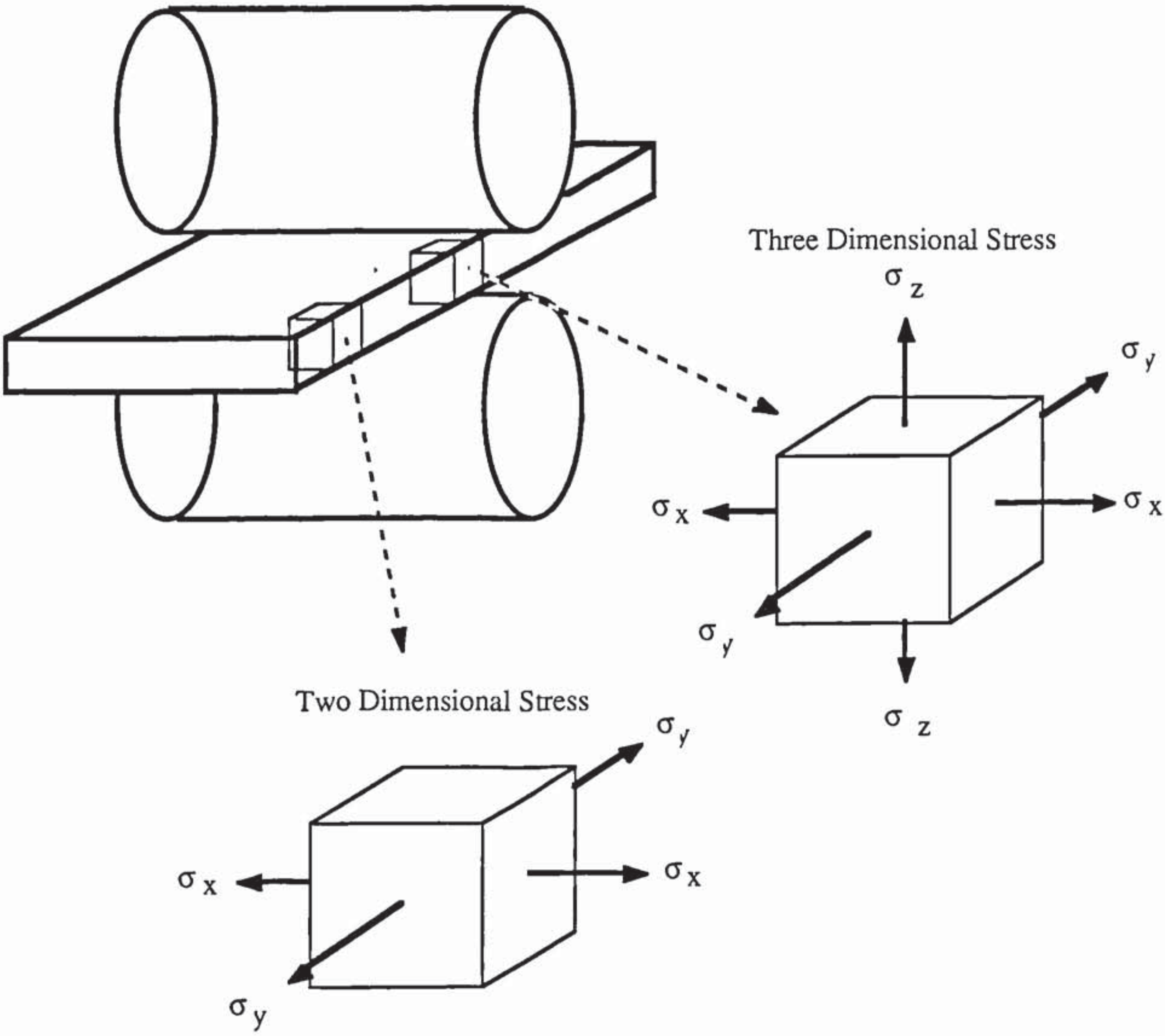


DIAGRAM 4.5 THEORETICAL STRESS CASES IN COLD ROLL-FORMING

Two dimensional stress and strain may be related to an equivalent one dimensional stress and strain using the following two equations. Firstly equivalent stress;

$$\text{Equivalent Stress } \sigma_{eq} = (\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2)^{\frac{1}{2}} \qquad (6)$$

Secondly the equivalent strain increment;

$$\text{Equivalent strain increment } de_{eq} = \left(\frac{2}{3}\right)^{\frac{1}{2}} (de_x^2 + de_x de_y + de_y^2)^{\frac{1}{2}} \qquad (7)$$

Further relationships are also required in the two dimensional case, between stress and strain. These equations define three important features of the stress-strain graph, i.e. the elastic region, the yield point, and the plastic region.

The elastic relationship for plane stress is described by Hooke's law;

$$\sigma_x = \frac{E\,(e_x + \upsilon e_y)}{1-\upsilon^2} \qquad \sigma_y = \frac{E\,(e_y + \upsilon e_x)}{1-\upsilon^2} \tag{8}$$

Where υ is Poisson's ratio

Several plastic yielding criteria exist. von Mises yield criteria states that yielding occurs in a plane stress system when the shear strain energy equals the shear strain at yield in uni-axial tension.

$$\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 \geq Y^2 \tag{9}$$

The relationship between stress and strain is a non-linear function. To obtain the stress at a particular point on the stress-strain graph, the history of the strain up to that point is required. A method of achieving the relationship is to relate increments of stress to increments of strain and integrate to obtain the stresses. The Prandtl-Ruess equations do this;

$$\begin{aligned} \delta e_x &= ((\sigma'^2_y + 2P)\,\delta e_x + (2\upsilon P - \sigma'_x\sigma'_y)\,\delta e_y)\,\frac{E}{Q} \\ \delta e_y &= ((\sigma'^2_x + 2P)\,\delta e_y + (2\upsilon P - \sigma'_x\sigma'_y)\,\delta e_x)\,\frac{E}{Q} \end{aligned} \tag{10}$$

Where

$$P = \frac{2He_{eq}^2}{9(E-H)}$$

$$Q = R + 2P(1-2\upsilon)$$

$$R = \sigma'^2_x + 2\upsilon\sigma'_x\sigma'_y + \sigma'^2_y$$

$$\sigma'_x = \frac{2\sigma_x - \sigma_y}{3}$$

$$\sigma'_y = \frac{2\sigma_y - \sigma_x}{3}$$

$H = \dfrac{\delta\sigma_{eq}}{\delta e_{eq}}$ = the material strain hardening rate.

4.2.3 MATHEMATICAL MODELLING METHODS

The modelling of cold roll-forming is a problematic exercise. There are several reasons;

1. The shape of the material between passes is not known.
2. The deformed strip is a complex three-dimensional body.
3. The forces acting on the strip cannot be quantified.
4. The strip undergoes bending in the plastic and elastic regions.

Various techniques are used in forming analysis, their description and applicability to cold roll-forming are discussed as follows;

Equilibrium method. An elemental volume is taken as a representative part of the whole body, and is studied during the forming. Forces acting on the element are resolved, at a particular instant, in equilibrium. The elemental behaviour is considered to be the same as the behaviour over the whole body. However, the complex geometry of the strip in cold roll forming does not allow there to be a representative element.

Visioplasticity. Stress and strain are studied by experimental observation of the deformation. In cold roll-forming one of the key aims is to be able to predict deformation, without any need for manufacturing of rolls. Hence this method is not applicable.

Finite element analysis. The body is divided into a mesh of elements, forces, deflections and other information can then be applied to the mesh. Each element in the mesh is resolved using a piecewise application of the Raleigh-Ritz equations. Stress, strain, geometry and other solutions can be output for each element. The technique is now a standard, powerful tool for solving a large range of engineering problems. Many commercial finite element packages are available, some of which are capable of tackling very complex applications. However, no work has been published on developments of finite element usage in cold roll-forming.

The lack of work using finite elements may be due to several important difficulties;

1. Finite element packages which model elastic-plastic bending need very large computers to run even simple problems and are rarely able to solve complex

problems accurately.

2. The forces needed as input to the finite element package are difficult to determine.
3. The shapes of the form rolls are difficult to model as input to the package.
4. Assumptions must be made which alter the true nature of the forming. For example, the process must be assumed to be static. Packages cannot take motion into account.

Limit analysis. Two power requirement values are computed, the upper-bound, and the lower-bound. The upper-bound limit is found by enforcing the equilibrium equations and gives a power requirement which is an overestimate of the load. The lower-bound limit uses volume constancy and compatibility equations to give an underestimate of the load. Limit analysis in cold roll-forming has concentrated on the upper-bound equations. Upper-bound technique assumes a velocity distribution in the material; calculates power to overcome resistance to deformation; and calculates power used in frictional effects.

The obvious deformation taking place in cold roll-forming is at the section bends, in the transverse plane, where springback has been recognised as being a problem. There is also the longitudinal deformation associated with the continuous movement of strip from one pass to the next. Although usually much less severe, the latter deformation is accepted as being responsible for many section defects, and is of equal importance.

Diagram 4.6 shows a strip geometry between two passes. The first pass imparts a 30° bend in the strip, the second a 60° bend. The path length AB is longer than CD, which implies there is a strain difference between the edge and centre of the strip.

If the centre of the strip is assumed to remain unstrained during rolling and the linear speed in the longitudinal direction is the same for all points on the strip (true due to the continuity of the process), referring to the symbols in diagram 4.6, the longitudinal strain in the edge AB is;

$$\text{Longitudinal strain} = \frac{\sqrt{(L^2 + X^2 + Y^2)} - L}{L} \qquad (11)$$

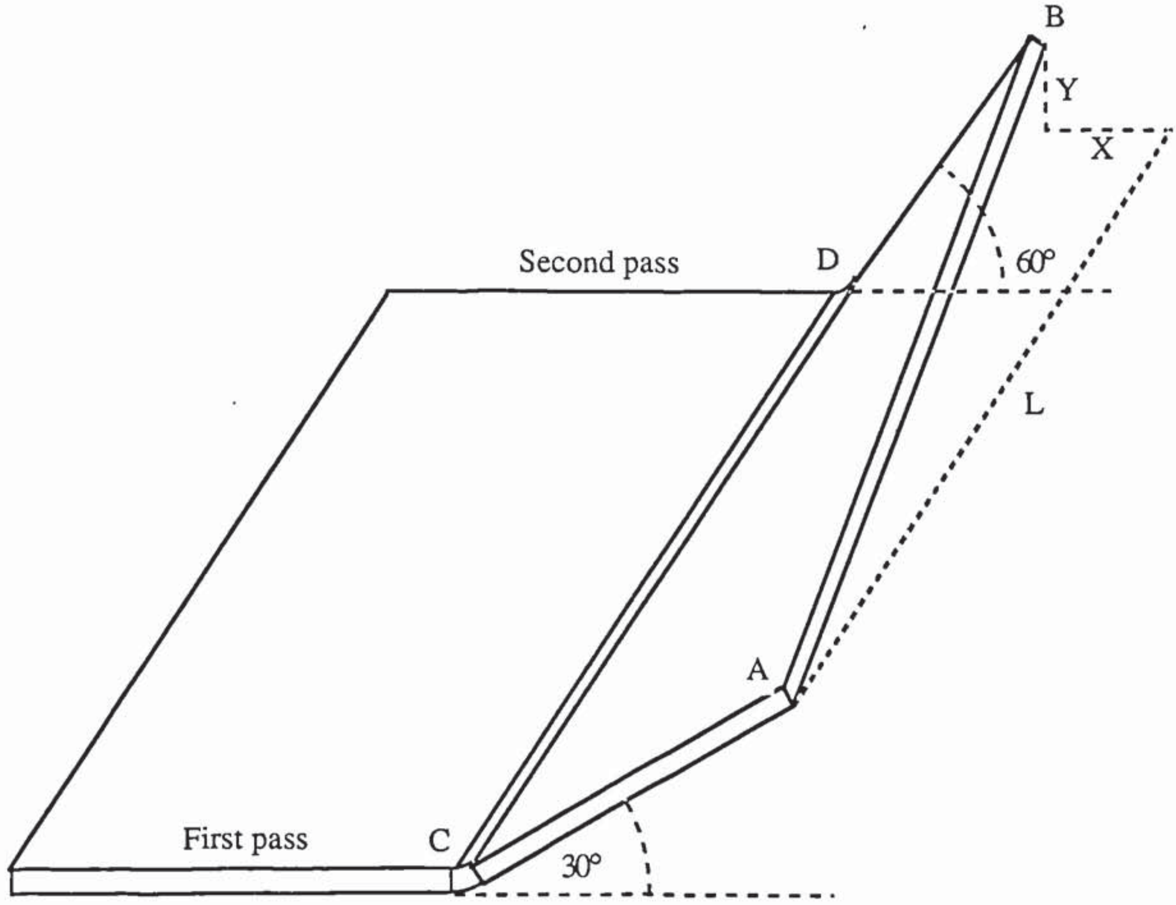


DIAGRAM 4.6 LINEAR PATH BETWEEN PASSES

If the material was perfectly plastic, with no strain hardening effects, that profile would be true. Materials used in cold roll-forming, however, do not have this idealised property. As a result, in practice, the profile is observed (see photographs P14 and P15 in chapter 7) to be unevenly distributed between passes as in diagram 4.7A.

It is required that the section be broken into smaller linear portions (principles of integration an finite element analysis), as in the diagram 4.7B, in order to calculate strain. The prediction of strain in this case becomes a complex problem.

Attempts to find solutions are described in the following sections.

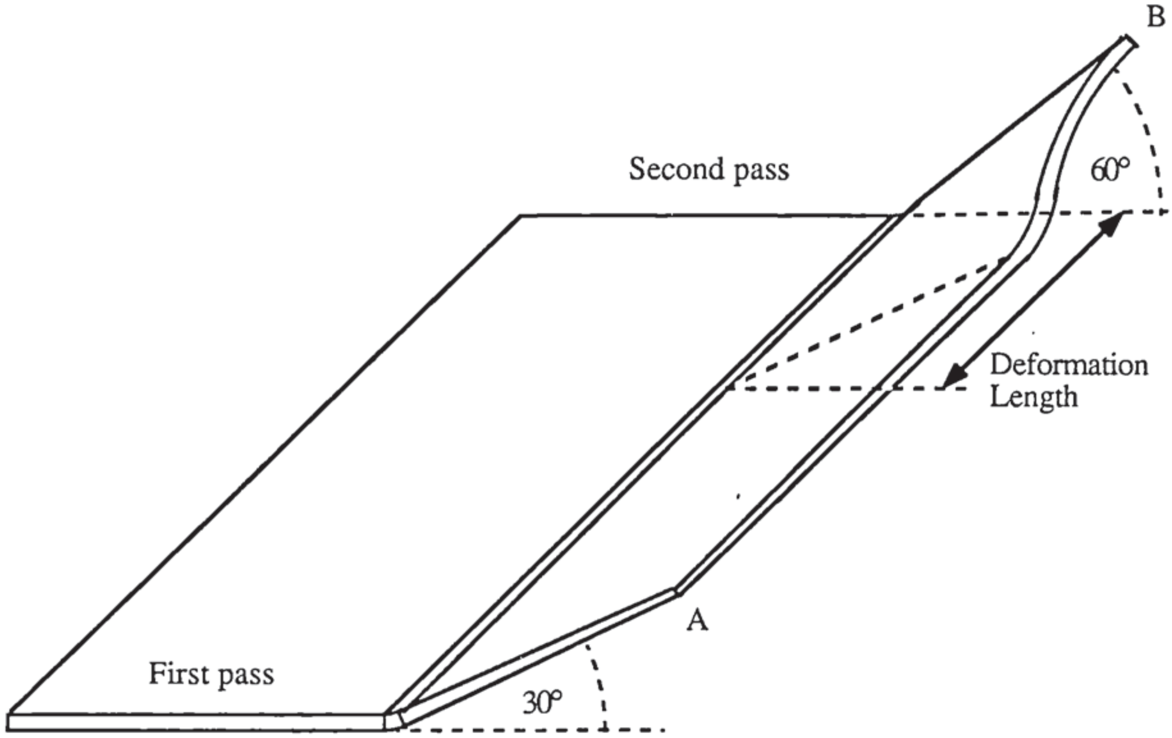


DIAGRAM 4.7A. OBSERVED STRIP SHAPE BETWEEN PASSES

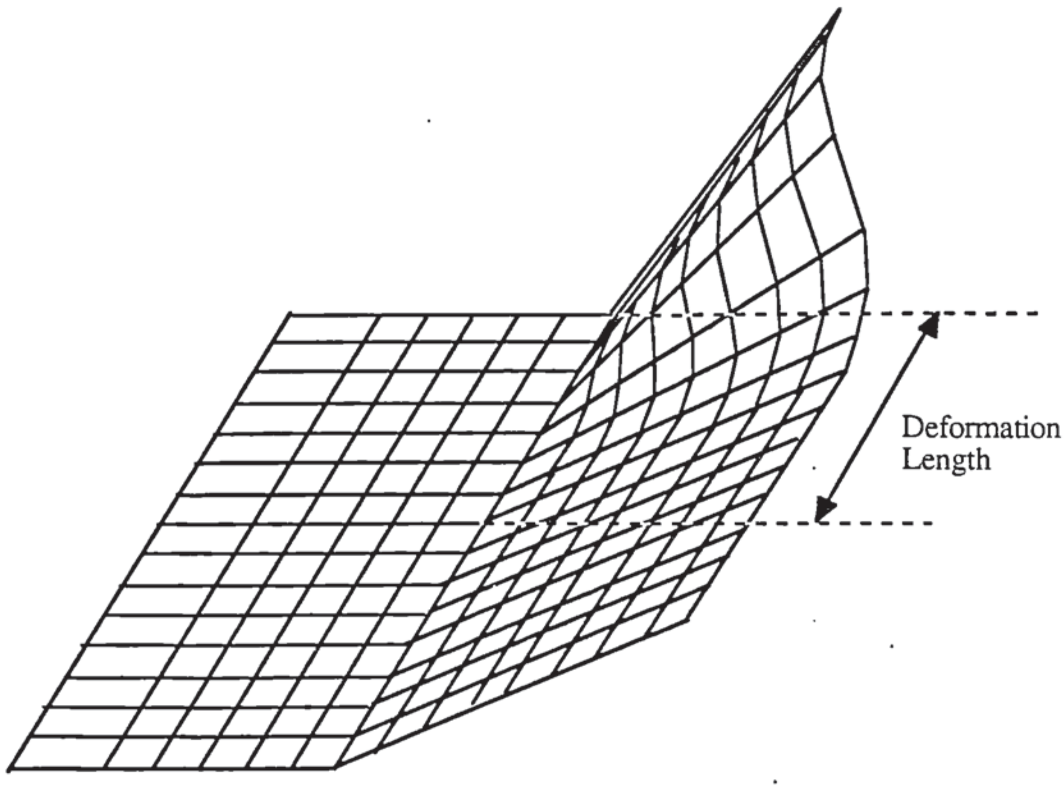


DIAGRAM 4.7B. GRID REPRESENTATION OF STRIP SHAPE BETWEEN PASSES

4.2.4 MINIMUM ENERGY SOLUTIONS

A major analysis of cold roll-forming has been performed by Kiuchi (114,122,125) and his collaborators. The scope of the model has been limited to simpler sections, primarily tubes (although channel sections and top hat sections have also been analysed). Kiuchi developed what he called a shape factor S(x) which geometrically described the shape of the metal strip between passes, and which is defined below (where the co-ordinate system is detailed in diagram 4.8).

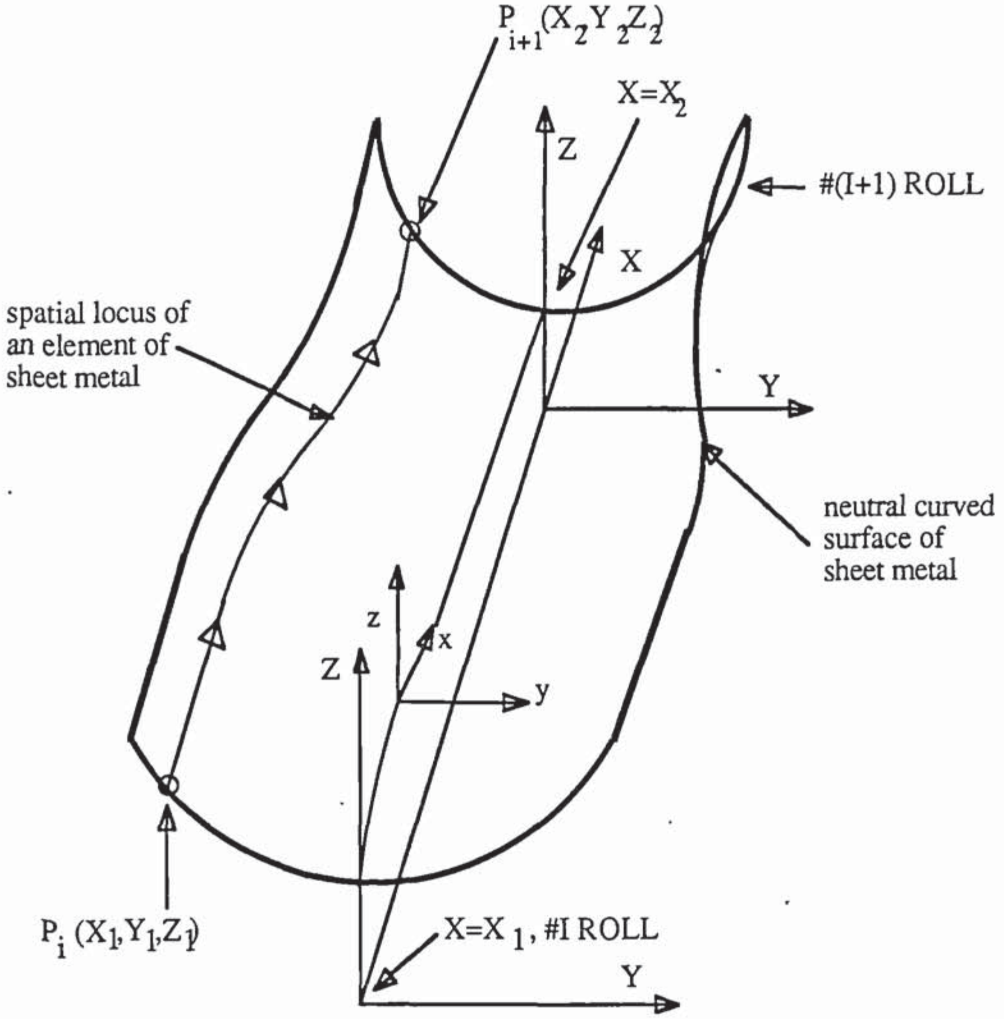


DIAGRAM 4.8 MODELLING OF TUBE ROLLING (BY KIUCHI).

$$S(x) = \sin[(\pi/2)(x/L)^n] \quad (12)$$

$$X = X(x,y)$$

$$Y = Y_1(y)+[Y_2(y) - Y_1(y)]\, S(x) \quad (13)$$

$$Z = Z_1(y)+[Z_2(y) - Z_1(y)]\, S(x)$$

Where Y_1, Z_1 are the Y and Z coordinates of the i th roll projected on the cross section which is perpendicular to the X-axis at $X=X_1$. And, Y_2, Z_2 are the Y and Z coordinates of the (i+1)th roll projected on the cross-section which is perpendicular to the X axis at $X=X_2$

The strain field is calculated from this shape by making the additional assumption that the front and rear cross sectional profiles of the deformed sheet strip are always included in planes which are perpendicular to the X-axis and can move along the X-axis. Knowing the strain field, the stress field can be calculated by the application of a yield criterion and the constitutive equations developed by Yamada (111). The power of deformation is calculated by dividing the strip into a large number of small elements and integrating numerically (the upper bound elemental technique). The variable n in equation (12) is then altered until the power of deformation is minimised, hence the shape and strain fields closest to the true values are achieved.

Kiuchi then went on to develop 'optimum' flower patterns for tubes (using the results of the simulation) by either equalising the edge strain or the power at each pass. Interestingly, Kiuchi's simulation obtained the relationship that the power in forming a tube (W) was related to the thickness (t) by the relationship.

$$W \propto t^{2.18} \qquad (14)$$

Which is very close to the standard expression obtained for the work done (W) in bending (per unit length)

$$W = Y\theta t^2 / 4 \qquad (15)$$

where Y is the yield stress and θ is the angle of bending.

or $W \propto t^2$

(Note: Eqn 15 can be further developed to give the power required for forming a bend; where

$W = Y\theta t^2 V / 4$, and V is the velocity of rolling).

Kiuchi's work can be said to be important because it is, to date, probably the most comprehensive attempt to model the cold roll forming process.

A method for the construction of a model for numerical analysis of the cold roll forming process has been detailed by Panton (126). The model is based on a minimum energy method and it probably represents the first attempt to analyse the form rolling process numerically for any general section. A new method for the geometric definition of the shape of metal between successive passes in the cold roll forming process has been devised, based on an experimental study of the distribution of bending between passes. The shape is defined by equation (16) which describes the distribution of bending between passes.

$$\theta = S\theta + (F\theta - S\theta)\, s(y) \qquad (16)$$

where $s(y) = e^{-a((Y-y)/y)b}$ or $\sin((\pi/2)(y/Y)^n)$

y is the distance from the preceding pass.

L is the distance between two successive passes (the pass length).

θ is the angle of bending at a distance y from the preceding pass.

$S\theta$ is the angle of bending at the preceding pass.

$F\theta$ is the angle of bending at the end of the pass.

n, a & b are variables

The model varies the shape of the metal between passes and takes the metal shape which minimises power as representing the actual shape. The model has been integrated into a cold roll forming CAD / CAM package. In parallel with the model, a series of graphical output packages have been written to provide a visual interpretation of the output from the model.

Bhattacharyya (120,127) has concentrated on the forming of channel sections. Both experimental and theoretical research has been performed. The experimental work (159,160) concerned the measurement of longitudinal strain in the rolling of channel sections and the influence of the strain histories on the product straightness.

The theoretical work (120,127) is concerned with predicting the shape of metal between passes in the cold roll-forming of channels, interestingly again a minimum energy approach has been adopted. It is assumed that no forming will take place in the pass until a certain point is reached. The distance from the downstream pass over which the forming takes place Bhattacharyya termed the 'deformation length'. Diagram 4.7A and B show the deformation length.

The assumptions are made that;

1. the material can be treated as rigid-perfectly plastic,
2. bending takes place only along the fold line ,
3. the leg adopts the shape which minimises the plastic work.

Bhattacharyya produced several useful models for calculation of roll load and deformation length. The work has concentrated on trapezoidal sections as shown in diagram 4.9.

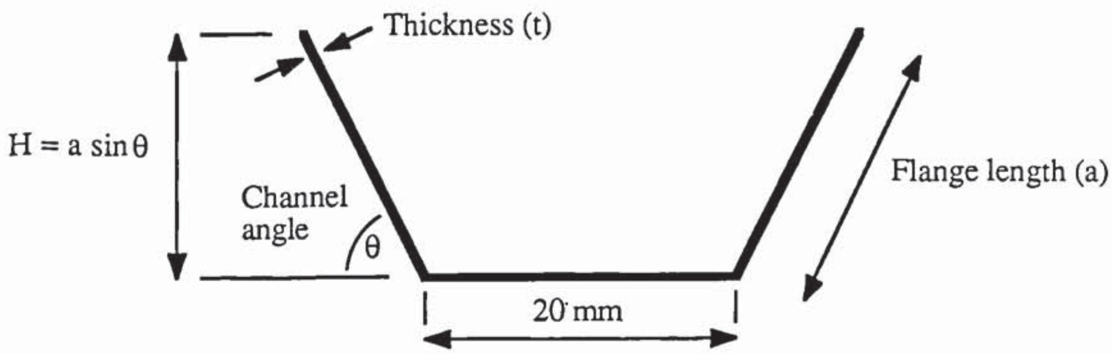


DIAGRAM 4.9 SECTION USED BY BHATTACHARYYA

By minimising the energy required for bending and stretching the strip metal, a theoretical model of deformation length was obtained. (Derivation in Appendix 1).

$$L = \text{Deformation length} = a\sqrt{\frac{8a\theta}{3t}} \qquad (17)$$

This work was extended into estimating the roll load by equating the external work with the total deformation work dissipated under one roll station, also taking into account the reverse bending of the deformed workpiece after it reaches the next roll station.

The total roll is divided into three components

P_{tf} the load due to transverse folding and associated longitudinal stretching

P_{lb} the added load due to longitudinal reverse bending after the deformed strip reaches the next roll.

P_c the clamping or bite load due to the clearance between the upper and lower form rolls.

The clamping load is ignored in the model, the total roll load being assumed to be $P_{tf} + P_{lb}$.

It is assumed that the flange adopts the shape that minimises the plastic work, which for a rigid-perfectly plastic material for one bend is (derived in Appendix 1);

$$W_T = Yt\int_0^L \left[\frac{t\theta}{4} + \frac{a^3}{6}\left(\frac{d\theta}{dz}\right)^2 \right] dz \qquad (18)$$

Where Y is the yield stress of the material, and the z direction is the vertical direction.

Assuming the roll pressure and the section height are linearly varying between the roll entry and the vertical plane through the roll centres, and considering the roll forming process to be quasi-static, the load due to transverse folding and stretching is shown to be (derived in Appendix 1);

$$P_{tf} = \frac{Yt^2\,\theta\,L}{2H} = Y\sqrt{\frac{2t^3\,\theta^3\,a}{3\sin^2\theta}} \qquad (19)$$

After passing through the a pair of rolls, the deformed workpiece normally curves downwards, reaches the next roll station at a lower point than if it had remained straight, and is lifted up as in diagram 4.10 .

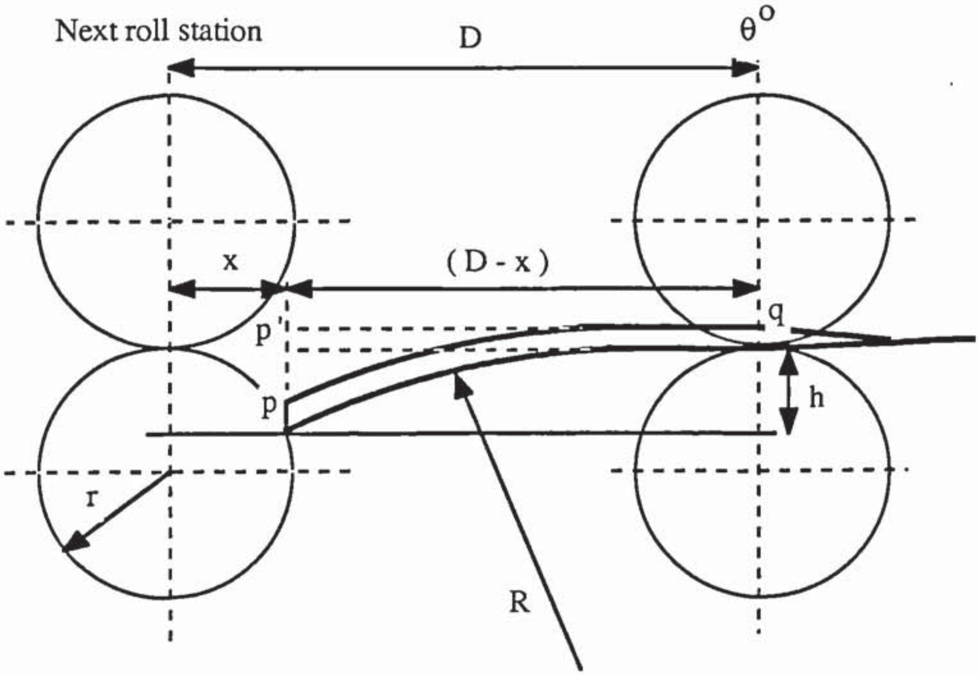


DIAGRAM 4.10 REVERSE BENDING OF DEFORMED STRIP

The reverse bending puts an added load on the form rolls. When the process becomes quasi-steady this bending is not visible, however the authors suggest that because the roll load does not vary from the initial situation, the reverse bending load must remain. The load required to lift the strip vertically through a height "h" is calculated using small deflection theory;

$$P_{lb} = \frac{3h\,EI}{(D - x)^3} \qquad (20)$$

I is the second moment of area of the section and the details of "h" and "x" are given in appendix 1.

A moc' l was also devised for the longitudinal peak strain in the channel flange edge (derivation in appendix 1.);

$$e = \frac{\delta l}{L} = \sqrt{1 + \frac{2a^2}{L^2}(1 - \cos\theta)} - 1 \qquad (21)$$

Furthermore, a model of recovery strain (e_{reco}) and remaining (residual) strain (e_r) in the channel, was calculated. Bhattacharyya was required to make several assumptions in producing the model;

1. The deformed strip leaves the forming roll station with the peak strain at its flange edge, i.e. the peak strain occurs at the vertical plane through the centres of the forming rolls.
2. Pure bending occurs longitudinally in the vertical plane without any warping or twisting.
3. The neutral plane coincides with the bottom of the flange and there is a linear strain distribution in the flange.
4. The material is elastic-perfectly plastic. The engineering strain of any fibre at a height z from the neutral axis is ;

$$e_z = \frac{z}{R} \quad \text{and similarly} \quad e_y = \frac{z_y}{R} \quad \text{and} \quad e_{peak} = \frac{H}{R}$$

$$\text{Therefore } z_y = H\left[\frac{e_y}{e_{peak}}\right] = \frac{H}{m} \qquad (22)$$

$$\text{where } m = \frac{e_{peak}}{e_y}$$

R is the radius of curvature of the rolled strip (see diagram 4.10), e_y is the strain at yielding and b is the section base width.

$$e_r = e_{peak} - e_{reco}$$

$$e_r = e_{peak} - \frac{\sigma'}{E} \qquad (23)$$

$$e_r = e_{peak} - \frac{3He_y}{\left[bt^2 + \frac{2(H^3 - t^3)}{\sin\theta}\right]}\left[\frac{bt^2m}{3H} + \frac{1}{\sin\theta}\left(H^2 - \frac{H^2}{3m^2} - \frac{2mt^3}{3H}\right)\right] \qquad (24)$$

(Derivation detailed in appendix 1.)

Experimental results are supplied and appear to correlate well with equation (24), the expression would seem to be both simple to use and accurate, thus it is surprising that it is not better known. The close similarity between theoretical and experimental results would seem to confirm the promise of the minimum energy approach.

4.2.5 THEORETICAL ANALYSIS OF SPRINGBACK

One aspect of metal forming which has received considerable research both theoretical and experimental and which is of relevance to cold roll-forming, is springback. Where springback is the name given to the tendency of sheet metal to return to its original shape.

As such, springback is a common problem encountered in many sheet metal forming processes, thus, whilst little research into springback has been primarily cold roll-forming orientated, there has been general research which is applicable to the process.

Gardiner's [107] equation (equation (25)) is the classic method of springback analysis. It provides an easily applicable method of estimating springback and is commonly applied. Gardiner's equation is derived by considering equilibrium and is as follows :

$$\frac{R}{r} = 1 - 3\left[\frac{(RY)}{(Et)}\right] + 4\left[\frac{(RY)}{(Et)}\right]^3 \qquad (25)$$

Where R = Radius before springback

r = Radius after springback

t = Thickness

Y = Yield stress

and, $AR = A'r$ (26)

where A = Angle before springback

A' = Angle after springback

The limitation on the accuracy of equation (25) is imposed by the validity of the simplifying assumptions, namely :

1. The neutral axis remains at the centre of the metal,
2. The material is elastic-perfectly plastic,
3. Conditions of plane strain exist,
4. The strain is directly proportional to the distance from the neutral axis,
5. There is no stress at the neutral axis, nevertheless, since Gardiner's equation provides an explicit statement of springback (for the general case), it provides a very useful approximation.

It has also been proved by Panton (126), that if it is assumed that the metal will return to the shape which minimises elastic energy, equation (25) is obtained. This is important for two reasons. Firstly by dividing the metal into a number of elements it is possible to integrate the elastic energy numerically and thus, by varying the radius after springback, it is possible to calculate the radius which gives the minimum elastic energy. Therefore it is possible to examine the springback when the simplifying assumptions are made more rigorous. For instance, it is not necessary to assume that the neutral axis is midway through the metal, or that the strain is constant at any distance from the neutral axis, or that the material is elastic-perfectly plastic.

Secondly the method has more potential in dealing with cold roll-forming problems. Many cold roll-forming defects can be seen as the tendency of the material to dissipate elastic energy and achieve a state of minimum elastic energy. For instance, when forming a symmetric channel a common problem is bow. This occurs when forming has been too severe and plastic straining occurs in the leg element.

Woo and Marshall (108) developed equation (2?) further by including more complex stress-strain relationships. If the stress-strain curve in the plastic region is assumed to be represented by equation (27)

$$\sigma = Y + A\,(e - e_y)^n \qquad (27)$$

where : e_y is the strain at yield of a fibre under bending (i.e. Y / E)

and A and n are material constants

It was proved that

$$\frac{R}{r} = 1 - 3\left[\frac{(RY)}{(Et)}\right] + 4\left[\frac{(RY)}{(Et)}\right]^3$$

$$-\left[24R^3A\left(\left(\frac{t}{2R}\right)-\left(\frac{Y}{E}\right)\right)^{n+1}\left(\frac{(n+1)\left(\frac{t}{2R}\right)+\left(\frac{Y}{E}\right)}{3Et\,(n+1)(n+2)}\right)\right] \qquad (28)$$

For a linear strain hardening material ; A=H and n=1.0 (where H is the strain hardening rate)

Equation (27) becomes $\sigma = Y + H(e - e_y)$ (29)

$$\frac{R}{r} = \left(1-\frac{H}{E}\right)\left(1-3\left[\frac{RY}{Et}\right]+4\left[\frac{RY}{Et}\right]^3\right) \qquad (30)$$

It can be noted that when H=0 equations (25) and (30) are identical ; which is what would be expected.

Other methods of estimating springback have been developed. Oh and Kobayashi (116) analysed the springback of metals in plane strain sheet bending, using the finite element method. As would be expected, they obtained considerably more detailed results concerning the shape of metal during bending, and residual stresses and springback after bending.

Levy (118) obtained equations for the springback of steels by using regression analysis techniques on sets of experimentally obtained values. The results of this approach of springback analysis are limited to the range of data from which they are derived. If the tool geometry or the material type are changed, then further experimental testing is required. Since it is necessary to calculate springback prior to manufacturing tooling and purchasing material, statistical analysis is unsuitable for cold roll forming.

Rondal [128] produced an incremental computer-based model for prediction of springback. Several assumptions were made (referring to z and r axes on diagram 4.12);

$$de_z = 0 \quad e_z = 0 \quad \sigma_r = 0$$

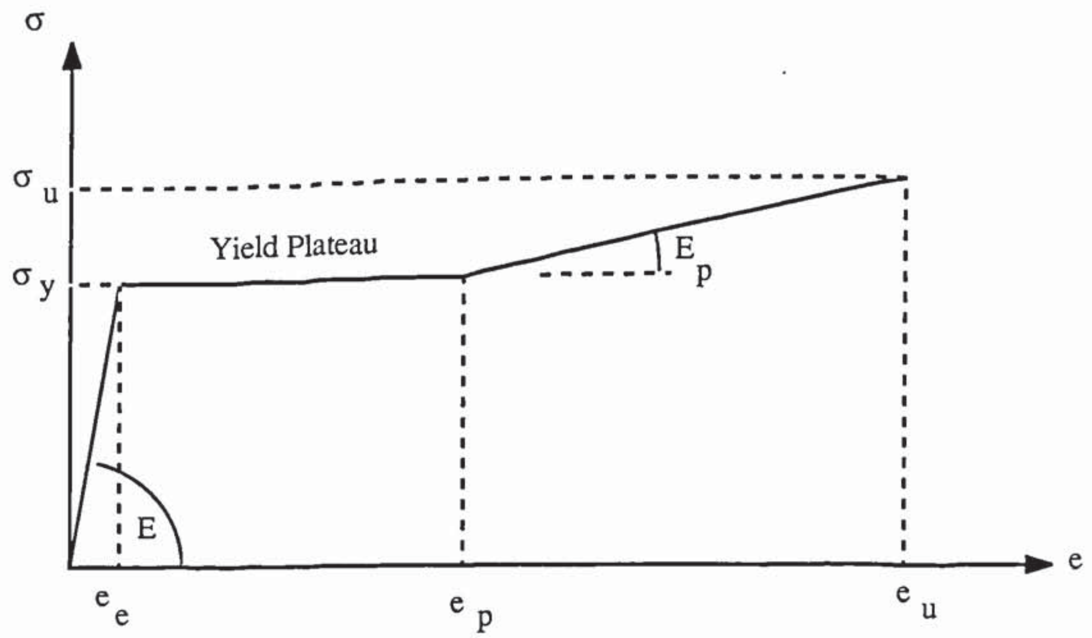


DIAGRAM 4.11 TRI-LINEAR STRESS STRAIN RELATIONSHIP

Also pure bending and a tri-linear stress-strain relation (Diagram 4.11) were assumed. The data inputs were; the inside radius of the final bend, the strip thickness, the parameters shown on the diagram 4.12, and the number of layers across the thickness (typically 40).

The computation is started with a flat plate, i.e. a zero curvature (c=0) and a neutral axis at the mid-depth of the thickness. The incremental curvature is given by;

$$dc = \frac{1}{rN_c} \tag{31}$$

Where dc is the incremental curvature

N_c is the number of the layer considered.

The number of the layer is determined so that the associated increase of circumferential stress at each step does not exceed 2% of the yield stress. This is required by the necessity to detect the end of the elastic range in the fibres with accuracy.

The increase in circumferential strain and position of the neutral axis is found for each increment in curvature.

$$de_{\phi}(i) = \frac{\rho_i - \rho_o}{1 + \rho_i c} \; \frac{dc}{1 + \rho_o c + \rho_o dc} \tag{32}$$

where ρ_o, which determines the position of the neutral axis, shifts towards the inside fibres as a result of the curvature and is given by;

$$\rho_o = \frac{t}{\ln \frac{1/c + t}{1/c}} - \frac{1}{c} \tag{33}$$

In each fibre, the behaviour is successively elastic, plastic and strain hardening. Hooke's law and the Prandtl-Reuss equations are used to determine the stresses and strains in these fibres.

To calculate the springback, the bending moment M required to produce the final curvature increment is calculated. On release from the rolls there is an unloading of this moment. This causes a stress redistribution which changes the curvature (springback). The unloading is elastic and is assumed to be produced by a bending moment equal but opposite to M.

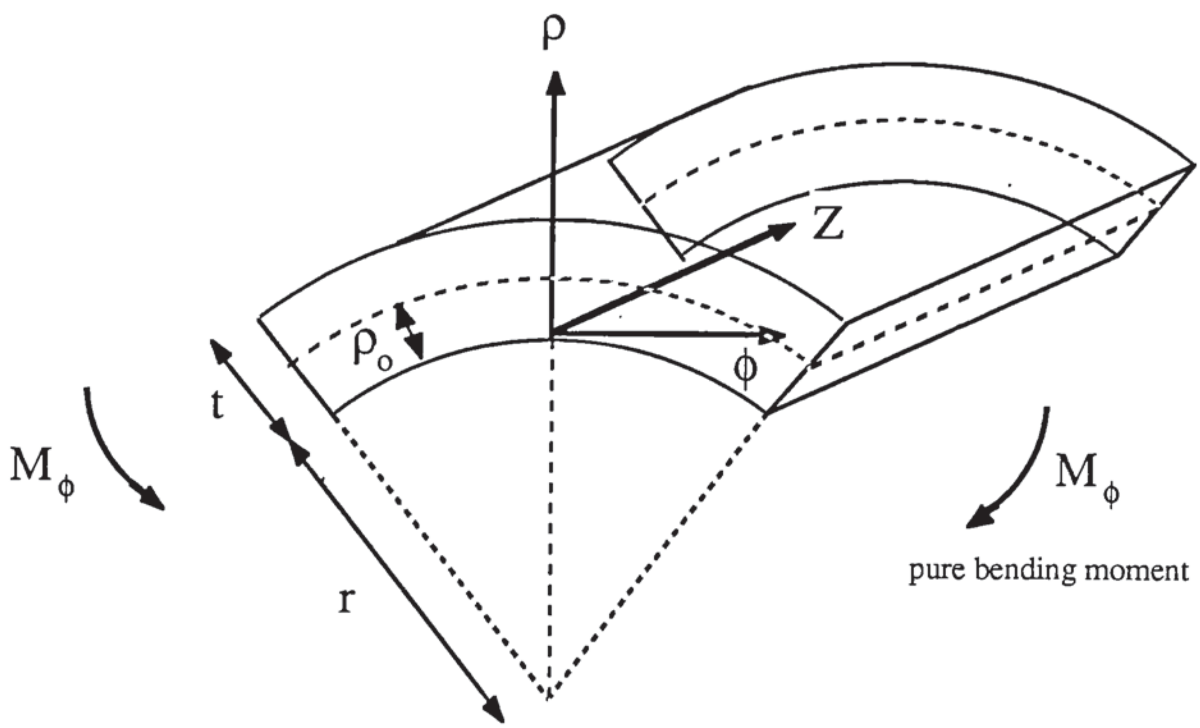


DIAGRAM 4.12 NOTATION FOR RONDAL SPRINGBACK MODEL

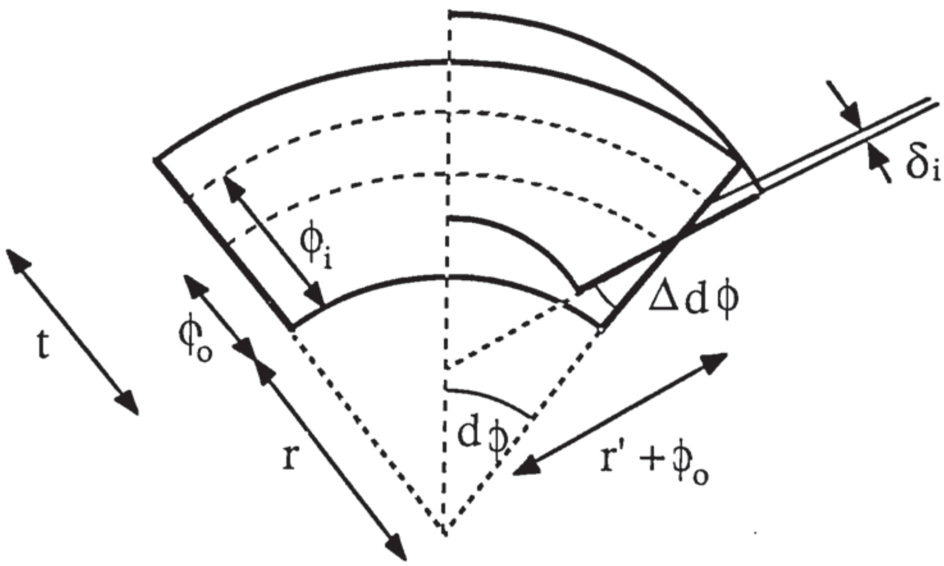


DIAGRAM 4.13 EFFECT OF AN INCREASE IN CURVATURE

$$\Delta M_e(i) = -\frac{\sigma_\phi(i) + \sigma_\phi(i+1)}{2} \frac{t}{N_t} \left\{ (i-1)\frac{t}{N_t} + \frac{t}{2N_t} \right\} \quad (34)$$

and

$$M_e = \sum_{i=1}^{N_t} \Delta M_e(i) \quad (35)$$

The associated relative angular variation is ;

$$\delta = \frac{\Delta d\phi}{d\phi} = \frac{M_e}{t\left(\frac{t}{2} - \rho_o\right)E} \quad (36)$$

The radius of curvature after unloading is then ;

$$r' = \frac{r + \rho_o}{1 + \delta} - \rho_o \quad (37)$$

The stresses associated with the unloading bending moment are ;

$$\sigma_\phi^e(i) = M_e \frac{(\rho_i - \rho_o)}{t\left(\frac{t}{2} - \rho_o\right)(r + \rho_i)} \quad (38)$$

The circumferential residual stresses in the bend are obtained by adding the stresses associated with loading and unloading of the bending moment.

$$\sigma_\phi^{res}(i) = \sigma_\phi(i) + \sigma_\phi^e(i) \quad (39)$$

The model shows that the neutral axis shifts towards the inside fibres during bending, but remains close to the centre due plastic yielding there. The circumferential and longitudinal stresses before elastic unloading are nearly identical, but of opposite sign, in the extreme fibres. Also these two stresses together with the circumferential residual stress are nearly proportional to the yield stress of the material.

For an elastic-perfect plastic material, the maximum strain in the corner is reached in the inside fibre and does not depend on the material yield stress. On the basis of simulations, the maximum strain may be expressed as a function of the relative radius r/t.

$$e_{max} = 0.40\,(r/t)^{-0.85} \quad (40)$$

For a strain hardening material without a yield plateau the function becomes;

$$e_{max} = 0.33\,(\,r/t\,)^{-0.85} \tag{41}$$

When the material is elastic-perfect plastic, the relative change of radius of curvature during the springback increases with the yield stress Y, and with the relative radius of curvature. This change is obtained approximately by the following expression;

$$\frac{\Delta r}{r} = 1.5 \times 10^{-5}\, Y \left(1.3 + \frac{r}{t}\right)^{1.06} \tag{42}$$

Where Y is in N/mm^2

For a strain hardening material, the springback depends on length of the stress-strain yield plateau. The relative radius of curvature can be obtained by interpolating between two limits;

Material with a yield plateau

$$\frac{\Delta r}{r} = 2.3 \times 10^{-5}\, Y \left(1.3 + \frac{r}{t}\right)^{0.83} \tag{43}$$

Strain–hardening material

$$\frac{\Delta r}{r} = 1.5 \times 10^{-5}\, Y \left(1.3 + \frac{r}{t}\right)^{1.06} \tag{44}$$

The study goes on to balance residual stresses in the longitudinal direction for three profiles ("L", "U" and "C"), in order to obtain equations for the longitudinal stresses of fibres in all elements of the section. Appendix 2 gives the particular equations for an "L" section.

The author acknowledges that each section shape requires its own series of equations, making a general solution impossible. However the approach to finding the stress equations is the same for all sections.

CHAPTER 5

EXPERIMENTAL REVIEW

5.1 INTRODUCTION

While theoretical studies have built up idealised models of cold roll-forming, experimental work has been used to gain an understanding of the true nature of the process. Panton (126) suggested a useful grouping of such studies;

1. Fundamental studies of roll forming
2. Investigations into optimum roll pass schedules
3. Investigations into specific sectional problems, the occurrence of these problems and the means of reducing them.

Fundamental studies are concerned with understanding the nature and interrelation of the parameters which define the cold roll-forming process in general. Diagram 5.1 shows these parameters under three headings; tool design, operating conditions and material properties.

A fundamental study of roll forming refers to research which is not orientated to solving a particular problem, i.e. restricting the occurrence of a particular defect or "optimising" the form roll design for a particular section, but is concerned with understanding the nature and interrelation of the parameters which define the cold roll-forming process in general. Diagram 5.1 details those parameters which collectively define the cold roll-forming process (this list may not be exhaustive). Clearly, any study which attempted to look at the cold roll-forming process overall would be immense. Thus, there have been very few studies which can be classified as fundamental, and those that exist must be considered of a piecemeal nature when viewed within the context of diagram 5.1 .

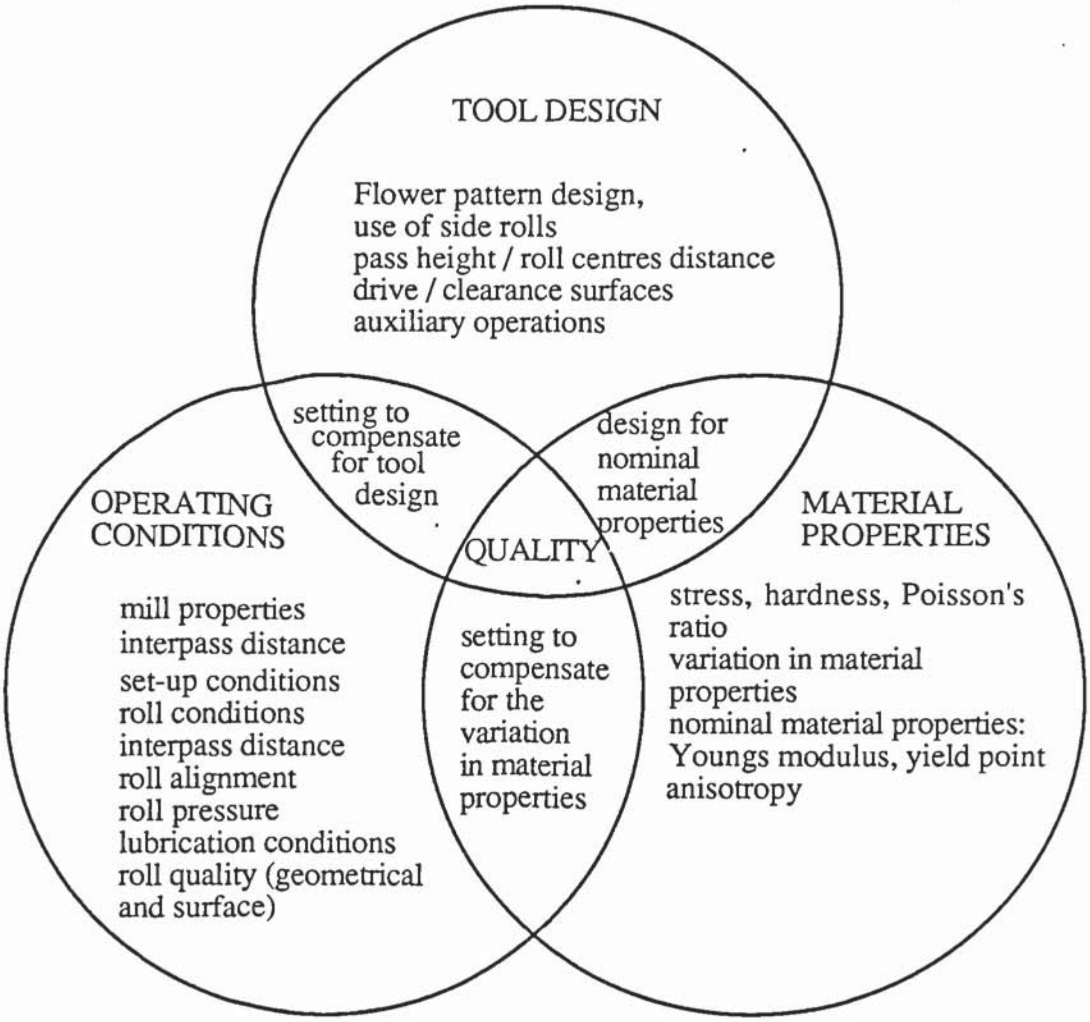


DIAGRAM 5.1 FACTORS DEFINING THE COLD ROLL FORMING PROCESS AND AFFECTING SECTION QUALITY

Investigations of roll pass schedules and "optimum" roll design can be considered to be studies of a fundamental nature where all the parameters are fixed except those pertaining to roll design. A major problem with optimising roll design is the difficulty in deciding on some statement of quality which can be optimised, or at least satisfied, by a particular roll design. Sectional quality is, in practice, a function of many interrelated parameters defining geometric accuracy and surface quality.

There appears to have been more work performed under the third grouping than the other two, that is, work which has been directed towards solving a problem with a specific section which is in production or is in the process of going into production. This would appear to reflect both the pragmatic nature of roll formers, and the inherent difficulties in the fundamental study of cold roll-forming. There are many examples of this type of research in the literature and almost certainly many more examples which have gone undocumented. To a certain extent, work which falls into category 3 is performed by all roll formers, in that often roll designs are modified and rolls remachined in order to reduce the occurrence of specific defects. However, in most cases such testing would appear to be carried out too unscientifically to justify the use of the word experimental.

5.2 CLASSIFICATION OF EXPERIMENTAL RESEARCH

For the purpose of quick reference, the literature relating to experimental research has been collected and summarised by tabular means in Table 5.1A and 5.1B. The numbers across the page refer to the reference numbers.

In the same way when studying any mechanical process, cold roll-forming has been most commonly studied by analysing the effect of one parameter on another and deriving relationships. Normally this means changing one of the parameters in table 5.1A and B, and observing the effect on either section quality or strain distribution .

Thus the first three headings, (material properties, operating conditions and roll design) contain those parameters which can be varied, whilst the fourth heading contains those parameters which can be measured; stress or strain or some function of quality. The parameters which have been used to define quality can be listed as follows:

1. Vertical curvature
2. Horizontal curvature
3. Twist
4. Geometrical cross-sectional accuracy
5. Surface finish
6. Buckling defects (web, edge, pocket waves)
7. Cracking

The fifth heading (section type) attempts to divide the papers depending on the type of section which is being considered. The sections are divided into the following four groupings;

TABLE 5.1A EXPERIMENTAL SUMMARY

Parameter \ Paper No	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148
Material																			
Thickness						■	■	■	■				■						
Type						■	■				■		■						
Operating Conditions																			
Rolling Speed						■	■												
Roll Pressure						■	■												
Roll Alignment						■	■												
Roll Condition																			
Inter-pass Distance						■	■												
Lubrication				■															
Roll Design																			
General Design	■				■	■	■			■							■		
Pass Schedules																	■		
Measurement By/Of																			
Stress		■							■							■			
Strain	■	■	■			■	■		■	■	■			■			■	■	
Curvature						■	■	■			■						■		
Twist																▩			
X-Sectional Geometry			■		■														
Buckling	■							■	■				■						
Cracking										▩							▩		
Surface Finish																	▩		
End Flare																	■		
Mechanical Properties										■									
Section Type																			
Channel		■				■	■					■		■			■		
Tube	■		■			■	■		■			■							
Wide Panel					■					■	■		■					■	
Miscellaneous				■				■											■
Language																			
English		■	■	■	■	■	■			■		■		■		■	■	■	■
Japanese	■							■	■		■		■						
Other																			

■ Quantified parameter ▩ Discussed not quantified

TABLE 5.1B EXPERIMENTAL SUMMARY

Parameter \ Paper No	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167
Material																			
Thickness																	■		
Type				■								■					■		
Operating Conditions																			
Rolling Speed																			
Roll Pressure	■								■										■
Roll Alignment	■								■										
Roll Condition																			
Inter-pass Distance										■									
Lubrication																			
Roll Design																			
General Design	■	■	■			■	■	■	■		■	■	■				■		
Pass Schedules		■	■			■					■	■	■				■		
Measurement By/Of																			
Stress										■						■			
Strain		■	■			■		■		■	■	■	■		■		■		
Curvature	■			■				■	■		▩	■					■	■	
Twist	■								■										
X-Sectional Geometry				■															
Buckling		■	■			■					▩		■						
Cracking			▩					▩					■						
Surface Finish										▩									
End Flare							■			■									■
Mechanical Properties																			
Section Type																			
Channel	■						■		■	■	■	■			■	■			■
Tube				■										■			■	■	
Wide Panel		■	■			■		■					■						
Miscellaneous					■														
Language																			
English				■	■			■	■	■	■	■		■	■		■	■	■
Japanese	■	■	■			■	■						■			■			
Other																			

■ Quantified parameter ▩ Discussed not quantified

1. Channel sections, (including symmetrical and asymmetrical channels and trapezoidal sections).
2. Tubes and circular arcs.
3. Wide panels.
4. Miscellaneous sections and techniques.

The final heading describes in which language the paper is written. Papers written in Japanese often have an English abstract and English annotation to the diagrams.

The following sections provide a summary of the existing literature, outlining the areas of existing knowledge. The papers are divided into four groups depending on the type of section being rolled (the groupings being the same as in Table 5.1A and B). Prior to this, however, there is a section dedicated to studies which have considered more than one of these section groups, and are of a more general nature than the others.

5.3 EXPERIMENTAL STUDIES ON GENERAL SECTIONS

Suzuki and Kiuchi (136) decided that whilst the cold roll-forming process can produce a wide range of products with varying cross-sectional profiles and sizes, these cross-sectional profiles could be considered as being composed of fundamental profiles. Of these fundamental profiles, circular arc, V (angle) and trapezoidal sections were considered the most important. Thus they investigated the effect of many parameters on the forming of these three profiles. The full scale of the project is indicated by Table 5.2, which describes the main parameters which have been measured or varied.

With regards to table 5.2, the apparent inlet angle is a function of the base line of the section and is defined in diagram 5.2. As a definition of quality, for each of the three sections, the authors defined a function which gave an indication of the cross-sectional accuracy of the profile. For the circular arc section they investigated the distribution of the value of the radius across the profile (the distribution of transverse bending radii). For the angle and channel sections they defined the formability coefficient as being the ratio of the transverse bending angle of the section to the bending angle of the roll. The parameter of longitudinal curvature was also selected as being a good statement of quality and was obtained for all three sections. Additional to these quality parameters the longitudinal strain values were examined and values for the roll separating force and the forming torque obtained.

MEASURED PARAMETER \ VARIED PARAMETER		apparent inlet angle	thickness	roll gap	cross sectional coefficient (circular)	ratio of concave: convex roll diameters	width of sheet	bend angle	bend radius	roll pressure	ratio of width / web	pass length
trapezoid section	forming torque	■		■		■	■					■
	forming load (roll separating force)	■		■			■					
	formability coefficient (trapezoid)	■		■			■				■	
	longitudinal curvature	■		■			■			■	■	
	longitudinal bending strain	■										
	longitudinal membrane strain	■										
angle section	forming torque	■	■	■		■	■					■
	forming load (roll separating force)	■	■	■			■					
	formability coefficient (angle).	■	■	■			■	■	■	■		
	longitudinal curvature	■	■	■			■	■	■	■		
	longitudinal bending strain	■										
	longitudinal membrane strain	■										
circular arc	forming torque	■		■			■					■
	forming load (roll separating force)	■		■			■					
	distribution of transversal bending radii	■	■	■	■		■					
	longitudinal curvature	■	■	■	■	■						
	longitudinal bending strain											
	longitudinal membrane strain	■										

TABLE 5.2 SUMMARY OF " EXPERIMENTAL INVESTIGATION OF COLD ROLL FORMING" (PAPER NO 136) BY SUZUKI AND KIUCHI.

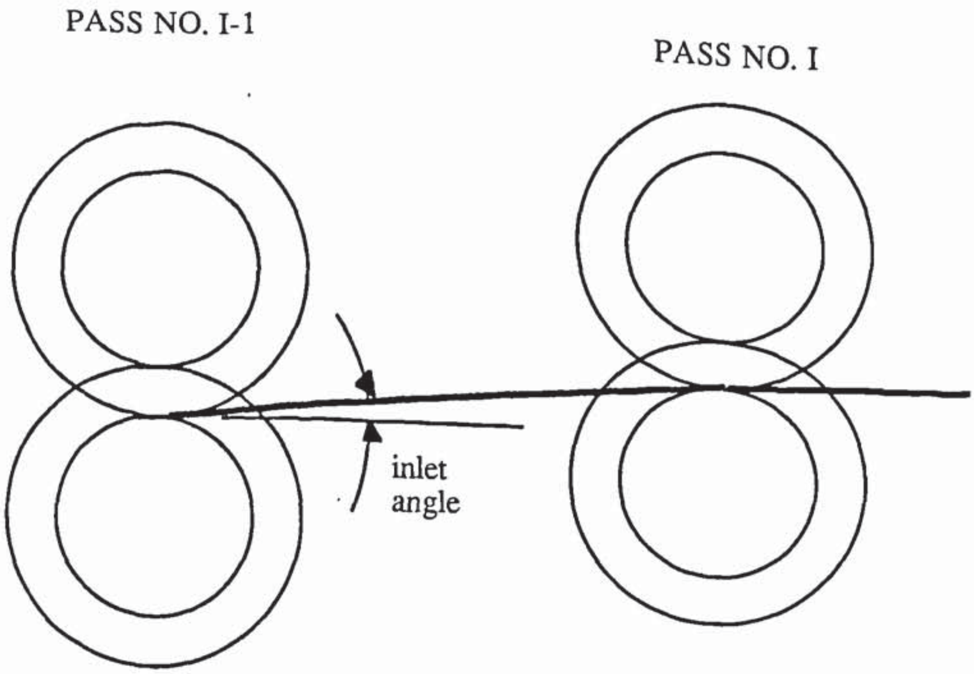


DIAGRAM 5.2 DEFINITION OF APPARENT INLET ANGLE FOR THE Ith PASS.

The authors considered that their studies clarified the following important characteristics of the deformation in cold roll-forming.

1. Usually each part of the sheet is greatly deformed just in front of the forming rolls in each roll station.
2. Each part of the sheet is often bent or bent back in the longitudinal direction while passing through the gap of the forming rolls.
3. At every forming step, the sheet is not always bent homogeneously in the transverse direction. For example, in the case when it is formed into a product with circular arc cross sectional profile, some of its parts are greatly bent in the transverse direction at a comparatively early stage whilst other parts are bent immediately before entering the rolls or during their passage through the roll gap.
4. The magnitude and sequence of transverse bending strain or other (redundant) strains observed during the forming process vary with the transverse position of the sheet, and are essentially affected by forming parameters and process variables.
5. Any strain component of the sheet does not always change with repeatability in the process.

6. The inlet path into the roll gap or the apparent inlet angle of the sheet has a great effect on the patterns of distribution and transition of transverse bending strain, or other redundant strain components.

7. The magnitude and sequence of redundant strain components change greatly according to the change in the apparent inlet angle of the sheet.

8. Especially when the apparent inlet angle is positive, there is seen to be a sharp difference between the magnitude of the transverse bending strain in those parts which are sufficiently bent in the transverse direction, and that in other parts not sufficiently bent, even while the sheet is just between the roll gap.

9. Regarding the longitudinal membrane strain and the longitudinal bending strain, the patterns of their distribution and transition during the forming process clearly correspond to the shape of the three-dimensional curved surface of the deformed sheet. Such patterns are related to the relative length of the spatial paths along which each part of the sheet progresses from one roll stand to another, the intensity and pattern of constraint given by the form rolls to the sheet, the balance of acting forces, etc.

In a similar report from the same source [140]; the distribution and magnitude of roll-metal interface pressure, and the distribution of areas of contact between roll and metal were examined. Again the three fundamental shapes, circular arc, angle section and trapezoid section were chosen and the measured parameters were obtained for a range of varied parameters. The following conclusions were obtained:

1. In each case of circular arc, V-type and trapezoidal cross-sectional profiles, if the pass line that is generally adopted for the actual production line is not followed (i.e the pass-line does not deviate extremely from the vicinity of the horizontal line), little substantial change occurs to the pattern of pressure distribution.

2. The patterns of contact pressure distribution of the flange parts of the V-type and trapezoidal cross-sectional profiles resemble each other, and according to the increase of the ratio of flange width to thickness, the region of high contact pressure between concave roll and sheet metal tends to shift from the edge part to the vicinity of the bending part, while the region of high contact pressure between convex roll

and sheet shows a tendency to deviate from the bending part to the periphery.

3. For the case of the trapezoidal section, when the flange width to thickness ratio increases to a certain extent, the distributions of contact pressure between concave roll and sheet metal at both the web and flange parts take the maximum value at a distance several times the sheet thickness from the bending part. The relationship between the maximum values varies with the forming conditions. As the ratio of flange width to thickness increases and as the cross-section becomes deeper, the maximum value on the web side increases. The pattern of contact pressure distribution of the web part is largely unaffected by the flange width.

4. From the results of the study, it is possible to estimate, for V and trapezoidal cross-sections, an outline of the pattern of contact pressure distribution for cases where the sheet thickness or flange width is different.

5. For the case of the circular arc, if the ratio of sheet width to transverse bending radius of roll is less than some constant value (K), the pressure distribution between the convex roll and the sheet metal is high at the centre and low at the edge, whilst for the concave roll, contact pressure only occurs at the edge part. However, if the ratio is greater than K the maximum value of contact pressure (between the sheet metal and the convex roll) occurs a certain distance inwards from the edge. The ratio has little effect on the contact pressure between the concave roll and the metal.

6. For all three cases, the sheet metal directly under the roll gap is rarely bent exactly to the roll profile. In most cases it is bent finely waving in the transverse direction. It seems that this trend is promoted as the ratio of strip width to thickness increases, and also as the cross-section becomes deeper with the progress of forming.

5.4 EXPERIMENTAL STUDIES ON CHANNEL SECTIONS

The following text describes investigations performed on the family of sections which are characterised by their having a single radial element and a single leg on each side. Since such sections are amongst the most fundamental possible shapes they have been extensively investigated.

Some researchers (for instance 135) have examined the forming of trapezoidal sections through a single pass. It should be remembered however that the behaviour of the metal as it enters the first pass is fundamentally different from subsequent passes, for the following reason. As the metal is bent from flat strip it adopts a shape such as diagram 5.3A , where metal is folding in from the edge, and the shape of the metal is extremely difficult to quantify. After the first pass the metal folds about the "hinge" formed by the bend (i.e., adopts a shape such as diagram 5.3A).

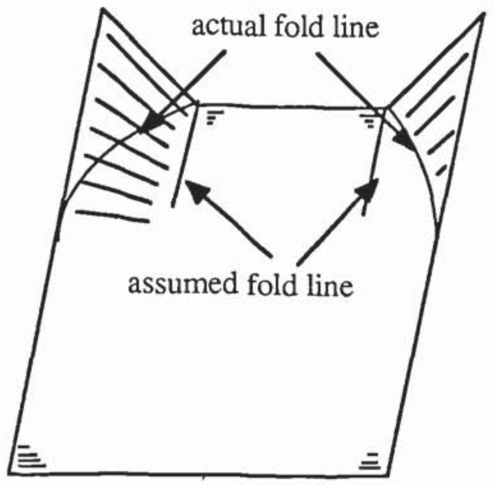


DIAGRAM 5.3A

ASSUMED AND ACTUAL FOLD LINE OF FIRST PASS

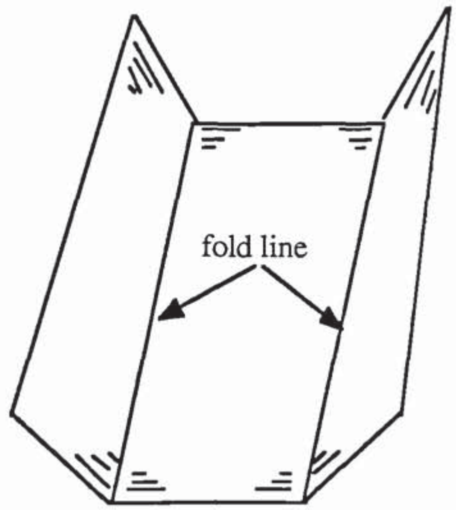


DIAGRAM 5.3B

FOLD LINE OF SUBSEQUENT PASSES

A large number of studies have attempted to measure the strain distributions in the metal strip as it passes through the mill (for instance papers 131, 143, 158, 159, 160, and 163). Of the methods of measuring strain, two are commonly used for cold roll-forming.

1. Measuring a deformed grid which has been previously machined, scribed or etched onto the metal surface. (NC machines are particularly effective for producing accurate grids relatively easily). The strain distribution can hence be obtained (163) and, if required, the stress distribution approximated (164).
2. Attaching strain gauge(s) to the metal sheet.

The first method is inherently inaccurate since it measures 'relaxed strains', (after springback). The second method gives the actual strain measurements prior to springback, although usually it requires more planning and equipment.

Diagrams 5.4, 5.5, 5.6 show examples of the external longitudinal strain distributions for channel sections (leg length 50 mm and inside radius 1 mm) of thickness 1 mm, 2 mm and 3mm respectively which have been obtained by machining a grid using a NC milling machine and then measuring the deformed grid. The strips were rolled as part of the preliminary experimental work at Aston University, from which followed the main bulk of experimental work detailed in Chapter 6.

With reference to diagrams 5.4 - 5.6, the values 2-25 (running down the page) refer to regions between two successive lines of scribed dots. (Where the value 3 is downstream from value 2 and so on). The values 2 -25 are not absolutely comparable between the three specimens since it is impossible to stop the mill exactly at a specified point. Similarly, the interface between pass 2 and pass 3 can only be positioned approximately. By considering diagrams 5.4 - 5.6, the following general observations can be made on the three main regions of the channel section, i.e. the leg (values P1 - P7 , P13 - P19), the bend (values P8 and P12) and the base (values P9 - P11).

1. In the leg: the maximum strains occur, in all cases, towards the upper edge of the channel, and the strains decrease towards the base of the leg. This is as would be expected since the metal movement increases towards the top of the leg.

2. In the bend: towards the base of the leg and in the area of the bend the longitudinal strains tend to become compressive. It would appear that, since the radius is small with respect to the thickness, a condition of plane strain no longer exists. Since the neutral axis shifts towards the inner surface, the overall strain is compressive. Ingvarsson (145) noted that the residual stresses in the longitudinal direction were compressive and increased with decreasing radius. It is known that these compressive strains in the bend are an important cause of section defects such as bow and twist in many sections.

3. In the base of the channel : the strains can be either tensile or compressive. In diagram 5.6 where the specimen is of thickness 3 mm, there is a distinct boundary between two areas; one of mixed tensile and compressive strains in the base of the section, and one of purely compressive strains in the base of the section. An explanation for this effect is as follows : - since pass 3 contains side rolls it cannot be

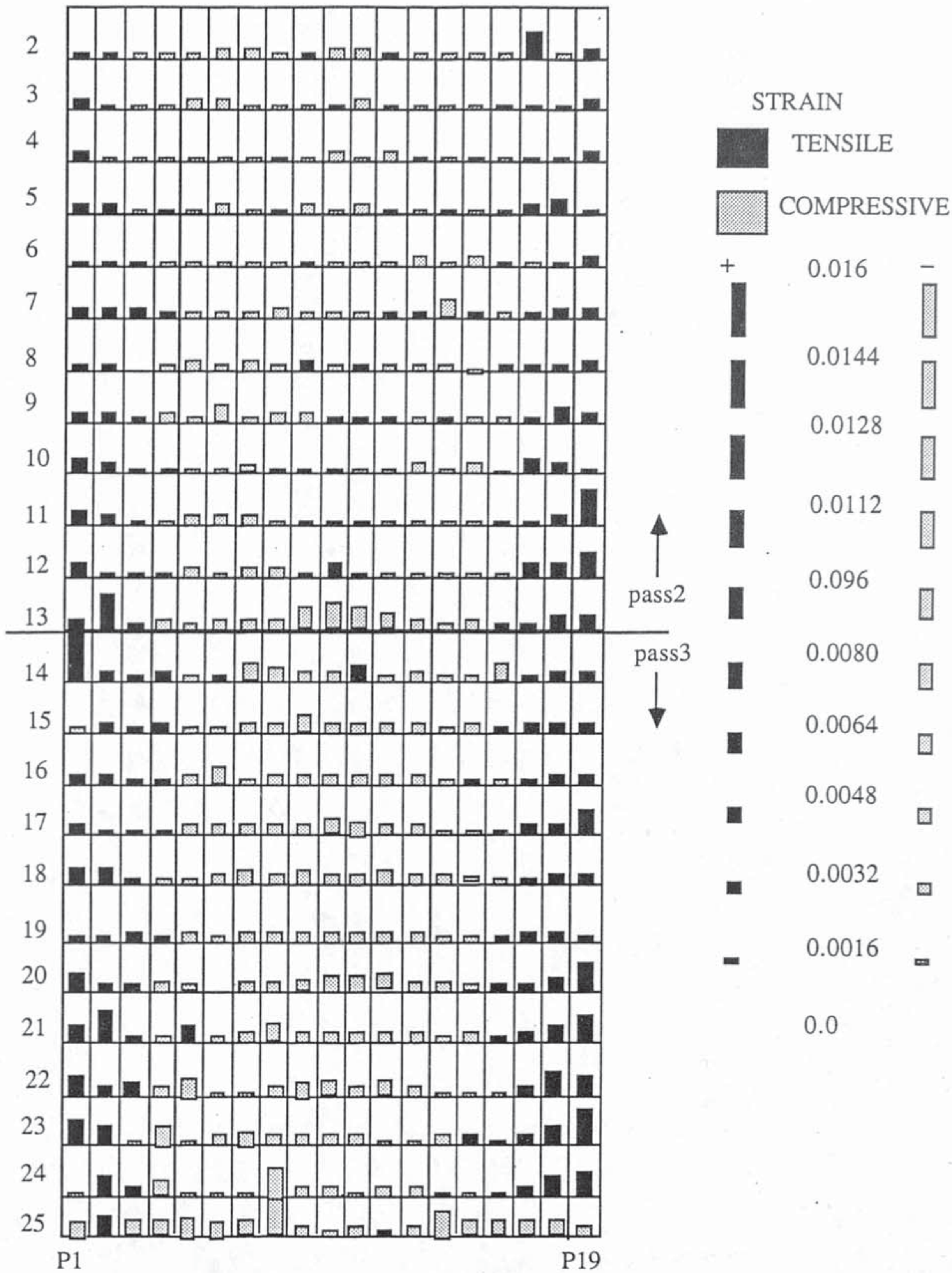


DIAGRAM 5.4 LONGITUDINAL STRAIN DISTRIBUTION
STRIP THICKNESS = 1mm

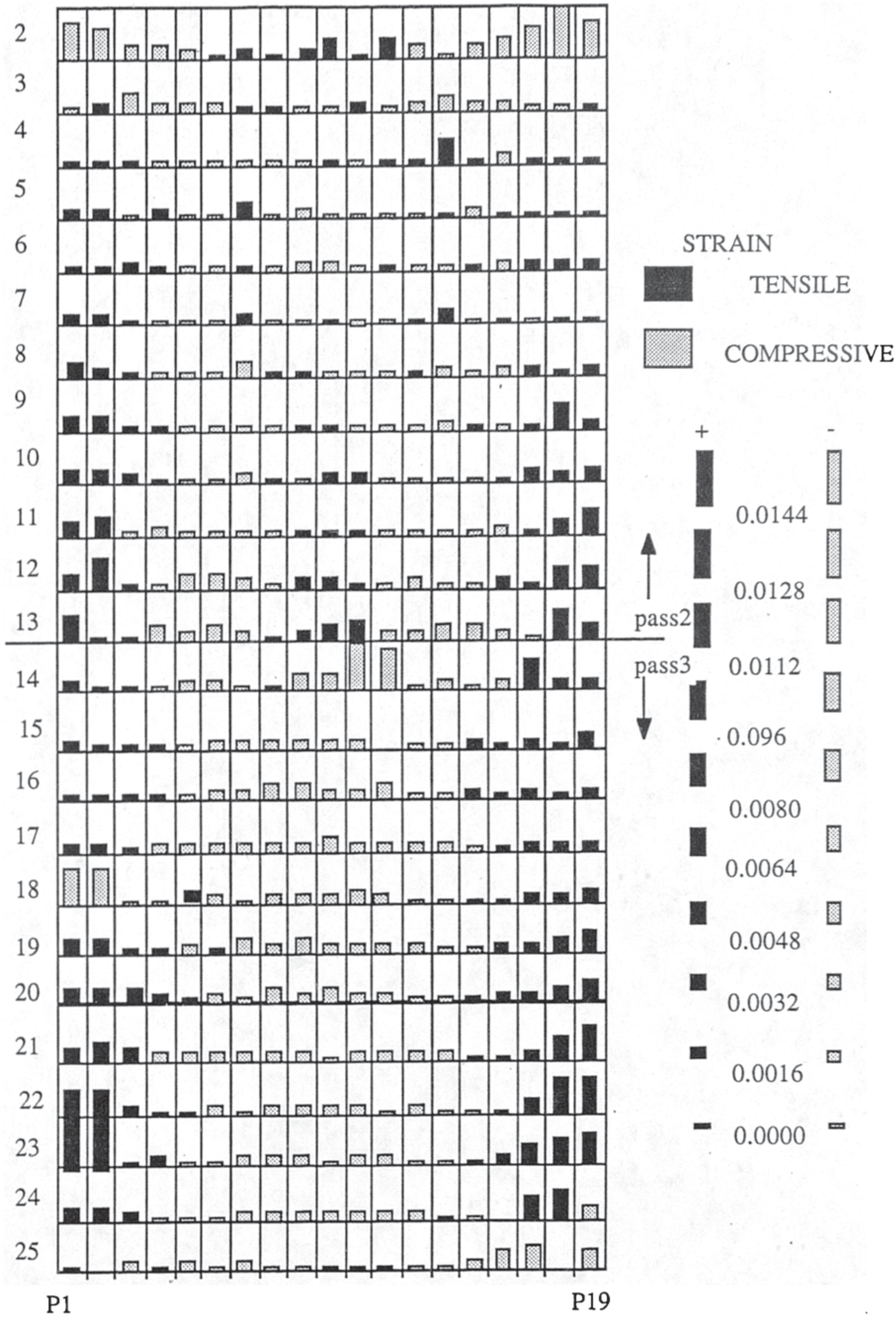


DIAGRAM 5.5 LONGITUDINAL STRAIN DISTRIBUTION
STRIP THICKNESS = 2mm

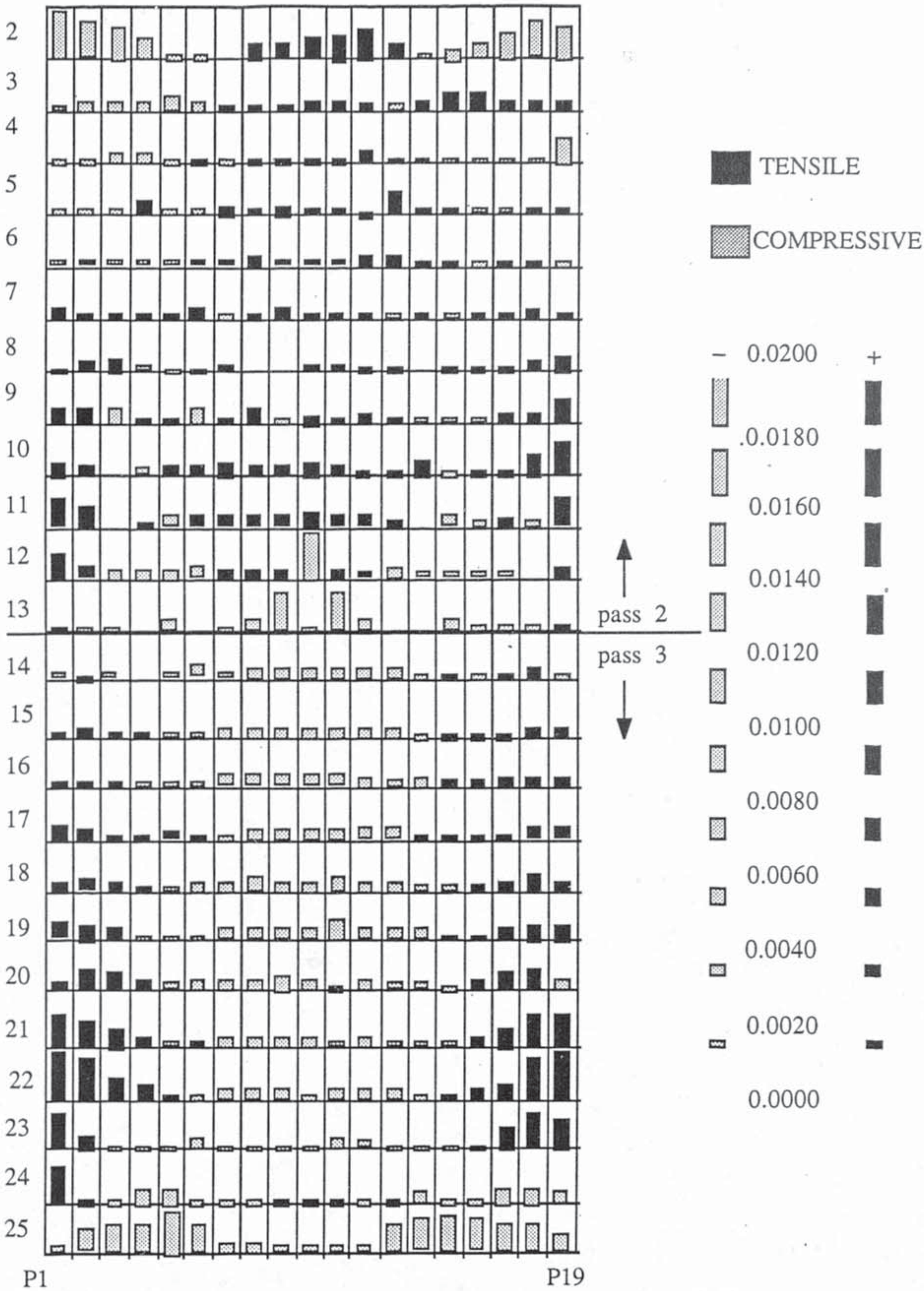


DIAGRAM 5.6 LONGITUDINAL STRAIN DISTRIBUTION
STRIP THICKNESS = 3mm

used to drive the metal, since the metal is relatively thick there is considerable resistance to the deformation caused by pass 3. In order to push the metal through pass 3 the roll loads have to be increased in pass 1 and pass 2. The high roll load in pass 1 means that the metal is being compressed in the thickness direction and hence causing tensile strains in the longitudinal direction. However when the metal has left pass 2 it is being pushed into pass 3, where it is experiencing considerable resistance to motion, hence compression results.

DIAGRAM 5.7 A
BASE BENDING AS THE METAL ENTERS THE ROLLS

DIAGRAM 5.7 B
THE METAL SHAPE UPON REACHING THE CENTRE OF THE ROLLS

An additional cause of straining in the base of the section is that the base does not always remain flat. Considering diagrams 5.7A and 5.7B, a cross-section through the metal perpendicular to the direction of rolling as the metal enters the pass would be given by diagram 5.7A. The upward bending of the legs causes the base to adopt a curved profile. As the section moves through the pass, the rolls flatten the linear element (as in diagram 5.7B). This 'bending and flattening' process produces relatively high compressive strains particularly in the second pass. Jimma and Ona (146) found the amount of this buckling in the base of channels to be a good statement of the severity of forming.

In general, it can be observed that as the thickness of metal increased the level of straining increased, this tendency has been supported by additional tests.

If only a limited number of results can be obtained, a common technique is to consider the longitudinal strain at the strip edge (143) and possibly at the centre of the section (159). This gives an indication of the maximum strain (which occurs at the strip edge). In general, the external edge strain for channel sections follows a pattern such as diagram 5.8 (best illustrated by Bhattacharyya (159)). The edge strain achieves a maximum value at some distance before the pass centre line, (where Jimma (163) found that the maximum longitudinal membrane strain occurred at a distance nearly equal to the leg length away from the pass centre line), the strain then reduces as it reaches the pass centre line, and levels off to form the residual strain value on exit. Sarantidis (143) concluded that results such as these (where the deformation was observed to occur in the region of the rolls) indicated that roll station position was of little consequence and need only be such as to give reasonable physical clearance. This appears to be a dangerous generalisation; in practice it would seem wise to ensure that the pass length is at least longer than the deformation length predicted by Bhattacharyya (see 4.2.4) plus an additional distance to ensure that the strip does not collide with the rolls on exiting the previous pass. In practice, the pass length required to allow the rolls to be mounted on the mill may be larger than this value, and hence must be chosen.

