BOLTED JOINTS AT THE ULTIMATE LIMIT STATE SUBJECT TO TORSION AND SHEAR

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TO MY WIFE

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by

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SUMMARY

This thesis examines the behaviour of stressed and unstressed bolt groups subject to in-plane single shear forces due to torsion and shear. The forces produced from this type of loading cause a bolt to fail in shear at the ultimate limit state for unstressed bolted joints. For a 'non' slip connection the failure of a friction grip bolted joint is considered as the point at which the joint slips.

A total of 138 tests have been carried out on different bolt configuration for various loading spans. Connections have been divided into two catagories i.e. untensioned bolted joints and tensioned bolted joints.

Single bolt properties of shear, bearing, tensile strength and load-deformation characteristic obtained experimentally are presented and related to multi-bolt group behaviour.

Experimental results of 117 tests for unstressed black bolts, high strength bolts and cheesehead fasteners and other authors (7, 18,46) for multi-bolt groups are compared with elastic, elastic-plastic and plastic methods and conclusions made as to their suitability for analysis and design purposes.

Test values of induced axial forces in single HSFG bolts obtained from strain gauge readings are compared with values obtained from turn-of-the-nut, torque wrench, direct extension measurements and load indicating washers. An alternative method to calculate the induced shank tension in the bolt for a measured extension is reported and values compared with 137 test results (17).

Experimental results for stressed bolts, for 21 connections at slip and ultimate load for single, two, four and six bolt groups are compared with theoretical values. Conclusions are drawn as to the most suitable method of analysis and design for slip and ultimate load.

SINGLE-SHEAR BOLTS CONNECTIONS FRICTION JOINTS

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NOTATION

A_s	Tensile stress area of unthreaded shank
A_t	Specified tensile stress area of threaded shank
b	Width of tensile test specimen
d_e	Measured effective diameter of bolt
E_s	Apparent Young's modulus of elasticity of unthreaded shank of a bolt
E_t	Modulus of elasticity of threaded shank of a bolt
e	Eccentricity of test load at ultimate limit state of failure of fastener
e_s	Eccentricity of test load at limit state of slip
F_D	Design force to be resisted by a bolt
F_E	Maximum shear force acting on a bolt from elastic analysis
F_p	Maximum shear force acting in a bolt from fully plastic analysis
F_t	Ultimate strength of a bolt in direct tension
F_v	Ultimate strength of a bolt in single shear for single or two bolt group
F_{vs}	Force on a bolt at slip for single or two bolt group
F_{max}	Maximum force on a bolt at ultimate limit state for multi-bolt group
$F_{s(max)}$	Maximum force on a bolt at limit state of slip for multi-bolt group
F_{sp}	Maximum force on a bolt at slip using fully plastic theory for multi-bolt group
f_b	Average bearing stress on plate hole
f_t	Tensile stress acting on a bolt at tensile failure
f_v	Shear stress acting on a bolt at failure due to single shear

H	Horizontal component of the applied load acting along the x-x axis, which passes through the centroid of the bolt group.
I_E	Instantaneous centre of rotation for elastic analysis
I_p	Instantaneous centre of rotation for plastic analysis
L_1, L_2, L_3, L_4, L_5	Dimensions associated with small and large rigs
ℓ	Length of tensile test plate specimen
ℓ_n	Thickness of nut
ℓ_s	Length of unthreaded shank
ℓ_t	Length of threaded shank between the nut face and thread run out.
ℓ_w	Distance between two washers
M_T	Torsional moment applied to a bolt group at ultimate limit state
n	Number of bolts in a group
P	Shank tension in the bolt at a given extension
P_a	Load applied to the joint at an angle θ with x-x axis
P_i	Initial bolt tension
P_s	Maximum load on a single bolted joint at major slip
$r_1, r_2 \ldots r_n$	Radial distance from the instantaneous centre of rotation to bolts 1, 2, ... nth in a group
T	Thickness of plate
t	Thickness of tensile test plate specimen
t_1	Thickness of nut-face-washer
t_2	Thickness of head-face washer
t_3	Thickness of load indicating washer (L.I.W) including protrusions
t_4	Thickness of load indicating washers without protrusions
V	Vertical component of the applied load P_a, perpendicular to x-x axis which passes through the centroid of the bolt

V_{test}	Calculated test load on the joint at ultimate limit state
$V_{s\ test}$	Calculated test load on the joint at the limit state of slip
W	Applied load on the rig at ultimate limit state
W_s	Applied load on the rig at limit state of slip
W_1, W_2	Self weight of the rig
$\overline{X}$)) $\overline{Y}$)	Coordinates of the instantaneous centre of rotation from axes which pass through the centroid of the bolt group for fully plastic analysis
$\overline{X}_E$)) $\overline{Y}_E$)	Coordinates of the instantaneous centre of rotation from axes which pass through the centroid of the bolt group for elastic analysis
x_i)) y_i)	Coordinates of ith bolt from axes which pass through the centroid of the bolt group
α	An arbitrary constant
α_D	Constant for direct tension test
α_T	Constant for torqued tension test
γ_E	Partial safety factor for load in elastic analysis
$\theta_1, \theta_2 \ldots\ldots \theta_n$,	Angles subtended by the radial lines form the instantaneous centre of rotation to bolts 1, 2 ..... nth and the x-x axis.
Δ	Total deformation of hole, plate and a bolt in single shear test.
δ_b	Total bolt extension
δ_n	Extension of the part of a bolt under the nut
δ_s	Extension of unthreaded shank
δ_t	Extension of the threaded portion between the nut face and thread-run-out
μ	Coefficient of friction
μ_s	Calculated coefficient of friction using elastic analysis

μ_p Calculated coefficient of friction using plastic analysis

Note: Some notations not included in the above list, will be specifically defined when they are first introduced.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 INTRODUCTION

A great deal of research has been carried out into the behaviour of steel building frames and their method of design but the critical part of the structure "a connection" between two members has been largely ignored. For the last twenty years very little work has been carried out on the behaviour of individual elements of the connection despite the fact that the majority of the structural failures are attributed to the elemental failure. More recently with the introduction of limit state design it has become necessary to re-examine the existing design methods. In this study the behaviour of eccentrically loaded connections will be considered, where failure of the bolt or "slip" of the joint is the main criterion.

1.2 ECCENTRICALLY LOADED CONNECTION

In practice bolting is generally associated with site connections. An eccentrically loaded connection, subject to in-plane shear forces, occurs in brackets fastened to a column, beam to beam connections, web splices in beams, connections of parts of a truss as shown in figure 1.1. Hot-driven rivets and the black bolts were used extensively for site connections of structural steelwork prior to the introduction of high strength and high strength friction grip (HSFG) bolts.

1.3 USE OF HIGH STRENGTH AND HSFG BOLTS

In 1934 Batho and Bateman investigated the possibility of transmitting work loads by friction between clamped members. The results included in three reports (1), demonstrated that an adequate

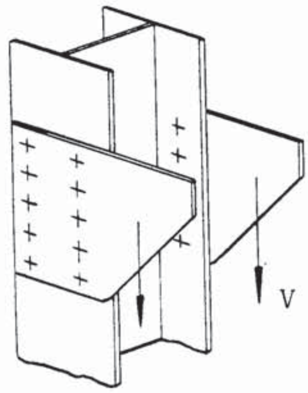


Figure 1.1 a Bracket connection

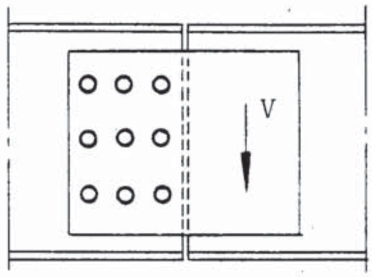


Figure 1.1 b Beam web splice

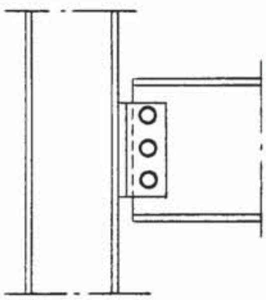


Figure 1.1 c Beam/column connection

FIGURE 1.1 ECCENTRICALLY LOADED CONNECTION margin of safety against slip between the members at normal working load could be obtained. The relationship between bolt tension, bolt tightening torque and slip load was established. Draft rules for design were recommended in the final report in 1936 for British Standard specification No 449.

Research was conducted at the University of Illinois in 1938 by Wilson and Thomas into the fatigue (2) qualities of joints assembled with high strength bolts. In conclusion it was stated that the fatigue strength of high strength bolts was as great as that of a well driven rivet provided the bolts were suitably tightened. A research council formed in 1947 in the USA issued the first specification in 1951 (3) which permitted the replacement of rivets by the same number of high strength bolts of the same size.

The rapid development of the high strength friction grip bolt stemmed from Wilson and Batho's work and installation was primarily dependent on torque control. The variance in this method was mainly caused by the variability of the thread condition, lubrication etc. Current specifications in the USA permit the use of calibrated wrenches, the turn-of-nut method or the use of direct tension indicators.

The British Standard specification (4) recommends the part-turn of the nut or the torque-control method of tightening the bolt and control by other methods is not Precluded provided the specified shank tension is attained. Controlling tension by the turn-of-nut method is basically a strain control and its effectiveness depends on the starting point and the accuracy of the rotational measurements. Several systems of direct tension indicator have been developed, such as Huck-bolt, GKN load indicating bolt and 'Coronet' load indicating washer, and are commercially available.

The effectiveness of the high strength friction grip bolted joint depends not only on the induced shank tension in the bolt but also depends upon the surface condition of the connected plates. The applied load can be transferred by friction on the contact surfaces depending on the direction of the applied load and the magnitude of the clamping force and the faying surfaces. In the British Standard the design is based on the consideration of interface friction. The term "designated slip factor" has been introduced which replaces the coefficient of friction. This change was made because the values obtained experimentally for the slip factor of bolted joints appeared to vary more than would be expected when measuring the coefficient of friction by direct means.

CHAPTER TWO

REVIEW OF PREVIOUS RESEARCH

The analysis of bolted joints at present is by elastic method which distributes the shear force equally between the bolts, and considers the torsional moment in proportion to the distance from the centroid of the group. The resultant force is the vector addition of these two forces and this method was used by engineers in about 1900. Although the concept of instantaneous centre of rotation was introduced in 1914 by Gullander (5) yet a text book by Morely (6) in 1921 applied the elastic method to rivet groups and makes no reference to the instantaneous centre of rotation. Hot-driven rivets and black bolts were extensively used for site connections during this period. As stated in the previous chapter Batho and Bateman (1) in 1934 introduced the tensioned bolt and the slip resistance of a joint in structural steelwork. In 1938 Wilson and Thomas (2) recommended the replacement of rivets by the same number of high strength bolts of the same size. Specification for the use of high strength bolts were issued in the United Kingdom and the USA during this period. Francis (7) in 1953, investigated the behaviour of aluminium alloy riveted joints in double shear. subject to axial and eccentric static loading. The elastic and inelastic behaviour of the joints was examined theoretically and experimentally. For the eccentrically loaded joints where failure occurred in the plates the ultimate strength of the joint agreed with plastic analysis. The elastic method predicted more accurately the ultimate strength in those specimens in which the rivet failed in double shear. No reference to the instantaneous centre of rotation was made in the analysis. Although the investigation was mainly confined to double shear joints it was inferred without any experimental evidence, that the same conclusions were also applicable to single shear joints. Ten tests on eccentric loaded specimens in which rivet failed will be used in Chapter 6 to compare results with unstressed bolts - although bolts deform less before failure than rivets.

In 1955 Munse et.al (8) carried out an extensive testing programme to establish the static and fatigue strength of structural joints for which high strength steel bolts were used as fasteners. All the joints tested were of double shear type and the load was applied axially. The authors compared the results with the strength of riveted joints and concluded that bolted joints were superior under static and fatigue loading, to the riveted joints. During these tests, plates slipped sufficiently to produce bearing on bolts at loads less than the ultimate load and the bolt tension had little effect on the ultimate strength of the joint.

Easton et al (9) in 1957 reviewed the practice on the use of high strength bolts in the United Kingdom and America. The authors outlined their own experience in the tightening technique 'Torque coefficient method' and clarified the simple theory of bolt tightening used in the UK. The half-torque half-turn technique was compared with torque coefficient method which was based on impirical constant, and suggested that the 'half torque half-turn method would lead to the use of power tightening.

During this period further research was being carried out in the Netherlands on the effect of the friction coefficient on the slip load of connections. In 1959 (10)Back and Bouwman published test results in which the tightening methods of bolts and the conditions of the faying surfaces were investigated. All connections considered were in double shear and tested in a tensile testing machine. The number of bolts in each joint varied from single bolt to three bolts. Although a total of fifty six tests were carried out, only two tests in each category were undertaken and it was concluded that the tightening methods, bolt quality, diameter of the bolt and number of bolts in a joint had no influence on the friction coefficient.

Toint (11) presented a paper at the 50th Anniversary meeting of the Chamber of Belgian Consulting Engineers at Brussels in 1959 in which he mentioned the single-track railway bridge in Germany, where high strength friction grip bolts were used. These bolts were made of high tensile steel grade 10 K of minimum tensile strength of 100 kg/mm^2. The bolts were tightened by means of a torque wrench to produce a shank tensile stress about 80 per cent of the lower yield point (90 kg/mm^2). The author suggested an impirical expression to calculate the torsional couple to be exerted on the nut to produce the required shank tension. This expression was not checked with experimental data but the design approach was more rational and the joint was designed on the basis of the interface friction rather than the shearing strength of the bolts.

In 1960 (12) Foreman and Rumph studied the behaviour of eight large compact bolted joints. These joints were fabricated and bolted up using the turn-of-nut method and the bolts were in double shear. In 1961 (13) Bruno Thurlimann presented the short summary of the same results with emphasis on certain points due to the revised specification. Distinction was made between the term "slip coefficient" and the coefficient of friction because the slip coefficient was based on the clamping force existing before any load was applied and not on the actual clamping force at the moment of slip. The coefficient of slip was based on half of the slip load because the joints considered had two slip planes. The tension elongation curve for A325 bolt shows that a direct tension test produces a higher ultimate load as well as a greater total elongation at failure than the case of tension induced by torque. The load/total elongation relationship for main test clearly demonstrated that up to the point of major slip this relationship was linear, then followed by slip deformation until the bolts were brought into bearing. During these tests two methods of tightening were used and the turn-of-nut method proved to be more reliable than the calibrated wrench. Similar conclusion were reached by Jones and Baker (14), Beer (15) in Austria and Tada and Naka (16) in Japan. No agreement was reached on the number of turns through which the nut must be rotated to induce a specific shank tension. All tests were of the double shear type where the joint was subjected to direct tensile loading.

It was recognised that a slip coefficient determined from the slip load and the initial clamping force may not compare directly with commonly used value of the static coefficient of friction, as determined from sliding block tests. A number of investigators tried to relate the shank tension in the bolt to a number of readily observed quantities such as torque, elongation, strain in the shank of a bolt, load cell output and turn-of-nut. In 1963 Rumpf and Fisher (17) carried out a large number of tests and discussed the advantages and disadvantages of each method. The torque required to turn a nut depends on the friction on the threads and on the contact surface under the nut. Rumpf and Fisher confirmed that bolts tightened to one-half turn of the nut from snug developed 85% to 95% of the available torque tension strength where the snugging load was taken at 8 kips. Despite the fact that considerable variations can occur in the bolt shank tension due to the torque technique, this method has been retained in specifications, along with turn of the nut method.

It was a common practice during this period to ignore the eccentricity of load on fasteners connecting web angles to a beam web and every attempt was made to avoid the use of eccentrically loaded connections. Allowable loads given in the 'steel construction' for standard beam connections with usual fastener configuration continued to ignore eccentricities. Some designers assumed an eccentricity equal to the distance from the face of the supporting member to the fastener group centroid and limited the load carrying capacity of the joint accordingly. Calculations were based on the elastic theory, assuming that the centre of rotation was at the centroid of the fastener group. It was known to some investigators that the test load carrying capacity of eccentrically loaded connections was greater than that calculated using the elastic theory. The American Institute of Steel Construction sponsored a series of 10 tests, which were carried out by Yarimci and Slutter (18) in 1963 at Lehigh University's Fritz Engineering Laboratory. Although this report is not available but the results from these tests have been used by other investigators. Steel rivets 3/4" diameter in double shear, bearing on 7/16" and 1/2" plates were used in this study. In 1964 Higgins (19) published the results of a series of ten eccentrically loaded double-shear, riveted cleat-angle connections. These tests are the same as reported by Yarimci and Slutter (18). The author assumed that the ultimate load of a similar single shear connection was one quarter of the experimentally applied load. It was indicated that the elastic theory underestimated the strength of the connection because the ratio of failure load to design load ranged from 4.03 to 5.03. Higgins introduced an emperical method employing "effective" eccentricity according to the number of fasteners in a gaugeline - and this method was incorporated in the AISC manual. The proposed formula was derived from results of riveted connections and it may not be applicable to HSFG bolts because the bolts have different failure properties to rivets. This formula applied only to symmetrically arranged fasteners with the load applied parallel to one of the axis. This method has further shortcomings; it is not easily adaptable to fastener groups not tabulated in the Manual; it is too conservative for large eccentricities and too liberal for small eccentricities; its emperical nature and lack of rational basis is unsatisfactory and it makes no reference to the instantaneous centre of rotation.

In 1965 Praynne (20,21) published results of his investigation into the effectiveness of a number of bolt tightening techniques and the effect of friction on simple bolted joints. Eight types of bolts were used and three methods of bolt tightening i.e. 'torque', 'turn-of-the-nut' and 'part torque part turn' were considered. It was recommended that the torque method with 15% coefficient of variation was more reliable for general use. Three methods of direct tension indicator such as the "Torshear" bolt, "Load indicating bolt" and "load indicating washer" were also investigated and it was concluded that both load indicating bolts and load indicating washers gave quite accurate results with only ± 5 per cent variation in the induced shank tension. Prynne examined the failure mode of a frictional interface and his findings revealed that the area of true contact for a single bolted joint was confined to that material immediately beneath the washer and the pressure induced by preload can reach 30 ton/sq in at the edge of the hole. He also stated that slip occurs by shearing the interlocked asperities in this highly stressed zone. These conclusions suggest the similarity between the mode of shear failure of spot welds and friction grip bolts. Prynne showed the surface roughness had no effect the friction coefficient unless it was very excessive and the coefficient was a direct function of the properties of the plate material, 0.45 for mild steel, 0.52 for medium tensile steel and 0.6 for high tensile steel plates. The above statement is in conflect with the published work concerning the 'slip factor' which shows that frictional coefficient is considerably increased by rust and shot blasted treatment.

During the same year Bannister (22) reported his investigation into the methods of tightening a high strength friction grip bolt. Turn of the nut method for an assembly based on parallel faces with flat washers and parallel faces with tapered washers were considered. The author compared his findings with the methods of establishing bolt preload given by Cullimore (23) and Rumpf and Fisher (17). Cullimore pointed out that a preload variation of ±15 percent can occur using the torque coefficient method. The torque coefficient method relates torque to preload by the expression $T = C W_p d$, where T is the torque applied, W_p the preload induced, d is the bolt diameter and C is the torque coefficient, which for bolts in 'as received' condition was taken as 0.2. Bannister (22) defined the 'snug fit' as the value of 60^o rotation from finger tight and a further 180^o for a shank tension to exceed the proof load provided the piles were in close contact before preload was applied.

In 1965 several authors (24, 25, 27, 29, 30) carried out an investigation into the bolted connections where high strength bolt were used as a structural fastener. Sterling et al (24) reported from the calibration tests of A490 high strength bolt, that the bolt tested in direct tension always gave higher ultimate loads than those from the same lot tested in torqued tension. In torqued tension tests few turns were required to produce failure with increased thread length in the grip. Fisher and Rumpf (25) developed a theoretical solution for double lap butt joints in which fasteners were in a state of bearing and double shear. The mathematical model established two relationship between deformation and load for the component parts of the connection throughout the elastic and inelastic regions. It assumes equal deformation of the plate on the inner and outer faces which is contrary to the experimental evidence. However, in this model the basic conditions of equilibrium and compatibility were satisfied. To solve the compatibility equations and analytical expression developed by Fisher (26) for elastic-inelastic load-deformation relationship for a single bolt was used. This expression is given in the form $R = R_{ult} (1-e^{-\mu\Delta})^{\lambda}$, where R_{ult} = ultimate shear strength, Δ = total deformation of the bolt and the bearing deformation of the connected material; μ and λ are regression coefficients and e base of the natural logarithm. The total deformation capacity Δ, for a given bolt and material is a function of the shear, bending and bearing of the bolt and the bearing deformation of the plate. This deformation will vary with the type of test, the type of bolt, the type of connected material and the thickness of gripped material etc. It is evident that the solution to the problem for long joints with many bolts would be very lengthy and laborious and it is of iterative nature. This iterative method usually requires several trials before the solution is obtained and it is best suited to a digital computer. A plate and bolt calibration tests would be necessary for each condition under consideration.