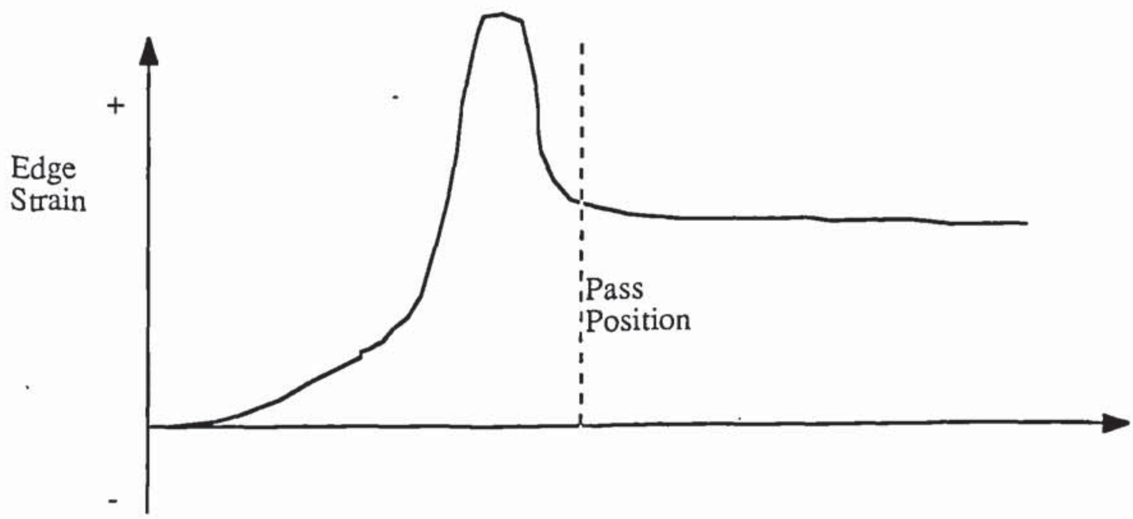


DIAGRAM 5.8 IDEALISED EDGE STRAIN PROFILE

By considering the longitudinal strain on the top and bottom surfaces it is possible to differentiate between longitudinal bending strain and longitudinal membrane strain (159). The longitudinal bending strain can have a considerable effect on the longitudinal strain distribution. Regions of tensile and compressive bending can be calculated. Thus the transition from tensile longitudinal strain to compressive strain in diagram 5.8 can be explained by the change in position of the radius of curvature, from one side of the strip to the other.

5.4.1 "OPTIMUM" ROLL SCHEDULES FOR CHANNEL SECTIONS

A number of workers (159,146) have investigated optimum flower pattern designs for the forming of symmetrical channels experimentally. It must be stated that, although there is as yet no "optimum" method for forming channels, the work that has been performed in this area has produced some useful by-products.

Battacharyya (159) found that the peak longitudinal strain (in forming trapezoidal sections) was independent of the roll angle at that stage, but was directly related to the increment of angle at that pass. The final difference between residual strain in the base and the leg (the cause of curvature) was found to be directly related to the final increment of angle; it was not significantly affected by the sequence or the number of passes prior to the final pass. It was also found that there was a maximum increment of angle (which could be determined experimentally), above which the channel was likely to wrinkle.

The method suggested by Bhattacharyya for establishing a flower pattern for producing symmetrical channel or trapezoidal sections can be summarised as follows:

1. Determine the fold angle above which wrinkling is likely to take place ($\Delta\theta_l$)
2. Determine the largest fold angle at the final pass commensurate with the acceptable level of straightness ($\Delta\theta_f$), (it was suggested that this should be 5°).
3. Allocate intermediate passes so that $\Delta\theta < \Delta\theta_f$

Jimma and Ona (146) performed a comprehensive investigation into the forming of two channels in three types of material (stainless and carbon steels and aluminium). Forty two combinations of the rolls 15°,30°,45°,60°,75°,85°,90° were examined with respect to curvature, surface damage, distortion near cut-off edges and edge waves.

It was noted that the curvature was determined by the severity of forming at the last pass and not by the number of passes. The effect of altering roll pressures was investigated and it was noted that a straight product could be rolled without adjusting the roll gaps if the correct flower pattern was used.

5.4.2 FORMING OF ASYMMETRIC CHANNEL SECTIONS

Jimma and Ona (149) have studied the forming the asymmetric channels (diagram 5.9); or more, accurately, they have studied means of overcoming the inherent out-of-straightness of such sections. Asymmetric channels will twist in the direction such that the higher flange approaches the lower one and curve horizontally, turning towards the higher flange side.

DIAGRAM 5.9 ASYMMETRIC CHANNEL SECTION

They found that mild distortion could be corrected by using an exit straightener. Transverse shift of the rolls was effective in correcting either the twist or the horizontal curvature (unfortunately twist decreases as the rolls are shifted towards the lower flange side whereas curvature is reduced as the rolls are moved in the opposite direction). Roll pressure could be used to control the vertical curvature but, as would be expected, was ineffective in reducing the twist and horizontal curvature. Over bend rolls, placed before the final pass, were tried and found to be effective in reducing twist and vertical curvature. A new twist forming stand was investigated and it was found that there were highly asymmetric channels which could not be rolled straight using any of these techniques.

5.5 EXPERIMENTAL STUDIES ON TUBE FORMING

Another fundamental group of section shapes are tubes and circular arcs. There have been a number of studies of tube rolling (for instance papers 130, 132, 136, 141, 152, 165, 166). The work of Suzuki and Kiuchi in this area has been quite extensive but was performed in conjunction with research on other section types, and so is discussed in section 5.4 (130, 162, 165).

An early researcher into form rolling was Masuda (132), who performed fundamental theoretical and experimental research into the forming of aluminium strips into circular arcs through a single pass. The major experimental conclusions of the research were; firstly that the transverse cross-section of the strip, before entering the pass, was parabolic but could be regarded as a circular arc, and secondly that the membrane strains were small (less than 10%) when compared to the bending strain on the strip surface. The experimental conclusions were used to predict the roll torque by using the strain energy method.

One of the few to have investigated the relationship between metal properties and the finished section shape has been Kato (152), who examined the effect of alloying elements or impurities in the rolling of circular arc through a single pass. A total of nineteen metal types including carbon and stainless steels, aluminium alloys, copper alloys, zinc and titanium were investigated. The following general relationships were observed; the edge stretch and longitudinal bending decrease but the springback increases as alloying elements and impurities increase in carbon steel, aluminium alloy and copper alloys. The material property found to be most relevant to edge stretch and longitudinal bending was the strain recovery at 1% tensile prestrain. The material property found to be most relevant to springback was the bending strain recovery at 2% bending strain. It was also noted that the Bauschinger effect and the work hardening at 1% prestrain were important factors regarding the value of longitudinal curvature. The importance of the entry guide height to the value of longitudinal curvature was also confirmed.

The research performed on the rolling and welding of pipes has been very much of a problem-solving nature, with the emphasis being on developing practical systems. As an example, Jimma (165) investigated a situation where the pipe chosen could be expected to provide particular difficulties. Firstly the material chosen was stainless steel which has a high tendency to springback and adverse thermal properties, (such as a relatively high coefficient of linear expansion and a relatively small heat transfer coefficient). Similarly, a difficult profile was chosen with the dimensions of the tube being diameter 22 mm with a wall thickness of 0.3 to 1.0 mm.

5.6 EXPERIMENTAL STUDIES ON WIDE PANEL FORMING

A highly important family of sections are the wide panels, familiar examples being corrugated and cladding sections. Wide panel forming exhibits a number of individual features, such that it can almost be considered a process on its own, and has hence formed the basis of a number of investigations(134,139,140,142,147,150,151,154,156,161).

A recurring theme in these papers is investigation into the compressive strains which occur in the bends of the panels, and the way in which these strains cause defects such as "oil canning", edge buckling and camber. Whilst compressive strains occur in the forming of all bends where the radius is reasonably small with respect to thickness, the large areas of flat sheet common to wide profiles tend to amplify the effect, and hence the defects become more pronounced.

Ona and Jimma (154) examined the causes of oil canning and edge buckling in the forming of wide profiles having two trapezoidal grooves (diagram 5.10). The following conclusions were reached.

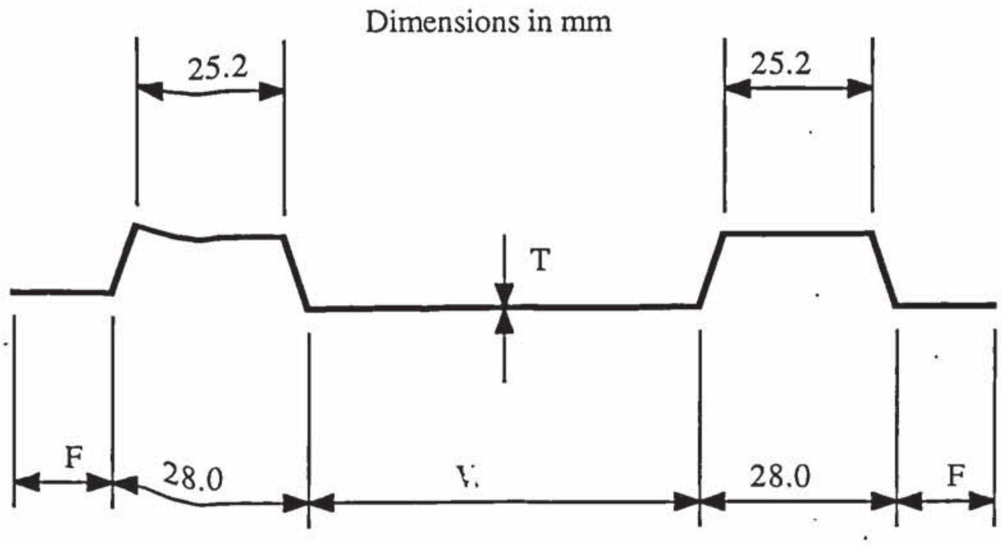


DIAGRAM 5.10 WIDE PROFILE EXPERIMENTED BY JIMMA AND ONA

1. All the wide profiles roll-formed in the experiment produced compressive strains in the longitudinal direction
2. The degree of oil canning and the degree of edge buckling increased with the level of longitudinal compressive strain
3. The longitudinal compressive strains were reduced by reducing the rate of increase of the bend angles at successive stages.
4. The degree of oil canning increased with the maximum amount of contraction in width of the wide profile per one stand in each of the pass schedules (W_{max}). However, the degree of edge buckling had no clear relationship with W_{max}, suggesting that edge buckling was caused not only by compression but also by shearing on the flange.
5. The limits of the occurrence of oil canning and edge buckling were given by
   $F/t < 250 / (W/t - 88)$ and $F/t < 40.8 - (W/t) / 30$
   (Where F, t and W are defined in diagram 5.10).
6. Elimination of oil canning was possible by applying tension to the wide profile in the forming process. The most proper position for applying tension was the exit of the roll stand, where the severest forming was being performed.

The investigations performed by Trishevskii (134, 147, 156) have been of a practical nature involving the development of systems for rolling wide panels. For instance paper 134 examined the forming of a wide panel which consisted of groups of corrugations separated by linear elements. It was found that where metal of thickness 1.5 mm was being rolled, waves were occurring in the linear elements. This problem was alleviated by first forming the metal for the corrugations into a single arc, and then progressively forming the sets of corrugations. Another description (147) is given for the development of a system for the rolling of corrugated sections from stainless steels, and the technical problems which may be expected.

The importance of equalising the compressive longitudinal strains in the bends in the top and bottom of trapezoidal corrugated sections, if problems such as camber and cross-camber are to be avoided, is also noted by Trishevskii (156). Amongst the parameters which can influence the value of the strains are the radius of the bend and the diameter of the upper and lower rolls. Varying the inside radius of the bends and hence equalising the strains was found to be a method by which wide panels could be rolled without cross-camber.

5.7 MISCELLANEOUS SECTIONS AND TECHNIQUES

Whilst the majority of experimental work can be grouped into the three families described in the last three sections, there are certain papers which relate to other section types (131, 133, 153) or special techniques (158). Mihara, for instance, describes an interesting development to the roll forming process; the roller die forming process (158), where the form rolls are replaced by a number of smaller diameter rolls (diagram 5.11). This, it is claimed, has the following advantages:- firstly there is less speed difference on the forming rolls and thus less scratches, secondly there is a smaller investment required for the new rolls compared to conventional rolls and thirdly higher accuracy and adjustability can be obtained with the new rolls. However the following disadvantages were also noted; firstly there are higher redundant strains due to the smallness of the roll diameter, and secondly the process is not suitable for small sections.

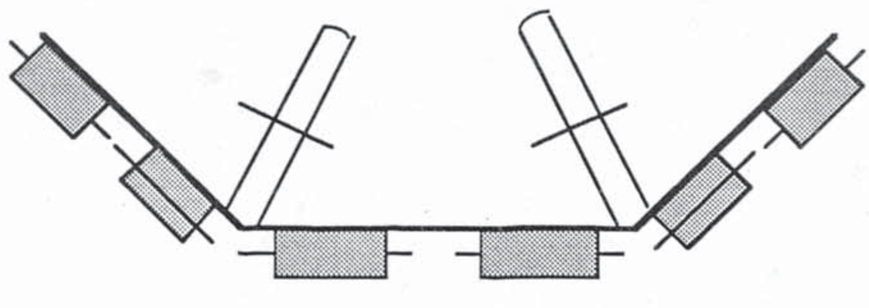


DIAGRAM 5.11 ROLLER DIE FORMING PROCESS

The rolling of square and rectangular sections from circular tube was described by Kiuchi(153). Experimental work is presented and particular attention is paid to the quality of the section profile. Additionally, formulae for the roll separating force are derived and, finally, a method for designing the optimum pass schedule is presented.

Kokado [138] investigated the forming of a section type which does not fall into any of the first three categories, this was a profile with a central circular arc with wide flanges. The following observations were made: the circular section contracted longitudinally at its centre (as would be expected from the observations on the rolling of circular profiles in general), the shoulder part of the profile was extended longitudinally, whilst the edge of the strip was found to be either compressed or extended depending on the forming conditions. It was confirmed that the occurrence of edge buckling was dependent on the magnitude of the strip width and the strip thickness, and that, for the profile rolled, edge buckling always occurred when the maximum compressive strain at the centre of the circular arc was over 0.4% and the thickness was over 0.8 mm.

5.8 AREAS FOR RESEARCH WORK.

The experimental literature review reveals the present limitations in cold roll-forming research. There are, therefore, many areas in which new work may be benefitial. The areas of particular value to manufacturers are considered to be as follows:

1. With reference to diagram 5.1, a major constraint on experimental analysis of cold roll-forming is the lack of any accepted general definition of section quality. Quality is inevitably a combination of a large number of individual elements. In cold roll-forming the components which collectively form quality have still to be isolated and defined. This means that, in general, whilst there are British Standards relating to sectional quality, the quality of cold roll-formed sections is still, to a large extent, assessed subjectively. Hence a limitation on experimental work is that, when varying any parameter of the cold roll-forming process, it is difficult to observe the effect on the components of quality. Valuable work, then, could be performed defining the quality of cold roll-formed sections. The following areas would be particularly rewarding.

   (I) Isolating and defining the ways in which a section can be considered unsatisfactory.

   (II) Developing methods for quantifying section defects.

   (III) Developing a standard terminology for section defects.

Such work would be of value to cold rolled section manufacturers, cold rolled section users and those performing experimental analysis of cold roll-forming.

2. Whilst isolating and defining the section defects, a parallel investigation would be to identify the mechanisms by which these defects occur and to study the relationship between strain distribution and defect occurrence. Many geometric defects can be considered as the tendency of the section to dissipate elastic energy. A potentially extremely rewarding area of work would be to investigate the derivation of expressions for section defects, such as curvature, using this method.

3. The conventional wisdom is that it is the magnitude of longitudinal straining which is the primary influence on the occurrence of section defects. However the setter can obtain "straighter" sections by using methods which clearly put additional straining into the metal (such as increasing roll pressure or moving the section out of line). This leads to the conclusion that it is not purely the magnitude, but the magnitude and distribution of longitudinal straining, which determines the occurrence of many section defects. With regard to this fact, potential areas of work are:-

   (I) To attempt to quantify the magnitude and distribution of additional straining required to produce the "straightest" section.

   (II) To investigate the most suitable method of introducing additional straining into the material to produce the straightest section.

4. With reference to diagram 5.1, it can be seen that the parameters which are known to define the cold roll-forming process and which collectively determine the section quality, can be generalised into three groups. Namely, operating conditions, material properties and tool design. However, within these three groups, the definitive list of parameters which determine sectional quality has yet to be compiled. This is one of the major limiting factors on the numerical analysis of form roll design and the generation of form roll design. Work is required in obtaining a more detailed understanding of the factors which define the form rolling process, their interrelationship and their influence on quality.

5. When investigating form roll design there is an argument that the range of sections which can be produced by cold roll-forming is so large that it is not possible to formulate methods for the general case. This leads to the conclusion that the range of sections should be divided into a number of subgroups. Rather than form these groups arbitrarily, there is a case for developing a coding system for cold roll-formed sections and hence, by cluster analysis techniques, to categorise these sections into sub groups and groups with similar characteristics. Developing a coding system for cold roll-formed sections would have the following additional advantages. Firstly, in general, rolling mills can be considered to be of two main types, either they are designed to form a particular section or they are designed to form any section (or any section within a wide range). By analysing the sections a company rolls it would be possible to form groups of sections requiring a similar type of rolling mill, hence it would be possible to advise on the appropriate designs of rolling mill and auxiliary equipment which should be owned by the company. Secondly, it is often useful for a designer to examine past designs of a similar nature when quoting for a job or designing a set of rolls. Using the coding system, a database of past designs could be collected on a computer and all designs of a similar nature could then be retrieved as required.

CHAPTER 6

EXPERIMENTAL METHODS

6.1 INTRODUCTION

Experimental work was designed to obtain as large a quantity of data concerning cold roll-forming as possible, from a minimal number of tests. The data obtained was used to show the influence of operating conditions on the section quality, to test mathematical models for accuracy and to indicate methods for quantifying operating parameters in an attempt to cover a part of the research work described in section 5.8.

Initially, a series of tests was devised to investigate the effects of roll load, roll alignment, inter-pass distance and roll speed on the quality of section rolled. These four parameters constitute the operating conditions, i.e. the variables under the operator's control (as discussed in chapters 2 and 5). Further tests were carried out later on the effects of roll diameter on section quality.

Quality was measured in terms of roll twist, longitudinal curvature and cross-sectional geometry. In addition the longitudinal strain profile of the section through the rolls was also recorded.

Preliminary tests were carried out on a Lockeformer rolling mill. However, this mill was designed for the production of one section and did not allow the variation of the operating parameters required without major alterations to its body. The mill allowed familiarisation with the problems associated with experimentation in cold roll-forming.

A suitable mill was offered for use by Hadley's Sections of Smethwick, a leading cold roll-forming company. The mill was being used in the production of window slides, but was made available for experiments in times between batch runs.

6.2 THE ROLLING MILL

The rolling mill was of standard in-board design, with 14 passes chain driven from a 20 h.p. three phase a.c. motor. Being of a more recent design, the mill also featured a Danfoss electrical speed controller, allowing a range of speed control. Various safety features were also incorporated, including an photoelectric "eye" which shut off the mill if operators were within close proximity to the rolls during rolling. This feature could be over-ridden, as was necessary for the tests. The mill was designed for rolling material of up to 3 mm thick, and carried roll spindles of 32 mm diameter. The bottom rolls were driven, the top being allowed to rotate freely.

6.3 THE EXPERIMENTAL TESTS

Each test involved rolling a pre-cut length of strip through the mill according to the following procedure;

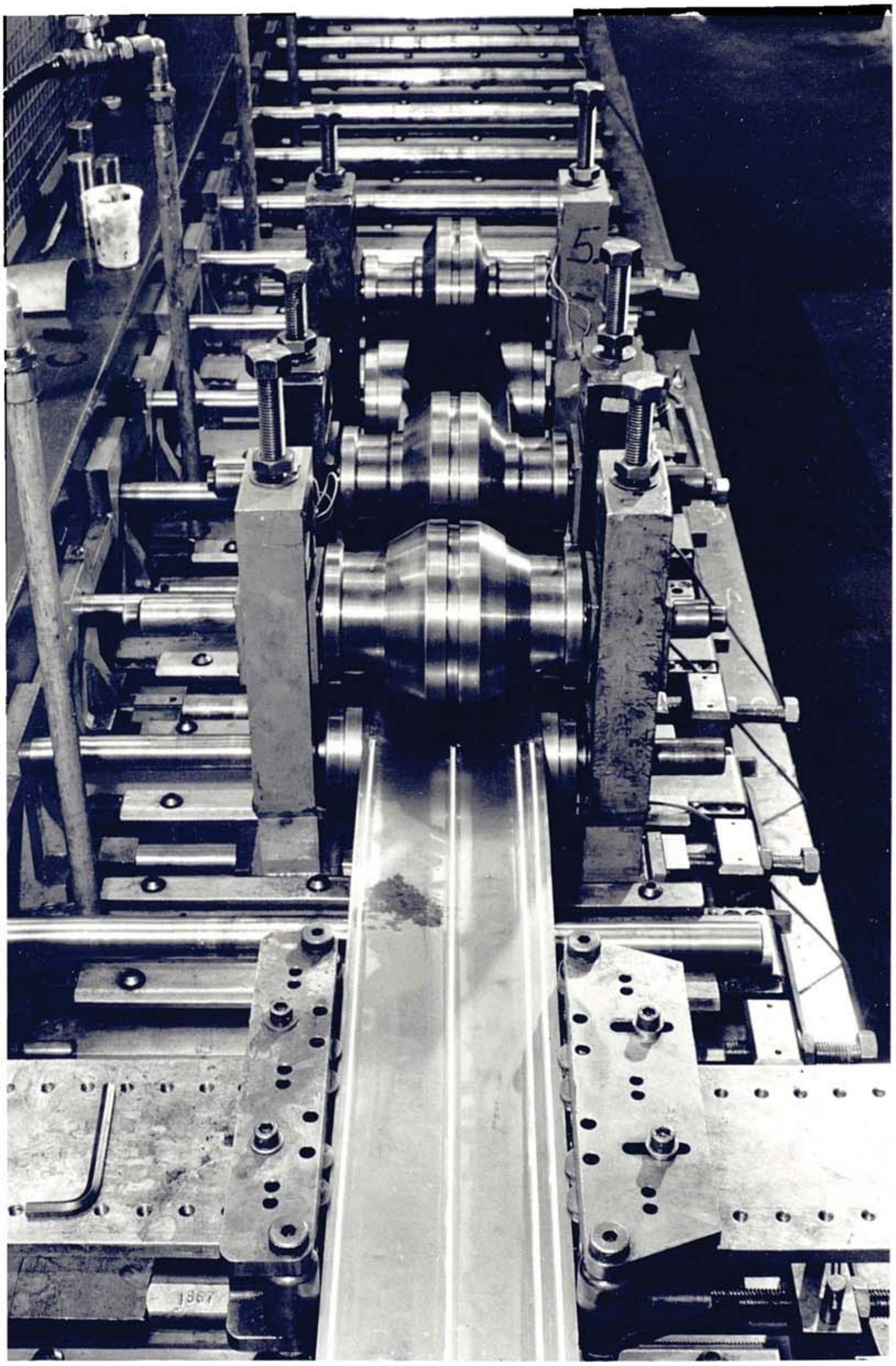
The leading edge of the strip was pushed into the first roll pass, and mill set up with the desired values of roll alignment, roll speed, inter-pass distance, roll load and roll diameter. The section was then rolled, stopping the mill after the strain gauges had passed through the final pass. A computer data collection device simultaneously recorded the signals from the strain gauges and roll load measurement equipment. Once finished, the formed strip was removed from the rolls; in some cases this required that the section be cut in two.

Due to the limited time available on the shop floor between production runs, the number of tests had to be kept to a minimum and performed quickly. Small groups of tests were therefore rolled sporadically throughout the research period.

Two sets of tests were carried out on the Hadley rolling mill. The part one tests were conducted first, and were directed to gaining a broad understanding of operating condition effects on quality. Part two tests concentrated on features to have emerged from the previous tests requiring further investigation. Throughout the time spent rolling, improvements to the test methods were discovered and applied. Numerous sections were rolled before recording any results, in order to learn the techniques of measurement and mill set-up.

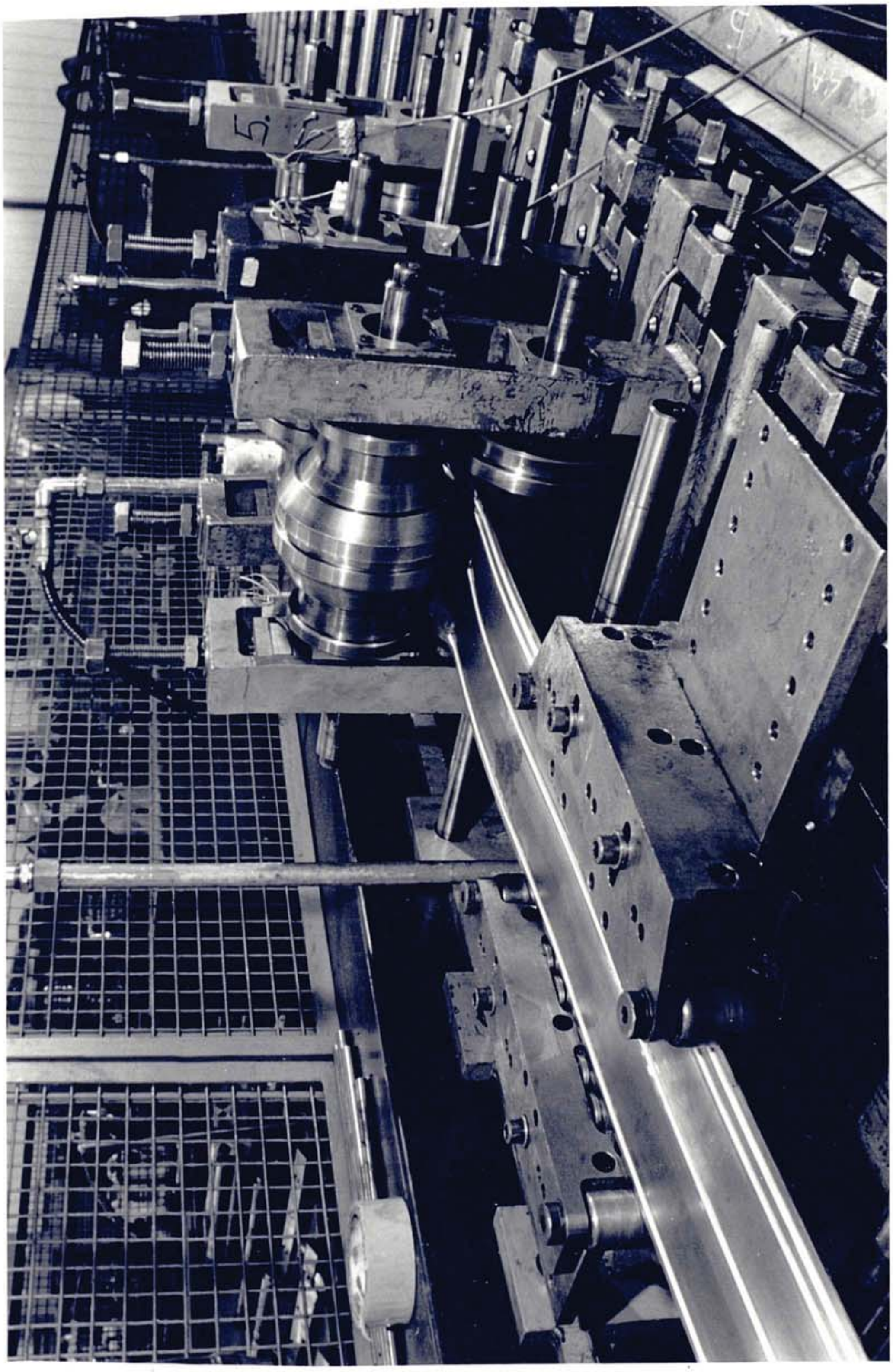
PHOTOGRAPH P1 THE ROLLING MILL

The photograph shows an overhead view of the mill used in the tests, with three passes in position. Strip can be seen entering the first pass from the strip guide. The white lines on the strip are the lead wires running from strain gauges. Cut-outs in the rolls allow the passage of the gauges through the roll gap.



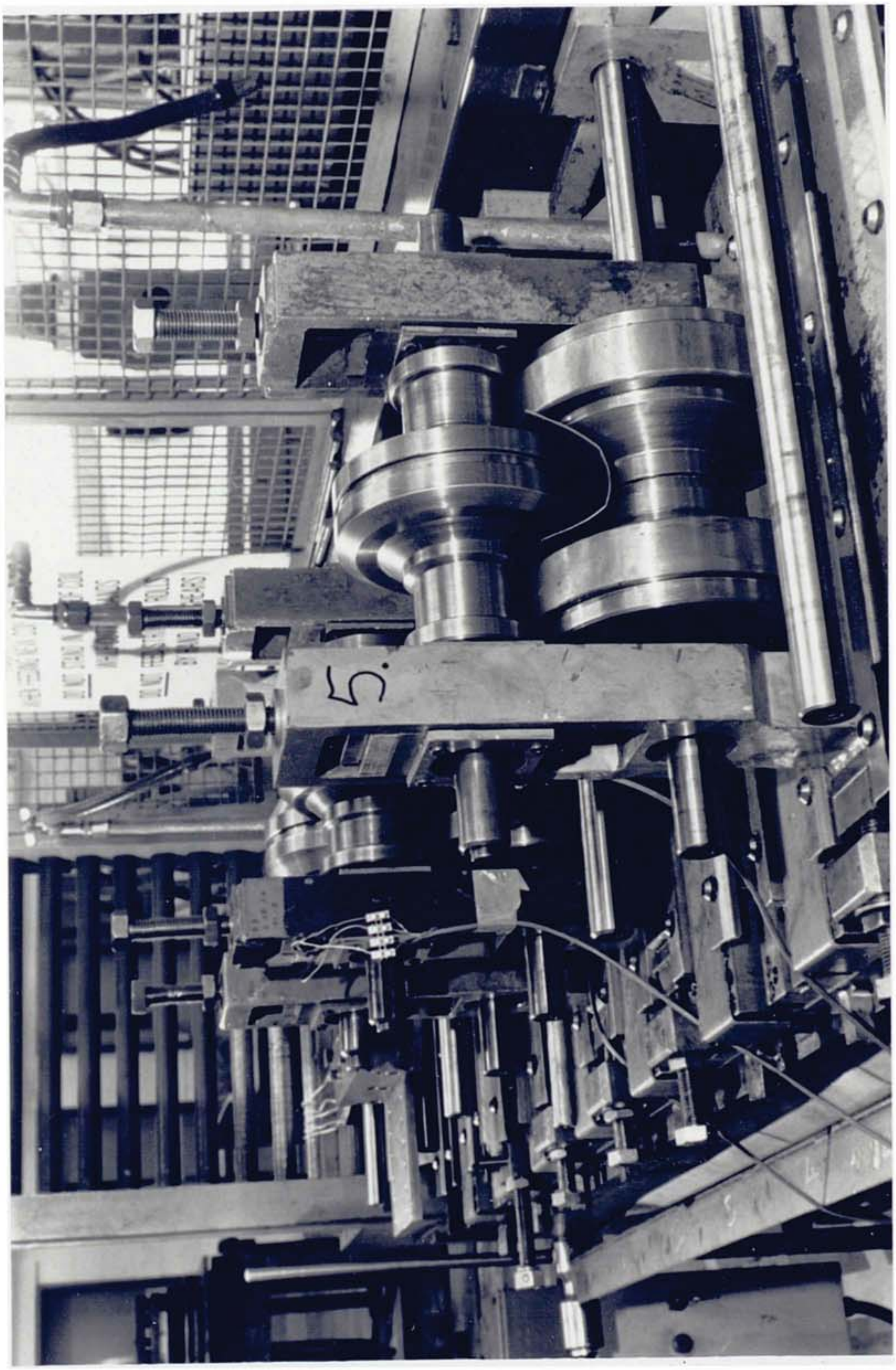
PHOTOGRAPH P2 THE ROLLING MILL

This oblique view shows wires running from the roll pillars. These are the wires connected to the load cells in the top bearing block.



PHOTOGRAPH P3 THE ROLLING MILL

Strip emerging from the third pass. It is not fully formed because the pillar bolts have been loosened as part of the setting procedure. Note the second to third inter-pass distance is longer than the first to second, in this test.



The tests were carried out on as simple a mill set-up as possible, for several reasons;

1. Past work had largely concentrated on specific rolling jobs. The conclusions from such tests could only be applied to the job tackled and so was of limited use. By taking a simple fundamental section, more of the information gained was applicable to a range of specific cases.
2. In conjunction with the experimental work there was the work concerned with estimating the accuracy of theoretical models. Theoretical work of the most wide range had been based on simple channel sections.
3. Starting with a very simple case allowed a natural starting point for the experimental study of cold roll-forming, even if, at this stage the information did not appear specific enough to help in the understanding of a complex mill setup. This avoided the formation of generalising conclusions drawn from specific cases.

The above indicated that a suitable section for experimentation was a symmetrical channel, produced in one pass.

Part one tests were carried out on the four rolling parameters;

1. Roll load
2. Roll alignment
3. Inter-pass distance
4. Roll speed

Various constraints existed which did not allow the use of one pass for all the tests.

1. For inter-pass distance tests there must be a minimum of two roll passes.
2. For roll alignment tests a minimum of three passes is required so the material does not slew (even with the use of roll guides before the first pass).

In order to reduce the length of time testing, reduce costs and gain a wide analysis of operating conditions, the number of tests was kept to a minimum.

TESTS ON ONE PASS

GROUP A — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70	1	2	3
110	4	5	6
150	7	8	9

GROUP A

GROUP B — Roll load / tf

high left	high right
10	11

(Uneven load put on each side of the pass).

GROUP B

TESTS ON TWO PASSES

GROUP C — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70		12	13
110	14	15	16
150		17	18

GROUP C

GROUP D — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70			
110	19	20	21
150			

GROUP D

TESTS ON THREE PASSES

GROUP E — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70	22		23
110	24		25
150	26		27

GROUP E

GROUP F — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70		28	29
110	30	31	32
150	33	34	35

GROUP F

GROUP G — Roll load / tf

Roll speed / rev/min	1.0	2.0	3.0
70	36	37	38
110	39	40	41
150		42	43

GROUP G

Operating Condition

Group	Inter-pass distance / mm	Roll alignment / mm out of line	Roll load	Roll speed / rev/min
A	n/a	n/a	shown	shown
B	n/a	n/a	shown	20
C	480	n/a	shown	shown
D	240	n/a	shown	shown
E	240 240	in line	shown	shown
F	240 240	1.7	shown	shown
G	240 480	in line	shown	shown

VALUES OF FIXED PARAMETERS

TABLE 6.1 PART ONE TEST NUMBERS, GROUPS AND OPERATING CONDITION VALUES

Instead of testing each parameter against all of the others, the tests may be grouped to reduce the total number. The tests were grouped according to table 6.1 and table 6.2.

Part two tests repeated several of the earlier tests with improved load control. Also a group of tests investigated the reversal of the first pass (it was considered this may have had an effect on the longitudinal curvature). Finally there were the tests on the effect of increasing the roll diameter of the second pass, in order to increase the longitudinal strain. Table 6.2 shows the part two tests.

TWO PASS TESTS

Roll Load / tf	1.0	2.0	3.0
Repeats GROUP H	44	45	46

Roll Load / tf	1.0	2.0	3.0
Increased Roll Diameter GROUP I	47	48	49

Reversed Pass GROUP J
50

Operating Condition Values

Group	inter-pass distance / mm	roll alignment	roll load / tf	roll diameter / mm	roll speed / rev/min
H	240	in line	shown	106.7	70
I	240	in line	shown	107.7	70
J	240	in line	2.0	106.7	70

TABLE 6.2 PART TWO TEST NUMBERS, GROUPS AND OPERATING CONDITION VALUES

6.4 THE SECTION CHOICE

The section chosen was designed to show clearly typical cold roll-forming phenomena. Diagram 6.1A shows the design. Geometric measurements after rolling were easier to apply to a rigid section, hence the material was heavy gauge and the channel deep. This also reduced springback, coupled with the small constant inside radius. Web width was large enough to allow access to measuring equipment and strain gauges. The flange was long to give rigidity,

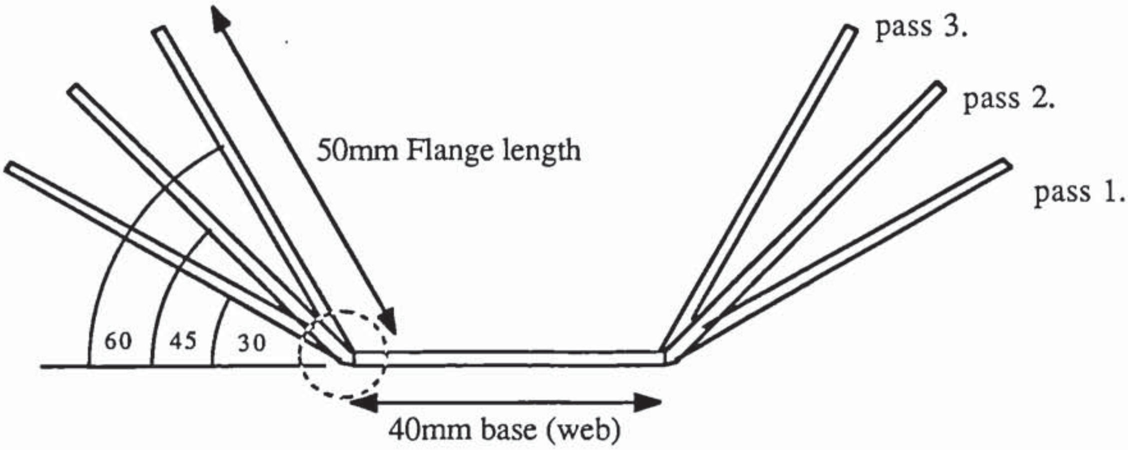


DIAGRAM 6.1 A SECTION PROFILES OF PASSES 1-3 (FLOWER PATTERN)

Detail in circled region

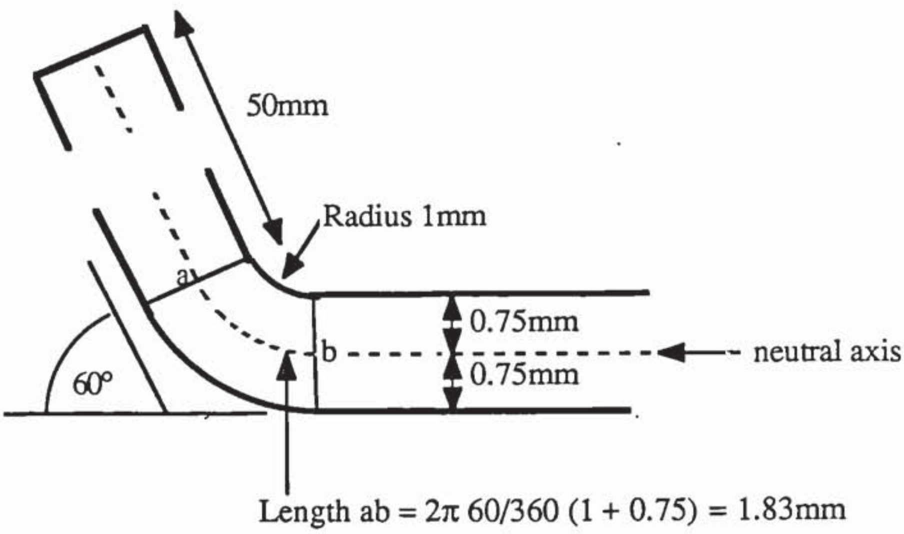


DIAGRAM 6.1 B CALCULATION OF BEND LENGTH

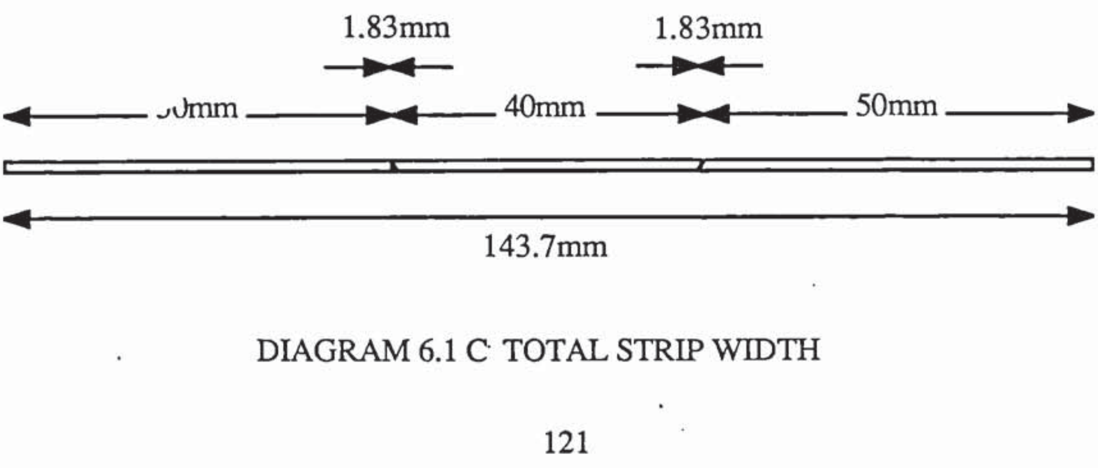


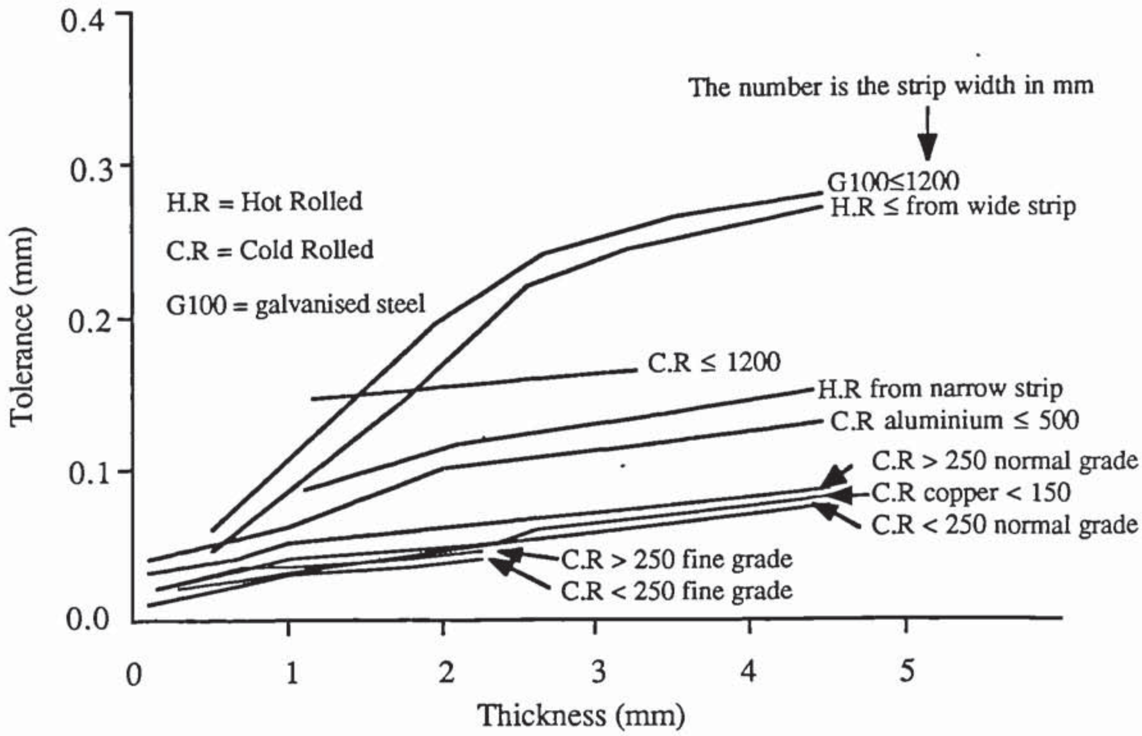
DIAGRAM 6.1 C TOTAL STRIP WIDTH

high edge strains, and space for strain gauges to be fitted. Using Bhattacharyya's deformation length formula (section 4.2.4), it was calculated that the flange length needed to be 50 mm to give a deformation length of 241 mm. This gave a situation where the inter-pass distance could be adjusted to be within, or outside, that length which was of interest. The section was symmetric to allow duplication of results on each side of the symmetry, and reduced the likelihood of twisting. Also the section was a typical shape used in past research at Aston, and similar to other researchers' choice of shape, hence results could be compared.

The first pass bend angle 30° was high, to give large straining effects and to produce a rigid section. The second pass added 15° of bend angle at the corners, and the third pass a further 15° as in diagram 6.1A. 60° was the maximum bend angle that could be accommodated. This gave such a large depth of forming that the roll centre-to-centre distance was at the limits of the roll pillar travel.

6.5 STRIP MATERIAL

The strip material was chosen to be a typical mild steel (the most common material used in cold roll-forming), with a close tolerance on thickness.



GRAPH 6.1 B.S. TOLERANCES ON SHEET METAL THICKNESS

By referring to British Standards B.S. 2994 (168) it was found that CR3 provided the highest tolerance on thickness for a mild steel, and so was chosen. Graph 6.1 shows the materials and their tolerances.

It was assumed that the neutral axis of the bend was at the centre of the strip thickness, for the calculation of strip width, as in diagrams 6.1B and 6.1C.

The strip was ordered in pre-cut lengths of 2 m, 143 mm wide and 1.5 mm thick. The width and thickness of each strip was checked for consistency, before and after rolling, at several points along the length.

6.6 THE ROLLS

The rolls were designed using the Rolform CAD / CAM package (described in chapter 3), and modified by hand to include the cut-outs needed to allow the passage of the strain gauges through the pass. The details of the design are shown in diagram 6.2. Seven rolls were manufactured; the three roll pairs, and an extra second pass bottom roll with increased roll diameter. Rolls were cut using a Torshalle CNC lathe from a blank of steel EN36B, and then hardened, following standard practice in the company.

6.7 MEASUREMENT OF ROLL ALIGNMENT

There were two methods of roll alignment used by the operators. The first was to locate the first roll pair at any transverse position, and then align the next pair by eye to the preceding one. Alternatively, some roll sets had a small groove cut in one of the surfaces of each of the roll pairs. Two lines were stretched from one end of the mill to the other, above and below marked roll. By aligning the wires (placed one above the other to allow parallax alignment) with the notch, each roll could be positioned in the correct transverse position. This latter method was the more accurate, usually allowing positioning to +/-1 mm (dependent on the operator's eyesight and judgment skill).

With both of these systems, however, there was no method of knowing how far the roll was being moved out of line when adjustments were made to maintain quality.

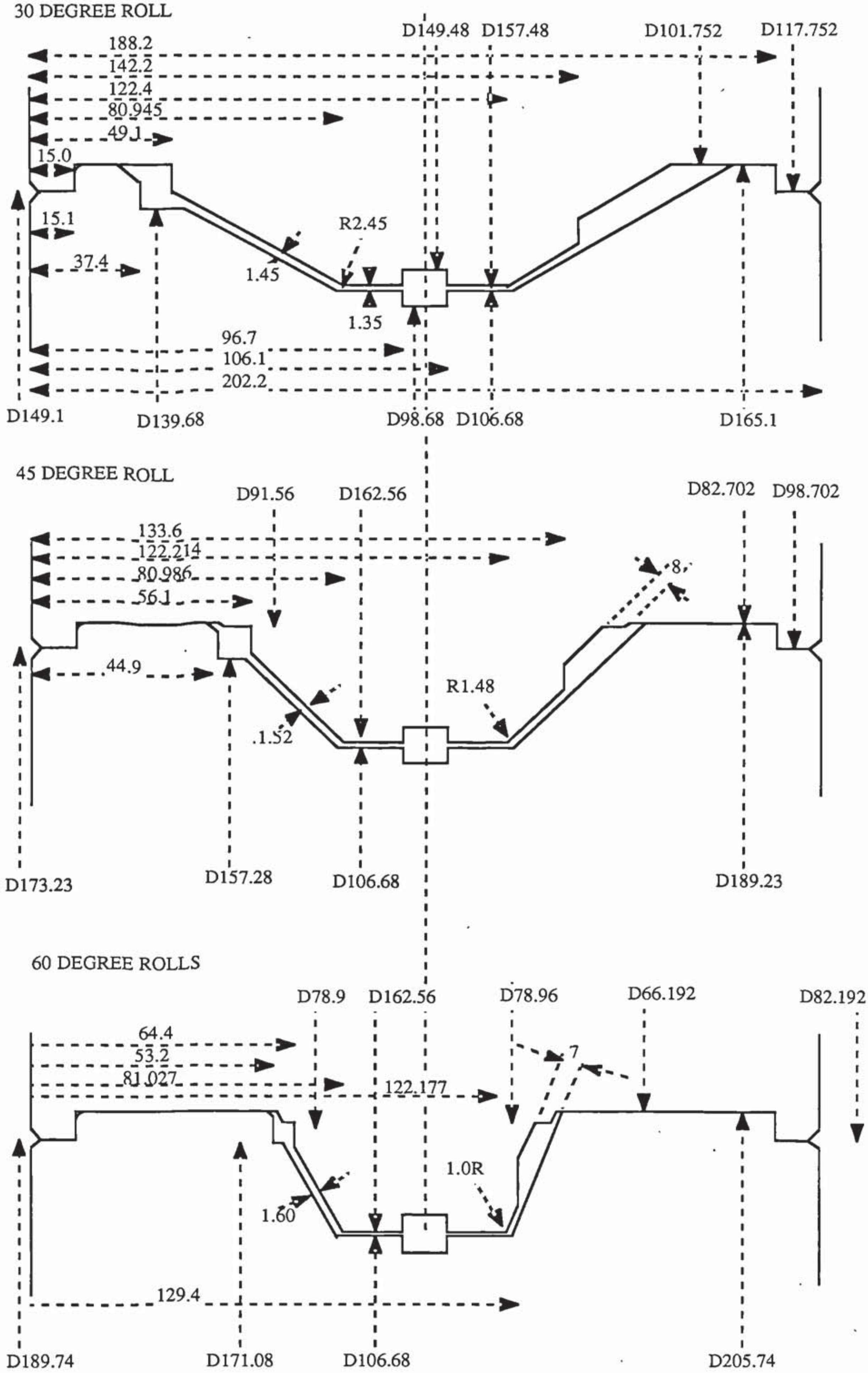


DIAGRAM 6.2 DETAILS OF THE ROLL DESIGN

PHOTOGRAPH P4 TOP ROLL OF THE FIRST PASS.

The photograph shows the keyway in the roll axle, and the roll profile, including gates and cut-outs.

PHOTOGRAPH P5 TOP AND BOTTOM ROLLS OF THE FIRST PASS

The two rolls are seen here locked together by the gating, as they would be in use. The roll gap can also be seen.

PHOTOGRAPH P6 A CLOSE UP OF THE FIRST PASS

The roll pair is shown here, in use, on the mill.

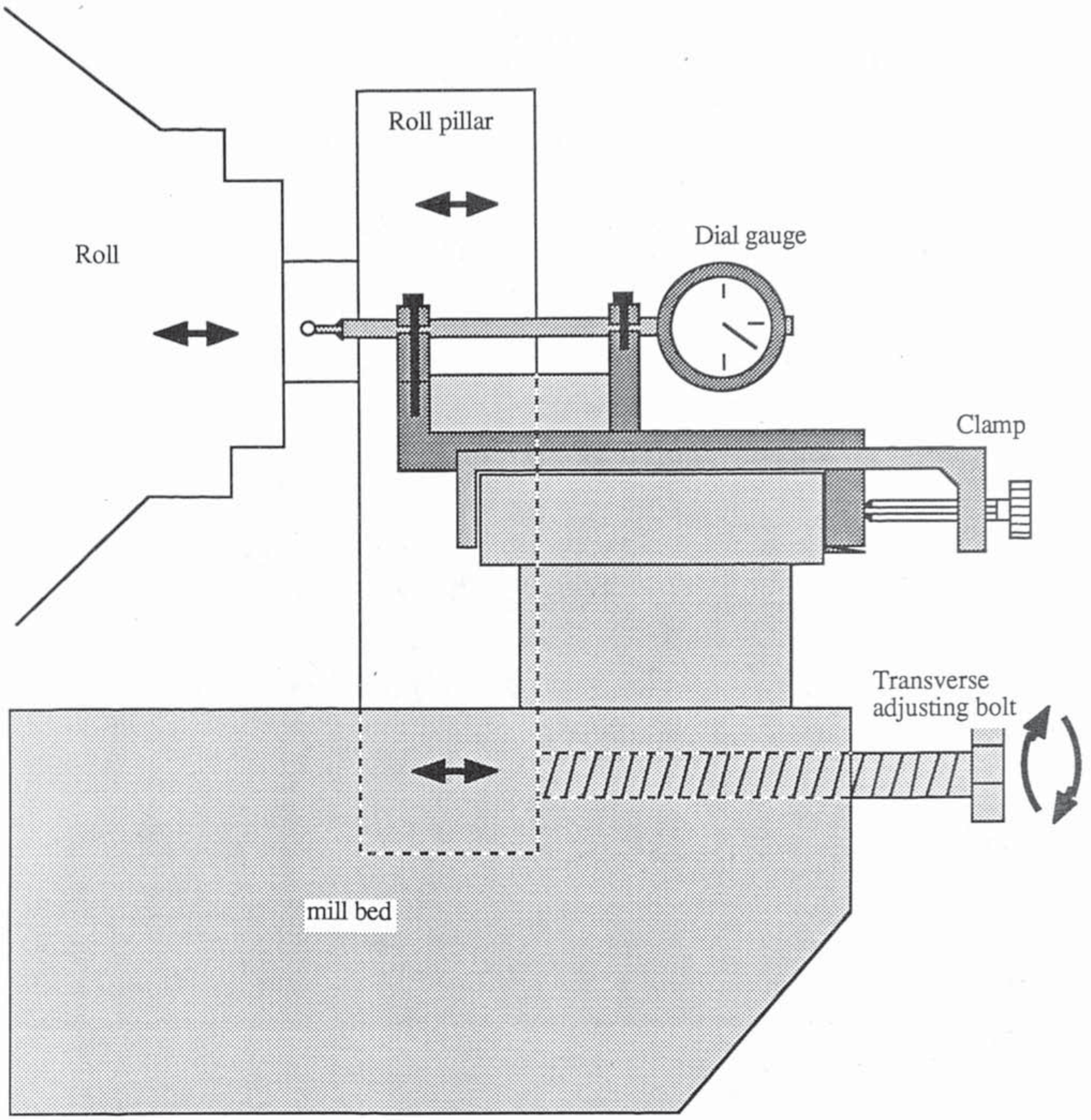


DIAGRAM 6.3 ROLL ALIGNMENT MEASUREMENT DEVICE

For the tests, a quantitative method of alignment was needed. The rolls were aligned using a dial gauge, set up as in diagram 6.3. Using the machined edge of the mill base as a datum, rolls could be aligned to +/- 0.1 mm. The alignment bolts were turned one complete revolution and the transverse movement in the roll recorded using the gauge. In this way the movement of the transverse adjusting bolts was calibrated. Unfortunately the dial gauge could not be left on the mill during rolling, (to give a more direct method of measuring alignment), as it interfered with the strip passage. It became apparent that during rolling the whole assembly of pillars, rolls and shafts deflected, causing the roll alignment to vary continuously. Measurement indicated these transverse movements to be +/-30 μm on the particular mill being used.

6.8 MEASUREMENT OF INTER-PASS DISTANCE

The three distances could only be multiples of the normal inter-pass distance, due to the construction of the mill. Two distances were used; the minimum 237 mm and, by missing out a station, a doubled length 478 mm. This allowed one inter-pass distance to be longer than the deformation length (as calculated from the Bhattacharyya model in section 4.2.4) and one to be within that length. Note that the inter-pass distance was nominally 240mm, however the measured values varied from 237 mm to 240 mm +/-0.5 mm, showing yet more inconsistencies in the mill construction.

6.9 MEASUREMENT OF ROLL SPEED

Roll speed could be varied using the Danfoss electrical controller, and the angular velocity of the roll shafts was measured using a rev-counter. Each shaft was chained to the next, so only one needed to be measured. The maximum velocity that could be achieved using the controller was 150 rev/min, and the minimum 70 rev/min. The three values chosen for the roll speed were 150, 110, and 70 rev/min. Note that the linear velocity of the strip depends on the angular velocity of the rolls and the roll diameter at the driving surface. Changes in roll diameter thus alter the linear strip velocity. For the first set of rolls cut, the bottom roll diameter at the base was 106.7 mm, giving the three linear speeds as 0.39, 0.61 and 0.84 m/s. This assumes that there is no slipping, and that the base of the section is the driven region. The rolls were designed for the drive to be at the section base, as can be seen from the roll drawings (Diagram 6.2).

The part two tests involved using a second pass, with an increased roll diameter in order to create a difference of driving speeds between the first and second pass. By driving the second pass faster than the first, it was hoped to induce longitudinal tensioning strain in the section. The second bottom roll diameter in this case was 10 mm larger, causing it to run 9.4% faster than the first in terms of linear velocity, whilst the angular velocities remained equal. The rev-counter was accurate to within +/- 1%.

6.10 MEASUREMENT OF ROLL LOAD

6.10.1 PILLAR DESIGN

The diagram 6.4 and photograph P7 show the roll pillar assembly used in this study. This is a typical example of a top and bottom assembly for holding the roll axles in position. By turning the pillar bolts the axles are brought closer to, or further from, each other so altering the roll load.

6.10.2 THE CHOICE OF MEASUREMENT DEVICE

Initially ideas of hydraulic, optical and electrical measurements of load were considered. These however were expensive and difficult to apply.

The simplest approach appeared to be to measure the vertical straining in the pillar. The straining would be a true indication of the vertical load being applied by the pillars on each side of the roll. Of the parts existing of the pillar assembly, those subjected to the purest vertical strain were the side plates and the pillar bolt (although in opposite senses). The pillar bolt however was not suitable due to the large amount of torsional strain which would be produced on tightening. (There would also be great difficulty in locating gauges on the thread).

The first approach was to fix strain gauges (probably the cheapest form of strain measuring device) to the sides of the pillar. This appeared good initially, in that most of the required criteria were fulfilled. Several problems became apparent however. Unless the side plates of the pillar were made to very high accuracy, every whole pillar assembly would have to be calibrated away from the mill. Unfortunately the side plates were flame-cut and welded to the bearing block, hence the tolerances were large. To change the method of manufacture to improve accuracy of the plates would be costly. Also to confirm the unsuitability of this

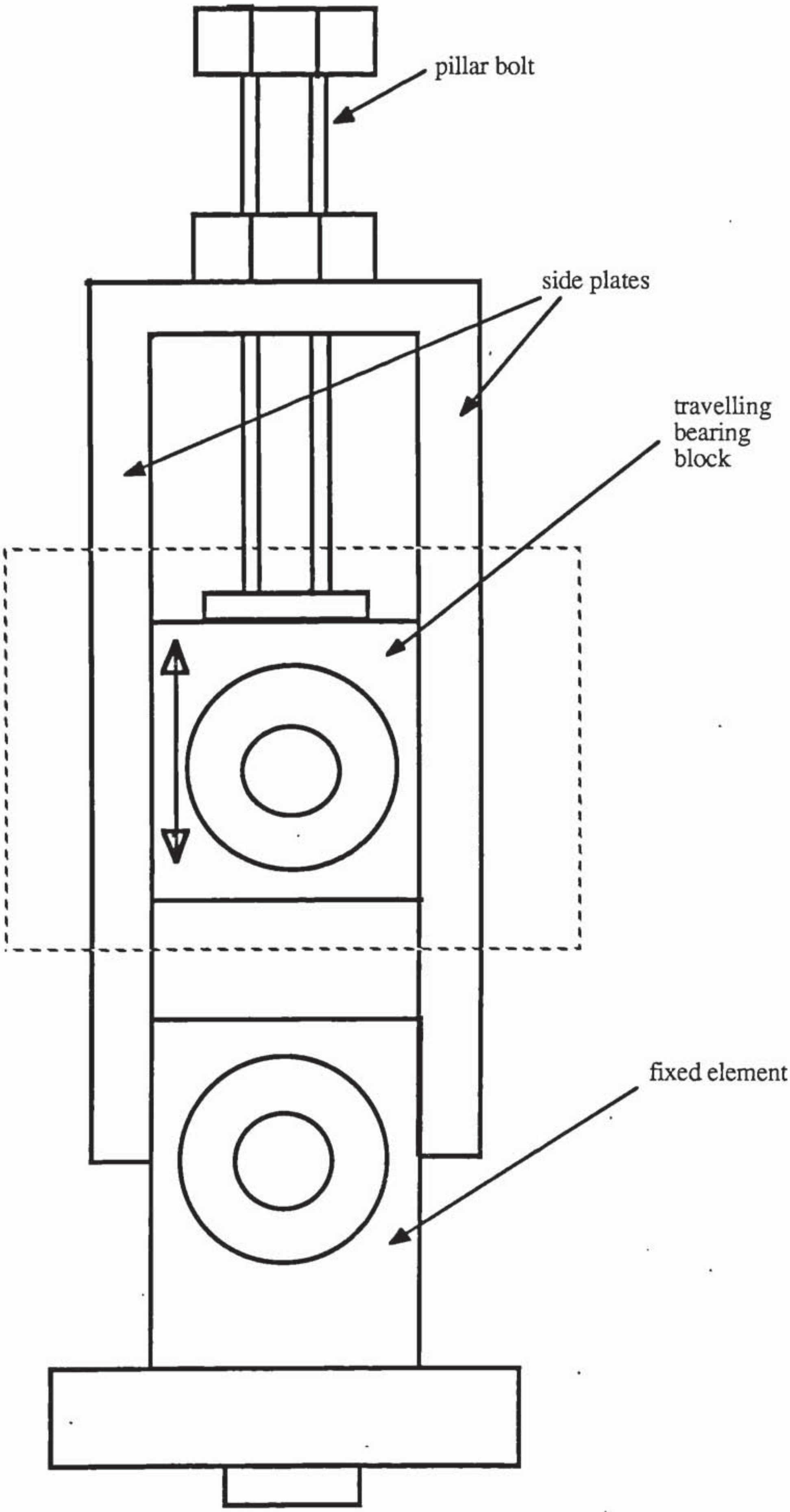
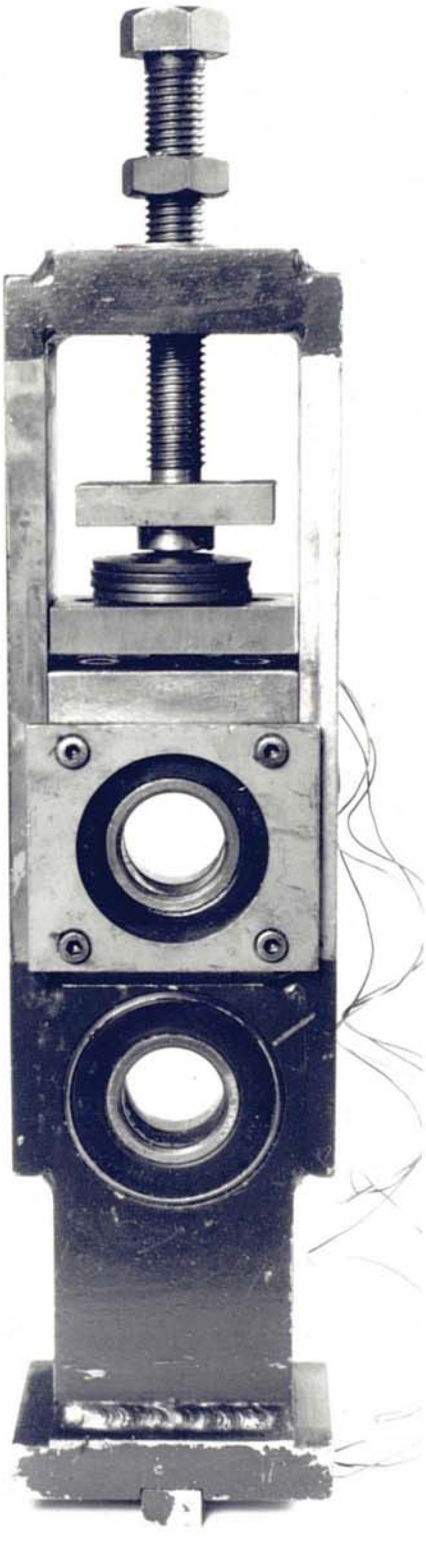


DIAGRAM 6.4 PILLAR ASSEMBLY

PHOTOGRAPH P7 ROLL PILLAR

The pillar shown is slightly different than the factory specification, to accommodate four Belleville washers which were needed to be used in the part two tests.



approach, it was found the plates were much too thick to give any reasonable elastic deformation to be measured by the strain gauges. The plates are designed to allow for high load applications, to reduce cost by promoting interchangeability and reducing stock. To use different plates for each application would be an expensive solution.

The problems associated with the plate idea, indicated a retrofit type device would suit the application. The device could then be tuned for high or low load cases to give high accuracy over a given range. It could also be calibrated away from the mill without any major interference to the pillar design.

A load cell was considered the best type of retrofit. The cell would fit under the main pillar bolt, and if designed carefully could satisfy all the criteria.

6.10.3 LOAD CELL DESIGN

The simplest load cell design for pure compressive loading is the column load cell. Typically there are a minimum of four strain gauges attached; two in the longitudinal direction, and two in the transverse to sense the Poisson strain. This allows a temperature compensated Wheatstone bridge circuit to be made, with each gauge forming the resistance in a bridge arm. Initially the output is zeroed by balancing the bridge. Load is then applied to the cell which elastically deforms so changing the balance of the resistors, and thus giving a complementary voltage output.

The load cell is cylindrical for ease of manufacture. Application of the load to each end of the cell must be as true to the vertical as possible and should not induce any torsion. To help even out these "end conditions" load cells often have enlarged ends.

When designing load cells an important consideration is that the ratio of height to diameter, which should be maintained at at least 1.5 to maintain linearity.

Referring to diagram 6.4. The bottom shaft is fixed vertically and the roll centre-to-centre distances and the roll load can be adjusted by moving the top shaft by rotating a threaded bar.

Diagram 6.5 shows a detail of the travelling bearing supporting the top shaft. Between the threaded bar and the bearing case are a number of washers. It was suggested that the roll load was best quantified by inserting a load cell beneath or above the washers.

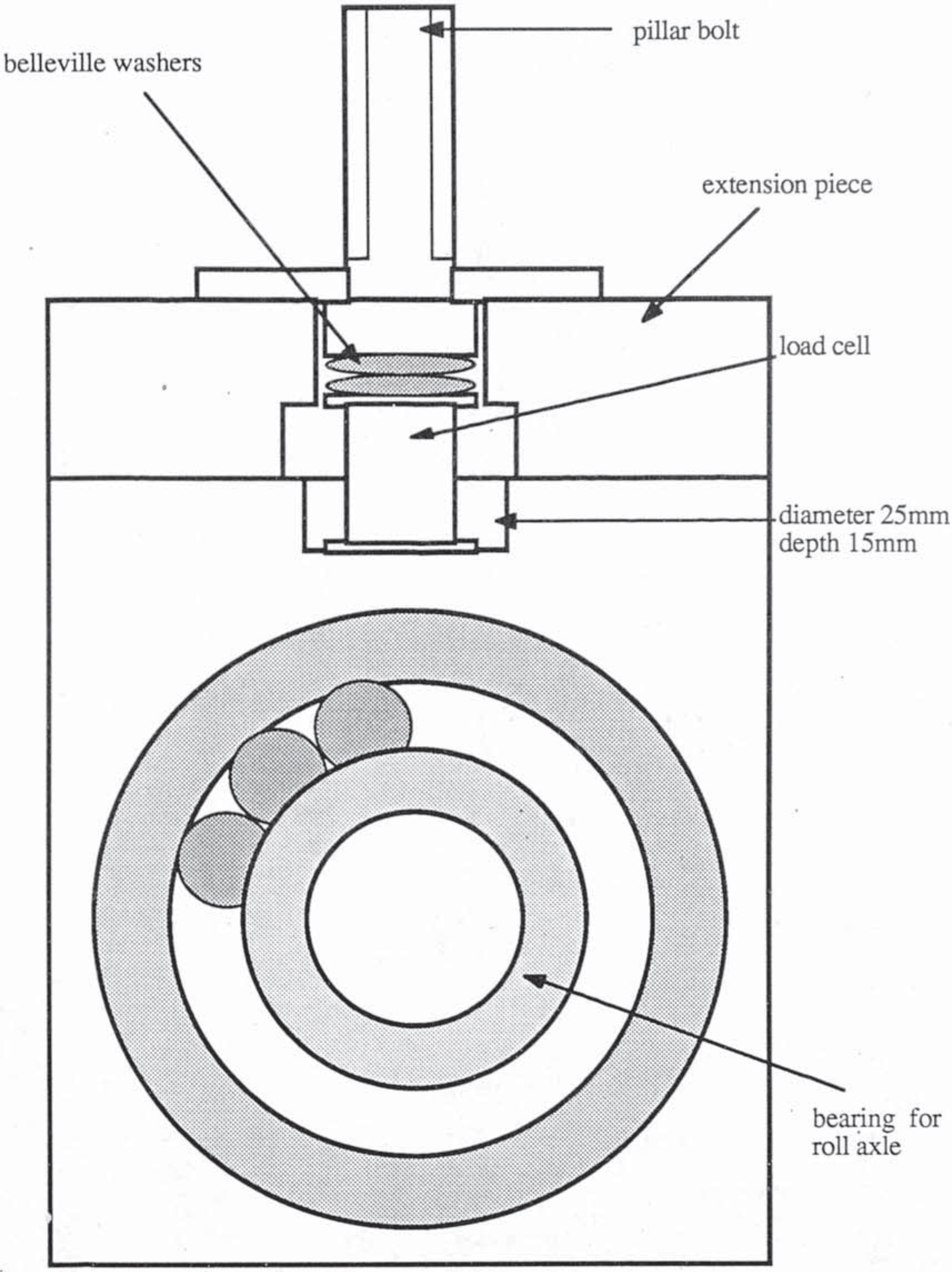


DIAGRAM 6.5 DETAILS OF THE TRAVELLING BEARING BLOCK

6.10.4 LOAD CELL CALCULATION

The following sections describe how the estimates of force applied to the load cell were calculated. A torque wrench on the pillar bolts gave a practical rough estimate.

6.10.4.1 MAXIMUM FORCE

This is concerned with estimating the maximum force acting on the load cell, for the worst possible case. It was assumed that the force consisted of two components, that force applied when setting the mill (to produce the motivation to move the metal through the mill and to reduce the effect of section defects), and the additional force created by the separating of the rolls when material of a larger thickness passes through the rolls.

therefore $G = W + S$ (1)

where G is the maximum force

S is the roll separating force

and W is the applied force

with reference to diagram 6.4, 6.5 and 6.7.

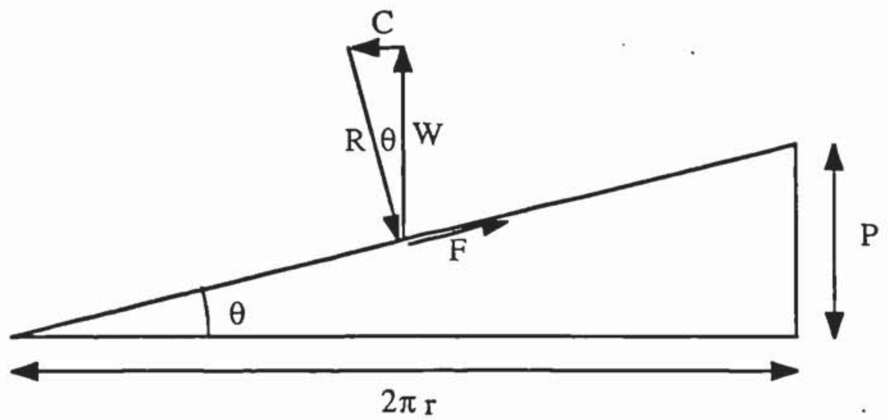


DIAGRAM 6.6 FORCES ACTING ON THREAD

where P is the thread pitch

r is the mean radius of the thread

T is the maximum torque expected

C is the tangential force on the periphery of the thread

F is the frictional force

R is the reaction force

for the worst case (when friction is low)

considering diagram 6.7 $\tan\theta = P / 2\pi r$

resolving horizontally $C = F\cos\theta + R\sin\theta = R(\sin\theta + \mu\cos\theta)$

resolving vertically $W = R\cos\theta - F\sin\theta = R(\cos\theta - \mu\sin\theta)$

hence $W / C = (1 - \mu\tan\theta) / (\mu + \tan\theta)$

$$W = C(1 - \mu\tan\theta) / (\mu + \tan\theta) \qquad (2)$$

and $$Cr = T \qquad (3)$$

from 2 and 3 $$W = (T / R)(1 - \mu\tan\theta) / (\mu + \tan\theta) \qquad (4)$$

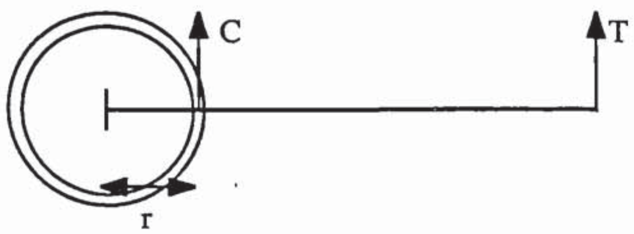


DIAGRAM 6.7 PLAN VIEW OF THREADED BAR

For the roll separating force, the worst condition occurs when all the components of the system can be considered rigid, except the washers. Replacing the washers by a spring gives the system shown in diagram 6.8 (with reference to diagram 6.5).

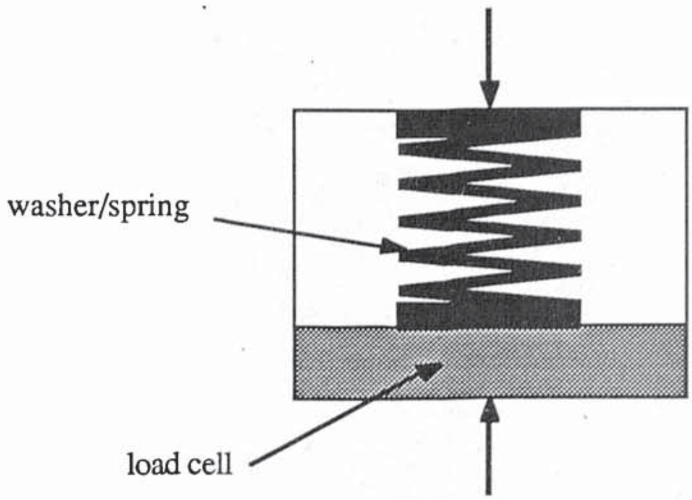


DIAGRAM 6.8 SPRING WASHER AND LOAD CELL SYSTEM

If λ is the washer stiffness and d is the deflection of the upper shaft due to roll separation

$$S = \lambda d \qquad (5)$$

And for the worst case d = maximum metal thickness - minimum metal thickness

Substituting (4) and (5) into (1)

$$G = (T/R)(1 - \mu \tan\theta)/(\mu + \tan\theta) + \lambda d \qquad (6)$$

where $\tan\theta$, can be measured directly, equals $P/2\pi r$ approximately 0.05

T can be established on site using a torque wrench

S (λd) can be calculated from the washer force / deflection equation

6.10.4.2 CALCULATION OF APPLIED FORCE

From on site observation it was noted that the maximum torque which was applied in practice was 105 Nm, and that the majority of cases where in the region of 10Nm - 20 Nm.

The pitch of the thread was measured as being approximately 2.5 mm

The radius of the thread was measured as approximately 8.0 mm

hence $\tan\theta$ equals $P/2\pi r = 0.05$

μ is taken from engineering tables as 0.10.

Therefore from (4) $W = (T/R)(1-\mu \tan\theta)/(\mu + \tan\theta) = 87062.5$ N

6.10.4.3 CALCULATION OF THE MAXIMUM ROLL SEPARATING FORCE

By consulting British Standards B.S. 1449 (170) for strip, it is found that (assuming the metal thickness is less than 4.5 mm) the largest tolerance on thickness is +/- 0.25 mm, hence the largest difference between maximum and minimum metal thickness is 0.5 mm.

The washers are of the "Belleville" type where the dimensions are defined in diagram 6.9. For washers of h/t > 0.5 the equation quoted by the suppliers for the force required to deform the washer is given by;

$$s = C\,C_1 E\,t^4 / R^2$$

where s is the load at deflection d from no load position

C is a factor depending on R/r

C_1 is a factor depending on d/t and h/t

E is Young's modulus (210×10^9)

Since there are 4 washers the maximum value of d is 0.5/4 mm.

From suppliers tables; for R/r = 2.15, C=1.4

And for d/t = 0.125/ 0.75 , h/t = 0.85/ 0.75, $C_1 = 0.3$

therefore $s = (1.4 \times 0.3 \times 210 \times 10^9 \times (0.75 \times 10^{-3})^4) \;/\; ((11.5 \times 10^{-3})^2)$

R = 11.5 mm	r = 5.15 mm
h = 0.85 mm	t = 0.75 mm

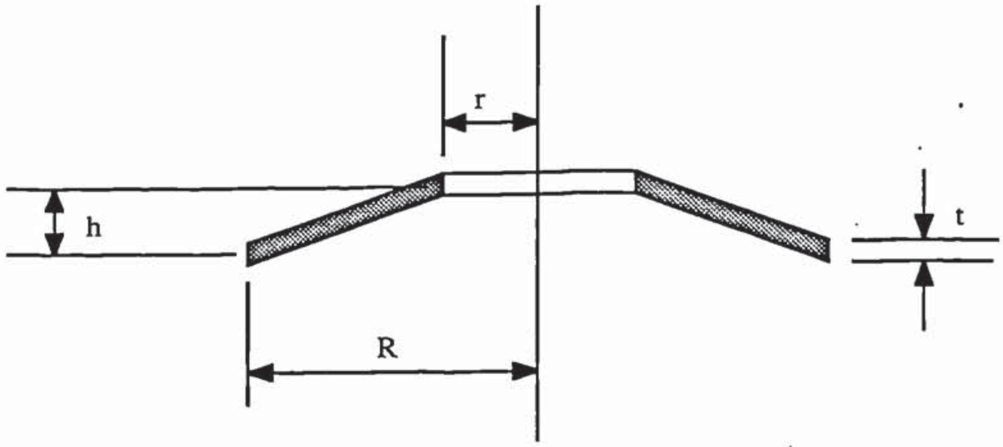


DIAGRAM 6.9 BELLEVILLE WASHER

Therefore the maximum roll separating force S = 208.0 N

And from 6 the total force G = 87062.5+208 = 87270.5N = 87.3 kN

6.10.5 LOAD CELL DIMENSIONS AND MATERIAL CHOICE

From diagram 6.5 it can be seen that the largest diameter of load cell, without the need for remachining, is 25 mm. Allowing room for the attachment of gauges, the maximum outside diameter is restricted to 20 mm.

Hence load bearing area (A) = $\pi d \times d/4 = 314.2 \text{ mm}^2$

Therefore minimum yield stress = $G/A = 87.4 / 314.2 \times 10^9 = 278 \text{ MN/m}^2$

A factor of safety of two is included making the minimum yield stress = 556 MN/m^2

(It should be remembered that the exceptionally high torque value chosen contains an inherent factor of safety).

Table 6.3 contains a list of the steels which are suitable for through heat treating, and which provide a yield stress greater than 560MN/m^2, (from B.S. 970 [(169)]).

From considering Table 6.3, and the availability of steels within the table, it was decided to choose an EN24 steel hardened and tempered to a yield stress of 560 MN/m^2.

The surface finish of the cell was to a ground finish, with the corners of the flanges blending smoothly on to the vertical cylinder part. The top and bottom of the cell had as close to a horizontal plane as possible, and as square to the vertical a cylinder element.

With reference diagram 6.5, in order to accommodate the height of 30 mm, it wa necessar to fit an extension piece on top of the bearing block (see diagram 6.12).

STEEL	EN NO.	YIELD STRESS MN / m^2	HEAT TREATMENT (C)	QUENCH MEDIUM	TEMPER (C)
530 M40	EN 18	680	850 - 880 830 - 860	Oil Water	550 - 700
605 M36	EN 16	755	840 - 870	Oil	550 - 680
606 M36	EN 16M	680	840 - 870	Oil	550 - 680
708 M40	EN 19A	755	860 - 890	Oil	550 - 700
709 M40	EN 19	850	860 - 890	Oil	550 - 700
722 M24	EN 40B	755	880 - 910	Oil	570 - 700
817 M40	EN 24	940-1235	820 - 850	Oil	660 MAX
826 M40	EN 26	940-1235	820 - 850	Oil	660 MAX
835 M30	EN 30B	1235	810 - 840	Oil	220 - 280
905 M39	EN 41B	680	880 - 920	Oil	550 - 700

TABLE 6.3 STEELS SUITABLE FOR THROUGH HARDENING WITH A YIELD STRESS GREATER THAN 560 MN/m^2 AND DIAMETER 25 mm (FROM BS 970).

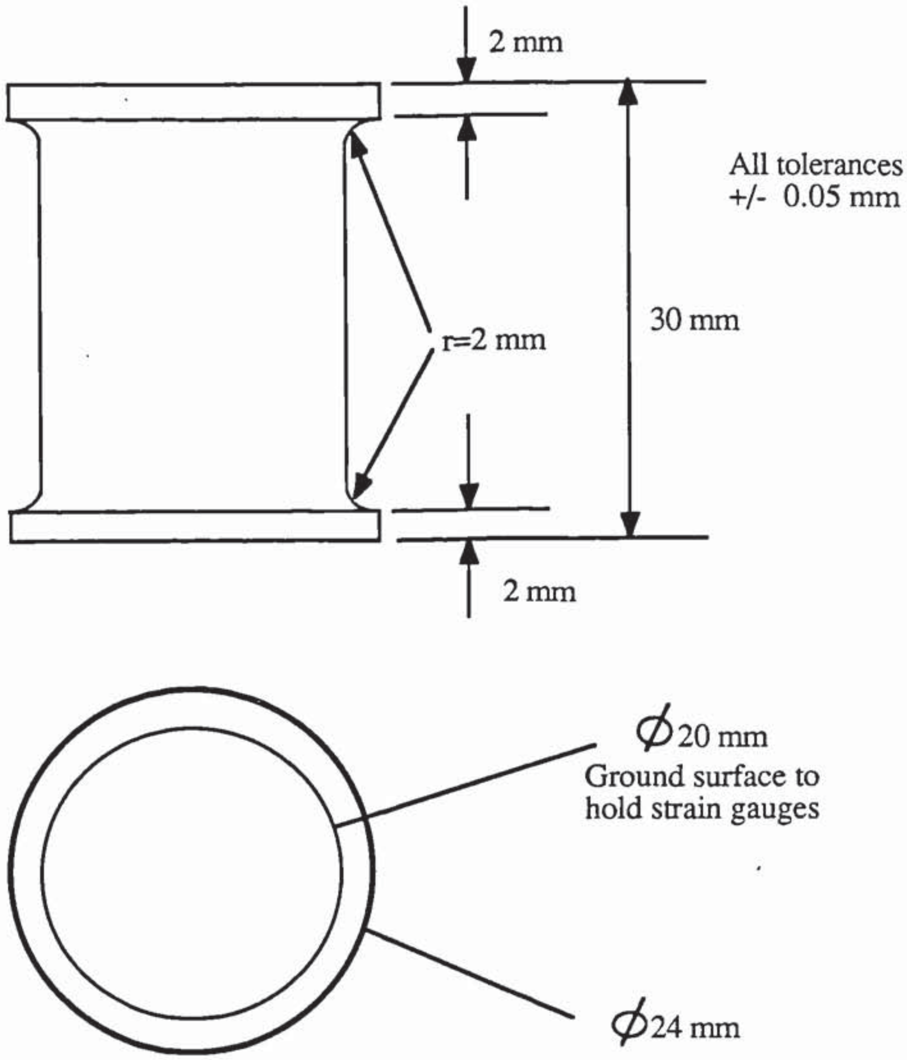


DIAGRAM 6.10 LOAD CELL DIMENSIONS

6.10.6 LOAD CELL STRAIN GAUGES

Four strain gauges were fitted to the load cell. Two gauges were positioned in the axial direction on opposite sides. Between them, two gauges were positioned to detect the transverse strain. Gauges were all of the same type. The gauge length was made as long as possible to cover the region of the cell expected to have a uniform axial strain field (found from a Finite Element model). Gauge length was limited by the space available for connecting terminals and wiring. The gauges did not have to have any special characteristics, and those used were 120 ohm, gauge factor 2.1, gauge length 6 mm.

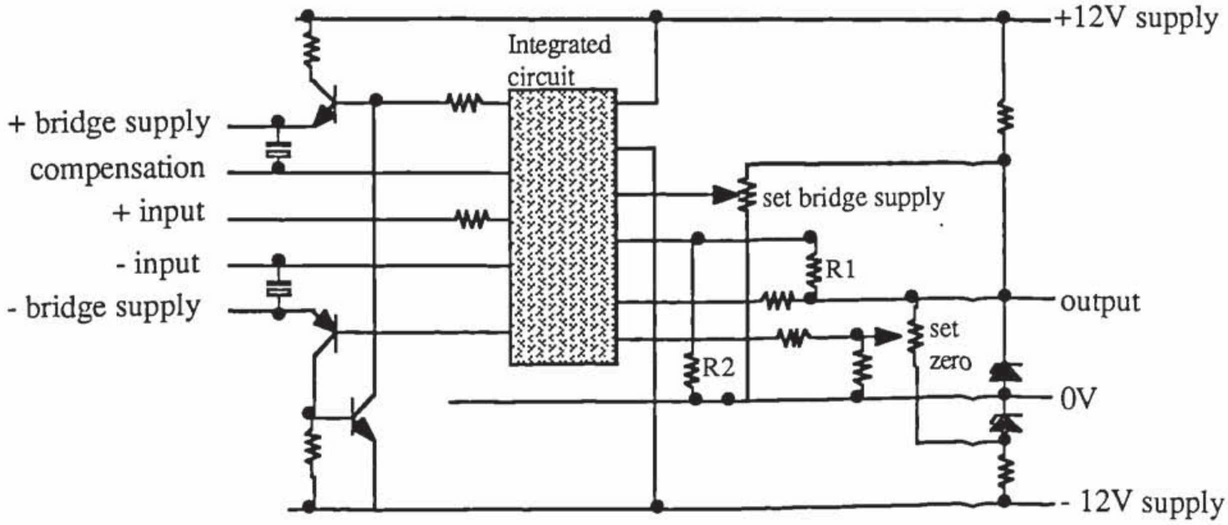


DIAGRAM 6.11 A AMPLIFIER CIRCUIT

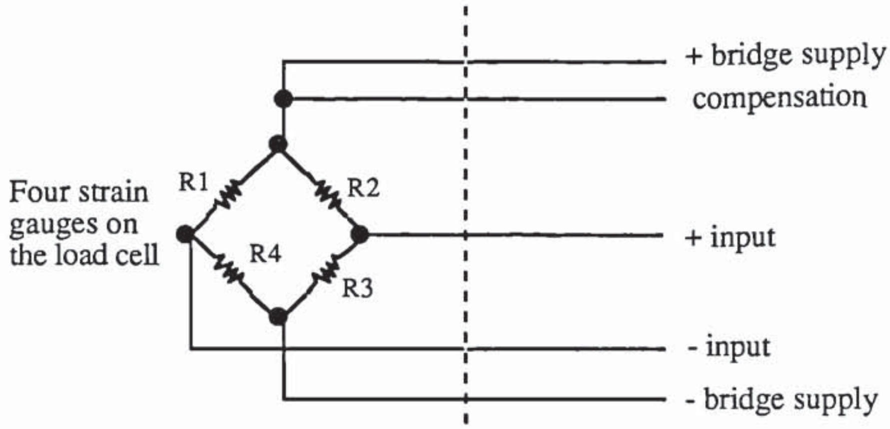


DIAGRAM 6.11 B FULL BRIDGE FOR LOAD CELLS

6.10.7 LOAD CELL CIRCUITRY

The four strain gauges were connected to a standard strain gauge amplifier circuit board shown in diagram 6.11A and B. This supplied the bridge with a stabilised voltage, allowed balance of the bridge, and had variable gain for amplifying the output voltage. Supply voltage was set to 4 V so as not to over heat the strain gauges, but still allow a measurable output signal. The bridge was balanced under a no load situation, and then the output measured using a digital voltmeter under loads up to the maximum expected in service. Gain was set, so that at maximum load the output would be approximately 10 V. The same gain was used for each of the cells, i.e. 1001.

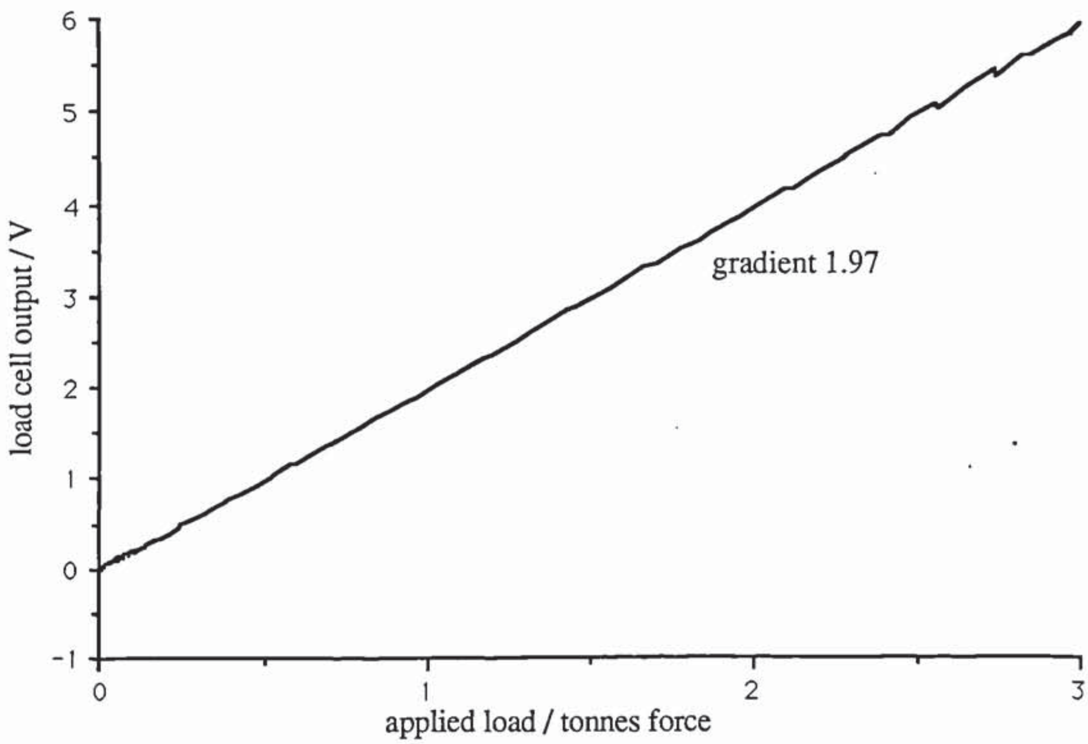
6.10.8 CALIBRATION

Six load cells were manufactured to the calculated specification. An Instron compression testing machine was used to calibrate the load cell output, against given loads up to 8 tf. The complete assembly was put in the testing machine, to try and duplicate the real conditions of loading. Load was gradually applied, then held for a minute at the maximum, and released.

By repeating the testing for the load cells in various assemblies, and at different rotational orientations, it was found that :

1. Each cell gave results repeatable to within 2% if held in the same configuration and gave linear load-to-output graphs (Graph 6.2).
2. The position in which the cell was held had a large effect on the load / output graph gradient. In different positions of rotation, the maximum gradient difference was 12%. This problem was overcome by pairing the cell with a bearing block, and packing it into position, so there could be no rotational slip. The block and cell, from calibration onwards to installation, were never parted.
3. Each cell had to be calibrated separately, with variations in output between cells of up to 20% for the same load. This was not a problem, provided that the cells were clearly labelled, and their output transfer function known.

GRAPH 6.2 LOAD CELL CALIBRATION



In application, the maximum force applied to the cell on tightening the pillar bolts was approximtely 3 tf. The actual loads used during rolling were found to be less than 0.5 tf, due to the method in which roll load was set. Operators tightened the pillar bolts to their maximum "hard on", and then slackened off a certain number of flats (chapter 2) to achieve the correct load. Load cells were thus found to be considerably over-designed, in order to be able to handle the maximum load.

6.10.9 IMPROVED DESIGN

From the information gained six further cells were made with greater resolution and improved location features. The cells were designed for the range of loading that was found to be the actual rolling load (up to 3 tf). This meant that the operators had to use the load cells to set the roll loads. Pillar bolts had to be tightened to the correct load, rather than over tightened and then slackened off.

The design of the cell and extension piece are shown in diagram 6.12 and photograph P12-13.

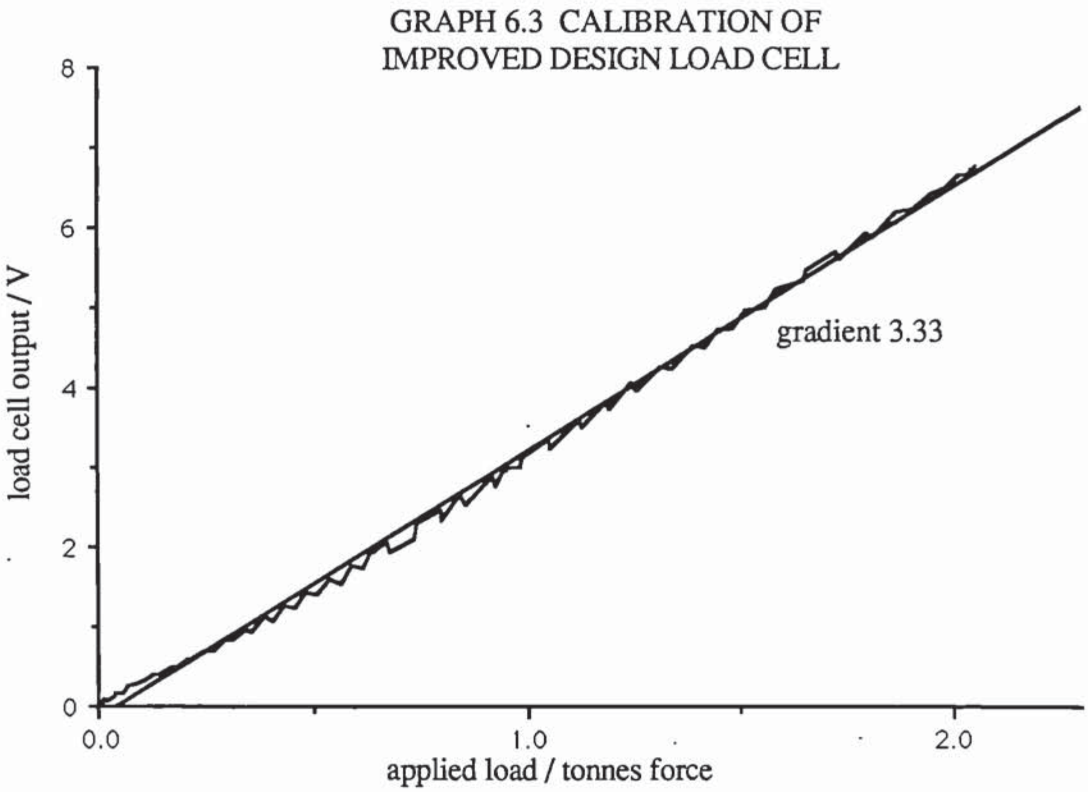
The load cell had an extended bottom flange, which ensured that it located centrally into the bearing block. Also there was a pin which allowed the cell to locate in only one position. There was no top flange, to allow access for fitting the strain gauges. The cell was hollow in order to increase its diameter, whilst retaining a given cross-sectional area, so that strain gauges were easier to fit.

The extension piece was designed so that load was applied vertically on to the cell, and so there was no torsion transmitted from the rotation of the pillar bolt.

The Belleville washers were later removed. They were found to be flattened out at such low loads that they did not act as springs during rolling.

The new design was tested and showed the load cells could be calibrated without the need for pairing with a particular bearing block. So the cells could be calibrated on their own and then fitted to any pillar. The resulting repeatability was within 7% error over the working range.

Graph 6.3 shows the calibration graph. If paired, the high repeatability in location improved the accuracy to within 2% error.



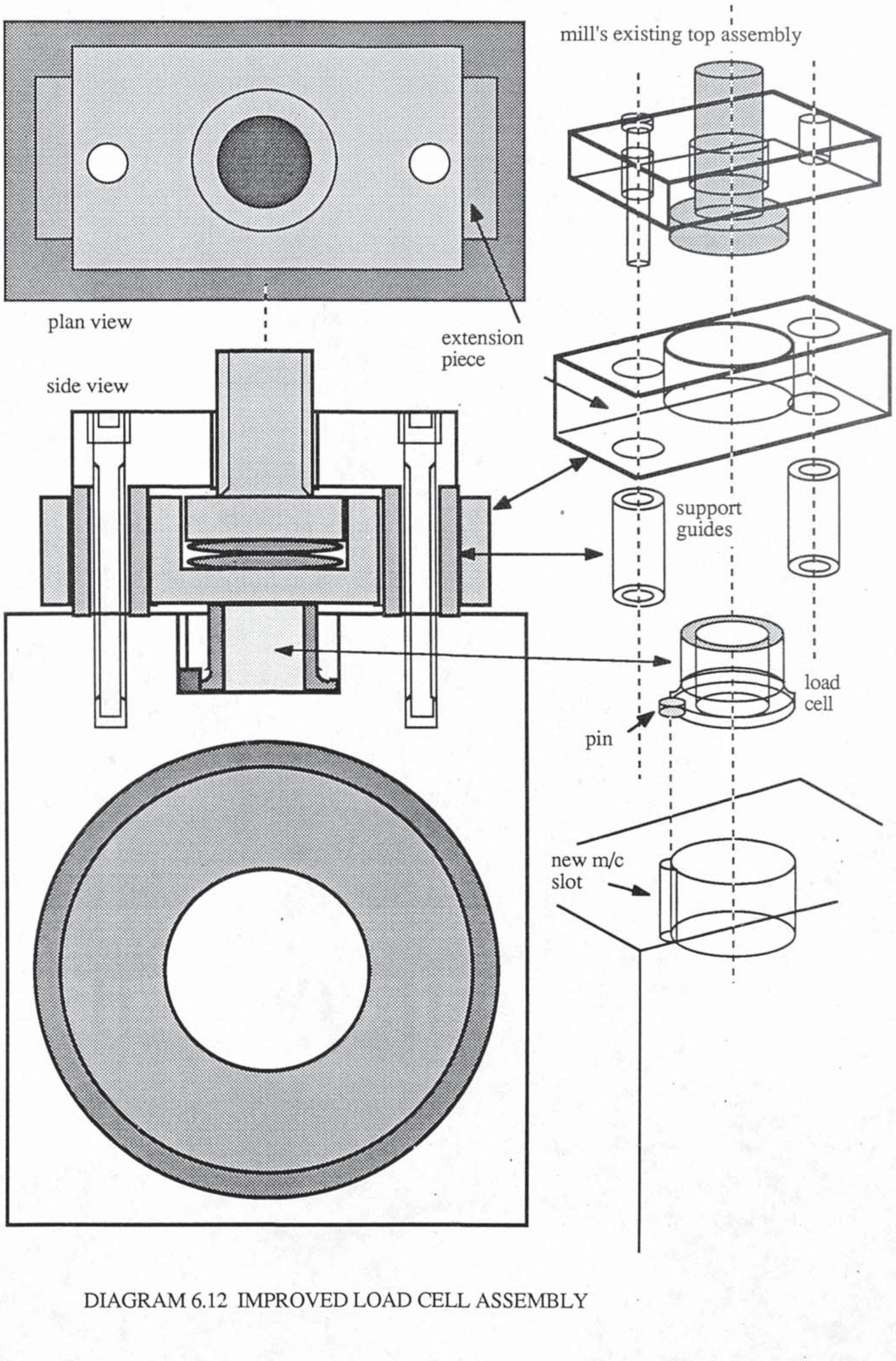


DIAGRAM 6.12 IMPROVED LOAD CELL ASSEMBLY

PHOTOGRAPH P8 THE LOAD CELL

The photograph shows a close up of one of the load cells used in the pillar. Through the protective coating one of the four strain gauges is just visible.

PHOTOGRAPH P9 NEW PIECES USED IN THE REDESIGNED PILLAR

Shown are the load cell, extension piece, support guides and stack of Belleville washers (used in part two tests).

6.11 MEASUREMENT OF STRAIN

6.11.1 THE STRAIN GAUGES.

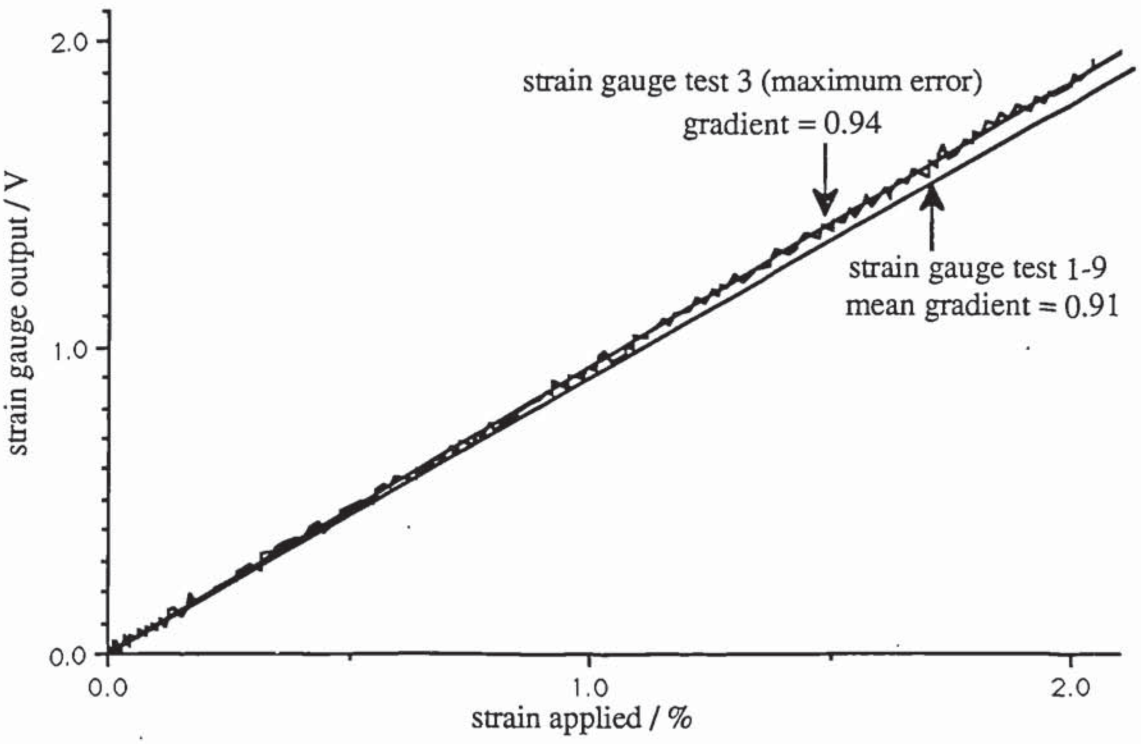
The strain gauges used had to be capable of measuring into the plastic deformation region, as preliminary work had shown longitudinal edge strains of over 2%. Such post-yield gauges were available in a limited number of sizes. The cut-outs in the rolls allowed a width of 10 mm maximum, so limiting the gauge size. T.M.L. YL-5 gauges were chosen, with the following specification;

base	16 x 6 mm
gauge length	5 mm
gauge width	2 mm
gauge factor	1.89
strain limit	10%

6.11.2 CALIBRATION

Various tests were carried out to check the accuracy and repeatability of the gauges. An Instron tensile testing machine was set up with a test strip of CR3. The strain gauge under test was attached to the strip, and gave a reading of strain using the amplifier circuit. Also a second reading of strain was given by a device fitted to the strip, over the same gauge length.

GRAPH 6.4 STRAIN GAUGE CALIBRATION



The device had to be calibrated against known strains, produced by moving the Instron jaws over exact distances. The two values of strain were compared, in order to asses the accuracy of the gauges. Graph 6.4 shows the results.

The strain applied is the engineering strain measured from the calibrated device, and the strain gauge output is the voltage recorded from the data collection system. Nine, nominally identical, strain gauges were tested. As can be seen, the average line of best fit for these nine gauges has a gradient of 0.91. The gauge furthest from this mean, was gauge No.3. Its individual plot is shown, with a line of best fit of gradient 0.94.

The gauges were proved to be repeatable, linear and alike. Accuracy was within +/- 5%, taking into account both the scatter of an individual gauge and the gradient range.

Strain gauge output $E = VFe / 4 \times$ amplifier gain

where V = bridge supply

F = gauge factor

e = strain (%)

The gauge factor quoted by the manufacturer could be checked from the graph 6.4:

Gradient = $E/e = m$

so $F = (100 \times 4m) / (V \times \text{gain})$

In this case bridge supply voltage was 4.0 V, gradient was 0.91 and gain was 48. The gauge factor is thus calculated to be 1.9. The manufacturers quoted value was 1.89, hence this supports the accuracy of the gauges and the method of calibration.

6.11.3 POSITION OF GAUGES

The gauges were positioned where they would least interfere with the roll design, but still obtain a large amount of data. The diagram 6.13 shows the choice of position.

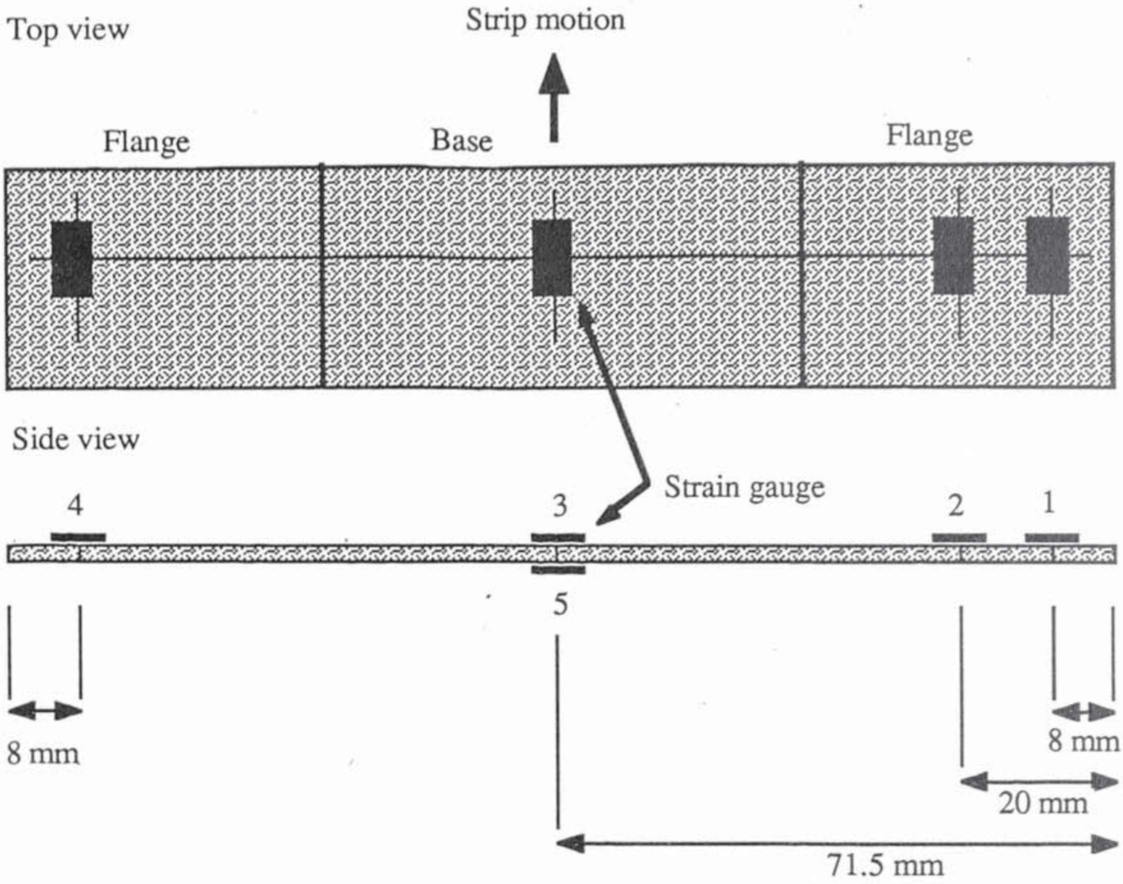


DIAGRAM 6.13 POSITION OF STRAIN GAUGES ON STRIP

There are two gauges at the edge of the strip, in order to obtain an idea of balance of strain in twisted sections. There are also two gauges on the top and bottom of the base, to measure longitudinal bending and stretching. A fifth gauge was situated in the middle of the flange, to show the graduation of strain from the folds towards the edges.

6.11.4 AFFIXING THE STRAIN GAUGES

6.11.4.1 MARKING THE GAUGE POSITIONS ON THE STRIP

Referring to diagram 6.14, the gauges positions were marked on the strip as follows;

1. The region where the gauges would be placed, was wiped clean.
2. A line across the width of the strip was scribed using a "T" square against the strip edge to ensure the trueness. This was important so all the gauges were at the same longitudinal position on the strip, before rolling. At the high sampling rate of the gauges, even a slightly longitudinally misplaced gauge would give a noticeably shifted time axis compared with the other gauges. This became apparent from testing.
3. Another line in the same longitudinal position was scribed on the reverse side of the

strip.

4. Longitudinal lines were then scribed at the required transverse positions of the gauges, causing cross-hairs with the transverse line already scribed on each side.

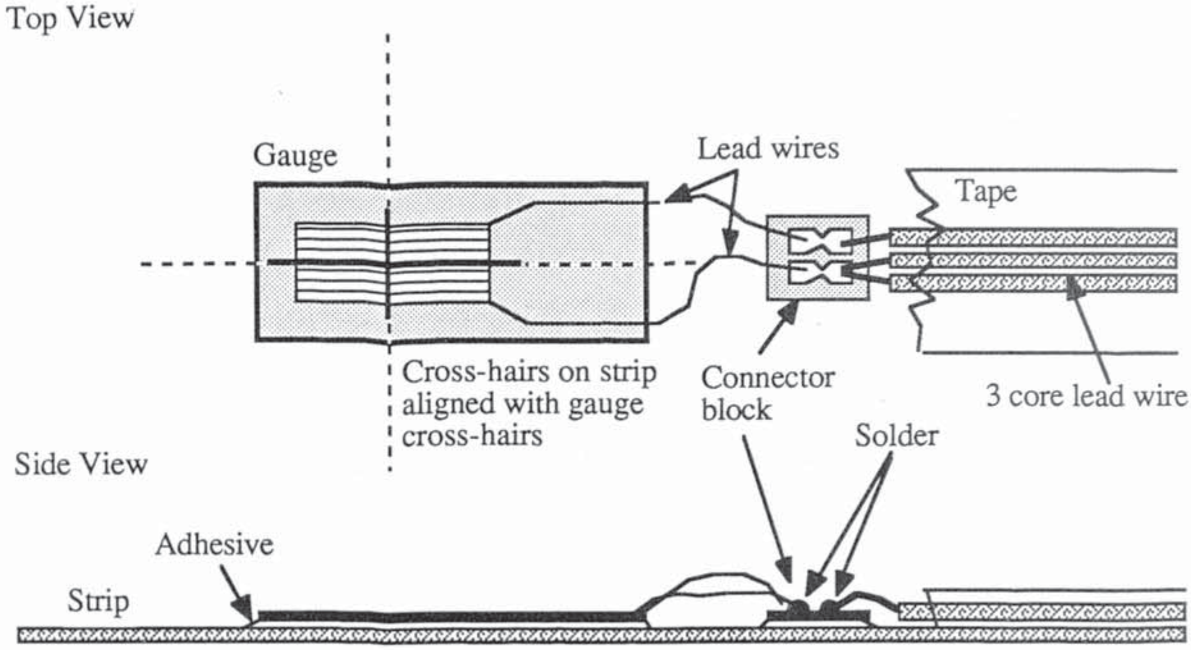


DIAGRAM 6.14 FITTED STRAIN GAUGE

6.11.4.2 SURFACE PREPARATION

It was important to clean the metal surface to which the strain gauges were glued. Any oil caught between the glued surfaces, caused the gauges to peel away easily from the strip. On several occasions this occurred, and so new surface preparation was required before a replacement gauge was affixed. Each gauge was tested for its firmness of location by attempting to peel a small portion of the corner. The preparation of the metal surface was as follows:

1. Cleaning away all oil and grease with Inhibisol, a strong solvent. Tissues were used to apply and remove the solvent. Only when all grease had been removed could the next preparation step be taken. (i.e. when there was no discolouration of the tissue from grease).

2. Conditioning the surface with an acid solution. The solution was dropped on to the cross-hairs and rubbed on to the metal with a medium grade abrasive paper. The paper was rubbed in such a way as to produce a "herring bone" pattern where the gauge would be stuck. This allowed a good keyed surface for the adhesive. (The scribed lines were not rubbed away by the abrasive paper).
3. The conditioning fluid was then wiped away and neutralised with an alkaline solution.This also served to wipe away any last traces of the debris left by the abrading. The surface was made neutral in pH, to avoid any reactions with the adhesive which might give a defective join.
4. The now fully prepared surface was sealed over with tape, to preserve its condition.

6.11.4.3 APPLICATION OF THE GAUGE TO THE PREPARED SURFACE.

The cyano acrylate adhesive is an anaerobic "super glue". The main points to bear in mind with its use is that, it gives its best bond when spread very thinly, without any air or grease at the join. It is important to apply hard pressure to spread the liquid adhesive to a thin layer and exclude any air, before it dries.

The gauges were applied as follows;

1. Tweezers were used to carry the gauges to a degreased pad. Gauges used were delicate and easy to get greasy.
2. On the pad, the connecting terminals and gauge were arranged as they would be on the strip.
3. Tape was then stuck over the two parts on to the pad.
4. The tape was peeled carefully from the pad with the terminals and gauge stuck to its underside.
5. The gauge cross-hairs were aligned over the scribed cross-hairs and then the tape stuck down.
6. The tape was then peeled up a little, and a small quantity of the cyano acrylate adhesive applied to the gauge and terminals.
7. The gauge and terminals were pushed back onto where they had been aligned using the tape, and hard finger pressure applied for about a minute.

8. Clamps were then fitted to apply pressure for a further five minutes.

9. The tape was peeled away from the strip leaving the gauge and terminals fixed in place. If at this stage the gauges peeled away with the tape, the whole preparation and application stages had to be repeated.

10. The gauge was painted in a varnish as a protective seal.

6.11.5 CONNECTION OF LEAD WIRES

The gauge and terminals had been positioned on the strip, so there was a gap of a few millimetres between them. (See diagram 6.14)

Connection of the lead wires to the terminals was as follows;

1. The lead wires were bent into a small arch over the gap. Any longitudinal straining in the metal could then be taken up by the slack of the arch, without causing direct strain and possible breakage in the wires.

2. The two terminals were roughed with abrasive paper to provide a clean surface for soldering.

3. The lead wires were cut to length so that their ends were over the terminals.

4. The lead wires were soldered to the terminals using a small soldering iron.

Once the lead wires had been soldered, the wires that led to the input of the data collection system were fitted. There were three wires needed for each gauge, and three core wire was used. The wire in tests would pass through the cut-outs in the rolls, and so had to be positioned accurately along the strip length. There was no information in the literature to describe how wires were located, various methods were hence considered.

At first double sided tape was tried as its application was very easy, but this did not provide a firm enough bond. Adhesives were considered, but the time needed in surface preparation would have been very great. A good solution was found in taping "Sellotape" over the wire on to the strip. Some cleaning of the strip was needed with methylated spirits, but this was not rigorous or very time consuming. The method had to be tested in rolling, as there was no way to tell if the tape would peel when strained.

Several strips were rolled on the mill and the wires examined. The tape did not peel, its flexibility allowing it to locate the wire even when strained. It was found later however that the tape began to lose its stickiness if left for a few weeks, and so the wires were stuck down close to the rolling date.

6.11.6 STRAIN GAUGE OUTPUT

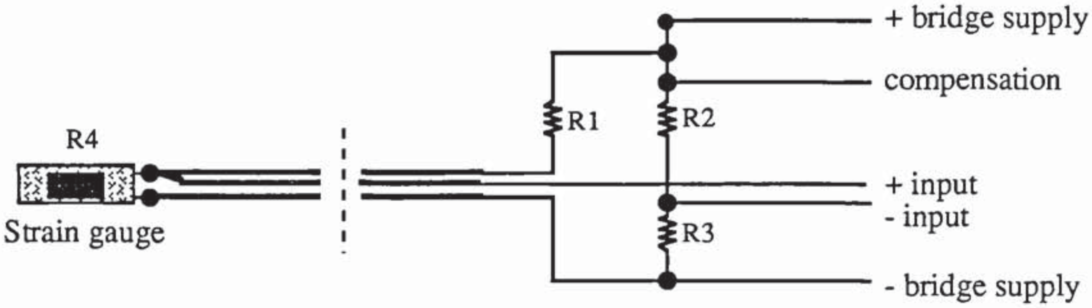


DIAGRAM 6.15 QUARTER BRIDGE FOR SINGLE STRAIN GAUGES

Diagram 6.15 shows the connection of lead wires to a bridge circuit. R1, R2 and R3 were precision resistors taking the place of dummy gauges in the configuration. The strain gauge, and the resistors all had resistance of 120 ohm. The three wires from the gauge are required, so that the resistance in the lead wires (due to their length of up to 1.5 m), does not affect the bridge balance.

The five connections from the circuit, were to the same amplifier used for the load cells. In this case, the gain was set to 241 to give a suitable voltage output. The bridge supply was kept at 4.0 V.

6.11.7 POSITION OF GAUGE DURING ROLLING

A method was needed to show the position of the roll passes on the strain profile. This was achieved by using one of the channels as a trigger When the strain gauge passed through the roll gap, the trigger was activated. After several tests had been completed, the position of the rolls in relation to the strain profile became obvious, and the trigger was no longer needed. Diagram 6.16 shows the trigger arrangement.

The wire A was positioned exactly over the strain gauge centre. Wire B was suspended between the rolls, in the roll gap. As the gauge passed through the roll gap, wire A and B contacted, a circuit was completed, and showed as a steady voltage on the trigger channel.

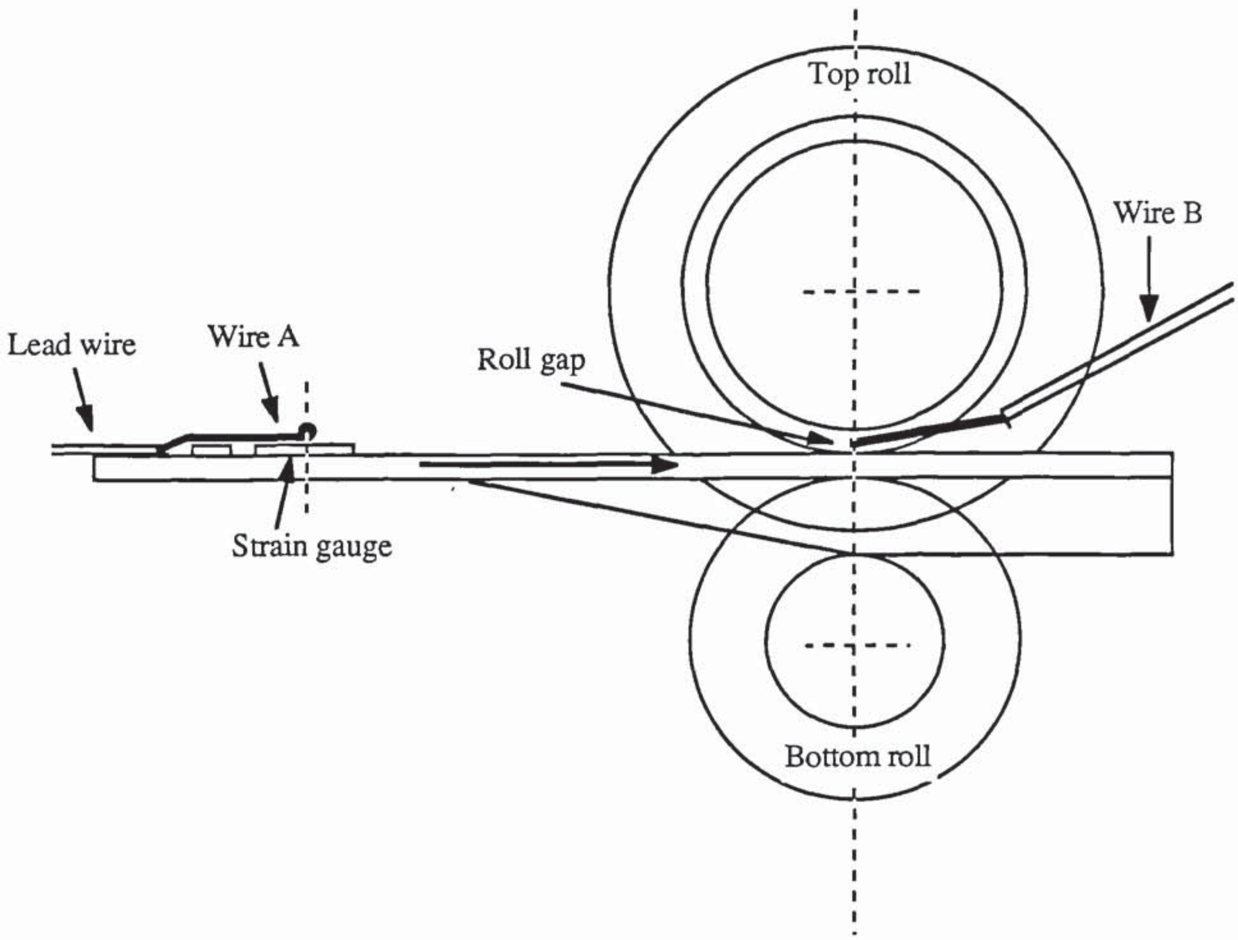


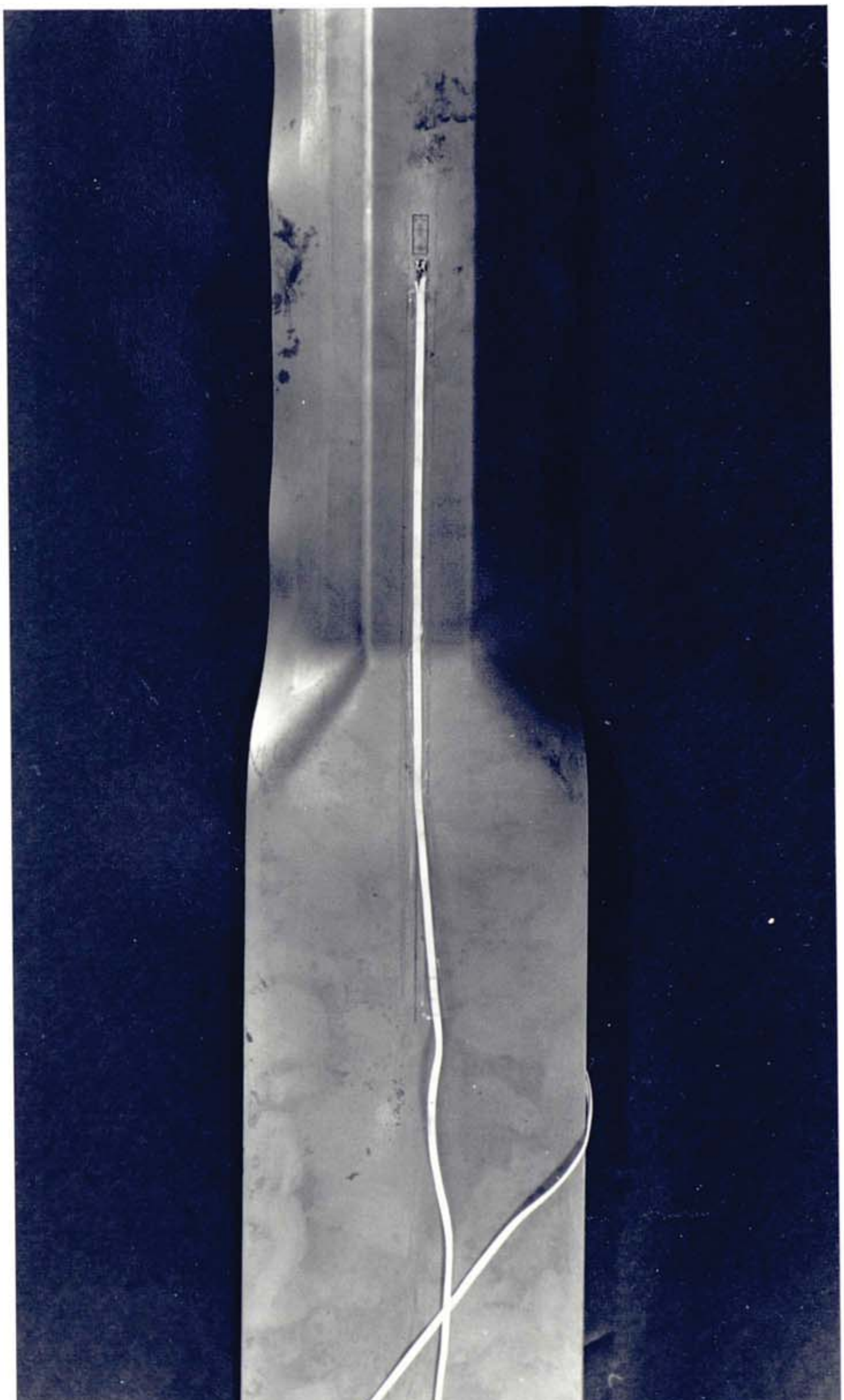
DIAGRAM 6.16 ARRANGEMENT FOR STRAIN GAUGE POSITION TRIGGER

PHOTOGRAPH P10 TOP VIEW OF ROLLED SECTION

The gauges 1-4 are shown labelled, on a rolled section.

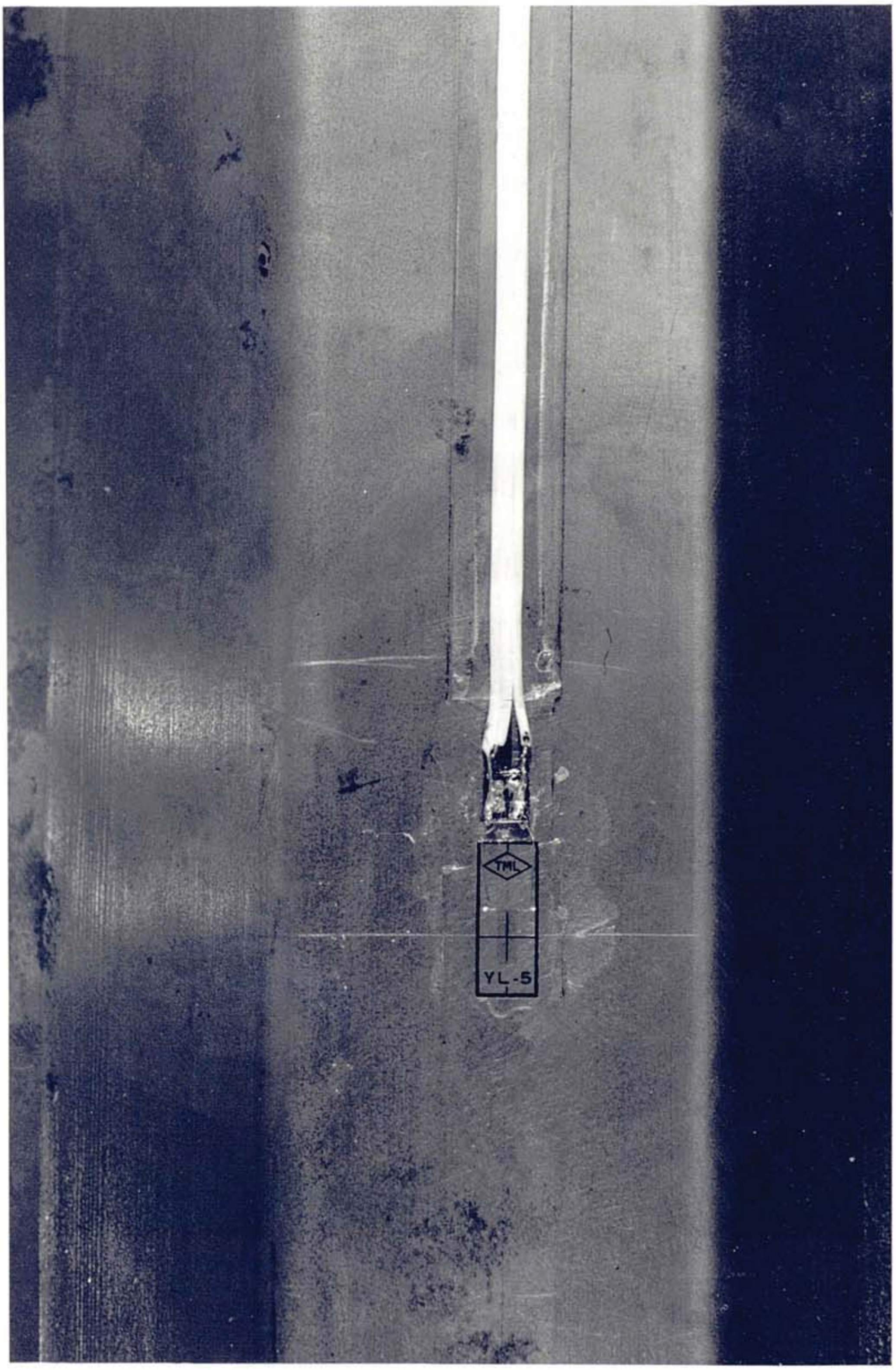
PHOTOGRAPH P11 BOTTOM VIEW OF ROLLED SECTION

The strain gauge 5 is shown in position.



PHOTOGRAPH P12 CLOSE UP OF A FITTED STRAIN GAUGE

Lead wires, soldered terminal blocks and scribed cross hairs are all visible.



6.12 MEASUREMENT OF SECTION QUALITY.

6.12.1 DEFINING QUALITY

A difficulty that emerged from studying previous work published on cold roll-forming was that there was no complete and standard method for describing section quality. A cold roll-formed product can be distorted in many ways. In the measurement of quality, past studies have divided defects into those of; cracking, transverse and vertical curvature, surface damage, end flare, springback, twisting, edge and web buckling, and thickness variation. This is because it is common for researchers to study the correction of a single defect. No complete definitions of quality have been found. In Industry, only the most basic quality measurements are made, because only the most basic tolerances are given by the purchaser, leading to a situation where too tight or loose tolerances can be put on undefined quality areas. Diagram 6.17 shows some of the section defects in a channel.

There are three separate cases of section defect

1. Breakage, e.g. cracking
2. Surface damage, e.g. scratching, tarnishing
3. Geometric inaccuracy, e.g. bow or twist

The three require separate methods of measurement.

1. Breakage. This is likely to be a visually obvious defect, implying rejection of the section.

2. Surface damage. Jimma and Ona [157] described four cases of surface damage in channel sections. The acceptance or rejection of a section, based on surface finish, is defined by the purchaser. The purchaser should specify the acceptable level of surface roughness. Different levels may apply for different elements of the section.

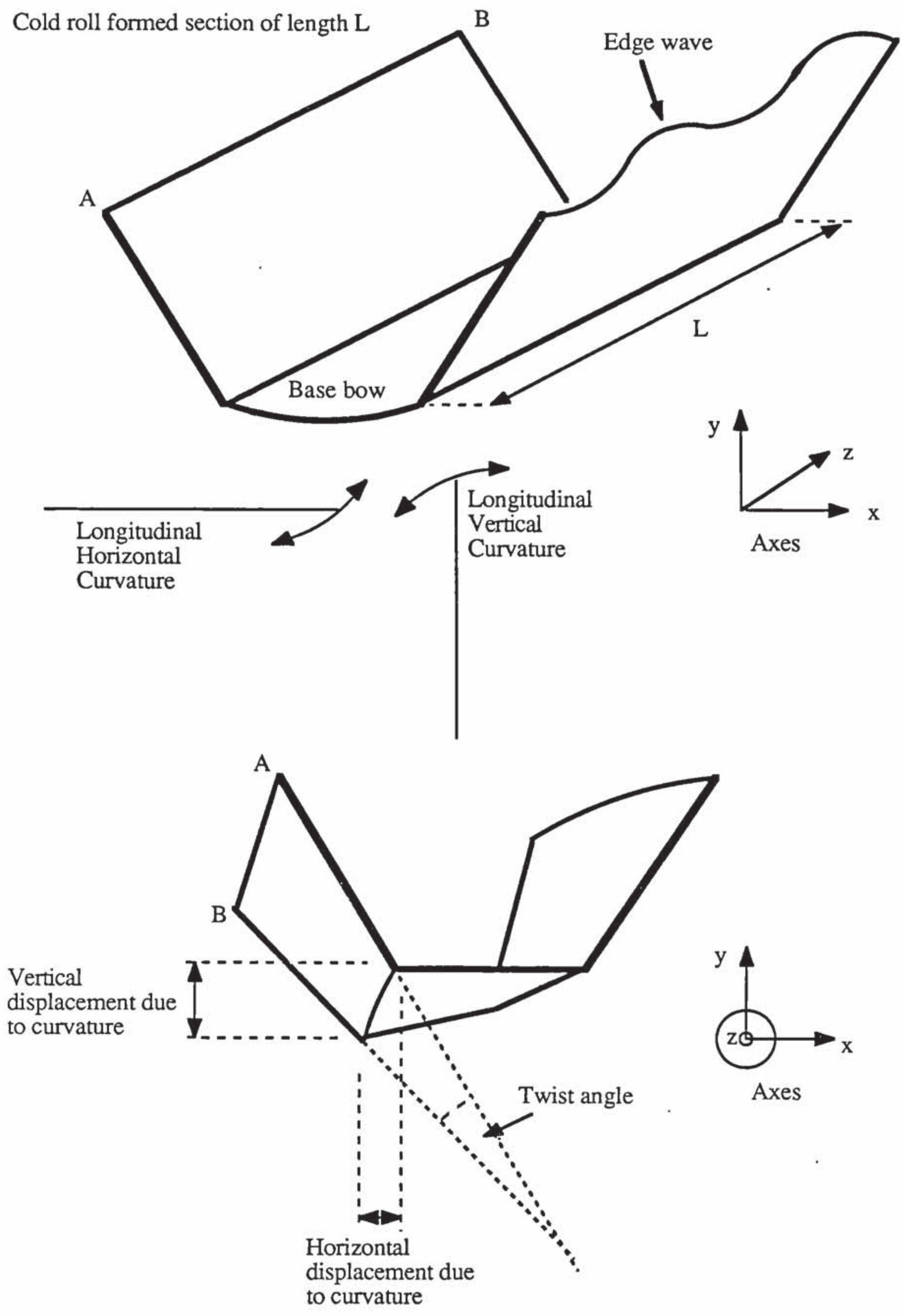
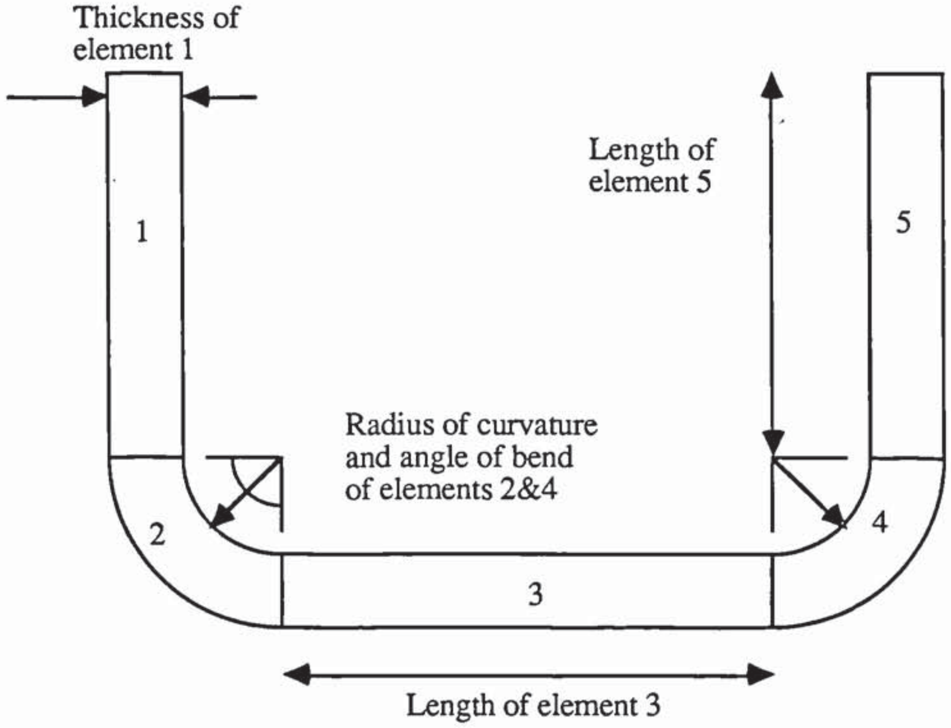


DIAGRAM 6.17 DEFECTS IN COLD ROLL FORMED SECTIONS.



6.18 DEFINITION OF QUALITY IN COLD ROLL-FORMED SECTIONS

3. Geometric inaccuracy. Consider a simple symmetric channel as in diagram 6.18. The section can be broken down into linear and circular elements. Each of the elements can have inaccuracy in the geometry, not simply in the length or radius and angle but also in the shape. Radii of curvature may not be constant and nominally straight elements curved. A table (table 6.4) can thus be drawn up showing the tolerances on each element :-

Element Number	Element Type		Tolerance on ;				
	Straight	Circular	Length /mm	Curvature	Radius /mm	Angle /degrees	Thickness /mm
1	✓		0.5	0.001			0.001
2		✓			0.001	1	0.001
3	✓		0.5	0.001			0.001
4		✓			0.001	1	0.001
5	✓		0.5	0.001			0.001

TABLE 6.4 TOLERANCES IN COLD ROLL-FORMED SECTIONS

Quality is thus largely established in the cross-sectional plane. This does not take into account the third dimension tolerances. These are the length itself, and the curvatures of each of the elements over the length. Again a second table could be drawn up of the elements and their lengthwise curvatures. However, it is simpler to consider only the transverse and vertical curvatures and the twist per unit length of the section, since this covers the combined effects of the curvature of each element.

A further point to consider is the variation of error. Edge waves and buckling may be obvious effects causing the section to be scrapped, but the cross-section at any point may be within the limits of the tolerance in the table. Hence the acceptable variation of tolerance per unit length may also need to be quoted to specify section quality more fully.

An important definition which must also be noted, is that of the sign convention. Positive and negative curvatures, twist and bow, are defined in different ways by different roll formers. Also the vertical and horizontal axes of a section, are merely nominal directions. Thus the definitions used in this work are described clearly.

Such definitions of quality as the above may be comprehensive, but the measuring of the quality may be time consuming. The possibility of measurement aids was therefore considered. From the cross-sectional tolerance table a "worst case" template could be produced. This can be passed over the section as a "go" gauge. A "no go" gauge can also be produced. These two simple aids allow an easy measurement of the cross-sectional accuracy. Further specialised devices are feasible for the measurement of the other quality limits.

6.12.2 EXPERIMENTAL QUALITY MEASUREMENTS.

A range of measurements was made to assess quality in the sections. These covered;

1. Vertical Curvature
2. Twist
3. Bend angle
4. Thickness

Sections that were measured had been stopped part way through the mill. Quality measurements were made on the part of the section that had been fully formed on exit from the final pass. The measurements were made away from the ends of the strip, since these parts were often damaged in transport.

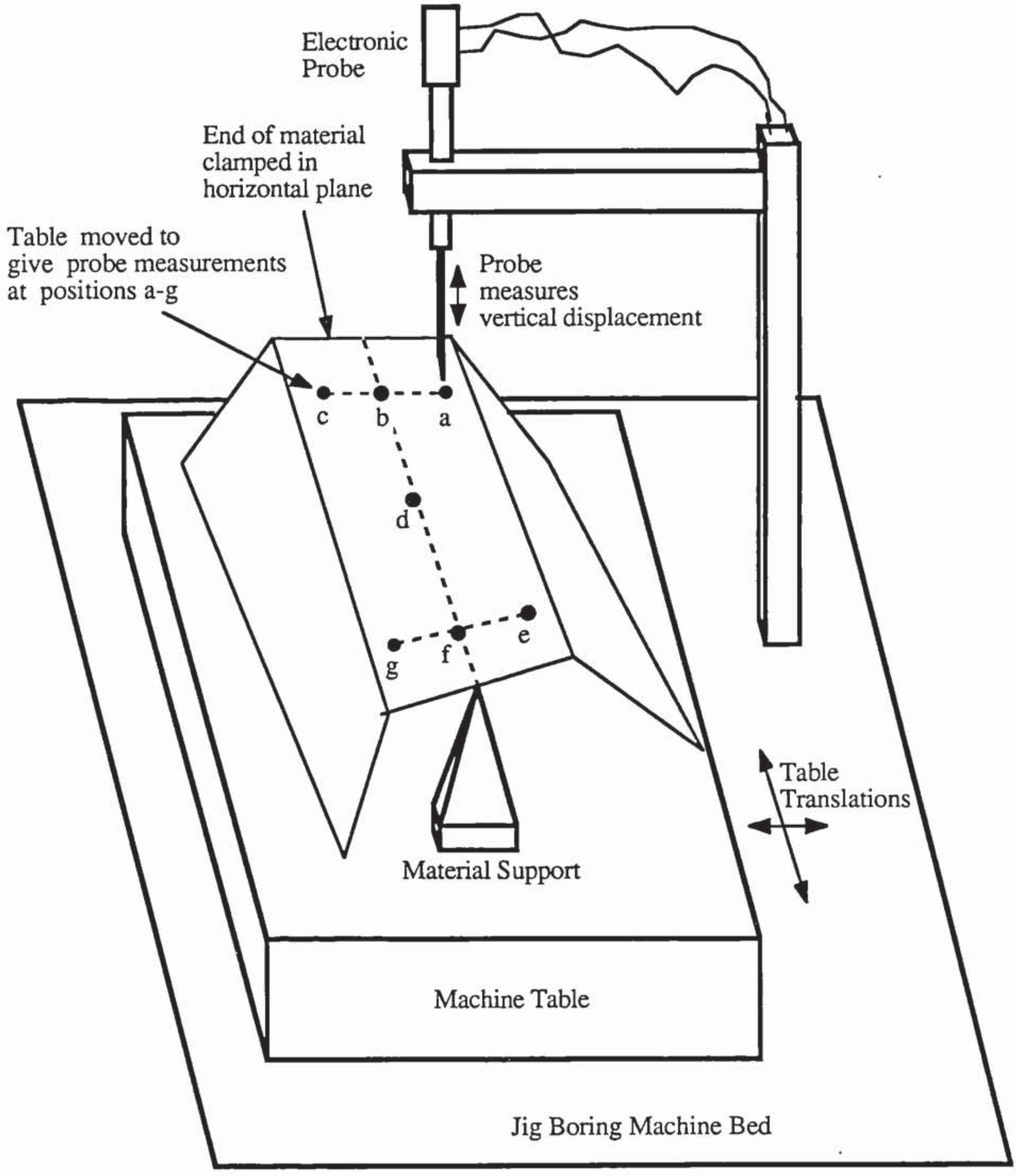
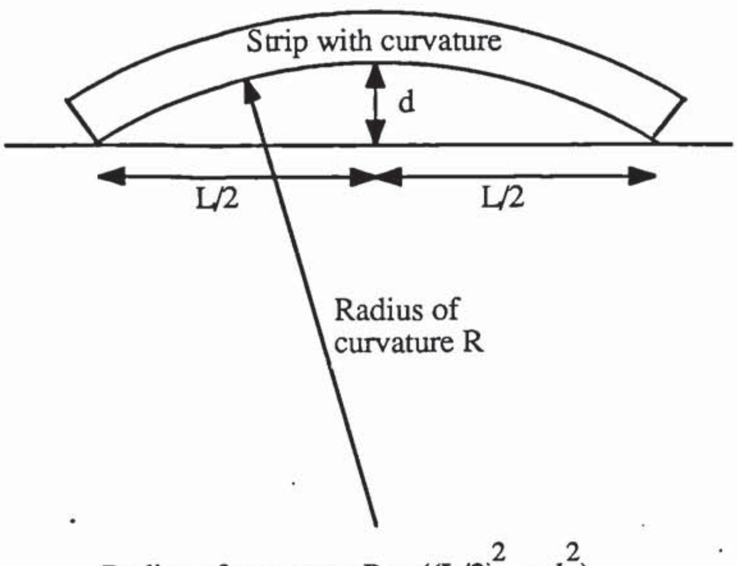


DIAGRAM 6.19 MEASUREMENT OF TWIST, WEB BOW AND LONGITUDINAL CURVATURE ON A JIG BORING MACHINE

To describe the detail of a complex surface by coordinates requires a very large number of points. The resolution of the definition comes from the number of points considered. To reduce the lengthy procedure of making the quality measurements, the number of coordinate readings was kept to the minimum that still showed obvious trends.

Vertical curvature and twist were measured using a jig boring machine. The strip was located on the machine bed as in diagram 6.19. Due to the rigidity of the section only light clamping was needed. The section was rested on supports to give the correct attitude for measuring, with the longitudinal centre line aligned with the axis of the table having the largest travel. The machine table could be moved in the horizontal plane shown, which allowed the seven points marked on the strip to be moved under the probe. Movements in this plane could be made to a resolution of 25 μm. Vertical displacements were read from a digital processor connected to the probe. These readings were repeatable to 0.1 mm.

To calculate curvature over a given length, the deflections at the ends and centre of that length were measured, as in diagram 6.20. For longitudinal vertical curvature the length was b to f, with d the centre point (see diagram 6.19).



$$\text{Radius of curvature } R = \frac{((L/2)^2 + d^2)}{2d}$$

$$\text{Curvature} = 1/R$$

DIAGRAM 6.20 CALCULATION OF CURVATURE

Length b to f was limited to 200 mm, due to limits in the machine table travel. The other distances were;

a-b, b-c, e-f, f-g = 127 mm

b-d, d-f = 100 mm

Curvature causes the strip edge outgoing from the final roll pass to deviate from its ideally linear path. By relating this deviation to the transverse and vertical axes of the mill the directions of the transverse and vertical axes in the section become standardised. In some cases this implies that the nomenclature of axes, for two apparently identical sections, may be different depending on the orientation of the section in the mill. However, the definition of axes in this way is logical in terms of correction of the setting parameters to reduce curvature. In the tests a positive vertical curvature was taken as a movement of the section leading edge rising up towards the roof, and a negative as descending towards the floor.

Twist was measured by calculating the angle of the base to the horizontal plane at point b and f. By subtracting these two values and dividing by the distance between them (200 mm) the twist per unit length could be estimated. A clockwise twist was taken as positive (i.e. when the leading edge of the section was rotated clockwise compared with a cross-section further back)

The strip thickness was measured on the web and on the flange before and after rolling. This showed if any thinning of the strip had taken place at the site of the applied load (the base), compared with the unloaded flange. Measurements were taken at three positions along the length using a micrometer accurate to +/- 10 μm.

Bend angle was measured using a vernier protractor. In certain cases the flange bow, web bow and edge wave made these readings difficult to measure. Accuracy was therefore to +/-0.3°, which was not the full potential of the measuring instrument. The protractor also allowed a visual assessment of flange and web bow. Diagram 6.17 shows the set-up. In cases of edge wave the measured angle was taken as an average value.

6.13 HARDWARE AND SOFTWARE.

The data capture system needed ideally to be able to read a maximum of twelve analogue inputs, at a minimum sampling rate of 40 Hz simultaneously. This would allow six load cells (from three passes) and six strain gauges to give a reading every 10 mm of length along the strip at the slowest roll speed. This was considered a reasonable resolution, from which the nature of straining could be observed graphically.

Pen recorders and tape recorders were considered too inaccurate and lacking in versatility compared with computer-based alternatives. In order to reduce the time spent setting up the system, it was decided to purchase a package, designed for data capture and processing, to run on a micro-computer (most of the common micros were available for use).

For multi-channel high speed data capture, micro-computers require an additional processor card to be installed, (the input and output ports not usually being designed for this kind of use). The cards can be controlled by conventional software although, due to the complexities of programming, companies offer languages or complete systems to ease the setting up. Most of the cards are suitable for the standard IBM PC computers, and can be controlled by software from many different suppliers, not necessarily the same supplier as the card manufacturer.

Manufacturers offered systems of varying degrees of sophistication, from sub-routine based languages for self-tailored applications, to menu driven programmes. It was noted that other research groups had spent a great deal of time writing programmes for sub-routine based software such as ASYST, which in this application was unnecessary. Menu driven packages offered the features required, cheaper, with very little time spent getting the system operative. For these reasons the package DT Notebook was purchased from Data Translation, with complementary processor card DT2801.

Of all the suitable processor cards available, eight was the maximum number of double-ended analogue channels that could be accommodated. Sixteen single-ended channels were available, but these were considered too inaccurate due to their susceptibility to electrical interference, noise, drift and zero errors. By installing another card, the number of channels could be doubled. However it was decided that eight data inputs was acceptable. If, after testing, more channels were judged to be necessary, then another card would be bought.

Input Analogue to Digital				Output Digital to Analogue		Input / Output
Analogue Channels	Analogue Resolution (bits)	Programmable Gain	Throughput Bits / s	Analogue Resolution (bits)	Analogue Channels	Digital Channels
8 Double Ended	12	1,2,4,8	13700	12	2	16

TABLE 6.5 DATA ACQUISITION CARD DT2801 SPECIFICATION

As can be seen from the specification (Table 6.5) the card gave very high resolution, and a throughput able to handle the minimum requirement (8 channels x 12 bits x 40 Hz = 3840 bits/s). Additionally, there was the capability for analogue output from the card which had the potential for feedback control and other features, so adding flexibility to the system.

The system was installed on an IBM PC XT micro-computer. This entailed fitting the processor card into one of the available application slots within the computer and loading the software onto the hard disk.

Table 6.6 shows the values, entered into the software, to set up the input channels. Other information was entered to set up the graphics, windows, files etc. using a simple menu-driven technique. Data files could be stored in formats that could be read by other well known packages such as LOTUS 123 and SUPERCALC. The software gave great flexibility, with many features in an easy-to-use form.

Essentially, the software was set-up to control the channel inputs, create a data file of the test, and monitor the input values graphically during the tests.

Number of Channels [1...100]	9								
Current Channel	0	1	2	3	4	5	6	7	8
Channel Type	analogue								time
Channel Name	Load cell 1	Load cell 2	Load cell 3	Strain gauge 1	Strain gauge 2	Strain gauge 3	Strain gauge 4	Strain gauge 5	Time
Interface Device	DT 2801								
Interface Channel Number [1...15]	1	2	3	4	5	6	7	8	9
Input Units	DC Volts								n/a
Input Range	+/- 10 Volts								n/a
Scale Factor	1.0								n/a
Offset Constant	0.0								n/a
Buffer Size	2048								
Number of Iterations	1								
Number of Stages [1...4]	1								
Sampling Rate, Hz	40								
Stage Duration, sec. [0.0...1.0E+09]	20								
Start/Stop Method	Normal								
Trigger Channel	0								
Trigger Pattern to AND [0...255]	0								
Trigger Pattern to XOR [0...255]	0								
Time Delay, sec [0.0...1.0E+06]	0.000								
Analogue Trigger Value	0								
Analogue Trigger Polarity	High								
Number of Samples to Save (pretrigger)	0								

TABLE 6.6 INPUT CHANNELS DEFINED USING DT NOTEBOOK

A selectable option in the software allowed a choice of input range from +/- 1.5 V to +/- 10 V. To obtain high resolution it was therefore necessary to produce a signal which, at its maximum, would fill the range. The input range was set to +/-10 V, so the strain and load cell signals had to be matched to this range, using the amplifiers.

The physical link from the amplifier outputs to the computer were made via a connector board (Data Translation DT707). Wires from the amplifier were screwed into the board, which was plugged directly into the processor at the back of the computer.

The power supply used paired voltage regulators to give a stable +15. 0. -15. dc voltage. The maximum current capacity was 1 A which was sufficient to supply all eight amplifiers.

Diagram 6.21 illustrates the complete system of computer based data capture.

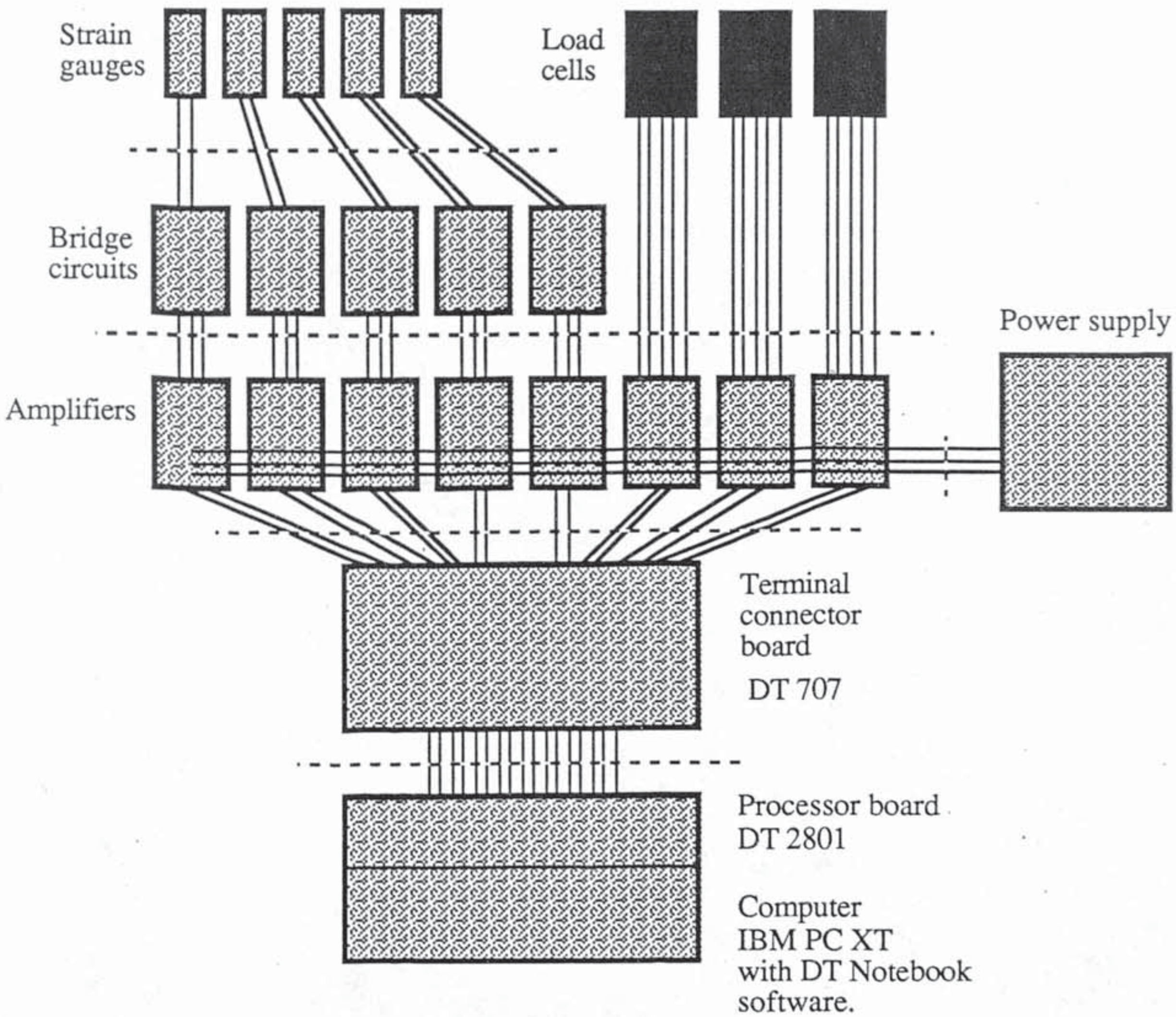
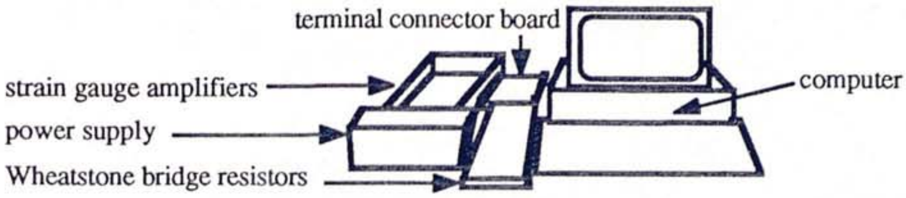
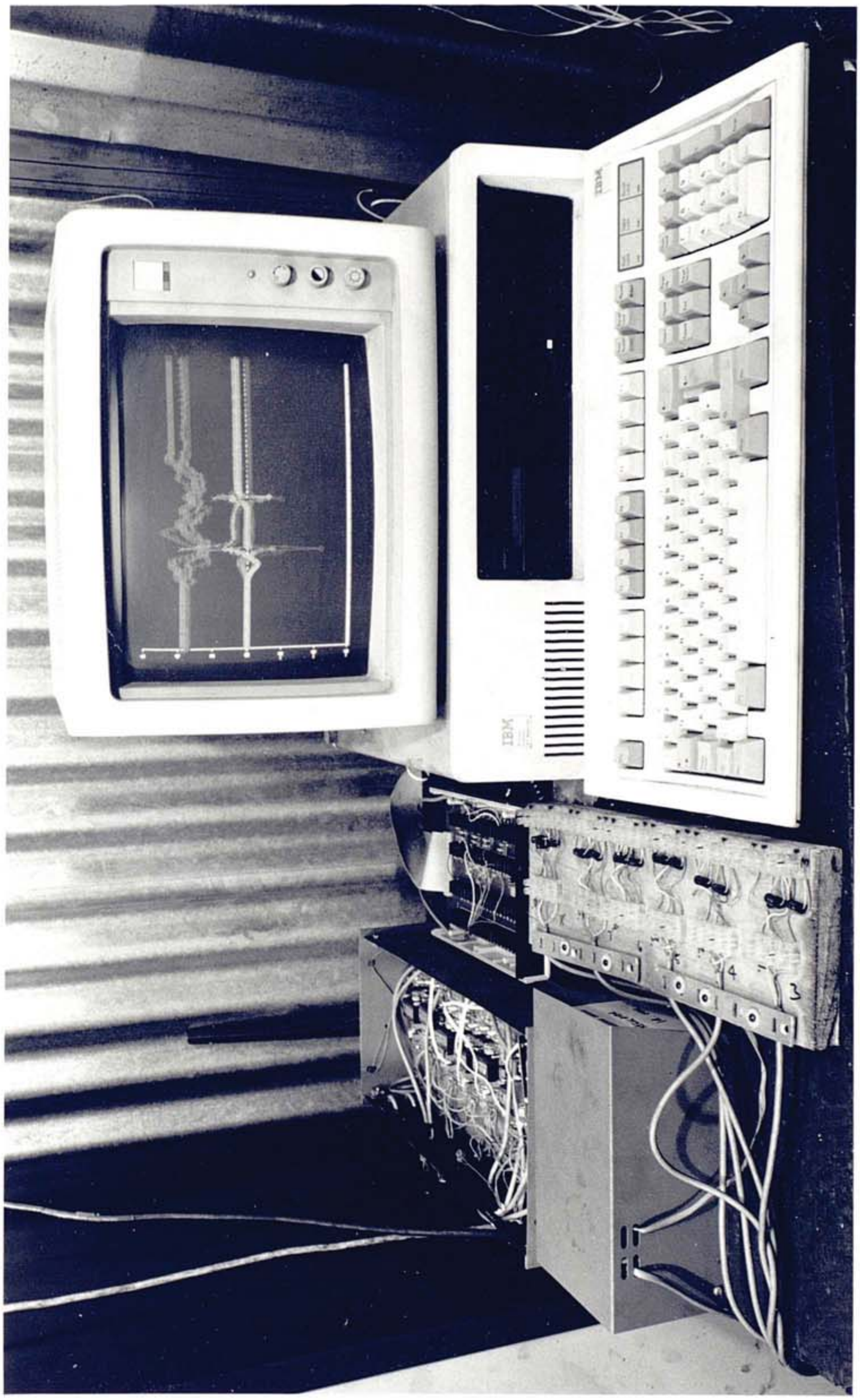


DIAGRAM 6.21 STRAIN AND LOAD CELL DATA COLLECTION SCHEMATIC

PHOTOGRAPH P13 DATA COLLECTION HARDWARE





CHAPTER 7

EXPERIMENTAL RESULTS

7.1 INTRODUCTION

The test results are discussed group by group followed by a broader discussion of all the results and an appraisal of mathematical models.

Results from each test are displayed graphically. There are three graphs for each test, showing the roll load, flange strains and base strains during passage through the rolls. Roll load is shown in tonnes force (1 tf = 9.81 kN), strain is shown in per cent. The x-axis is the same for the three graphs, and shows the distance travelled by the strip from its starting position in millimetres. Additionally, the results of the quality measurements made in each test are tabulated. Diagram 7.1 shows the position of the roll pillars referred to on the graphs as r_1, r_2, r_3, l_1, l_2 and l_3. Positions of the strain gauges are shown in diagram 6.13.

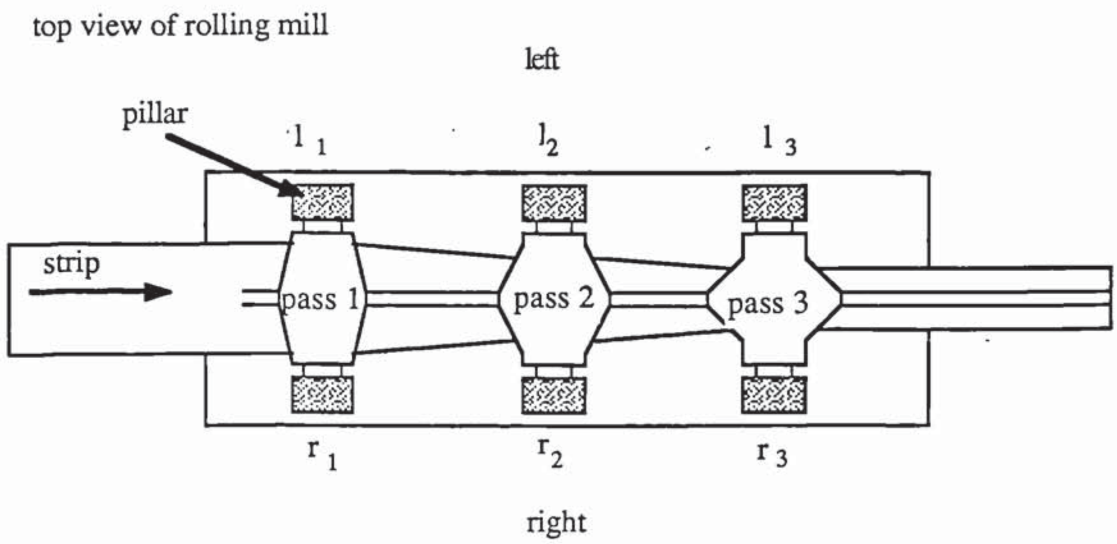


DIAGRAM 7.1 PILLAR NOMENCLATURE

The sign convention used in the tests is shown in diagram 7.2. It highlights the difficulty in defining quality in even the simplest section, with the orientation of the strip needing to be referenced according to its direction of passage through the mill.

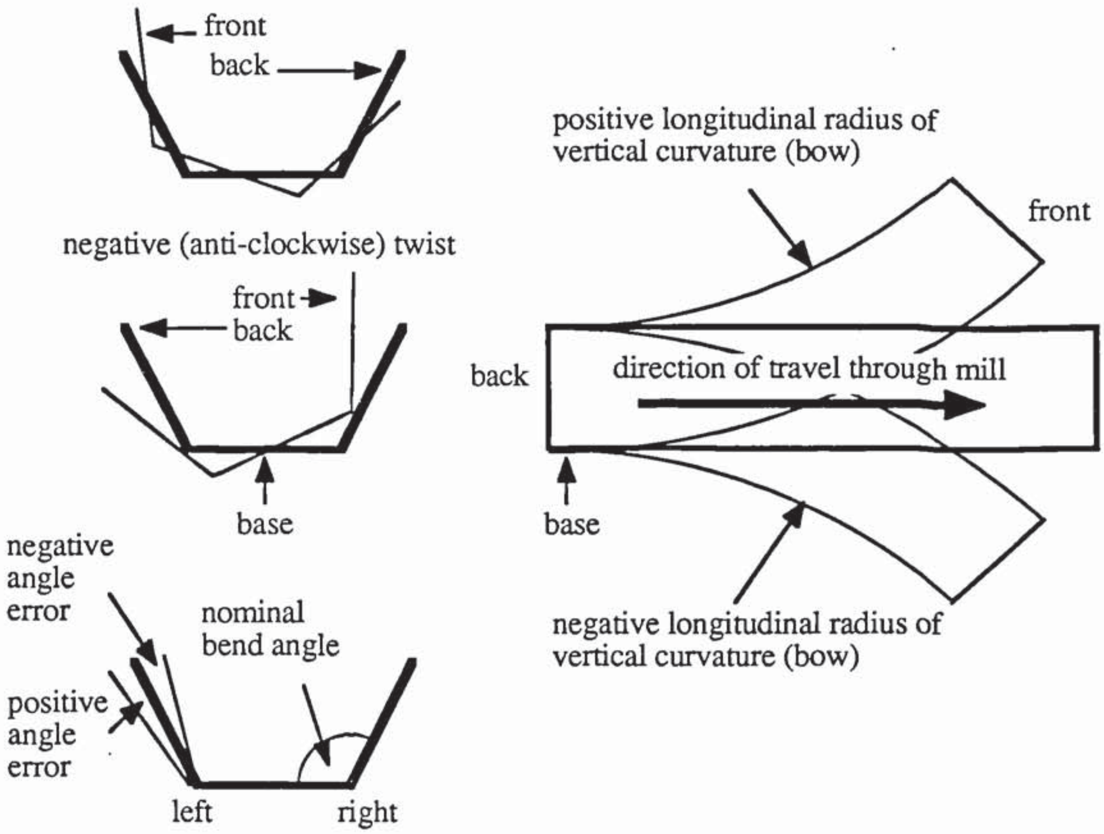


DIAGRAM 7.2 SIGN CONVENTION FOR THE TESTS

On occasions (in 3 cases) strain gauges were damaged by the rolling process. This was obvious from the output, which would jump to 10 V due to formation of a short circuit, or be reduced to zero due to peeling. These parts of the graphs have been removed for clarity.

7.2 GROUP (A) RESULTS

Description; nine tests rolling through a single pass, using three roll loads and three roll speeds.

Test 1 show many of the features that are typical of all the following tests (2-50). Firstly the roll load is not static during rolling. There is a large, smooth, continuous variation; in this case from 0.9 tf to 1.4 tf. However the balance between loads applied from the left and right pillars is maintained, with the two load cells giving approximately matched outputs.

Test 3 is the least balanced test, with differences between the left and right pillar load of up to 0.6 tf.

The problem in setting specific roll load became obvious, with there being no method of control during rolling. Setting the desired load at the start of the test was the only control available with the existing mill design. This prompted a new set of tests on roll load outside those planned, and an investigation into the redesign of the roll pillars for greater roll load control (tests 43-50).

Nominally, tests had been grouped in terms of low, medium and high roll load. In certain cases the actual roll load at points during the tests became very high or low, and did not necessarily tally with the nominal description.

Flange strains show a large peak approximately 45 mm before entering the roll gap, and a smaller peak after exit from the roll guide approximately 300 mm before the first pass. The edge strain gauges (1 and 4) give the highest peaks, with the mid-flange gauge (2) giving a reduced peak.

The importance of resolution became apparent in interpreting the graphs. Tests 4-7 and 9 were the first to be carried out, and were run with a sampling rate of 10 Hz, all other tests were then run at 40 Hz, to give better resolution (sacrificing real time graphical monitoring). It can be seen that a lot of detail, especially at peaks in the strain graphs, is lost with the lower resolution. At 40 Hz only the detail of the peak tip shape is lost, and it can be estimated from the surrounding points. On some graphs, the maximum flange strain is likely to occur between the two points that make the apparently squared-off top to the peak, and may be of a higher value (see diagram 7.3). However the resolution obtained at 40 Hz was considered high enough to allow the significant features of straining to be illustrated without the creation of very large unmanageable data files. To prove this, several tests were carried out using a sampling rate of 80 Hz. With eight inputs, the overall throughput of data was too high for the system. Therefore a single channel was used to gain information showing the detail of the strain peaks.

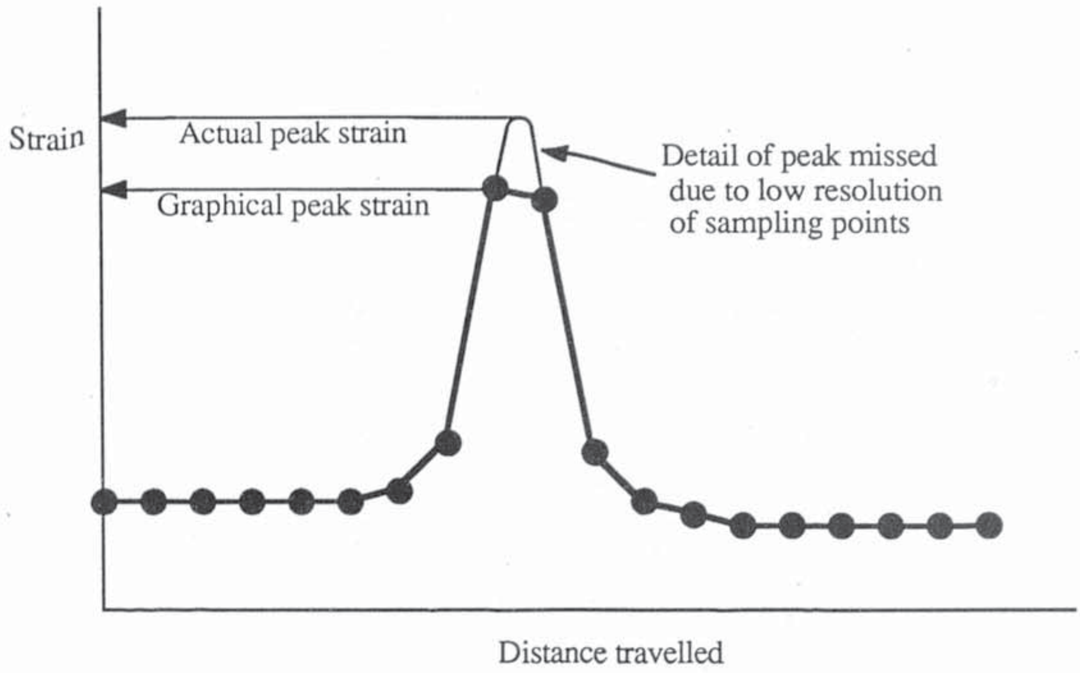


DIAGRAM 7.3 ERRORS IN GRAPH PROFILE DUE TO LOW RESOLUTION

The edge gauges show approximately balanced strains in all of this group of tests. Considering the symmetry of the section, balance of roll load and alignment of rolls, this is expected. These strains follow a standard profile. On exit from the strip guide the strain dips into the compressive strain region, before rising to a steady low tensile value, and then peaking dramatically approximately 45 mm in front of the roll gap. No peaking occurs during passage through the roll gap but a low tensile strain occurs after the peak remained in the strip on exit from the region, so forming the residual strain in the final section.

Similarly, the mid-flange strain follows a standard pattern, this time dipping into the compressive strain region before rising to a tensile peak (lower than that of the edge strains) 45 mm in front of the rolls. The final residual strain is a similar value to that of the edge strain.

Base strains follow a repeated profile in each test. Top and bottom base strains can be seen to approximately mirror each other (they are of different sign). The peak values occur in the same region as those of the flange strains. The top strain follows a pattern of longitudinal compression, tension and compression peaks, with the bottom strain exhibiting tension, compression and tension.