Fisher and Beedle (27) examined criteria for designing bearing-type bolted joints and the concept of 'balanced design', where ultimate strength of the fasteners in shear should equal to the tensile capacity of the net section of the main material. The authors used the test results reported by other investigators (28) and found that the concept of balanced design lead to inconsistant allowable bolt stresses for different plate material. The concept of balanced design was inapplicable to long joints because the end fasteners "unbutton" before the plate material and the interior bolts could attain its full strength. In this report it was suggested that fixed factor of safety against shear strength of the fastener would be a more logical criterion for design.

Wallaert and Fisher (29) reported results of 174 tests of 7/8" and 1" high strength A325, A354BC, A354BD and A490 bolts installed in test jigs where bolts were subjected to double shear. The authors investigated the effect of a number of variables, such as the condition of faying surfaces, initial preload in the bolt, the location of the shear planes and the type of connected material etc, on the shear strength and the deformation at the ultimate load. The complete load deformation relationship of the bolts was also established. The authors concluded that the initial induced shank tension and the type of connected material had little effect on the shear strength of the bolt when the shear planes passed through the unthreaded shank. It was also pointed out that for a grip-loading span ratio of 2:1, the grip and loading span had no significant effect on the shear strength or deformation at ultimate load. Although this paper provides a useful information about the behaviour of a single bolt in double shear, yet it gave no guidance for a bolt in single shear.

The work on joints was extended by Chesson, Faustino and Munse (30), who investigated the strength and behaviour characteristics of single high strength bolt subjected to various combinations of tension and single shear. These results were then related to the strength and behaviour of rivets under similar loading condition. Interactive equations for tension and shear specifically for the bolts were represented by various ellipses depending upon the location of the shear plane. For A325 bolts with shear plane through the threads was represented approximately by the ellipse $x^2/0.64^2 + y^2 = 1$ where x = ratio of shear component of load on the bolt to the ultimate load in tension and y = ratio of tensile component of load on the bolt to the ultimate load in tension. A total of 116 specimens were considered in the program but only three tests, where tension-shear load ratio was 0:1 and the shear plane passed through the threaded protion, are of special interest to this research. These results are used later for comparison.

Misalignment on double-shear bolted tension joints was studied by Vasarhelyi et al. (31,32,33) in 1956, 1959 and 1965. From a series of tests carried out on misaligned bolted joint specimens, they indicated the possibility of inducing considerable secondary stresses in the connected plates which might reduce the joint efficiency. But their results showed that the misalignment did not significantly affect the ultimate load of the connection whereas the method of punching of holes does affect the efficiency of the joint. To date, no published work is available, which deals with the affect of misalignment on eccentrically loaded connections. Therefore it was ensured that the holes in the test specimens were fully aligned.

Since the frictional resistance is a function of the clamping force due to induced shank tension in the bolt, to achieve economy, it is essential to optimise the specified minimum shank tension. In 1966, Gill (34) carried out a survey of over 800 approved tensile tests and suggested that some of the bolts, which do satisfy the minimum specified strength, would be susceptible to tightening failure, if minimum shank tension were specified at too high a level. He revealed the formula P = CT/d, used by GKN to esablish the relationship between applied torque and induced bolt tension, where P = bolt tension (tons), T = applied torque (lb ft), d = nominal diameter of bolt (ins) and c an impirical constant having an average value of 0.030 which depends on the condition of bolt and condition of each application. From this survey the author concluded that the problem of undertightening or bolt fracture during tightening can be eliminated if the minimum preload were specified at 70% of the minimum ultimate tensile strength. The minimum preload suggested by the author appears to be reasonable but the use of simple formula, where the value of c can vary considerably due to conditions of thread, thread friction, methods of tightening and the type of material clamped, needs further investigation.

In 1966 Abolitz (35) produced a theoretical solution for the ultimate load.based on rigid body movement and fully plastic behaviour of the bolt. The method was basically the same as applied by Koenigsberger (36) in 1951 to eccentrically loaded welded joints where the concept of the instantaneous centre of rotation was applied to this type of problem. Abolitz transformed a line of discrete bolt into a continuum and was able to apply the Koenigsberger intergration method to produce a solution. Abolitz presented his solution finally in a graphical non-dimensional form plotting shear resistance against torsional resistance. The paper gave interactive curves for a number of simple groups; however, for other groups machine computation was advised to generate curves. For design purposes a line defining the applied eccentricity was plotted on the curves and from the interception of this line with the curve, the maximum possible applied load was calculated. The interactive curves published deals mainly with single line of bolts at a constant pitch. The use of computer was essential in order to extend this method for a general case. Abolitz used results from Higgins (19) tests, but he did not tabulate the ratio of experimental and theoretically predicted loads.

Vasarhelyi and Chang in 1967 (37) studied the possible variation of the coefficient of friction in multiple faying surface joints. Two separate terms "nominal coefficient of friction " and "slip coefficient" were used in describing the slip phenomena of a joint. The authors redefined clearly that the difference between two coefficients lies in the difference of definition of the slip load. For the coefficient of friction, the slip load is the load at which a movement of one entire jointed element is first detected e.g. with a dial gauge. For the slip coefficient, the slip load is the load at which "the friction bond is definately broken and the two surfaces slip with respect to one another a relatively large amount. Therefore the coefficient of slip would have a higher value than coefficient of friction. Sixteen test specimens of direct tension type having two and four faying surfaces were considered in order to find a possible standardization in the coefficient of friction. Four different types of steel were used and faying surfaces in all joints were the original "as rolled" mill scale. The authors found that the nominal coefficient of friction varied between 0.23 and 0.34 for the type of steel considered, the average for all steels being 0.28. It was concluded that the values do not seem to be connected to the mechanical properties of the steel contrary to the finding of Prynne (21) and they depend on the condition under which the mill scale forms. The tests showed that the nominal coefficient of friction decreased slightly when the number of contact surfaces was doubled. This paper does not provide sufficient information on the load-slip relationship in the graphical or tabular form and it gives no guidance on the coefficient of friction for a single contact surface.

During the same year i.e. 1967, the American Society of Civil Engineers published an extensive bibliography (38) which complemented the comprehensive literature review on high strength bolts published by Loubster (39) in 1962.

Cullimore presented a paper in 1970 (40) in which he reviewed an investigation on the basic mechanism of friction grip-bolted joints in which fasteners were subjected to in-plane shear forces and the load was transferred wholly by friction between faying surfaces. This theoretical and experimental investigation of the effect on a statically loaded friction-grip bolted joint of initial bolt tension, surface finish of faying surfaces, strength of the plate material and joint geometry was carried out by Eckhart (41). The author observed that the induced shank tension in the bolt reduced as the load on the joint was increased. This reduction in the bolt tension was greater than that to be expected from the thinning of the plate material due to lateral restraint. It was suggested that this discrepancy occurs due to tangential displacement, resulting in the shortening of the bolt. Eckhart confirmed Upton's (42) finding that in friction grip bolted joints, the plate contact is limited to an area close to the bolt-hole. It was also shown that the geometrical parameters T/d and w/d contributed to the load carrying capacity of the joint. A semi-emperical solution for calculating the slip load of a connection was formulated. The suggested design approach is applicable to a limited range of small joints only.

In 1971 Shermer (43) published a paper dealing with eccentrically load joints. He presented design coefficients in the tabular form based on the plastic method of analysis reported by him in 1964 (44). He referred to the inconsistency of elastic theory and gave an example of a centrally-loaded connection in which it is assumed that the stresses are uniformly distributed throughout the joint which is contrary to the experimental evidence that distribution at working loads is not uniform even in the simple connection. He commented on the irrationality of Higgins' proposals. The theory Shermer proposed was based on the assumption that all fasteners transferred an equal load. The author recognised that, although the assumptions for theory were simple yet the solution was tedious and of iterative nature.

In 1971 (43) the author argued that with the aid of a computer the tabulated coefficients, to give the safe design values based upon ultimate strength, can be produced easily. He implied that these tables should replace the tables given in the AISC 7th edition of the Manual which were based on effective eccentricity.

During the same year Higgins (45) recognised Sermer's finding (43) and accepted that with the advent of computer the solution to typical configuration, using plastic theory, can be readily obtained and presented in the tabular form. However he pointed out that with small eccentricities, the distance from the centroid of the fastener group to the centre of rotation is large and the instantaneous differences in deformation at several elements of the group are small, so that variation in deformation with increasing load is of minor significance. But in the case of large eccentricities the differences in deformation throughout the fastener group becomes large and the strain in the outer element could reach the point of rupture before the elements near the centroid of the group are stressed to their assumed 'yield' value. In this paper, the author compared the factor of safety given for three design methods using test results reported by Yarimci and Slutter (18) on 7/8" diameter steel rivets in double shear with small eccentricities. The design methods used for comparison were; elastic analysis using actual eccentricity, elastic analysis using effective eccentricity and plastic method using actual eccentricity. From this comparison the author concluded that in terms of standard deviation the plastic analysis provides the best fit to the test results and the factor of safety agreed reasonably with five control tests performed on single-rivet specimens. The author cautioned that before revising the tables based on plastic analysis, further investigation should be carried out on joints with large eccentricities.

The main comments about the work reported by Higgins and Shermer are that although both have agreed that the plastic theory accurately predicted the ultimate load of the compact group of fasteners, they make no examination of the basic load-deformation behaviour of such a fastener. Several tests performed on fasteners (bolts and rivets) to determine their deformation under a double shear type loading have been reported by Wallaert and Fisher (29) in 1965. The deformation referred to here includes bending, shear and bearing of the fasteners and bearing deformation of the plates. It is apparent from the double-shear/deformation curves that no plateau exists at the theoretical shear yield value and the double-shear deformation relationship of rivets exhibits more ductility than bolts. No experimental investigation was carried out on the behaviour of individual high strength bolts or eccentrically load bolt groups, where bolts were subjected to single shear. Therefore, it would have been more appropriate for the authors (44,45) to conclude that plastic theory accurately predicted the ultimate load of riveted connections in double shear.

Crawford and Kulak in 1971 (46) pointed out the inconsistancies of both simple elastic and simple plastic theories and published a rational method for predicting the ultimate strength of an eccentrically loaded fastener group. This paper was based on the author's finding reported in 1968 (47). The concept is very similar to that used by Francis (7) and considers the experimentally obtained load/deformation relationship of a single fastener to predict the ultimate strength of eccentrically loaded fastener groups. The authors used the load/deformation relationship of a single fastener in double shear expressed by Fisher (26), $R = R_{ult}\ (1 - e^{-\mu\Delta})^{\lambda}$. In order to find the regression coefficients six tests were carried out on single fasteners in double shear, in a compression jig. For analytical solution Crawford and Kulak considered the bolts as discrete elements and used a non-linear load deformation characteristic. This combined with equilibrium of forces, compatibility of rotation about an instantaneous centre of rotation produced a complex solution. The solution is of iterative nature, therefore a trial-and error procedure was used to determine the ultimate load on a connection and a program for a digital computer was written. The program increased the value of radius of rotation by small increments, from initial approximation, until the condition of equilibrium was satisfied within ± 2 Kips. Eight full size specimens, which included four different bolt configuration with varying eccentricity, using 3/4 diameter A325 bolts, were tested and the results analysed with the computer program.

To substantiate the validity of their theory, the authors used results on riveted connections reported by Yarimci and Slutter (18). The maximum rivet force R_{ult} of 55 Kips and a maximum deformation Δ_{max} of 0.3" were considered in this comparison. But the regression coefficient used was for A325 bolts, it implies that the shape of the load deformation curve for rivets is similar to that of bolts, which is contrary to the finding reported by Wallaert and Fisher (29).

The following comments may be made of this paper:-

a) The investigation is limited to double shear only and the conclusions are based on small numbers of tests with small eccentricity.

b) A set of separate regression coefficients are required for each type of fastener in conjunction with each type and thickness of connected material. This is due to the fact that the load-deformation relationship for a fastener is dependent on the shear deformation of the fastener, bending of the fastener and in particular the bearing stresses on the plate.

c) The comparison with riveted results using regression coefficients for bolts is unjustified due to the variation in the shape of load/deformation curve.

d) The program presented is ill-conditioned for large eccentricities and time consuming.

The author's approach depends upon the many primary assumptions and involves the use of regression coefficients. Numerous other unknowns are non-quantifiable parameters governing the complex connection behaviour. The unavoidable differences in the connection as designed and as fabricated further compounds the problem. In view of these many intangibles the writer contends that excessive theoretical refinement in the development of a practical design tool is unrealistic, unnecessary and of illusory precision.

In 1973 Struik et al (48) studied the load-gap relationship of 'coronet' load indicators with both A325 and A490 bolts. The coronet (load indicating washer) was placed between the head of the bolt and the gripped material and five bolts with washers were tested for each combination. The parameters investigated were; influence of grip length, effect of parallel surfaces and out-of-parallel surfaces on the gap measurement.and bolts installed in simulated joints. The authors concluded that the average load reached at a gap of 0.015" was always equal or greater than the specified minimum bolt tension. The average gap closure for parallel and out-of-parallel surfaces can be utilized as an indication of the bolt tension. It was stressed that complete closure of the gap at all points around the washer should be avoided, since it could result in overtightening and difficult to inspect.

In certain practical cases it is almost impossible to see or to measure the gap, if a load indicating washer is used under the head of the bolt. Under such circumstances, it is unavoidable to place the load indicating washer under the nut. The authors have given no guidance on this arrangement. Although the manufacturers of load indicating washers have suggested the use of hardened washer under the nut and a different gap closure requirements, very little independent experimental data is available to substantiate their specification.

Cullimore and Eckhart published a paper in 1974 (49) and presented the flowchart for finite-element method used to obtain the distribution of clamping pressure at the interface of lap joints. The finite-element presented uses the element derived by Zienkiewicz (50) which enables the boundary conditions along the interface to be adequately presented. This paper is based on the work reported by Upton (42) and Eckhart (41) and it shows that the pressure at the edge of the hole is maximum due to induced bolt shank tension. The pressure decreases as the ratio of the total joint thickness to the hole diameter increases and is a function of the ratio of the thickness of the outer to inner piles.

Russian Engineering journal published papers by Novikova 1973 (51) and Baranov 1976 (52) on the strength calculations of a bolt in single shear. Novikova developed a simple analytical model assuming the full end fixity at both the bolt head and under the nut, to calculate the effect of bending stresses on the bolt due to the presence of a hole clearance. Semi-emperical solution produced indicated that as the hole clearance increased, normal bending stresses increased until the clearance reached a critical point and any further clearance had no influence on the value of the normal bending stresses. Baranov attempted to produce a solution which would establish the moments at the head and the nut of a bolt in a single shear joint. He assumed that the ends of the bolt elastically held and having a finite stiffness. He formulated differential equations which took into account the shear and bending deformation of the shank and the gripped parts. The expressions became very complex and difficult to use in practical calculations. Therefore, an assumption was made that the clearance in the holes was very small. This enabled the author to assess the stress state of the highly stressed places of a bolt. Both authors have made a reasonable attempt to find a solution to a very complex problem. However, the basic assumption in both cases that ends are rigidly fixed is erroneous and to have no clearance in the holes is impractical.

Purkiss in 1976 (53) reported several test results on eccentrically loaded HSFG bolted joints. Two test rigs, one with 12 mm thick plate and the other with 19 mm thick plate, incorporating 20 mm dia HSFG general grade bolts were used for these experiments. To ensure that the bolts were tightened to their minimum shank tension, load indicating washers were placed under the bolt head and it was considered that a minimum shank tension of 144 kN was reached when the average gap measured 0.015". The test specimens were used again and again and the faying surfaces were blast cleaned each time. This resulted a coefficient of friction which varied from test to test due to the change in the size of grit used. The failure load was defined as the load at which the joint slipped into bearing and test bolts were used twice before they were discarded. The author attempted to formulate an emperical expression to fit the test result but finally accepted that the plastic method of design provided the most suitable approach.

The following comments may be made on this investigation:-

a) The author assumed that a minimum shank tension of 144 kN was reached for an average gap of 0.015" and made no attempt to verify this assumption.

b) In the use of load indicating washers, the specified gap of 0.015 inch merely indicates that a minimum specified shank tension has been reached and it does not predict the actual tension in the bolt which could be greater (48) than 144 kN.

c) It does not clearly identify the tests where bolts were used a second time.

d) The author stated that the coefficient of friction for 12 mm thick plate varied between 0.615 and 0.5 from test to test, but made no attempt to record each test value separately. Unfortunately, he presented his results, dividing each failure load by the corresponding coefficient of friction, which makes it impossible to separate one value from the other.

e) Test results reported on 19 mm thick plate, where coefficient of friction was stated to be constant, may be of some interest to this research.

Last year (1979) Surtees and Pape (54) reported an investigation on eccentrically loaded friction grip bolted joints, where bolts were in single shear. This paper was based on the work carried out by Pape in 1970 (55). The main purpose of this investigation was to verify the assumption made in rigid plate/plastic bolt theory that bolt forces equalized at failure. Non-slip joints were considered and the failure was defined at the point at which the static frictional resistance was overcome. On the onset, the authors referred to the inconsistencies of the elastic theory and commented on the Crawford and Kulak's (46) method, in as much that the force/displacement relationship included post-slip behaviour and the coefficients for tabular results were not suitable for non-slip joints.

To examine the behaviour, a series of nine tests were performed. The test rig consisted of 10 mm and 12 mm thick mild steel plates on which various configuration of holes were drilled. The faying surfaces of the plates were as-rolled condition and the bolt used were HSFG general grade, 16 mm and 22 mm diameter. Three small foil gauges placed equidistantly around the bolt shank immediately under the head were used in some bolts to measure the bending strain in the bolt shank. The joints were eccentrically loaded to failure and the bending strain recorded at suitable load increments.

Configuration of six to 24 bolts under eccentricity ranging from 203 mm - 1384 mm were examined. A series of computer programs were written to accelerate the plastic design process. From the strain vectors recorded during the experiments a zone of rotation was established in the bolt group. The authors proved that rigid plate/plastic bolt theory, accurately predicted the ultimate behaviour of joints. However, it was suggested that elastic bolt theory should be retained in the design of non-slip joints.to allow for inaccuracies resulting from an incorrect tightening procedure, misalignment of faying surfaces and non-random deviation in bolt slip load.

The authors have provided a new technique to establish the position of the centre (zone) of rotation and also a substantial computer program to facilitate the use of the plastic bolt theory.

The stresses and strains produced near the head of a bolt due to shank tension, bending of the shank, restricted shear deformation of the shank due to bolt head and partial fixity provided by head and nut, are of highly complex nature. The writer maintains that an extensive research programme is required to substantiate that the use of foil gauges near the head can adequately sense the magnitude and direction of shear transmitted at the bolt position.

It is rather unfortunate, that these tests were not continued to ultimate failure of bolts in single shear in view of the very limited experimental data available to date.

The results from these tests will be used later to compare with the findings of this research for an ultimate limit state of slip.

An extensive review of the existing literature suggested that there are three basic theories i.e. rigid plate/elastic bolt theory, rigid plate/plastic bolt theory and rigid plate/non-linear force - displacement theory (46), published to date, which may be used to establish the strength of a bolted connection. There is considerable contention amongst the authors about their suitability for small and large eccentricities on a bolted connection. The experimental data available to date, which could help to clarify these points is very limited.

The introduction of limit state design in the draft steel code (56) requires that the strength of the bolt group be determined at the ultimate limit state. Practising engineers prefer a simple formula, tables or graphs for design purposes. In order to check the validity of the assumptions and the accuracy of the design method, an extensive series of tests on unstressed bolts and on full scale HSFG bolted connections were undertaken in this programme.

CHAPTER THREE

EXPERIMENTAL RESULTS OF UN-TENSIONED BOLTS

3.1 INTRODUCTION

It is evident from the previous chapter that the number of test reported on bolted joints subjected to in-plane forces in double and single shear, considering the failure of bolt as the main criteria, are very limited. This chapter is concerned with the experimental determination of the behaviour of joints at the ultimate limit state "failure of a bolt". This will be the critical limit state for black bolts, high strength and fitted bolts. The parameters considered are the load-deformation relationship of a bolt in single shear, the effect of varying the thickness of connected plates at the failure stage of a bolt, the relationship of deformation and bearing stress on bolt and plate, and its application to a group of bolts in a joint. High strength friction grip bolts subject to torsion and shear i.e. the in-plane forces will be considered at the limit state of serviceability "slip" and ultimate limit state "failure of a bolt". The behaviour of friction grip bolts will be discussed in detail in Chapter 4.

3.1.1 Referencing of tests

Due to the large number of tests in the programme undertaken in the present work it was considered necessary to identify each piece of the material used. Plates and bolts were taken from different batches. The average tensile and shear strength in each batch therefore varied and so that the results may be compared later on, the following system of referencing was used.