With increasing load, the residual base strains switch from being compressive to tensile. At less than 1.2 tf roll load the straining is tensile, and from 2 tf upward the straining becomes increasingly tensile. This suggests that high roll load induces a crushing of the strip passing between the rolls, so causing it to stretch longitudinally. To confirm that crushing was taking place, measurements in reduction of strip thickness were taken. They showed that the roll load caused no detectable thinning (less than 10 μm). Variations in strip thickness were themselves +/- 10 μm.

Base strain values are very low, peaks being approximately 1% and residual strains of less than 0.5%.

Diagram 7.4 shows the layout of the quality measurements in each group to follow, and the table below (Table 7.1) gives the particular results for group A. There are no immediately obvious trends in twist, curvature or bend angle as a result of changes in roll load or roll speed. It would be expected that certain features of the quality could be predicted from the strain graphs, however, the interpretation is particularly difficult.

Large amounts of twisting would be expected to be shown by imbalance in the left and right flange strains, this, however, is not confirmed experimentally. Test 6 notably has a large imbalance in final residual strain and, although twisted, is not the most twisted section.
At high speed, the twist and bow appear to be less affected by roll load.

A noticeable point, is that the direction of bow is indicated from the base strains. When the top base strain (strain gauge 3) is larger than the bottom strain (strain gauge 5), the bow is negative. It is the difference between the top and bottom strain that effects the bow and not whether the base strains are in the tensile or compressive region. A large difference between the two strains gives rise to a large bow, as shown in Test 3. However, even in this test, the difference between top and bottom base strain is only 0.15%.

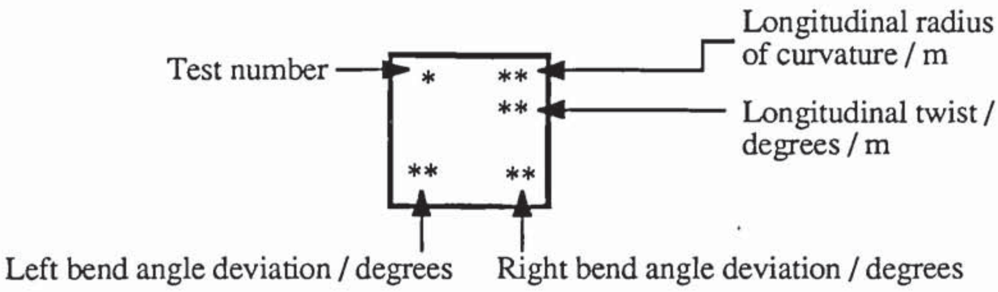


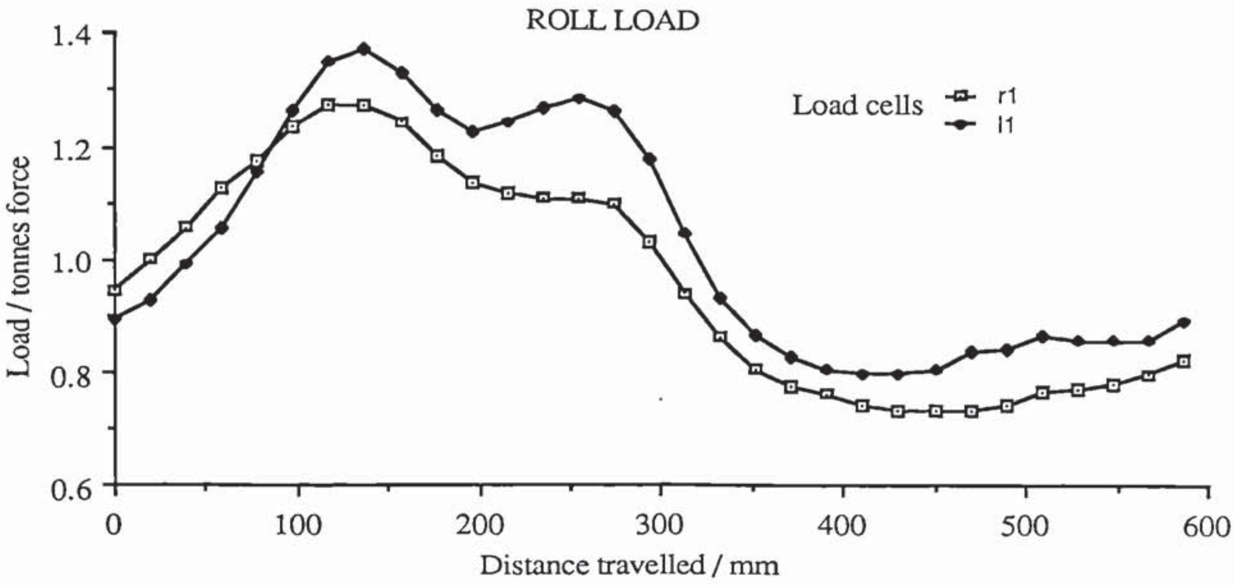
DIAGRAM 7.4 LAYOUT OF QUALITY MEASUREMENTS

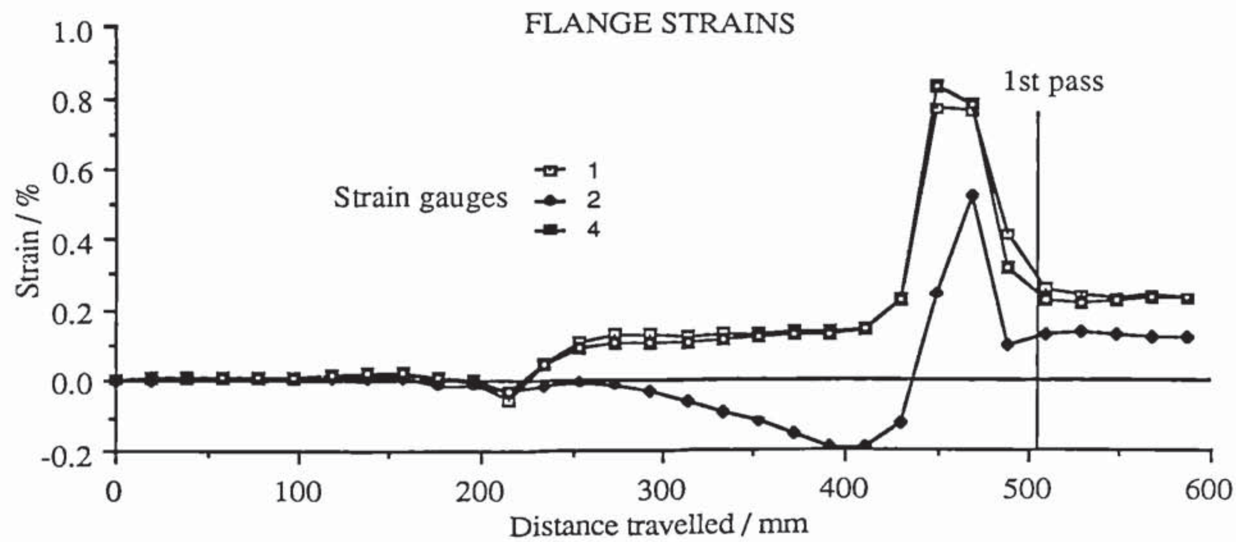
		Roll Load: low	Roll Load: med	Roll Load: high
Roll speed	low	1 -5.1 6.1 0.0 0.7	2 -5.1 20.1 0.0 1.9	3 32.2 30.1 0.7 2.6
	med	4 -3.8 -0.5 0.2 1.0	5 -12.9 5.9 -0.3 1.3	6 -10.1 14.9 0.0 5.4
	high	7 -4.7 15.5 -0.6 1.0	8 -5.0 17.4 -0.4 1.0	9 -2.7 14.9 -0.5 3.4

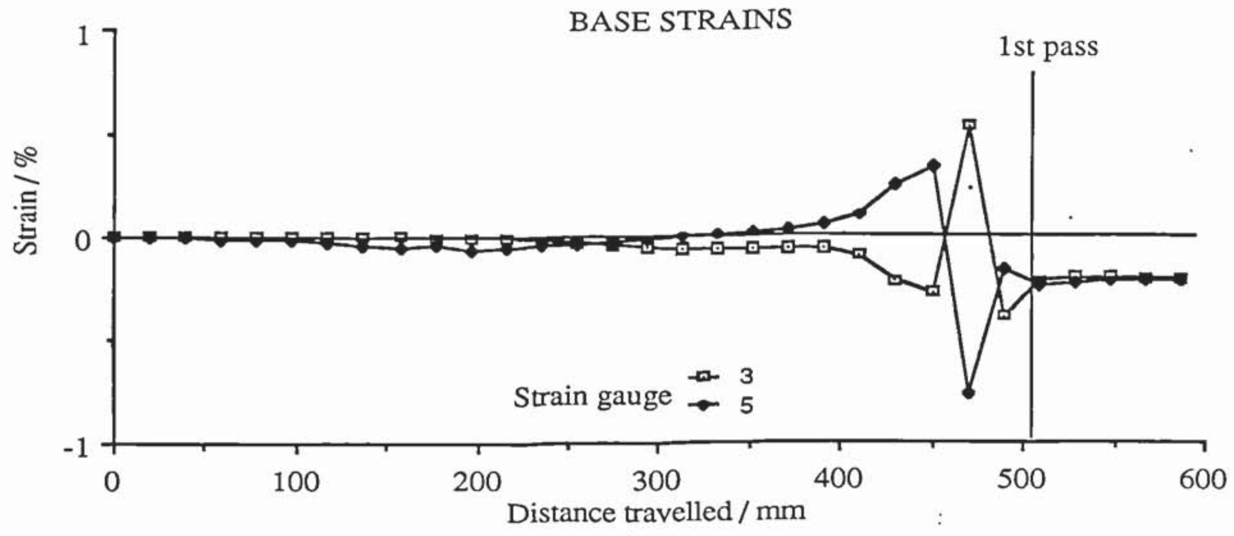
TABLE 7.1 GROUP (A) QUALITY MEASUREMENTS.

The right hand bend angle is markedly more inaccurate than the left. On close inspection of the strip it became clear that this was because the cut-outs in the right side of the roll allowed the strip greater freedom than the left side. With increasing roll load, the right hand bend angle increased. The left bend angle remained within +/- 1° of the nominal angle (30°), for all nine conditions of roll load and speed. It would be expected that springback could only cause a positive value of angle error. For a negative angle error other parameters must be affecting the bend angle.

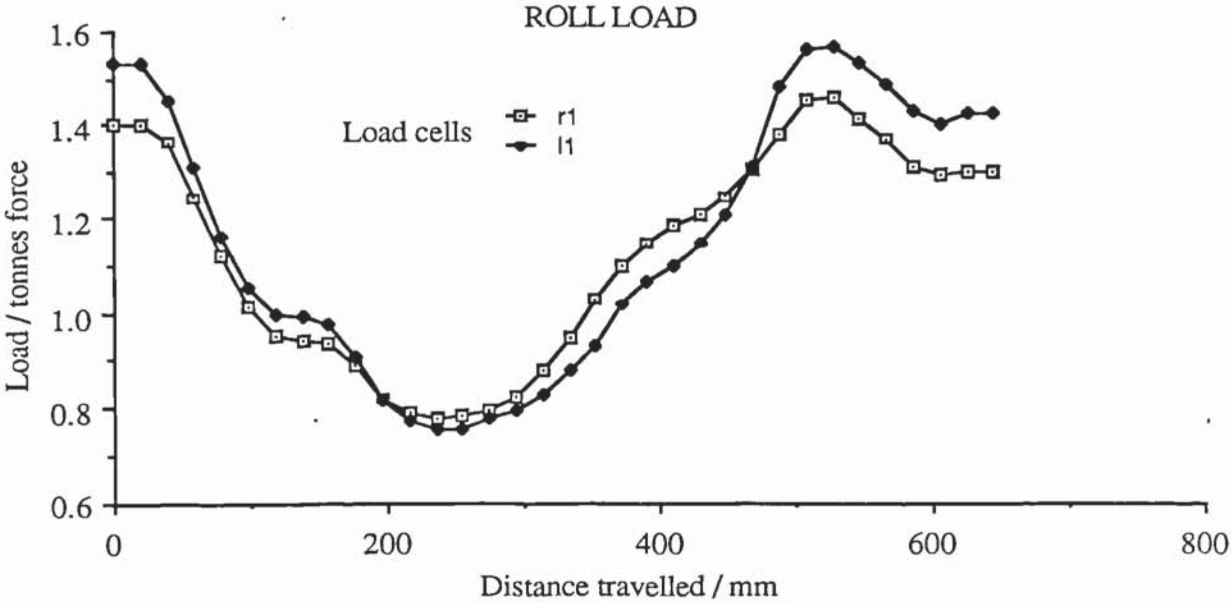
TEST 1

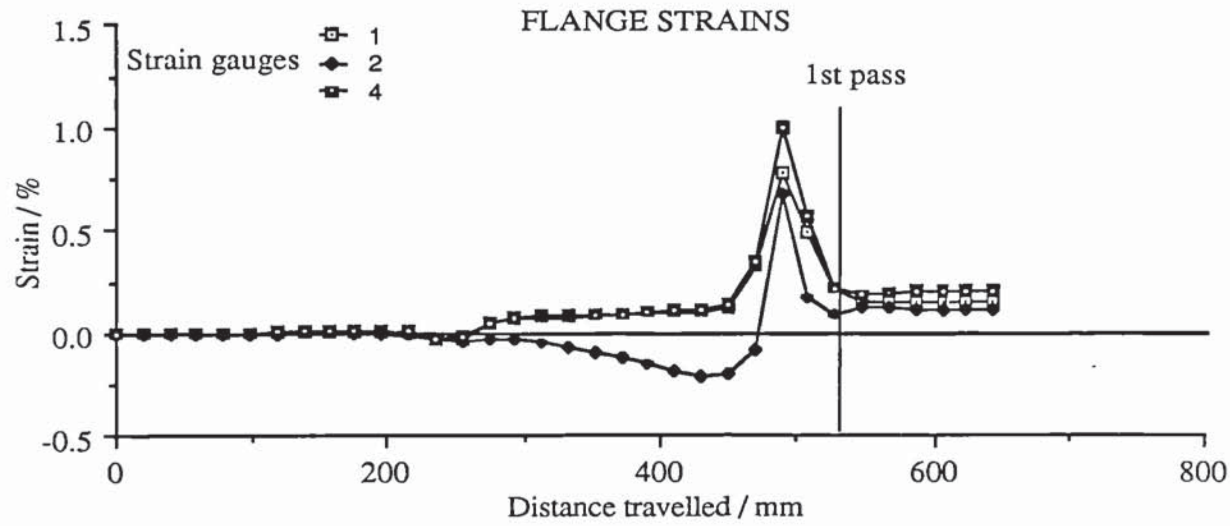

ROLL LOAD
Load cells
r1
l1
Load / tonnes force
1.4
1.2
1.0
0.8
0.6
0
100
200
300
400
500
600
Distance travelled / mm

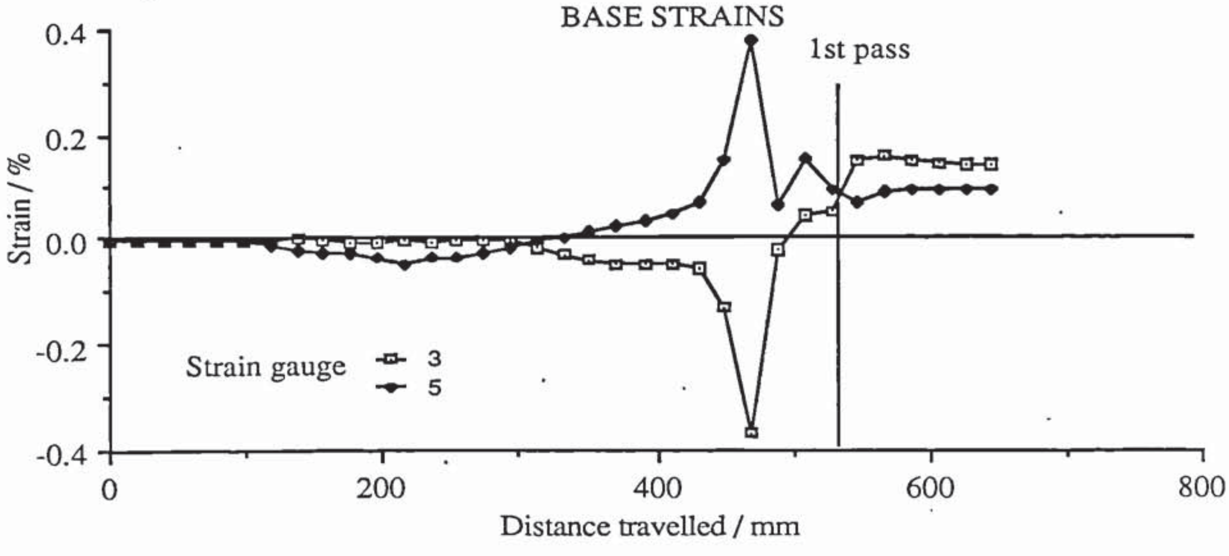

FLANGE STRAINS
1st pass
Strain gauges
1
2
4
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
100
200
300
400
500
600
Distance travelled / mm


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
1
0
-1
0
100
200
300
400
500
600
Distance travelled / mm

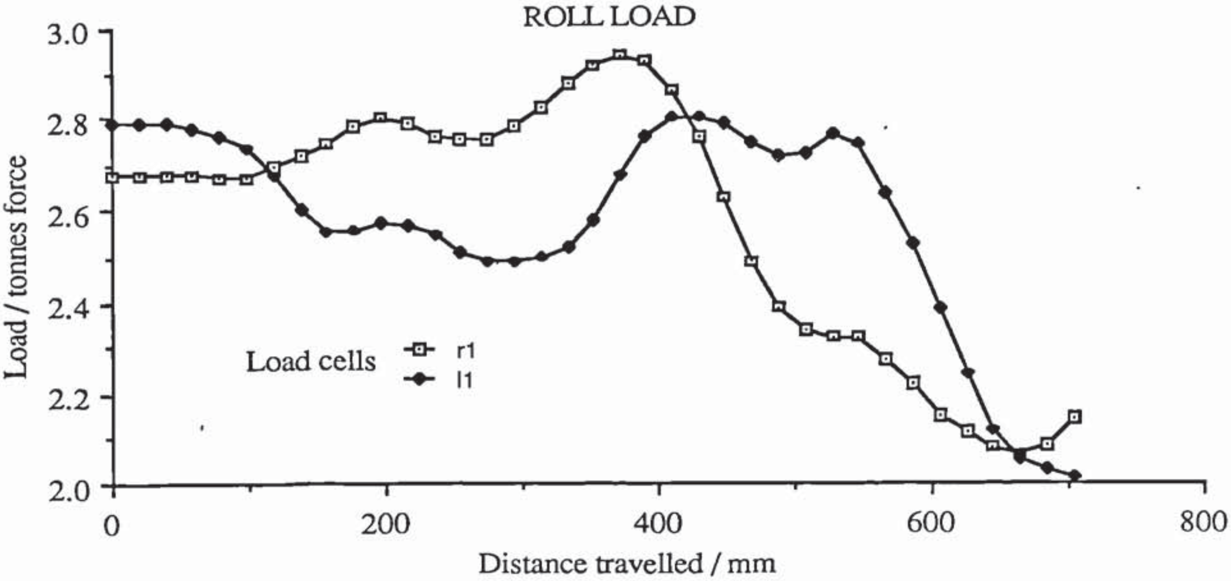
TEST 2


ROLL LOAD
Load cells
r1
l1
Load / tonnes force
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
Distance travelled / mm

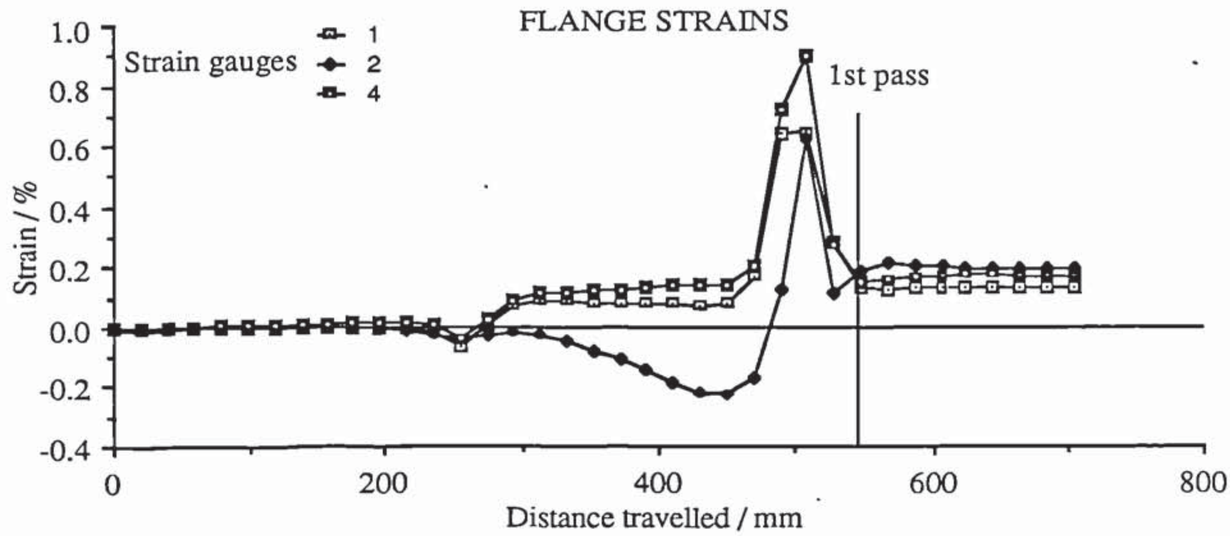

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm

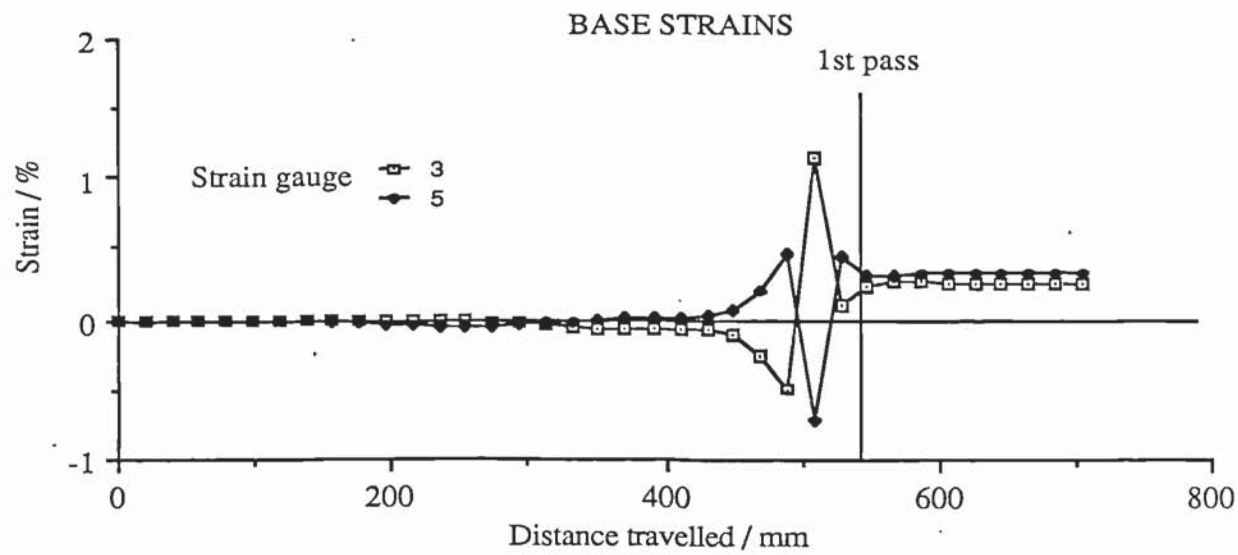
TEST 3



ROLL LOAD
Load / tonnes force
3.0
2.8
2.6
2.4
2.2
2.0
Load cells
r1
l1
0
200
400
600
800
Distance travelled / mm

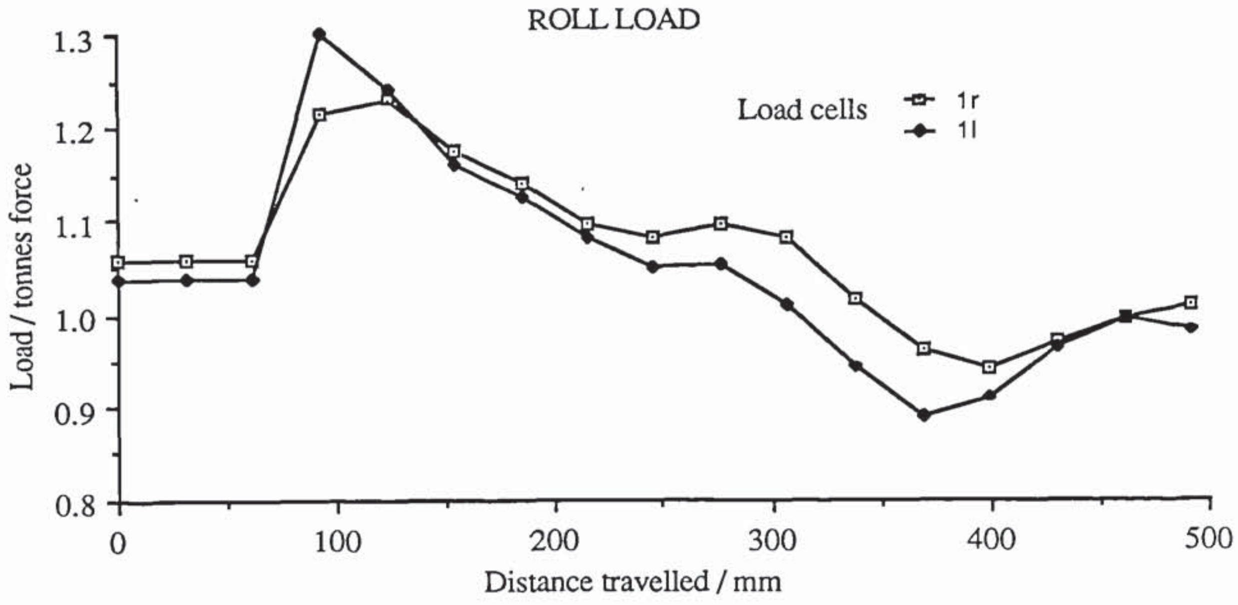


FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm

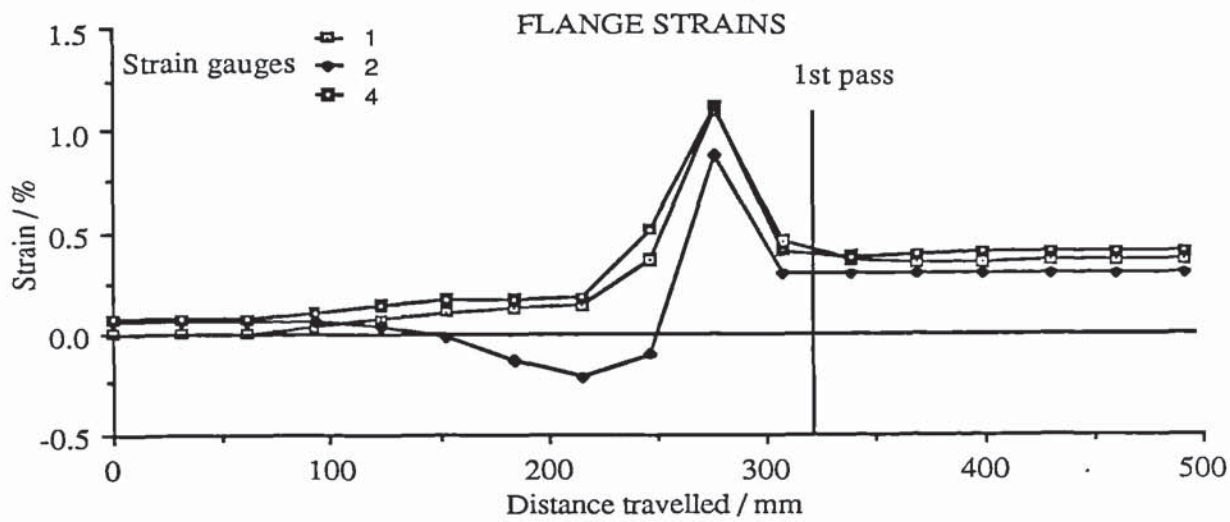


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
2
1
0
-1
0
200
400
600
800
Distance travelled / mm

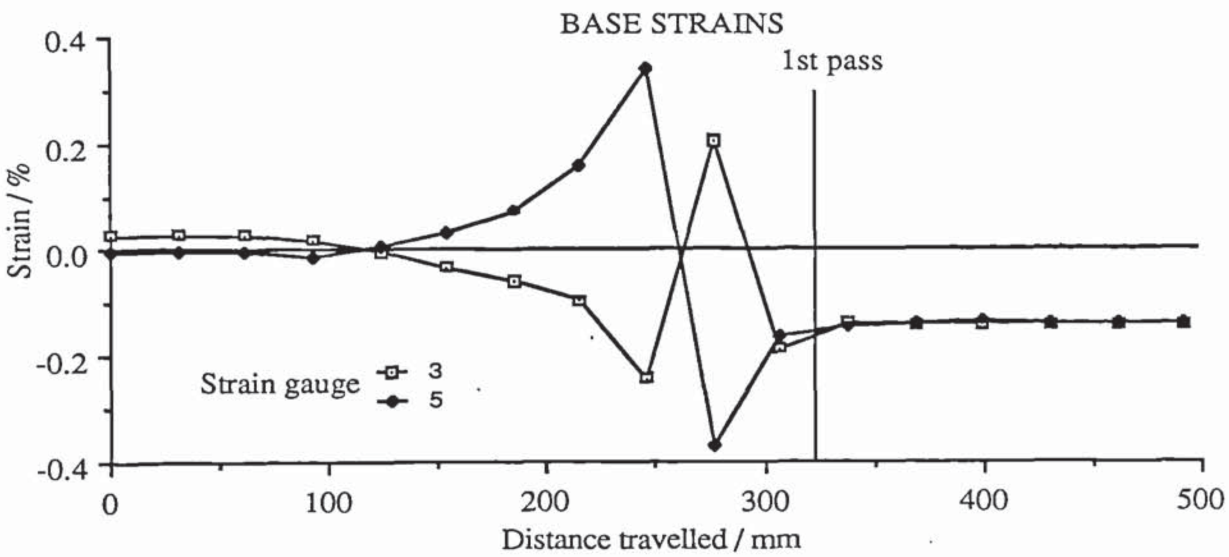
TEST 4



ROLL LOAD
Load cells
1r
1l
Load / tonnes force
1.3
1.2
1.1
1.0
0.9
0.8
0
100
200
300
400
500
Distance travelled / mm

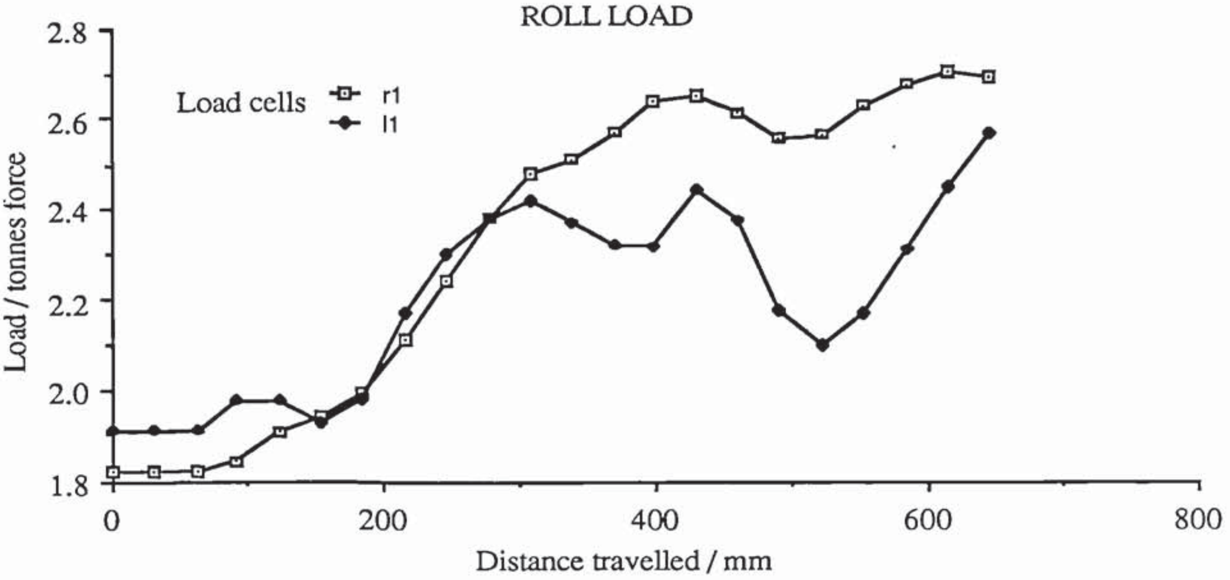


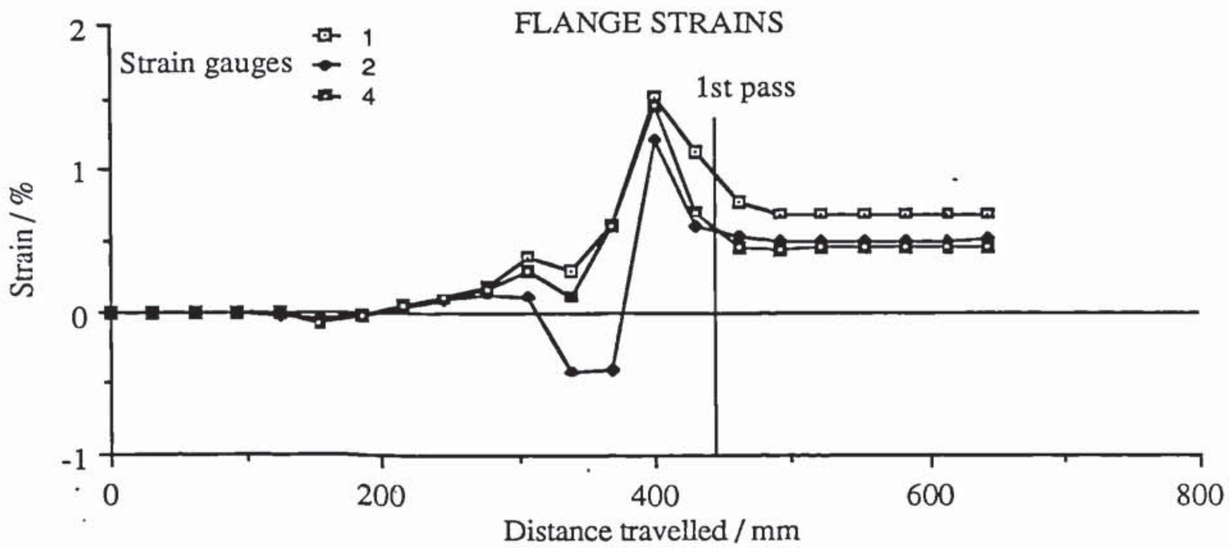
FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
100
200
300
400
500
Distance travelled / mm

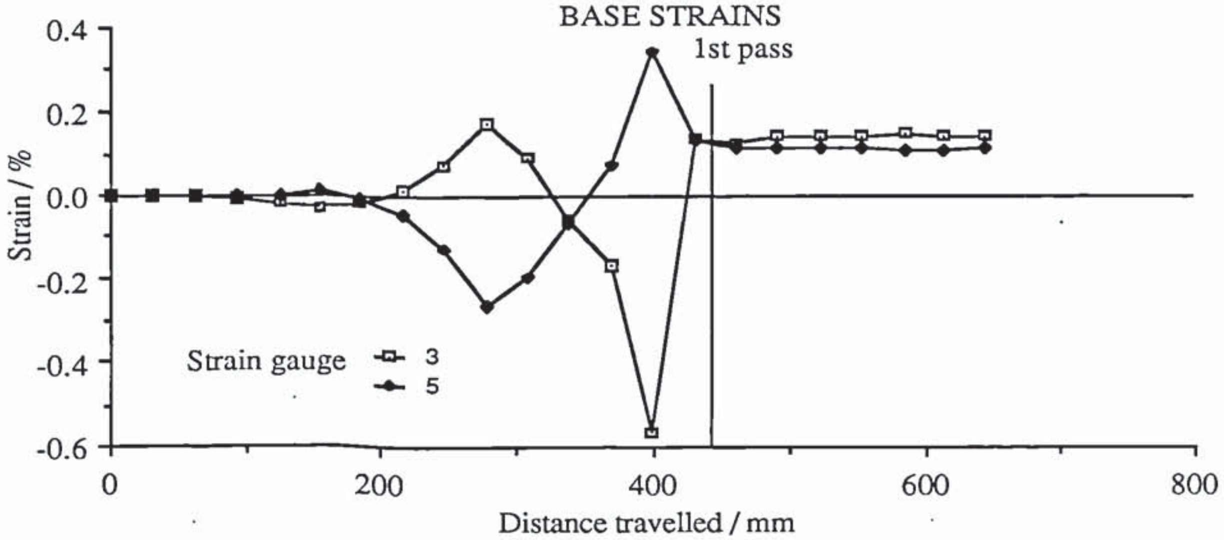


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
100
200
300
400
500
Distance travelled / mm

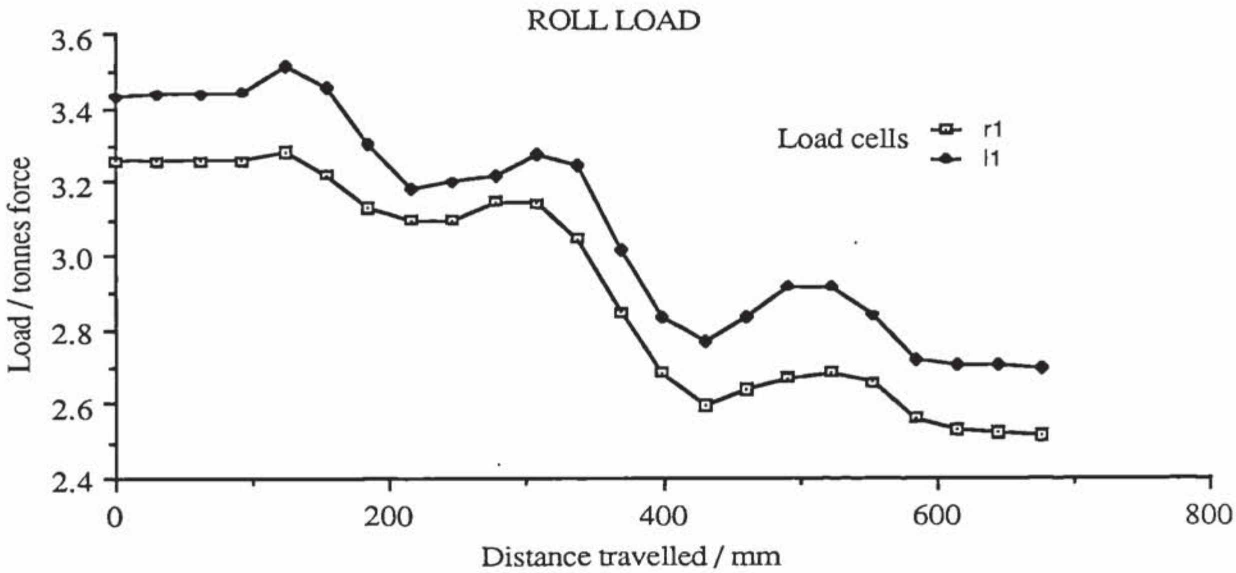
TEST 5

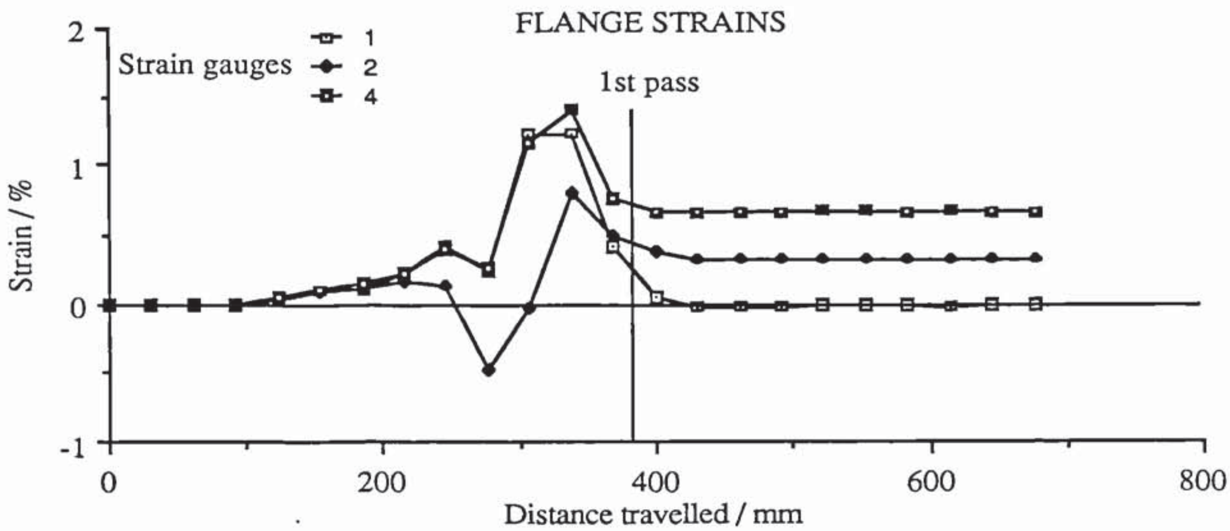

ROLL LOAD
Load cells
r1
l1
Load / tonnes force
2.8
2.6
2.4
2.2
2.0
1.8
0
200
400
600
800
Distance travelled / mm

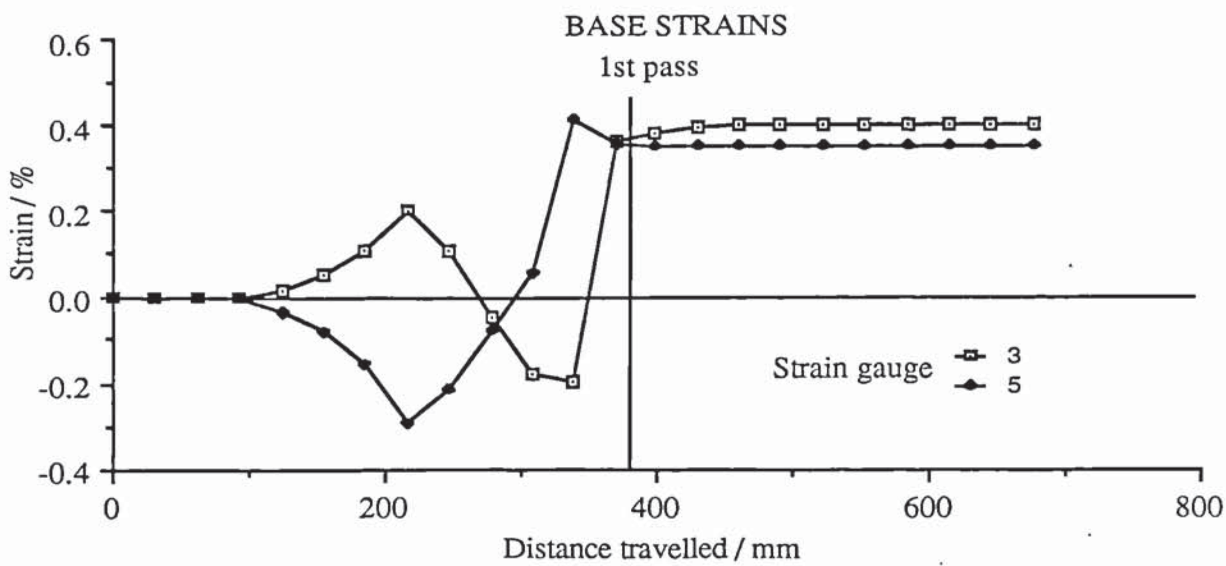

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
2
1
0
-1
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
Distance travelled / mm

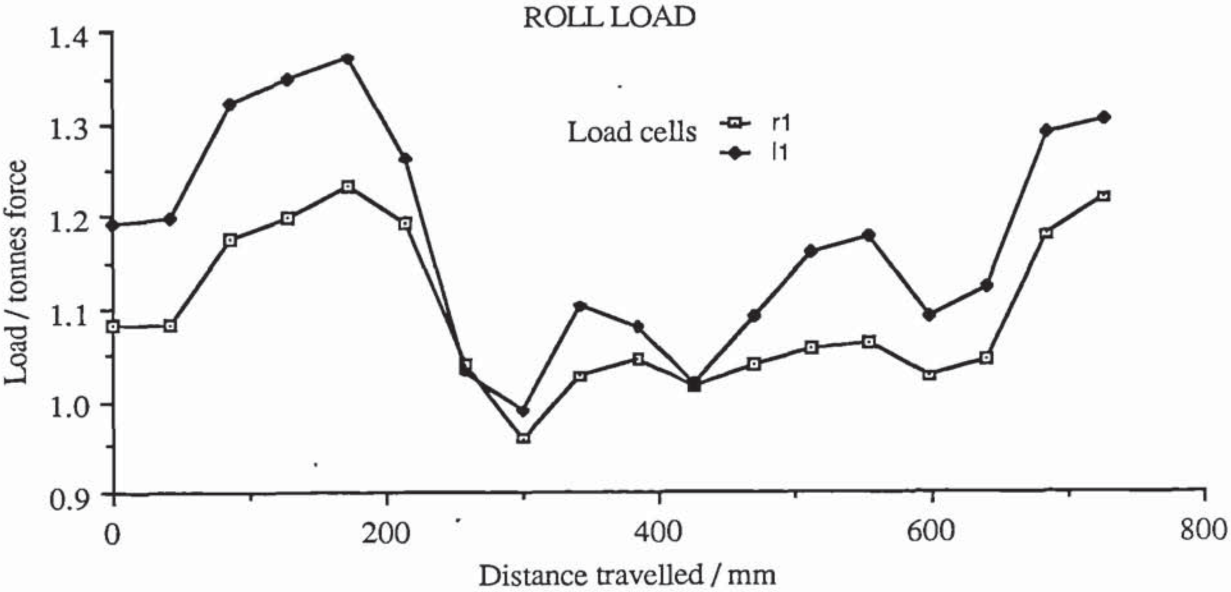
TEST 6

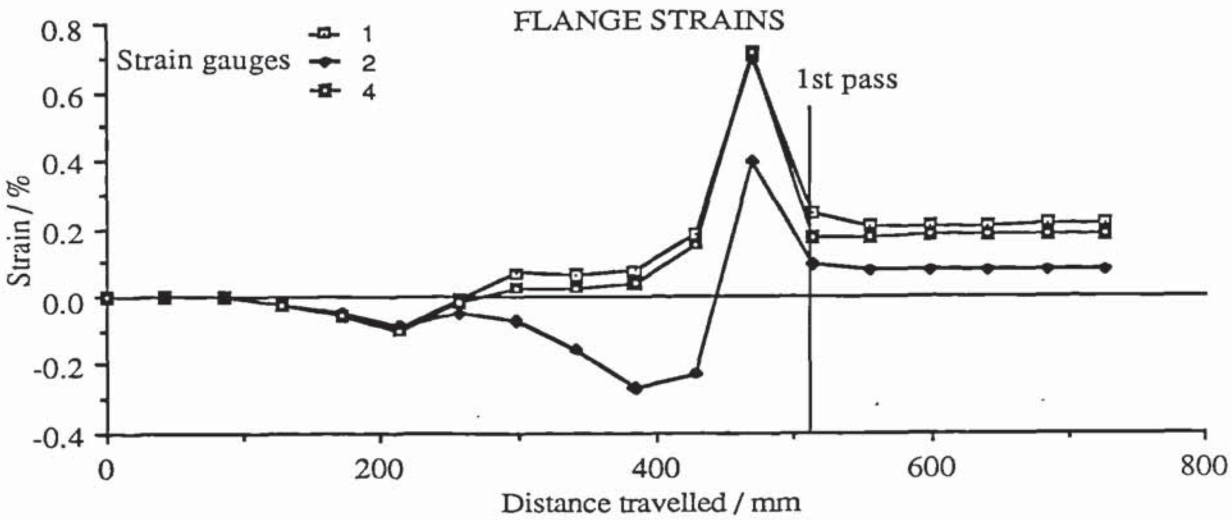

ROLL LOAD
Load / tonnes force
3.6
3.4
3.2
3.0
2.8
2.6
2.4
0
200
400
600
800
Distance travelled / mm
Load cells
r1
l1

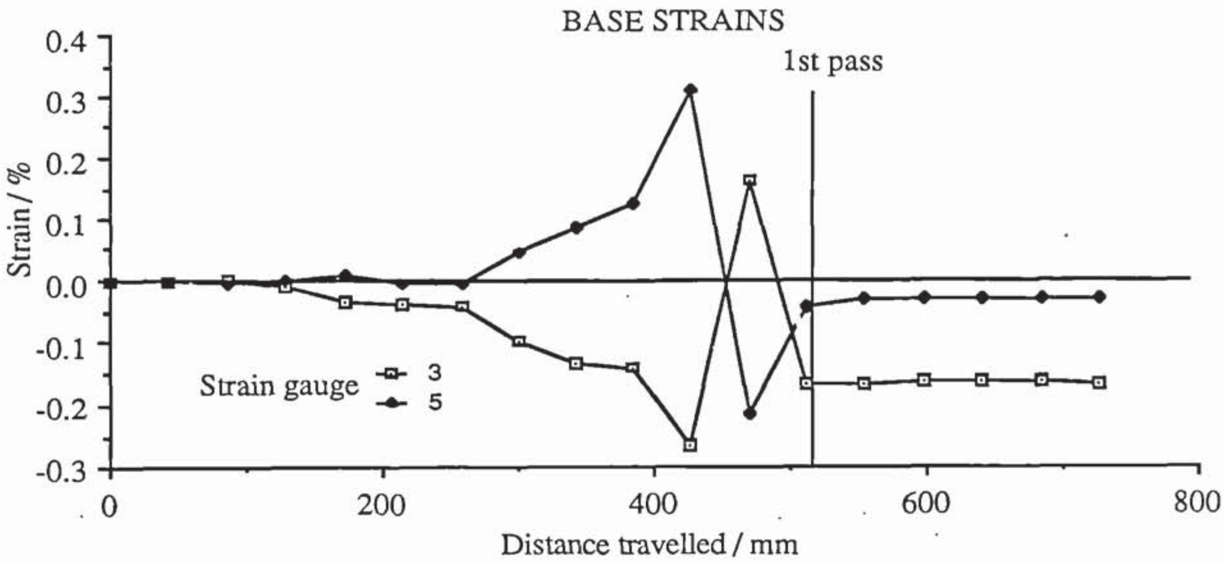

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
2
1
0
-1
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm
Strain gauge
3
5

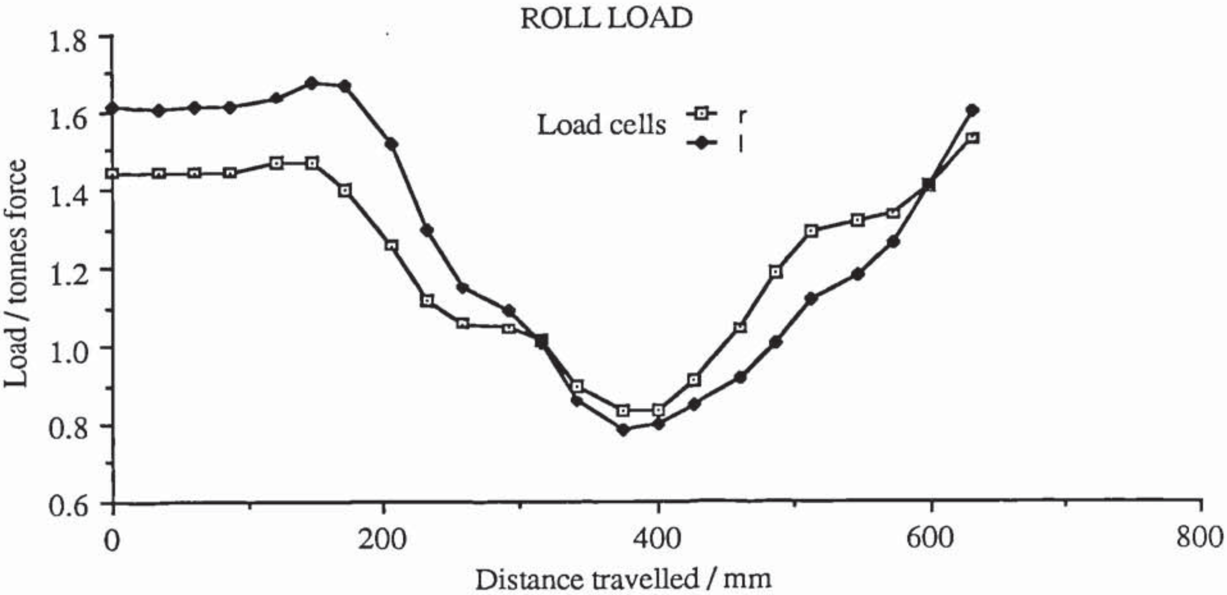
TEST 7


ROLL LOAD
Load cells
r1
l1
Load / tonnes force
1.4
1.3
1.2
1.1
1.0
0.9
0
200
400
600
800
Distance travelled / mm

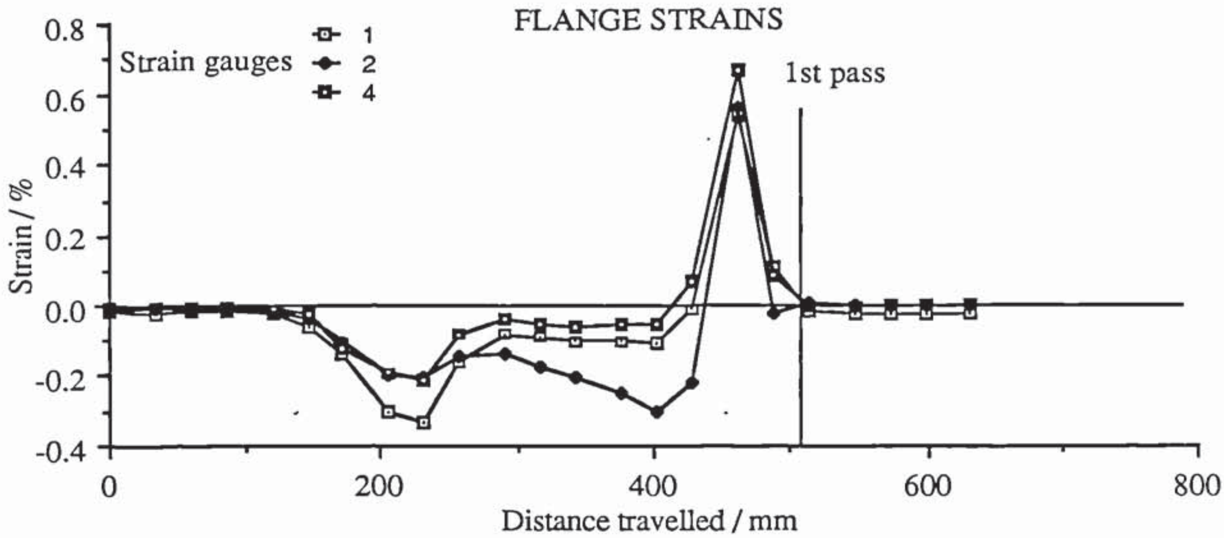

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
Distance travelled / mm

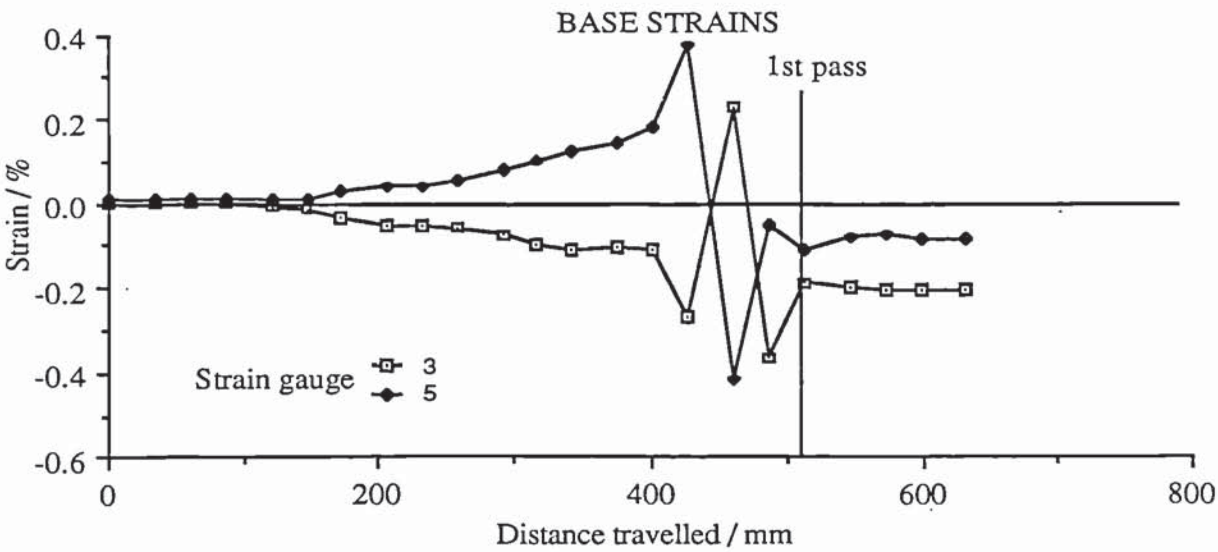
TEST 8



ROLL LOAD
Load cells
r
l
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Load / tonnes force
0
200
400
600
800
Distance travelled / mm

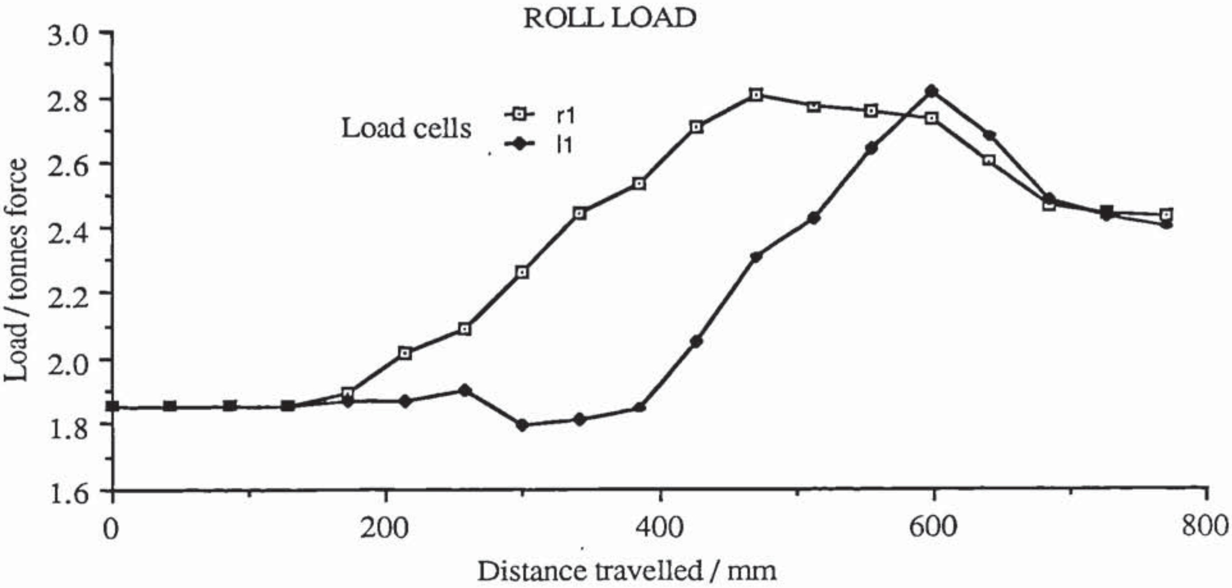


FLANGE STRAINS
Strain gauges
1
2
4
1st pass
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Strain / %
0
200
400
600
800
Distance travelled / mm

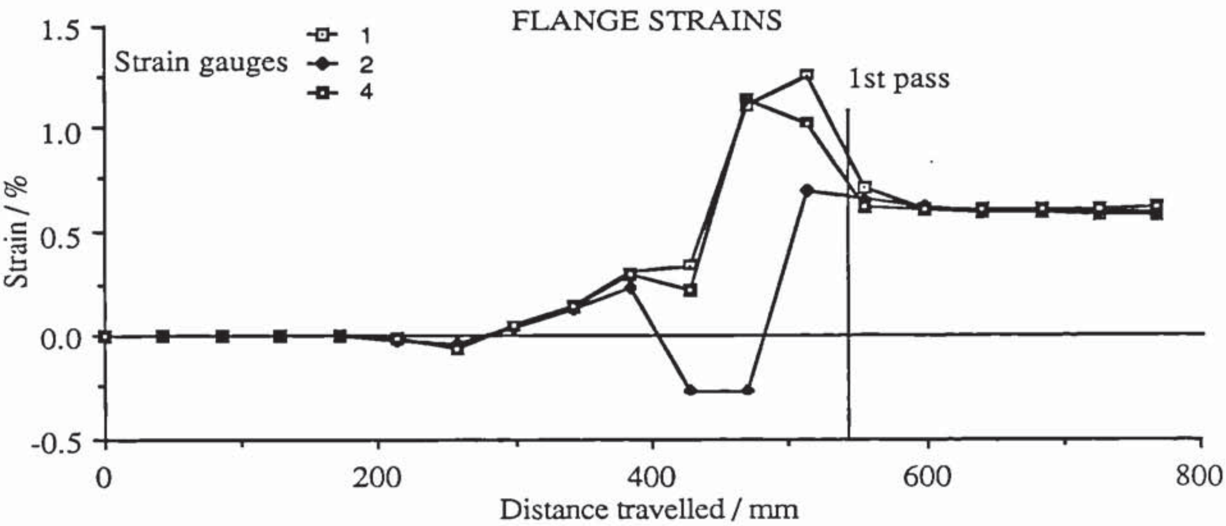


BASE STRAINS
1st pass
Strain gauge
3
5
0.4
0.2
0.0
-0.2
-0.4
-0.6
Strain / %
0
200
400
600
800
Distance travelled / mm

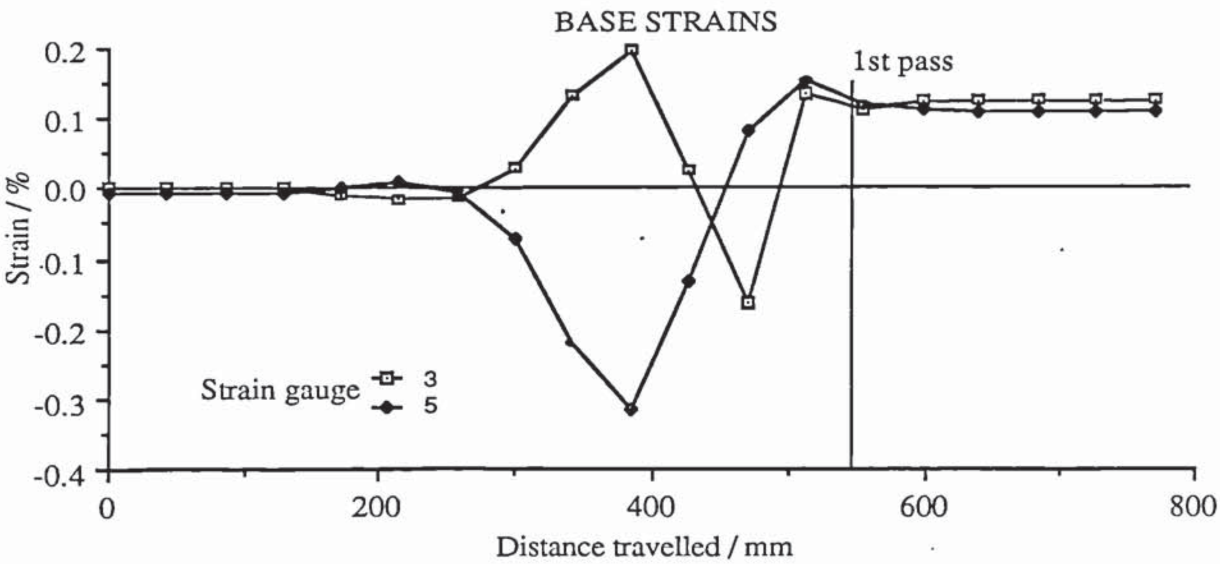
TEST 9



ROLL LOAD
Load cells
r1
l1
Load / tonnes force
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
0
200
400
600
800
Distance travelled / mm



FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
Distance travelled / mm



BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
200
400
600
800
Distance travelled / mm

7.3 GROUP (B) RESULTS

Description ; Two tests, rolling through a single pass with unbalanced left and right roll loads.

Roll Load

High left		High right	
10	-6.2 14.9	11	-7.7 13.7
-0.2	2.4	0.4	1.8

TABLE 7.2 GROUP (B) QUALITY MEASUREMENTS

It was expected that imbalance in the loads applied from the left and right pillar, would cause imbalance in the edge strains, that would result in a twisted section. The test show that, in fact, the two conditions give very similar quality and strain results.

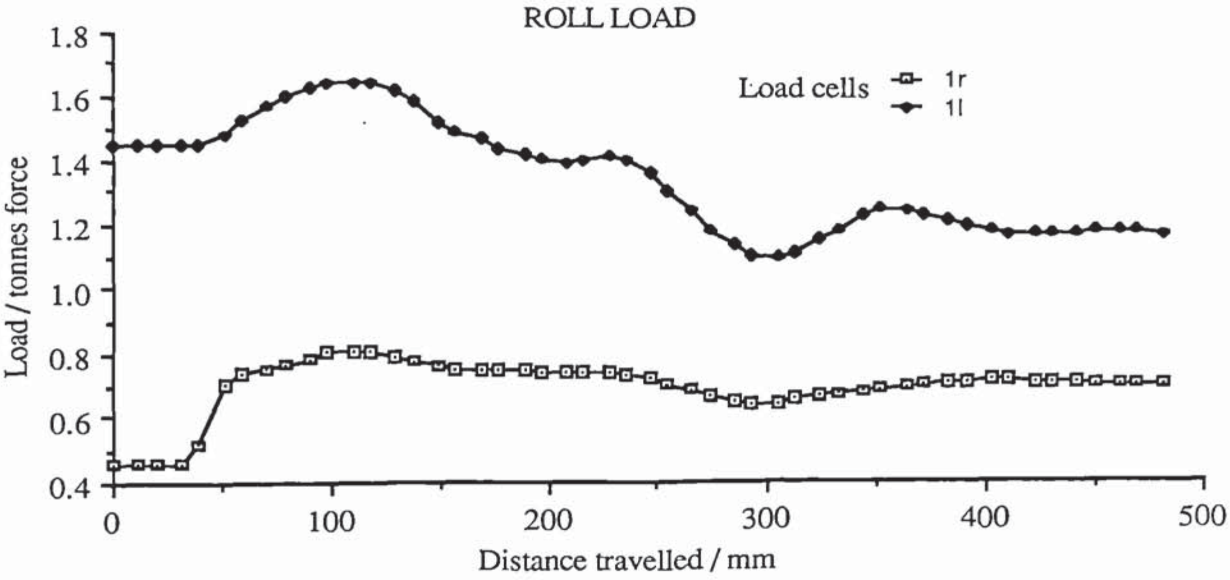
The main difference between the two tests is that with a high right load (Test 11) strain gauge 2 gives a compressive final strain and with a high left load (Test 10), the strain is tensile. Test 11 also has a larger amount of twist than Test 10, although both are in the same direction.

By increasing the right roll load, it would be expected that the right side of the section would be strained more than the left, so causing an anti-clockwise twist. Experimentally little effect is observed, with both loads giving a clockwise twist and the right loading giving slightly lower clockwise twist than the left.

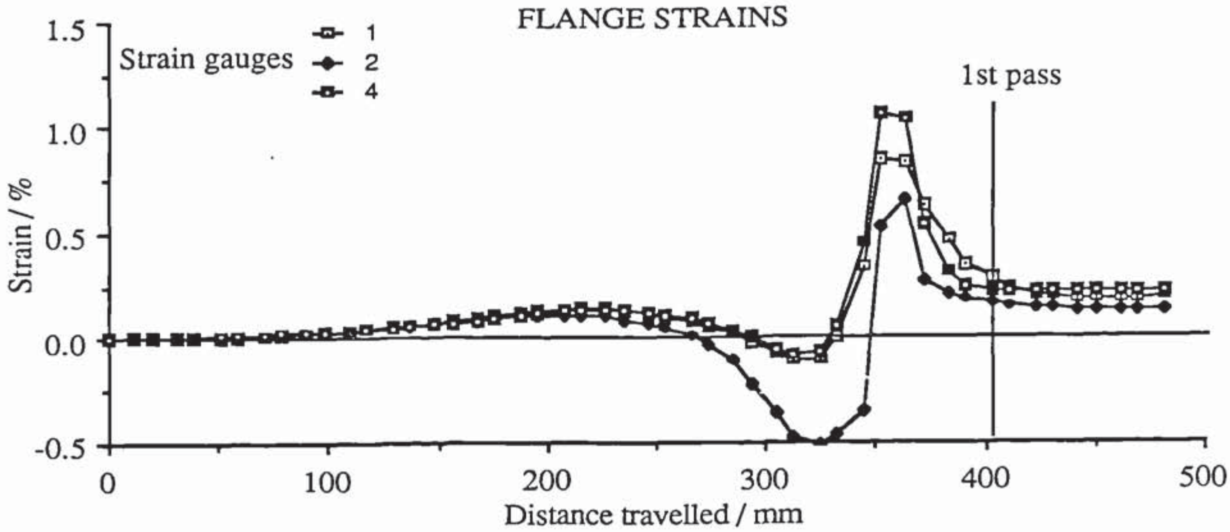
These results suggest that there may be parameters, other than balance of roll load, that have greater effect on twisting.

Again, both negative and positive bend angle error are present. With high left load, the left angle error is negative and with high right, positive. The right angle error remain positive and of higher value in both cases.

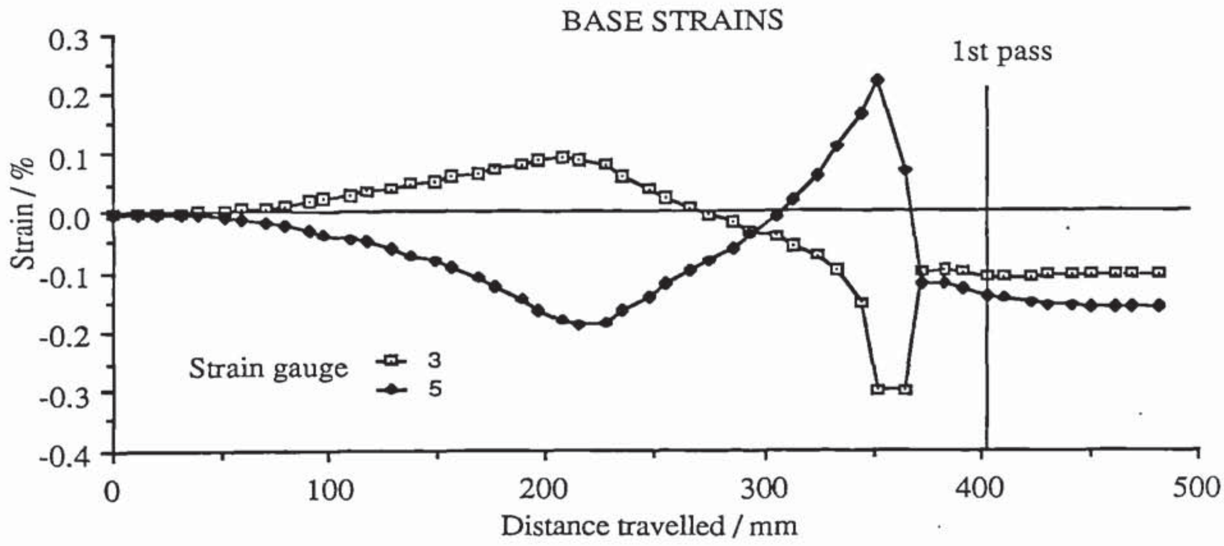
TEST 10



ROLL LOAD
Load cells
1r
1l
Load / tonnes force
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
100
200
300
400
500
Distance travelled / mm

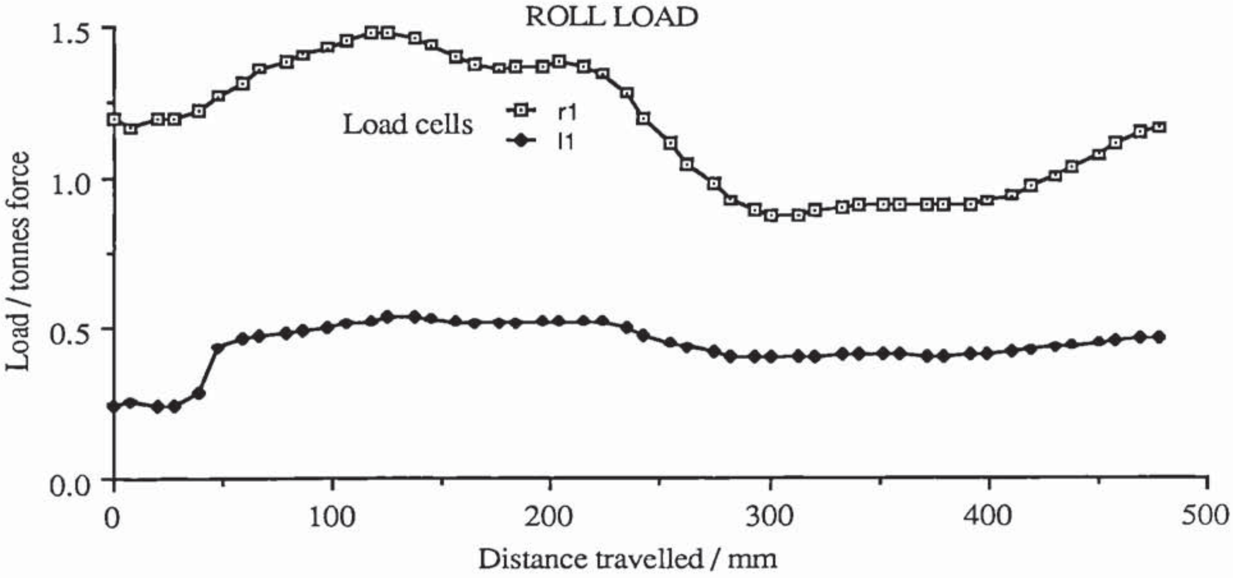


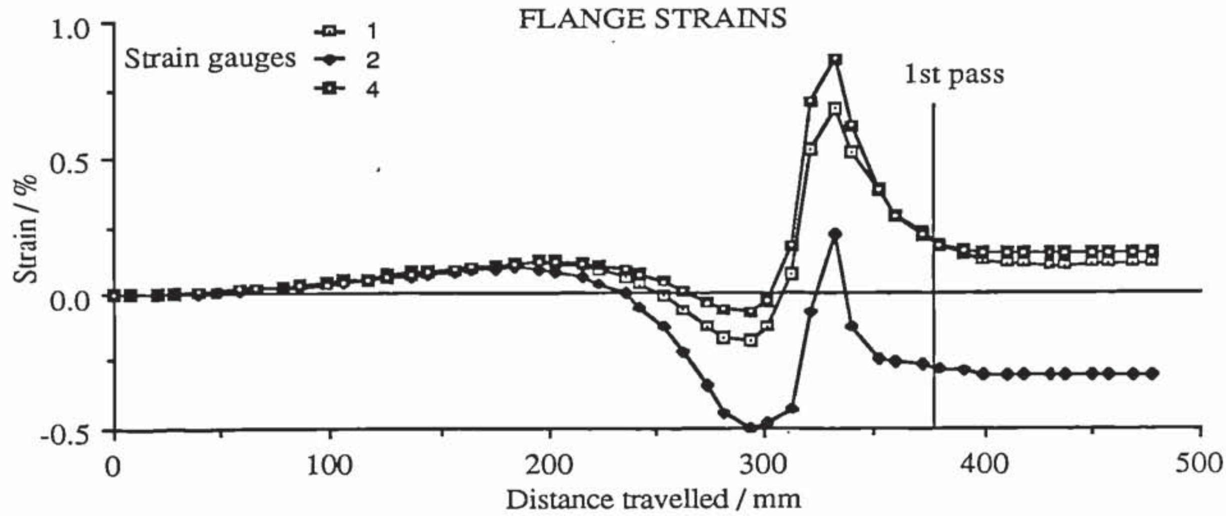
FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
100
200
300
400
500
Distance travelled / mm

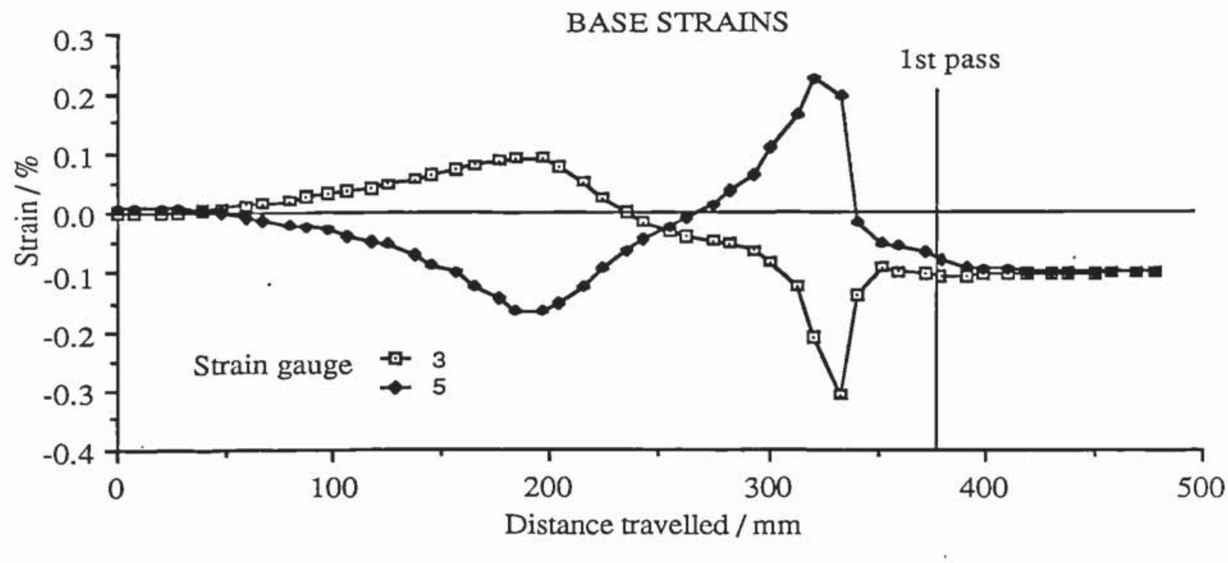


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
100
200
300
400
500
Distance travelled / mm

TEST 11


ROLL LOAD
Load cells
r1
l1
Load / tonnes force
1.5
1.0
0.5
0.0
0
100
200
300
400
500
Distance travelled / mm


FLANGE STRAINS
Strain gauges
1
2
4
1st pass
Strain / %
1.0
0.5
0.0
-0.5
0
100
200
300
400
500
Distance travelled / mm


BASE STRAINS
1st pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
100
200
300
400
500
Distance travelled / mm

7.4 GROUP (C) RESULTS

Description ; seven tests rolling through two passes, with a long inter-pass distance, using three roll speeds and three roll loads.

		Roll Load		
		low	med	high
Roll speed	low		**12** -41.5 -11.4 -0.5 -1.0	**13** 15.9 -2.2 0.2 -0.4
	med	**14** -23.3 -7.8 0.1 0.5	**15** -39.3 -2.6 -0.3 -0.3	**16** 206.5 -4.1 -0.2 -0.6
	high		**17** -52.7 -2.3 0.1 -0.3	**18** 16.4 -4.7 -0.5 -0.7

TABLE 7.3 GROUP (C) QUALITY MEASUREMENTS

These tests were the first set of two pass tests. Generally the first pass shows repeated strain features of the single pass tests, 1-11. A flange strain of about 0.2% is introduced at the first pass and then maintained after exit from the second. The peak flange strain at the second pass is lower than the first pass, averaging 0.5%. Also the flange strain profile through the second pass does not dip into compressive strain and the region of peaking is smaller than that of the first pass. Both peaks occur at about 45 mm before the associated pass.

Roll load and roll speed appear to have little effect on the flange strain profiles.

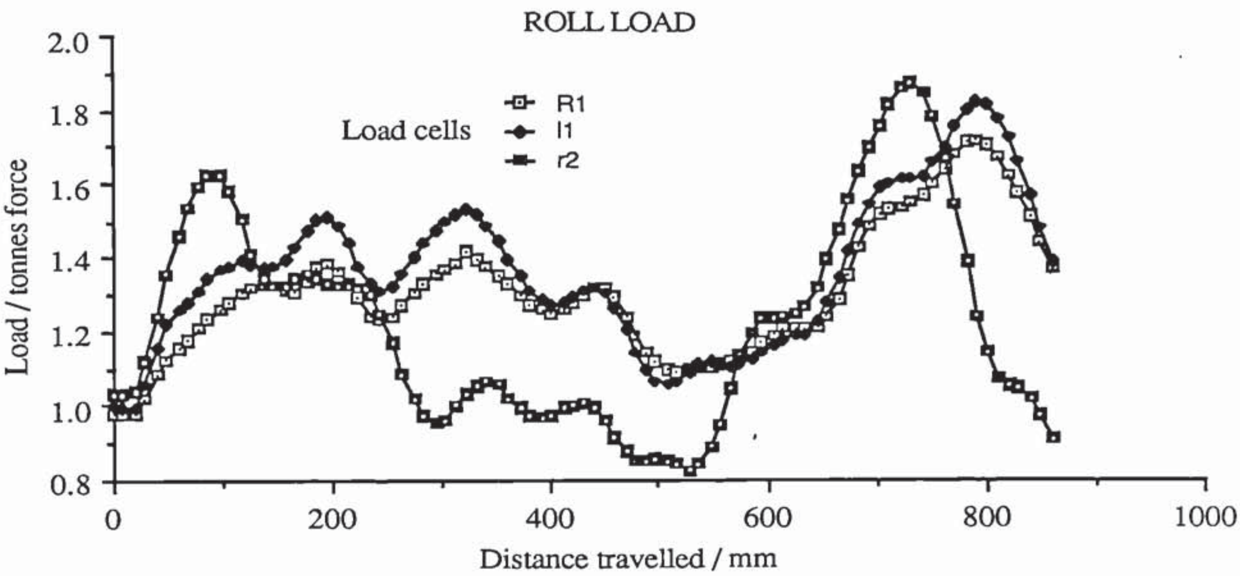
Base strain profiles for the first pass are similar to the single pass profiles. Low roll load under 1 tf again causes the overall base strain to be compressive. Higher loads cause tensile straining up to 0.2%. The bottom base strain is the more tensile. On approach to the second pass, the strain profile follows a similar path to the first pass but with a sudden jump in strain, in the case of the top gauge into the compressive region and into the tensile region for the bottom gauge. It is likely that this strain profile is also followed at the first pass but, due to the resolution of the graph, the detail is missed. Certainly group (A) graphs on a single pass show the characteristic strain jump.

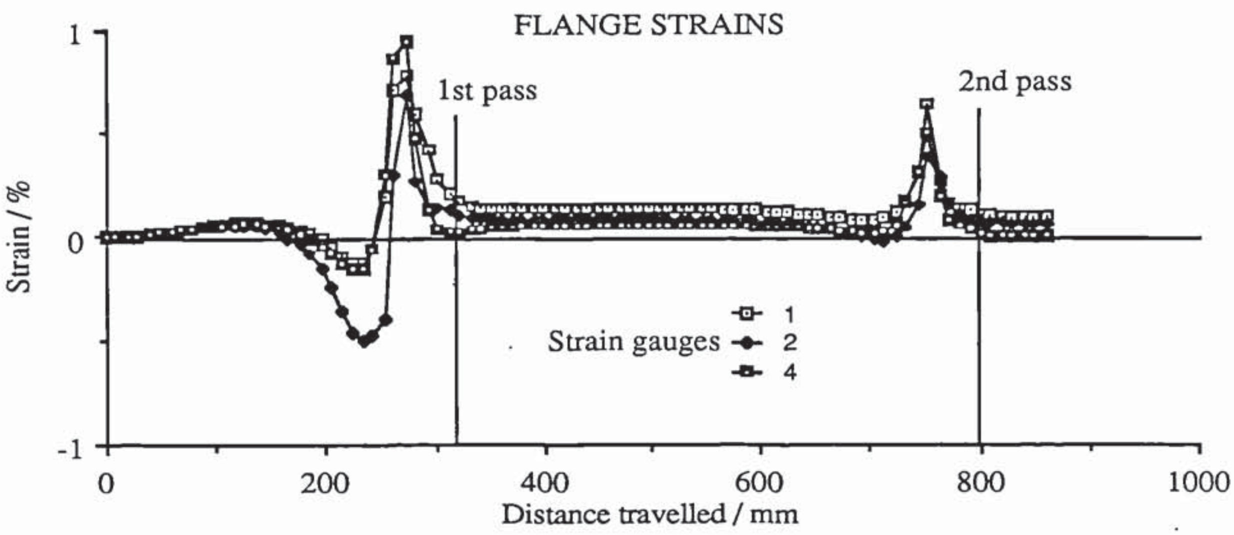
The residual strain on leaving the second pass is higher than that of the strain between passes. This implies that the second pass adds a further tensile strain to that created by the first pass. The added strain is greatest when the roll pressure at the second pass is high. Strains of about 0.2% are added at the maximum load. Again the bottom strain is higher than the top strain, indicating the likelihood of positive bow in the strip.