The tests are divided into three series according to the number of bolts in the group in each test. Series 1 one bolt. Series 2, two bolts. Series 3, more than two bolts were tested. These tests are cross-referenced to the batch of bolts or plate used in each series. Each specimen is labelled by a number showing the number of bolts used, followed by a letter, with suitable sufficies where required, indicating the type of bolt and ending with numeral denoting the test number. Four letters B (Black bolts), C (Cheese head bolts), H (High strength bolts un-tensioned) and H_t (HSFG bolts tensioned to a given force) were used to differentiate the type of bolts in each test. **A typical example is:-**

Series 2 batch 2b specimen label 2H8

3.2 Material properties

Each batch of bolts and steel plates used in the test were clearly marked and a number of specimens taken at random to establish the material characteristic such as yield strength, ultimate strength and modulus of elasticity.

3.2.1 Tensile tests on bolts

Two types of tensile tests were employed, one using full size bolts to establish the ultimate strength, second turned down in diameter bolts to find out the yield stress and the modulus of elasticity. A Denison Universal Testing Machine type T42B4 serial No 29169, maximum loading capacity of 500 kN was used for the 20 mm diameter bolts, and a Hounsfield Tensometer type W for the 5 mm diameter cheese head screws. To find the ultimate strength of a bolt the annular, screw threaded chucks, as shown in plate 3.1 were manufactured from high tensile steel and used on the Denison machine.

3.2.1.1 Black Hexagon Bolts - Batch 1

Black bolts M20 x 70, 4.6 to BS 4190 (57) together with appropriate nuts and washers to the same BS were tested. A set of 20 bolts from a batch of 200 was selected and examined for defects. Dimensions such as diameter and length were measured and compared with specifications and found satisfactory. Fifteen full size bolts were tested for the ultimate strength. Each bolt was carefully assembled in the testing jig with two washers, one under the head and the other under the nut. The nut was turned such that the gap between both chucks was maintained constant in each test. During the first two tests thread stripping of a bolt took place as shown in plate 3.1 at a load greater than minimum tensile load 96 kN specified in BS 4190 (57). To determine the ultimate strength of a bolt two nuts were used, maintaining a free threaded length equal to the nominal thread diameter of a bolt, to eliminate thread stripping. A constant rate of loading of 0.25 kN/sec was used during the test. The ultimate strength of bolts and the position of the fracture plane is recorded in Table 3.1. It was observed that in direct tension the fracture plane deviated from the classical cup and cone shape due to the effect of threads. The mean ultimate strength of the bolts was 55.9% higher than that specified in BS 4190 (57).

The remaining five bolts were turned down to 16.2 mm diameter over a length of 25 mm. Three strain gauges were attached to the reduced shank of each bolt and tested in the Denison, strain gauges became ineffective at a stress of 531.93 N/mm^2. The stress-strain graph of a typical test is shown in Figure 3.1. The results of other test were similar and the mean ultimate tensile stress for these tests was 624.5 ± 8.6 N/mm^2 these results are not representative of typical black bolts.

Plate 3.1 TENSILE TESTING JIG AND TESTED BOLTS

Test No	Ultimate tensile Strength (kN)	Location of failure
*1	136.15	Threads stripping
*2	141.53	" "
3	149.51	Fracture at threads
4	146.32	" "
5	151.11	" "
6	152.70	" "
7	147.72	" "
8	151.70	" "
9	151.70	" "
10	149.71	" "
11	151.31	" "
12	147.72	" "
13	146.32	" "
14	149.71	" "
15	151.62	" "
Mean tensile	149.78 ± 2.16	

* Indicates that these tests are not included to calculate the mean tensile strength

TABLE 3.1: TENSILE STRENGTH OF FULL SIZE BLACK BOLTS

(Batch 1)

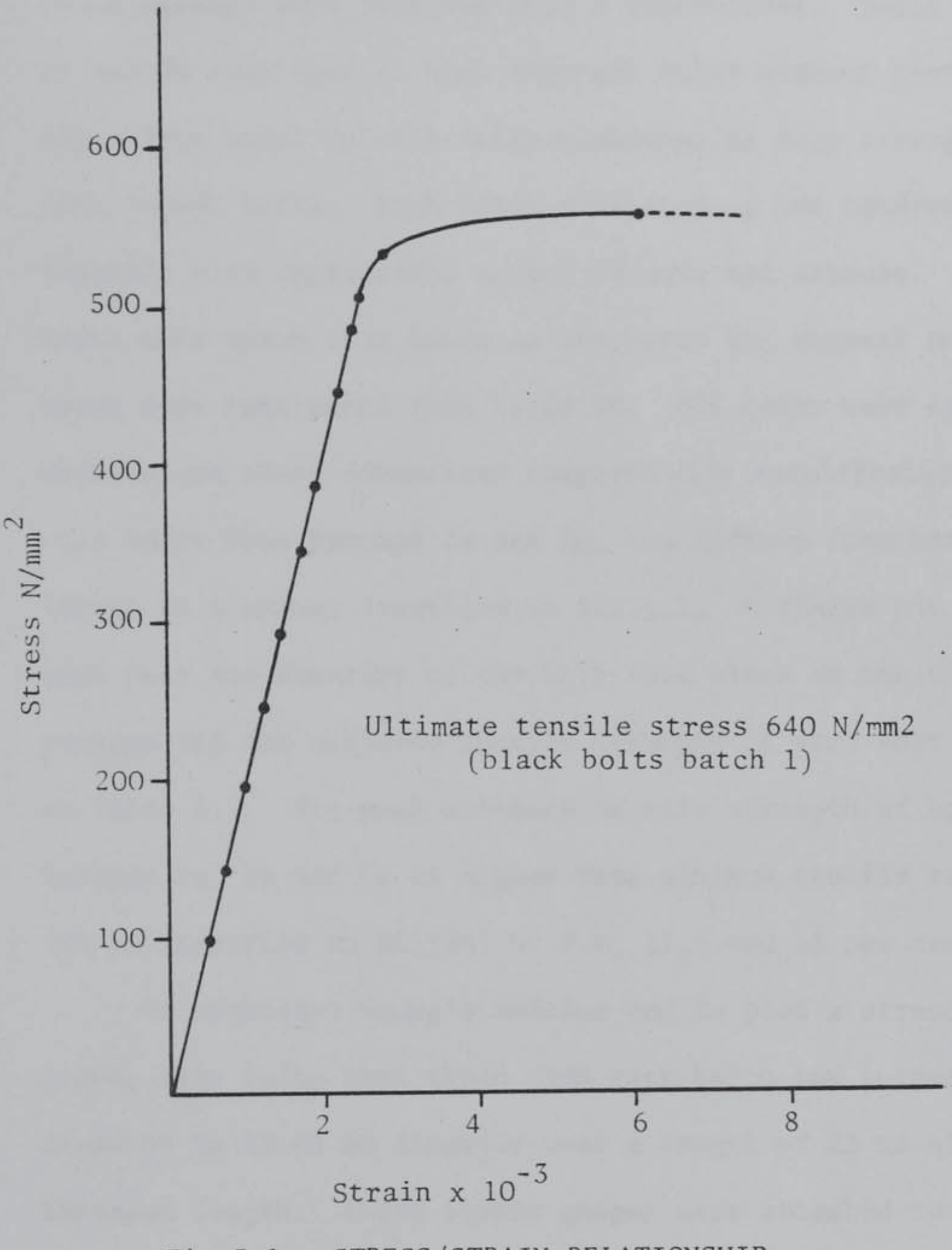


Fig 3.1: STRESS/STRAIN RELATIONSHIP
(Black bolts)

3.2.1.2 High Strength Friction Grip Bolts Batches 2a, 2b and 2c

Three separate batches of HSFG bolts M20 x 70 general grade to BS 4395 Part 1, 1969 (58) together with M20 nuts and M20 flat round washers were received from a stockholder. Bolts from batches 2a and 2b were used as high strength bolts without pretension and bolts from batch 2c were fully tensioned as high strength friction grip (HSFG) bolts. Each batch consisted of two hundred bolts together with appropriate number of nuts and washers. Twenty five bolts were taken from batch 2a and batch 2c, whereas only twenty bolts were considered from batch 2b. All bolts were examined for defects and their dimensions compared with specification. Twenty full size bolts from batches 2a and 2c, and fifteen from batch 2b were tested in a manner described in 3.2.1.1. A single nut was used in each test and fracture of the bolt took place at the threaded portion and the ultimate tensile strength of each bolt is recorded in Table 3.2. The mean ultimate tensile strength of bolts from batches 2a, 2b and 2c is higher than minimum tensile strength of 203 kN specified in BS (58) by 9.4, 11.6 and 13 per cent respectively.

To establish Young's modulus and to plot a stress-strain graph, five bolts were taken from each batch and turned down in diameter to 16.48 mm diameter over a length of 25 mm along its threaded length. Three strain gauges were attached to the reduced shank of each bolt and an average of three readings was taken to eliminate the effect of bending on a bolt, and the assembled specimen was tested in the Denison testing machine. During testing, the strain gauges became inoperative at a load greater than the yield load. A stress-strain graph of a typical bolt from each batch is

Test No	Ultimate tensile strength (kN) Batch 2a	Ultimate tensile strength (kN) Batch 2b	Ultimate tensile strength (kN) Batch 2c
1	219.78	221.77	233.23
2	224.26	233.23	225.26
3	224.26	222.27	221.27
4	224.26	224.27	234.23
5	216.79	221.27	244.20
6	219.28	219.28	229.25
7	222.27	217.79	233.24
8	224.26	249.18	233.23
9	225.26	224.76	229.25
10	219.28	233.23	224.26
11	229.25	222.27	228.25
12	219.78	235.60	230.24
13	221.77	217.80	230.24
14	219.28	226.79	226.26
15	221.27	231.13	236.23
16	218.28	-	219.28
17	224.27	-	233.23
18	225.26	-	224.27
19	220.27	-	230.24
20	223.27	-	224.26
Mean tensile strength	222.12 ± 3.05	226.71 ± 8.5	229.49 ± 5.73

TABLE 3.2: TENSILE STRENGTH OF FULL SIZE HSFG BOLTS
(Batch 2a, 2b and 2c)

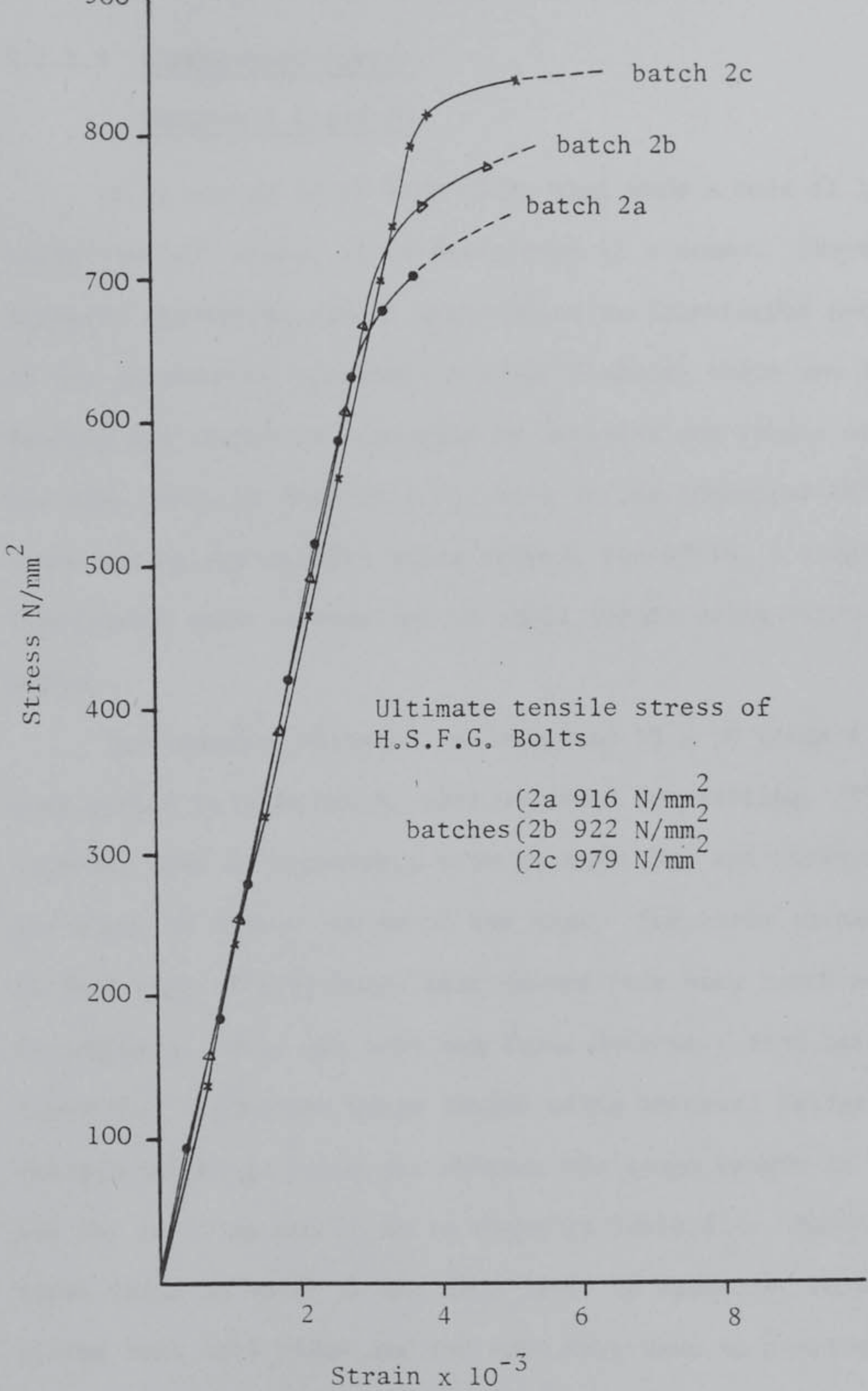


FIG 3.2: STRESS/STRAIN RELATIONSHIP
(H.S.F.G. Bolts)

shown in Figure 3.2. The results of other tests were similar. The mean ultimate tensile strength for five bolts from batches 2a, 2b and 2c was 915.8 ± 7.2 N/mm^2, and 1054.9 ± 15 N/mm^2 respectively.

3.2.1.3 Cheese-head Screws
Batches 2 a and 2b

It is stated in BS 4190 (57), that when a bolt is threaded along its full shank, it is designated as a screw. Therefore 5 mm diameter cheesehead screws were chosen to investigate the validity of the theoretical approach on small diameter bolts and its choice enabled the author to economise on material and labour costs. It has been shown by Francis (7), that in the behaviour of joints, there was no appreciable scale effect, therefore, a large number of experiments were carried out on small joints using small diameter bolts.

Two separate batches, one thousand M5 x 30 grade 4.8 cheese-head screws in each batch, were acquired for testing. These bolts (screws) were in accordance with BS 4183 (59) and threaded along the shank to within 1.6 mm of the head. The screw threads were to BS 3643 (60). Fifty bolts were chosen from each batch and examined for defects. Only one bolt was found defective from batch 3a and rejected. A constant gauge length using internal calipers of 15 mm was maintained in batch 3a, whereas the gauge length in batch 3b was set to 20 mm and 22 mm as shown in Table 3.4. During the first seven tests in batch 3a and five tests in batch 3b, thread stripping of the bolt took place and two nuts were used to overcome this problem. The test results for batch 3a and 3b are shown in Table 3.3 and 3.4 respectively. The mean ultimate tensile strength of batch 3a was 7.39 ± 0.89 kN. The strength at yield point was 89.4% of

Test No	Load at Yield Point (kN)	U.T.S. (kN)	Gauge Length (mm)
1	-	-	15.0
2	-	7.5	15.0
3	-	7.6	15.0
4	-	7.3	15.0
5	-	6.7	15.0
6	-	7.7	15.0
7	-	7.6	15.0
8	6.95	8.0	15.0
9	7.30	7.90	15.0
10	5.0	5.80	15.0
11	4.90	5.70	15.0
12	5.40	6.70	15.0
13	7.45	8.10	15.0
14	5.65	6.10	15.0
15	7.50	8.30	15.0
16	5.80	6.25	15.0
17	6.5	7.85	15.0
18	5.0	5.75	15.0
19	4.9	5.75	15.0
20	6.9	8.0	15.0
21	7.5	7.95	15.0
22	6.7	7.75	15.0
23	7.1	7.7	15.0
24	6.75	7.65	15.0
25	7.2	8.0	15.0
26	5.4	6.1	15.0
27	7.2	7.85	15.0
28	6.95	7.9	15.0
29	7.4	8.2	15.0
30	7.05	7.8	15.0
31	7.3	7.95	15.0
32	7.2	7.9	15.0
33	7.0	8.15	15.0
34	5.3	6.1	15.0
35	7.0	7.6	15.0
36	7.15	7.8	15.0
37	5.9	6.2	15.0
38	7.35	8.2	15.0
39	7.15	7.75	15.0
40	6.70	7.50	15.0
41	6.90	8.15	15.0
42	7.05	8.15	15.0
43	5.25	5.95	15.0
44	6.85	7.65	15.0
45	7.0	7.9	15.0
46	5.1	5.7	15.0
47	7.25	8.0	15.0
48	7.20	8.0	15.0
49	7.05	7.80	15.0
50	7.45	8.45	15.0

Meam ultimate tensile strength = 7.39 ± 0.89 kN
Mean yield tensile strength = 6.59 ± 0.86 kN

TABLE 3.3: TENSILE STRENGTH OF CHEESEHEAD SCREWS (Batch 3a)

Test No	Load at Yield Point (kN)	U.T.S. (kN)	Gauge Length (mm)
1	7.0	-	22.0
2	6.50	-	22.0
3	7.0	-	22.0
4	7.0	-	20.0
5	7.0	-	20.0
6	7.05	7.94	22.0
7	6.80	7.84	20.0
8	6.40	7.49	20.0
9	7.0	7.98	20.0
10	6.70	7.68	20.0
11	6.70	7.80	20.0
12	6.80	7.60	20.0
13	7.0	7.55	20.0
14	7.0	8.05	20.0
15	6.80	7.40	20.0
16	6.50	7.95	20.0
17	6.80	7.95	20.0
18	6.70	7.82	20.0
19	6.80	7.57	22.0
20	6.70	7.65	22.0
21	6.90	7.52	22.0
22	7.0	8.0	22.0
23	7.40	8.29	22.0
24	7.20	7.85	22.0
25	7.0	7.82	22.0
26	7.0	7.95	22.0
27	7.0	7.67	22.0
28	7.20	7.90	22.0
29	7.0	8.0	22.0
30	7.0	7.72	22.0
31	7.10	7.98	22.0
32	7.0	8.15	22.0
33	6.80	7.41	22.0
34	6.80	7.30	22.0
35	7.0	8.10	22.0
36	7.0	7.83	22.0
37	7.0	7.88	22.0
38	6.80	7.45	22.0
39	6.80	7.51	22.0
40	7.0	7.78	22.0
41	7.0	7.90	22.0
42	6.50	7.20	22.0
43	7.20	7.71	22.0
44	7.0	7.91	22.0

Mean ultimate tensile strength = 7.77 ± 0.25 kN
Mean yield tensile strength = 6.91 ± 0.20 kN

TABLE 3.4: TENSILE STRENGTH OF CHEESEHEAD SCREWS (Batch 3b)

the ultimate tensile strength (UTS). The mean ultimate tensile strength of 7.77 ± 0.25 kN in batch 3b was 5% greater than batch 3a. The strength at yield point in batch 3b was 88.9% of the ultimate tensile strength.

3.2.2 Tensile Tests on Plate Steel

In order to determine the properties of the plate material, tensile tests were performed on specimens from each batch of steel. These specimens were obtained from the batch length and were cold sawn. Tensile tests were performed in an Avery-Denison hydraulic compression-tension testing machine, which incorporates a 50 mm gauge length strain recorder and automatic plotter.

3.2.2.1 Plate steel

Batch P1

Steel plate from batch P1 was used in conjunction with bolts from batches 1, 2a and 2b. Four specimens 250 mm long were cold sawn from a sample length of plate steel grade 43A to BS 4360 (61). The specimens were subsequently machined to a uniform cross-section in accordance with BS 18 (62). The yield stress and modulus of elasticity were obtained using an automatic strain recording for the tensile tests and an ultimate tensile stress calculated. Three further specimens in the form of a rectangular strip were sawn from the same sample plate. These specimens were machined to a uniform cross-section and tested in the same manner as the previous four. The yield stress and modulus of elasticity were obtained from the graph and the ultimate tensile strength calculated. The size of the specimens and the results from these seven tests are recorded in Table 3.5. It is evident from the comparison of results that both types of specimens gave similar values of yield stress and

Test No	Type of sample	Sample size t x b x l (mm)	Yield stress N/mm^2	Ultimate stress N/mm^2
1	To B.S. 18	19.78 x 15.15 x 250	268.90	483.21
2	To B.S. 18	15.08 x 10.10 x 250	271.00	499.71
3	To B.S. 18	9.99 x 15.00 x 250	276.48	501.60
4	To B.S. 18	19.77 x 15.06 x 250	266.37	489.59
5	Rect. strip	19.78 x 15.01 x 250	273.46	503.16
6	Rect. strip	19.78 x 10.21 x 250	275.12	492.31
7	Rect. strip	19.77 x 12.16 x 250	270.21	498.26
Mean stress			271.65	495.41
			±3.57	±7.272

TABLE 3.5: TENSILE STRENGTH OF PLATE STEEL

(Batch P1)

ultimate stress. From this comparison it was considered adequate to use rectangular strips for the tensile test for the remaining batches of plates.

The minimum guaranteed tensile yield stress by a manufacturer for a grade 43A steel to BS 4360 (61) is 250 N/mm^2. The average yield stress from these tests was 271.65 N/mm^2 which is 8.66% higher than the minimum specified. The modulus of elasticity was determined for all the tensile tests, and the average was 200 N/mm^2. This value will be used throughout.

3.2.2.2 Plate Steel

<u>Batches P2 and P3</u>

The material for these batches was ordered as grade 43A to BS 4360 (61) in two different thicknesses. Plate for batch P2 was 10 mm nominal thickness and used for tests on cheesehead screws batches 3a and 3b. Steel plate for batch P3 was 20 mm thick and was used to establish the single shear load deformation relationship of bolts from batch 2b for different thickness of plate material. The consistancy in yield strength was obtained by machining specimens from the 20 mm thick plate to required thickness. Five rectangular strip specimens were taken from batch P2 and four from batch P3, and tested as outlined in 3.2.2.1. The specimen sizes and results are shown in Table 3.6. The mean yield strength for batch P2 was 256.38 N/mm^2 whereas the mean yield strength for batch P3 was 221.87 N/mm^2 which is less than the minimum specified strength of 250 N/mm^2.

3.2.2.3 Plate Steel

<u>Batch P4</u>

The plate material for this batch was 20 mm thick, grade 43A

Batch No	Test No	Sample size b x t x l (mm)	Yield stress N/mm^2	Ultimate stress N/mm^2
P2	1	23.71 x 9.9 x 320	250.4	416.9
P2	2	20.00 x 9.9 x 320	253.6	420.1
P2	3	17.00 x 9.9 x 320	259.1	432.0
P2	4	15.00 x 9.9 x 320	258.4	428.2
P2	5	12.00 x 9.9 x 320	260.3	435.3
Mean Stress			256.38 ±4.15	426.64 ±7.93
P3	1	20.20 x 15.70 x 250	227.85	408.50
P3	2	19.27 x 18.37 x 250	225.25	408.80
P3	3	20.55 x 18.85 x 250	210.00	406.00
P3	4	24.59 x 15.53 x 250	224.40	409.25
Mean stress			221.87 ±8.05	408.13 ±1.5

TABLE 3.6: TENSILE STRENGTH OF PLATE STEEL

(Batches P2 and P3)

Batch No	Test No	Sample Size b x t x l (mm)	Yield stress N/mm^2	Ultimate stress N/mm^2
P4	1	13 x 20 x 250	306.6	548.2
P4	2	13 x 20 x 250	306.6	545.9
P4	3	13 x 20 x 250	295.2	532.8
P4	4	13 x 20 x 250	299.0	539.7
P4	5	13 x 20 x 250	306.6	551.2
Mean stress			302.8 ±5.3	543.5 ±7.3

TABLE 3.7: TENSILE STRENGTH OF PLATE STEEL

(Batch P4)

to BS 4360 (61) and it was used with HSFG bolts from batch 2c for tensioned connections, which are discussed in detail in Chapter 4. Five rectangular tensile test specimens were cut from this batch of steel and tested in the Denison machine using the automatic strain recording plotter. The yield stress and modulus of elasticity were obtained from the graph and the ultimate tensile strength calculated. The size of the specimens is recorded in Table 3.7. The average yield stress from these tests was 302.8 N/mm^2 as shown in Table 3.7, which is 21% higher than the minimum specified yield strength of 250 N/mm^2.

3.3 Single Bolt Tests - Series 1
Shear Strength of a Single Bolt

The theoretical analysis of bolt groups at the ultimate load depends on the shear strength of a single bolt and the corresponding load deformation relationship. Therefore, the primary objective of these tests was to define the shear strength and load-deformation relationship of a bolt subjected to in-plane forces in single shear, and to relate these results to the strength and behaviour of a group of bolts under similar load conditions. The deformation at the ultimate load is the summation of shear deformation of the bolt, the bending of the bolt and the elongation of the hole due to bearing stresses.

The shear capacity of a bolt depends on the location of the plane of loading, as the shear resistance of the bolt is directly proportional to the available resisting area. The shear area at the threaded portion is about 78% of the area of the unthreaded shank as given in BS 4190 (57). The draft steel code (56), states that the nominal area of the unthreaded shank should be used to calculate the shear strength of a bolt. However for ordinary bolts in clearance holes it is sometimes not possible to locate the shear plane in the untreated part.

The tests were carried out on black bolts, cheesehead screws and high strength bolts. All bolts had washers at the head and nut, and it was arranged that failure always occurred on the threaded part. These tests are described in detail in Series 1.

3.3.1 Single Bolt Tests - Series 1

3.3.1.1 Black hexagon bolts

Five bolts were taken from batch 1, examined and set aside for single shear tests. The test rig consisted of two identical plates 20 mm thick taken from batch P1, and a 22 mm diameter hole was bored through each plate. An additional small plate was welded on one side of each test plate to minimise the out of plane effect Figure 3.3 and Plate 3.2 shows the overall dimensions of the test specimen and the position of demec spots attached to the plates. One washer at the head and one under the nut was used to ensure that failure always took place at the threaded portion. In these tests the friction between the plates was eliminated by using a perspex sheet grease pack 4 mm thick. To minimise the effect of induced tension in the bolt due to tightening of the nut, and to achieve consistancy in the nominal tensile force in the bolt, the bolt was tightened with a torque wrench set to a torque of 13.5 Nm. The assembled specimen was placed in a Denison universal testing machine and a dial gauge was attached to the specimen, on the opposite face to the demec spots, to compare the deformation on each side. The load was applied at a constant rate of 0.25 kN/sec and the deformation was recorded at suitable intervals until the

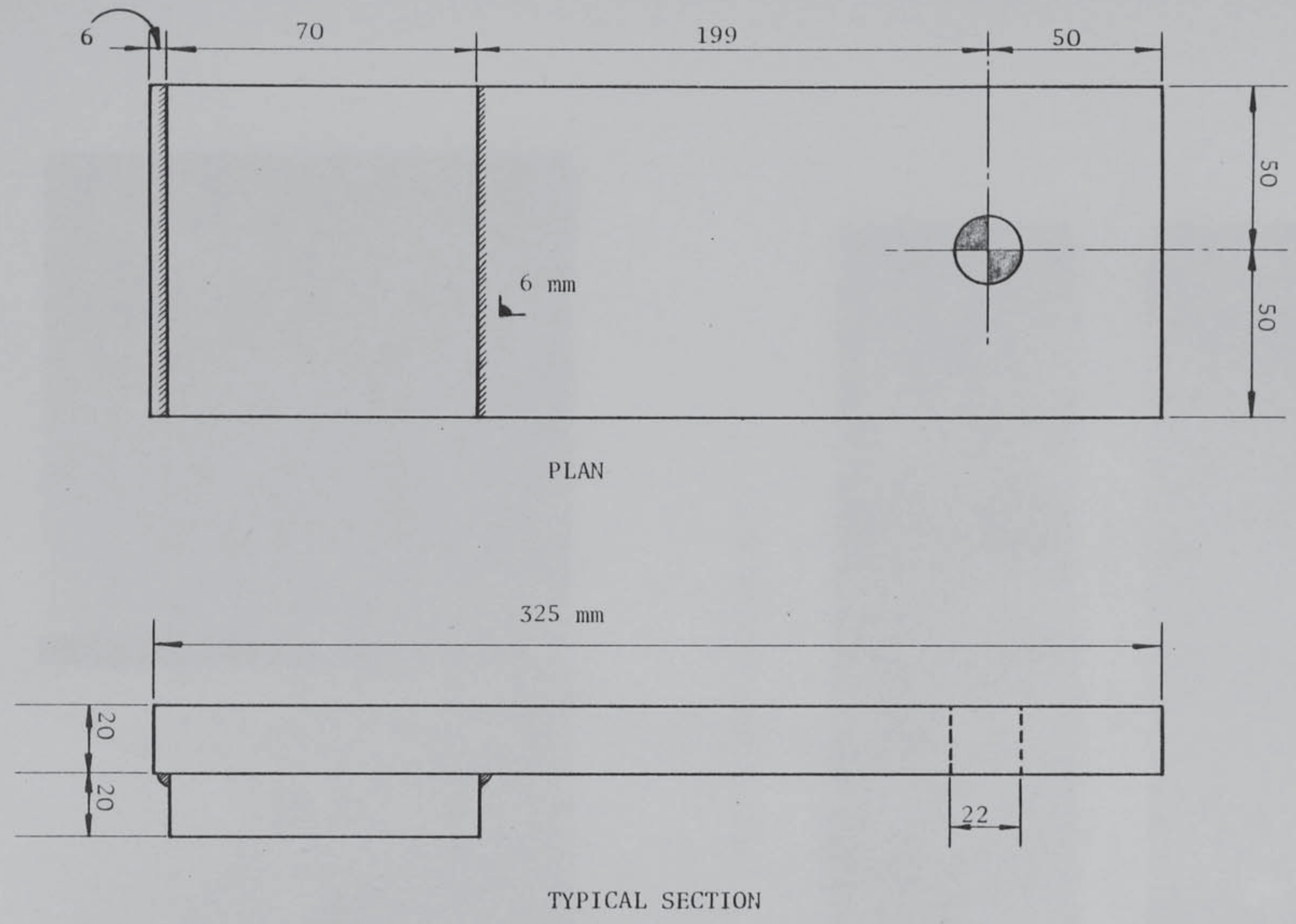
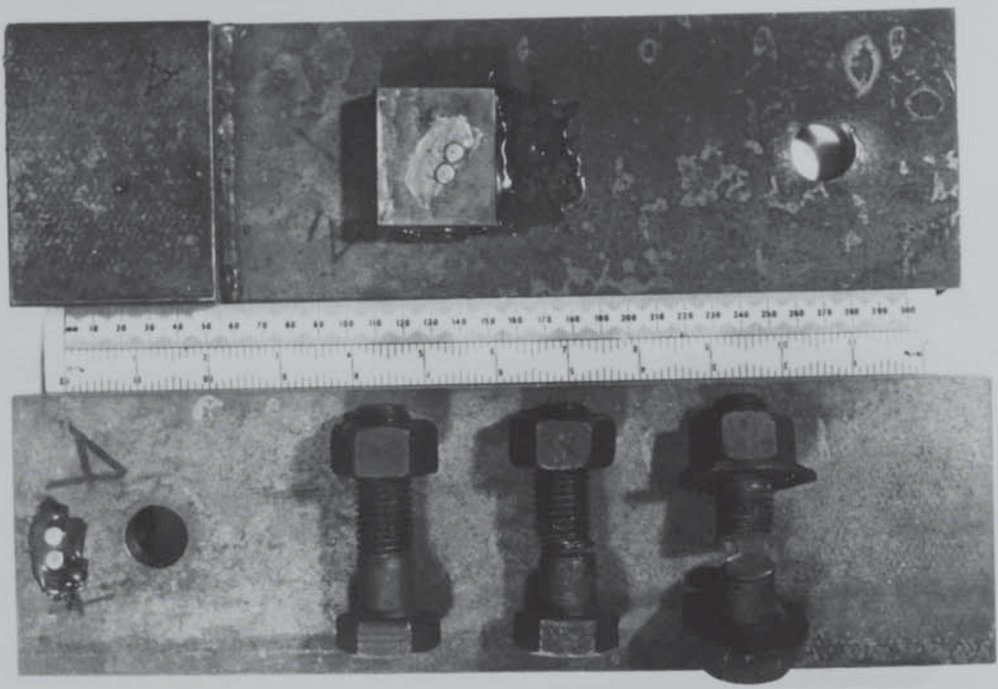
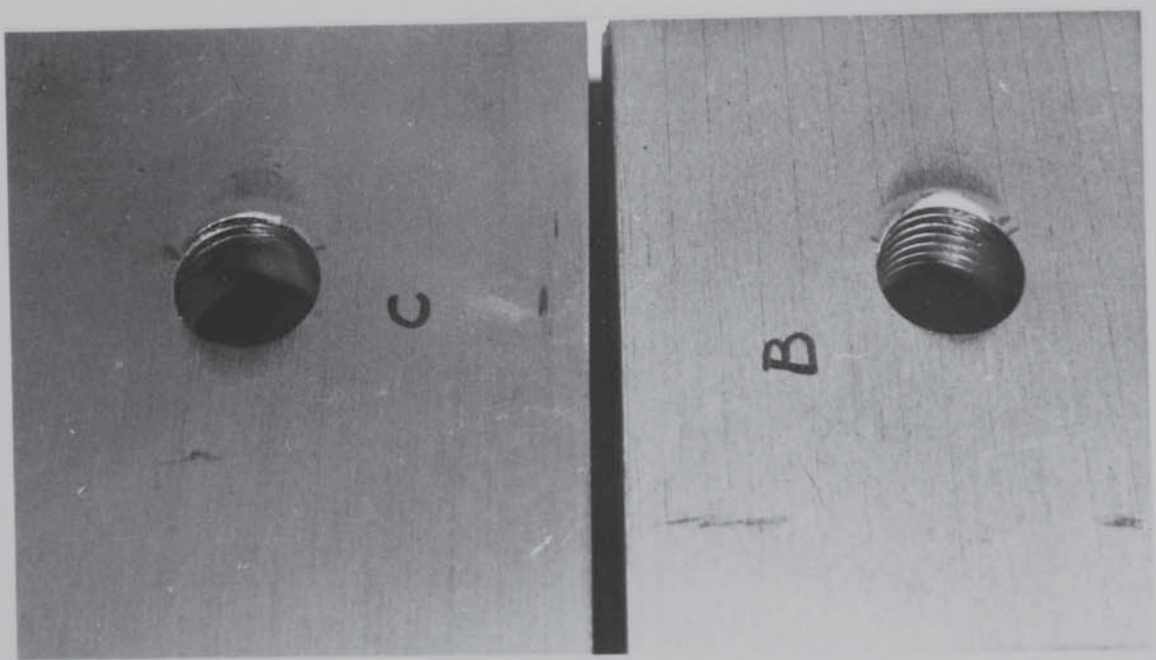


FIG 3.3 SINGLE SHEAR TENSION RIG



TEST SPECIMEN AFTER FAILURE



DEFORMATION OF HOLES

Plate 3.2 SINGLE SHEAR TEST RIG (Single bolt)

bolt was close to failure in single shear. The results of these five tests are recorded in Table 3.8 and a typical load-deformation relationship is shown in Figure 3.4. After the bolt failure the plates were removed from the testing machine and the deformed shape of the holes was measured and sketched as shown in Appendix Table A3.1. This permanent deformation of the hole at failure load was separated from the total deformation. Line oa' in Figure 3.4 indicates the load-deformation relationship of the bolt due to bending and shear.

Figure 3.4 shows that the load-deformation relationship of the connection changes from linear to non-linear at the average bearing stress of 200 N/mm^2. The average bearing stress has been calculated in accordance with BS 20 draft (56) using the projected area $d_e \times T$, where d_e is the effective diameter of the bolt and T is the thickness of the connected ply. The mean yield stresses of the plate material and the bolts were 271.65 N/mm^2 (Table 3.5) and 475 N/mm^2 (Figure 3.1) respectively. The possible explanation of this non-linear relationship at low bearing stress is that the distribution of stress over the plate thickness is not uniform as assumed in calculating the average bearing stress. It is evident from the deformed shape of the holes that the stress distribution is closer to a parabola for the thickness of plate under consideration. The stress near the faying faces is higher than that at the outer faces.

The average tensile and shear strengths in each batch of bolts and steel plate vary considerably and in order that the results may be compared, the ratio of the shear strength to tensile strength (F_v/F_t) has been used throughout. The mean value of F_v/F_t for these tests was 0.74.

Test No	1	2	3	4	5
Load kN	DEFORMATION (mm)				
2	0	0	0	0	0
10	0.425	0.514	0.662	0.339	0.410
20	0.668	0.835	0.987	0.672	0.693
30	0.867	1.064	1.209	0.914	0.905
35	0.955	1.166	1.308	1.020	0.995
40	1.040	1.265	1.414	1.127	1.093
45	1.129	1.365	1.511	1.219	1.207
50	1.215	1.467	1.613	1.325	1.296
55	1.300	1.573	1.711	1.428	1.396
60	1.392	1.672	1.812	1.546	1.495
65	1.497	1.776	1.912	1.646	1.597
70	1.569	1.873	2.007	1.759	1.701
75	1.680	2.001	2.113	1.885	1.814
80	1.800	2.172	2.286	2.044	1.926
85	1.932	2.414	2.574	2.247	2.107
90	2.111	2.672	2.838	2.533	2.322
95	2.334	3.005	3.204	2.865	2.597
100	2.659	3.320	3.611	3.282	2.932
105	2.863	-	4.322	3.867	3.430
108	-	-	-	-	Failed
108.2	-	-	-	Failed	-
110	Failed	-	-	-	-
112.8	-	Failed	-	-	-
114.4	-	-	Failed	-	-

TABLE 3.8: SHEAR STRENGTH OF BLACK BOLTS
(Batch 1)

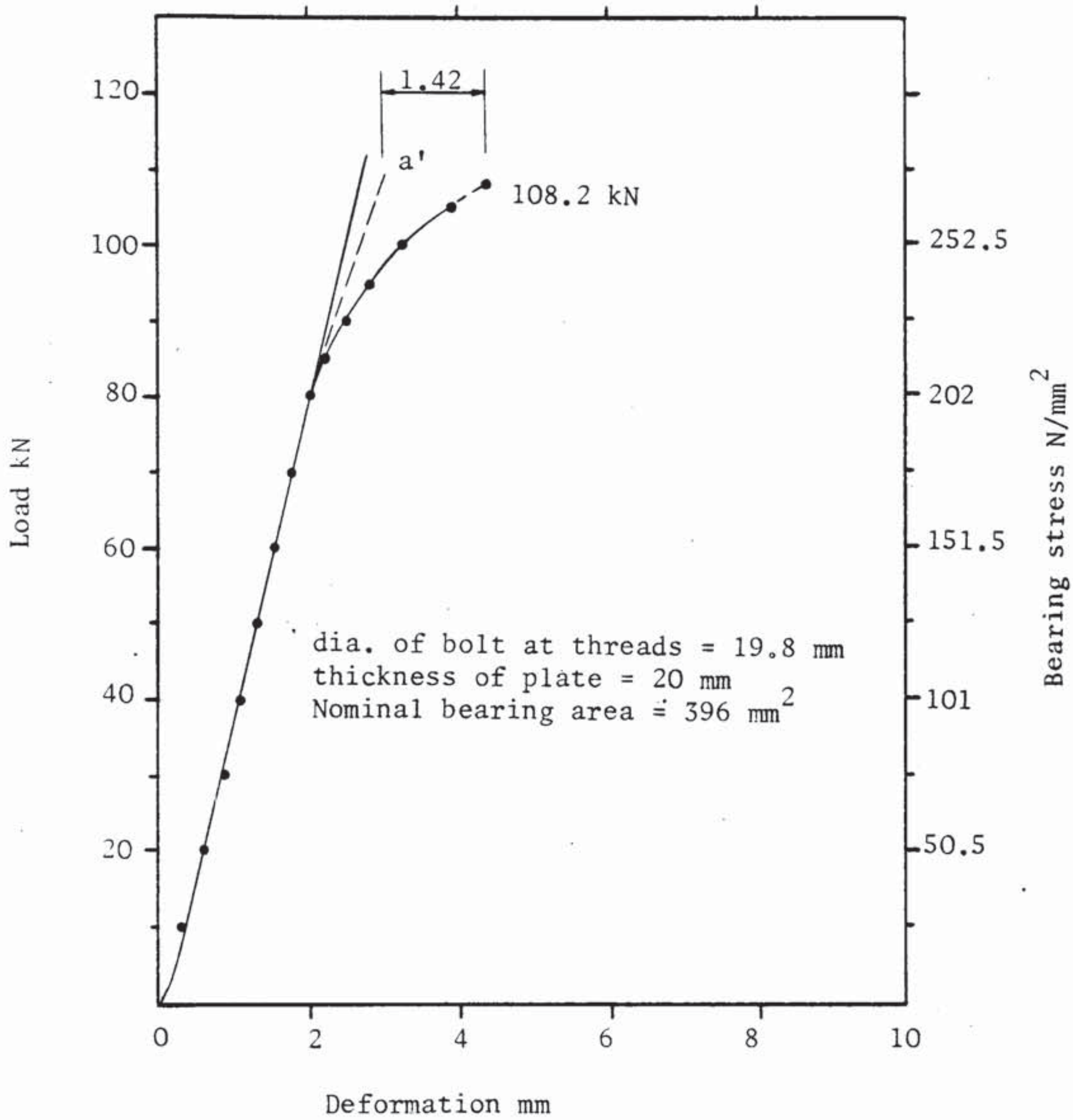


FIG 3.4: LOAD/DEFORMATION CURVE
(M20 single black bolt in single shear)

Note

The deformation shown dotted is extrapolated but may be even greater than shown if the shear deformation of the bolt is included.