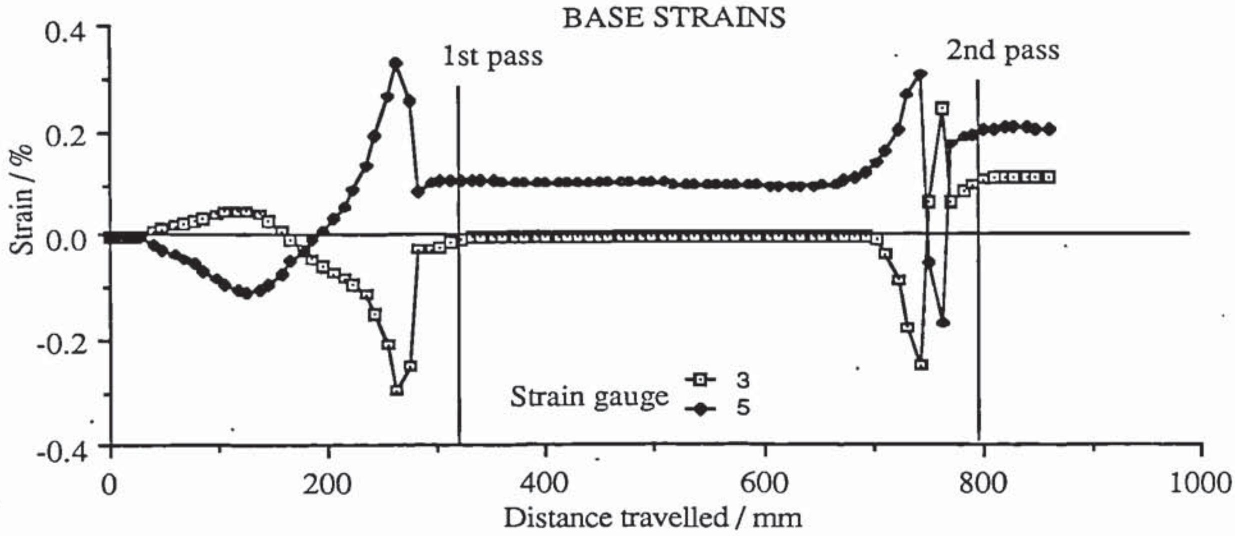
Looking at table 7.3, it can be seen that only when the roll load is high is the strip bowed in the positive direction. The addition of a second pass reduces the amount of bow and twist.

Angle error is generally larger and negative for the right side than the left. The left error can be negative or positive but is generally of less extremes than in the one pass tests.

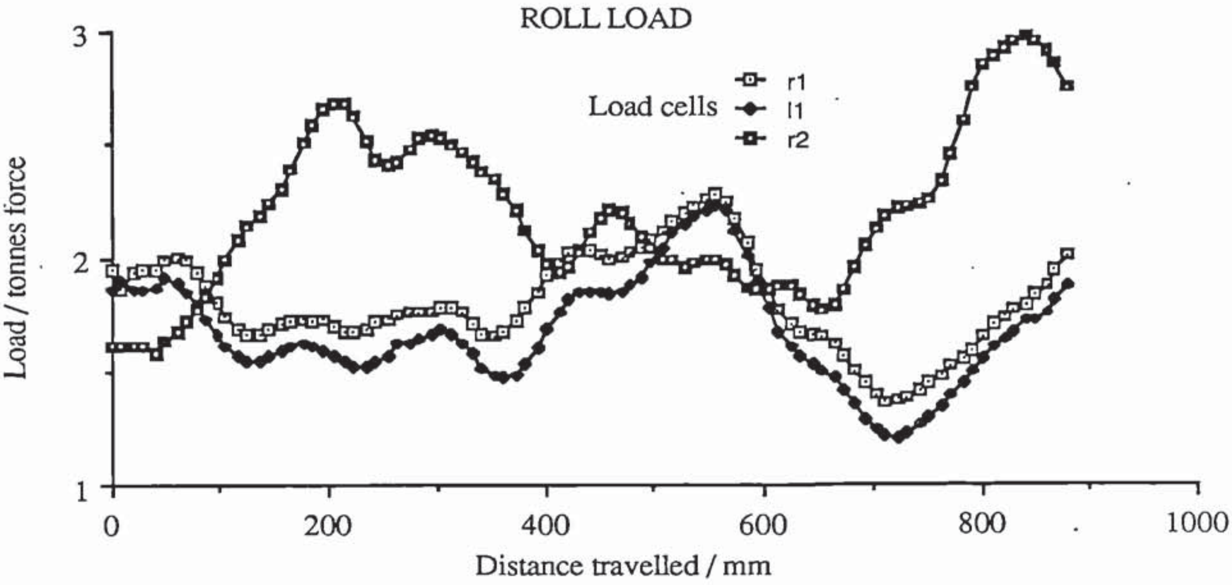
TEST 12

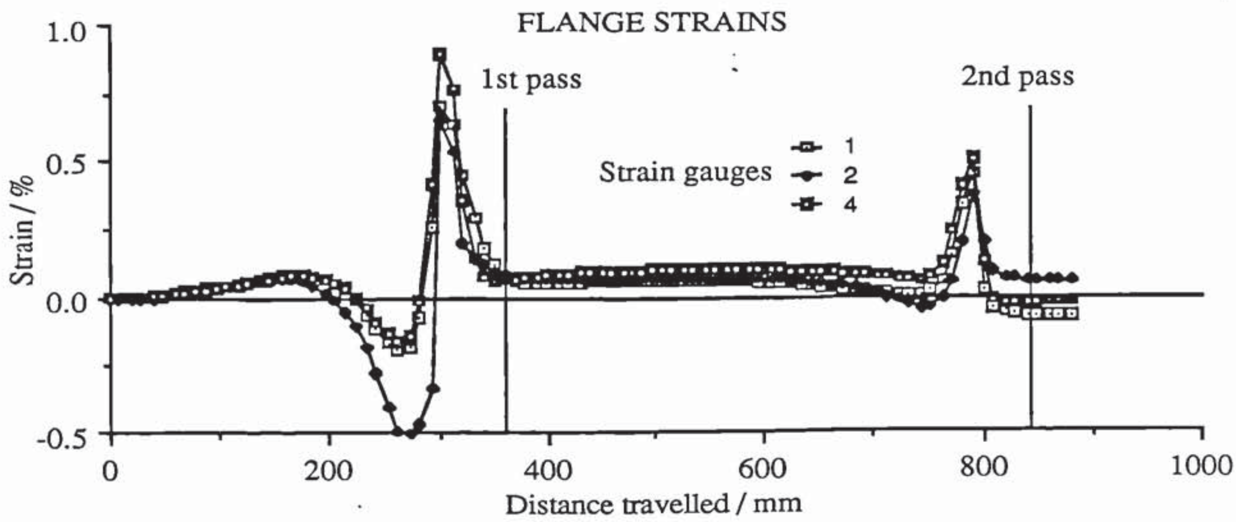

ROLL LOAD
Load cells
R1
l1
r2
Load / tonnes force
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0
200
400
600
800
1000
Distance travelled / mm

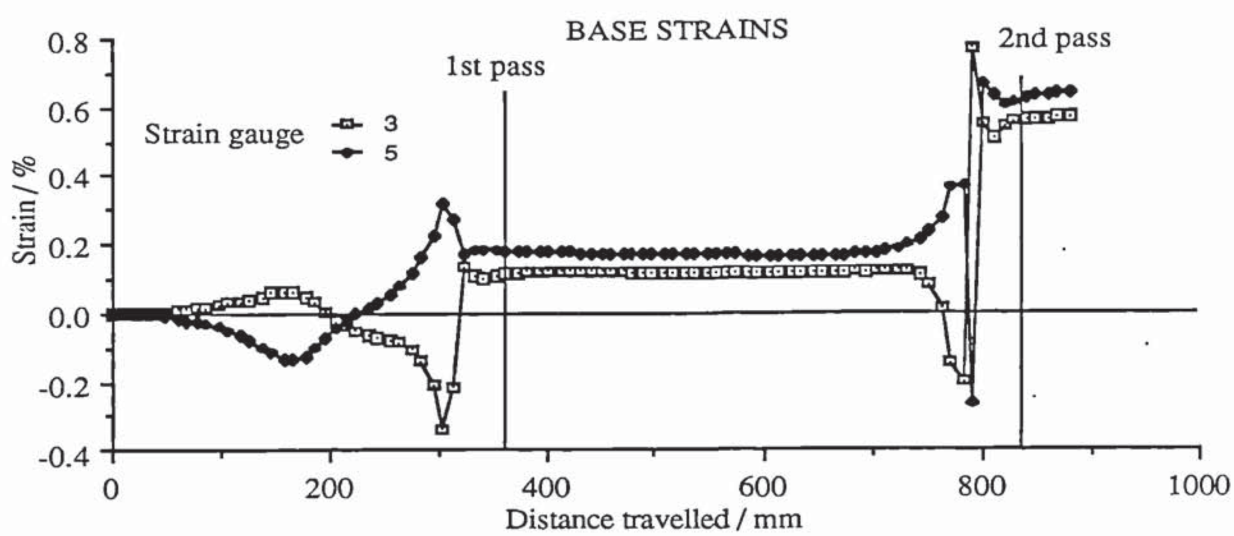

FLANGE STRAINS
1st pass
2nd pass
Strain gauges
1
2
4
Strain / %
1
0
-1
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

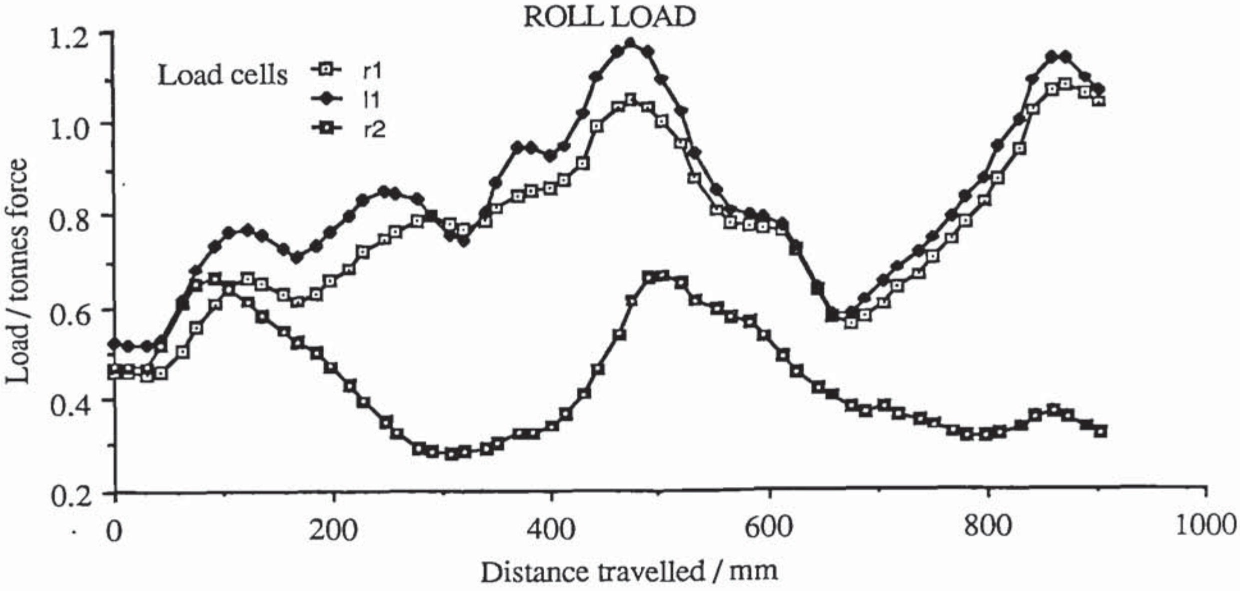
TEST 13

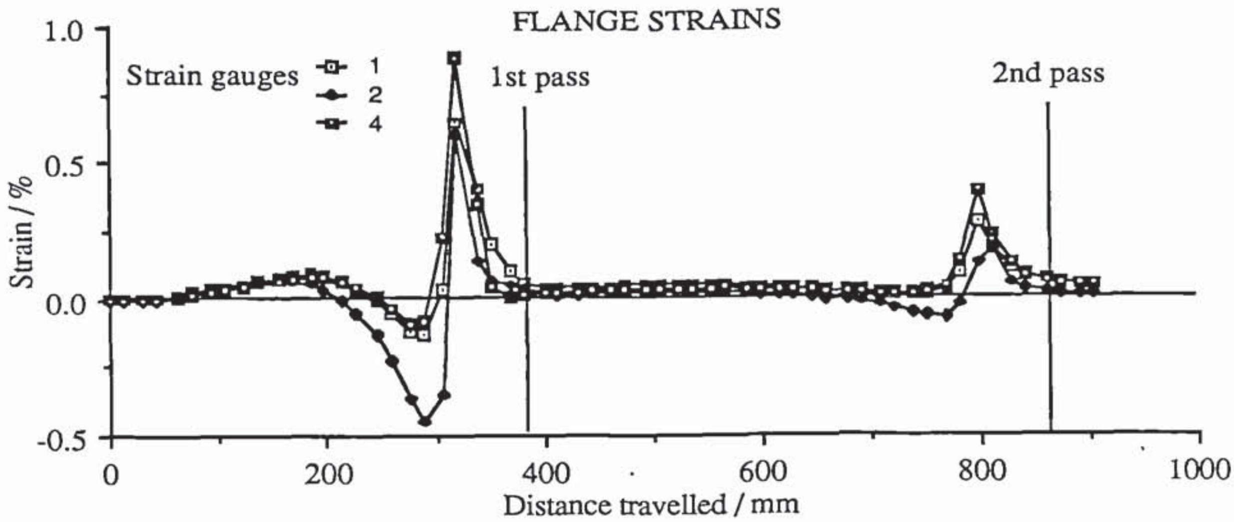

ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
3
2
1
0
200
400
600
800
1000
Distance travelled / mm

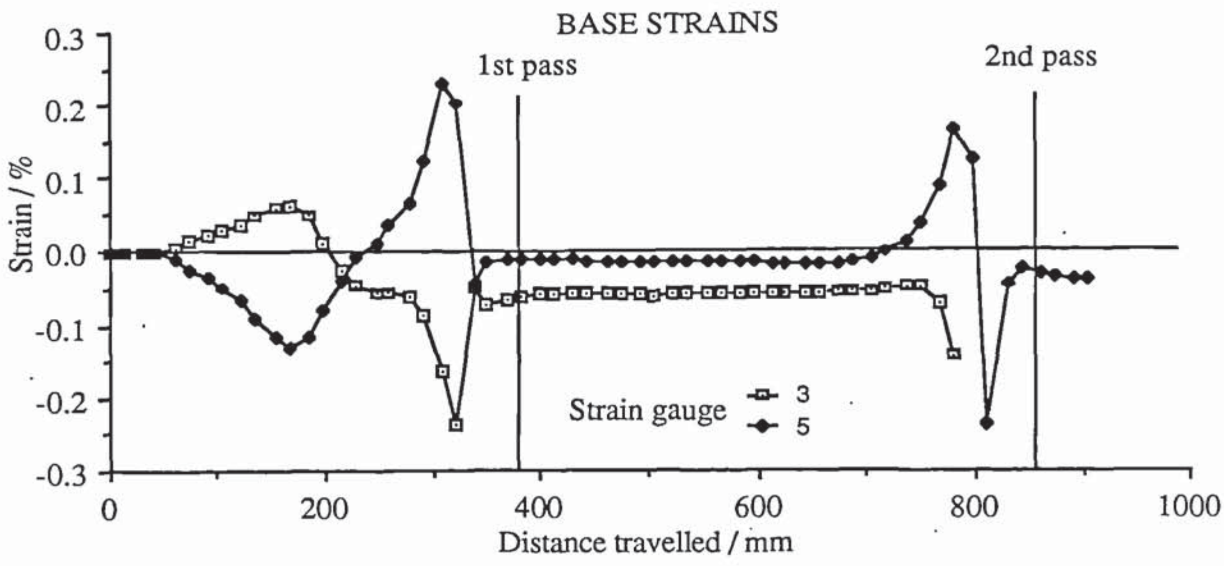

FLANGE STRAINS
1st pass
2nd pass
Strain gauges
1
2
4
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

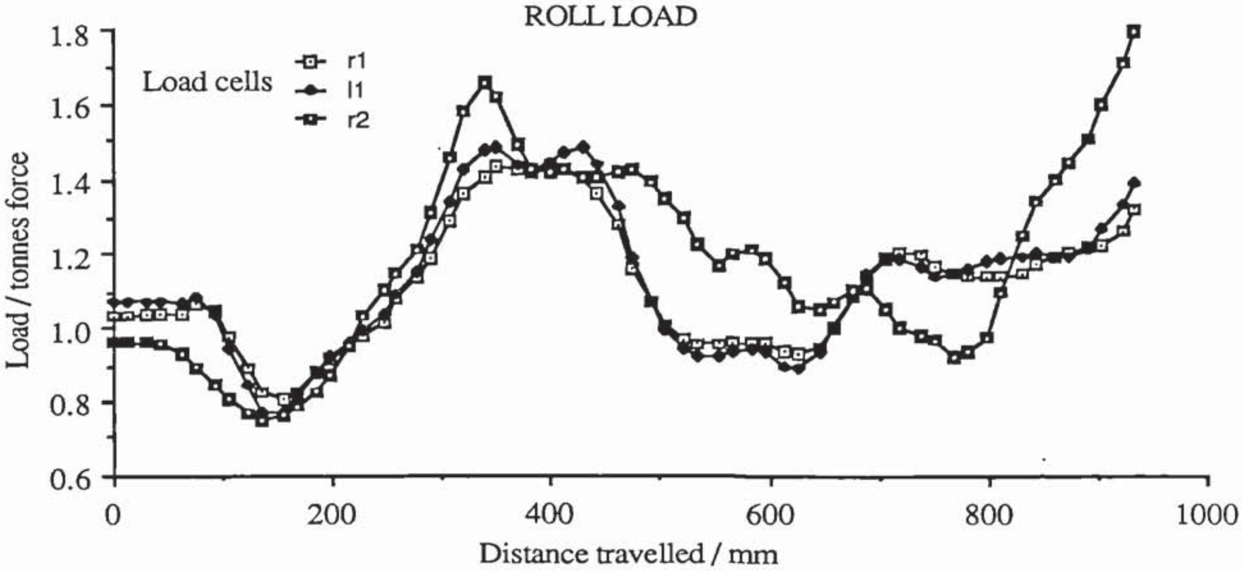
TEST 14


ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
1.2
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
Distance travelled / mm

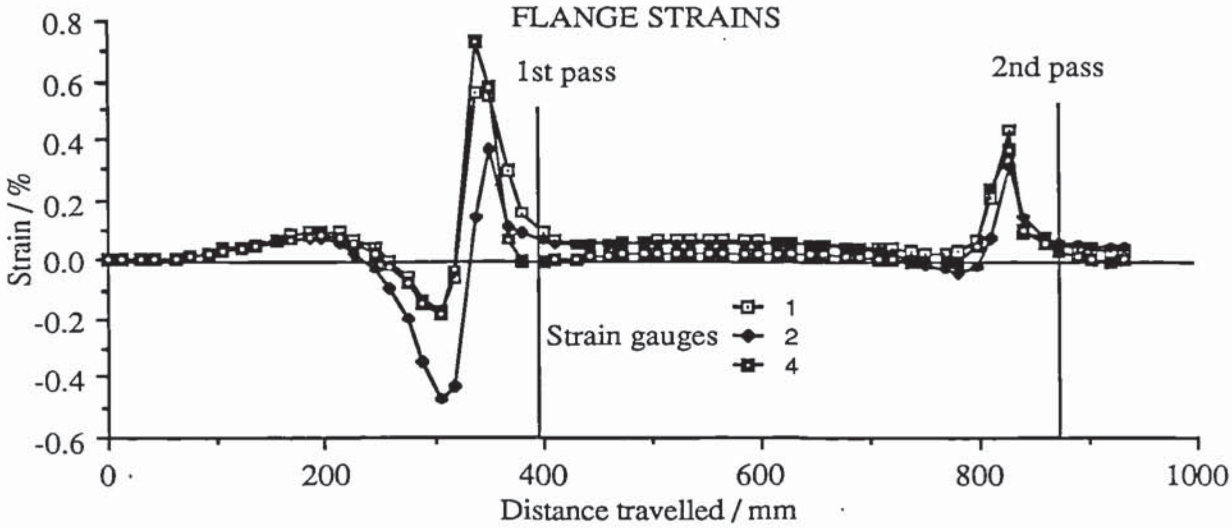

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
1000
Distance travelled / mm

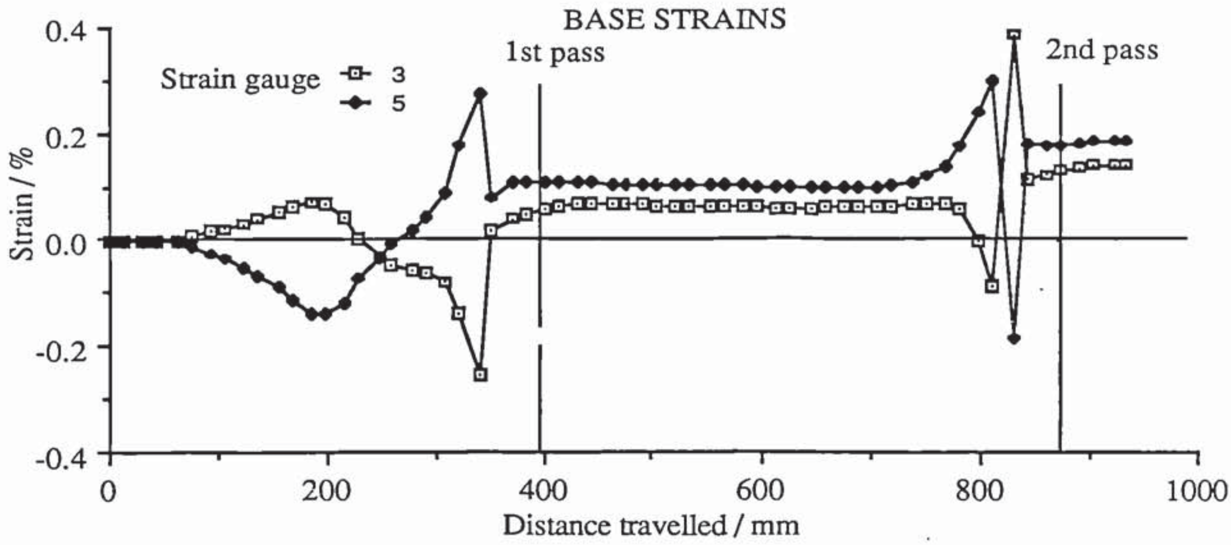
TEST 15



ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
1000
Distance travelled / mm

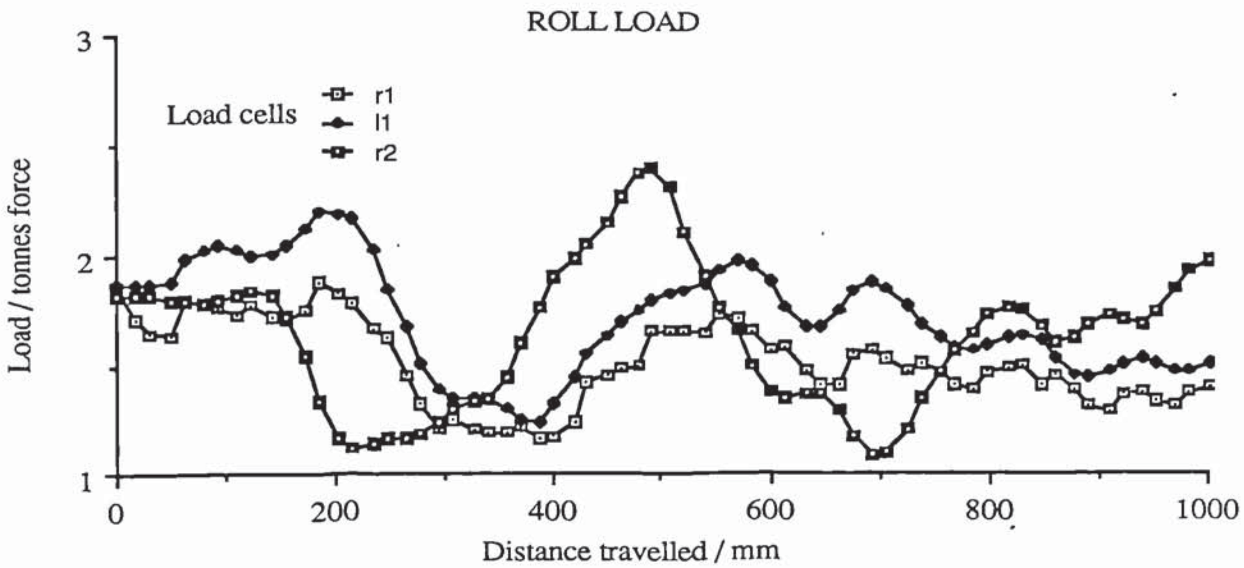


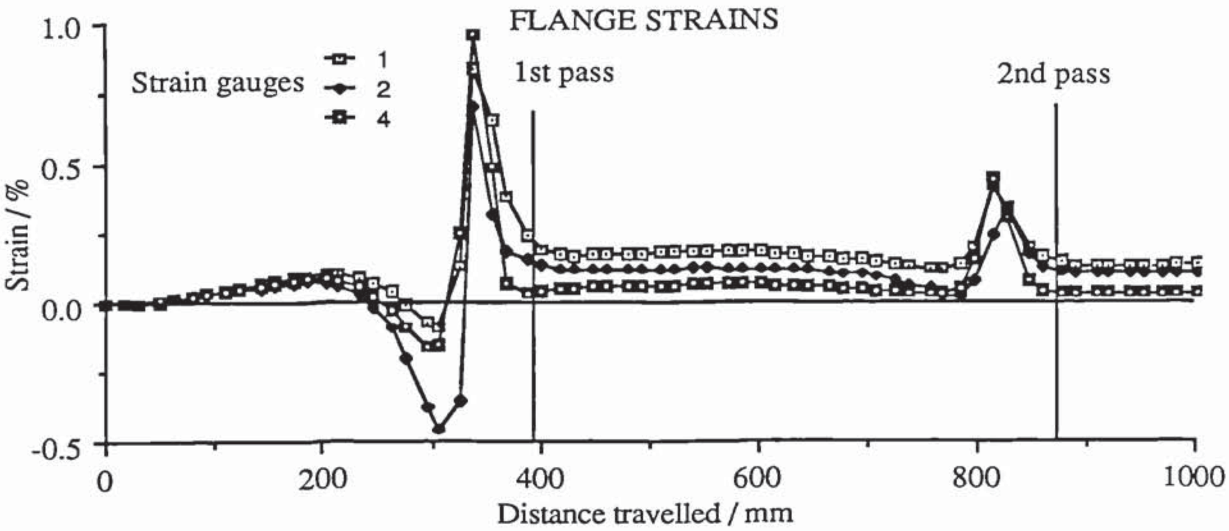
FLANGE STRAINS
1st pass
2nd pass
Strain gauges
1
2
4
Strain / %
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
Distance travelled / mm

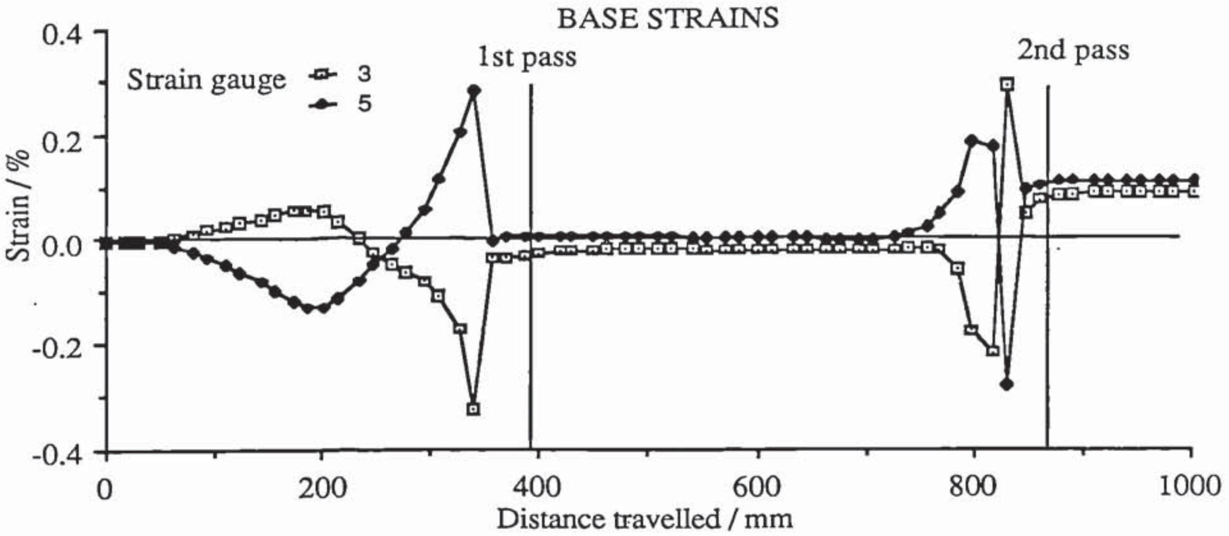


BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

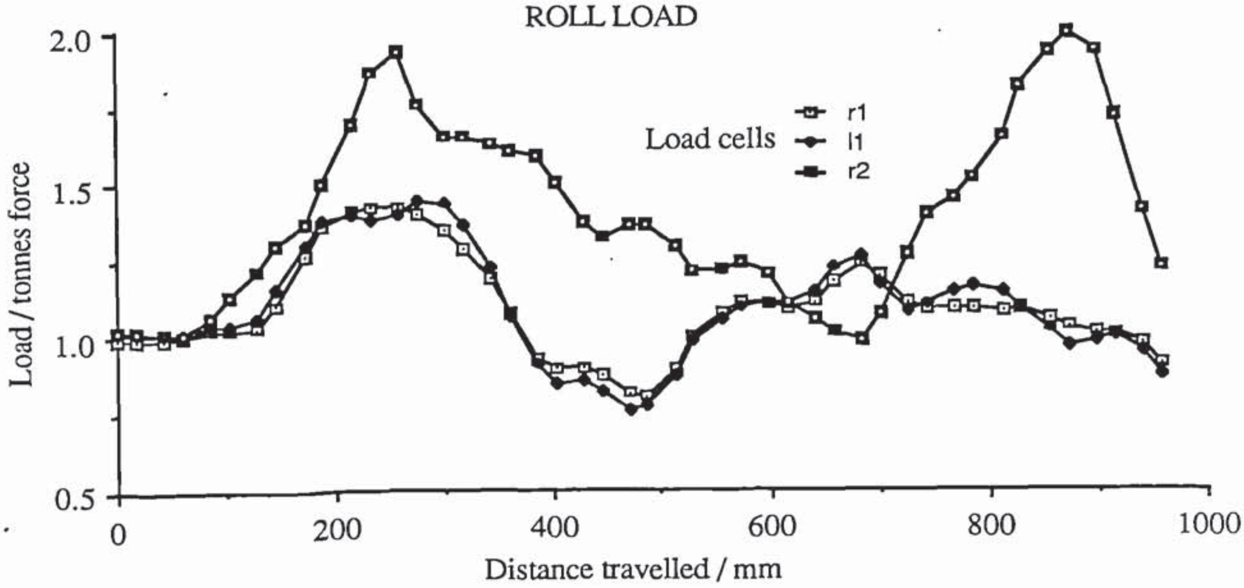
TEST 16

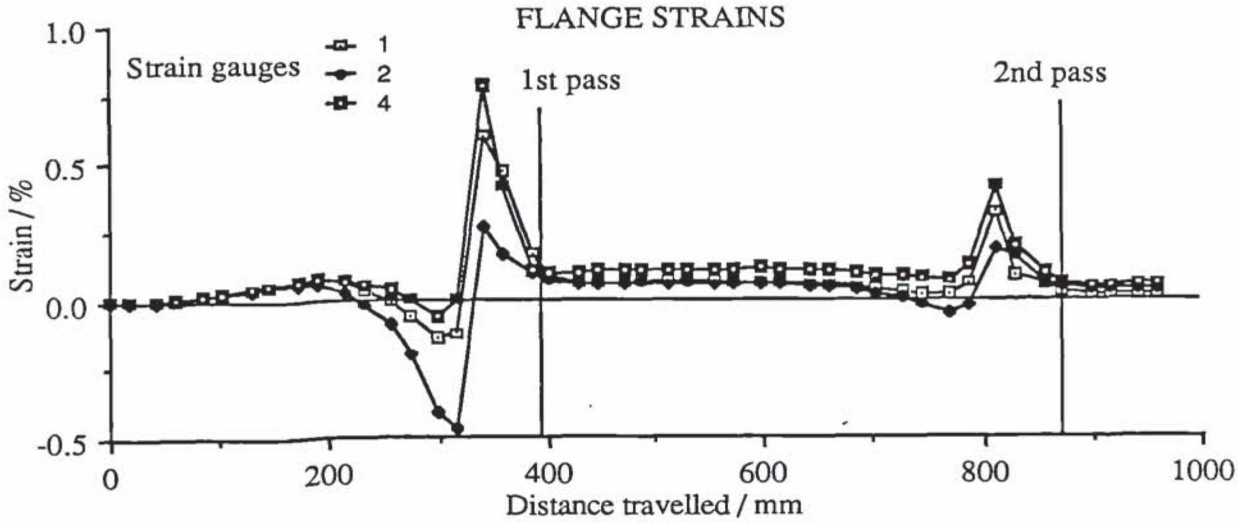

ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
3
2
1
0
200
400
600
800
1000
Distance travelled / mm

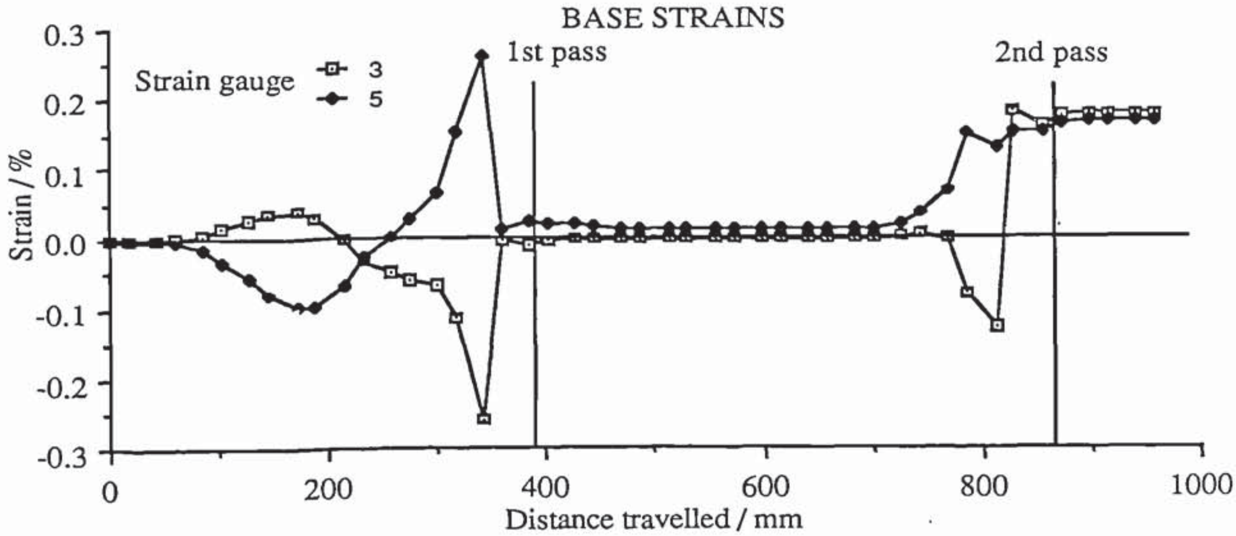

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

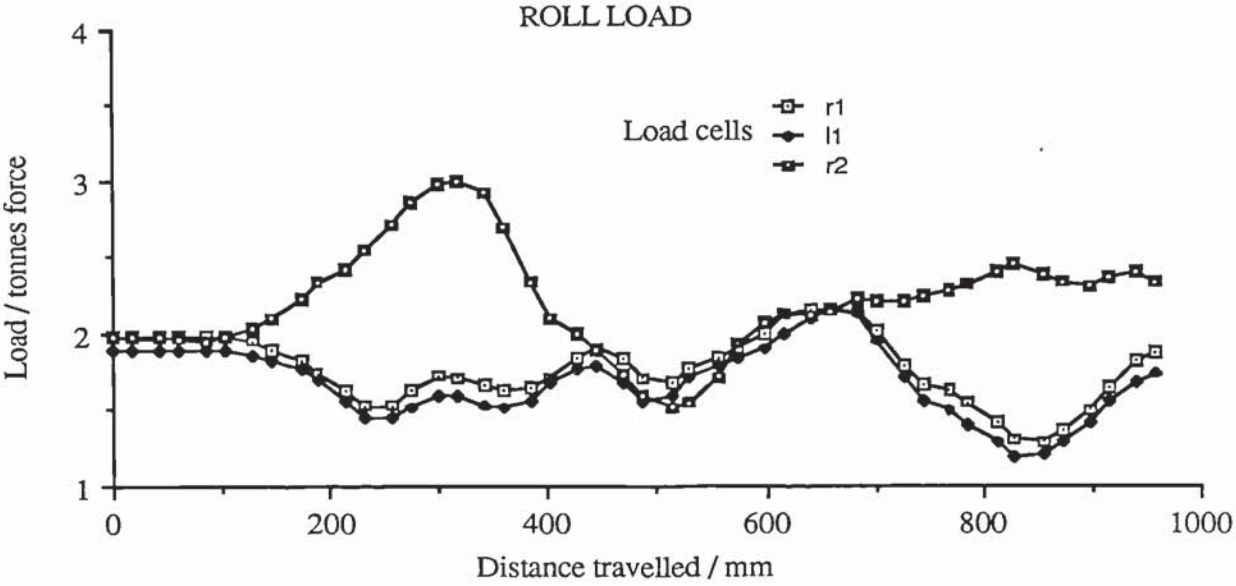
TEST 17


ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
2.0
1.5
1.0
0.5
0
200
400
600
800
1000
Distance travelled / mm

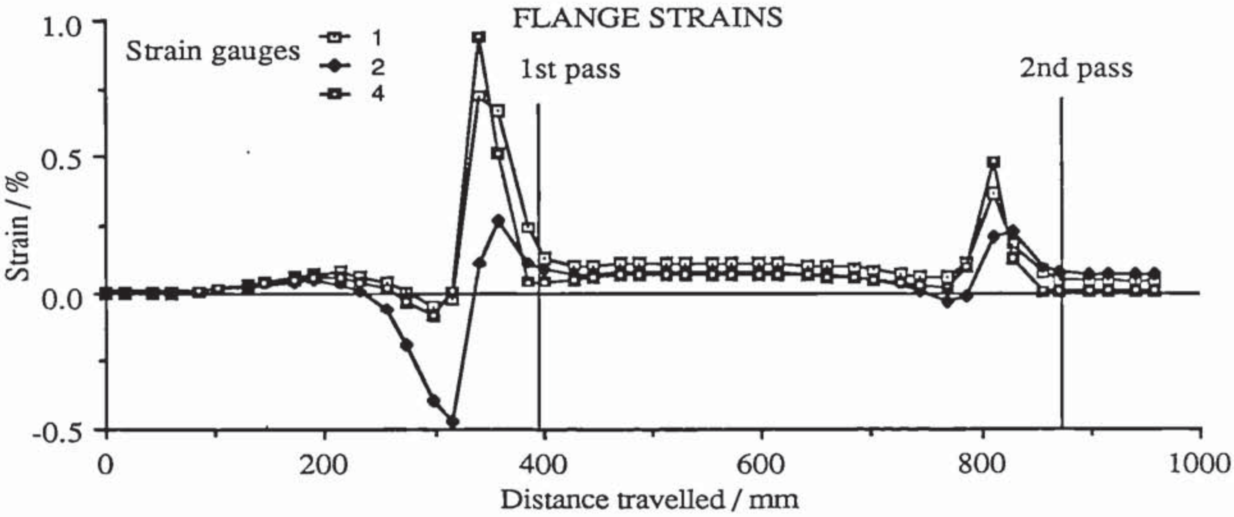

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
1000
Distance travelled / mm

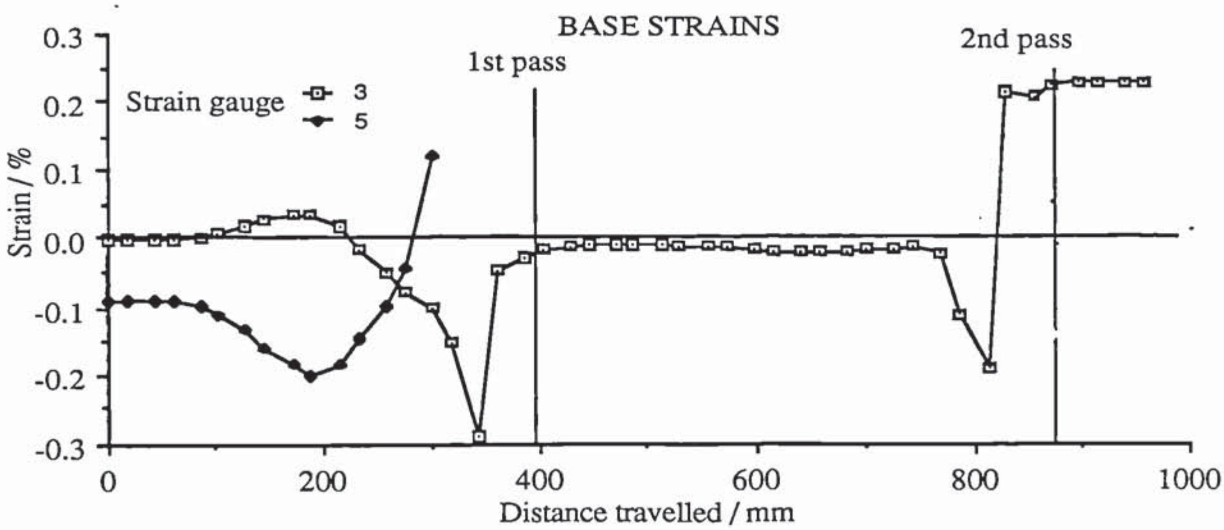
TEST 18



ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
4
3
2
1
0
200
400
600
800
1000
Distance travelled / mm



FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm



BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
1000
Distance travelled / mm

7.5 GROUP (D) RESULTS

Description ; three test rolling through two passes, with a short inter-pass distance, using three roll loads.

Roll Load

low		med		high	
19	-6.8 -1.6	**20**	-15.2 -5.3	**21**	-22.1 -3.1
-1.5	-0.6	-0.9	-1.6	-1.3	-0.5

TABLE 7.4 GROUP (D) QUALITY MEASUREMENTS

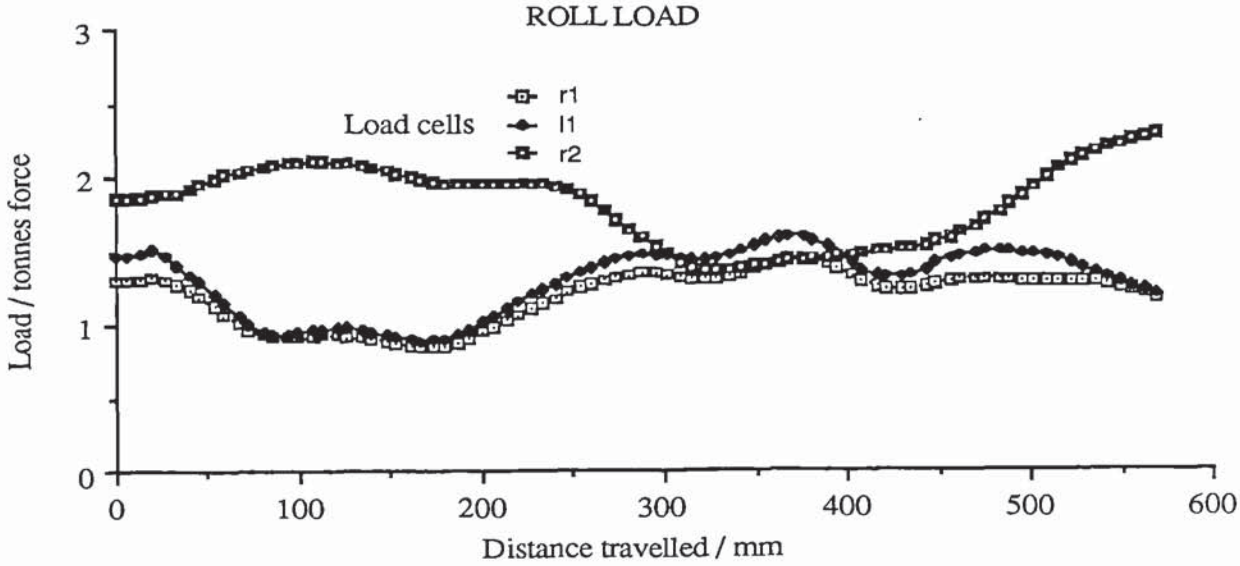
These tests were designed to show the effects of reducing inter-pass distance. The flange strains between passes and residual strains are notably higher than in the long inter-pass distance tests (group C). They are generally strained to 0.5%.

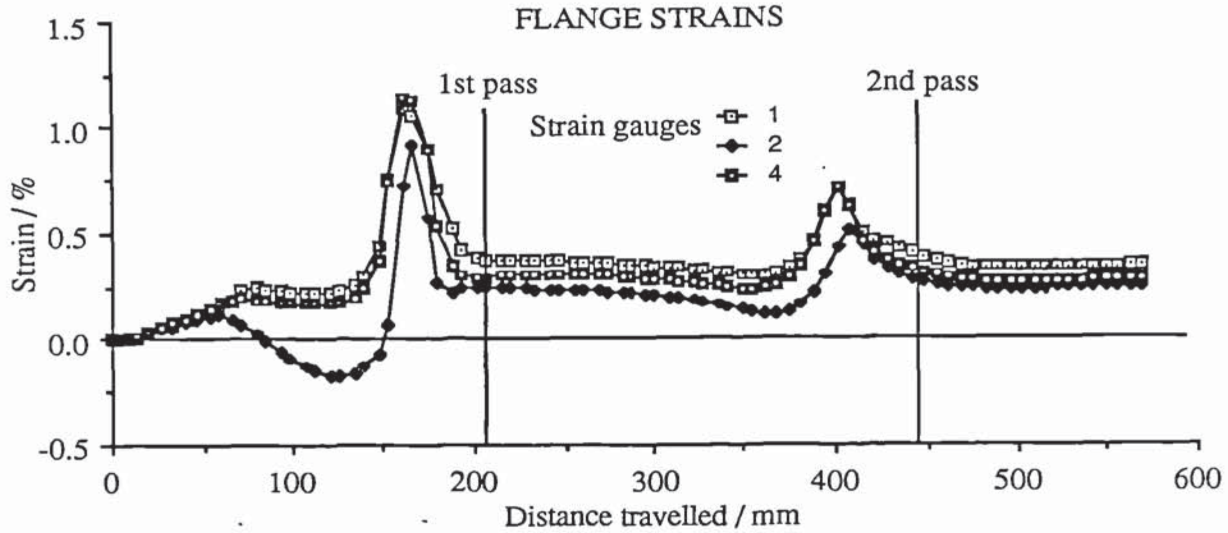
Straining in the base is similar to the profile in the group C tests however, the residual strain and strain between passes is tensile on the bottom of the strip and compressive on the top in tests 20 and 21. The level of residual strain and strain between passes are equal, with a maximum of 0.2%.

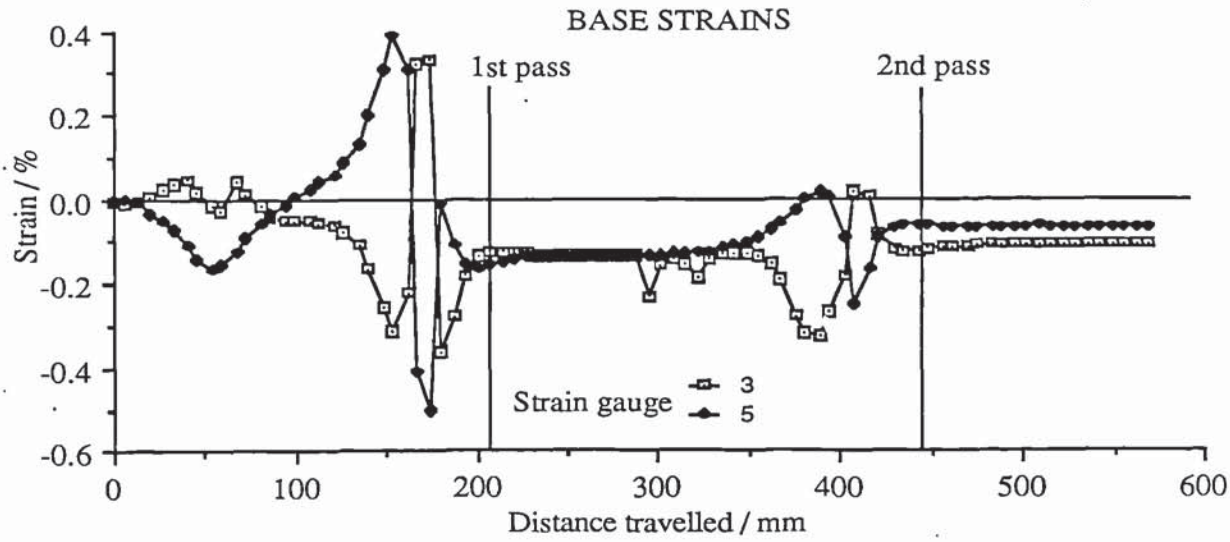
Bowing is considerably increased in this group of tests, compared with group C. The tensile straining in the top of the base and compression in the bottom is compatible with the negative bow shown. Twist remains at approximately the same level in groups C and D.

The reduction of inter-pass distance does appear to affect the straining and quality of the section, in this case reducing the section quality by increasing bow.

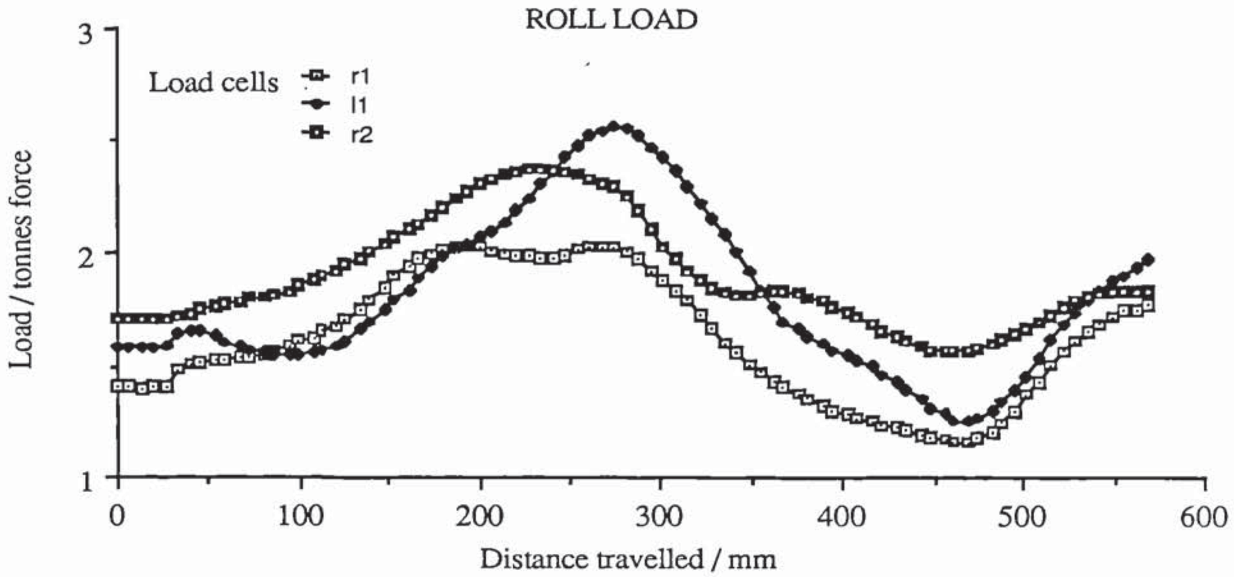
TEST 19

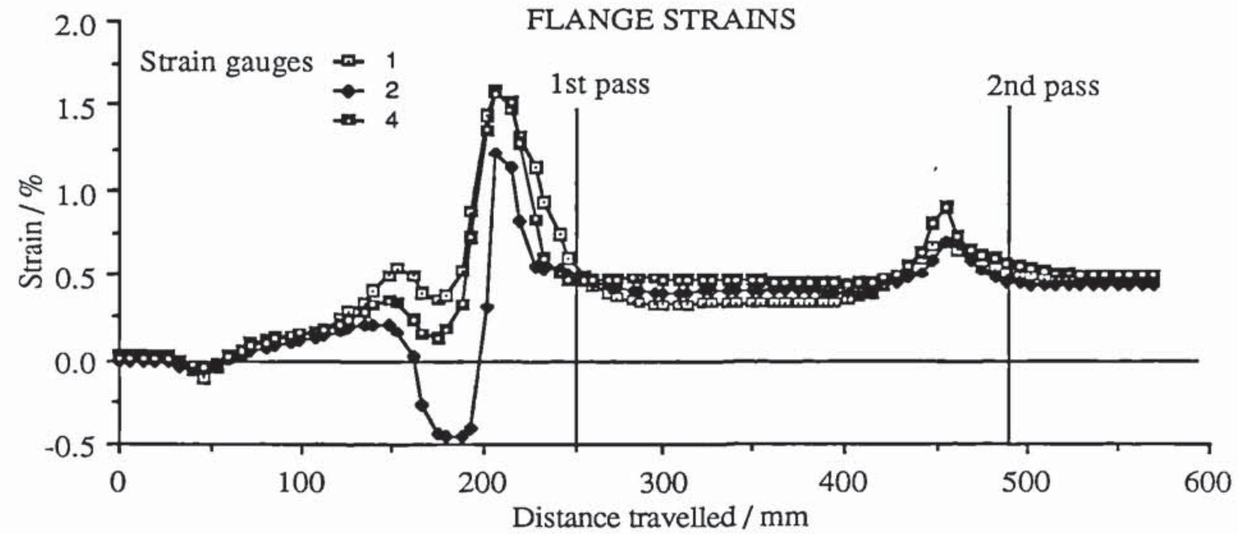

ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
3
2
1
0
0
100
200
300
400
500
600
Distance travelled / mm

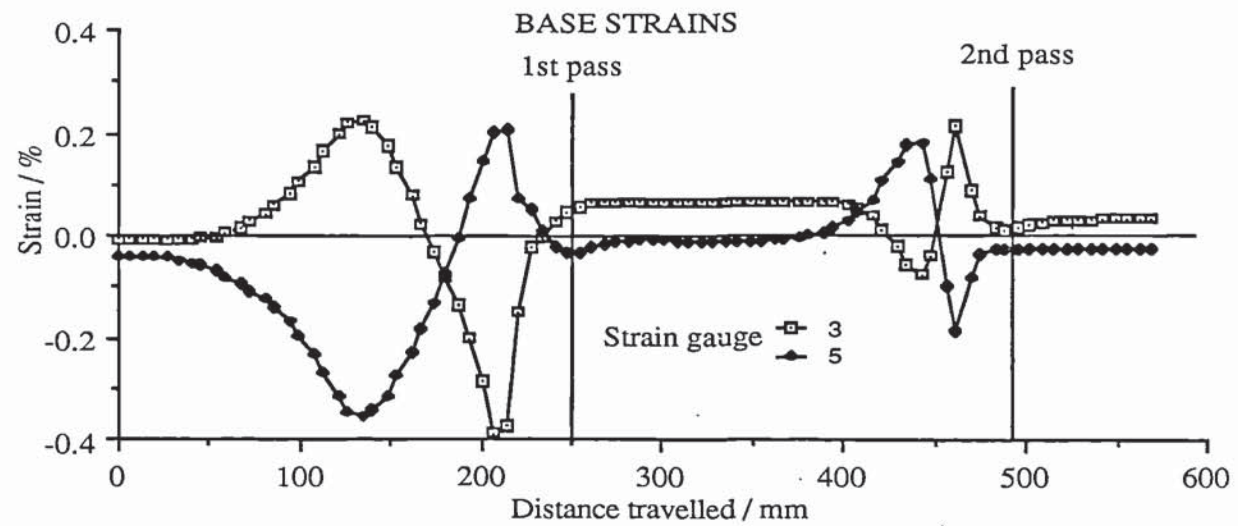

FLANGE STRAINS
1st pass
2nd pass
Strain gauges
1
2
4
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
100
200
300
400
500
600
Distance travelled / mm

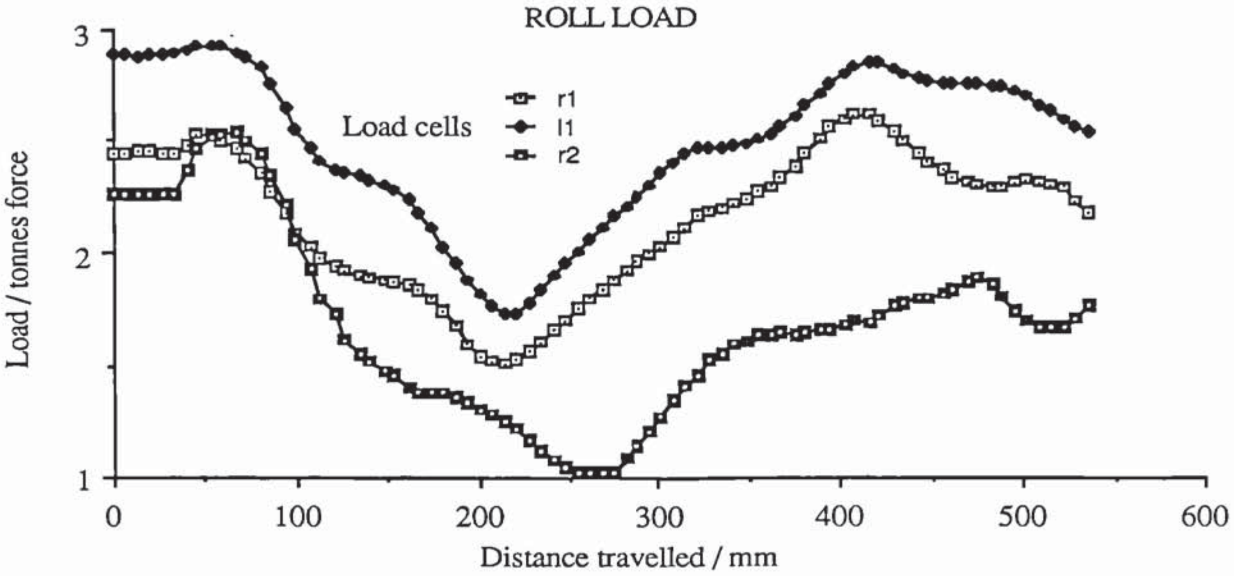

BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
100
200
300
400
500
600
Distance travelled / mm

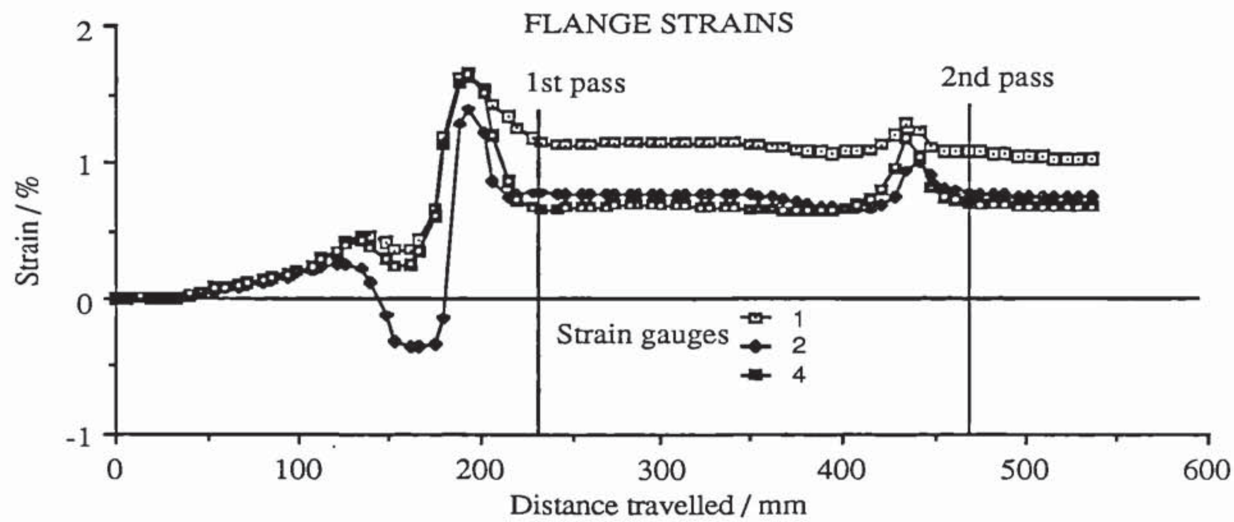
TEST 20

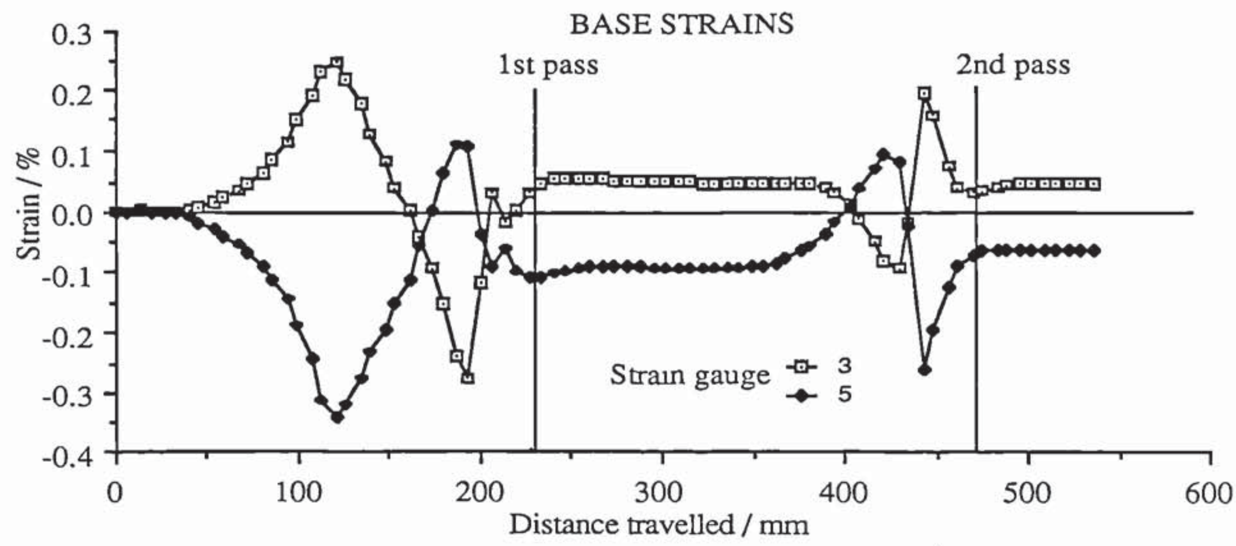

ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
3
2
1
0
100
200
300
400
500
600
Distance travelled / mm


FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
Strain / %
2.0
1.5
1.0
0.5
0.0
-0.5
0
100
200
300
400
500
600
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
100
200
300
400
500
600
Distance travelled / mm


ROLL LOAD
Load cells
r1
l1
r2
Load / tonnes force
3
2
1
0
100
200
300
400
500
600
Distance travelled / mm


FLANGE STRAINS
1st pass
2nd pass
Strain gauges
1
2
4
Strain / %
2
1
0
-1
0
100
200
300
400
500
600
Distance travelled / mm

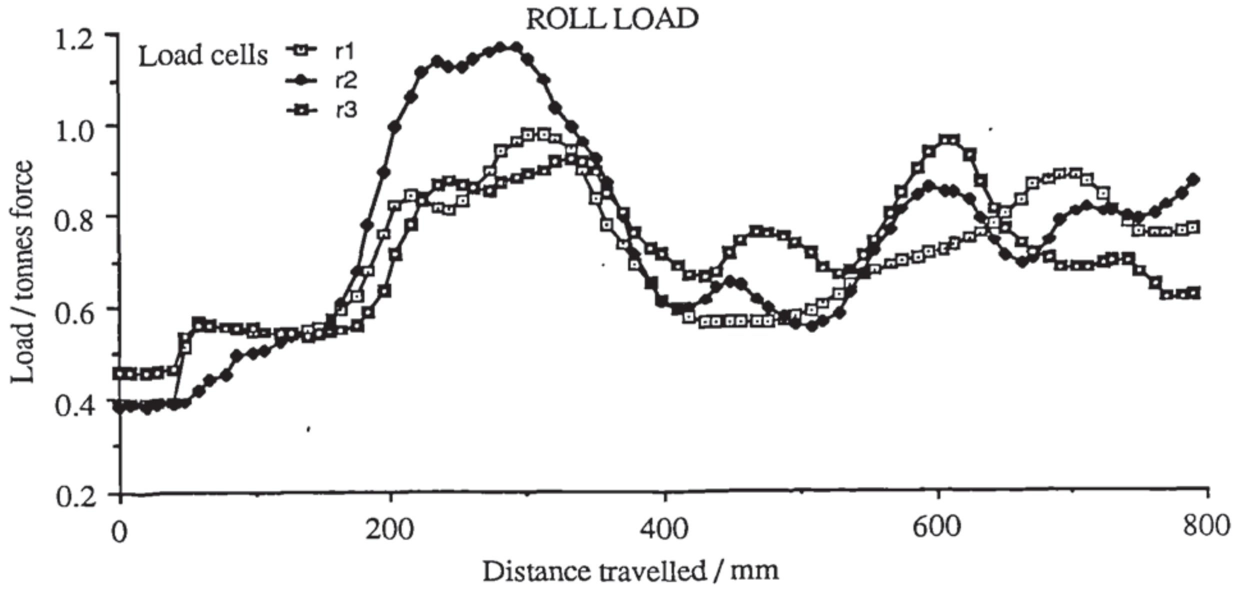

BASE STRAINS
1st pass
2nd pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
100
200
300
400
500
600
Distance travelled / mm

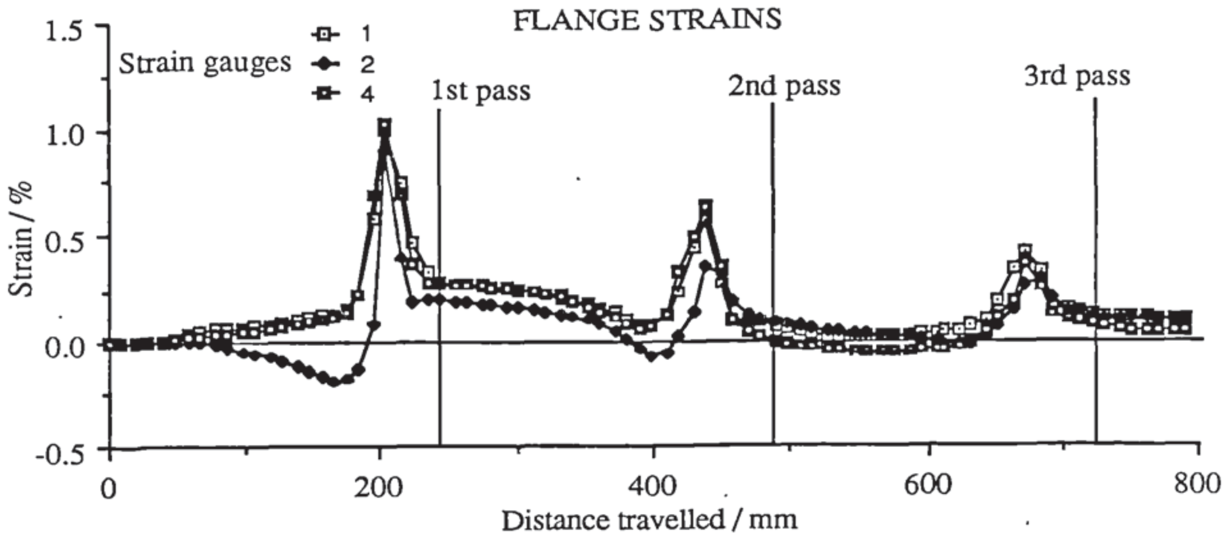
Base strain profiles follow the patterns of previous tests. Tests 22, 24, 25 and 27 have a more tensile bottom base strain than top, and vice versa for tests 23 and 26. The higher the roll load the more tensile the base strain. Where the loading is low (e.g. Test 22), the final base strain is compressive and, where high, tensile. In tests where the roll loading is even at each pass there is a progressive increase in tensile strain (e.g. Test 27). If the loading at a pass A is lower than the preceding pass B, then there is a tendency for the strain to become more compressive on exit from A, than B (e.g. second and third pass of test 26).

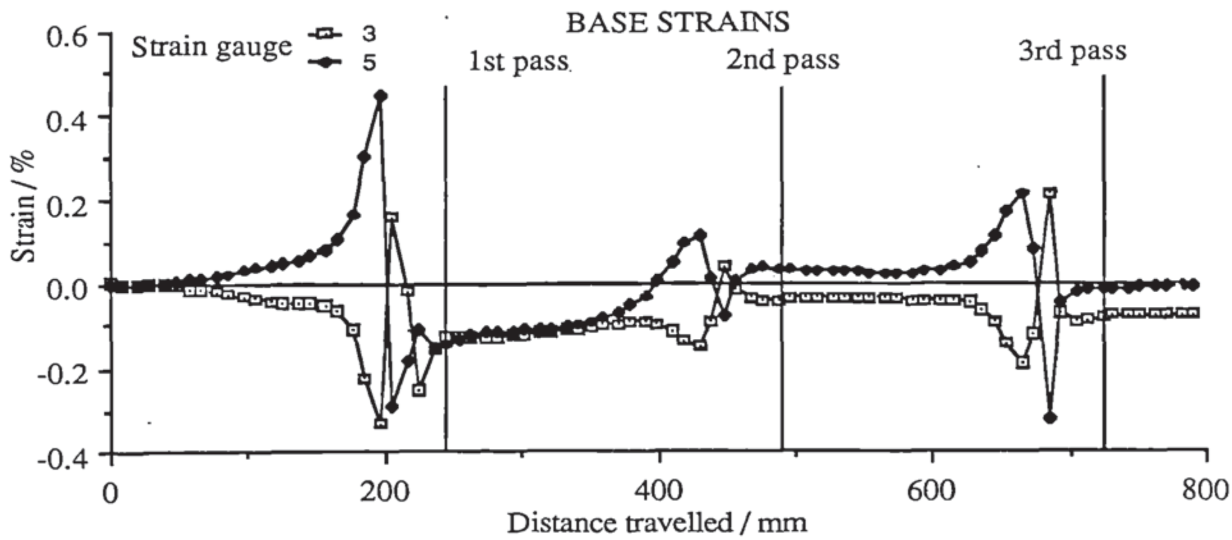
These tests have low twist and bow compared with the two pass and one pass tests. High load appears to introduce positive curvature (Tests 23, 25,27), which coincides with the tensile values of residual base strain. Differences in right and left edge flange strain do not indicate the direction or quantity of twisting in these tests.

The angle errors are more positive in the right side (some positive and some negative), with all the left errors being negative.

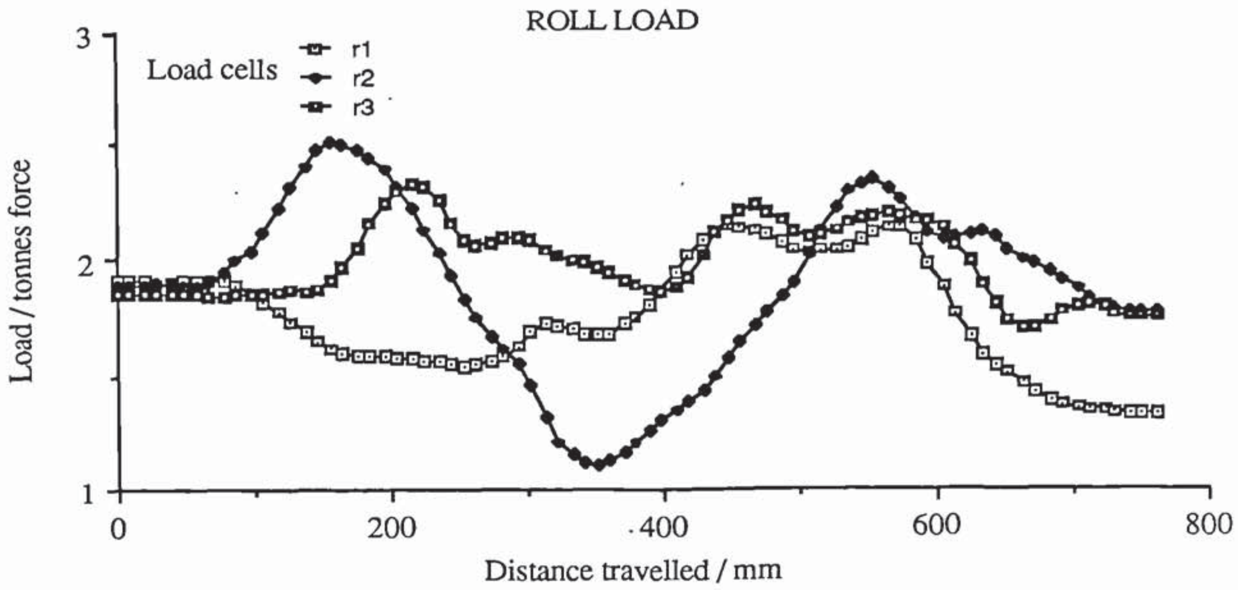
TEST 22

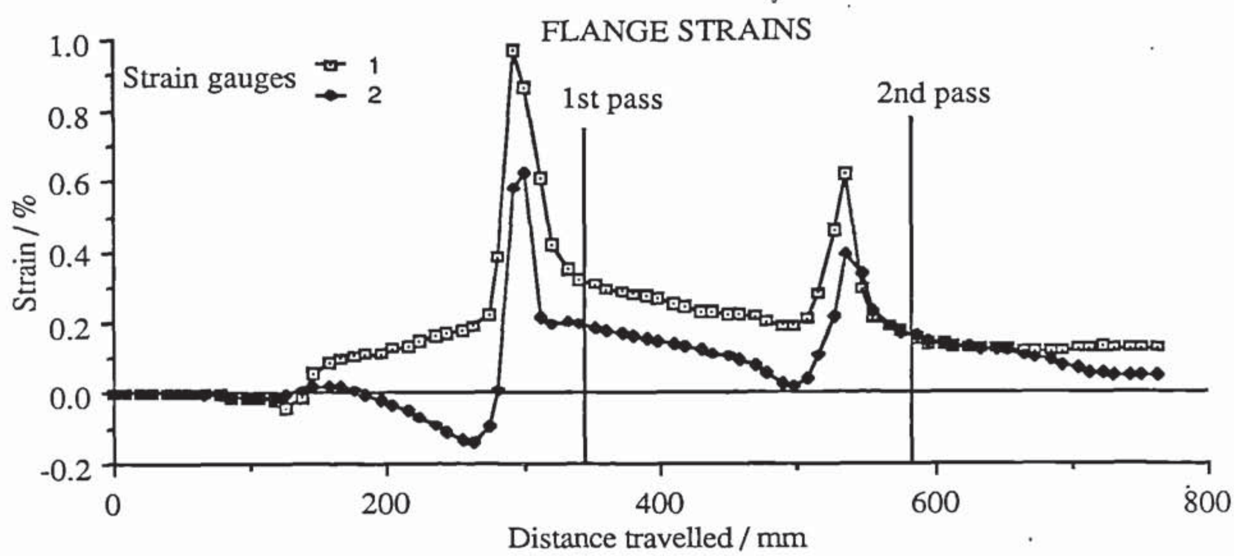

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.2
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
Distance travelled / mm

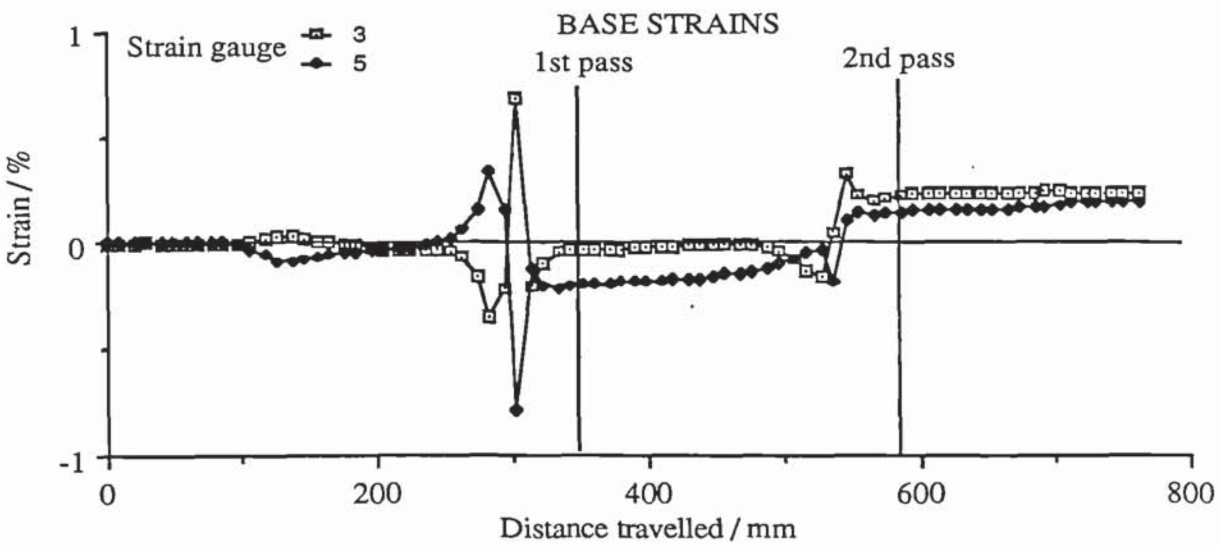

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm

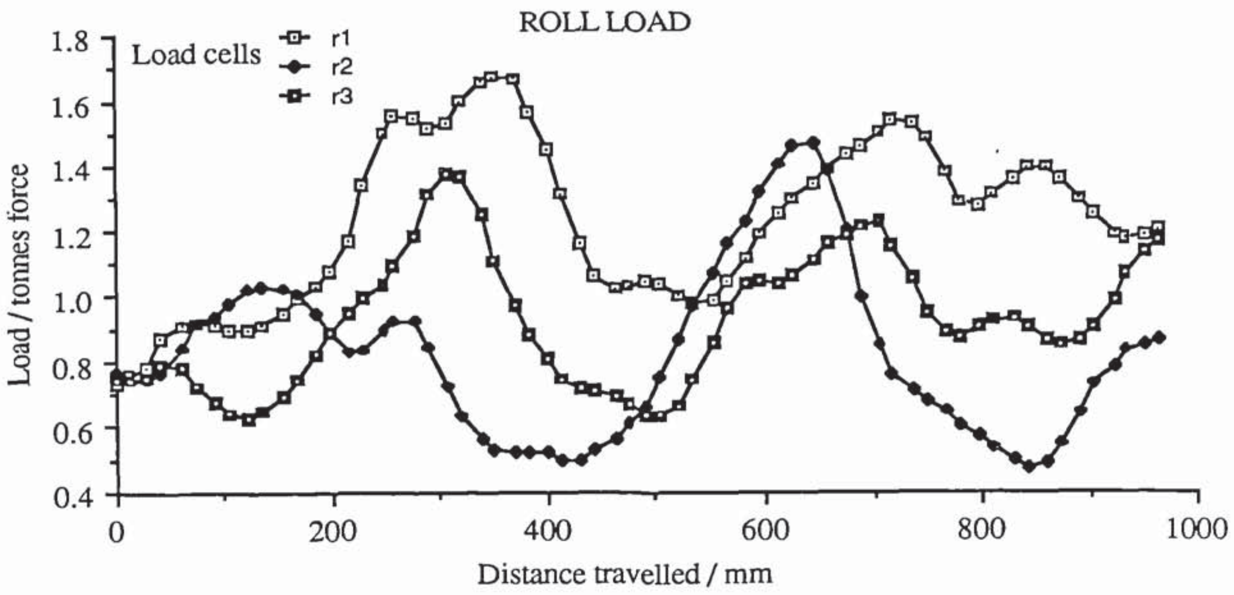
TEST 23

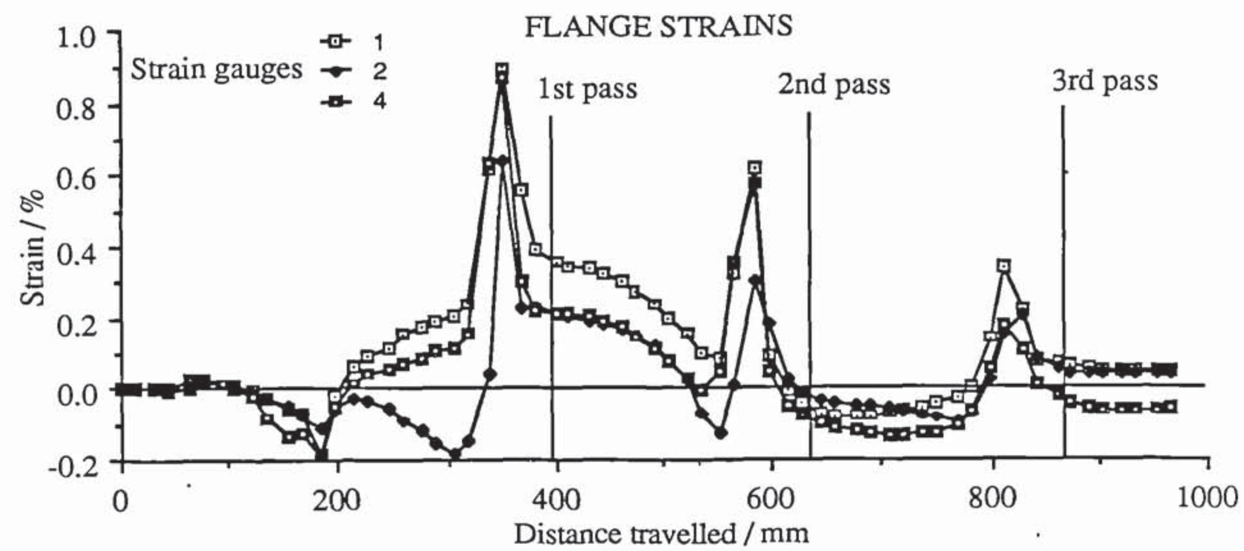

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
3
2
1
0
200
400
600
800
Distance travelled / mm

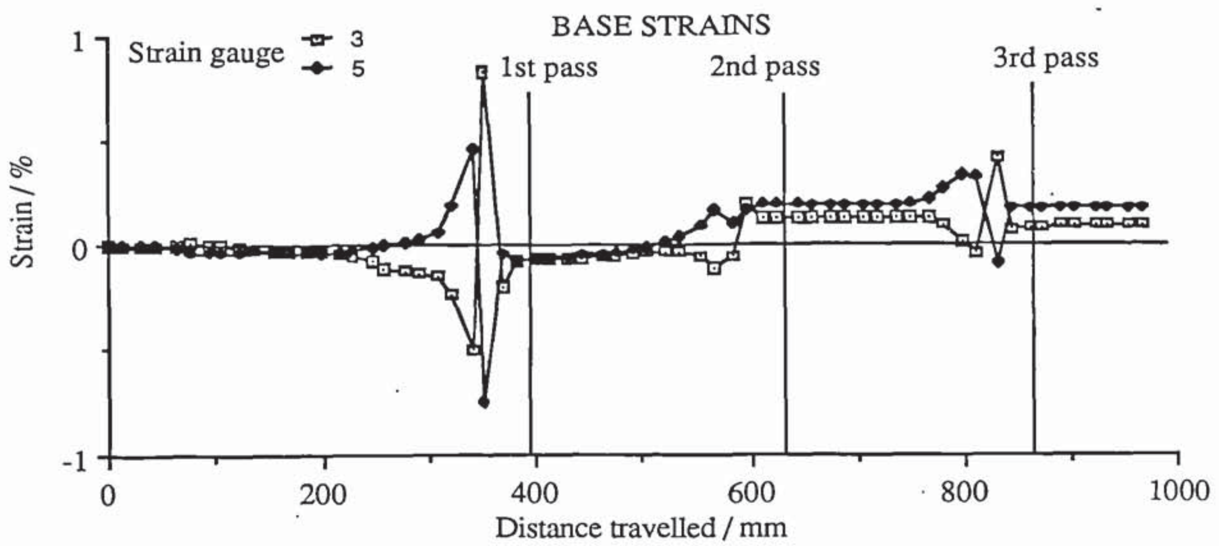

FLANGE STRAINS
Strain gauges
1
2
1st pass
2nd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
Strain / %
1
0
-1
0
200
400
600
800
Distance travelled / mm