3.3.1.2 Cheesehead Screws - Series 1

Twenty bolts from batch 3a and fifty bolts from batch 3b were selected for single shear tests. A 10 mm thick mild steel plate from batch P2 was used for these tests. A special rig for single shear in tension was designed as shown in Figure 3.5 and it was manufactured from mild steel and machined to a close tolerance of ± 0.5 mm. The test rig consisted of two identical but eccentric tee-pieces with smooth inside vertical faces. The configuration of the rig was adopted in an attempt to minimise the prying forces on the bolt. The head of the rig tee-pieces was pre-drilled to fit the self aligning nose pieces of the Hounsfield Tensometer by means of mild steel pins. The test plate was connected to one half of the rig with two mild steel bolts inserted into coincident pre-drilled holes and to the other half by means of the test bolt through a 5.1 mm diameter drilled hole. The inside faces of the rig were highly polished and the test plate was smeared with grease to minimise friction. One washer at the head and one under the nut was used and the nut was finger tightened. The arrangement of the test rig and the tested bolt is shown in Plate 3.3. After the bolt failed the specimen was dismantled and it was noted that the test plate and the rig showed signs of bearing deformation near to the faying faces, similar to the large bolts. The results of these tests are recorded in Table 3.9.

Four additional bolts, two from each batch were tested to establish the load-deformation relationship. The total deformation close to failure was measured with a magnetic backed deflection gauge attached to the specimen reading to one five hundredth of a millimetre. The experimental data is recorded in Appendix A Table

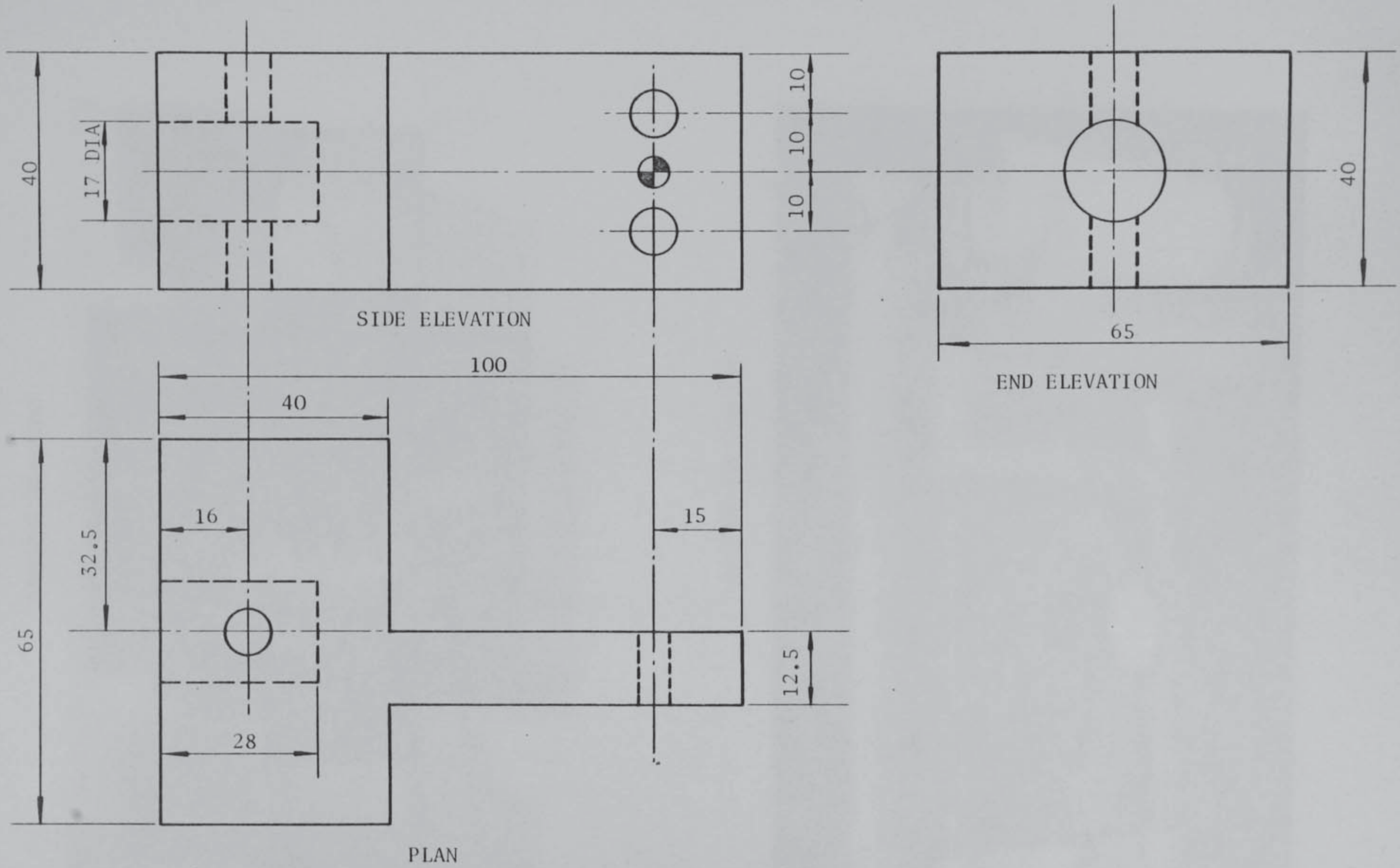
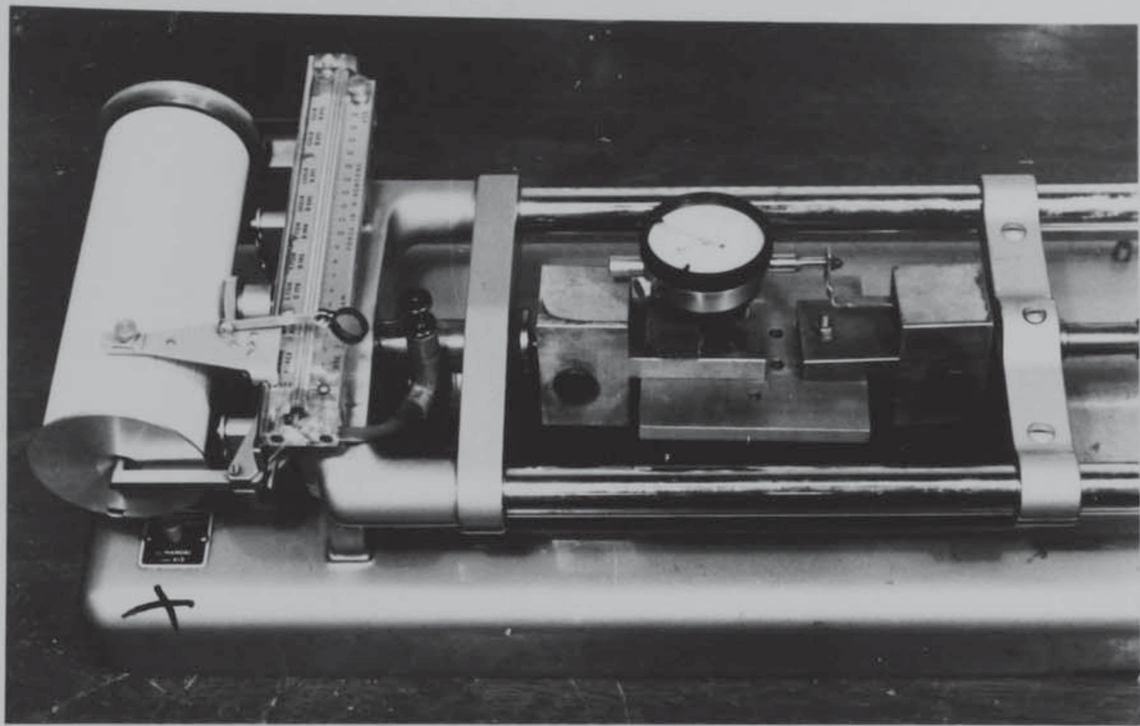
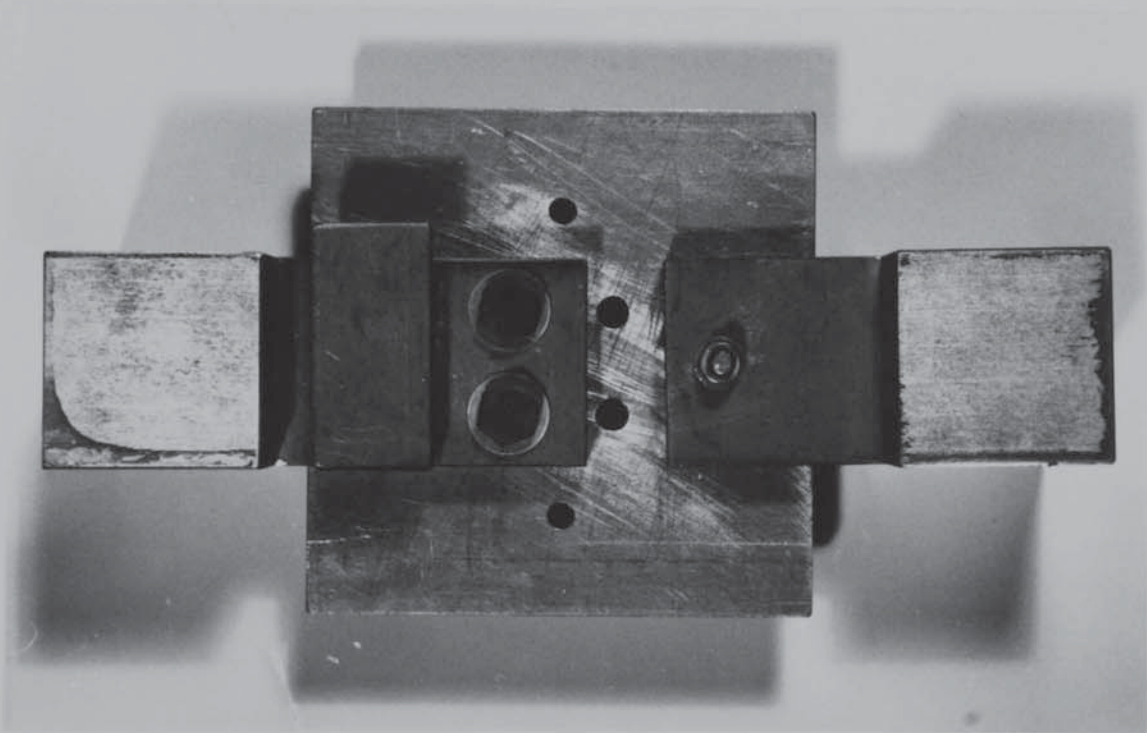


FIG 3.5 SINGLE SHEAR TENSION RIG



SPECIMEN DURING TEST



ASSEMBLED SPECIMEN

Plate 3.3 SINGLE SHEAR TEST RIG (Cheese-head screw)

Test No	Ultimate load (kN)
1	4.97
2	4.72
3	4.87
4	5.12
5	4.72
6	4.97
7	4.65
8	4.87
9	4.90
10	5.00
11	5.10
12	4.77
13	5.02
14	4.97
15	4.77
16	5.02
17	4.87
18	5.02
19	4.9
20	4.8
Mean	4.9 ± 0.13

TABLE 3.9: SHEAR STRENGTH OF CHEESEHEAD SCREWS
(Batch 3a)

Test No	Ultimate load (kN)	Test No	Ultimate load (kN)
1	4.98	26	5.28
2	5.25	27	5.58
3	5.38	28	5.73
4	5.35	29	5.28
5	5.18	30	5.93
6	4.83	31	5.88
7	5.23	32	5.48
8	5.08	33	5.13
9	5.18	34	5.13
10	5.53	35	5.73
11	5.03	36	5.13
12	5.48	37	5.08
13	5.13	38	5.13
14	5.23	39	5.18
15	5.33	40	5.63
16	4.83	41	4.83
17	5.68	42	5.03
18	5.53	43	5.23
19	5.23	44	5.63
20	5.68	45	5.63
21	4.93	46	5.93
22	5.83	47	5.53
23	5.43	48	5.83
24	5.83	49	5.43
25	5.13	50	4.98
Mean ultimate load			5.36 ± 0.31

TABLE 3.9 (cont.) SHEAR STRENGTH OF CHEESEHEAD SCREWS
(Batch 3b)

A.3.2. A typical load-deformation graph for a black bolt is drawn in Figure 3.4. Comparable load-deformation relationship for cheese-head bolts is linear until the ultimate failure load.

The ratio of the mean values of shear strength (F_v) to tensile strength (F_t) for batches 3a and 3b were 0.66 and 0.69 respectively.

3.3.1.3 High Strength Bolts - Series 1

The deformation at ultimate load is related to the elongation of the hole which is related to the bearing stress. Therefore the thickness 'T' of the specimen appears to have an influence on the load-deformation curve of the bolt under test. To investigate this parameter and the single shear strength of the high strength friction grip bolts, hereinafter termed as high strength bolts, four tests were carried out using a nominal plate thickness of 12, 14, 17 and 20 mm. Consistancy in yield strength was achieved by machining specimens from the batch P3, 20 mm thick plate and the bolts were used from batch 2a.

The test rig was identical to the one described in 3.3.1.1 and shown in Figure 3.3 except the variation in the plate thickness. The whole testing procedure such as elimination of friction, bolt tightening and rate of loading etc was similar to the tests on black hexagon bolts.

The results of these tests are recorded in Table 3.10, and Table 3.11 shows the relationship between average bearing stress on plate and the total deformation. The permanent deformation of the holes and its deformed shape was measured after the tests and is sketched in Appendix A Table A.3.3.

It is to be noted that the deformation of the hole is more uniform, across the thickness of the plate, in 12 mm thick specimen as compared with 20 mm thick plate. It shows that bearing stress on the hole and the bolt changes from parabolic to rectangular distribution depending on d_e/T ratio. Figure 3.6 shows the effect of d_e/T ratio on load-deformation curve and it is evident that as d_e/T ratio increases, the elastic flexibility and ultimate deformation increases but it does not effect the ultimate strength of the bolt appreciably. However, it is obvious, on examination of the holes after failure (Table A.3.3) that when the d_e/T ratio exceeds a certain value the plastic flow will occur in the plate because of high bearing stresses.

The load-deformation relationship for these tests is shown in Figure 3.7 and the permanent deformation of the hole is recorded as a dotted line. At failure the shear load is seen to be approximately constant despite the change in plate thickness, a result that agrees with experiments by Wallaert and Fisher (29) where the fastner was in double shear.

The deformation of the hole at ultimate load is a function of yield strength of the plate and the applied bearing stresses. The yield strength of the plate in tests No 3 to 6 inclusive, was kept constant, and Figure 3.8 relates the average bearing stress to deformation for high strength bolts. The average bearing stress - deformation relationship is linear until the yield strength of the plate is reached. The ultimate deformation is seen to be directly related to the average bearing stress as shown by the line a-a in Figure 3.8. The mean value of F_v/F_t for these tests was 0.67.

The large number of bolts used in the tests described in series 1 were taken from different batches. The average tensile and shear strengths in each batch therefore vary and so that

Test No	1	2	3	4	5	6
Plate Batch No	P1	P1	P3	P3	P3	P3
Plate Thickness mm	20.00	20.00	20.15	17.10	14.10	12.07
Load (kN)	DEFORMATION (mm)					
2	0	0	0	0	0	0
10	0.274	0.213	0.18	0.20	0.25	0.30
20	0.477	0.414	0.35	0.41	0.50	0.61
30	0.648	0.597	0.53	0.61	0.73	0.91
40	0.805	0.776	0.71	0.81	0.97	1.20
50	0.965	0.989	0.90	1.02	1.22	1.51
60	1.127	1.160	1.07	1.22	1.45	1.81
65	1.203	1.241	1.15	1.32	1.58	1.92
70	1.274	1.318	1.22	1.42	1.70	2.08
75	1.355	1.396	1.32	1.51	1.81	2.24
80	1.426	1.443	1.41	1.62	1.83	2.38
85	1.504	1.524	1.50	1.73	2.07	2.51
90	1.579	1.593	1.59	1.84	2.19	2.70
95	1.666	1.697	1.68	1.95	2.30	3.00
100	1.749	1.784	1.77	2.10	2.45	3.22
105	1.833	1.887	1.90	2.25	2.65	3.47
110	1.946	2.027	2.08	2.42	2.90	4.71
115	2.050	2.205	2.28	2.65	3.28	3.95
120	2.194	2.387	2.51	2.88	3.70	4.25
125	2.347	2.591	2.81	3.21	4.25	4.92
130	2.547	2.841	3.10	3.55	4.80	5.60
135	2.788	3.200	3.45	4.10	5.35	6.20
140	3.088	-	3.88	4.80	6.11	7.20
145	3.414	-	-	-	-	-
146.52	-	-	-	-	Failed	-
146.72	-	-	Failed	-		-
147.31	-	-		Failed		-
148.11	-	-				Failed
148.6	-	Failed				
156.2	Failed					

TABLE 3.10 SHEAR STRENGTH OF H.S.BOLTS

(Batch 2a)

Test No 1		Test No 2		Test No 3	
Bolt dia. d_e = 19.9 mm		Bolt dia. d_e = 19.9 mm		Bolt dia. d_e = 19.72 mm	
f_b N/mm2	Δ N/mm2	f_b N/mm2	Δ N/mm2	f_b N/mm2	Δ N/mm2
5.0	0	5.0	0	5.0	0
25.12	0.274	25.12	0.213	25.16	0.18
50.25	0.477	50.23	0.414	50.33	0.35
75.38	0.648	75.38	0.597	75.49	0.53
100.51	0.805	100.51	0.776	100.66	0.71
125.63	0.965	125.63	0.989	125.83	0.90
150.76	1.127	150.76	1.160	150.99	1.07
175.88	1.274	175.88	1.241	176.15	1.22
201.01	1.426	201.01	1.443	201.33	1.41
226.48	1.579	226.48	1.593	226.48	1.59
251.27	1.749	251.27	1.784	251.66	1.77
276.39	1.946	276.39	2.027	276.82	2.10
301.52	2.194	301.52	2.387	301.99	2.51
326.65	2.547	326.65	2.841	327.16	3.10
351.77	3.088	351.77	3.921	352.33	3.88
392.48	5.481	373.38	5.351	369.24	5.30

f_b = Average bearing stress on plate

Δ = Total deformation

TABLE 3.11: BEARING STRESS/DEFORMATION OF HIGH STRENGTH BOLTS

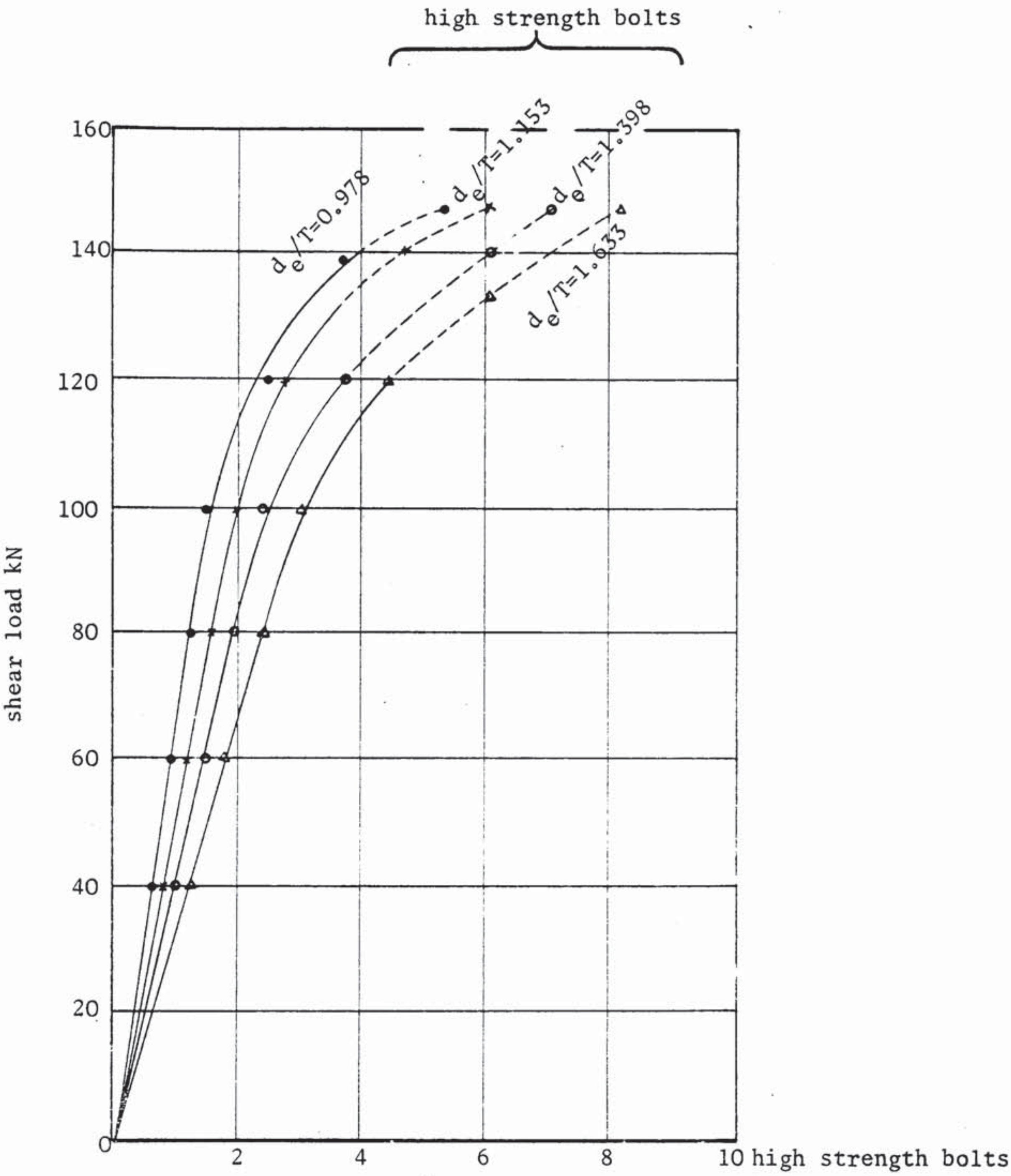
(Batch 2a)