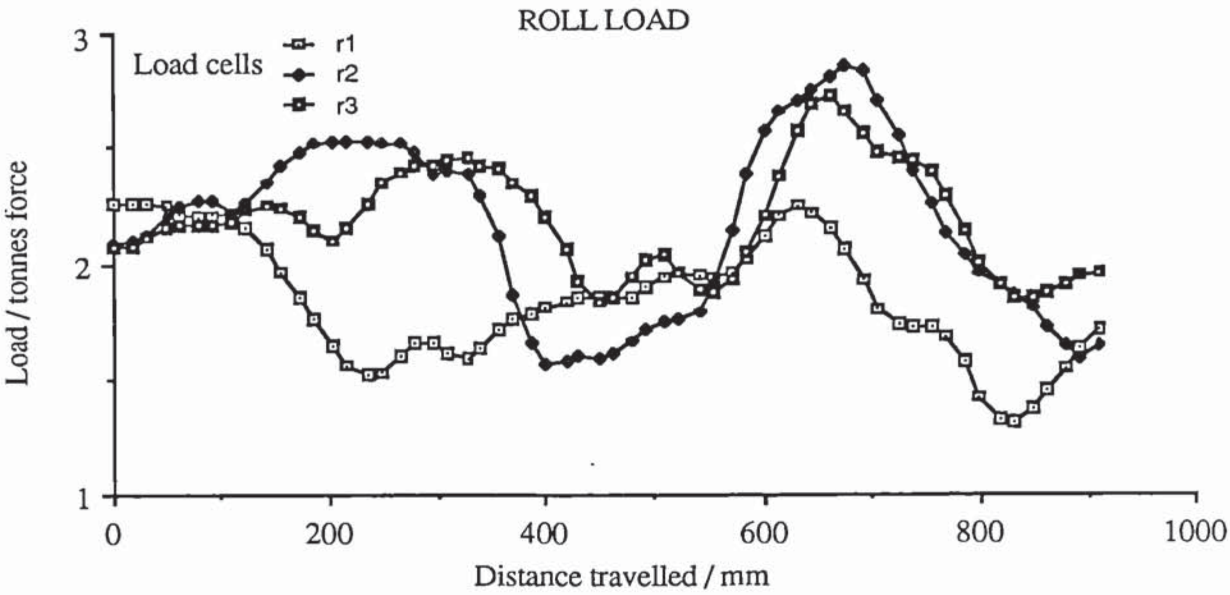
TEST 24

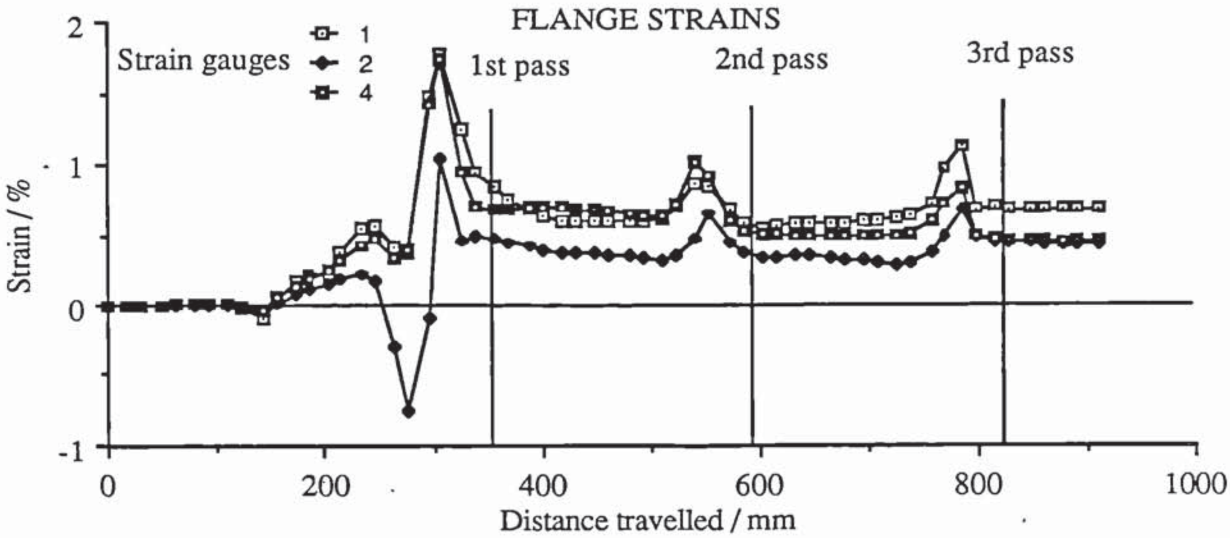

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
200
400
600
800
1000
Distance travelled / mm

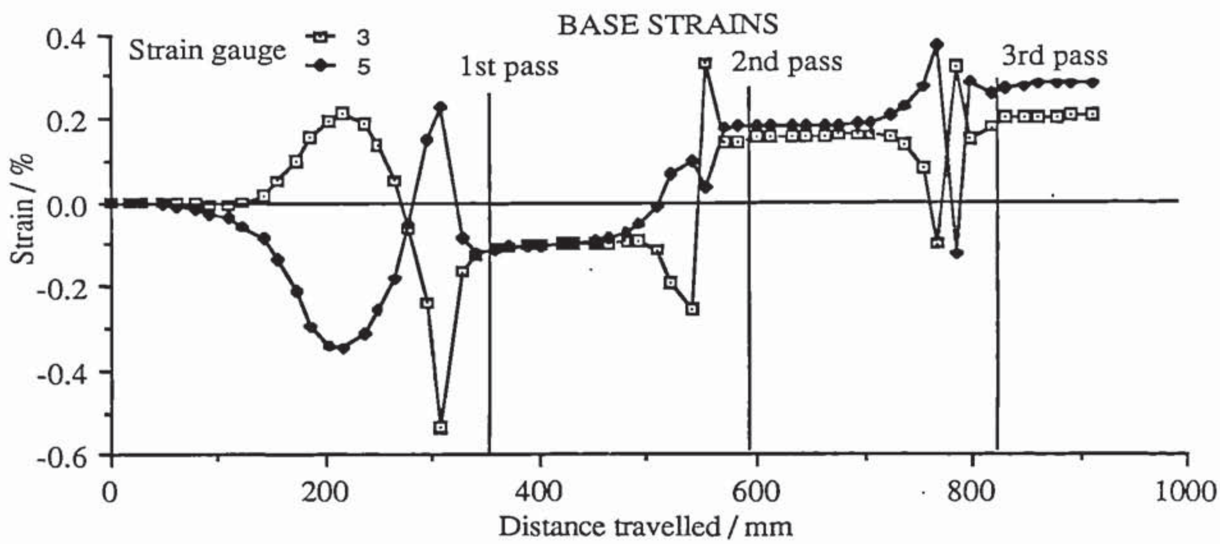

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
1
0
-1
0
200
400
600
800
1000
Distance travelled / mm

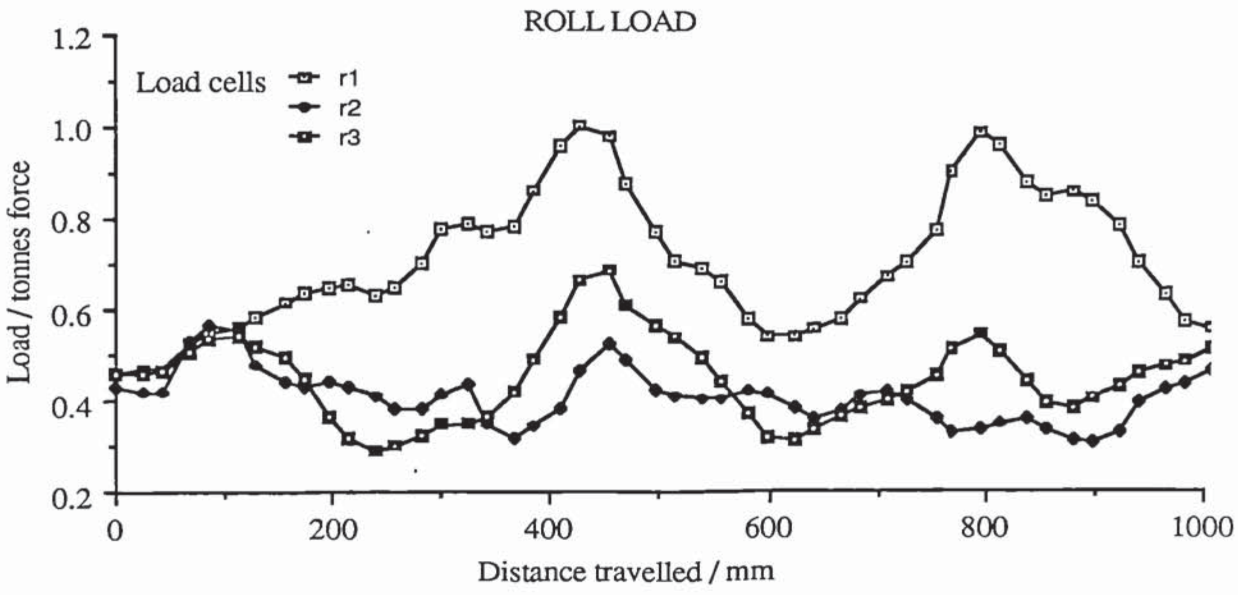
TEST 25

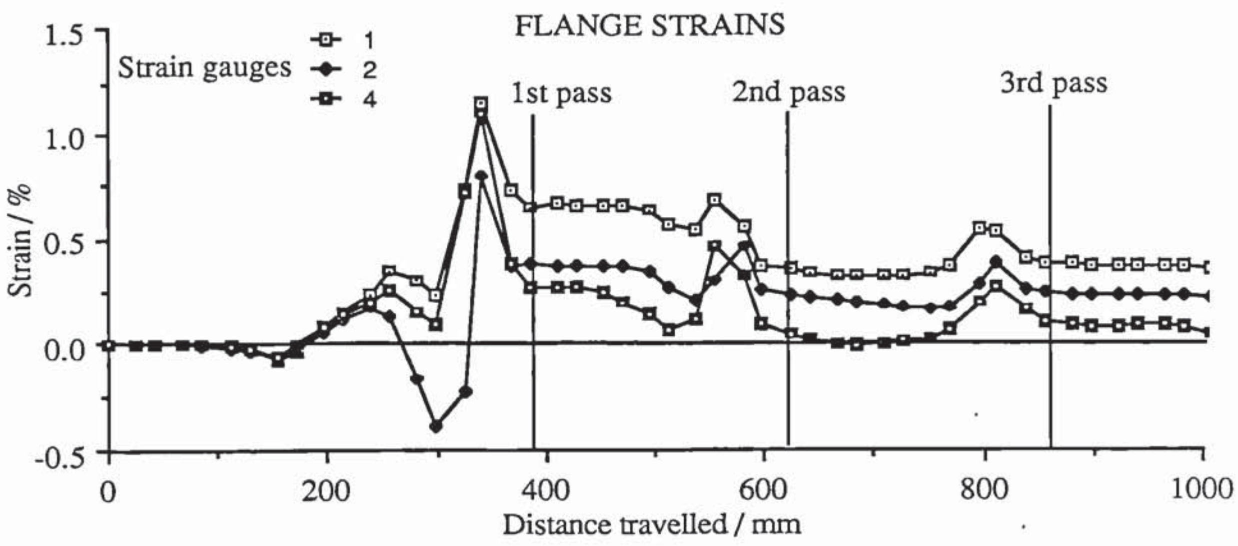

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
3
2
1
0
200
400
600
800
1000
Distance travelled / mm

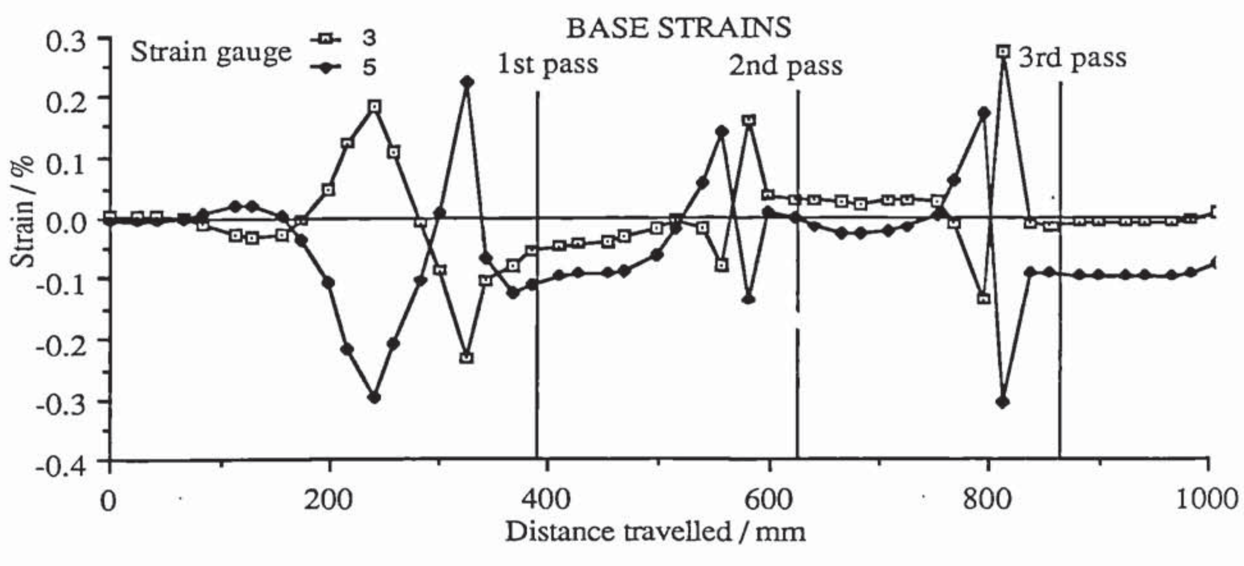

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
2
1
0
-1
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
Distance travelled / mm

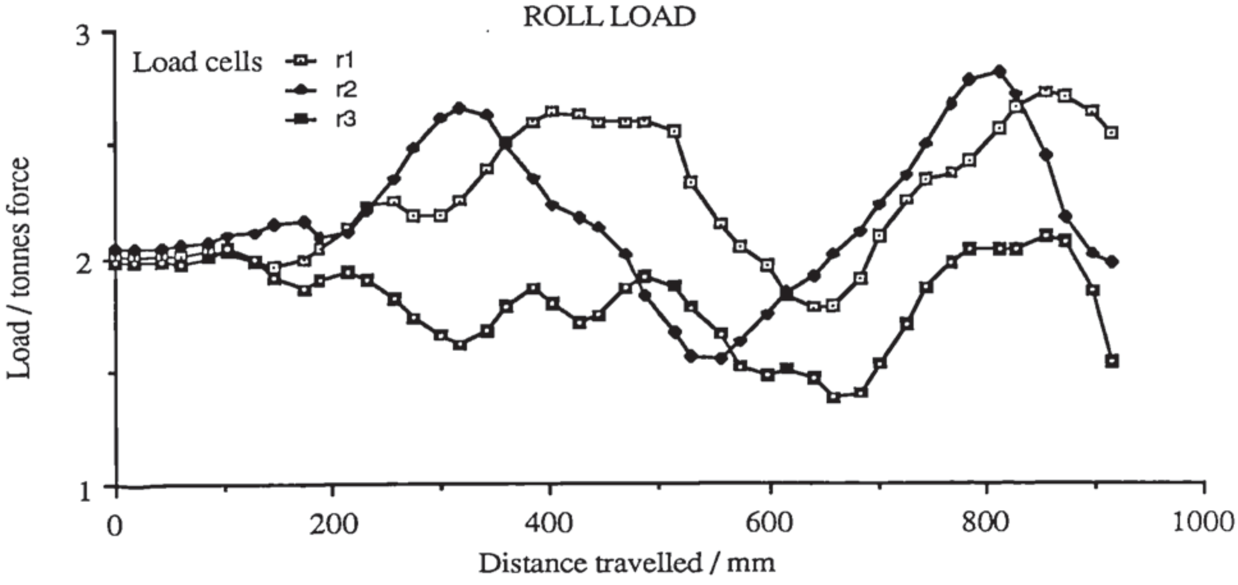
TEST 26


ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.2
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
Distance travelled / mm

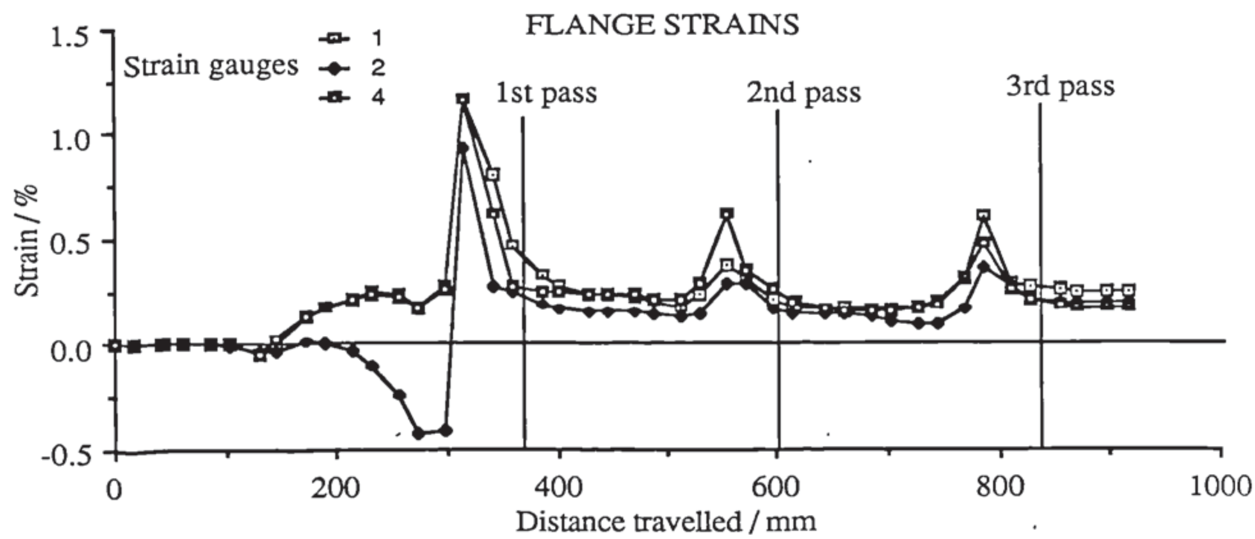

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
0
200
400
600
800
1000
Distance travelled / mm

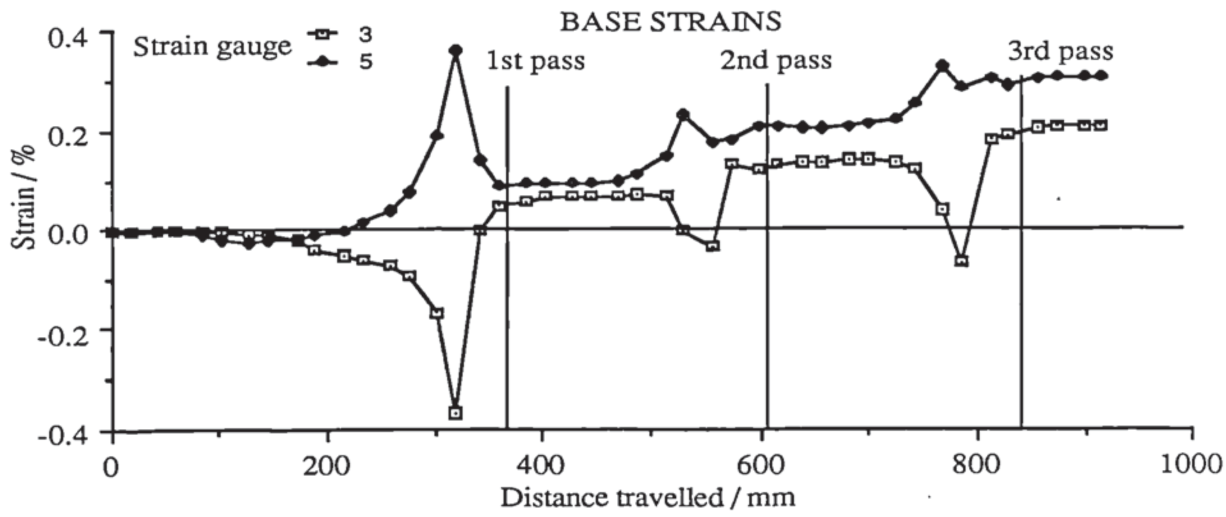
TEST 27



ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
3
2
1
0
200
400
600
800
1000
Distance travelled / mm



FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm



BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

7.7 GROUP (F) RESULTS

Description ; eight tests rolling through three passes, with short inter-pass distances, using three roll loads and three roll speeds, the last pass being out of line 1.7 mm to the right.

Roll speed \ Roll Load	low	med	high
low		**28** -16.9 5.9 -0.7 0.0	**29** 13.4 -1.4 -1.1 0.5
med	**30** -12.0 1.6 -0.7 1.2	**31** -28.0 0.1 -1.9 -0.3	**32** -1720.5 -1.7 -1.5 0.3
high	**33** -29.2 5.9 -1.3 -1.0	**34** 1147.0 -2.5 -1.5 -1.5	**35** 20.2 2.1 -0.8 -0.1

TABLE 7.6 GROUP (F) QUALITY MEASUREMENTS

These tests essentially duplicate the aligned group E, confirming the observations already discussed regarding strain profiles of base and flanges. In setting mills, roll alignment is known to affect the section quality, however, the effects resultant in these tests are difficult to interpret.

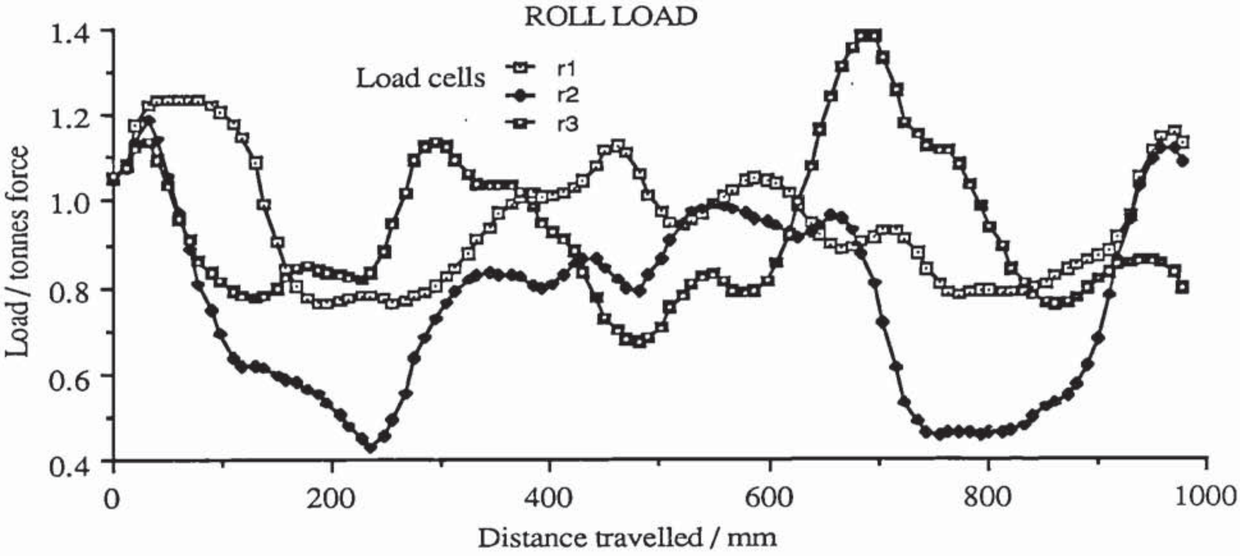
Certainly twisting has been influenced by the change in alignment. Tests 28, 30, 31, 33 and 35 all show positive curvature in the section and the remaining tests give low values of negative curvature. Group E tests all gave higher negative curvature. Alignment to the left has thus introduced a positive curvature.

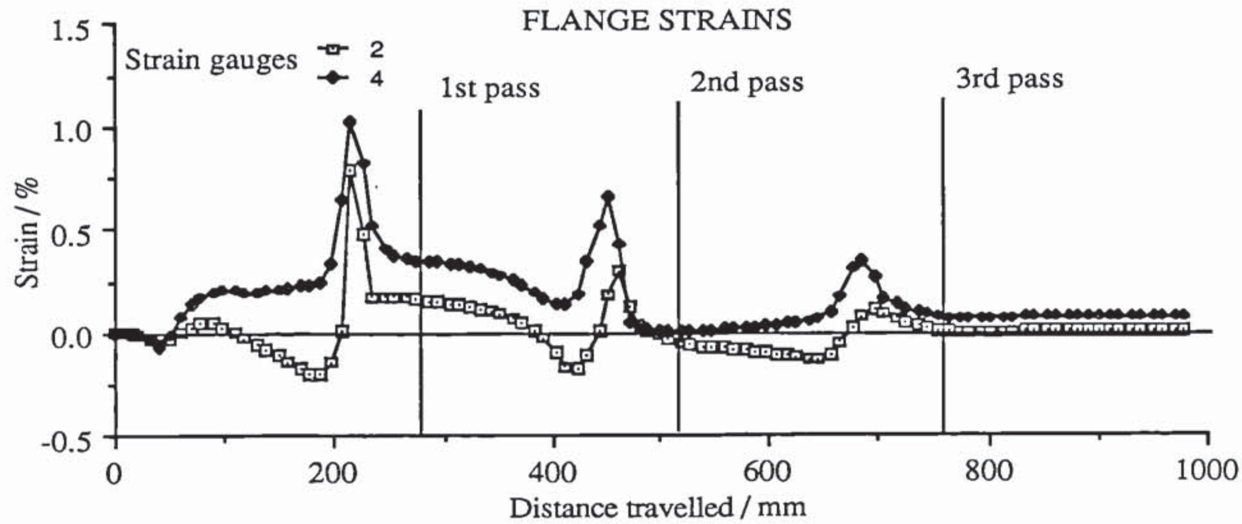
It was expected that the flange strain profiles would have indicated the direction of twist and given noticeable differences to the profiles of the group E tests. However, there is no clear indication of a difference between the groups; a high residual right flange strain can give either a positive or negative twist, as can a high left strain.

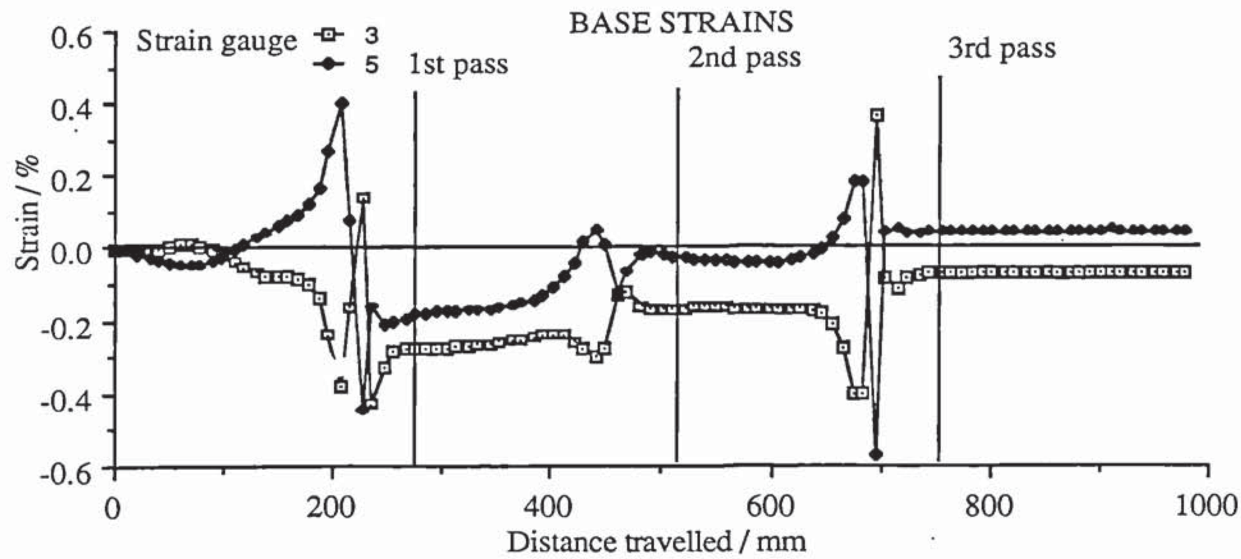
Bowing measurements in this group of tests are similar to group E values, indicating that bow is unaffected by alignment in these tests.

Angle errors for the left are higher than the previous group and are all negative. The right side has a mixture of positive and negative errors.

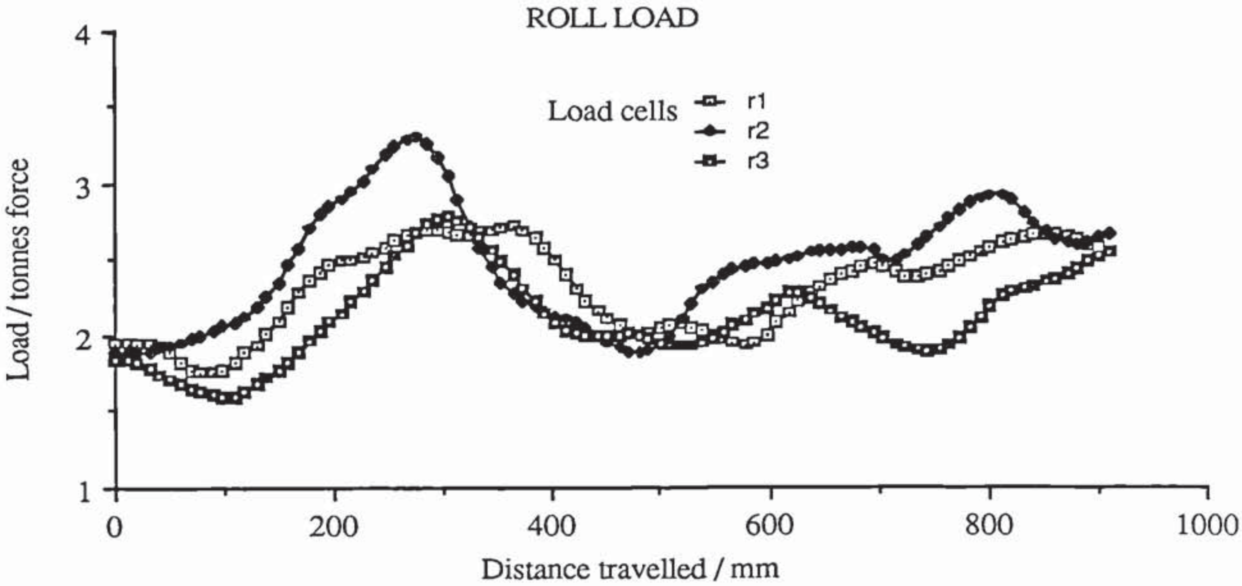
TEST 28


ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.4
1.2
1.0
0.8
0.6
0.4
0
200
400
600
800
1000
Distance travelled / mm

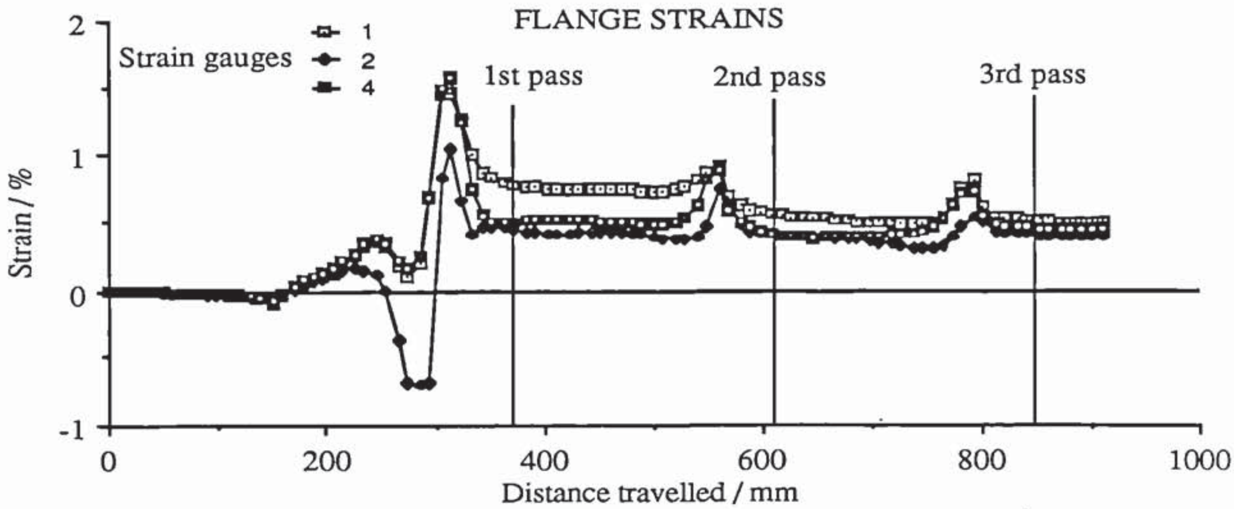

FLANGE STRAINS
Strain gauges
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
Distance travelled / mm

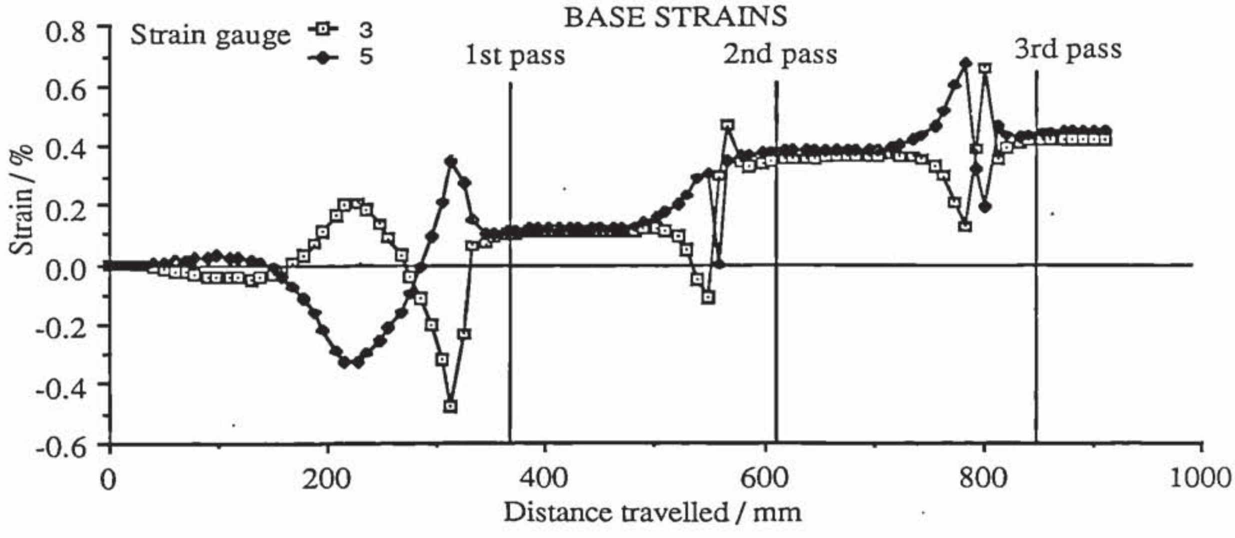
TEST 29



ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
4
3
2
1
0
200
400
600
800
1000
Distance travelled / mm

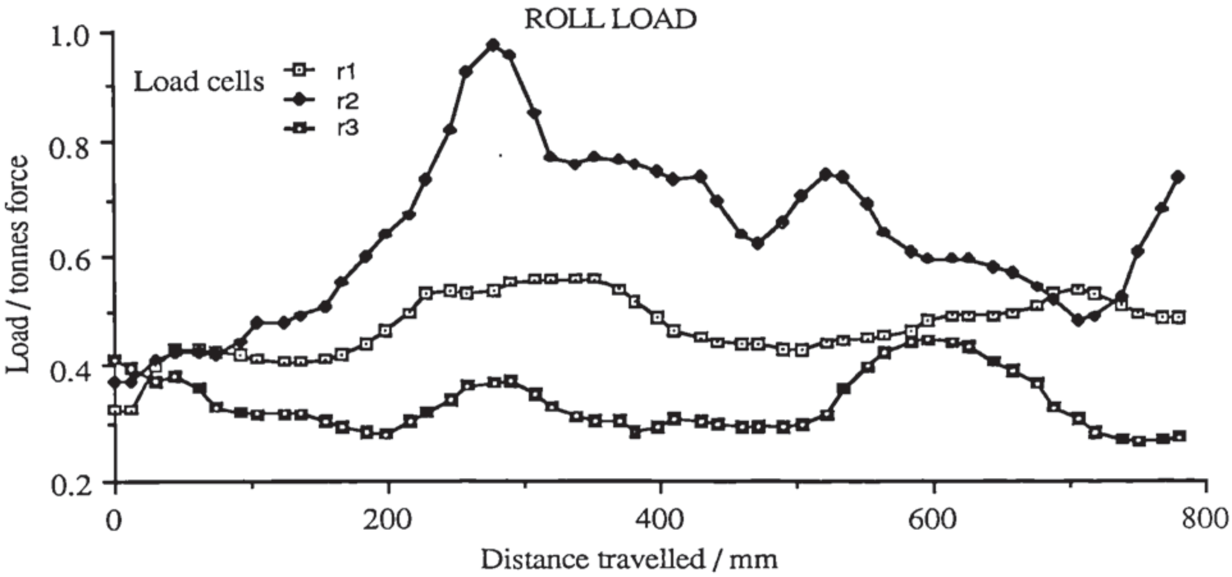


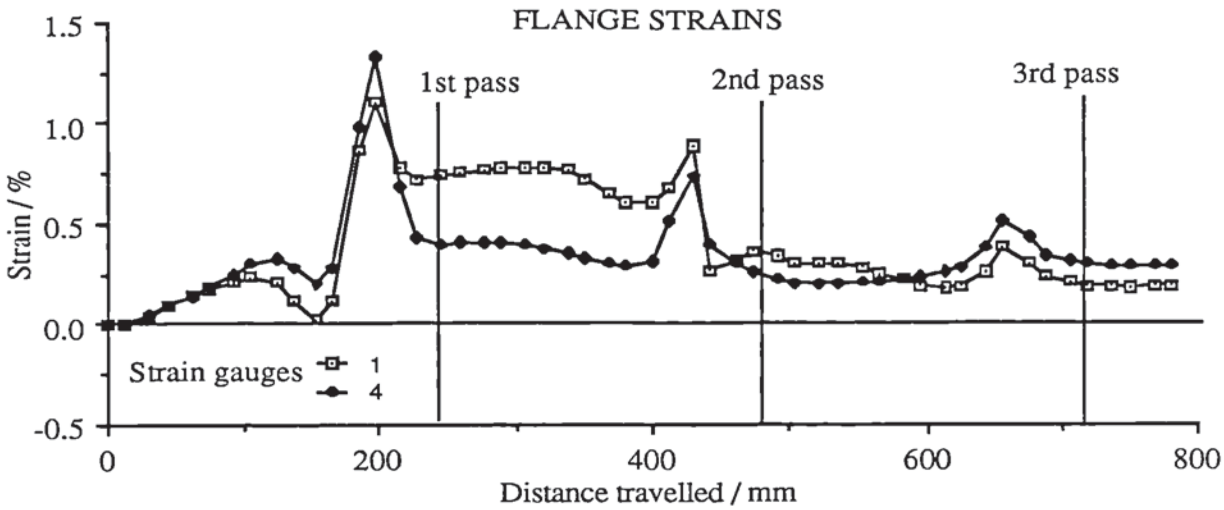
FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
2
1
0
-1
0
200
400
600
800
1000
Distance travelled / mm

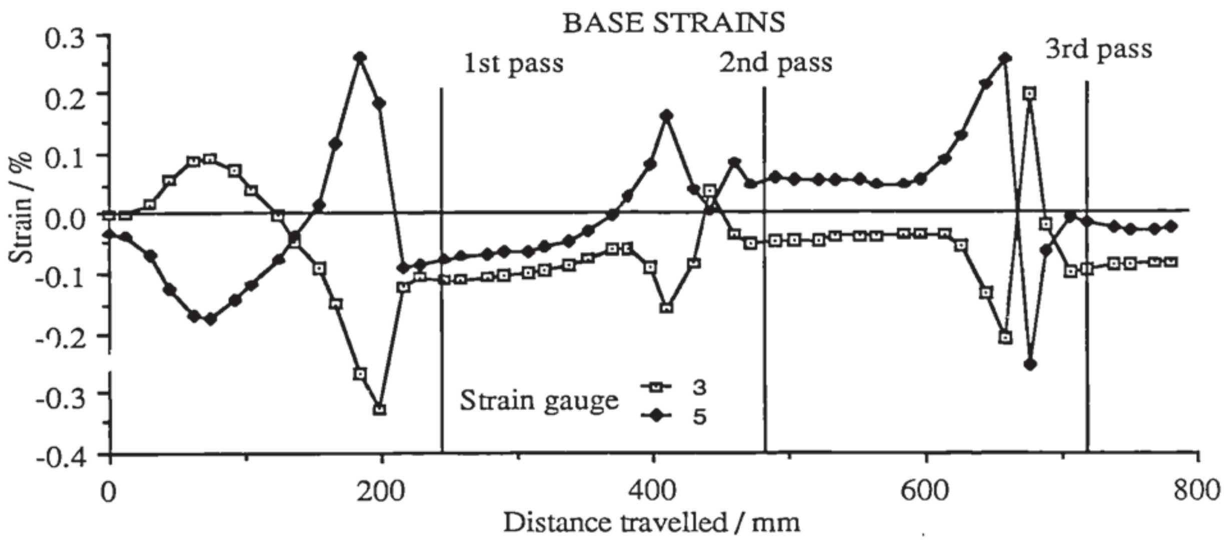


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
Distance travelled / mm

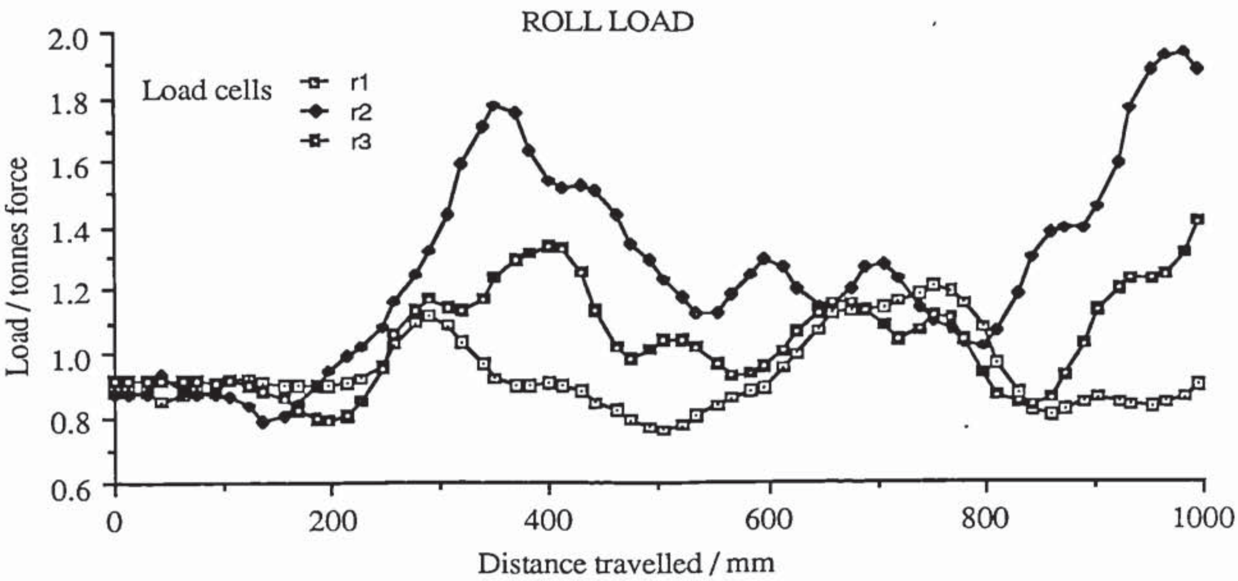
TEST 30


ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
Distance travelled / mm

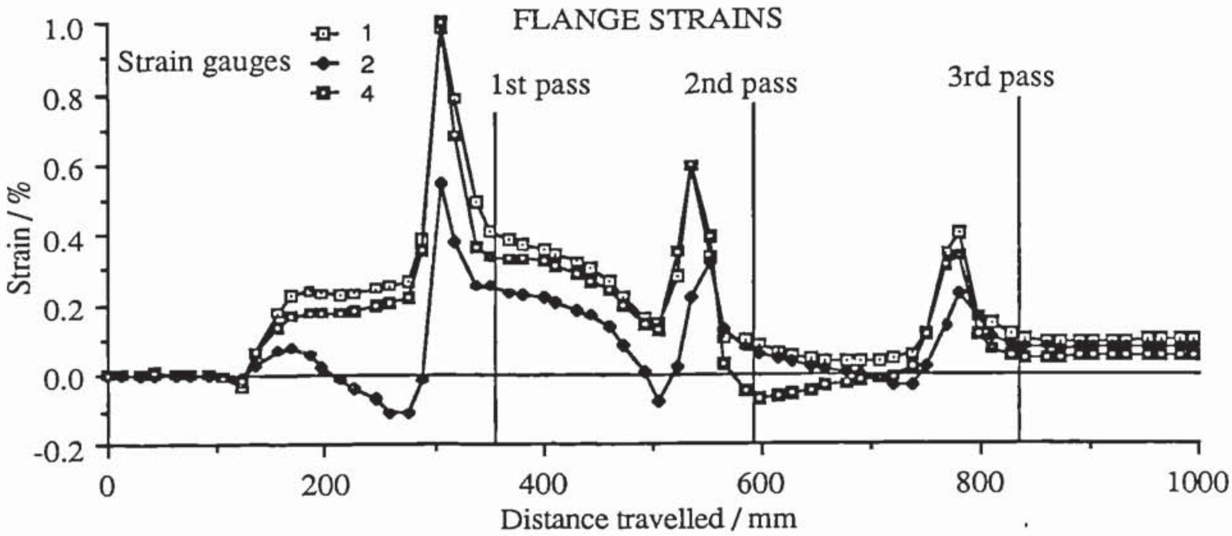

FLANGE STRAINS
1st pass
2nd pass
3rd pass
Strain gauges
1
4
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
3rd pass
Strain gauge
3
5
Strain / %
0.3
0.2
0.1
0.0
-0.1
-0.3
-0.4
0
200
400
600
800
Distance travelled / mm

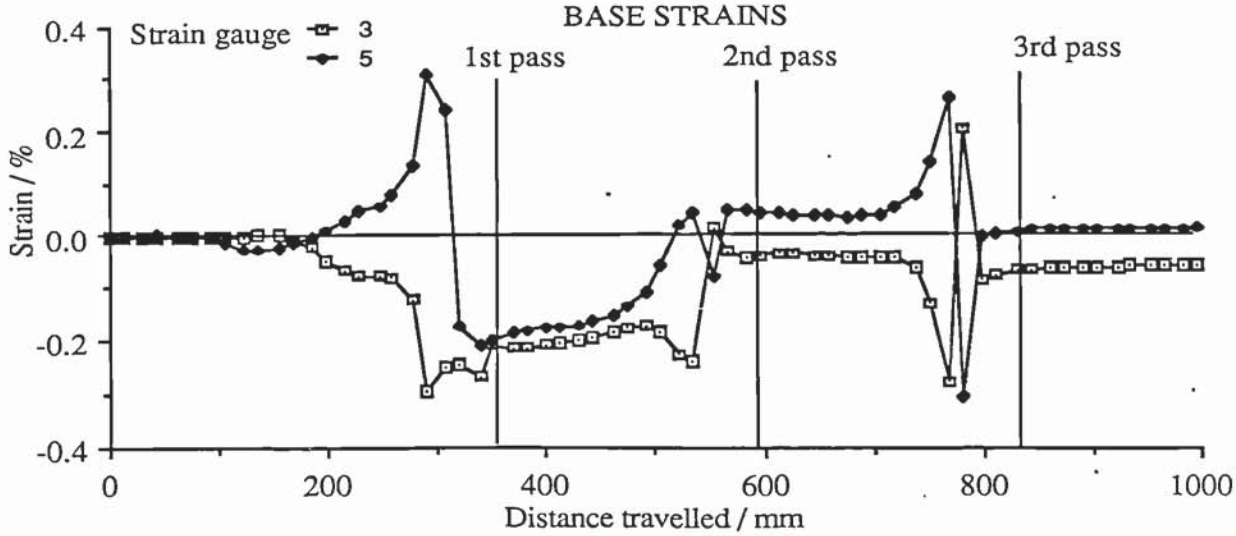
TEST 31



ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
1000
Distance travelled / mm

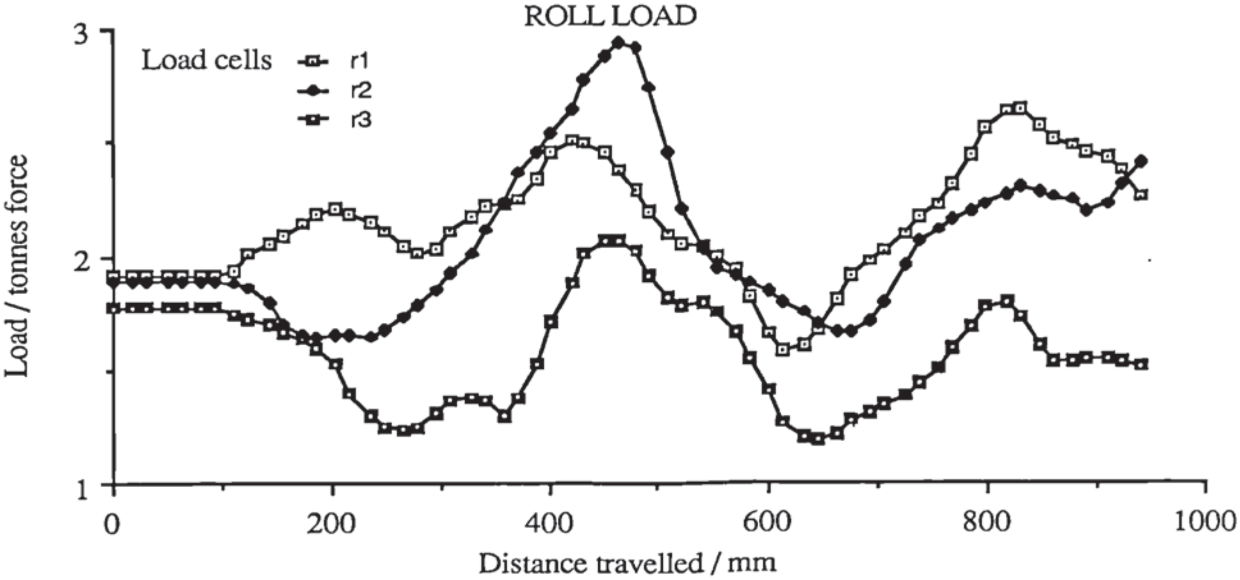


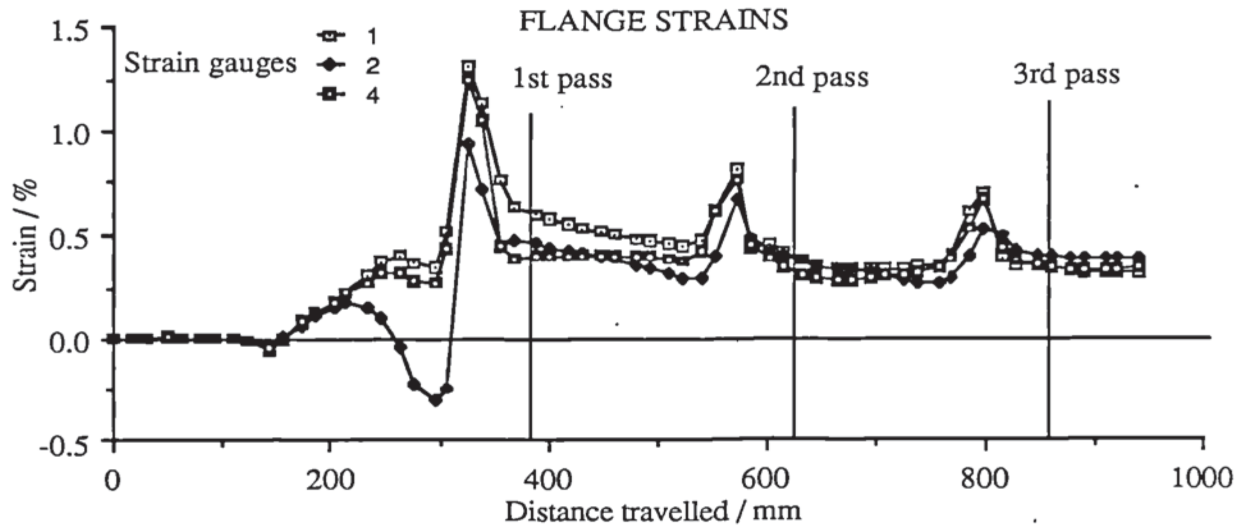
FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
1000
Distance travelled / mm

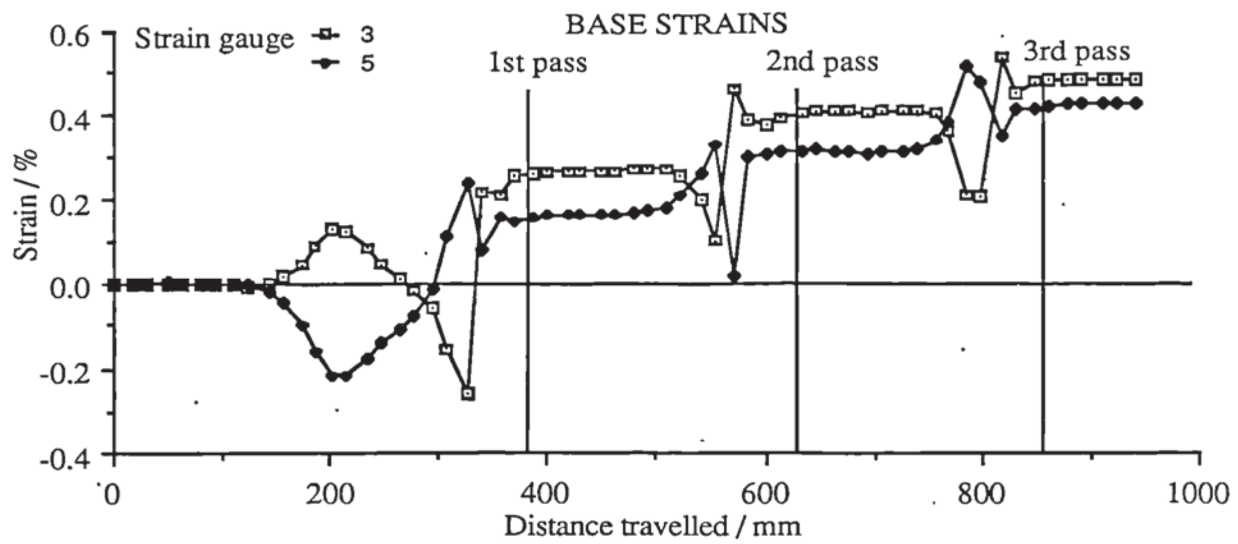


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

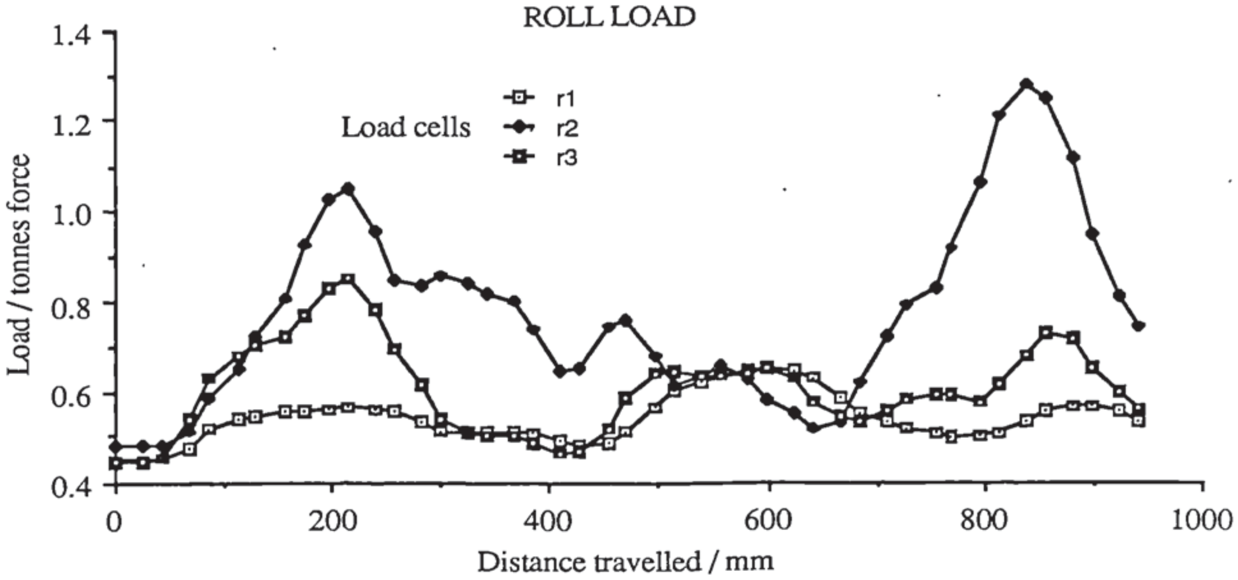
TEST 32

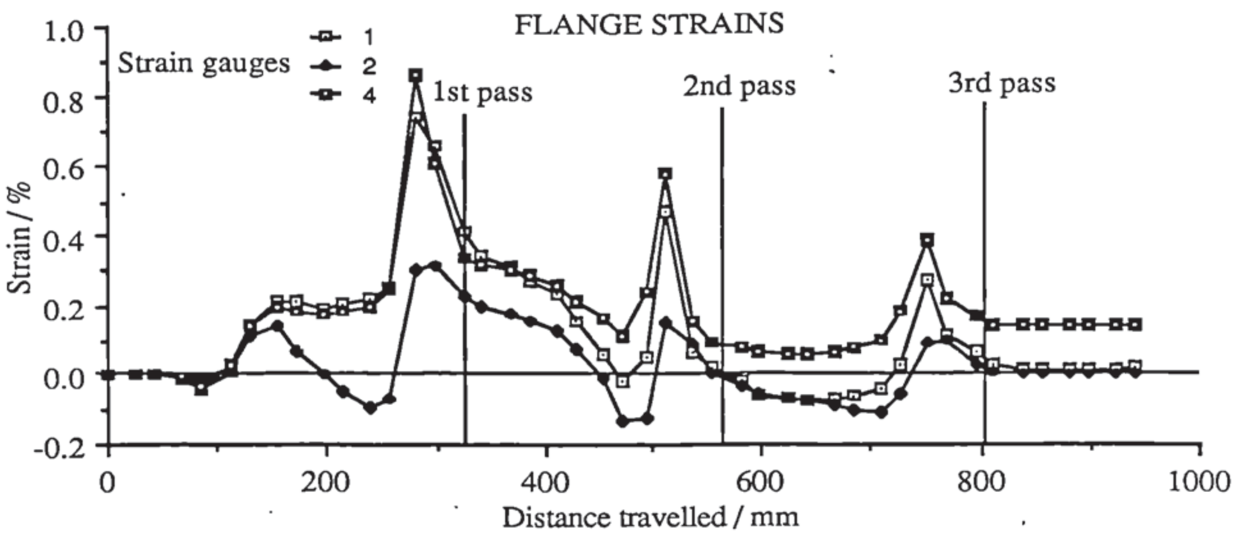

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
3
2
1
0
200
400
600
800
1000
Distance travelled / mm

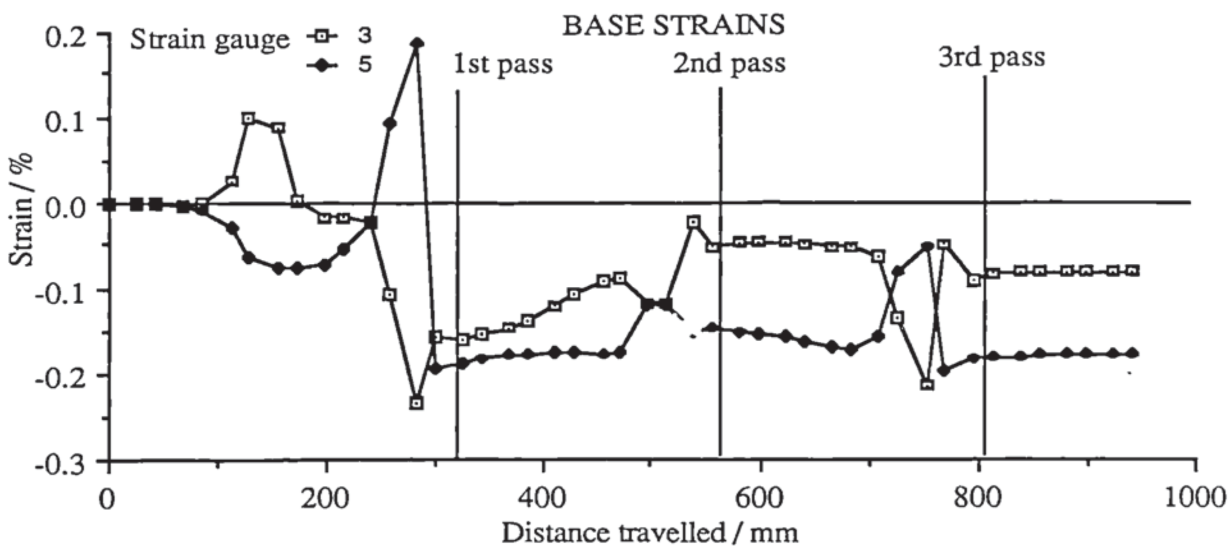

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.5
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

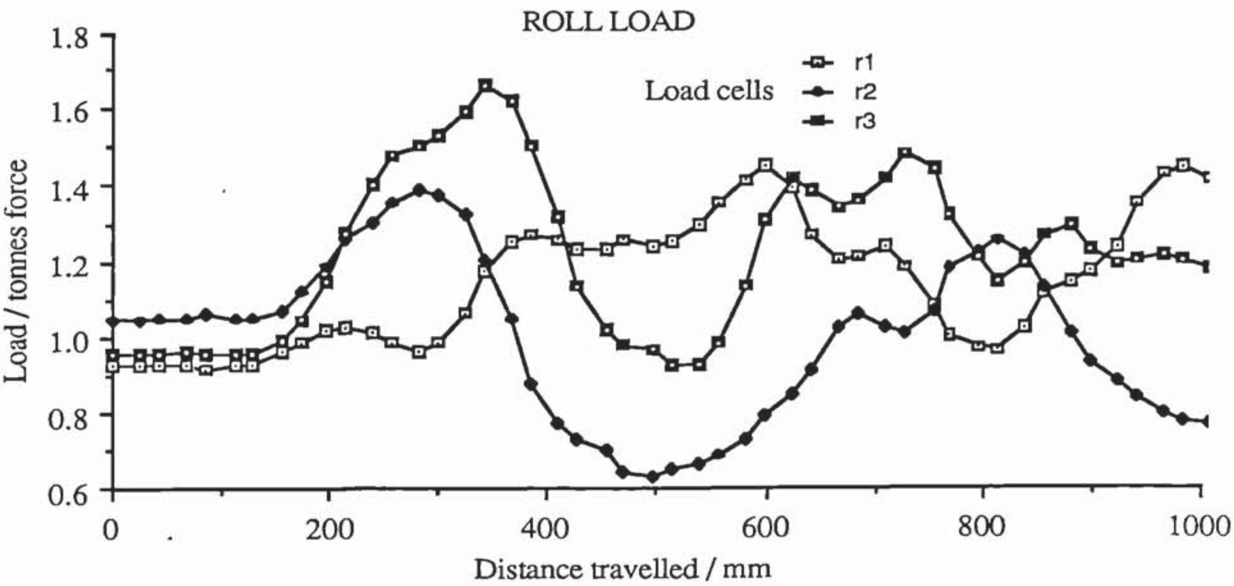
TEST 33

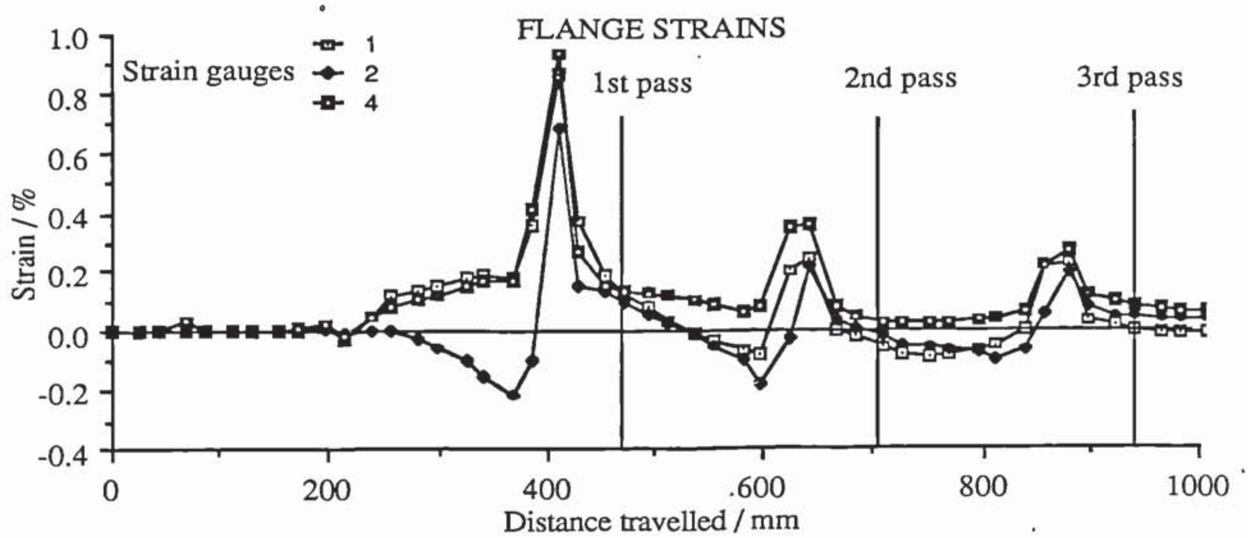

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.4
1.2
1.0
0.8
0.6
0.4
0
200
400
600
800
1000
Distance travelled / mm

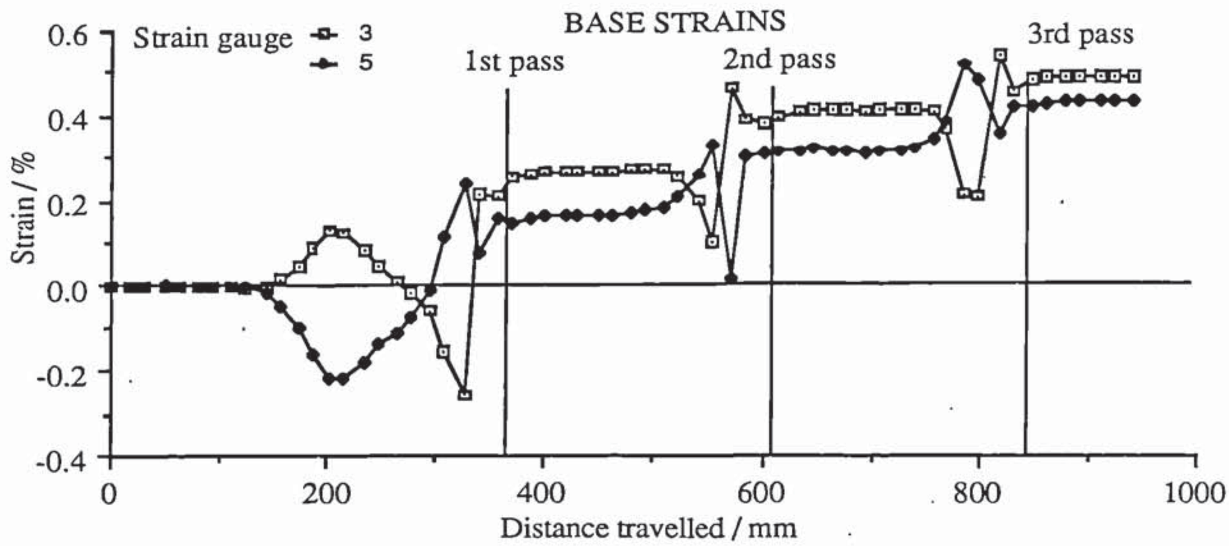

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
1000
Distance travelled / mm

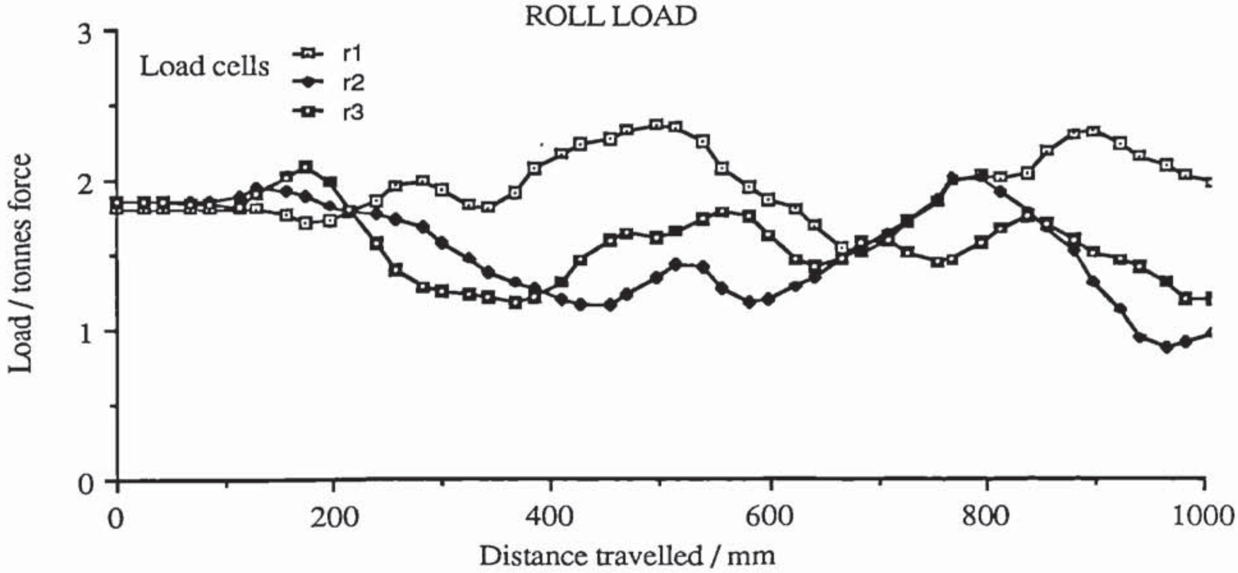
TEST 34

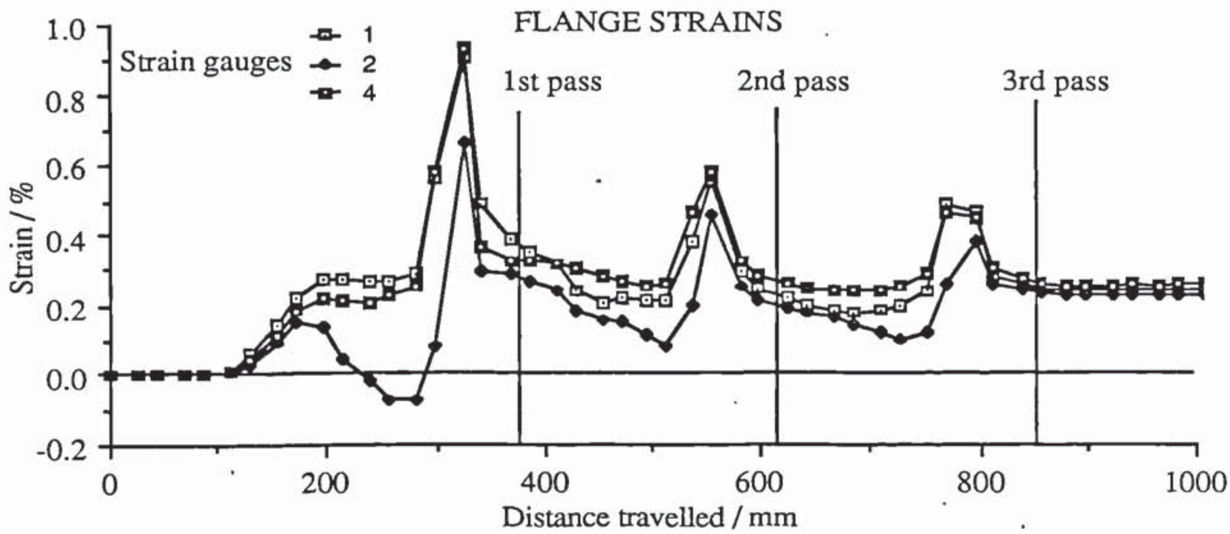

ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
1000
Distance travelled / mm

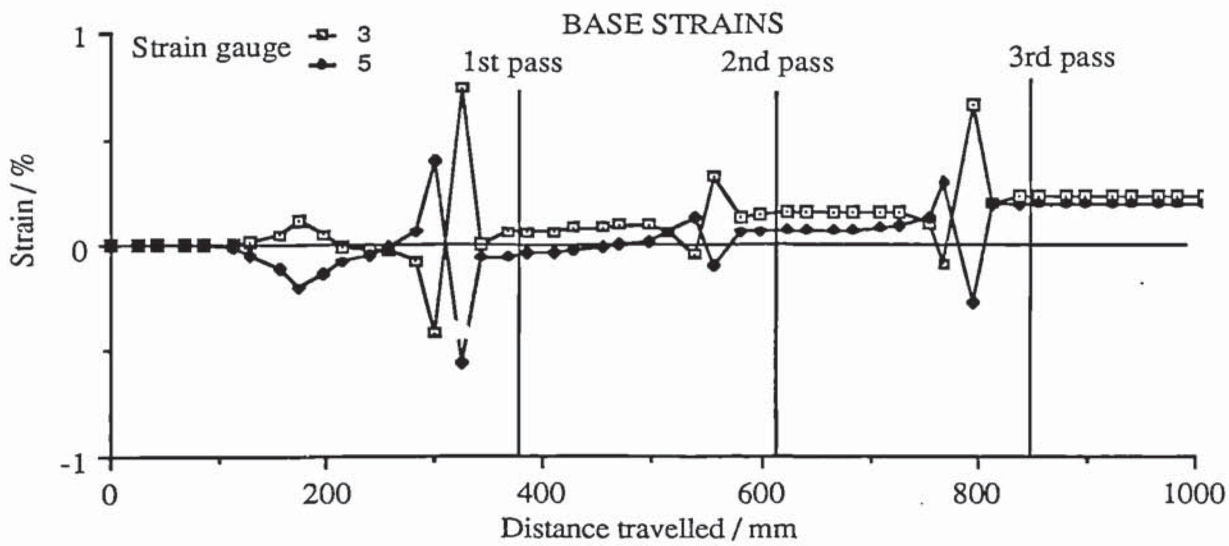

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
Distance travelled / mm

TEST 35


ROLL LOAD
Load cells
r1
r2
r3
Load / tonnes force
3
2
1
0
0
200
400
600
800
1000
Distance travelled / mm


FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
1
0
-1
0
200
400
600
800
1000
Distance travelled / mm

7.8 GROUP (G) RESULTS

Description ; eight tests, rolling through three passes, with an extended inter-pass distance between the second and third pass, with three roll loads and three roll speeds.

Roll speed \ Roll Load	low	med	high
low	**36** -65.8 -6.0 0.1 0.5	**37** -20.8 -5.3 -1.5 -1.5	**38** 31.1 -4.4 -0.6 0.0
med	**39** 24.9 -1.6 -0.1 0.2	**40** -26.1 -4.7 -1.5 -1.2	**41** 32.0 -3.2 -0.8 0.0
high		**42** -70.2 -2.5 -1.0 -0.3	**43** -491.6 -3.4 -0.5 0.0

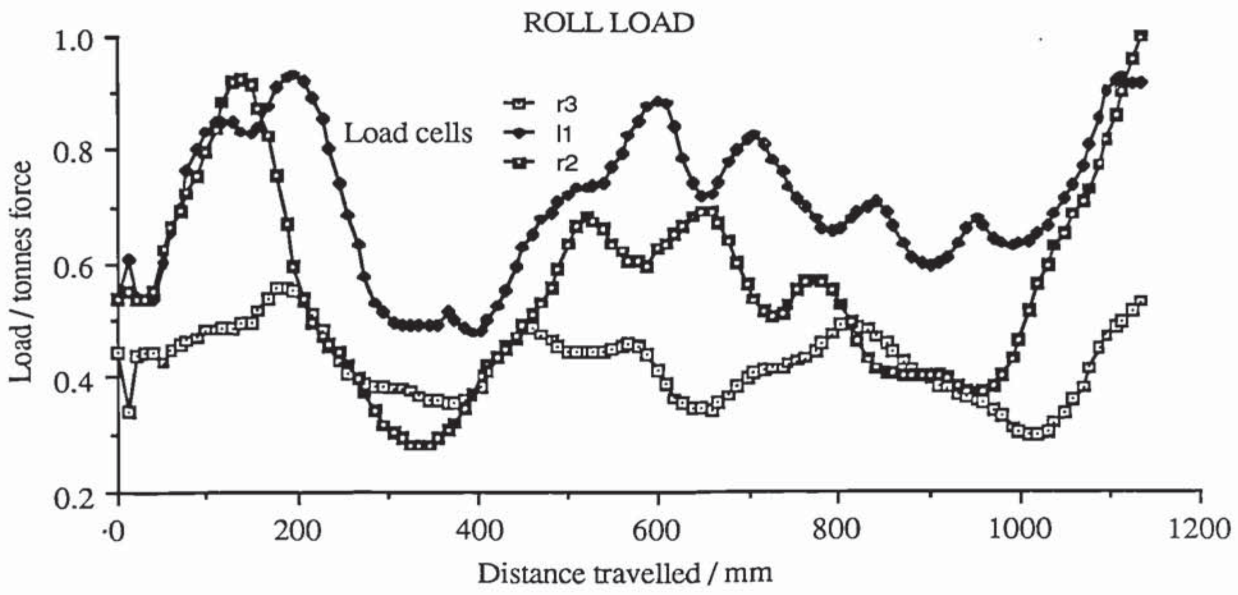
TABLE 7.7 GROUP (G) QUALITY MEASUREMENTS

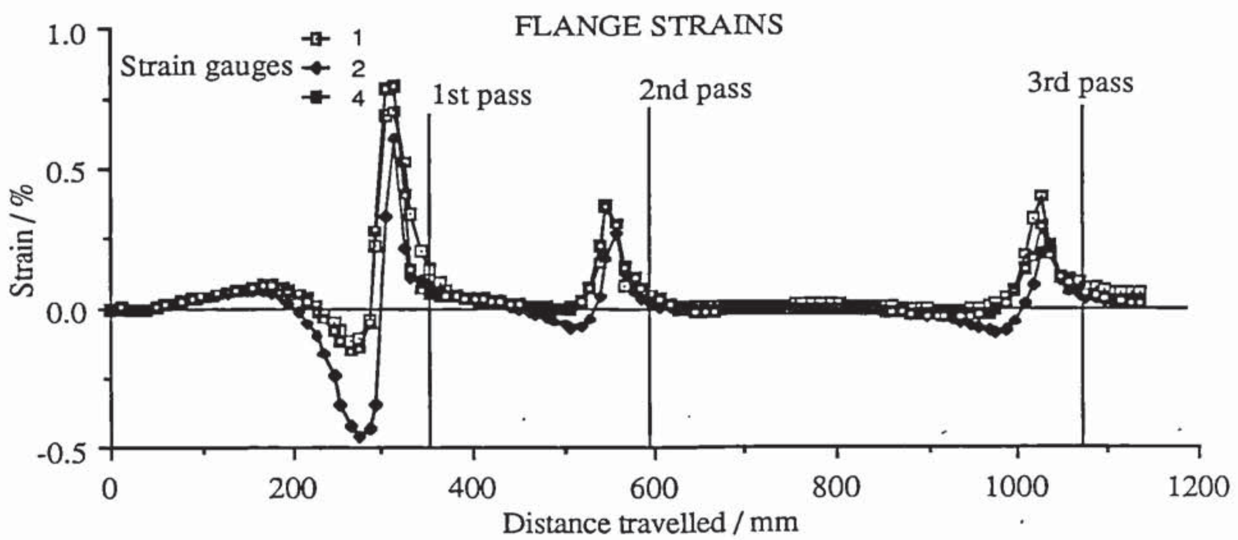
(Note, in some of these tests (37, 39, 40, 42) the complete profile was too large to be recorded by the system, hence, the less important first pass has been omitted).

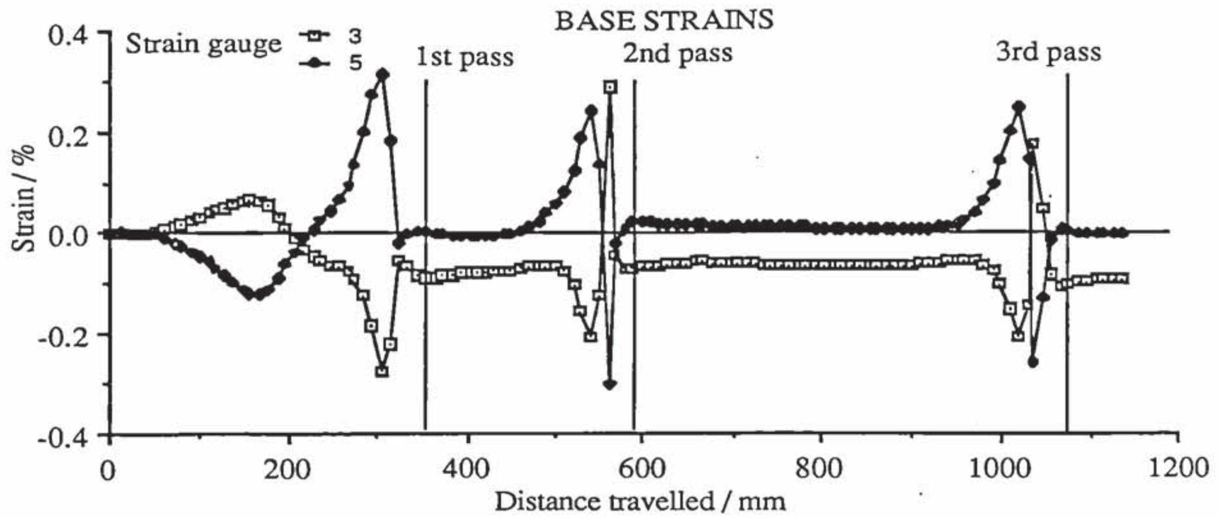
The results of Group E and F were very similar to the results from these tests. Curvature, twisting and strain profiles were all close repeats of the earlier tests, so confirming their validity. Extension of the second inter-pass distance had no noticeable effect on quality, compared with Group E tests.

The most noticeable change, affected by increasing the inter-pass distance, was that the final pass peak flange strains were higher than the second pass peak strains. In the other three pass tests they were lower.

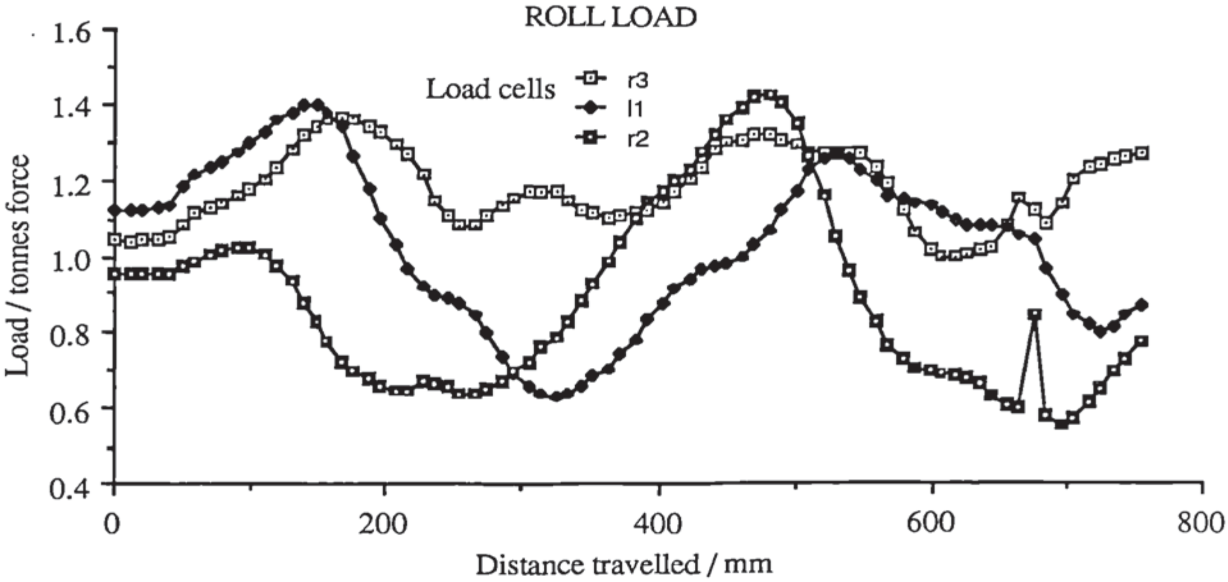
Both left and right angle errors vary in sign, but the left values are more negative than the right in all cases.