Test No 4		Test No 5		Test No 6	
Bolt dia. d_e = 19.72		Bolt dia. d_e = 19.72		Bolt dia. d_e = 19.72	
f_b N/mm2	Δ N/mm2	f_b N/mm2	Δ N/mm2	f_b N/mm2	Δ N/mm2
5.0	0	5.0	0	5.0	0
29.66	0.20	35.96	0.25	42.01	0.30
59.31	0.41	71.92	0.50	84.02	0.61
88.96	0.61	107.88	0.73	126.03	0.91
188.62	0.81	143.85	0.97	168.05	1.20
148.27	1.02	179.80	1.22	210.05	1.51
177.93	1.22	215.78	1.45	252.08	1.81
207.58	1.42	251.72	1.70	294.07	2.08
237.24	1.62	287.70	1.83	336.11	2.38
266.89	1.84	323.64	2.19	378.09	2.70
296.55	2.10	359.64	2.45	420.13	3.22
326.21	2.42	395.61	2.90	462.14	4.71
355.85	2.88	431.57	3.70	504.15	4.25
385.50	3.55	467.53	4.80	546.17	5.60
415.17	4.80	503.50	6.11	588.18	7.20
435.09	6.05	527.67	7.11	616.417	8.50

f_b = Average bearing stress

Δ = Total deformation

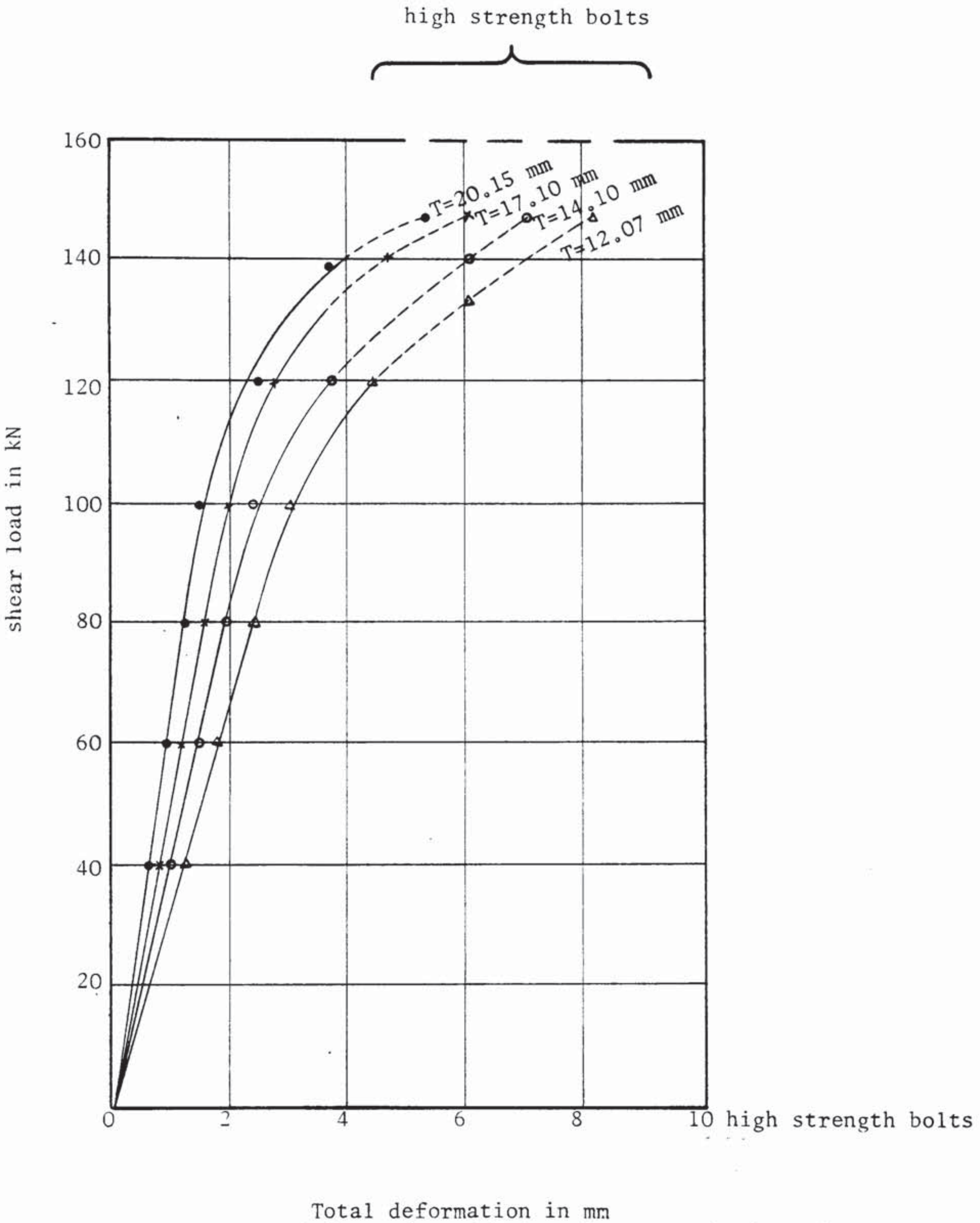
TABLE 3.11: BEARING STRESS/DEFORMATION OF H.S. BOLTS (Batch 2a)



Total deformation in mm

Note: permanent deformation of holes shown as broken line

FIG 3.6: RELATIONSHIP BETWEEN LOAD AND DEFORMATION FOR SINGLE BOLT TESTS (bolts failed on threads in single shear)



note: permanent deformation of holes shown as a broken line

FIG 3.7: RELATIONSHIP BETWEEN LOAD AND DEFORMATION FOR SINGLE BOLT TESTS (bolts failed on threads in single shear)

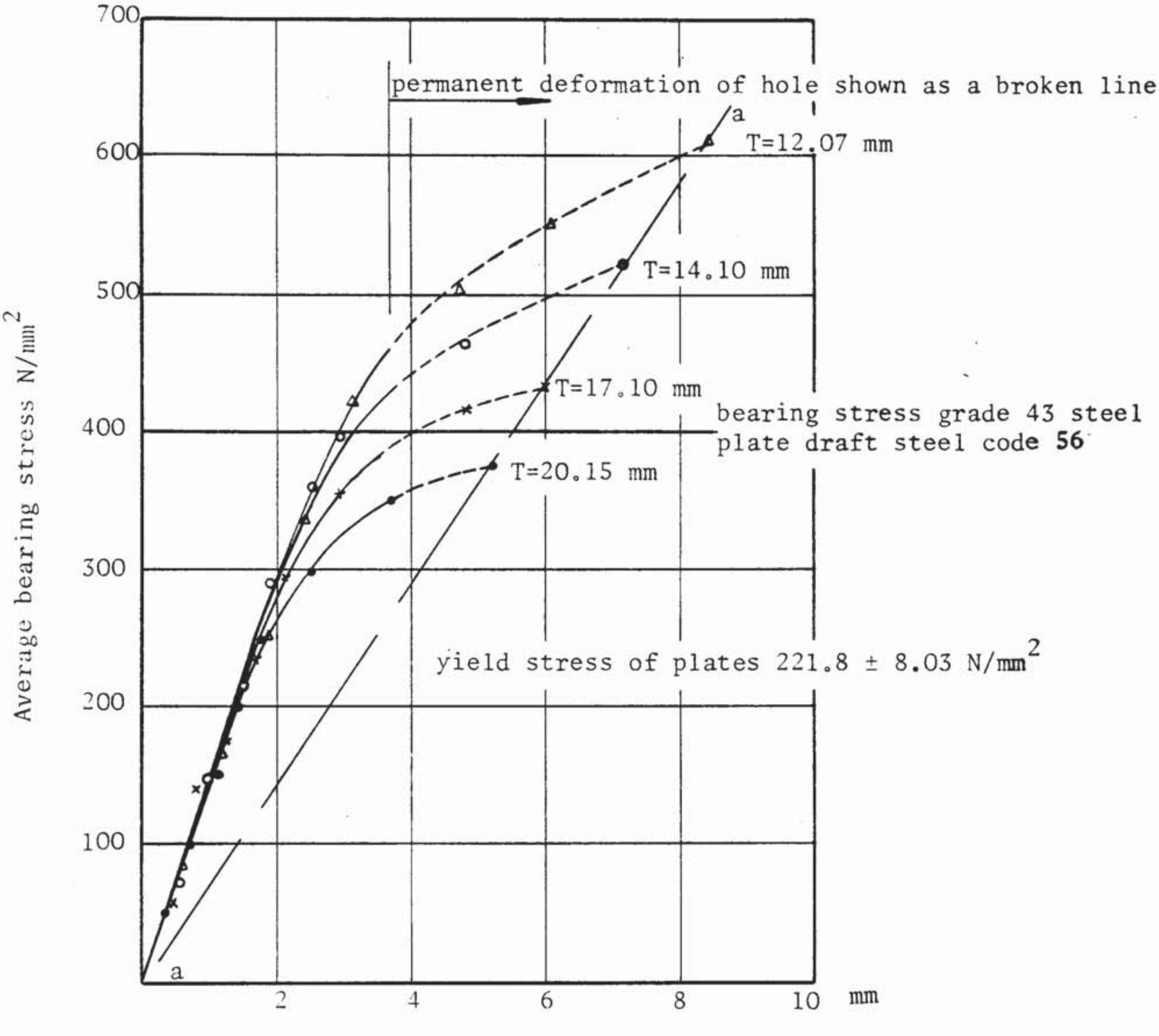


FIG 3.8: RELATIONSHIP BETWEEN BEARING STRESS AND DEFORMATION FOR AN M20 HIGH STRENGTH SINGLE BOLT TEST (bolts failed on threads in single shear at a shear stress = 600 N/mm^2)

Type of bolt	Length mm	Nominal Diameter of bolt/ hole in Plate mm	Tensile stress area of bolt mm^2	Nominal thickness of plate mm	Yield stress of Plate N/mm^2	Single Bolt Tests (series 1)				
						Ultimate Tensile strength F_t (f_t) kN (N/mm^2)	Ultimate Shear strength F_v (f_v) kN (N/mm^2)	Ratio F_v/F_t	Ultimate Nominal Bearing stress N/mm^2	Deform. at Ultimate Load mm
Black bolt (batch 1) BS 4190 (57)	70	20/22	245	20 batch P1	271.7 ± 3.6	149.8 ± 2.2 (611.0 ± 9.0)	110.7 ± 2.8 (451.8 ± 11.4)	0.74	276.8	4.0
High strength (batch 2a) BS 4395 (58)	70	20/22	245	20 batch P1	271.7 ± 3.6	222.0 ± 3.1 (906.0 ± 12.7)	148.9 ± 3.7 (607.0 ± 15.1)	0.67	372.3	5.3
Cheese Head (batch 3a) BS 4183 (59)	30	5/5.1	15.77	10 batch P2	256.4 ± 4.2	7.39 ± 0.89 (468.7 ± 56.5)	4.90 ± 0.13 (310.8 ± 8.2)	0.66	98.0	0.74
(batch 3b)					256.4 ± 4.2	7.77 ± 0.25	5.36 ± 0.31	.69	107.2	0.81

Mean ratio $F_v/F_t = 0.69$

Notes: ultimate tensile and shear stresses calculated using tensile stress area; all holes in plates were drilled

TABLE 3.12: SINGLE BOLT PROPERTIES

results may be compared the ratio of the shear strength to tensile strength (F_v/F_t) has been used throughout. Table 3.12 summarises the single bolt properties. The value of F_v/F_t is seen to vary from different types of bolts, but the mean value of 0.69 is considered to be important. This value will be compared with mean values from series 2 and 3.

3.3.2 Two Bolt Tests - Series 2

The object of the two bolt tests was to consider the effect of shear and torsion in establishing the in-plane shear forces on the bolt. The two bolt tests were considered to be important as an alternative method of obtaining a shear value to be compared directly with the single bolt tests. There is no evidence that single bolt values obtained with a simple tension-shear test are identical with values obtained using more complicated test rigs.

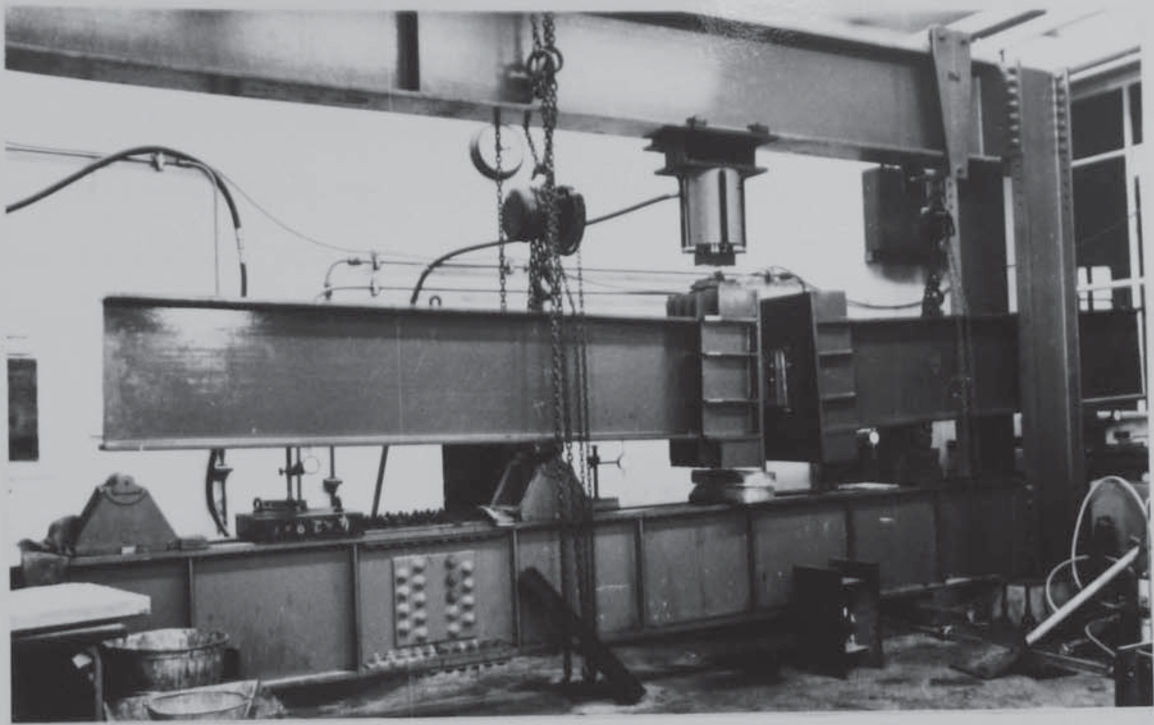
Two special rigs were designed, one for 20 mm diameter bolts and the other for cheesehead screws. The main feature of both the rigs was that a range of values of torsion and shear forces could be applied to the bolt group. The construction details and dimensions of test specimen are described under appropriate series of tests. During the tests the rig rotated from the horizontal because of clearance in the holes, bolt shear deformation and yield bearing stresses. The forces at the supports were therefore not vertical. Five dial gauges and a travelling telescope were used to record the rotation of the rig and the movement of bolts with respect to a given arbitrary set of axes. A typical set of data recorded and detailed calculations are shown in Appendix A.3.4. The error associated with this effect was found to be very small. Therefore no correction have been made in the calculations to determine the ultimate strength of the bolt group.

3.3.2.1 High Strength Bolts - Series 2

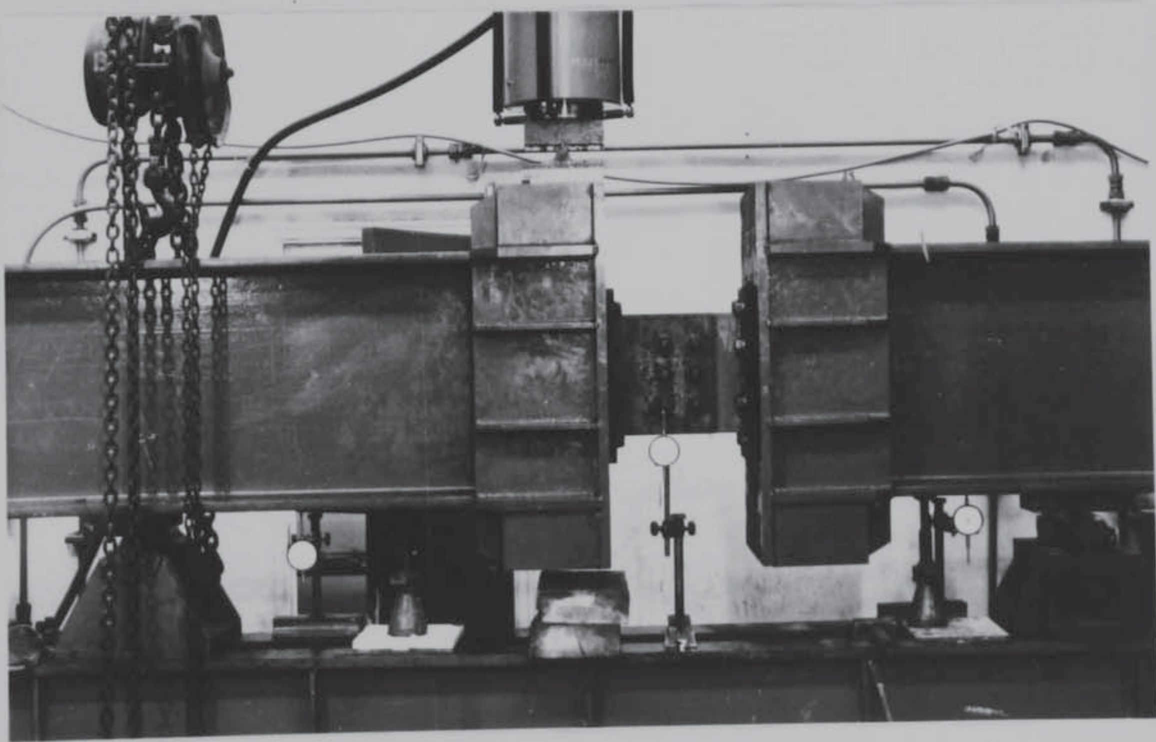
Twenty four M20 High Strength Bolts were selected from batch 2b and the 20 mm thick mild steel plate for the test specimens was taken from batch P1. The large test rig, as shown in Plate 3.4, consisted of two 3.045 m long pieces cut from a 610 x 305 x 179 kg/m U.B. of high yield steel. A 25 mm thick end plate, structural steel grade 50, machined on one face to a close tolerance of ±0.5 mm was welded to the beams and adequately stiffened. A large number of 24 mm diameter, concentrically spaced, bored holes in the end plates were sufficient to connect the back plate of the test specimen. The rig was capable of carrying a safe load of 2340 kN in pure shear and a safe bending moment of 977 kNm.

The test specimen shown in Figure 3.9 consisted of two identical but eccentric tee-pieces. This configuration of the test specimens was adopted in an attempt to minimise the prying forces on the bolts. The test plates were connected to each half of the rig with four 24 mm diameter, close tolerance, 8.8 strength grade bolts. The friction between the test plates was eliminated by using a perspex sheet grease pack. Two number test bolts were inserted in the test plates and one washer under the head and one under the nut was used. The nut was tightened with a torque wrench to a nominal torque set at 13.5 Nm.