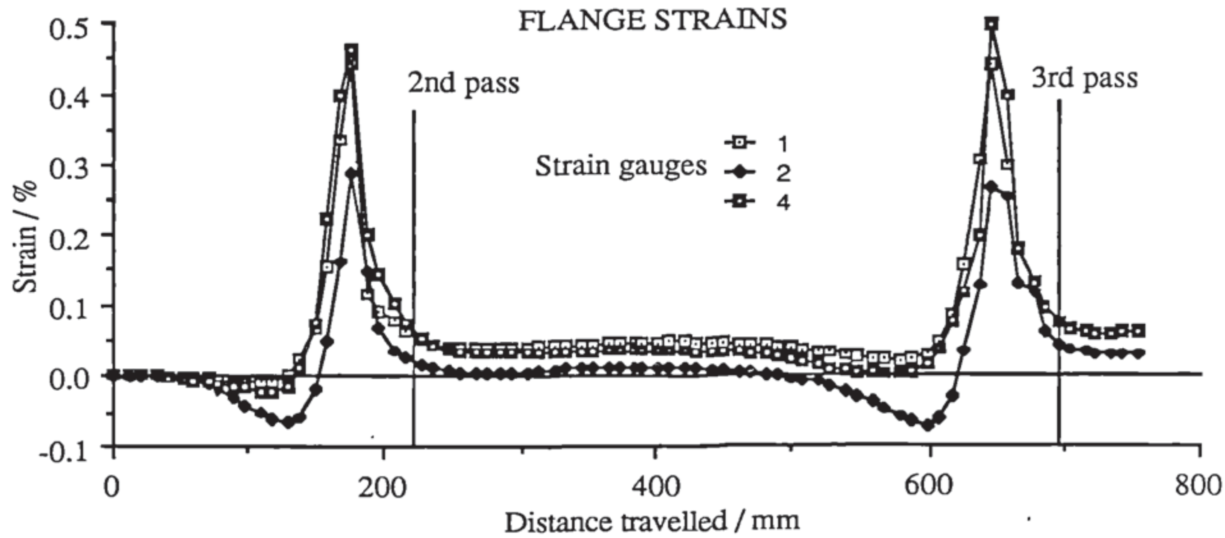

ROLL LOAD
Load cells
r3
l1
r2
Load / tonnes force
1.0
0.8
0.6
0.4
0.2
0
200
400
600
800
1000
1200
Distance travelled / mm

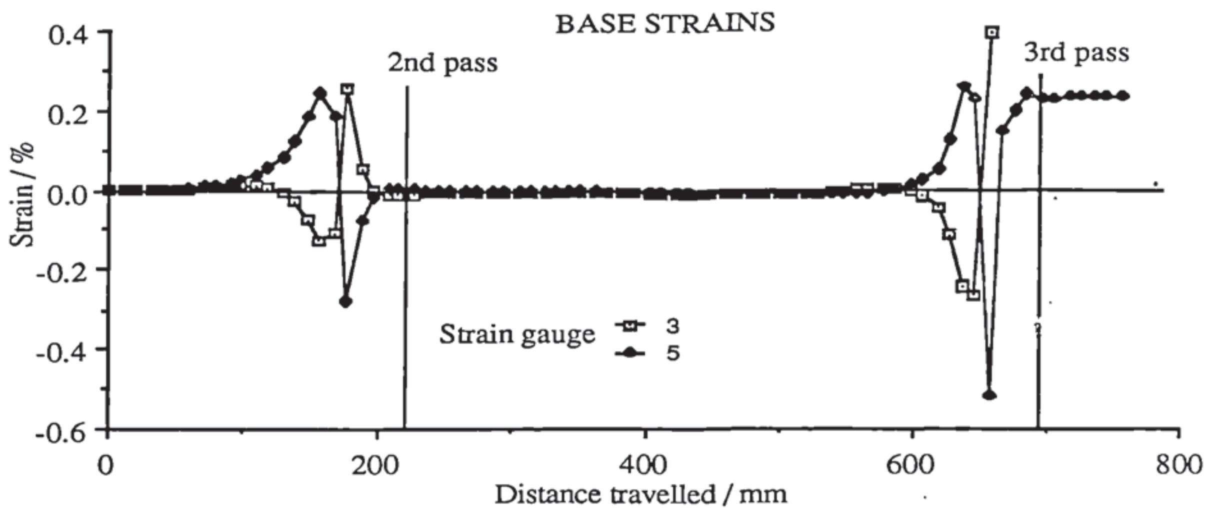

FLANGE STRAINS
Strain gauges
1
2
4
1st pass
2nd pass
3rd pass
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
1200
Distance travelled / mm


BASE STRAINS
Strain gauge
3
5
1st pass
2nd pass
3rd pass
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
1200
Distance travelled / mm

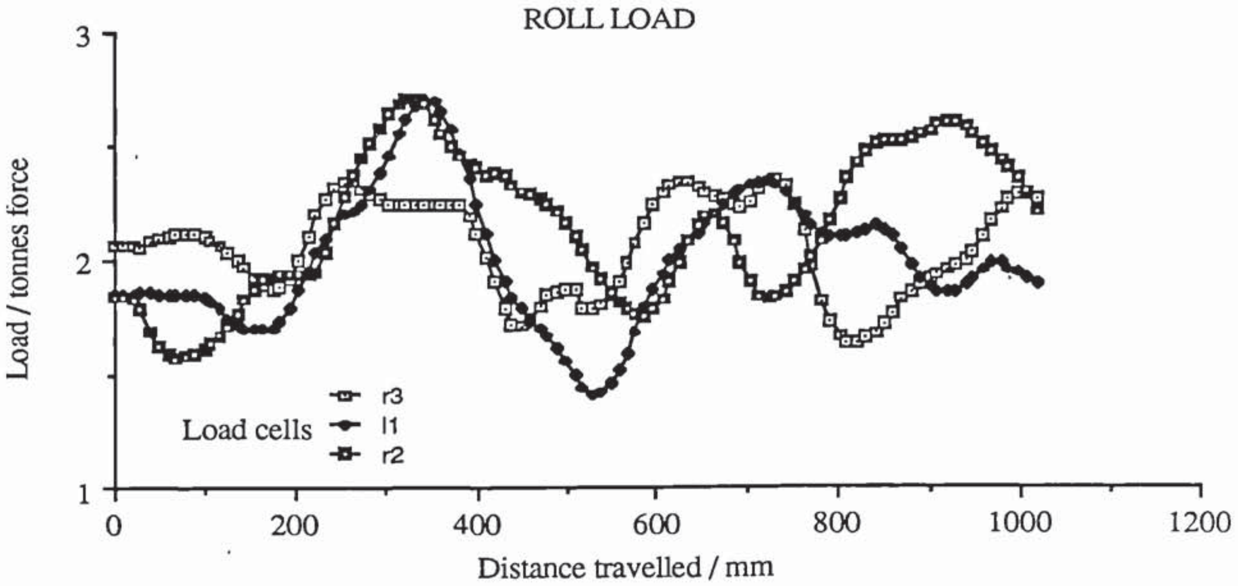
TEST 37


ROLL LOAD
Load cells
r3
l1
r2
Load / tonnes force
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
200
400
600
800
Distance travelled / mm

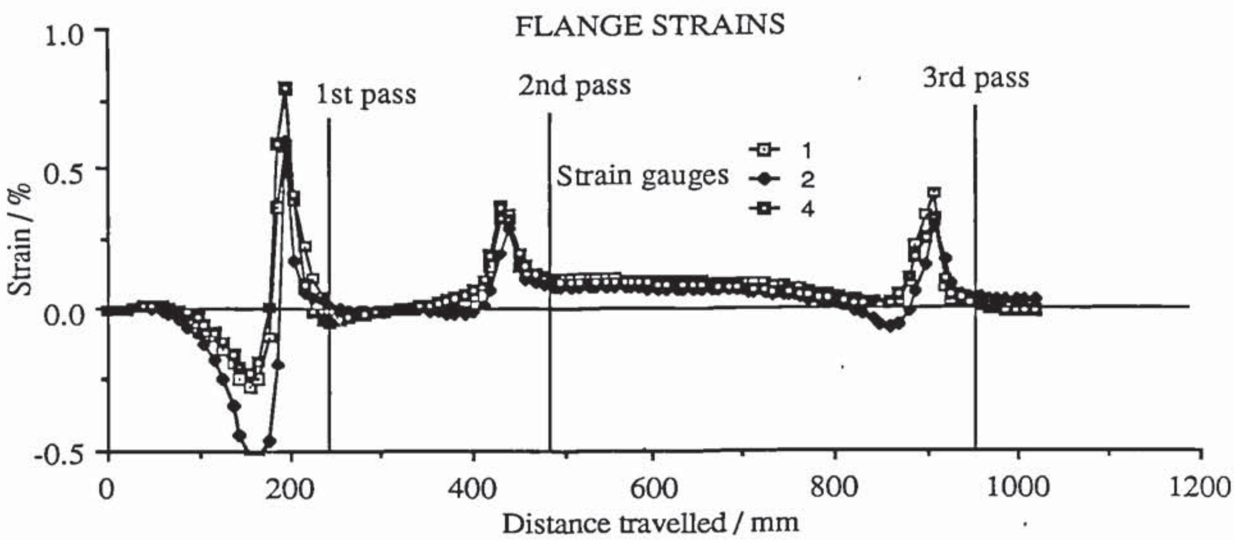

FLANGE STRAINS
2nd pass
3rd pass
Strain gauges
1
2
4
Strain / %
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
2nd pass
3rd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
Distance travelled / mm

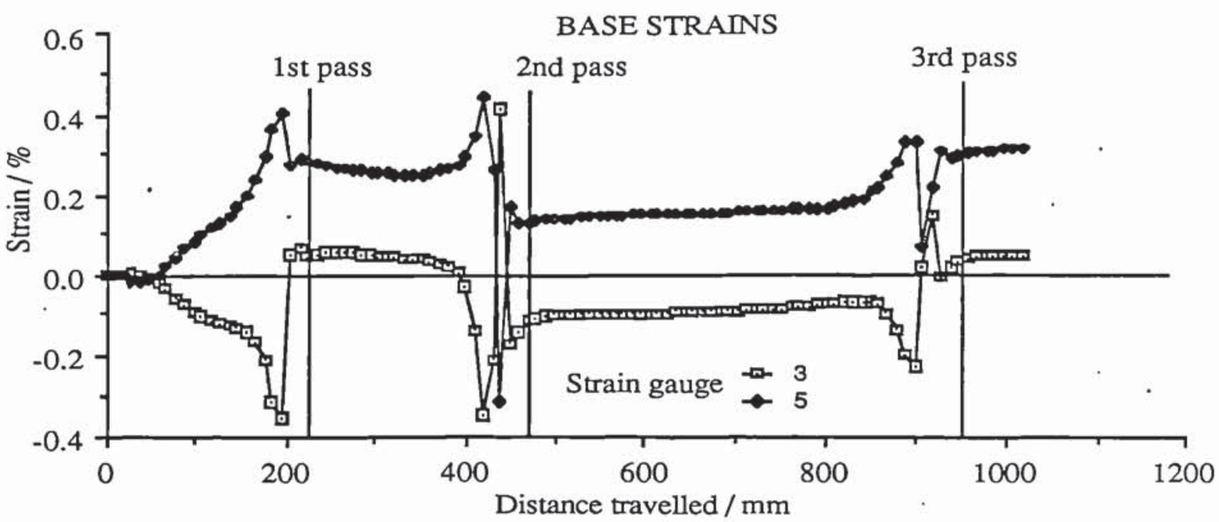
TEST 38



ROLL LOAD
Load / tonnes force
3
2
1
Load cells
r3
l1
r2
0
200
400
600
800
1000
1200
Distance travelled / mm

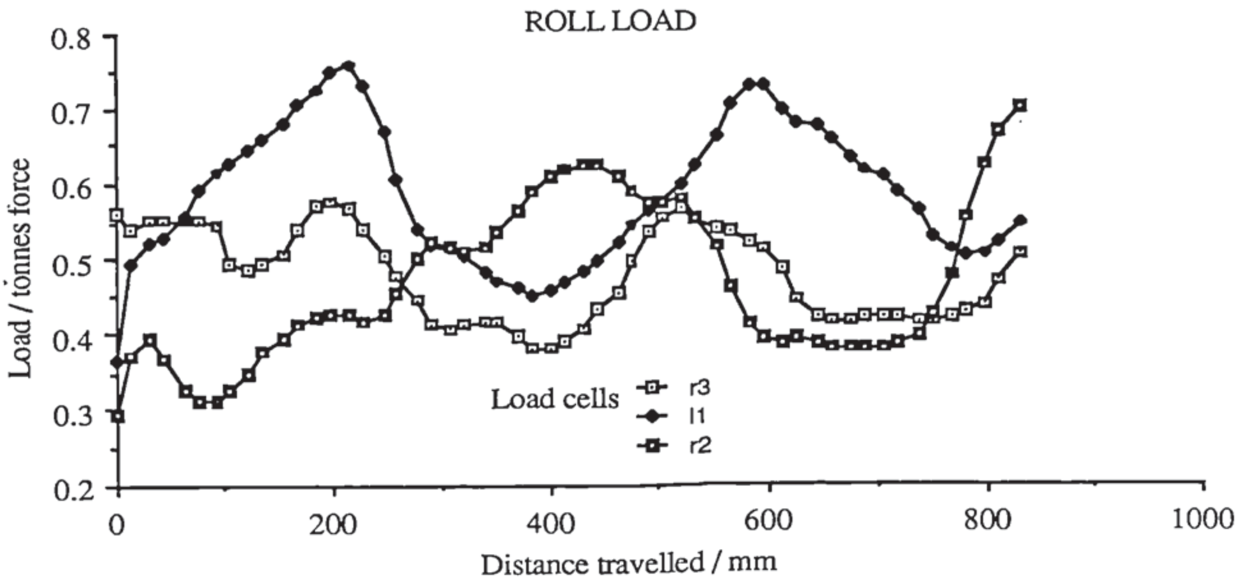


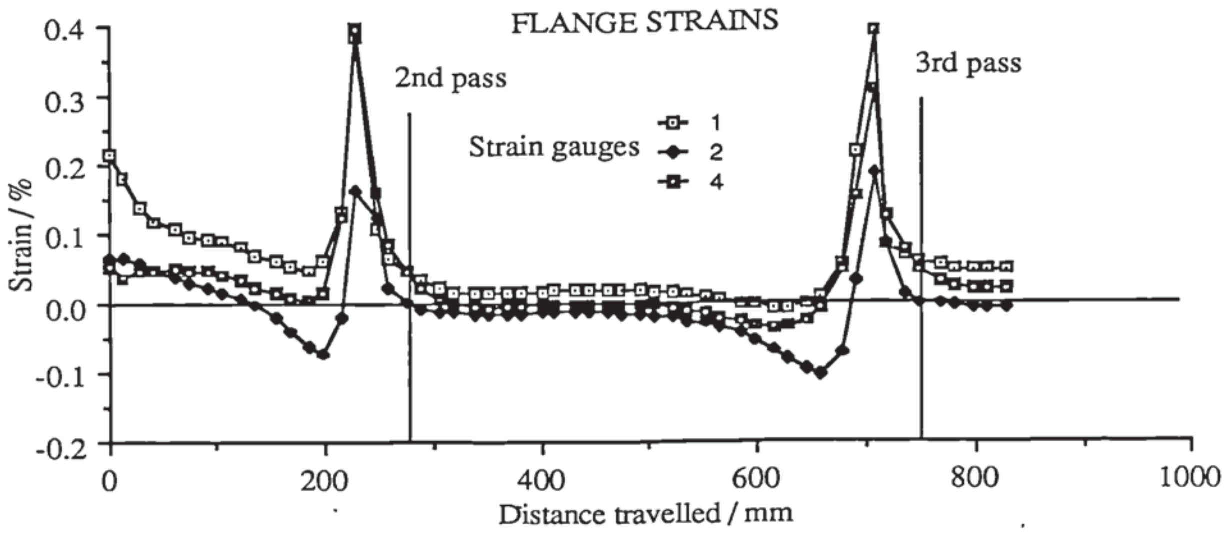
FLANGE STRAINS
1st pass
2nd pass
3rd pass
Strain gauges
1
2
4
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
1200
Distance travelled / mm

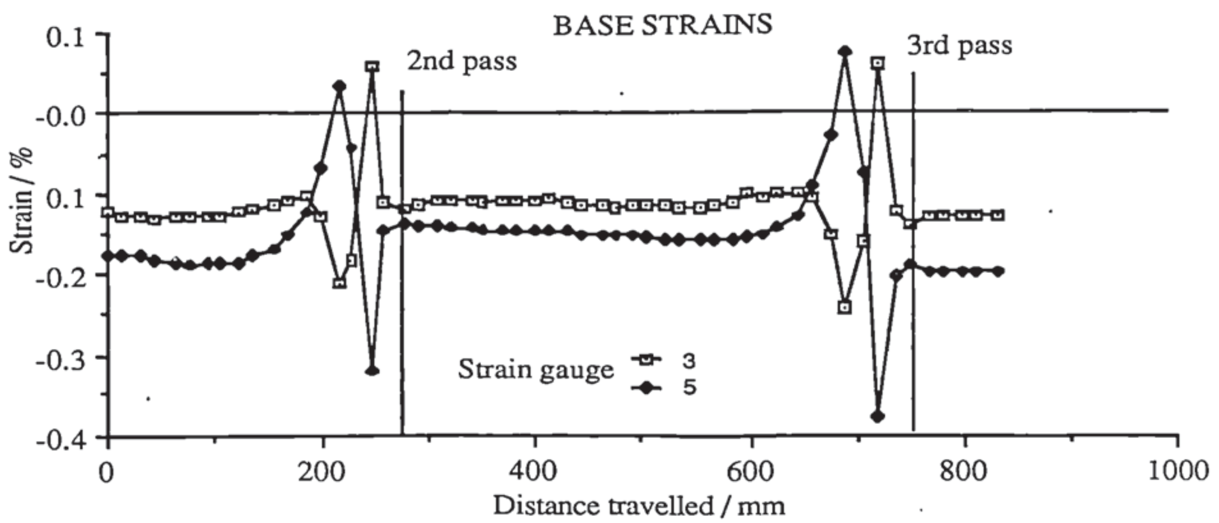


BASE STRAINS
1st pass
2nd pass
3rd pass
Strain gauge
3
5
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
1200
Distance travelled / mm

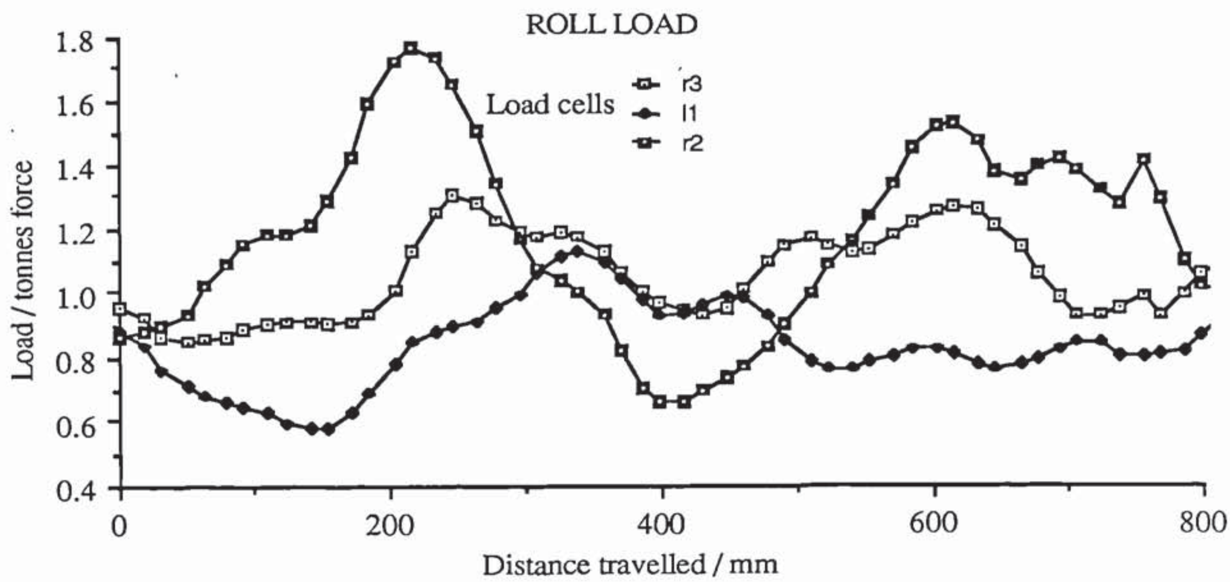
TEST 39

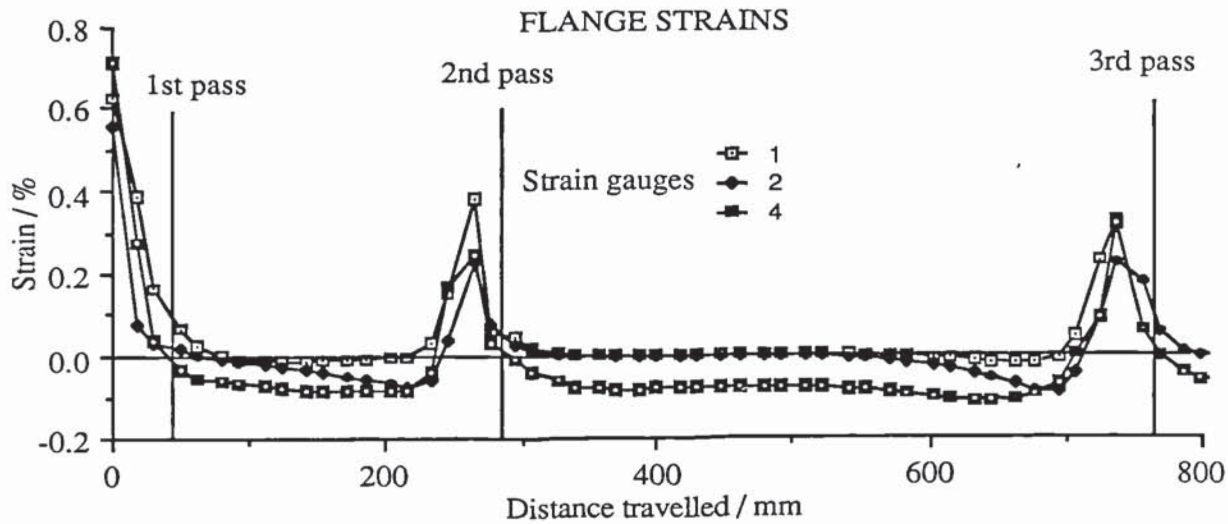

ROLL LOAD
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Load / tonnes force
Load cells
r3
l1
r2
0
200
400
600
800
1000
Distance travelled / mm

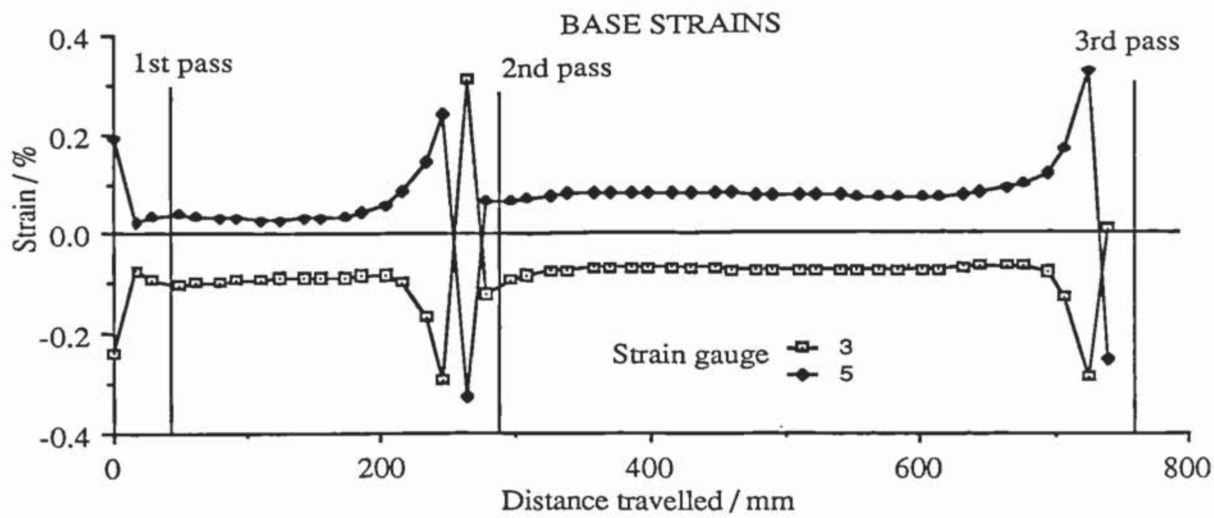

FLANGE STRAINS
2nd pass
3rd pass
Strain gauges
1
2
4
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
Strain / %
0
200
400
600
800
1000
Distance travelled / mm


BASE STRAINS
2nd pass
3rd pass
0.1
-0.0
0.1
-0.2
-0.3
-0.4
Strain / %
Strain gauge
3
5
0
200
400
600
800
1000
Distance travelled / mm

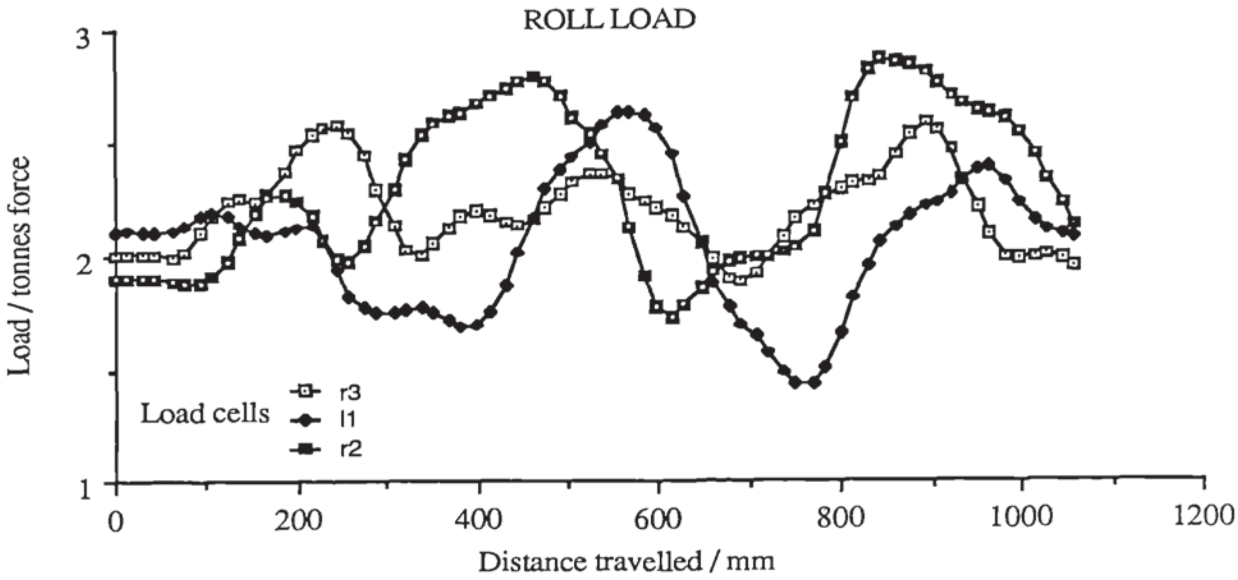
TEST 40

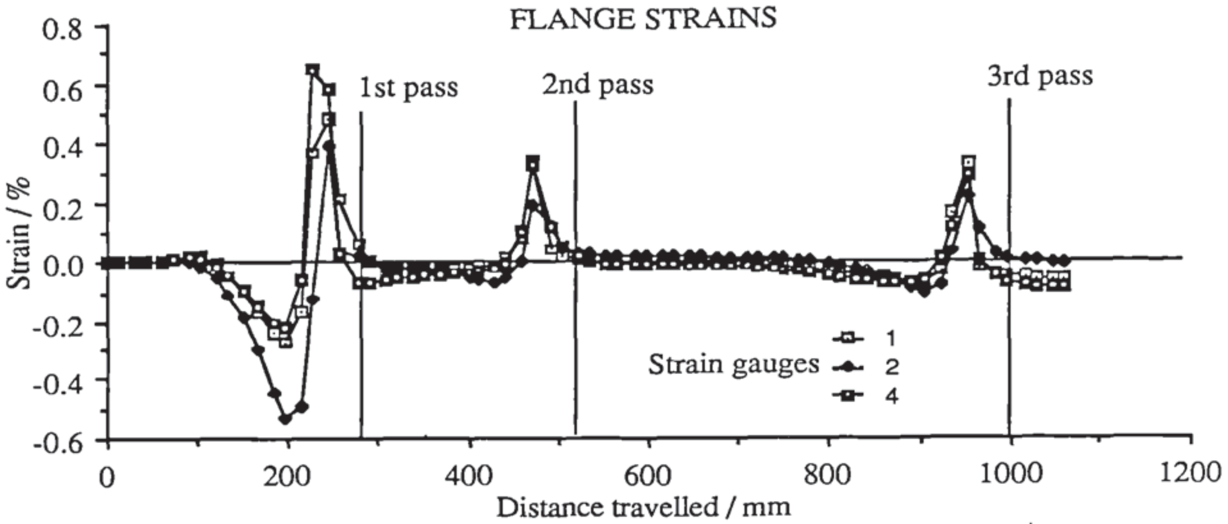

ROLL LOAD
Load cells
r3
l1
r2
Load / tonnes force
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
200
400
600
800
Distance travelled / mm

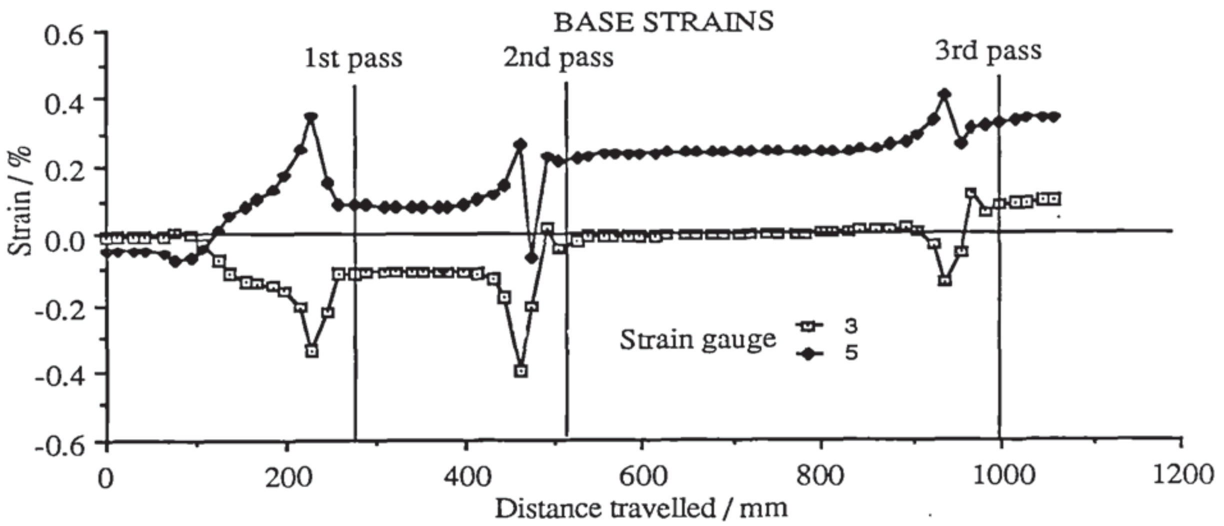

FLANGE STRAINS
1st pass
2nd pass
3rd pass
Strain gauges
1
2
4
Strain / %
0.8
0.6
0.4
0.2
0.0
-0.2
0
200
400
600
800
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
3rd pass
Strain gauge
3
5
Strain / %
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
Distance travelled / mm

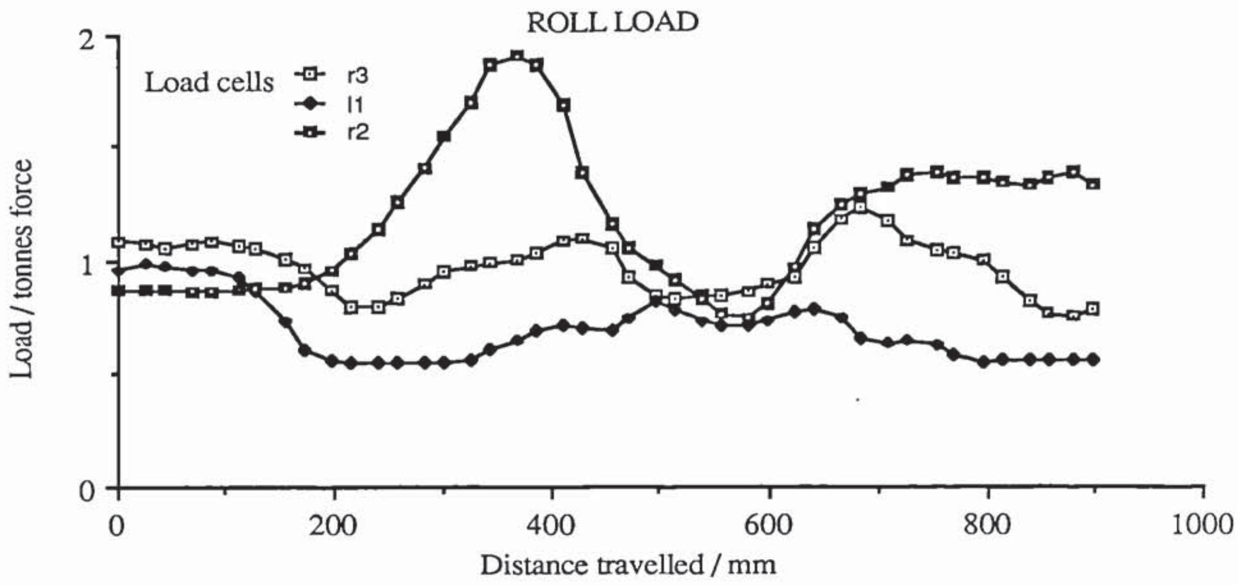
TEST 41


ROLL LOAD
Load / tonnes force
Load cells
r3
l1
r2
Distance travelled / mm
0
200
400
600
800
1000
1200
1
2
3

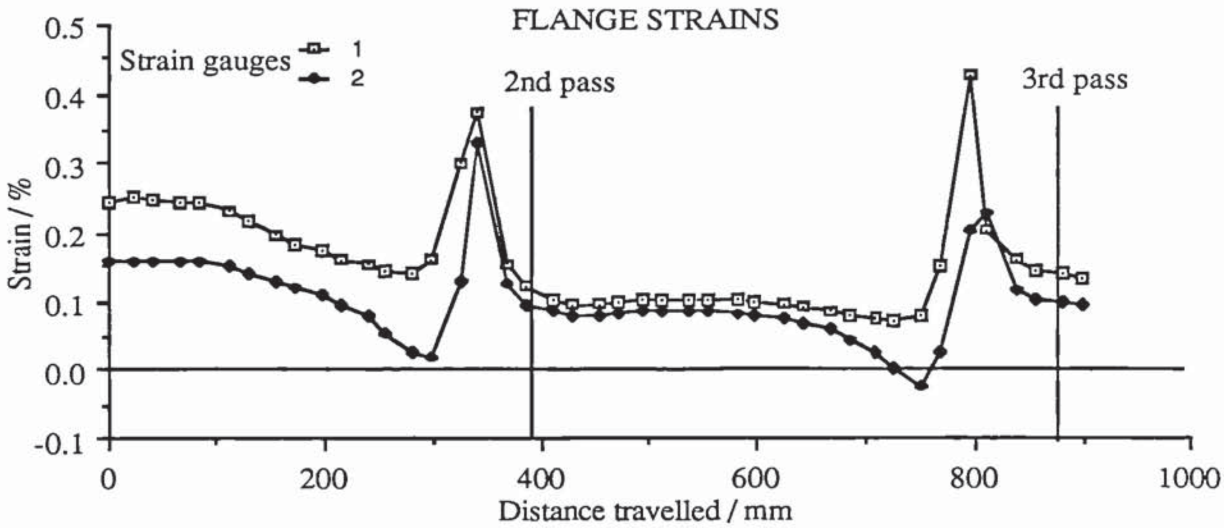

FLANGE STRAINS
1st pass
2nd pass
3rd pass
Strain / %
Strain gauges
1
2
4
Distance travelled / mm
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
1200


BASE STRAINS
1st pass
2nd pass
3rd pass
Strain / %
Strain gauge
3
5
Distance travelled / mm
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
200
400
600
800
1000
1200

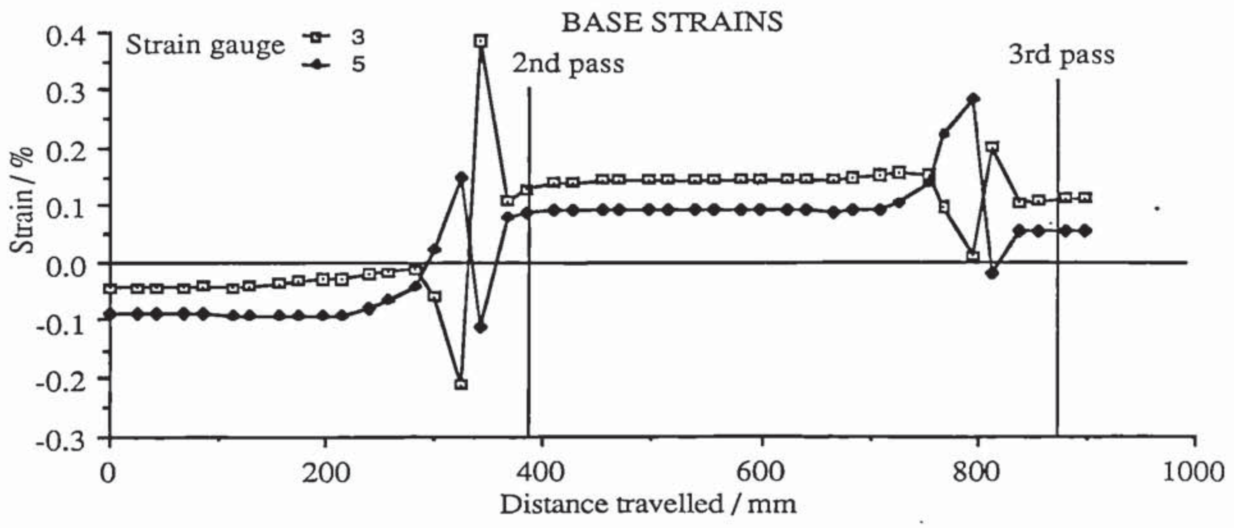
TEST 42



ROLL LOAD
Load cells
r3
l1
r2
Load / tonnes force
2
1
0
0
200
400
600
800
1000
Distance travelled / mm

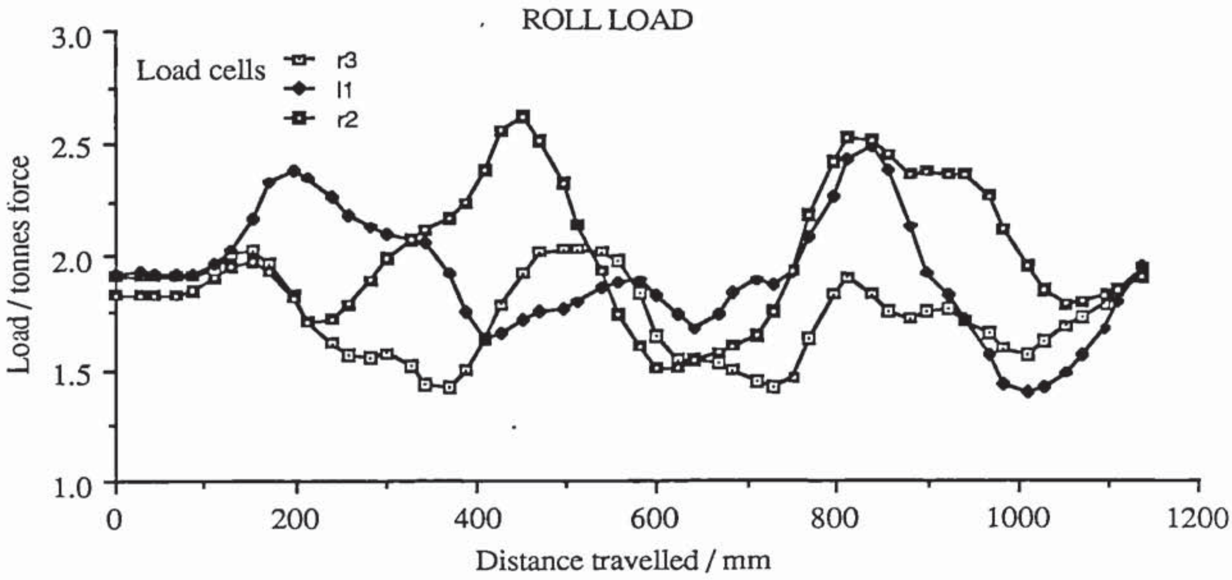


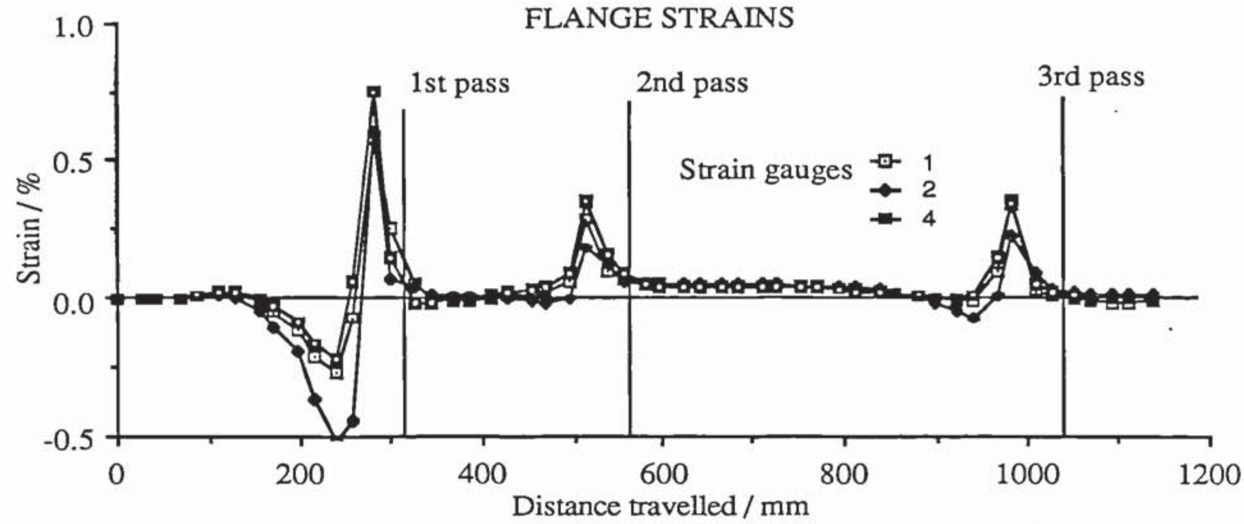
FLANGE STRAINS
Strain gauges
1
2
2nd pass
3rd pass
Strain / %
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
0
200
400
600
800
1000
Distance travelled / mm

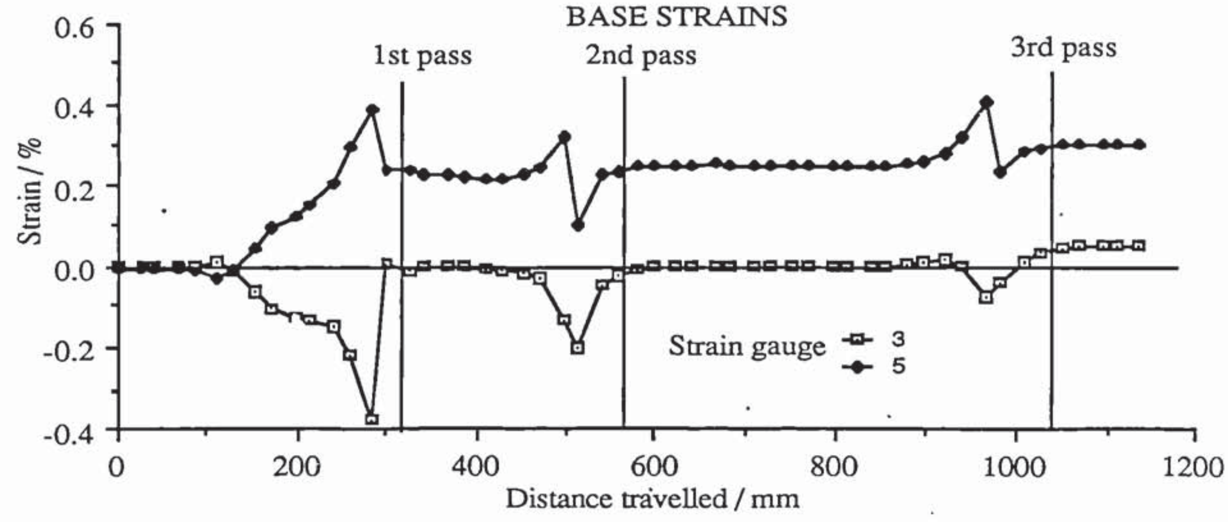


BASE STRAINS
Strain gauge
3
5
2nd pass
3rd pass
Strain / %
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
200
400
600
800
1000
Distance travelled / mm

TEST 43


ROLL LOAD
Load cells
r3
l1
r2
Load / tonnes force
3.0
2.5
2.0
1.5
1.0
0
200
400
600
800
1000
1200
Distance travelled / mm

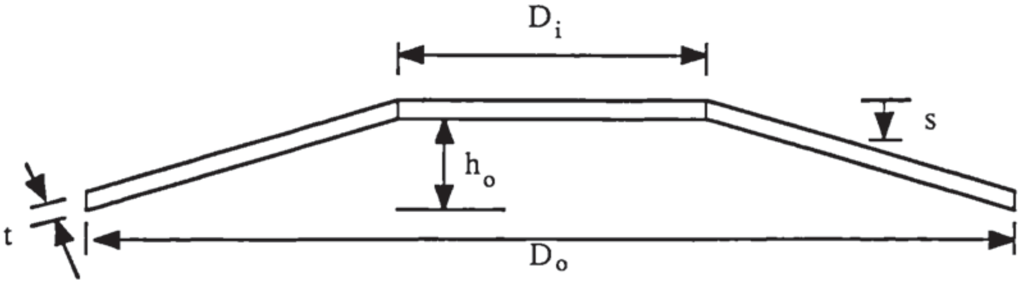

FLANGE STRAINS
1st pass
2nd pass
3rd pass
Strain gauges
1
2
4
Strain / %
1.0
0.5
0.0
-0.5
0
200
400
600
800
1000
1200
Distance travelled / mm


BASE STRAINS
1st pass
2nd pass
3rd pass
Strain gauge
3
5
Strain / %
0.6
0.4
0.2
0.0
-0.2
-0.4
0
200
400
600
800
1000
1200
Distance travelled / mm

7.9 PART TWO TESTS

In these tests, the problem of roll load control was reduced by the implementation of spring washers in the pillar. Spring washers were already incorporated into the design (diagram 6.5) and had been claimed to improve section quality consistency. However, on testing, it was shown that these washers were too small to provide any effect. They were crushed at below 0.25 tf roll load and were thus well outside their working range. A disk spring manufacturer was consulted (Metrol Springs Ltd) and suitable springs purchased.

Diagram 7.5 shows a typical disk spring washer (Belleville washer), and its dimensions.



t = thickness
h_o = maximum deflection on crushing
l = disk unloaded height
D_i = inside diameter
D_o = outside diameter
s = applied deflection

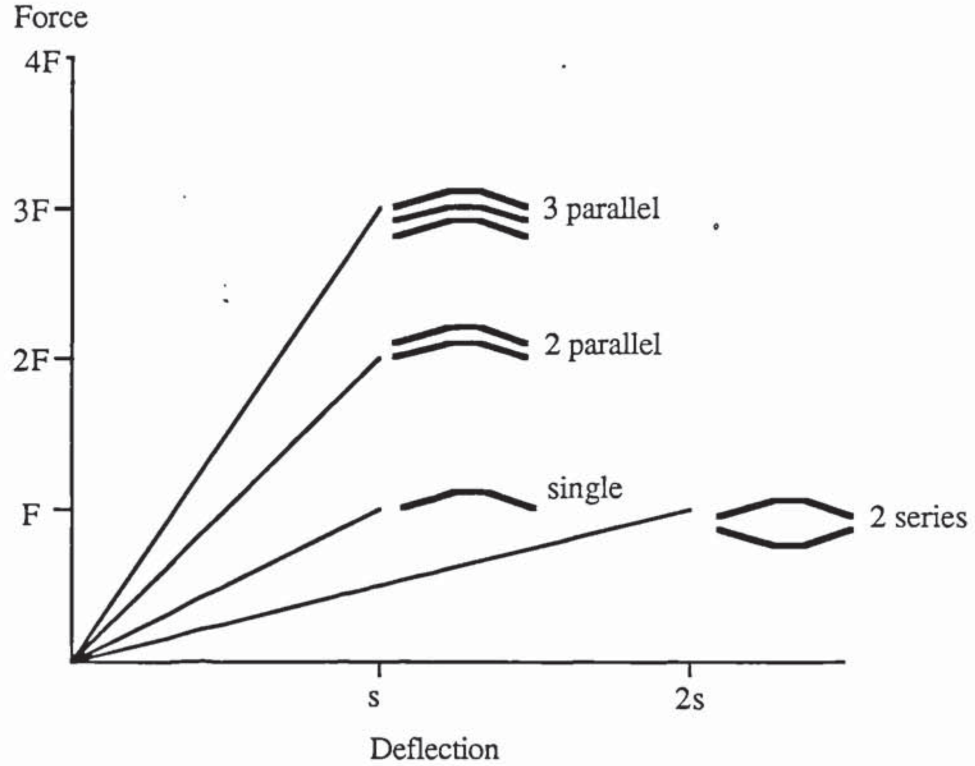
DIAGRAM 7.5 BELLEVILLE DISK SPRING DIMENSIONS

The washer was positioned under the pillar bolt on top of the sliding bearing block. This required very few changes to the pillar design, but restricted the maximum washer outside diameter to approximately 70 mm. (See photograph P7 in chapter 6).

Graph 7.1 shows the characteristics of spring washers depending on their configuration and number. Generally, a large diameter washer can be replaced by two smaller washers in parallel. The paired washers will however have a reduced maximum deflection on crushing. By pairing washers in series the maximum deflection on crushing is doubled. The ratio of s (applied deflection) to h_o (maximum deflection on crushing) ideally should be low, for a low deviation in load.

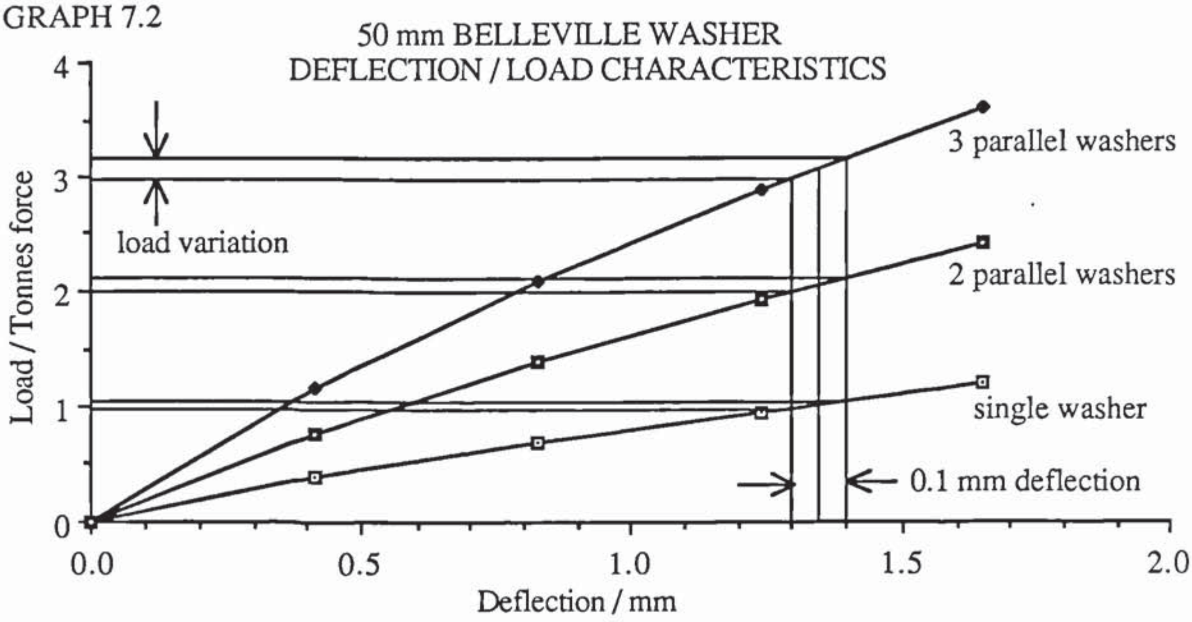
The applied deflection in the tests was caused by the eccentricity of the roll bearings and the small variations in strip thickness. In total, these were measured at a maximum of 0.12 mm using a dial gauge placed against the top roll.

GRAPH 7.1 BELLEVILLE DISK SPRING CHARACTERISTICS



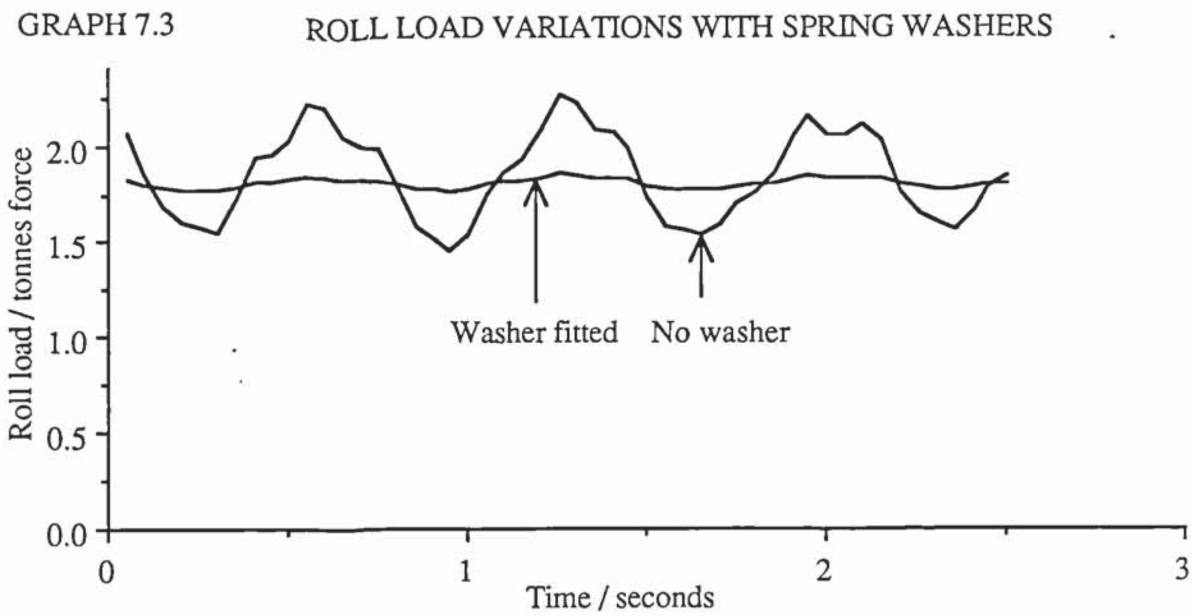
Graph 7.2 shows the particular deflection load characteristics for a 50 mm outside diameter washer in three cases. This washer was suitable for the tests in part two, as loads of up to 3 tf could be maintained within the ranges shown for a 0.1 mm deflection. By pairing the washers in series, the load range could be further reduced, although for the 3 tf case the height of the six washer stack was too high to fit in the roll pillar.

GRAPH 7.2



The improvement in roll load consistency is illustrated in graph 7.3. The use of two 50 mm spring washers in parallel reduces the load oscillation amplitude considerably.

GRAPH 7.3



Note, in the part two tests, the roll load remained constant (+/-5%), so it was not necessary to display the load graph in the results. The value of the load is shown at the top of each test graph.

7.10 GROUP (H) RESULTS

Description ; three tests rolling, through two passes, using three roll loads.

	Roll Load: low		Roll Load: med		Roll Load: high	
low speed	44	--25.4 10.1	45	-102.0 6.1	46	48.7 3.3
	-0.3	0.4	-0.7	0.0	-0.8	-0.2

TABLE 7.8 GROUP (H) QUALITY MEASUREMENTS

The control of roll load allows these tests to illustrate more clearly points deduced from the part one tests.

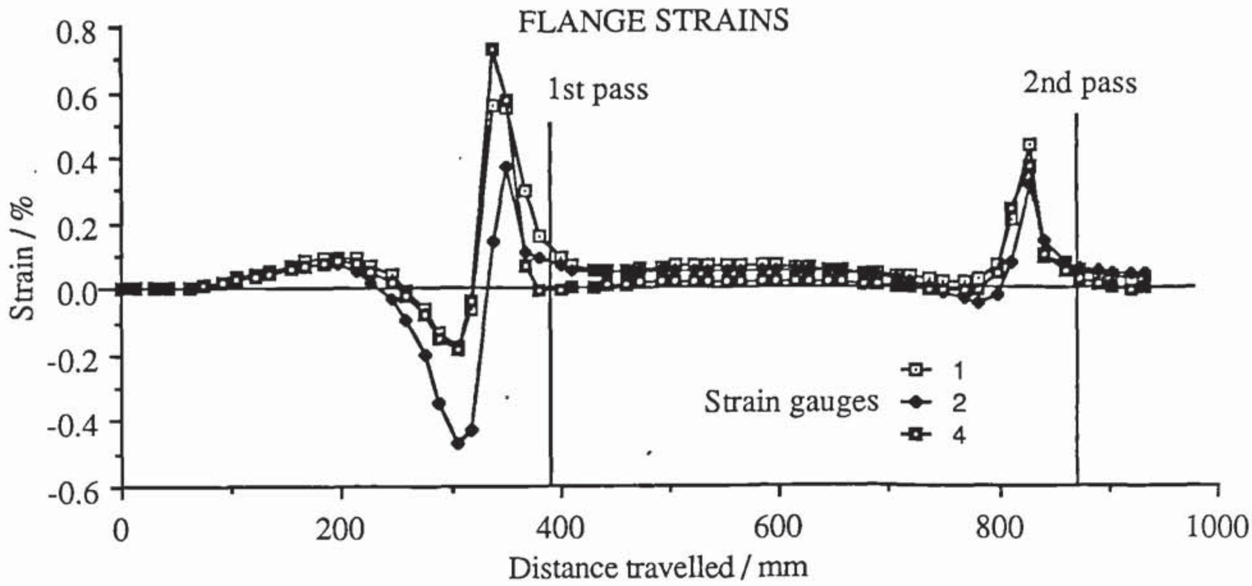
The familiar flange strain profile is produced, with all the features repeated from the previous two pass test (Group C). Close control of the roll load has not produced any different effects.

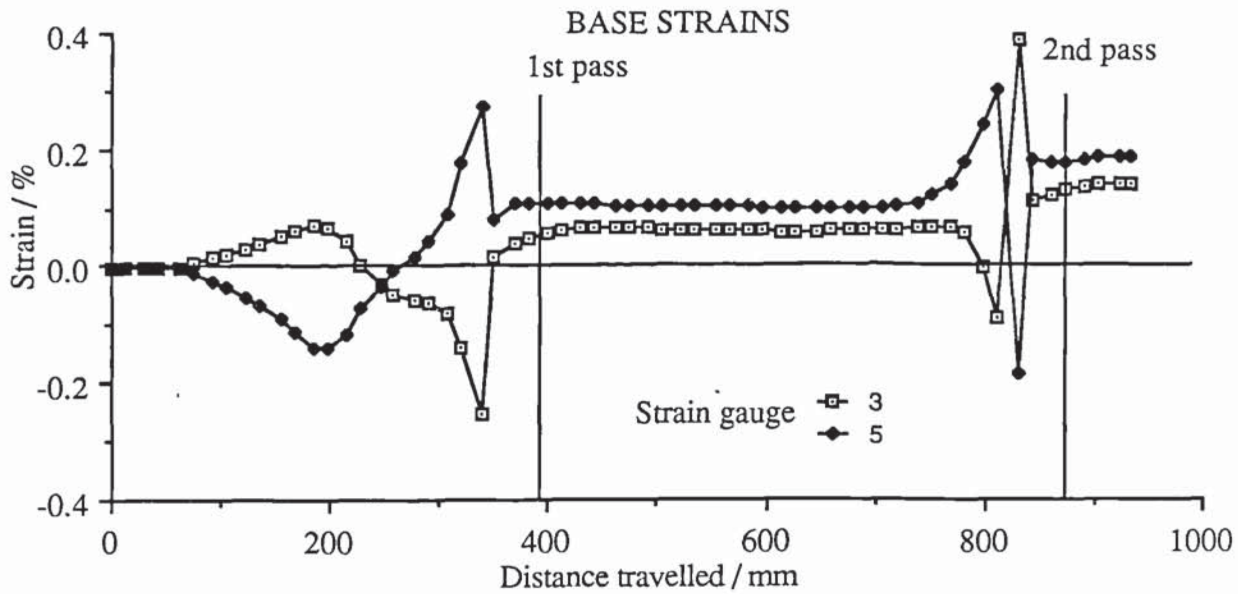
These tests confirm observations made on earlier tests, i.e. increased roll load increases the tensile base straining and positive curvature in the section. Also the peak load strains at both passes are increased with increased load.

Left angle errors are all negative, whereas right values are of both signs. The values are similar in range to those of earlier two pass tests (Group C and D).

TEST 44

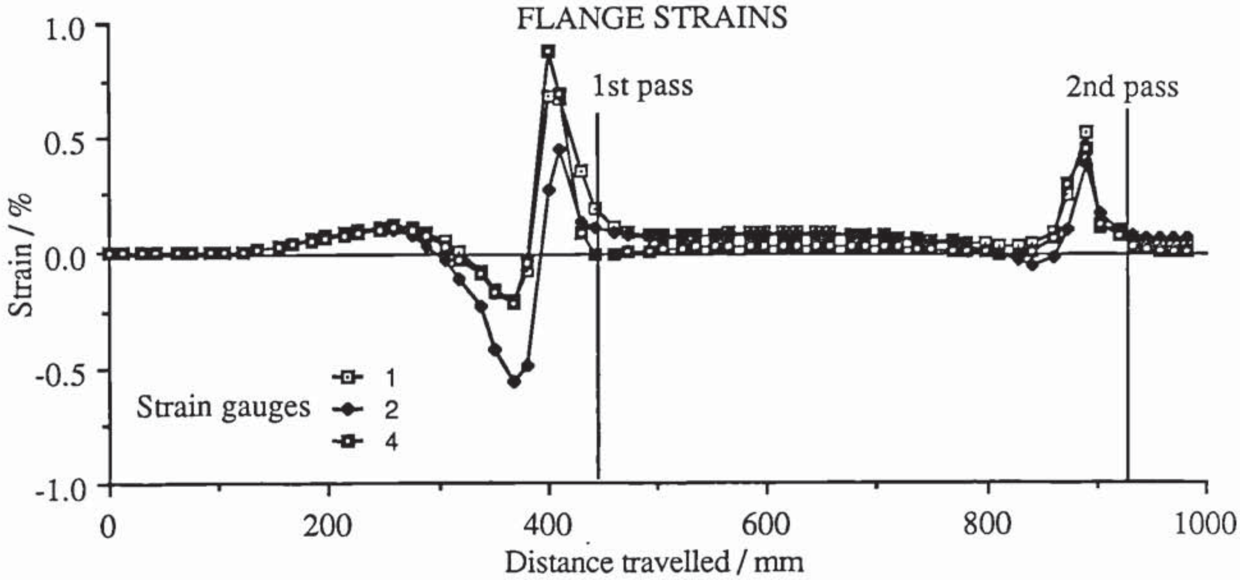
ROLL LOAD = 1 tf

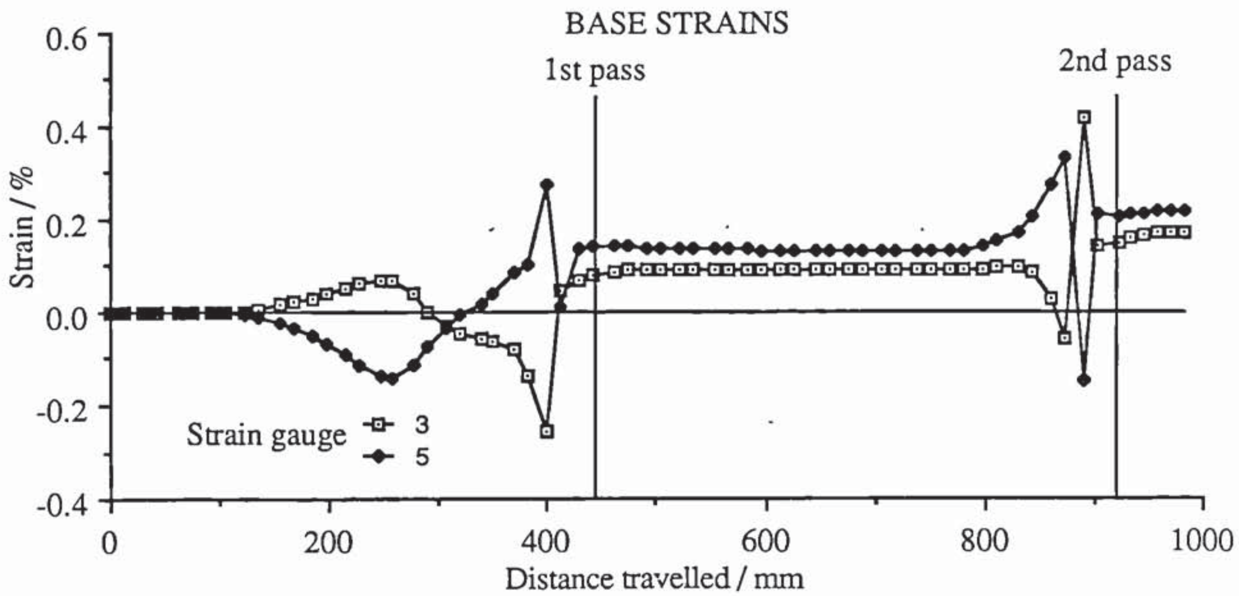




TEST 45

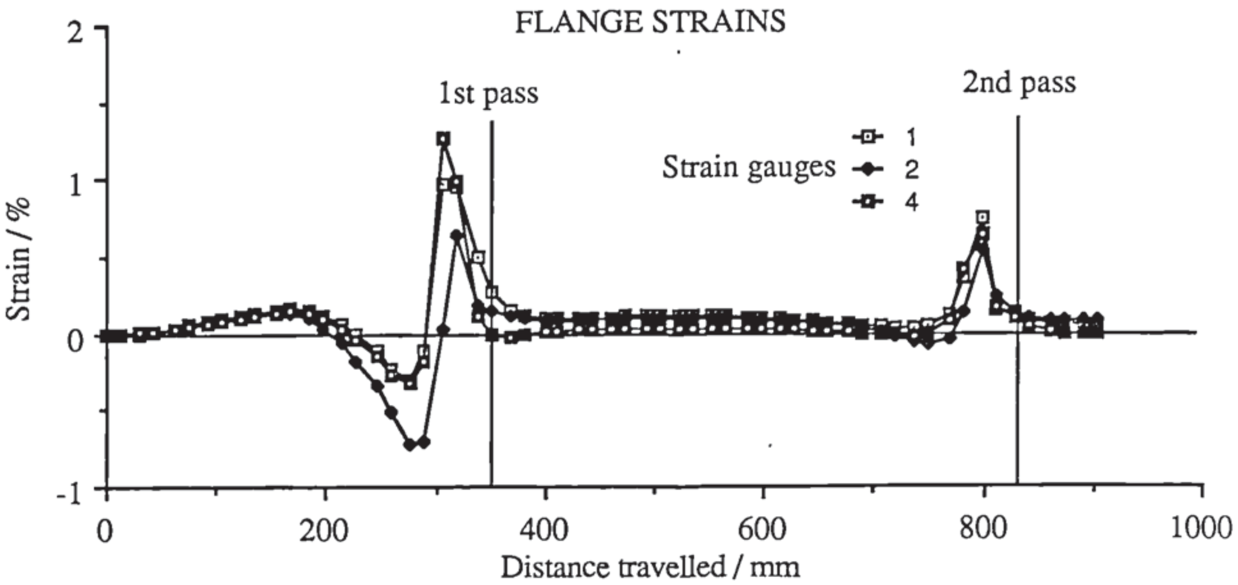
ROLL LOAD = 2 tf

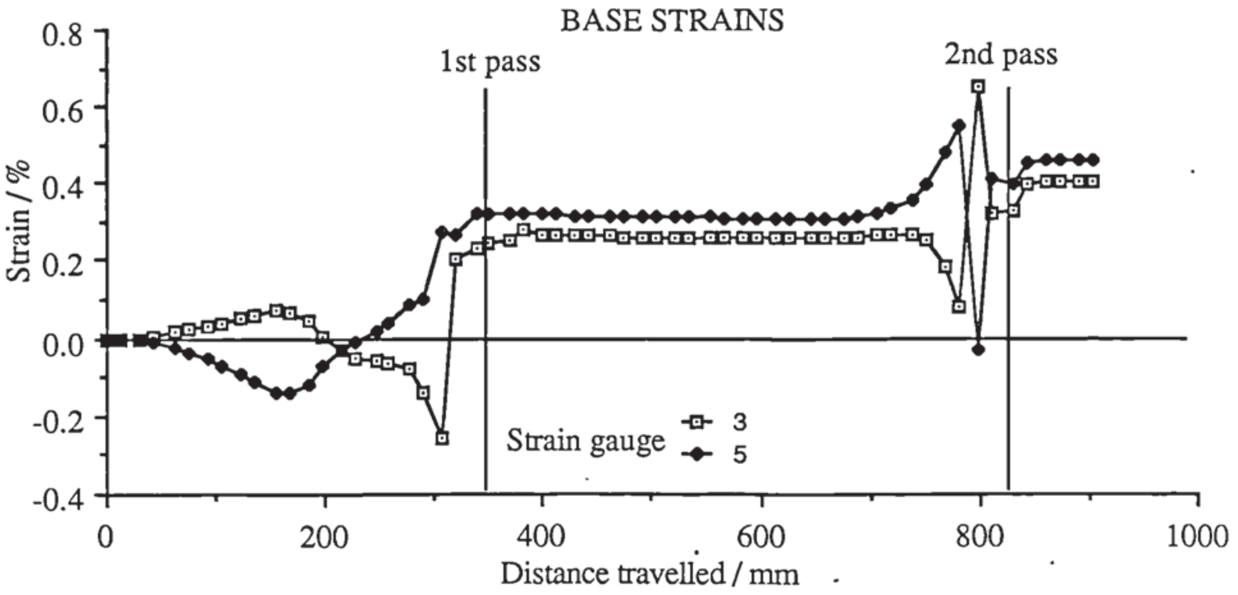




TEST 46

ROLL LOAD = 3 tf





7.11 GROUP (I) RESULTS

Description ; three tests, rolling through two passes, the second pass with an increased diameter bottom roll, using three roll loads.

	Roll Load low		med		high	
low speed	**47**	31.2 5.4	**48**	11.9 5.3	**49**	6.3 4.4
	-0.6	0.0	-0.8	-0.3	-1.1	-0.7

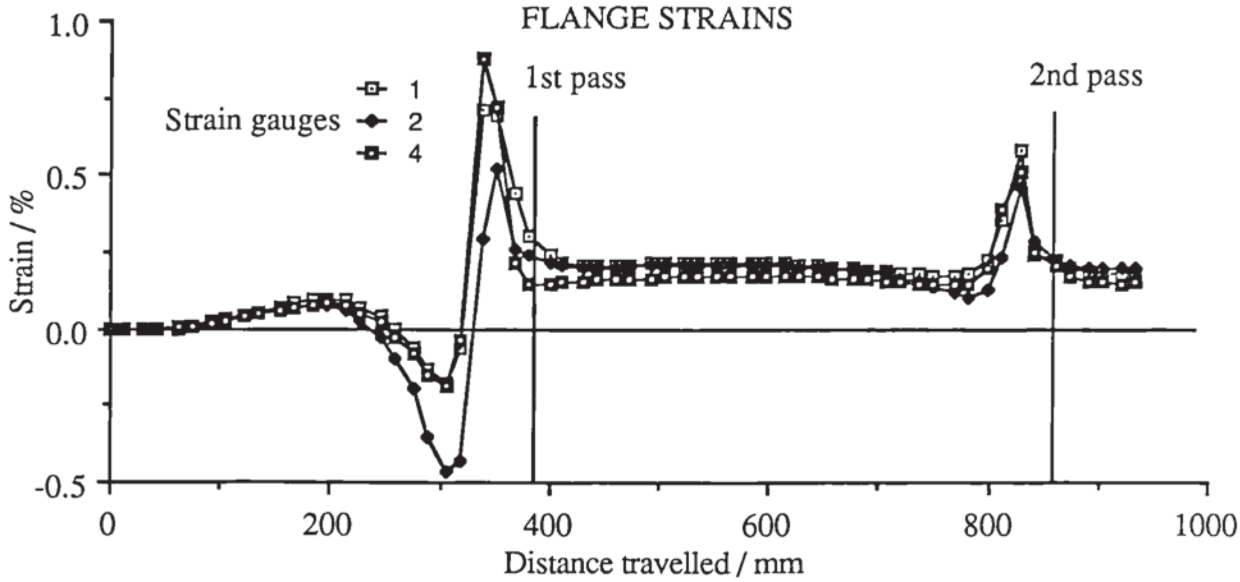
TABLE 7.9 GROUP (I) QUALITY MEASUREMENTS

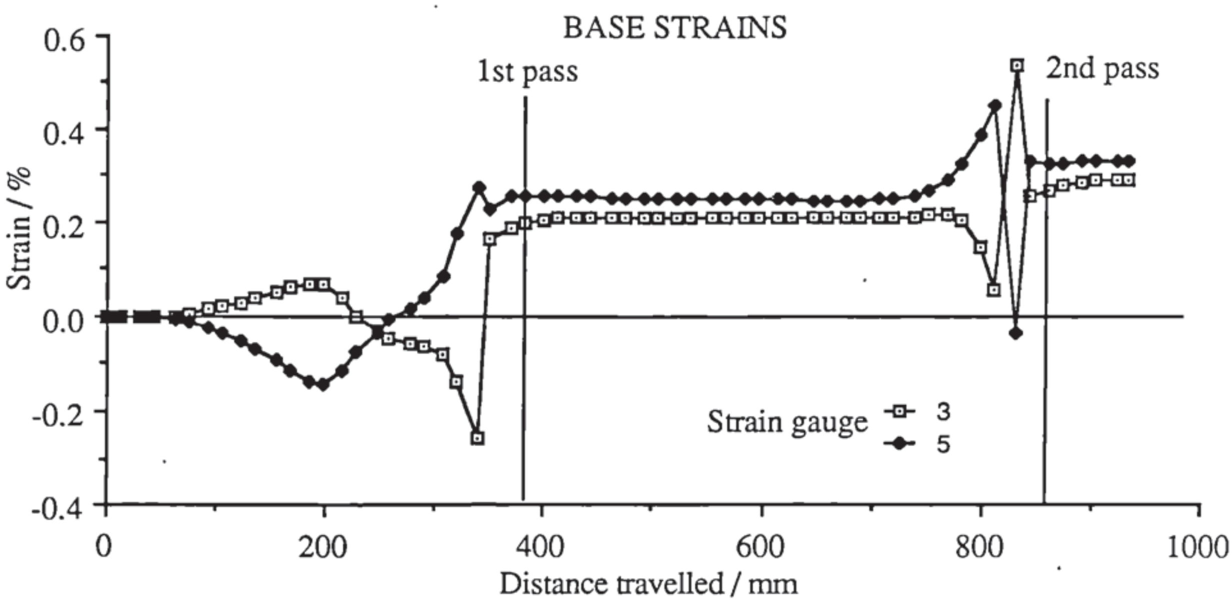
The main point to be illustrated by this graph is that, the increase in surface speed of the second pass has caused increased tensile straining in the section base, so influencing curvature. The effect of the differential roll surface speed is increased with increasing roll load. Curvature is greatly influenced by this speed parameter. Twist remains unaffected.

The angle errors appear of increased negative value to those in Group (J).

TEST 47

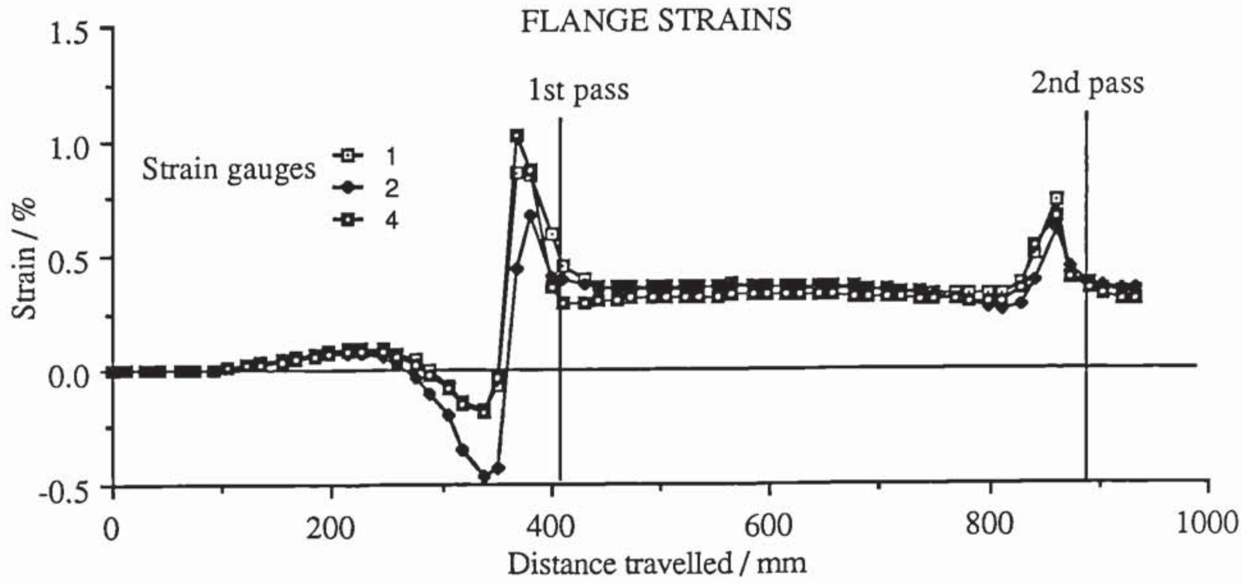
ROLL LOAD = 1 tf

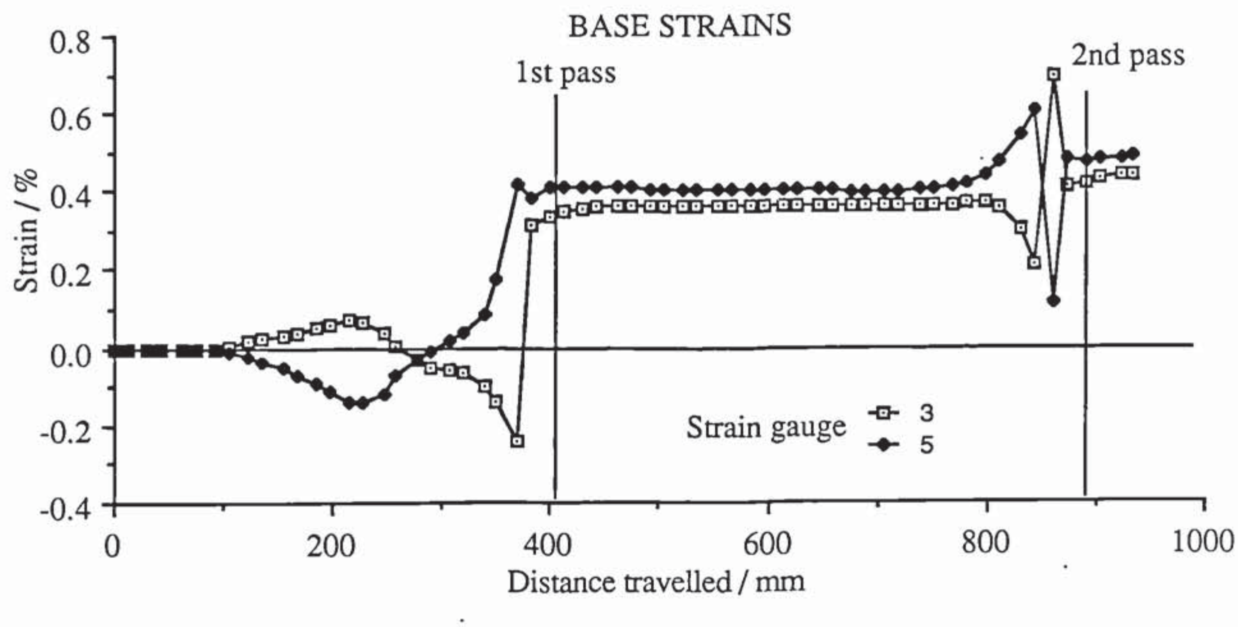




TEST 48

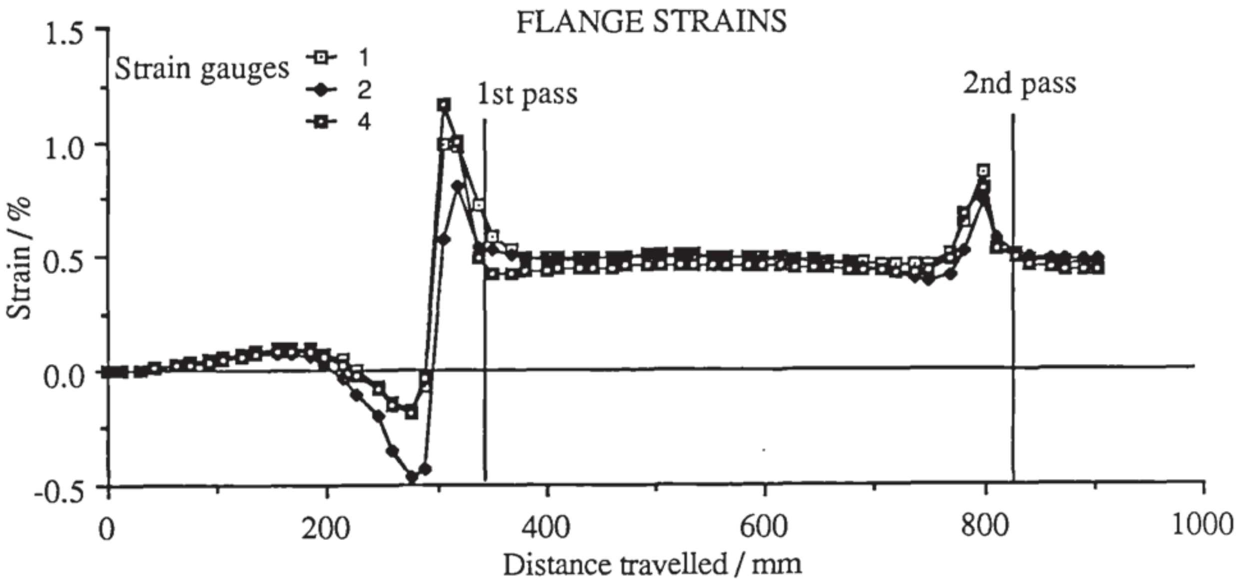
ROLL LOAD = 2 tf

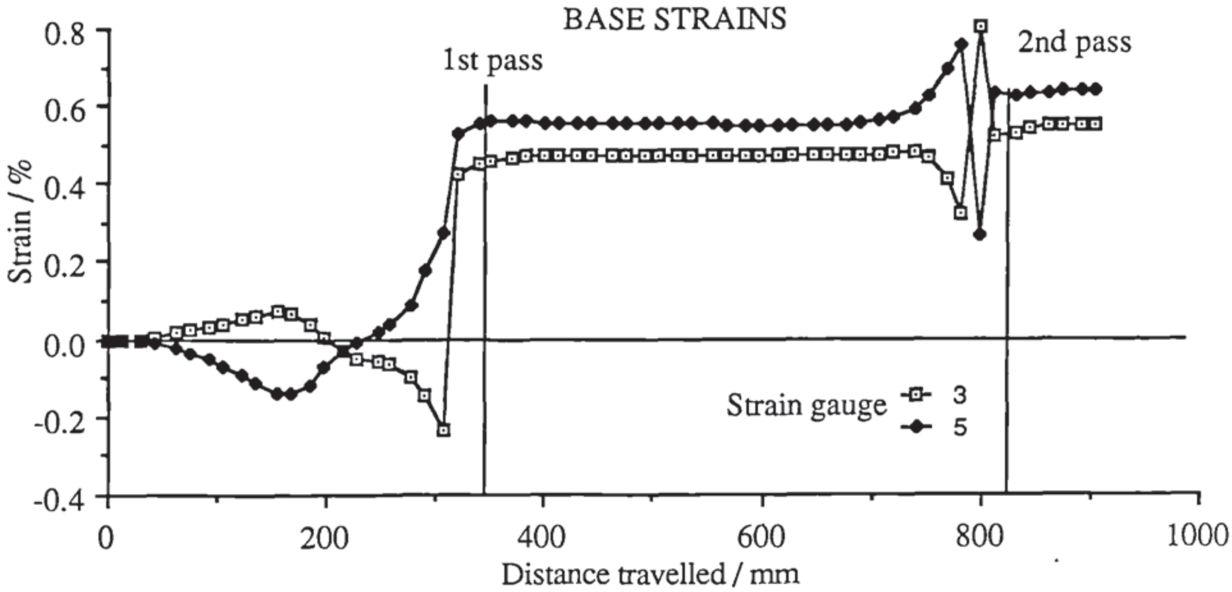




TEST 49

ROLL LOAD = 3 tf





7.12 GROUP (J) RESULTS

Description; one test, rolling through one pass with the complete roll pillar assembly reversed.

	med roll load	
low speed	50	-14.6 6.1
	-0.7	-0.3

TABLE 7.10 GROUP (J) QUALITY MEASUREMENTS

Diagram 7.6 shows the effect on curvature when the top roll is not located vertically above the bottom roll. This situation could arise if there was play in the pillar slideway, or bearings. (Note the pillars used in the tests were new, with little play). By reversing the whole pass as in this test, the importance of the vertical roll alignment to curvature could be estimated.

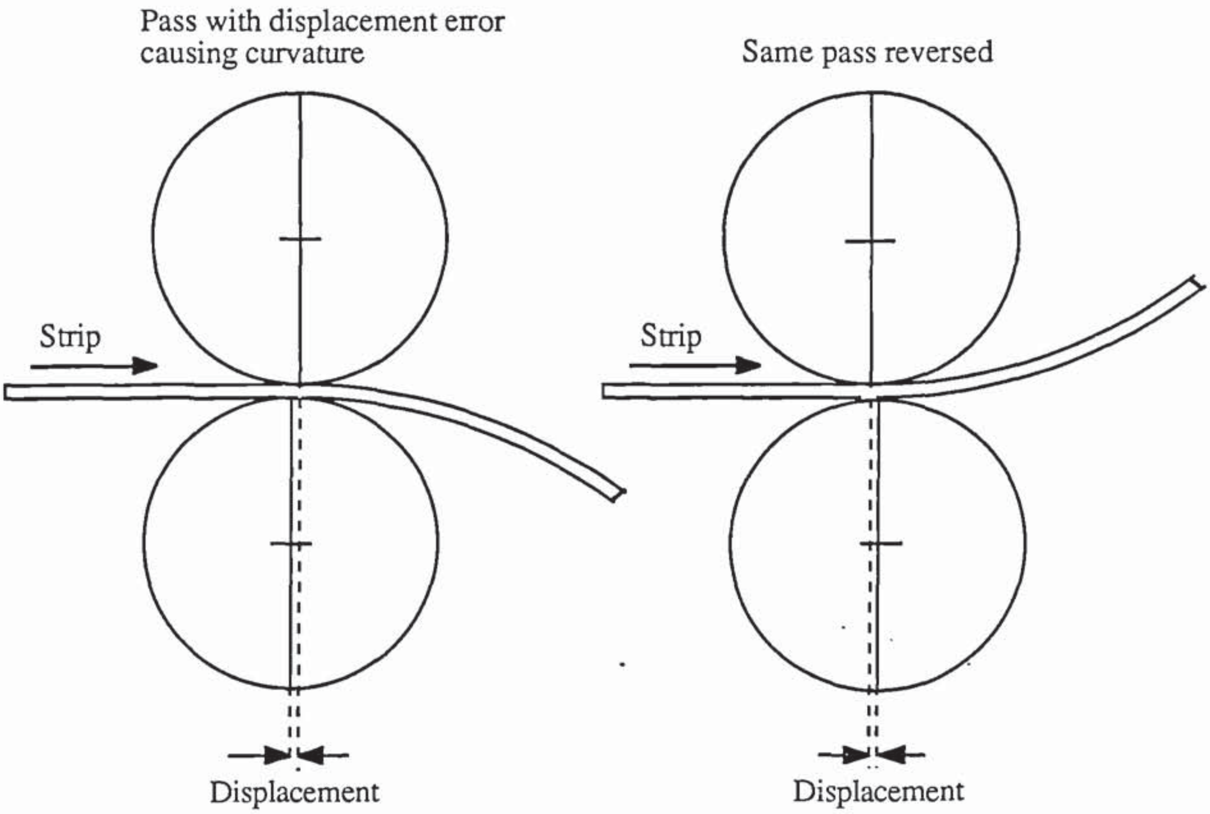


DIAGRAM 7.6 PILLAR DISPLACEMENT ERRORS

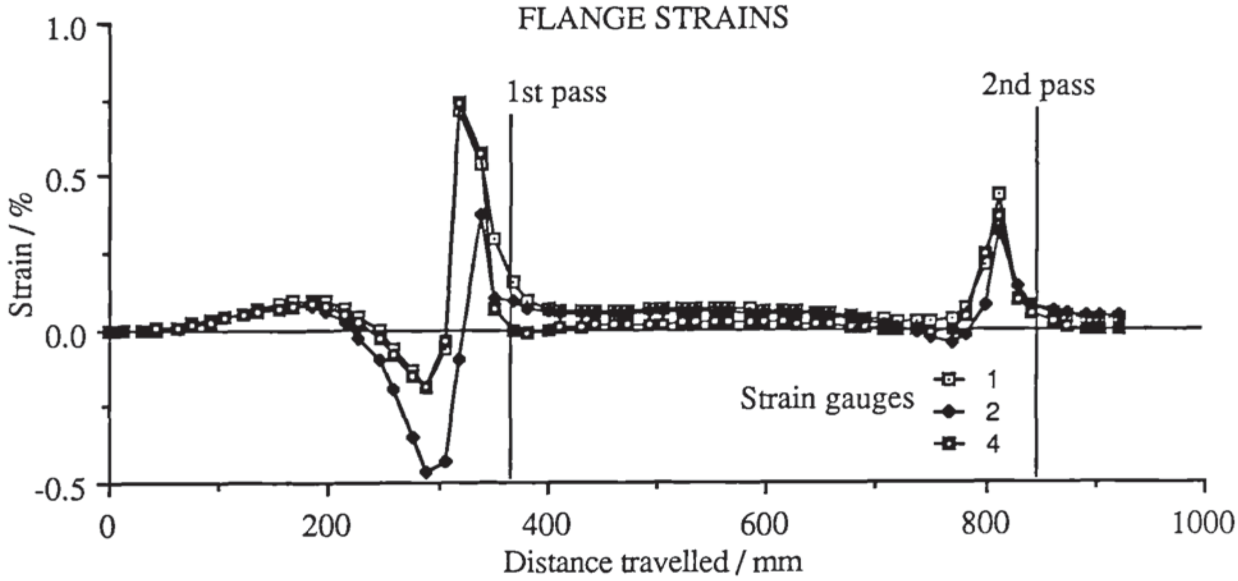
The strip material had to be put into the rolls with the nominally righthand gauges 1 and 2 on the left side and 4 on the right, due to the reversal of the pass (the cut-outs were now also reversed).