The load was applied to the top flange of the beam by means of a motorised hydraulic ram of 1000 kN capacity. This load was measured by a load cell connected to the Lausen test machine. Knife edges were used throughout to transmit the load from the ram to the beam. These knife edges were bolted to the head of the ram



GENERAL VIEW



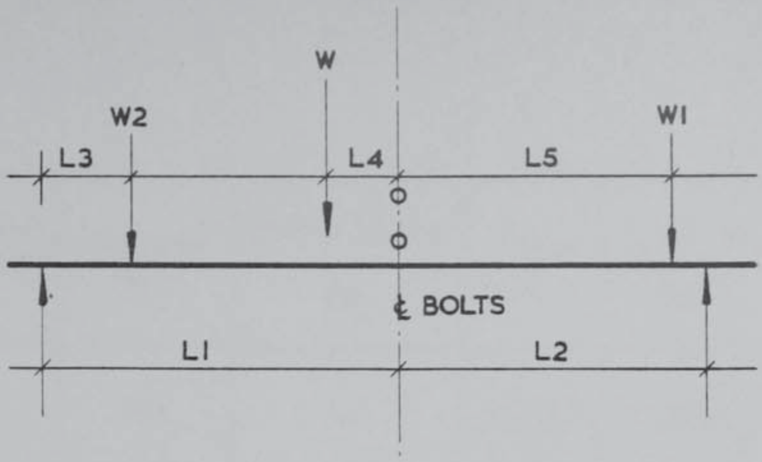
SIX BOLT SPECIMEN UNDER TEST

Plate 3.4 LARGE TEST-RIG (Multi-bolt group) and one half of the rig through stiff plates. During the preliminary test, it became evident that this system of loading produced an unknown force between the ram and its supporting beam as the rig rotated from its horizontal position. This unknown horizontal force was eliminated by the use of needle bearing between the ram and its supporting beam.

Basically, the testing procedure for all the tests was the same. First the rig was made horizontal and checked with a spirit level, then zero readings were taken for all the deflection gauges and the travelling telescope. An approximate failure load was predicted for the bolt group to be tested and increments of loading were applied slowly. At each increment the load was held constant and all deformations were allowed to stop before readings were taken.. This procedure was continued until failure. Usually, when the inelastic behaviour of the connection was detected, the load increments were reduced. At this stage of the test, the dial needle would move a few divisions during the readings, but at this point the deflections were large so that this change was negligible. Failure was defined at the physical shearing of one of the bolts in a group under consideration. It was not possible to record any deflection reading at failure due to their large rate of increase.

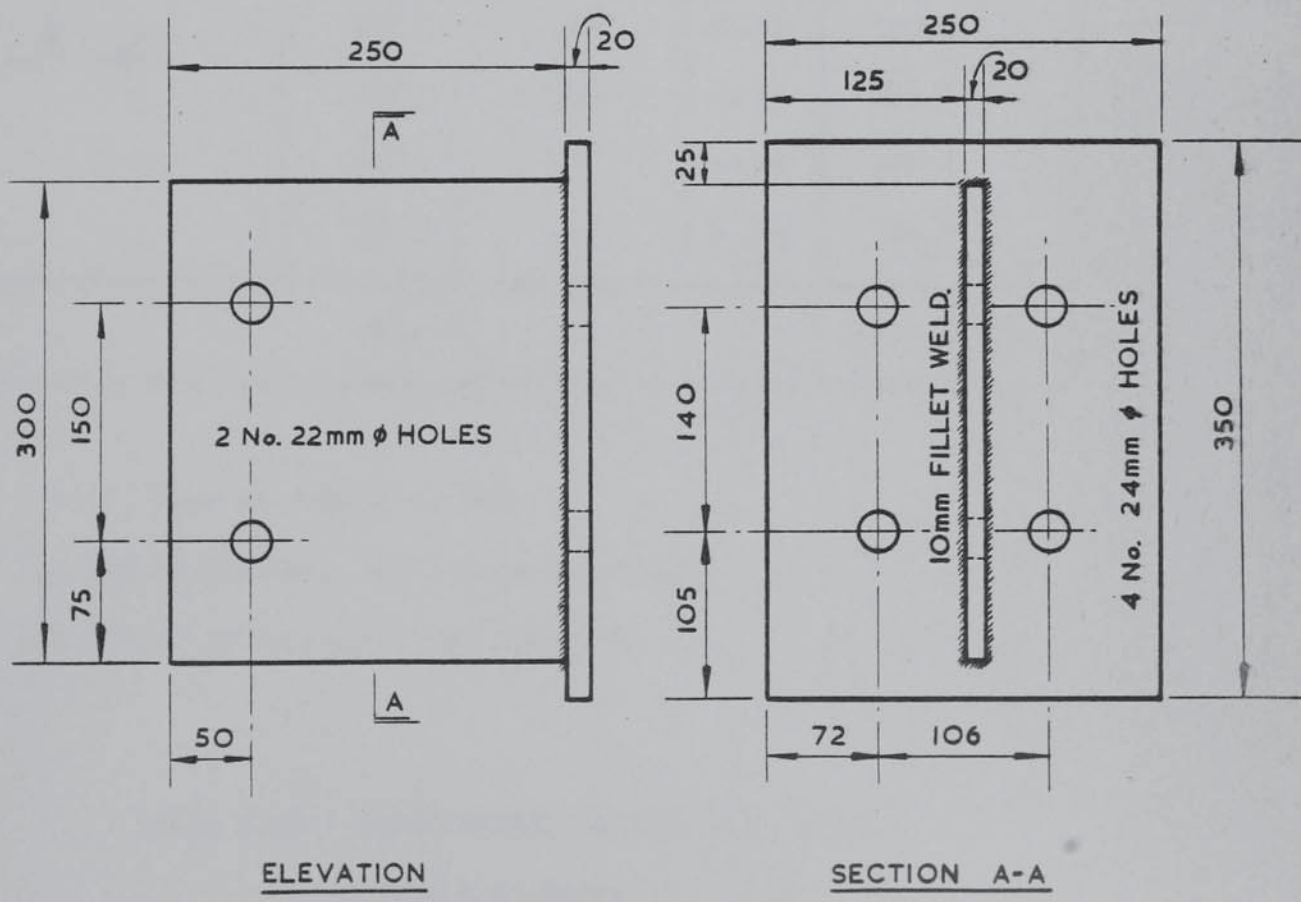
It is impossible, for such a large testing programme, to refer to the individual behaviour of each bolt group tested and to present the readings in the appendix. Representative tests are therefore selected from each series and discussed.

The failure load obtained for each test as well as the variation in the span are recorded in Table A.3.5. Table 3.13 shows



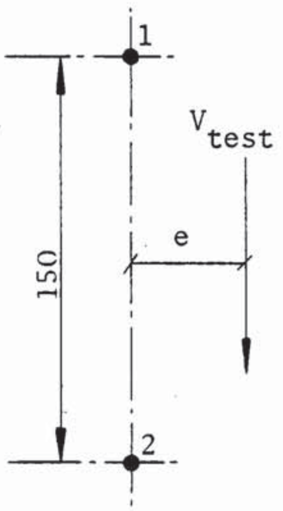
W = APPLIED LOAD. (KN)
W1 = SELF WEIGHT OF R.H.S. + SPECIMEN = 7·643KN
W2 = SELF WEIGHT OF L.H.S + SPECIMEN = 7·985 KN
L4 = 311mm.
L5 = 1311mm.

Loading System.



Two Bolts Test Specimen.

FIG. 3·9 LOADING AND BOLT SPACING ARRANGEMENT.

Arrangement and spacing of bolts mm	Specimen Label	Eccentricity e mm	V_{test} kN	Force on Bolt F_v kN
	2H1	∞	24.81*	165.4
	2H2	∞	24.34*	162.2
	2H3	3922	5.48	143.3
	2H4	2573	9.97	171.0
	2H5	2398	10.11	161.8
	2H6	1929	12.53	161.2
	2H7	904	28.64	173.3
	2H8	626	38.41	161.5
	2H9	300	82.75	170.3
	2H10	259	90.24	162.7
	2H11	207	108.43	159.4
	2H12	59	250.76	159.5
Mean F_v				162.6 ± 7.6

i * Torsion moment in kNm

ii 20 mm dia H.S. Bolts from batch 2b

iii 20 mm thick plate from batch P1

TABLE 3.13: EXPERIMENTAL RESULTS H.S. BOLTS

(Two H.S. Bolts)

the calculated values of V_{test}, eccentricity 'e' of the load V_{test} with respect to the centroid of the bolt group and the maximum force F_v on the furthest bolt from the centre of rotation. Typical calculations for specimen label 2H10 are shown in Appendix A.3.4.

The mean value of F_v from Table 3.13 is 162.6 kN and the ratio of F_v/F_t for this batch of bolts is 0.72.

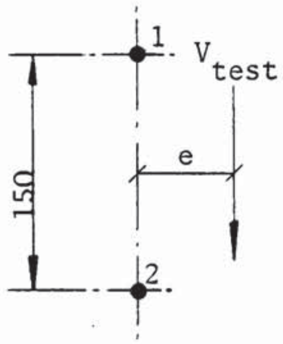
3.3.2.2 Black Hexagon Bolts - Series 2

Fourteen black bolts from batch 1b were tested in this series and the test specimen was manufactured from 20 mm thick mild steel plate from batch P1. The two black bolt test specimen was identical to the specimen used for high strength bolts, shown in Figure 3.9. The large test rig, the method of loading and testing procedure were similar to two high strength bolt tests described in 3.3.2.1. As previously the bolts were arranged such that the fracture plane always occurred on the threaded portion.

Various loading spans and the failure load at which one of the bolts in each joint failed are recorded in Table A.3.6. The loading system for the test specimen labeled 2B1 was arranged such that the force induced on the bolt group was due to torsional moment only.

The rotation of the rig for the black bolts was slightly larger, as expected, compared to high strength bolts, but it was considered that no corrections were necessary in calculating the maximum force F_v, at failure, on the furthest bolt from the centre of rotation.

The calculated values of the applied force V_{test}, the eccentricity e and the maximum force F_v on the bolt are shown in Table

Arrangement and spacing of bolts mm	Specimen label -	Eccentricity e mm	V_{test} kN	Force on Bolt F_v kN
	2B1	∝	15.83*	105.5
	2B2	10581	1.43	101.1
	2B3	5498	2.76	101.3
	2B4	2073	7.35	101.7
	2B5	1295	12.37	106.9
	2B6	866	19.87	115.1
	2B7	593	24.61	98.1
Mean F_v				104.0 ± 6.1

i   * Torsion moment in kNm

ii   20 mm diameter black bolts from batch 1b

iii   20 mm thick plate from batch P1

TABLE 3.14: EXPERIMENTAL RESULTS BLACK BOLTS

(Two black bolts)

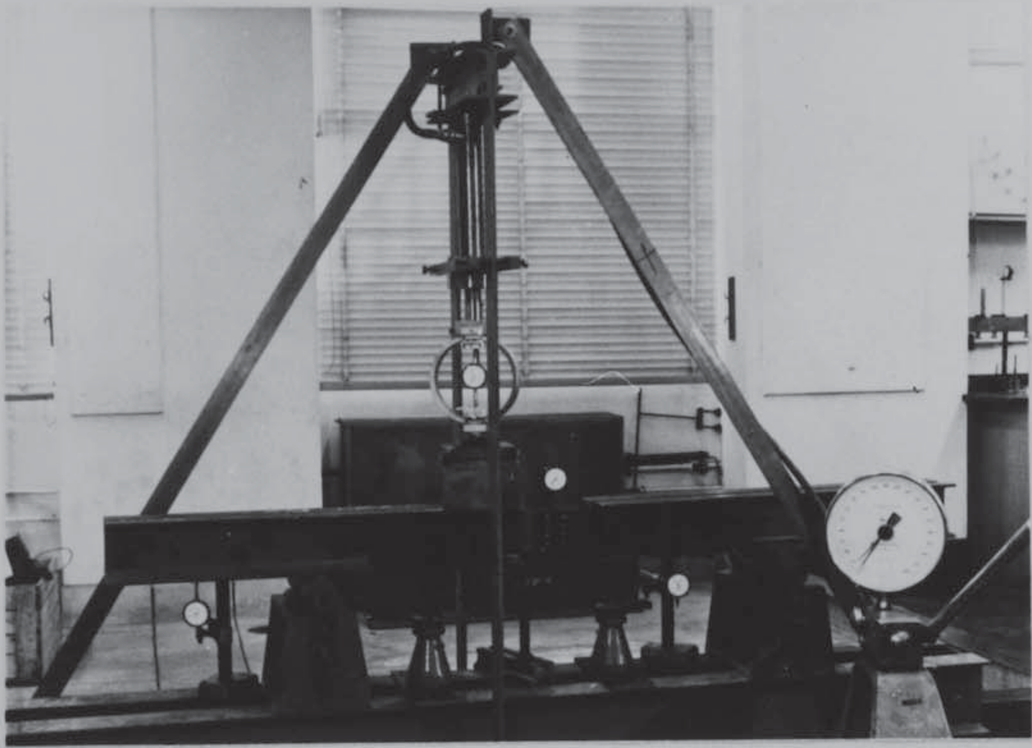
3.14. The mean force F_v for the seven tests is 104 kN and the ratio of F_v/F_t for two bolts is 0.69.

3.3.2.3 Cheesehead Screws - Series 2

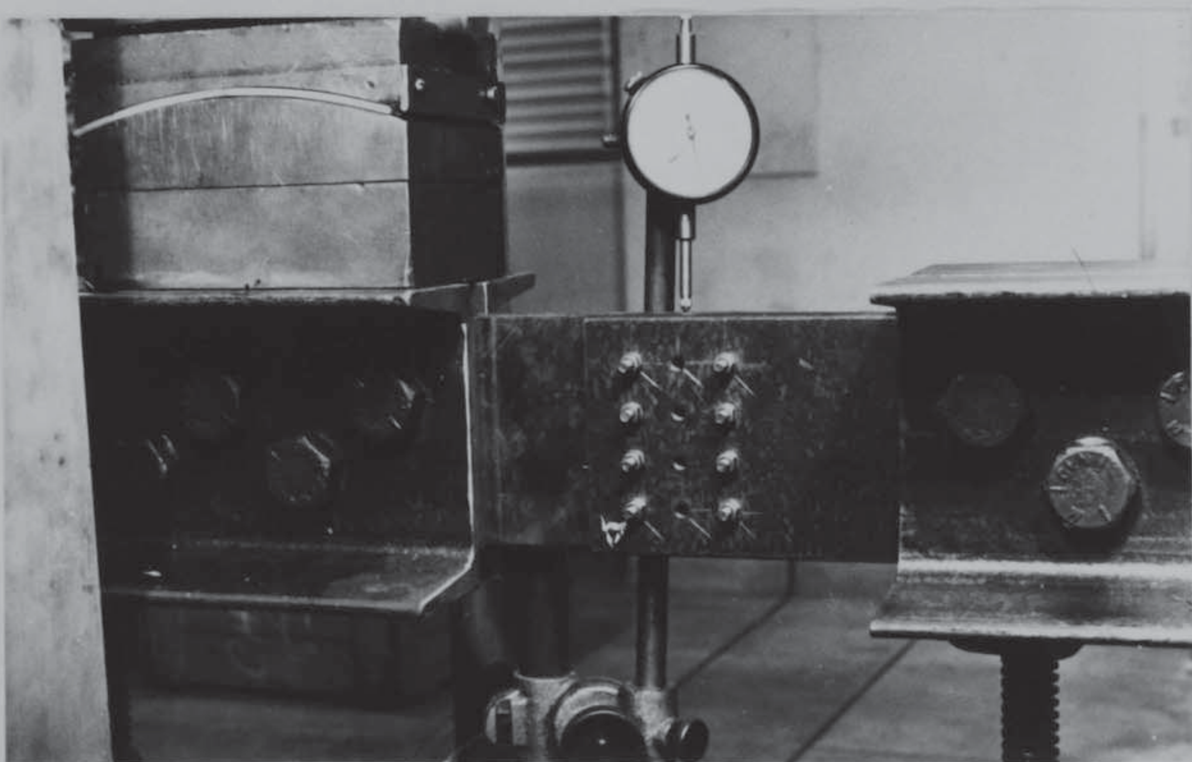
Since experiments by Francis (7) have shown that in the behaviour of joints there was no appreciable scale effect, a large number of experiments were conducted on small joints. It was necessary to ensure similarity between large and small rigs as far as possible. As previously the ratio of shear strength F_v to tensile strength F_t was used in comparing the results.

A special light weight rig shown in Plate 3.5 and Figure 3.10 was used for these tests. Six two bolt specimens from batch 3a and six from batch 3b were tested in this series. The test plate specimens were made from 10 mm thick mild steel plate taken from batch P2. The light weight rig çonsisted of 4 No 127 x 64 x 14.9 R.S.C. 'Rolled mild steel channels' connected back to back with 20 mm diameter high strength friction grip bolts passing through 2 - 10 mm thick mild steel packing pieces. The 10 mm thick test specimens drilled with 5.1 mm diameter holes were also bolted to each half of the rig. These test plates were packed on opposite faces to minimise the effect of prying action. The rig was placed on two adjustable roller supports, liberally greased to minimise the friction between the rollers and the channel flanges. The faying faces of test plates were also smeared with grease to reduce friction.

For simplicity one support was permanently placed under the centre of gravity of one half of the rig and the other support was adjusted to introduce a different span length. Both halves of the rig were connected with 5 mm diameter cheesehead test screws with



RIG SET UP



ENLARGED VIEW

Plate 3.5 SMALL MULTI BOLT GROUP RIG (Cheese-head screws)

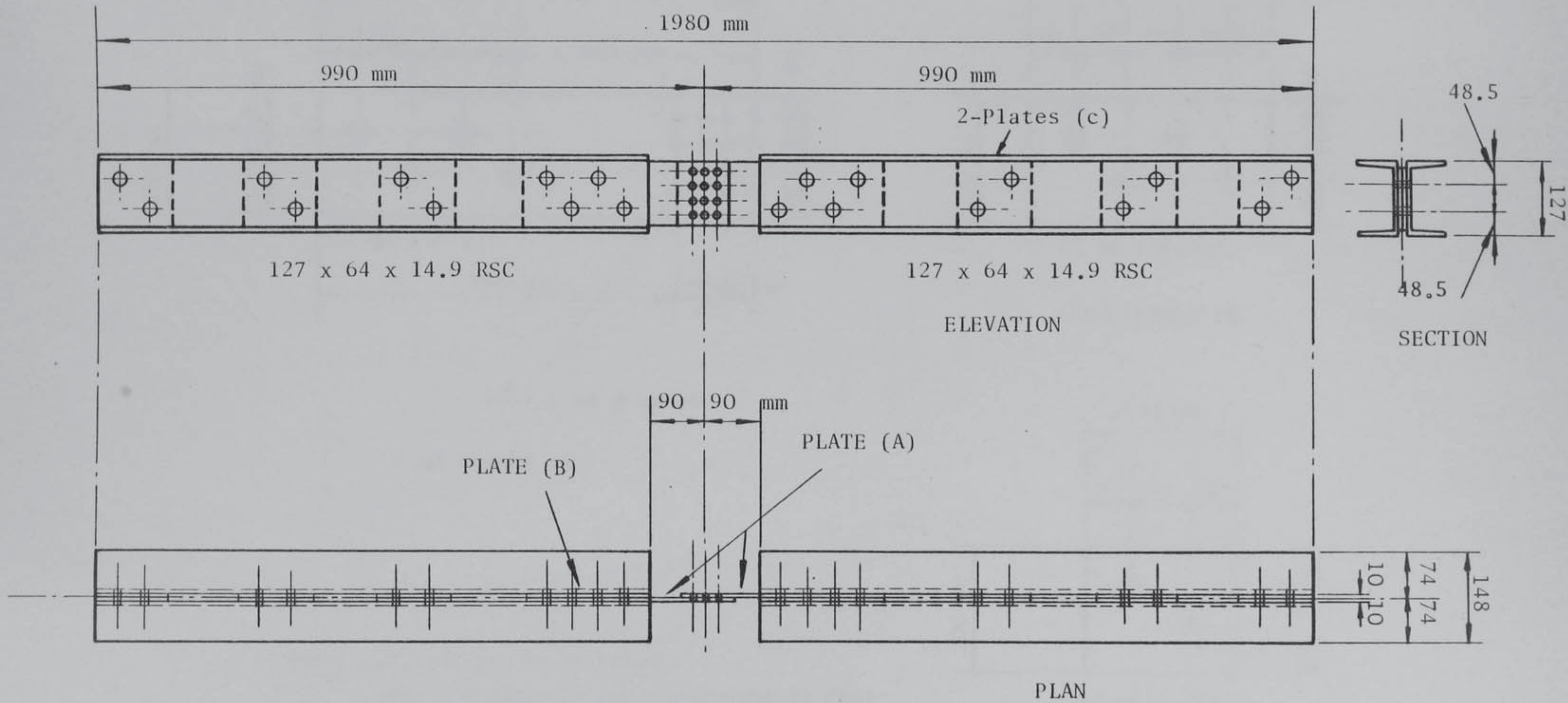
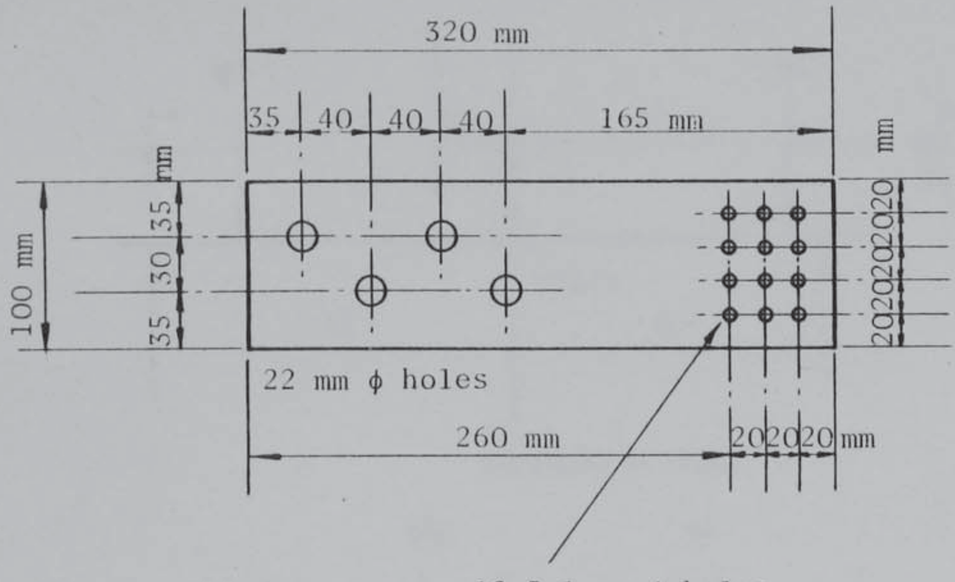
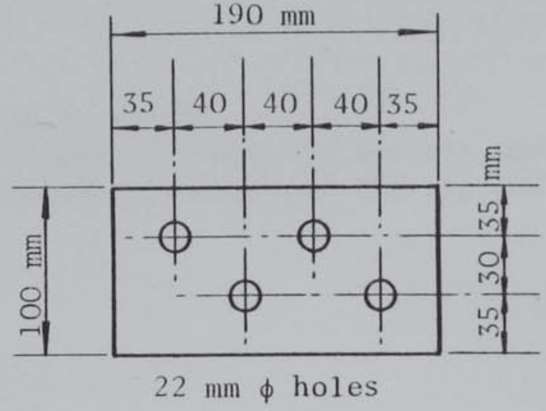