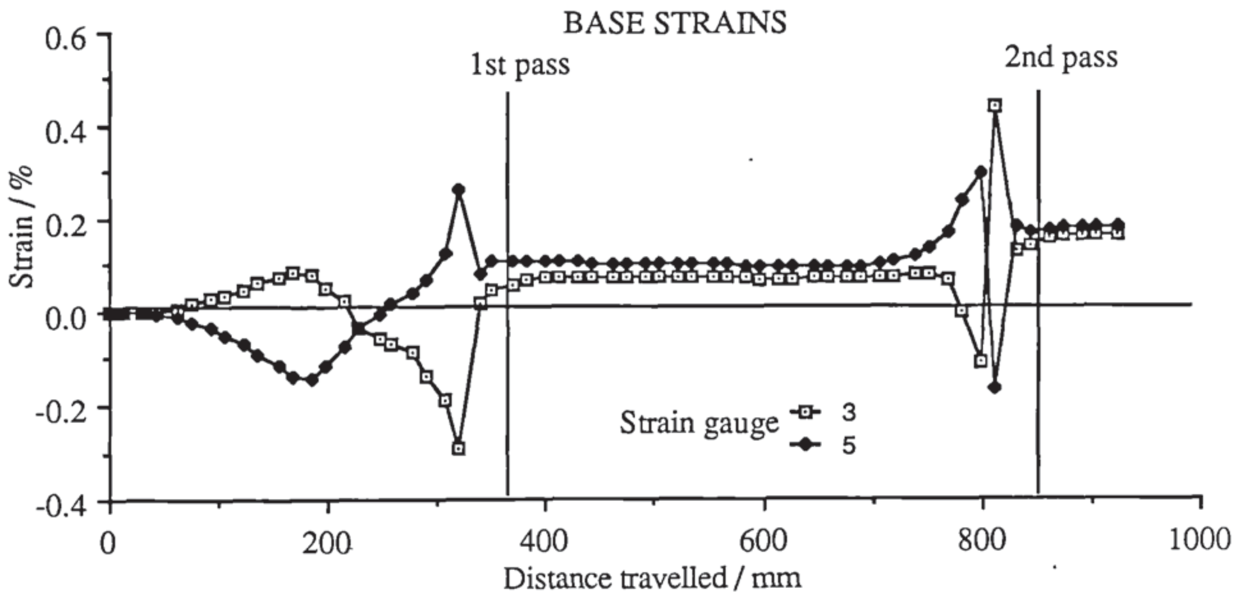
The test shows that there is very little change in the resultant curvature or strain profile. This may indicate that the roll pillars were vertically true with little play, or that the rolls take up the same vertical position which ever way round the pass is located.

Also, the test shows that the geometry of the rolls is contributing to the twist in the section. In this test the twist is positive, but in the equivalent test 45 twisting is negative. Asymmetry in the rolls (due to the cut-outs) or in the relative position of top and bottom rolls, may be the cause of this twisting.

TEST 50

ROLL LOAD = 2 tf





7.13 GENERAL DISCUSSION OF RESULTS

7.13.1 VARIABILITY

To find variability in quality, a series of six tests were repeated under nominally the same operating conditions. The tests were rolled under the same condition as Test 45, but without strain gauges. Results are shown in table 7.11. Curvature, twist and springback all vary within a range of values, confirming the lack of control of parameters affecting quality.

	Test 45	Repeat 1	Repeat 2	Repeat 3	Repeat 4	Repeat 5
Radius of Curvature /m	-102.0	-63.0	-72.4	-222.7	-108.0	-78.4
Twist degress / m	6.1	11.3	10.0	7.7	5.9	9.2
Left bend error / degrees	-0.7	-0.7	-0.7	-1.0	-0.4	-0.5
Right bend error / degrees	-0.0	-0.1	-0.0	-0.1	-0.3	-0.3

TABLE 7.11 VARIABILITY TESTS

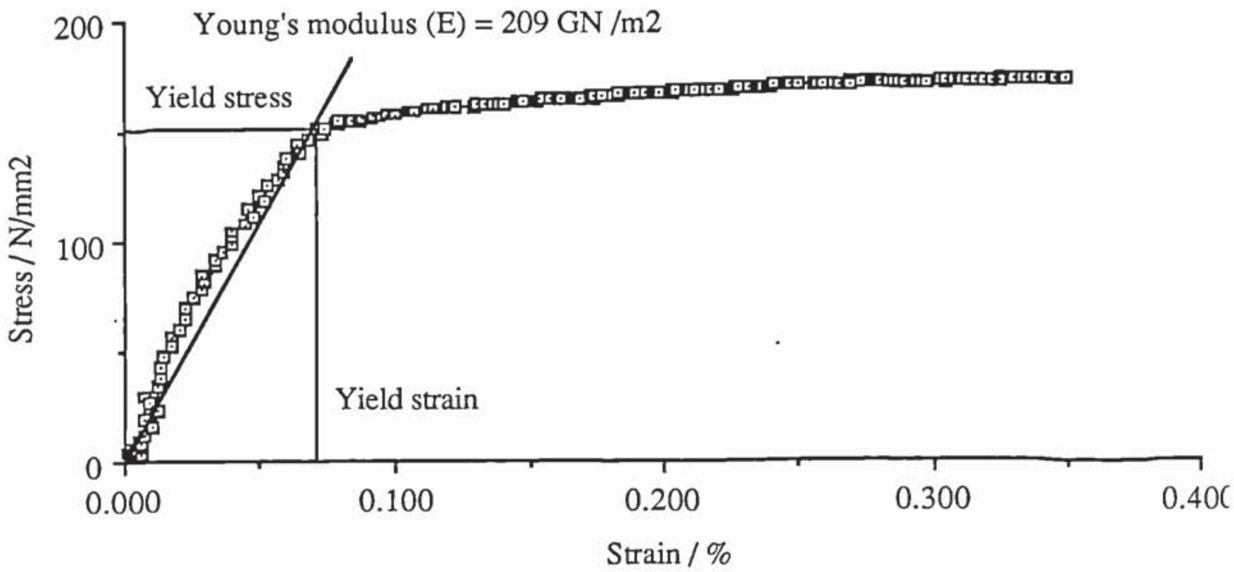
7.13.2 FLANGE STRAINS

Flange strains in all the tests follow a pattern of peaking approximately 45 mm before each pass. Jimma [163] found that the maximum longitudinal strain occurred at a distance nearly equal to the leg length in front of the pass. For this section that distance is 50 mm, hence these results reinforce the observation.

With increasing roll load, the peak flange strains are increased, as too is the strain on exit from the rolls and residual strain. In all cases the increases are tensile. Flange strains peak, exceeding the elastic deformation region of the metal and hence must induce plastic longitudinal straining.

Graph 7.4 shows the low strain portion of the stress-strain curve for CR3, derived experimentally on an Instron tensile testing machine. Yielding takes place at approximately 150 N/mm^2 stress, corresponding to a yield strain of 0.07%. Any strain above 0.07% in the strain profile must indicate yielding and hence permanent plastic deformation.

GRAPH 7.4 STRESS-STRAIN CURVE FOR CR3



Edge strains are generally thought (e.g. 120 126 114) to be caused by stretching due to the path followed by the strip, and straining due to flattening. Bhattacharyya (120,127) also included a third factor due to reverse bending when the strip contacts the following pass (obviously not present in one pass tests). The increases of strain with load can only be due to the affect of flattening, as the strip path remains the same. Hence, although the roll gap at the flanges is higher than at the base, some load must be being applied there.

The edge strains peak with approximately 1% strain, with each 1 tf of roll load adding 0.2%. A lower increase in strain is found in the strain on exit from the passes; about 0.1% per 1 tf. The first pass is exceptional in its flange strain profile, straining is more severe and fluctuates more widely from compressive to tensile peaks than following passes. Formation of the plastic bend (section 5.4) has been used to explain this individuality and certainly the pattern of straining indicates a unique metal shape on approach and entry to the first pass. The earlier experimental work, measuring strains from scribed grids (Chapter 5), shows very similar patterns and levels of straining to those of the tests, adding strength to their validity.

The model used by Bhattacharrya to calculate the peak edge strain is ;

$$e = \frac{\delta l}{L} = \sqrt{1 + \frac{2a^2}{L^2}(1 - \cos\theta)} - 1$$

The equation is derived from purely geometric considerations, and the value of L, the deformation length, comes from minimisation of plastic work (Appendix 1) giving;

$$L = \text{Deformation length} = a\sqrt{\frac{8a\theta}{3t}}$$

For the first pass

$a = 50$ mm $\theta = 30° = 0.52$ rad $t = 1.5$ mm

The deformation length L is calculated to be 341 mm.

The longitudinal peak edge strain is calculated to be 0.288%

For the second pass and third pass

$a = 50$ mm $\theta = 15° = 0.26$ rad $t = 1.5$ mm

The deformation length L is calculated to be 241 mm.

The longitudinal edge strain is calculated to be 0.147%

The values calculated are similar to the experimental strains found at the exit from passes, however they are not close to the peak edge strains. A further model is used to calculate the residual strain after leaving the final pass. Elastic strain (labelled the recovery strain),which is released as the confines of the roll geometry are left, is subtracted from the peak strain to give the residual strain;

residual strain = peak strain - recovery strain

$$e_r = e_{peak} - \frac{3He_y}{\left[bt^2 + \frac{2(H^3 - t^3)}{\sin\theta}\right]}\left[\frac{bt^2m}{3H} + \frac{1}{\sin\theta}\left(H^2 - \frac{H^2}{3m^2} - \frac{2mt^3}{3H}\right)\right]$$

For the first pass;

Flange height $H = 25$ mm

Yield strain $e_y = 0.00067$

Peak strain $e_{peak} = 0.00288$

Strain ratio $m = e_{peak} / e_y = 4.299$

Base width $b = 40$ mm

Thickness $t = 1.5$ mm

Residual strain = 0.00189 = 0.19%

Peak strain = 0.00288 = 0.29%

Recovery strain = 0.00099 = 0.10%

For the second pass

Residual strain = 0.00054 = 0.05%

Peak strain = 0.00147 = 0.15%

Recovery strain = 0.00093 = 0.09%

For the third pass

Residual strain = 0.00053 = 0.05%

Peak strain = 0.00147 = 0.15%

Recovery strain = 0.00094 = 0.09%

The models are based on several assumptions.

1. The material can be treated as rigid-perfectly plastic.
2. Bending only takes place along the fold line.
3. The leg adopts the shape which minimises plastic work.
4. The deformed strip leaves the forming station with the peak strain at its edge, i.e. the peak strain occurs at the vertical plane through the centres of the rolls.
5. Pure bending occurs in the vertical plane, without any warping or twisting.
6. The neutral plane coincides with the bottom of the flange, and there is a linear strain distribution in the flange.

The inaccuracies inherent in these assumptions must lead to inaccuracy in the model, and may explain the discrepancy between experimental and theoretical results. Taking each assumption in turn as numbered above;

1. The stress-strain curve for CR3 (graph 7.4) is clearly not rigid perfectly plastic. Strain hardening takes place, and the yield point is not clearly defined.
2. In formation of the first pass profile, there is no clear point of folding, subsequent passes do however hinge around the fold. It is clear that the highest transverse strains must be at the folds, however lower transverse strains must be introduced by the flattening action of the rolls, and may formed by the longitudinal strain patterns, in the same way that Poisson strains are formed.
3. Minimisation of plastic work is an assumption made by several of the models, and cannot be experimentally verified by these tests. However it appears logical that a section will relax so that strains balance into a pattern using the least energy, rather than a higher energy.
4. Experimental results clearly show that the peak strain occurs before the first pass, and leaves with a value slightly above the residual strain. It is true that the peak strains occur at the flange edge, although the peak strains in the centre of the flange are often very close to the edge strain values.
5. The assumption implies there is no overall straining in the base of the section. At high loads this is untrue, since tensile straining is introduced. Also, as stated, the strain at the centre of the flange is not usually half the strain at the flange edge, hence, the relationship between flange height and strain is not linear.

For the first pass, the deformation length is calculated as 341mm, and for the second and third passes 241 mm. Tests show that for the first pass, the length of influence on strain of the first pass is about 340 mm, in good agreement with the model. Visually the deformation length appears only to about 140 mm long, and its path is not straight (as can be seen in photograph P14 and P15). The second pass deformation length is much harder to interpret from the strain profiles, since there is no datum strain level (i.e. zero strain). Strain changes continually from exit of the first pass to peaking at the second. A range of deformation length can be interpreted, with 240 mm being a feasible value in the range. With the accuracy of the first pass deformation length being so high, it is reasonable to accept that the model is also true for the second and third pass. The assumptions made in this model are not as limiting as those made in the estimation of peak strain. Note however that the model includes no material properties, and is hence material independent. It is unlikely that geometric parameters are the only parameters affecting deformation length.

The experimental strains are higher than those predicted from the model. If the path of the flange edge could be modelled to fit closer the experimental "S" shape, the peak strain would be higher, due to the extra distance travelled in following the path. Referring to diagrams 7.7-7.9 a model of a cosine curved path length has been devised.

From Pythagoras' theory

$$dl^2 = dh^2 + dy^2$$

For half the cycle required, i.e. 90°.

$$h=\frac{H}{2}\cos\left(\frac{\pi y}{Y}-\frac{\pi}{2}\right)$$

Hence;

$$dh=\left(\frac{\pi H}{2Y}\sin\left(\frac{\pi y}{Y}-\frac{\pi}{2}\right)\right)dy$$

Substituting;

$$dl=\sqrt{\left((dy)^2+\left(\frac{\pi H}{2Y}\right)^2\sin^2\left(\frac{\pi y}{Y}-\frac{\pi}{2}\right)(dy)^2\right)}$$

Integrating, and doubling to give the length over an 180 degree cycle;

$$L=2\int_0^{Y/2}\sqrt{\left(1+\left(\frac{\pi.H}{2Y}\right)^2\sin^2\left(\frac{\pi.y}{Y}-\frac{\pi}{2}\right)\right)}\,dy$$

This integral has no perfect solution, but by using Simpson's Rule values may be approximated.

$$\int_a^b f(x)\,dx \quad approx=\frac{h}{3}\left\{f_0+f_n+4\left(f_1+f_3+\ldots f_{n-1}\right)+2\left(f_2+f_4+\ldots f_{n-2}\right)\right\}$$

DIAGRAM 7.7 VIEW OF METAL GOING INTO FIRST PASS

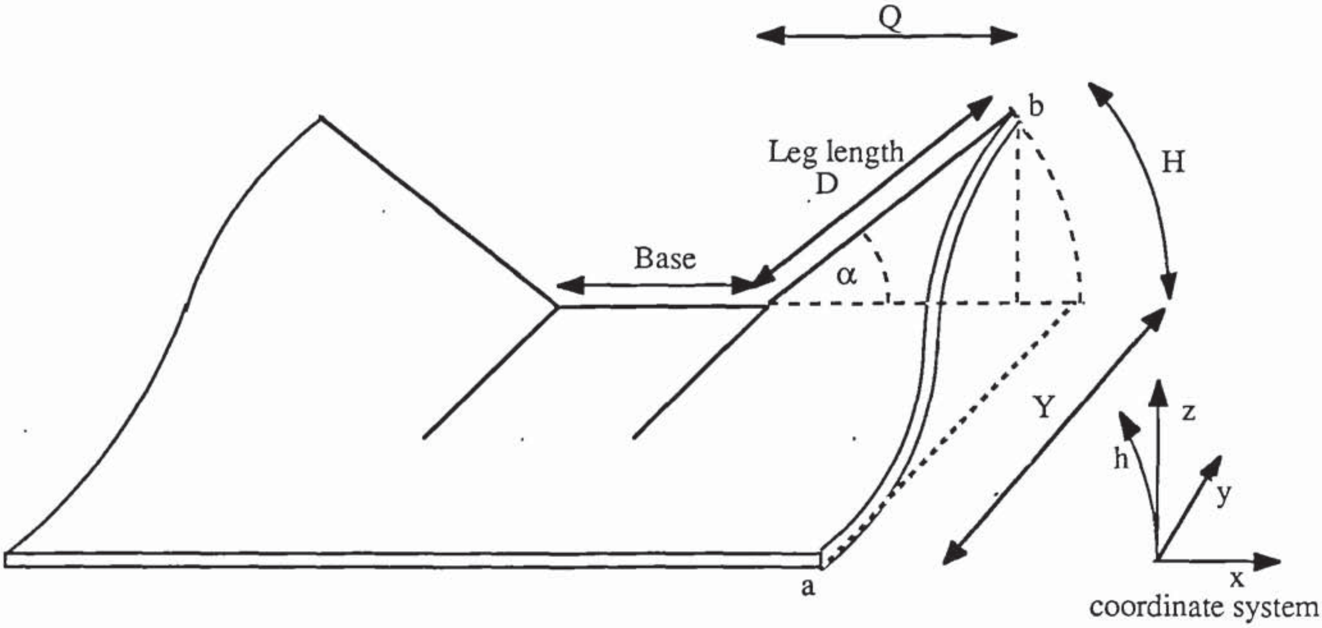


DIAGRAM 7.8 EDGE PROFILE IN ASSUMING A COSINE WAVE. FROM a TO b

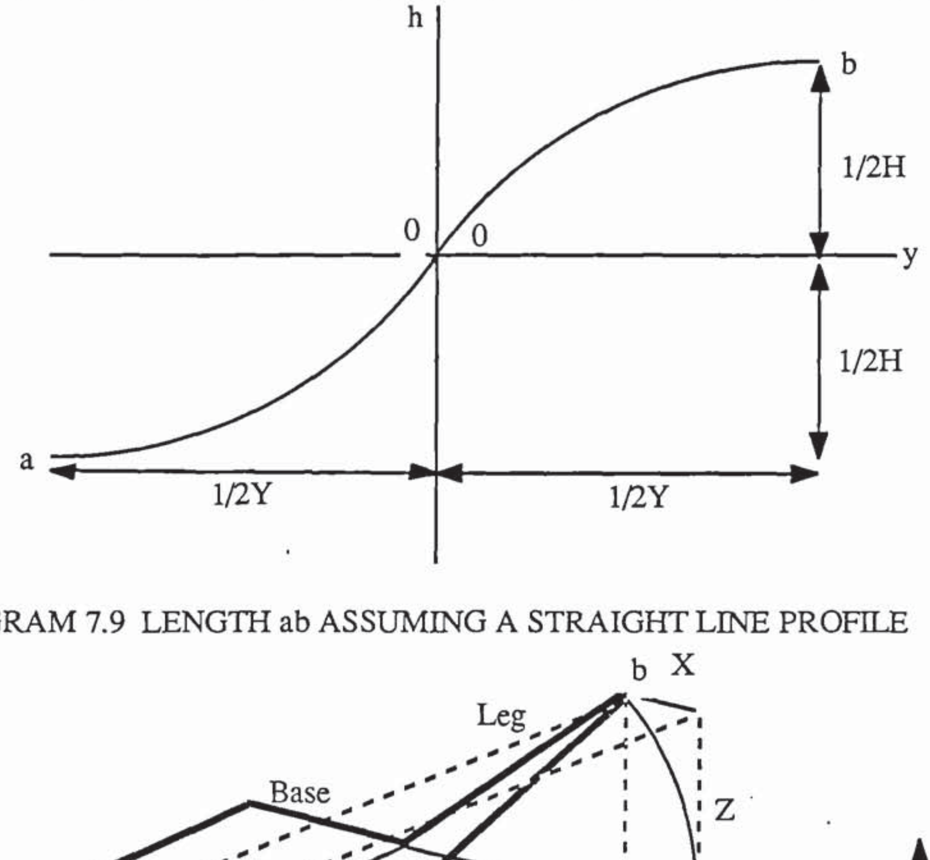
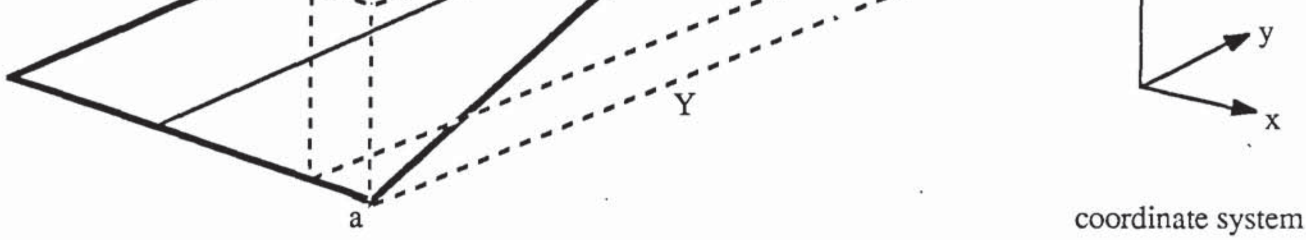
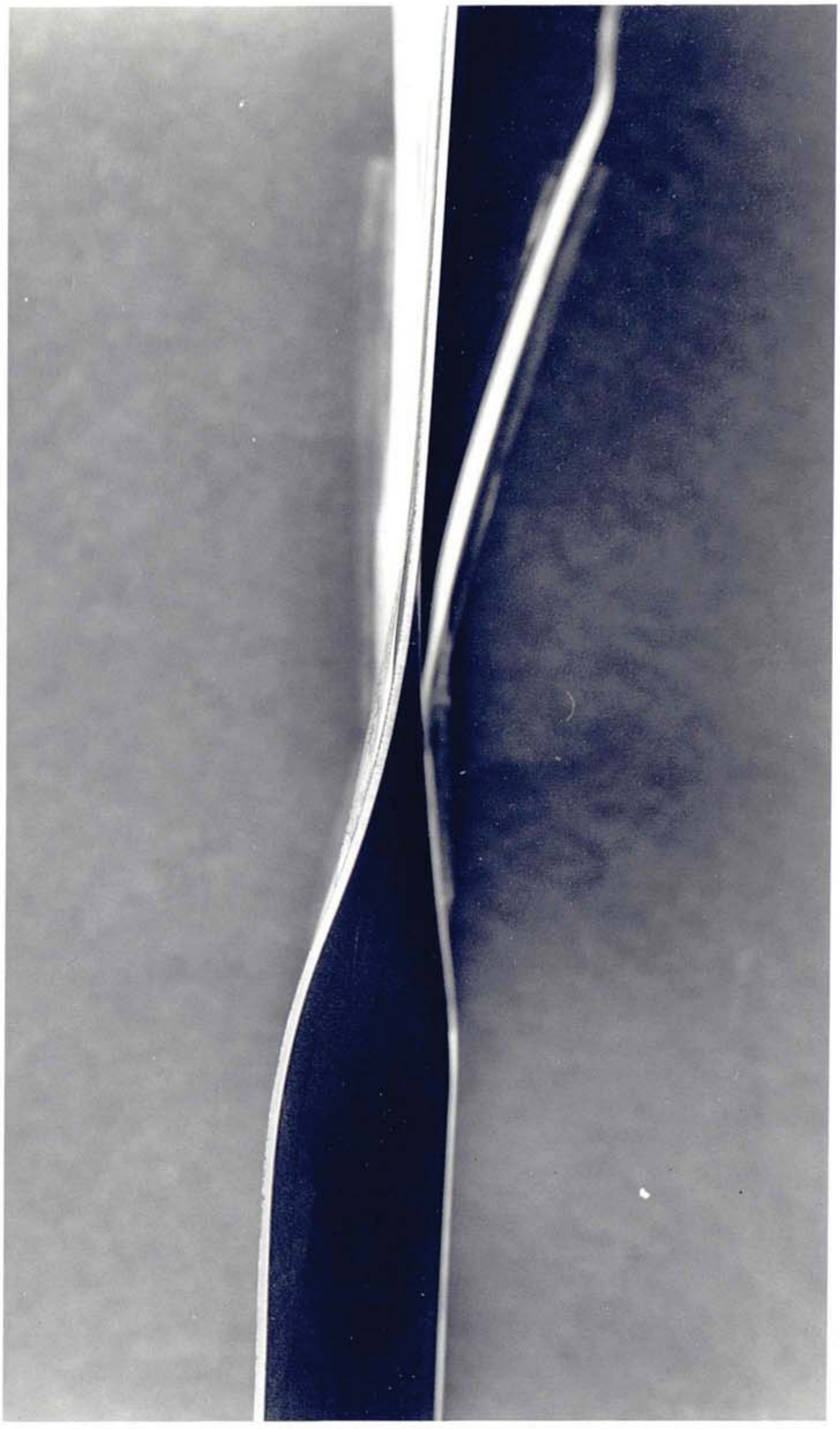


DIAGRAM 7.9 LENGTH ab ASSUMING A STRAIGHT LINE PROFILE



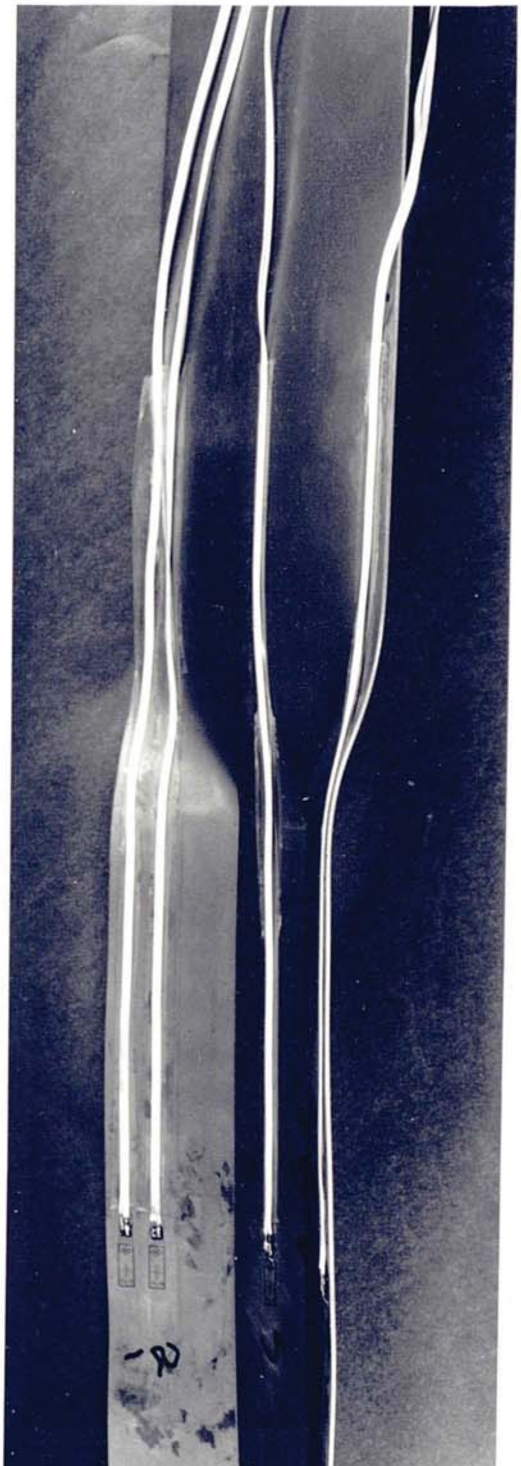
PHOTOGRAPH P14 EDGE PROFILE OF ROLLED STRIP

The typical "S" shaped edge profile can be clearly seen.



PHOTOGRAPH P15 WHOLE VIEW OF ROLLED SECTION

Note the edge profile and edge wave.



Taking the deformation length as 341 mm, the strain can be calculated to be 0.31% for the first pass. The difference is small in this case. Perhaps of more importance is the exact shape of the deformation zone. The distinct "S" shape of the edge is only visible for about 140 mm, most of the deformation takes place here, with a small amount occurring in the preceding 200 mm. If the deformation length is taken as 140 mm, the peak strain is calculated to be 1.75%. The exact shape of the deformation length is a compromise of two shapes; there is a long low strained bow, followed by a more highly strained "S" shaped.

If the peak strain is taken as the strain at the roll pass, and not the peak 45 mm before, then the peak and recovery strain values become realistic. 0.3% strain is average for the group one residual strain, with the value in roll gap being 0.4%. Bhattacharyya, however, claimed the model predicted the peak strain, before the roll.

An important oversight in the strain model is its neglect of taking roll load into account. Experimental results show that high roll load introduces increases in tensile straining in the whole section, both in the peak strains and residual strains. The model of roll load acknowledged roll load as a factor affecting strain but neglected the effect. Two loads were modelled; the load due to transverse bending and stretching, and the load necessary to straighten the bowed section on its entry into a following pass.

The load due to transverse bending and stretching is;

$$P_{tf} = \frac{Yt^2 \theta L}{2H} = Y\sqrt{\frac{2t^3 \theta^3 a}{3 \sin^2 \theta}}$$

Taking Y, the yield stress, as 150 N/mm^2, the first pass the load is calculated to be 1205N. This, according to the model , should be the load required to form the first pass. If a second pass is used, the load increases since the section curvature must be straightened. The load due to this bending action is;

$$P_{lb} = \frac{3h\,EI}{(D-x)^3}$$

"I" is the second moment of area of the formed section = 31.25×10^3 mm^4

"D" is the inter-pass distance = 238 mm

"x" is the horizontal distance from the second pass, to the position at which the strip contacts the second pass bottom roll (see diagram 4.10 and Appendix 1) = 94.5 mm

"h" is the vertical distance from the base height of the first pass, to the position at which the strip contacts the second pass bottom roll = 0.717 mm

"E" is Young's modulus = 209 kN / mm^2

The load due to straightening $P_{lb} = 4561N$

Total roll load = 4561 + 1205 = 5.77 kN (or 0.58 tf)

The summed loads predict the minimum load required to form the section. They are well below the actual loads used in forming. By using much higher loads, longitudinal stretching is introduced by the flattening action and so can be used for curvature control. The use of the model is thus limited greatly by ignoring the load causing stretching and cannot be applied to the experimental tests.

7.13.3 BASE STRAINS

Base strains are shown by the results to reflect both the curvature of the section and the applied load. Although bending in the base has lower peaks and residual strain, the straining is clearly not zero. Through the design of the rolls, most of the roll load is exerted on the base. There is a complex, but repeated, pattern of bending just before entry to the rolls. If the top and bottom strains are summed, the resultant pattern is much smoother. This indicates that the strain peaks are due to pure bending rather than stretching. It therefore may be true that the peaks on the flange graphs also have an element of strain associated with bending, which gives high peak strains. In this case the Bhattacharyya peak strain model becomes more realistic.

7.13.4 LONGITUDINAL CURVATURE AND TWIST

Twisting in a symmetrical section indicates an imbalance in strain. From theoretical considerations, it is easier to assume there is no imbalance in straining across symmetrical sections, so twisting becomes impossible. Indeed there are no theoretical models for predicting twist in cold roll-formed sections.

The twisting found in the tests, can be attributed to imbalances in roll load, roll symmetry and alignment. Generally, sections twisted clockwise out of the first pass. This was best explained by the asymmetry of the rolls (due to the cut-outs).

Load imbalance had a small effect on the twist, which is expected with most of the load being concentrated at the base, and with low levels of strain being formed as a result.

By the addition of a second and then third pass, twist was reduced. By forcing the twisted material back into another straight pass, with the addition of a roll ironing action, it is understandable that section becomes less twisted. Passage through rolls must cause the imbalance in transverse strain to be reduced.

Changes in roll alignment of the final pass cause one edge of the flange to travel further than the other, so setting up a strain imbalance. Results showed that there was a slight increase in clockwise curvature, with a 1.7 mm shift of the last pass to the right. The increase in twist showed that the right edge was strained more by a shift of the pass to the right. Mathematically, it may be simplest to treat twist as a combination of transverse and vertical bow, calculated separately. For a section to twist about its centroid, exceptional loading and cross-sectional geometry would be necessary.

Curvature in the tests was reduced by the number of passes, for the same reasons as twist. However, its presence is not dependent on imbalance in the transverse direction, but in the vertical. In the Bhattacharyya model, curvature from a pass is simplified by assuming the base remains unstrained and the strain in the flange is in proportion to its distance from the base. This leads to the equation (Appendix 1);

$$e_{peak} = H/R \quad \text{where R is the radius of curvature}$$

For the first pass this gives the curvature as -8.7 m.

For the second pass -23.6 m

For the third pass -28.9 m

These results fall in the range of experimental values. However the model can never give a positive curvature, as the base strain can never be higher than the peak strain. It is clear that ignoring base straining limits the model to inaccuracy.

7.13.5 SPRINGBACK

The values of fold angle error, are a measure of springback in the transverse plane.

Gardiner's springback equation is;

$$\frac{R}{r} = 1 - 3\left[\frac{(RY)}{(ET)}\right] + 4\left[\frac{(RY)}{(ET)}\right]^3$$

Where R = 1 mm, Y = 150 N/mm^2, E = 209 kN/mm^2, T = 1.5 mm for the first pass.

Springback = 0.9986

and from AR = A'r

The angle of the sprungback fold = 29.96°

Angle error = 0.04°

The improved model by Woo and Marshall (108) is;

$$\frac{R}{r} = \left(1 - \frac{H}{E}\right)\left(1 - 3\left[\frac{RY}{ET}\right] + 4\left[\frac{RY}{ET}\right]^3\right)$$

Where H is the strain hardening rate = 600 N/mm^2 from B.S. 1449 (170).

Springback = 0.9957

The angle of the sprungback fold = 29.87

Angle error = 0.13

The model of Rondal (128) for springback is found by interpolating between two limits;

Material without a yield plateau

$$\frac{\Delta r}{r}\,(\%) = 0.0023\, f_y \left(1.3 + \frac{r}{t}\right)^{0.83}$$

Strain–hardening material

$$\frac{\Delta r}{r}\,(\%) = 0.0015\, f_y \left(1.3 + \frac{r}{t}\right)^{1.06}$$

"r" is the radius of curvature of the bend angle = 1 mm

"t" is the thickness of the strip = 1.5 mm

"Y" is the yield stress in N/mm^2 = 150

This gives the radius ratio as 0.60% for all three passes for a material without yield plateau and as 0.46% for a strain hardening material. Using AR = A'r as before, it is calculated that in the first case the sprungback angle is 29.82°, angle error = 0.18°. In second it is 29.86°, angle error = 0.14°

These values are all positive, and are well within the range of angle error measured in the tests. It is clear that the accuracy of the bend angle is affected by parameters that give a much larger variation in results than can be attributed to springback. For a bend to occur that is of different angle to that of the roll, there are two explanations. Firstly, the strip to roll geometry may be inaccurate, e.g. the rolls may be forced apart, move to an incorrect position, or the strip may enter the rolls at an angle other than 90°. Secondly a pattern of straining may be induced in the strip that causes the relaxed shape of the metal to be incorrect; this not only accounts for springback in the bend, but also covers the recovery strain in all the regions of straining, i.e. all over the section.

7.13.6 INTER-PASS DISTANCE

The reduction of inter-pass distance causes the strain on exit from the first pass to be increased, by the closer proximity of the second pass. Sarantidis (143) assumed that there would be no change by the reduction of the distance. When the deformation length exceeds the inter-pass distance, it is clear that the second pass affects the strip exiting the first pass. Consider a case where the first pass is in the deformation length of the following pass. The component of strain of the deformation length at the first pass is added to the strain imparted by the first pass. It is also important to note that the summed strain is then carried through the second pass and is not reduced even when the third pass has a longer inter-pass distance. An increase of strain at the first pass can therefore cause an increase at the final pass.

7.13.7 ROLL SPEED

Changes in roll speed appear to have no effect over the section straining and quality. It may be said, however, that at higher speeds the mill vibration and noise is increased greatly and also the power requirements of the motor are higher.

7.13.8 DIFFERENTIAL ROLL SPEED

By causing the second pass to run faster than the first, strain is induced in the base and flanges. The diameter of the second pass (116.68 mm) was 10 mm larger than the first (106.68 mm). This causes the surface speed at the base of the second pass to be 9.4% faster than the first. In a case of no slipping, 9.4% strain would be resultant in the base. Results show that the level of straining is much lower than this, varying from 0.2 to 0.6%, depending on the roll load. By increasing the roll load, the degree of slipping is reduced, so more strain is imparted into the strip. The effect of changing roll speed is greater than that of any of the other operating parameters. Curvature is markedly affected, with large positive bows resulting.

7.13.9 THICKNESS

Roll load was shown to affect longitudinal straining. The straining was thought to be a result of flattening of the strip, which would cause reduction in thickness. However permanent reduction in strip thickness is not confirmed experimentally. Measurements of thickness on the flange and base, before and after rolling show; firstly that variations in strip thickness before rolling are +/- 5 μm, and secondly that after rolling, reduction in the base is less than 1 μm at the highest roll load. Reductions in thickness less than 1 μm, are undetectable, as the micrometer resolution is +/- 1 μm.

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7.13.10 EQUIPMENT

Equipment for measurement of rolls speed, roll load, strain and inter-pass distance all worked well. The largest problem was in the width of error in strain readings; +/-6% variation allows a large possible spread of results. Poor repeatability in part one tests is due to the lack of control over roll load. Part two tests show a marked improvement in repeatability (e.g. Tests 50 and 44). Measuring strain with strain gauges gives a much clearer indication of straining than using a scribed grid pattern. It is unfortunate that the cut-outs appear to affect the twisting in the section.

The mill itself proved to have large tolerances on values that are expected to be constants, those measured being;

Roll eccentricity +/-0.1 mm

Inter-pass distance +/- 2 mm

Pillar movement +/-30 μm

Pillar alignment +/-0.1 mm

CHAPTER 8

CONCLUSIONS

8.1 INTRODUCTION

Conclusions are formed from a discussion of the results. There then follows an analysis of reduction of down-time and a costing appraisal. Finally the areas for future work are detailed.

8.2 CONCLUSIONS

The nature of forming in cold roll-forming is complex. Sections rolled under nominally the same operating conditions are formed into varying shapes. It can be concluded that the factors affecting section quality must therefore be changing out of the control of the roll designer or mill operator. Operators must frequently change operating conditions to compensate for these variations.

The most obvious parameters changing out of control of the operator are the strip dimensions, strip condition and strip properties. Tolerances on these properties are defined by the roll forming purchaser, and are ensured by the supplier. Rolling companies, ideally, should specify fine tolerances on their material order, however, costs of such material is higher than that with lower tolerances. CR3 (experimentally shown to vary by +/- 5 μm) has a finer tolerance on thickness than most steels used in cold roll-forming and yet the variability of section quality is still high. Variability test show that curvature, twist and angle error, all vary under nominally identical rolling parameters

Operating conditions are set by the operator to judged values. It is assumed that these values remain the same once set. This is proved not to be so.

8.2.1 ROLL LOAD

Roll load is shown to vary greatly during rolling and is thus out of control. Variation is due mainly to eccentricity of the roll bearings (changes in material thickness must also be a cause). Although only slightly out of true (+/- 0.1 mm), the effect on roll load is considerable. The problem is greatly reduced by the use of spring washers in the pillar and improved repeatability in section quality results. Variations are also caused by the lack of rigidity and play in the roll pillar. Roll positions become floating due to the lack of rigidity, especially in old mills with worn slideways and pillars. These problems become further exaggerated for larger sections involving higher forces. The source of the variation lies in the inaccuracy in machining of the roll pillars. Solutions reduce the effect of this variation. Similar inaccuracies in machining apply to the whole mill and affect all the operating conditions.

Increasing roll load increases the tensile strain in the base of the channel. This in turn increases positive curvature in the section. Roll load can thus be used to control curvature. By changes in left and right load the amount of twist can also be controlled.

8.2.2 ROLL ALIGNMENT

Roll alignment has a lesser effect on the section quality than roll load. Moving the final pass out of line causes an increase in twist. Alignment cannot be gauged by pushing the pillar bases up to known block lengths from the back edge of the mill, because the mill itself is not straight and pillar bases are of variable size. The method used by the mill setters uses no datums from the mill itself, acknowledging its inaccuracy, and is only accurate to +/- 1mm.

8.2.3 ROLL SPEED

Increasing roll speed appears not to affect section quality. At high speeds however, the noise levels and power requirements of the mill increase. These do not, at present, limit the mill speed. The main restriction in rolling speed is the speed of the cut-off press. The press must to be able to keep pace with the outgoing section to keep the length accuracy. Press motion is linear and thus involves large accelerations, forces and inertia. This gives the upper limit to cut-off speed, in spite of continual advances,such as the development of computer-controlled flying shears. An ideal, although currently impractical cut-off press, would run at a constant velocity and would need to be rotary.

When pre-cut lengths of strip are rolled, the problem becomes making the feed continuous. The use of cut-off presses in most cold roll-forming companies indicates the problems of feeding are larger than in cut-off. At present the limitation in rolling speed still lies in the cut-off press design. Should developments increase press speeds, the limitations may then be caused by the rolling mill or strip material.

8.2.4 DIFFERENTIAL ROLL SPEED

The use of a larger second pass was intended to create tensile straining in the base between passes. This effect is shown to take place and can be considered a method of curvature control, but not of twist control. An obvious problem with the parameter is that it is not directly under the operators control, but is controllable by roll load indirectly. Unfortunately roll load has its own effects on section quality. Ideally the two could be separated. It is likely that the power requirements of the mill will need to be increased to handle this rate of straining, as the rolls are "fighting" each other. Although effective, this method of quality control is over-straining the material and hence is more likely to cause surface finish problems (e.g. scuffing) and defects such as cracking. In moderation, the use of increased diameter rolls may be very useful in curvature control.

8.2.5 INTER-PASS DISTANCE

Inter-pass distances are found not to be exactly equal, there is variation of +/- 2 mm, indicating more inaccuracy in the mill construction.

By reducing the inter-pass distance to less than the deformation length, higher longitudinal straining between passes is introduced into the strip. To avoid the complications added by this parameter, it is important to let the deformation length be less than the inter-pass distance. In some cases this will be impractical, as the summed deformation lengths of each pass will exceed the total mill length.

8.2.6 MATHEMATICAL MODELS

Accurate models of rolling offer many benefits to roll formers. The models developed have attempted to predict section quality, from geometric information of the rolls and strip, material properties, and operating conditions. Claims of the accuracy of computer based models, cannot be substantiated, unless the programme is available. None of these models is currently commercially available, therefore testing of the mathematical principles necessitates writing new programmes, in a lengthy repetition of work. Simpler models, however, have been tested and give some accurate results. Bhattacharyya's model of deformation length is confirmed by the experimental tests, however, the prediction of edge strain is not accurate. Some assumptions made in the models are shown to be experimentally untrue and hence error in the results is expected, but without these assumptions the models become too complex to solve. Computers are more able to cope with extremely complex calculations, and so may be able to model the bending more accurately. Much more work must be done on modelling as the potential uses of quality prediction prior to rolling are large; roll design can be optimised,and down-times reduced.

In spite of highly idealised assumptions, models of cold roll-forming give results within the range of experimental results. It is clear that the accuracy of output data from a model is not only dependent on the accuracy of the model, but also on the accuracy of the input data. Inputs are usually taken as a set values, for instance of material properties such as yield stress, Young's modulus and rate of shear strain. These values may not be constant throughout the material and are normally estimated from tables. Input values from the rolling mill, such as position of the rolls, roll geometry, roll load and roll speed, as well as strip geometry are also all taken as constants. In most cases these values change during rolling. The whole process of rolling is thus subject to continual change and, at best, a model can give a range of possible output values.

The emphasis in rolling parameters must therefore be to find ways to give tight control and high repeatability. This is also true for the material supplier, although this falls outside the direct control of cold roll-formers.

It is very unlikely that there will e .er b- sufficient control over material and rolling parameters to allow rolls to be designed from theoretical considerations and then for the section to be of acceptable quality, without some variable input to compensate for small variations in parameters during rolling.

For example, the use of spring washers has improved the control of roll load greatly, however, the value of load is a nominal constant. A further step is to control the roll load during rolling without stopping the mill. In this way, the pillar load can be estimated and set to a theoretical value, then adjusted, should changes in material properties or mill parameters occur.

Feedback systems allow the on line control of parameters. In the case of cold roll-forming, choosing the parameter(s) to control and finding a method of on line quality monitoring are the problems to overcome before a system can be set up.

Both differential roll speed and roll load have a large influence over section quality. Roll speed is attractive choice of control parameter, in that motor drive control is a well understood area and easily suited to feedback systems. However the effect of changes in roll speed only have influence in the vertical plane and so cannot be used to take out twist and transverse bow. Also power requirements may be high and the method can only add tensile strain. For its application there are two possible avenues. Firstly certain rolls can be driven at a different speed, via a gearbox or totally separate drive. A separate drive would allow on-line adjustment of the surface speed to achieve the desired quality, with the possibility of feedback control. Alternatively, using theoretical models, the ideal roll diameter could be calculated and manufactured. In this case there is no room for error, there would need to be another control such as roll load to "fine tune" the quality. The range of quality in sections which come from a mill with nominally the same set-up conditions indicates there must be some kind of variable parameters on the mill to maintain control. Feedback control is the ideal solution in such a changeable environment.

Roll load can be used to adjust for twist and bow in transverse and vertical planes, but the mechanism for load adjustment will need careful design and is likely to be costly and cumbersome (increasing set-up times). Again only tensile strain can be imparted in the strip, so in the case of the tests section, a positive curvature could only be made more curved by increasing roll load. The design of rolls needs to ensure that the section rolled under light load will be slightly negatively bowed, so that increases of load reduce that bow.

8.3 REDUCTION OF DOWN-TIME

The down-time associated with operating conditions, is the set-up and re-set time. This time accounts for a large unpredictable portion of total down-time and is thus important to be reduced and controlled. The actions that are time consuming in setting are the check, adjust, recheck actions, which are required at each pass. Physical difficulties in access, and then judgment by eye and by feel, cause setting to be lengthy and prone to repetition, due to error.

The ideal setting procedure should;

1. set parameters correctly
2. monitor parameters
3. compensate for changes in section quality

8.3.1 SETTING PARAMETERS CORRECTLY

In order to set a parameter there must be some method of measurement of that parameter. The measurement device must be accurate, and the value to which the parameter is set must also be correct, before section quality is assured. Correct values of parameters may be calculated from models or learned from experience. Their values can be entered on a setting sheet (table 8.1) to reduce operator estimation and the associated errors.

There is little point in fitting highly accurate measurement equipment to an inaccurately machined, or worn mill. Therefore, before parameter measurement devices are fitted to mills, the mills themselves must be graded and if possible manufactured to tighter tolerances;

1. Mills can be accurately measured and graded according to their accuracy. The higher grade mills can be used for sections demanding higher control.
2. Mills can be remachined to higher tolerances and part added to increase rigidity and reduce play.
3. Mills can be constructed with higher tolerances with improvements in design (higher rigidity, and reduced play), as standard.

SETTING SHEET NUMBER				SECTION NUMBER		
Pass Number	Inter-pass Distance	Roll Speed	Roll Alignment	Roll Load		Bottom Roll Diameter
				Left	Right	
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
Lubricant						

TABLE 8.1 SETTING SHEET FOR CALCULATED IDEAL VALUES

Measurement devices must be found for the operating parameters;

Roll alignment can be made simpler by indexing the mill transverse slideways into which the pillars fit. In essence a ruler would be scribed on to each slideway. The pillars can then be lined up to particular lines on the mill, their values indicated by the setting sheet. Alternatively, the pillars can be pushed up to slip blocks (their size indicated by the setting sheet) using the back of the mill as a datum line. Both methods are simpler to use, faster and more accurate than the conventional method but rely on mill and pillar accuracy being high.

The Danfoss speed controller is an adequate method of setting speed. It is has both a measurement of speed and a control of speed. It must be noted, however, that the controller indicates the speed in terms of percentage of the fastest speed of the motor and does not show the r.p.m of the rolls. Changes in the gearbox alter the motor to roll speed ratio, hence, the setting sheet must be clear to state the gearing as well as the controller setting.

Inter-pass distance does not need to be continuously variable. Accurate production of the mill ensures that its value is the same for each pass. From the table it can be shown whether some passes may need to have double pass lengths to avoid forming within the deformation length.

Roll load can be measured by load cells in the pillars. The loads cells help operators set the desired load (from the setting sheet) and allow the values of load to be recorded when a section is rolled to the quality requirements (data used in producing the setting sheet). In this method, however, each pillar requires all the equipment of the data collection system used in the tests (even if simplified). To reduce this complexity and speed setting further, pillars can be preset to given load values. Knowing the characteristics of the spring washer in the pillar (from the manufactures specification), the load can be set as follows:-

The pillar is tightened up to a point where the spring washers are half flattened. This point is calculated in terms of the angle through which the pillar bolt is turned once it contacts the unloaded springs. The angle through which the bolt is turned can be measured in terms of flats (each bolt flat being a sixth of a turn). Different washers are selected for different load requirements. The information for selection of washer and angle of bolt rotation is read from the setting sheet. Note that a finer thread on the pillar bolts increases the accuracy to which this value can be set and is thus recommended. Washers must be able to be easily inserted into the pillars, alternatively, they could be sealed in place and the pillar marked in terms of its load-displacement characteristics (e.g. by colour or other easily identifiable code).

All other parameters are treated as constants and need not be measured in setting. The improved design of the mill helps reduce their variability (e.g. movement of rolls is reduced by increased rigidity) although it must be appreciated they do vary.

8.3.2 MONITORING PARAMETERS

To monitor a parameter varying during rolling a measurement device must be present. The most important monitored parameter is the quality. The errors in section quality indicate the changes that must be made to the operating conditions. Monitoring section quality is particularly difficult in cold roll-formed sections. There are many measurements that need to be taken to completely specify the shape of a section, as discussed in chapter 6.12. Normal methods of quality control are to look at the section bow, twist and cross-section at intervals, if they are not satisfactory the mill is stopped and re-set. A far improved approach is to measure the quality of each section during rolling, to give an immediate indication of error thus reducing scrap and down-time. Automatic measurement of section quality, however, cannot take place before or close to the cut-off press due to the very large vibrations in excess of the deflections needed to be measured. This implies that the section must be measured after leaving the mill. A system capable of measuring quality on-line must therefore be able to; position the rolled section in the measurement device, take the necessary quality measurements and either reject or accept it, in the time of a cut-off stroke. Ideally, also the system could cope with many different section designs. Certainly this is a criteria that is difficult to fulfil and machines being developed now, for particular sections, do not measure every strip. On-line automatic quality measurements does more than reduce scrap and down-time present in manual methods, it also allows the possibility of closed-loop feedback to the mill parameters.

8.3.3 COMPENSATING FOR CHANGES IN QUALITY

Roll load and alignment have control over curvature and twist, which covers a large percentage of the errors in sections. Automatic control of these parameters, from an on-line quality measurement system, is desirable. Control of the parameters indicates that they must be able to be varied. The parameters can be varied, however, their alteration necessitates stopping the mill. It is a great advantage to be able to change these parameters, whilst rolling, to avoid down-time.

The use of spring washers is in effect a self compensating system, which maintains constant roll load in spite of parameter changes, e.g. strip thickness. This type of system is, however, pre-set and is not controlling quality as a feedback system does.

To retain section quality roll load or alignment must be altered as a result of quality error. The error output measurement from the quality measurement system is input to a feedback model.

The model is programmed to make the changes in parameter that are needed to rectify a particular error signal. Thus the model outputs a message to rolling parameter controllers, causing them to change their values, until there is no error.

In the present situation the section quality is measured by hand. The model used is human experience and the alteration to roll parameter are made by hand. Each of these elements can be replaced by automatic devices. The automatic measurement system can output a signal to a computer based model. The model outputs signals to servo motor drives on the pillar bolts, or alignment bolts to correct the error. In this way, the quality control becomes on-line, and the down-time in setting is eliminated. Much work will be needed to be carried out to make such a system possible, however, the advantages are great due to reduced scrap, ensured high quality and low down-time.

8.4 COSTING ESTIMATE

Although the costing of a particular order is specific, general values can be quoted as a rough estimate. At Hadley's Sections it has been estimated that a rolling mill costs £50 per hour when not running and, when in use, makes £100 per hour. These figures can only be used as a rough guide. The actual costing calculation for a particular order must take into account many variables. Table 8.2 shows a typical costing sheet used in an order.

Estimates of scrap, set-up times and length of strip rolled per hour are inputs to the costing calculation. These inputs are variable and are estimated cautiously. Values of material cost per tonne, transport costs, etc are more constant and accurate in comparison.

The calculation requires a minimum profit level before a section becomes viable to roll. In some cases, when the variable elements of the costing are favourable, profits are increased above those calculated. Conversely, in other cases, the profit margin may be reduced. It is clearly advantageous to reduce and predict accurately; mill down-time, mill set-up time and scrap level, to achieve accurate costing. By implementing higher accuracy mills, parameter measurement devices and quality control equipment costing becomes increasingly accurate.

CUSTOMER DETAILS		
Length		SKETCH
Length Tolerance		
General Tolerance		
Drawing Number		
Section Number		

Material		Current price		Mark up		Selling price/tonne	

Strip Width	Gauge	Weight / 100m	Scrap %	Gross Weight / 100m

Metreage Quoted				
Material price used £ per tonne				
Set Up Time Hours at £				
Rolling Metres per Hours at £				
Strip Time Hours at £				
Pre Pierce Allowance				
Profit % / £ per Hour				
Transport £ / tonne / lump sum				
Packing				
Price per 100m				
Price per Length				
Presswork Price per Length				
Total Price per Length				
Contribution to Material Cost				

Tooling Cost	Delivery Time	Number of Passes	Tooling Terms

TABLE 8.2 COSTING ESTIMATE SHEET FOR FOUR QUANTITIES OF STRIP

The variations in cost sheets between sections are so high that an overall calculation of the savings of new technology will require a complete study. Much of the information will come from implementation and testing. It is clear, however, that the savings will be long term and necessary for cold roll-forming companies to remain competitive.

8.5 FUTURE WORK

This work has started an area of research that will need to be extended much further to yield further improvements in the following areas:-

1. Testing
2. Implementation
3. Reduction of down-time
4. Development of models
5. Rolling Speed Limitations

The continuation of experimental testing must take place to understand the effects of further parameters (e.g. material properties) on more sections (e.g. sections other than symmetrical channels). This will broaden the knowledge of the process.

A redesigned mill, with the features suggested for higher control, must be manufactured and tested so as to prove the advantages in implementation. In the short term, the new roll pillars must be implemented and cost savings calculated from their use.

Further work should continue in designing equipment for reduction of set-up times. This must include a study of on-line quality measurement and feedback quality control, as well as, mechanical features on the mill to aid setting and to control and monitor parameters.

A great advance will be the production of an accurate mathematical model of forming. If section quality can be predicted at the roll design stage optimisation of roll design is possible. For this to happen the control of all rolling parameters must be ensured. Work in modelling the process must therefore continue backed up by evaluations from experimental work.

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When down-time is minimised, it will become important to overcome the problems limiting speed of rolling. Therefore, investigations on speed limitations, such as cut-off design, feed systems and on-line quality measurement systems, must be carried out.

REFERENCES OF COLD ROLL-FORMING

The References have been divided into four Groupings, namely:

(1) General

(2) CAD / CAM

(3) Theory

(4) Experimental

(5) British Standards

These five sections are then arranged in chronological order.

There are some papers which would fit into more than one category, in this case the papers have been positioned according in the category which occupies the greatest part of the paper.

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APPENDIX 1

BACKGROUND TO BHATTACHARYYA MODELS

PLASTIC WORK IN BENDING.

If sheetmetal is bent through an angle θ the plastic work dissipated per unit length of one bend is ;

$$W_b' = \frac{1}{4} Y t^2 \theta \qquad 1.$$

PLASTIC WORK DUE TO STRETCHING

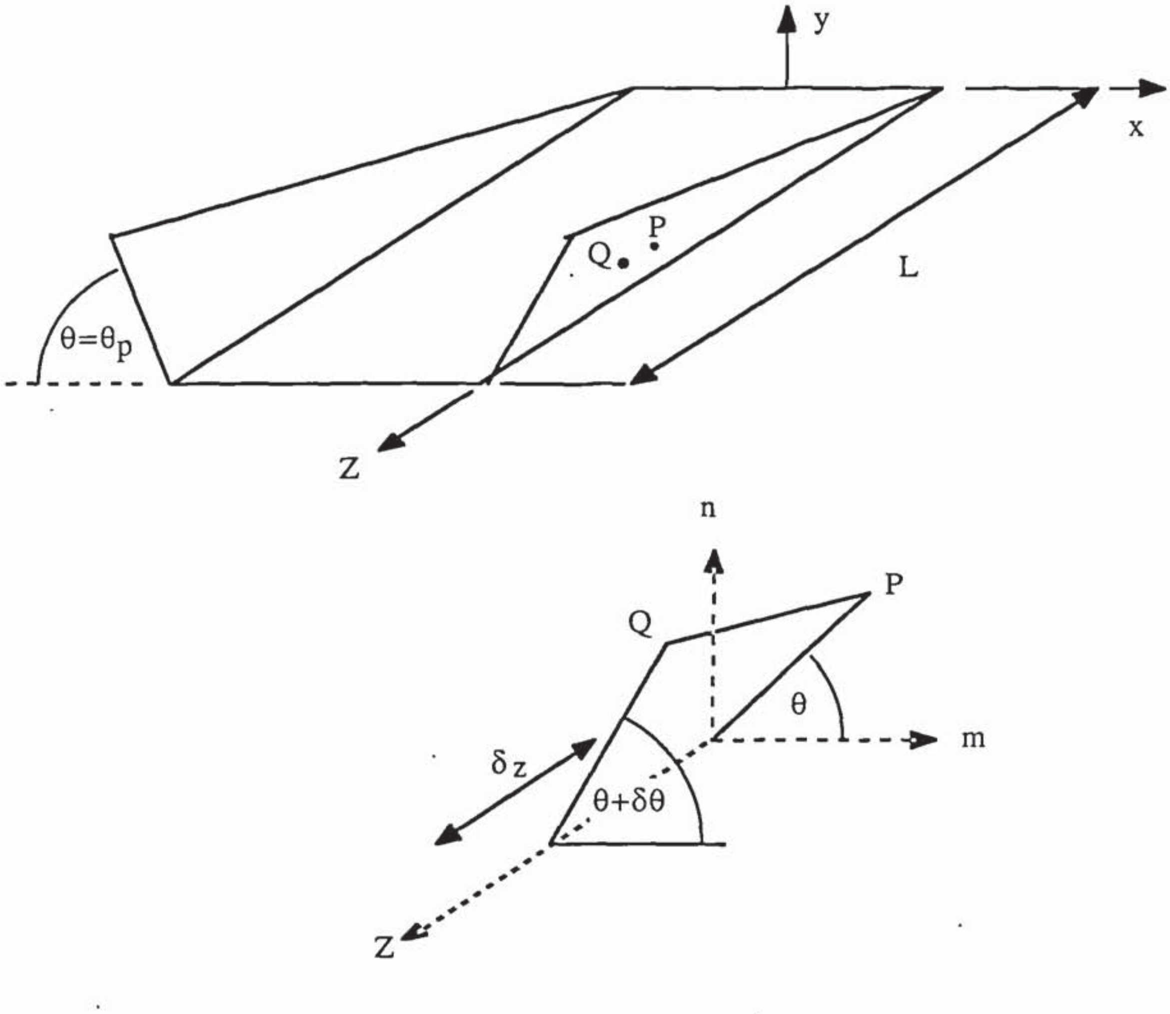

DIAGRAM A1. RELATIVE POSITIONS OF . AND Q AND THE CO-ORDINATE SYSTEM IN THE FORMATION OF A BEND

Work done in stretching can be calculated by considering two points P and Q (diagram A1) on the flange originally at a distance δz apart lying on a line parallel to the z axis. Using the m-n-z co-ordinate system, so that the plane m-n contains P, the new positions of P and Q are given by:-

[x cosθ, x sinθ, 0] and [x cos(θ + δθ), x sin(θ + δθ), δz], respectively.

Since δθ is small, the length PQ is given by ;

$$PQ^2 = x^2(\delta\theta)^2 (\sin^2\theta + \cos^2\theta) + \delta z^2 = x^2(\delta\theta)^2 + \delta z^2 \qquad 2.$$

Expanding and neglecting higher order terms

$$PQ = \delta z\left[1 + \frac{1}{2}x^2\left(\frac{d\theta}{dz}\right)^2\right] \qquad 3.$$

the engineering strain is given by ;

$$e = \frac{1}{2}x^2\left(\frac{d\theta}{dz}\right)^2 \qquad 4.$$

since this strain is small the plastic work done per unit volume

$$= \frac{1}{2}Yx^2\left(\frac{d\theta}{dz}\right)^2 \qquad 5.$$

thus the plastic work done per unit length of the hinge is

$$W_s = \int_0^a \frac{1}{2}Yx^2\left(\frac{d\theta}{dz}\right)^2 (tdx) = \frac{1}{6}Ya^3t\left(\frac{d\theta}{dz}\right)^2 \qquad 6.$$

MINIMISATION OF TOTAL PLASTIC WORK

Combining equations 1 and 6, the plastic work per unit length is ;

$$W_t = W_b + W_s = \frac{1}{4}Yt^2\theta + \frac{1}{6}Ya^3t\left(\frac{d\theta}{dz}\right)^2 \qquad 7.$$

Therefore the total work done for one bend

$$= \int_0^L \left[\frac{1}{4}Yt^2\theta + \frac{1}{6}Ya^3t\left(\frac{d\theta}{dz}\right)^2\right] dz$$

$$= Yt\int_0^L \left[\frac{t\theta}{4} + \frac{a^3}{6}\left(\frac{d\theta}{dz}\right)^2\right] dz \qquad 8.$$

The function θ(z) which minimizes this expression satisfies the Euler equation ;

$$\frac{\partial F}{\partial \theta} - \frac{d}{dz}\left(\frac{\partial F}{\partial \theta'}\right) = 0 \qquad 9.$$

where $F = F(z,\theta,\theta') = \frac{t\theta}{4} + \frac{a^3}{6}\left(\frac{d\theta}{dz}\right)^2$

which has the general solution

$$\theta(z) = \frac{3}{8}\frac{t}{a^3}z^2 + Az + B \qquad 10.$$

the two integral constants can be determined from the end conditions

$\theta(0) = 0$ and $\theta(L) = \theta_p$ so that

$$\theta(z) = \theta_p\frac{z}{L} + \frac{3}{8}\frac{t}{a^3}z(z-L) \qquad 11.$$

Since the flange slope is continuous at each end $\theta'(z) = 0$

at $z = 0$ and L, the condition $\theta'(0) = 0$ gives an expression for the length of the deformed region ;

$$L = a\sqrt{\frac{8a\theta_p}{3t}} \qquad 12.$$

It is not possible to satisfy the second condition as well as the first because of the neglect of bending in the flange. Experimental work by the author suggested that this was of negligible influence on the length of the deformed region. Note also that the model is independent of material properties as is expected from assuming a rigid-perfectly plastic stress-strain model.

EDGE STRAIN

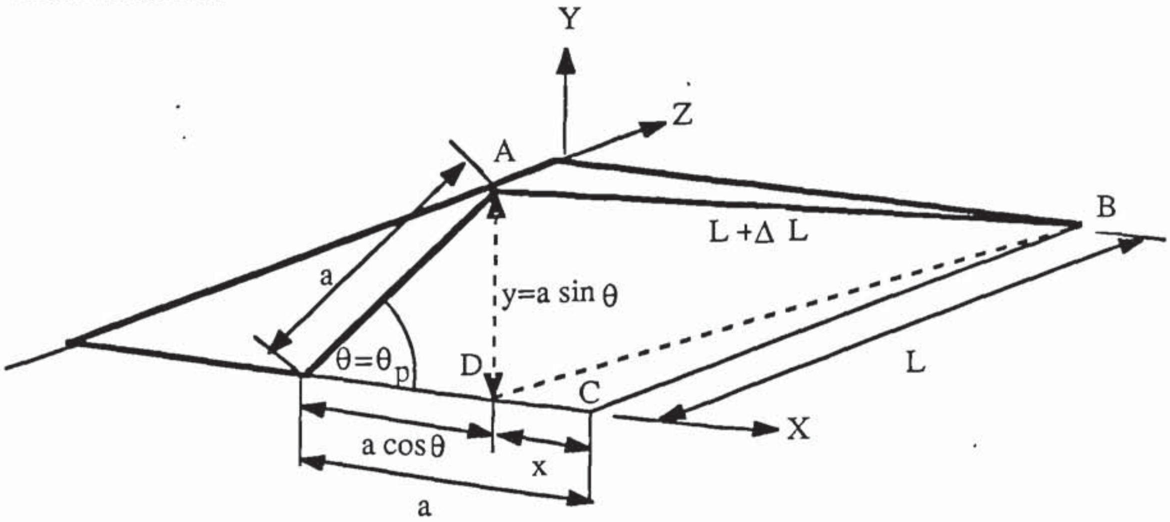

DIAGRAM A2. ESTIMATION OF EDGE STRAIN BASED ON GEOMETRY

$x = a - a\cos\theta = a(1 - \cos\theta)$

$y = a\sin\theta$

$z = L$

The distance from C to A is

$V^2 = 2a^2(1 - \cos\theta_p)$

Thus the length from A to B is ;

$(L + \delta L)^2 = L^2 + V^2$

The extension of the edge is ;

$$\delta L = \sqrt{2a^2(1 - \cos\theta_p) + L^2} - L \qquad 13.$$

Therefore the engineering strain is ;

$$e = \frac{\delta L}{L} = \frac{\sqrt{2a^2(1 - \cos\theta_p) + L^2}}{L} - L$$

$$= \sqrt{1 + \frac{2a^2}{L^2}(1 - \cos\theta_p)} - 1 \qquad 14.$$

RECOVERY STRAIN (e_{reco}) AND REMAINING (RESIDUAL) STRAIN (e_r).

Bhattacharyya was required to make several assumptions in producing a model of recovery and redundant strain ;

1. The deformed strip leaves the forming roll station with the peak strain at its flange edge, i.e. the peak strain occurs at the vertical plane through the centres of the forming rolls.
2. Pure bending occurs longitudinally in the vertical plane without any warping or twisting.
3. The neutral plane coincides with the bottom of the flange and there is a linear strain distribution in the flange.
4. The material is elastic-perfectly plastic. The engineering strain of any fibre at a height z from the neutral axis is ;

   $e_z = \frac{z}{R}$ and similarly $e_y = \frac{z_y}{R}$ and $e_{peak} = \frac{H}{R}$

   $$\text{Therefore } z_y \simeq H\left[\frac{e_y}{e_{peak}}\right] = \frac{H}{m} \qquad 15.$$

   where $m = \frac{e_{peak}}{e_y}$

The linear strain distribution in the flange and the corresponding stress-strain diagram are shown in the diagram A3. When the strip leaves the roll station there is no external moment acting on it. When this moment is released, the internal moment is released, the internal moment must also vanish for equilibrium. As the material unbends the internal stress distribution (diagram A4.) results in zero bending moment. The remaining strain in the flange tip can be calculated by subtracting the elastic strain due to fictitious stress σ', from the peak flange strain.

$$e_r = e_{peak} - \frac{\sigma'}{E} \qquad 16.$$

The external moment is $M_e = 2\int_0^H \sigma' dAz$ 17.

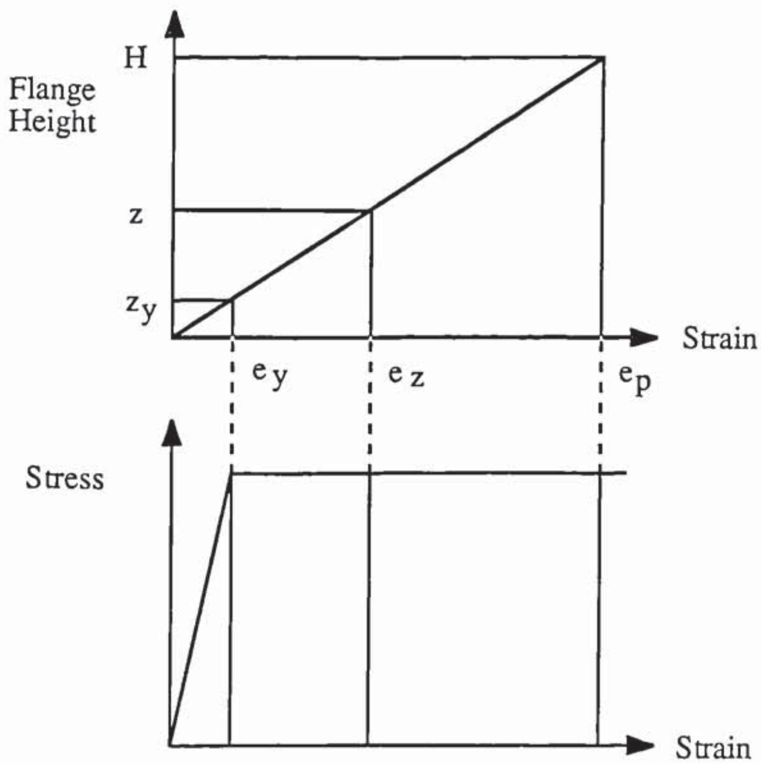

DIAGRAM A3. DISTRIBUTION OF STRESS AND STRAIN IN THE FLANGE FOR A RIGID-PERFECTLY PLASTIC MATERIAL

As the material is elastic-perfectly plastic the stress at height z_y where the strain reaches the elastic limit e_y will reach the yield stress Y. Therefore ;

$$\sigma = Y\frac{z}{z_y} \quad \text{for} \quad 0 \le z \le z_y$$

$$\sigma = Y \quad \text{for} \quad z_y \le z \le H \qquad 18.$$

Also the area dA

$$= \frac{1}{2}\,bdz \quad \text{for } 0 \le z \le t$$

$$= \frac{t}{\sin\theta}dz \quad \text{for } t \le z \le H \qquad 19.$$

Hence equation 17 becomes

$$M_e = \int_0^t Y\frac{z^2}{z_y}\,bdz = 2\int_t^{z_y} Y\frac{z^2}{z_y}\,\frac{t}{\sin\theta}\,dz + 2\int_{z_y}^{H} Y\,\frac{zt}{\sin\theta}\,dz$$

$$= \frac{Ybt^3}{3z_y} + \frac{2\,Yt}{Z_y\sin\theta}\cdot\frac{(z_y^3 - t^3)}{3} + \frac{Yt}{\sin\theta}\,(H^2 - z_y^2) \qquad 20.$$

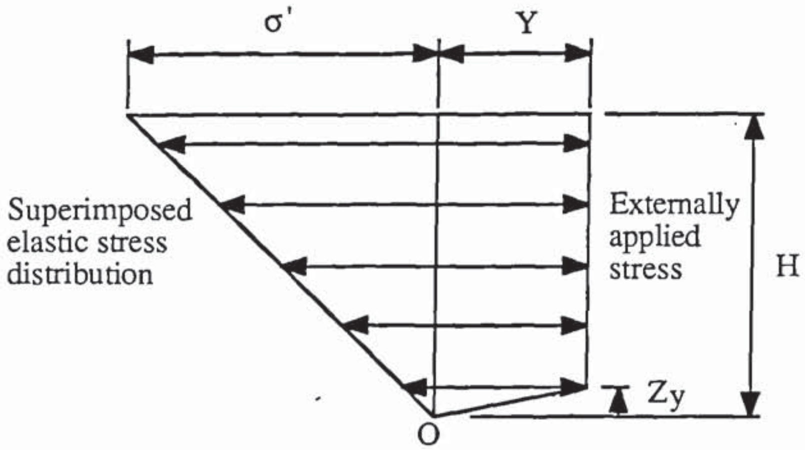

DIAGRAM A4. DISTRIBUTION OF STRESSES IN THE FLANGE AND WEB AFTER RECOVERY

Similarly the internal moment is

$$M_i = \int_0^t \sigma'\,\frac{z^2}{H}bdz + 2\int_t^H \sigma'\,\frac{z^2t}{H\sin\theta}dz$$

$$= \frac{\sigma' t}{3H}\left[\,bt^2 + \frac{2(H^3 - t^3)}{\sin\theta}\,\right] \qquad 21.$$

Equating M_e and M_i gives

$$\sigma = \frac{3HY}{\left[bt^2 + \frac{2(H^3 - t^3)}{\sin\theta}\right]}\left[\frac{bt^2}{3z_y} + \frac{2(z_y^3 - t^3)}{3z_y\sin\theta} + \frac{(H^2 - z_y^2)}{\sin\theta}\right] \qquad 22.$$

Substituting z_y from 15 into 22 and using 16, the remaining strain can be calculated as

$$e_r = e_{peak} - \frac{3He_y}{\left[bt^2 + \frac{2(H^3 - t^3)}{\sin\theta}\right]}\left[\frac{bt^2m}{3H} + \frac{1}{\sin\theta}\left(H^2 - \frac{H^2}{3m^2} - \frac{2mt^3}{3H}\right)\right] \quad 23.$$

VERTICAL LIFT (h)

The leading edge of the strip comes out of the forming station with a radius of curvature, which depends on e_r and the channel depth H. Upon entering the subsequent roll station the point p is lifted to a position p' over a vertical distance h. The lifting action imposes a compressive bending strain on the flange, and places an extra load on the forming rolls. The magnitude of the vertical distance h can be calculated when some of the other geometrical parameters are known.

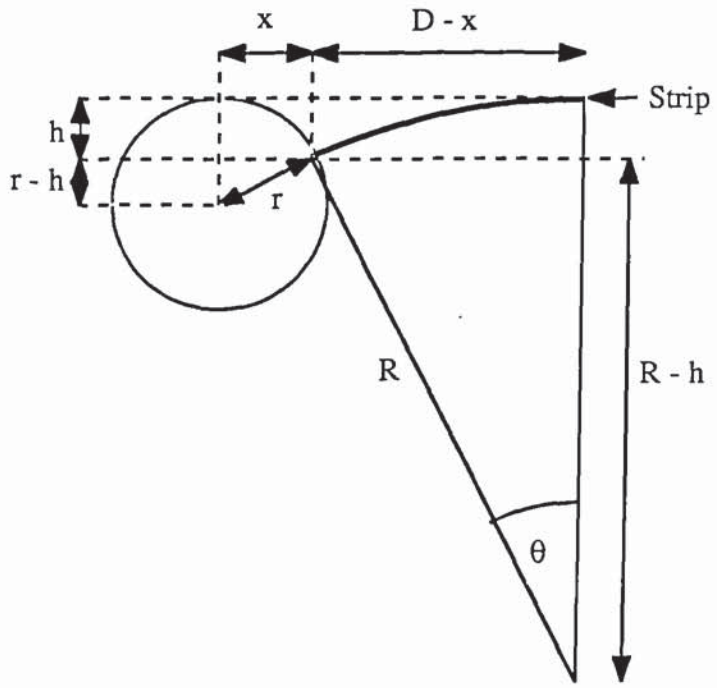

DIAGRAM A5. GEOMETRICAL REPRESENTATION OF A DEFORMED STRIP ENTERING A ROLL STATION

From geometry in diagram A5;

$$R^2 = (R-h)^2 + (D-x)^2$$

Where $R = \frac{e_r}{H} = \frac{e_r}{a\sin\theta}$

Simplifying $h^2 - 2RH + (D-x)^2 = 0$ 24.

Also $r^2 = (r-h)^2 + x^2$

So $h^2 - 2rh + x^2 = 0$ 25.

From equations 24 and 25

$$h = \frac{D\,(D-2x)}{2\,(R-r)} \quad 26.$$

Substituting h into equation 24

$$x = \frac{D\,(D^2 - 2Rr + 2r^2) \pm D\sqrt{4Rr\,(R+r)^2 - D^2\,(R-r)^2}}{2[D^2 + (R-r)^2]} \quad 27.$$

ROLL LOAD ESTIMATION

The total work done to deform the strip can be estimated by considering the work done to stretch the flange and that required to bend the strip.

Therefore Total work = Bending work + Stretching work

From equations 1. and 6.

$$\text{Total work done} = \int_0^L \frac{Yt^2\theta}{4} dz + \int_0^L \frac{Ya^3t}{6}\left(\frac{d\theta}{dz}\right)^2 dz \quad 28.$$

since $\theta(z) = \frac{3t}{8a^3} z^2 + \left(\frac{\theta}{L} - \frac{3}{8}\frac{t}{a^3}L\right)z$

$= \frac{\theta}{L}z + \frac{3t}{8a^3}(z^2 - zL)$

and $\theta'(z) = \frac{\theta}{L} + \frac{3t}{8a^3}(2z - L)$

$$\text{Bending work} = \int_0^L \frac{Yt^2}{4}\left\{\frac{\theta z}{L} + \frac{3t}{8a^3}(z^2 - zL)\right\} dz$$

$$= \frac{Yt^2}{4}\left[\frac{L\theta}{2} - \frac{tL^3}{16a^3}\right] \qquad 29.$$

$$\text{Stretching work} = \int_0^L \left[\frac{Ya^3t}{6}\left\{\frac{\theta}{L} + \frac{3t}{8a^3}(2z - L)\right\}^2\right] dz$$

$$= \frac{Yta^3}{6}\left[\frac{\theta^2}{L} + \frac{3t^2}{64a^6}L^3\right] \qquad 30.$$

Total work done for one bend

$= W_T =$ Bending work + Stretching work

$$= \frac{Yt^2}{4}\left[\frac{L\theta}{2} - \frac{tL^3}{16a^3}\right] + \frac{Ya^3t}{6}\left[\frac{\theta^2}{L} + \frac{3t^2L^3}{64a^6}\right] \qquad 31.$$

Substituting $L^2 = \dfrac{8a^3\theta}{3t}$

$$W_T = \frac{1}{12}Yt^2L\theta + \frac{1}{12}Yt^2L\theta$$

$$= \frac{1}{6}Yt^2L\theta \qquad 32.$$

the forming pressure $p_x = \dfrac{P}{L_c}x$

depth of channel $H_x = \dfrac{H}{L_c}x$ 33.

Hence the external work done for one bend =

$$\frac{1}{2}\int_0^{L_c} p_x(bdz)\,H_z = \frac{bpHL_c}{6} \qquad 34.$$

Using equations 32 and 34 the forming load =

$$P_{tf} = \frac{bpL_c}{2} = \frac{3W_T}{H} = \frac{Yt^2L\theta}{2H} = Y\sqrt{\frac{2t^3\theta^3a}{3\sin^2\theta}} \qquad 35.$$

APPENDIX 2

THEORETICAL WORK OF RONDAL

LONGITUDINAL STRESSES IN AN "L" PROFILE.

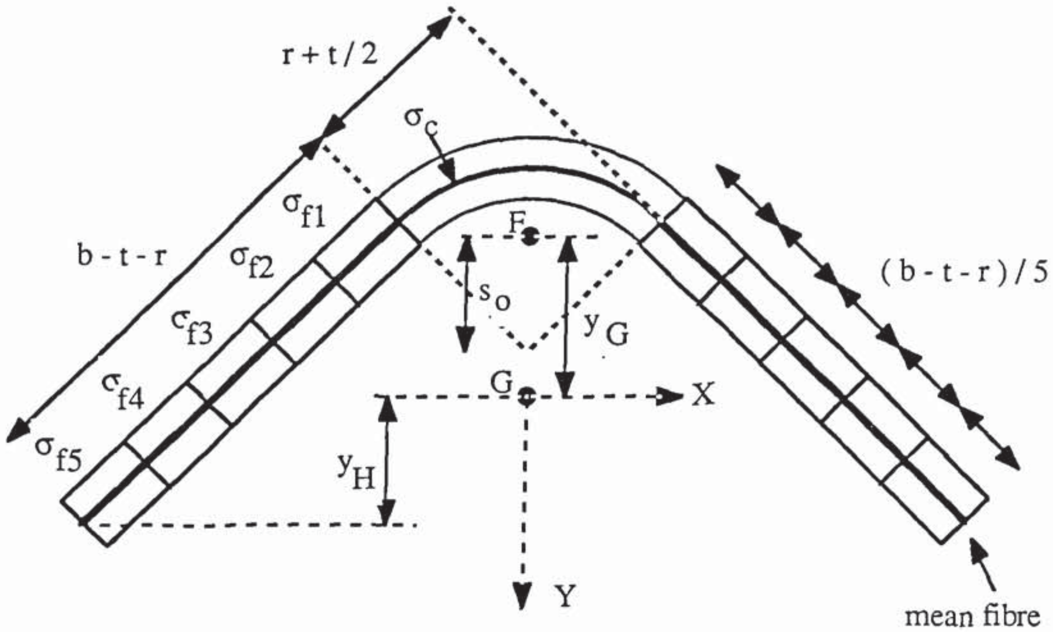

DIAGRAM A6. NOTATION FOR THE CALCULATION OF RESIDUAL STRESSES OF AN ANGLE

The diagram A6 shows how the section has been broken down into the bend and five straight sections making up each flange. Longitudinal stresses of each section are equilibrated to obtain solutions. In order to simplify the computation the "equilibrium coefficients" are computed at the level of the mid-depth of the plate and the obtained values are used when considering any fibre. The resulting force in the corner is ;

$$F(i) = \sigma_z(i) \frac{\pi}{2} t \left(r + \frac{t}{2} \right)$$

The residual stresses having been equilibrated can be computed from the knowledge of the force F, by means of the normal forces and bending moment. Using the symbols in Diagram and by restricting to five values on each flange the following equations are obtained;

$$\sigma_c^{res}(i) = \sigma_z(i) - F(i)\left(\frac{1}{A} + \frac{y_G^2}{I_{min}}\right)$$

$$\sigma_{f1}^{res}(i) = F(i)\left(-\frac{1}{A} + \frac{y_G y_1}{I_{min}}\right)$$

$$\sigma_{f2}^{res}(i) = F(i)\left(-\frac{1}{A} + \frac{y_G y_2}{I_{min}}\right)$$

$$\sigma_{f3}^{res}(i) = F(i)\left(-\frac{1}{A} + \frac{y_G y_3}{I_{min}}\right)$$

$$\sigma_{f4}^{res}(i) = F(i)\left(-\frac{1}{A} + \frac{y_G y_4}{I_{min}}\right)$$

$$\sigma_{f5}^{res}(i) = F(i)\left(-\frac{1}{A} + \frac{y_G y_5}{I_{min}}\right)$$

$$y_1 = y_H - \frac{9}{10}\,\frac{b-t-r}{\sqrt{2}}$$

$$y_2 = y_H - \frac{7}{10}\,\frac{b-t-r}{\sqrt{2}}$$

$$y_3 = y_H - \frac{5}{10}\,\frac{b-t-r}{\sqrt{2}}$$

$$y_4 = y_H - \frac{3}{10}\,\frac{b-t-r}{\sqrt{2}}$$

$$y_5 = y_H - \frac{1}{10}\,\frac{b-t-r}{\sqrt{2}}$$

Where

$$c = b - t - r$$

$$A = 2ct + \frac{\pi}{2} t \left(r + \frac{t}{2} \right)$$

$$s_o = \frac{2\sqrt{2}}{3\pi} \frac{(r+t)^3 r^3}{t\left(r + \frac{t}{2} \right)}$$

$$d_G = \frac{\frac{c^2 t}{2} + ctr + \frac{3}{2}ct^2 + \frac{\pi}{2} t\left(r + \frac{t}{2} \right) - \frac{1}{3}[(r+t)^3 - r^3]}{2ct + \frac{\pi}{2} t\left(\quad + \frac{t}{2} \right)}$$

$$y_G = s_o + \sqrt{2}\,(d_G - r - t)$$

$$y_H = \frac{c}{\sqrt{2}} - \frac{r + \frac{t}{2}}{\sqrt{2}} - \sqrt{2}\,(d_G - r - t)$$

$$I_{min} = \frac{c^3 t + ct^3}{12} + ct\left(\frac{c}{2} - 2d_G + r + \frac{3t}{2} \right)^2 + t\,(r + t)^3 \left(\frac{\pi}{4} + \frac{1}{2} - \frac{4}{\pi} \right)$$

$$+ \frac{\pi}{2} t\left(r + \frac{t}{2} \right)\left[\sqrt{2}\,(d_G - r - t) + \frac{2\sqrt{2}}{3\pi} \frac{(r+t)^3 r^3}{t\left(r + \frac{t}{2} \right)} \right]^2$$