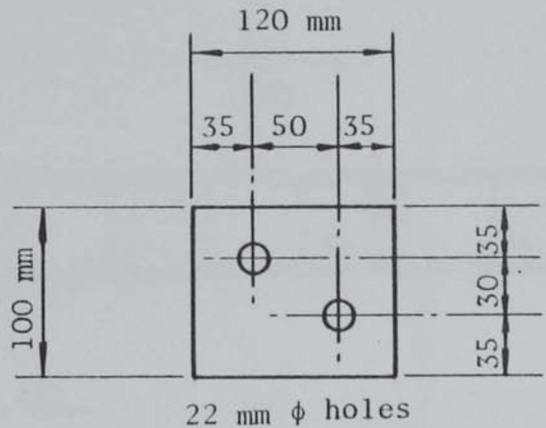
FIGURE 3.10 DETAILS OF TESTING RIG



2 NO PLATES (A)



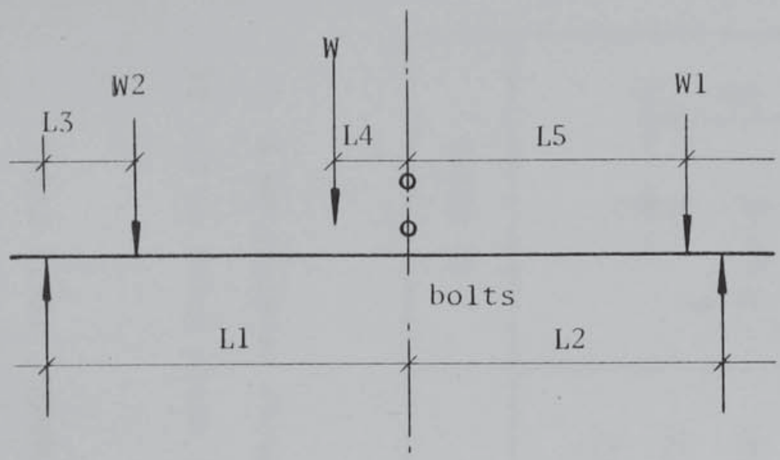
2 NO PLATES (B)



12 NO PLATES (C)

Note: all plates 10 mm thick
the clearance is small compared to that
which would occur in large bolt holes.

FIG. 3.10 (Cont.) DETAILS OF TESTING RIG



W = applied load (kN)
W1 = self weight of R.H.S. of the rig and specimen = 0.3922 kN
W2 = self weight of L.H.S. of the rig and specimen = 0.3789 kN

LOADING SYSTEM

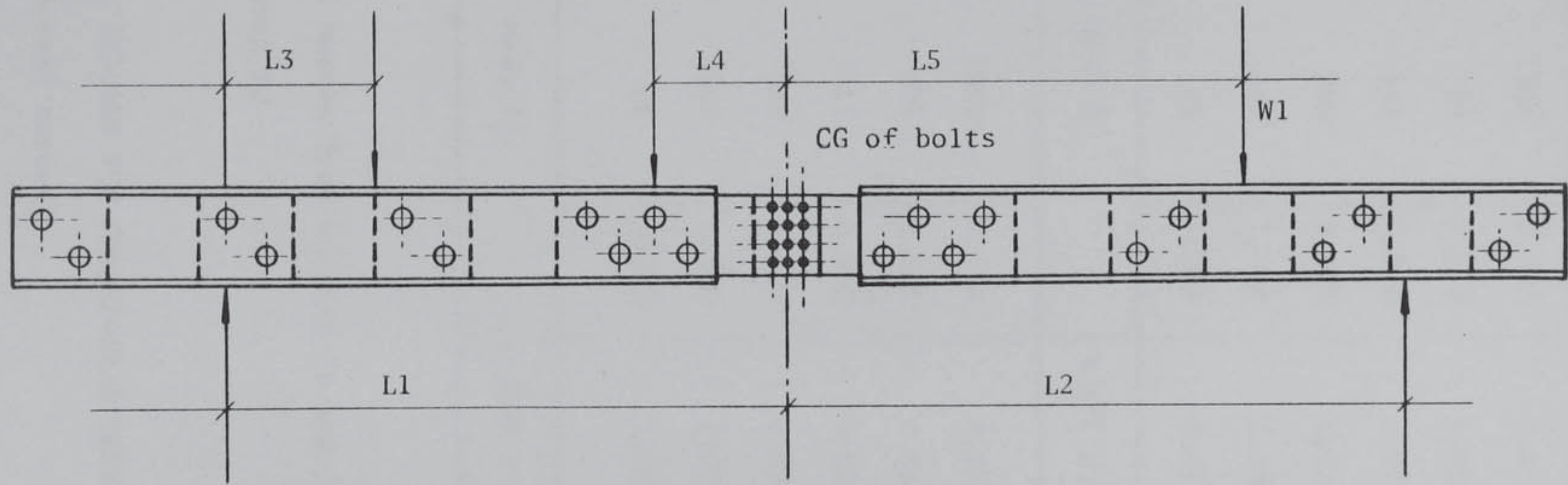
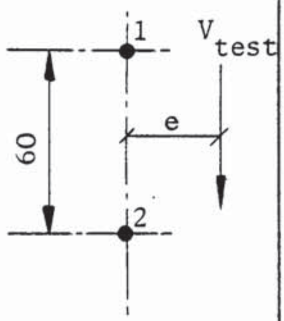
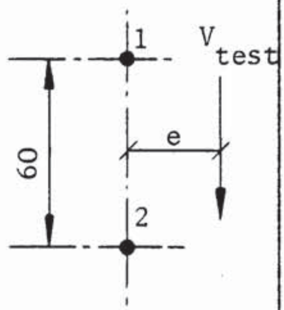


FIG. 3.11 LOADING AND BOLT SPACING ARRANGEMENT

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_v kN
	2C1	1344	0.244	5.457
	2C2	792	0.375	4.953
	2C3	514	0.568	4.871
	2C4	260	1.125	4.914
	2C5	149	1.703	4.304
	2C6	85	3.085	4.614
Batch 3a	Mean F_v			4.852 ± 0.384
	2C7	1469	0.194	4.748
	2C8	795	0.367	4.868
	2C9	514	0.585	5.023
	2C10	260	1.123	4.905
	2C11	162	1.860	5.095
	2C12	95	3.059	5.101
Batch 3b	Mean F_v			4.956 ± 0.140

i 5 mm diameter cheese-head screws from batches 3a and 3b

ii 10 mm thick plate from batch P2

TABLE 3.15: EXPERIMENTAL RESULTS FOR CHEESE-HEAD SCREWS

(Two cheese-head screws)

Type of bolt	Length mm	Nominal Diameter of bolt/hole in Plate mm	Tensile stress area of bolt mm^2	Nominal Thickness of plate mm	Yield Stress of Plate N/mm^2	Two Bolt Tests (series 2)			
						Ultimate Tensile Strength F_t (f_t) kN (N/mm^2)	Ultimate Shear Strength F_t (f_v) kN (N/mm^2)	Ratio F_v/F_t	Ultimate Nominal Bearing stress N/mm^2
Black bolt (batch 1) BS 4190 (57)	70	20/22	245	20 batch P1	271.7 ± 3.6	149.8 ± 2.2 (611.0 ± 9.0)	104.0 ± 6.1 (424.5 ± 24.9)	0.69	260.0
High strength (batch 2b) BS 4395 (58)	70	20/22	245	20 batch P1	271.7 ± 3.6	226.7 ± 9.5 (925.3 ± 38.7)	162.6 ± 8.1 (663.6 ± 33.1)	0.72	406.5
Cheese head (batch 3a) BS 4183 (59)	30	5/5.1	15.77	10	256.4 ± 4.2	7.39 ± 0.89 (468.7 ± 56.5)	4.85 ± 0.38 (307.6 ± 24.1)	0.66	97.0
(batch 3b)				batch P2		7.77 ± 0.25 (492.8 ± 15.9)	4.96 ± 0.14 (314.6 ± 8.9)	0.64	99.2

mean ratio F_v/F_t = 0.68

Notes: ultimate tensile and shear stresses calculated using tensile stress area, all holes in plates were drilled

TABLE 3.16: SINGLE BOLT PROPERTIES AND TWO BOLT TESTS

with one washer under the head and one under the nut for each bolt. The assembled rig was levelled by means of screw jacks and the test bolts were hand tightened. The load was applied gradually at small increments along the centre line of the rig by means of a hydraulic ram via a proving ring and the deflection recorded until one of the bolts failed.

The failure load, together with the variation in span are recorded in Table A.3.7, and loading system is shown in Fig 3.11.

Table 3.15 shows the calculated values of applied force V_{test}, the eccentricity e and the maximum force F_v on the bolt. The mean values of the force F_v for batches 3a and 3b are 4.852 kN and 4.956 kN respectively.

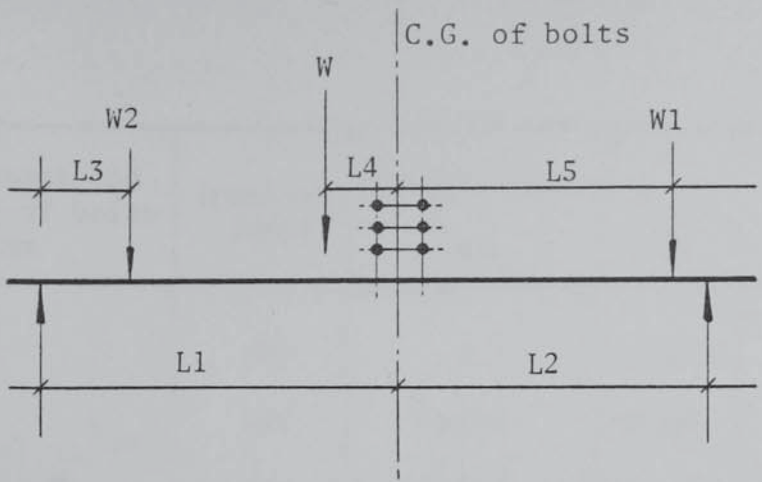
It was stated in series 1 that two bolts tests were considered to be important as an alternative method of obtaining a shear value to be compared directly with the single bolt tests. The results of all the two bolts tests are summarised in Table 3.16 and the F_v/F_t ratio for single bolt tests series 1 was 0.69 as shown in Table 3.12. It is possible however that the two bolt test will produce a low result because the weaker of two bolts always fails. The ratio F_v/F_t reflects this because the mean value for two bolts is 0.68, i.e. slightly less than the single bolt value of 0.69. Therefore it is evident that the average value of F_v/F_t for single and two bolt tests are in reasonable agreement.

3.3.3 Multi-Bolt Group Tests - Series 3

The multi-bolt group tests were carried out to investigate the parameters of type, strength, diameter, and spacing of bolts and plate thickness. The detailed results are given under appropriate headings for various type of bolts. Generally, in these tests the bolt furthest from the instantaneous centre of rotation failed first. The bolt furthest from the instantaneous centre of rotation is subjected to a shear force F_{max} at failure, and values of F_{max} have been calculated for each bolt group using equation 5.2.9 and including the value of load V_{test} obtained in the test. This equation assumes a linear load-deformation characteristic for the bolts and if this theory is applicable the ratio F_{max}/F_t shall be equal to the values of F_v/F_t obtained from the single and two bolt tests. If the ratio of F_{max}/F_t is greater than the single bolt values of F_v/F_t the theory is conservative.

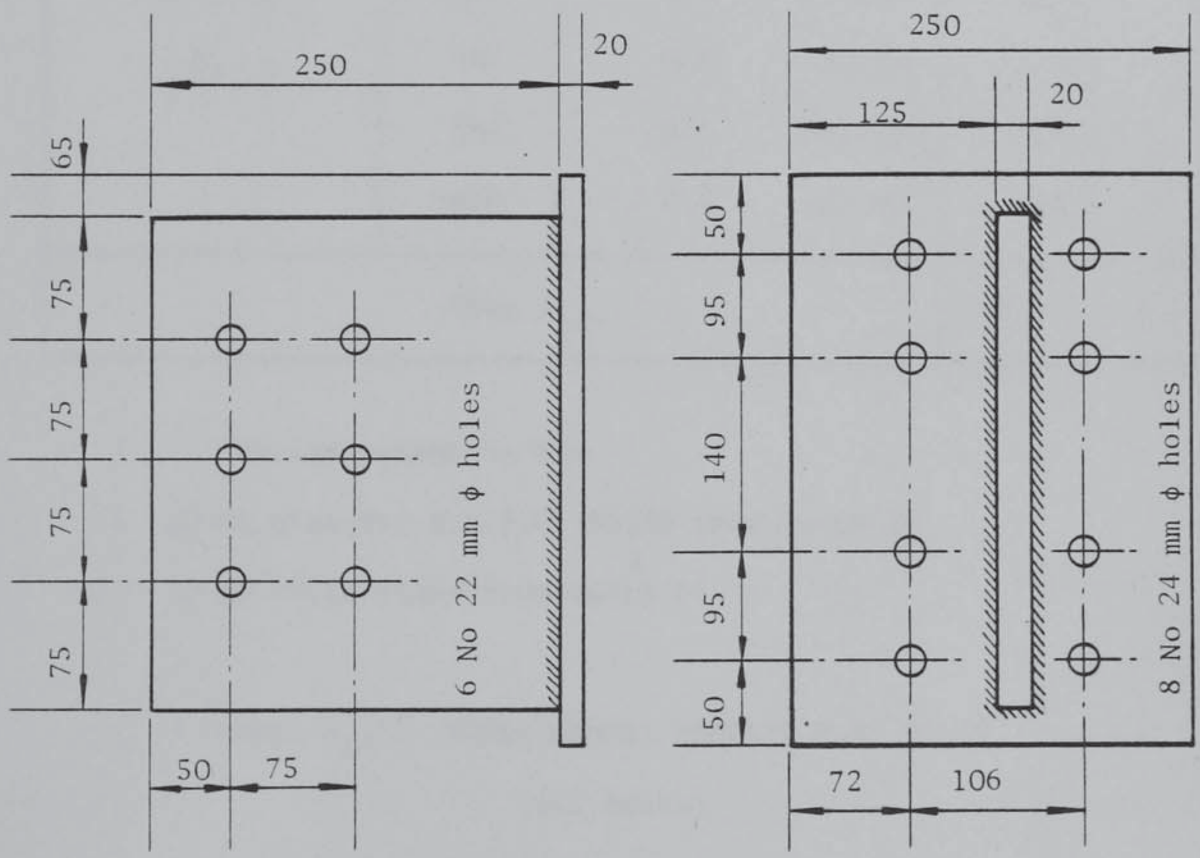
3.3.3.1 High Strength Bolts - Series 3

To investigate the behaviour of the fasteners themselves and those portions of the connection parts immediately adjacent to these fasteners, in a larger bolt group, six bolt connection was selected. Six bolt connection was just strong enough to utilise the full capacity of the loading system at relatively small eccentricity. The test specimen shown in Figure 3.12 was fabricated from 20 mm thick mild steel plate from batch P1 and the 20 mm diameter bolts were selected from batch 2b. The large test rig, loading device and method of testing was the same as outlined in 3.3.2.1. Ten full size connections were tested to cover a wide range of eccentricity varying from 210 mm to 3476 mm by adjusting the position of roller supports. A spreader beam was used to produce an infinite eccentricity. The variations of loaded span and the corresponding failure loads are recorded in Table A.3.8. As expected for large eccentiricities, it was the bolt furthest from the centre of rotation that failed first and the bolts near to the centre of rotation showed little deformation. The calculated



W = applied load (kN)
W1 = self weight of R.H.S. of the rig and specimen = 7.643 kN
W2 = self weight of L.H.S. of the rig and specimen = 7.985 kN
L4 = 282.5 mm
L5 = 1297.5 mm

LOADING SYSTEM

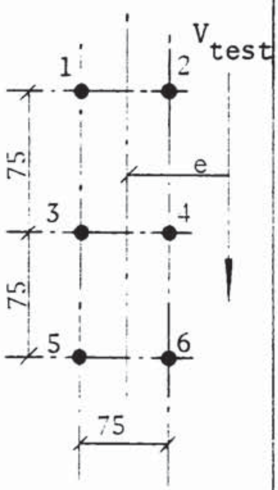


ELEVATION

SECTION A-A

MULTI BOLTS TEST SPECIMEN

FIG 3.12 LOADING AND BOLT SPACING ARRANGEMENT

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	6H1	∞	60.01*	162.7
	6H2	3476	16.35	155.3
	6H3	2797	19.91	152.4
	6H4	1672	34.02	156.8
	6H5	1330	44.23	162.9
	6H6	1329	43.57	160.3
	6H7	899	65.43	164.7
	6H8	665	81.19	152.9
	6H9	320	161.75	154.0
	6H10	210	227.45	150.2
Mean F_{max}				157.2 ± 5.1

i * Torsion moment in kNm

ii 20 mm diameter H.S.F.G. Bolts from batch 2b

iii 20 mm thick plate from batch P1

TABLE 3.17: EXPERIMENTAL RESULTS H.S. BOLTS

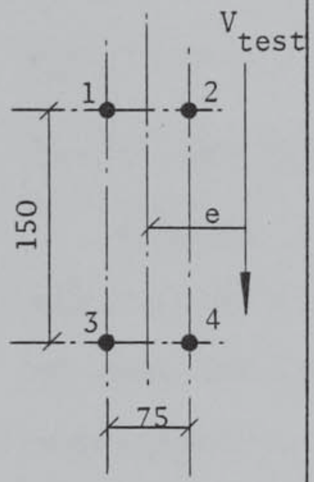
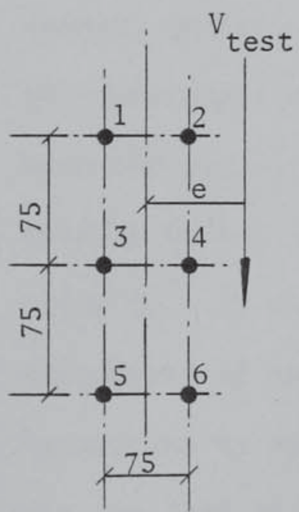
(Six bolts)

results of eccentricity e, applied force V_{test} and the maximum force F_{max} on the furthest bolt are recorded in Table 3.17. The mean value F_{max}/F_t from this table is 0.69 which is 4.1% smaller than the mean value obtained from two bolt test and it indicates that the linear load theory is marginally non conservative.

3.3.3.2 Black Hexagon Bolts - Series 3

The load carrying capacity, in shear, of a fastener depends on the location of the plane of loading. In practice, it is sometimes difficult to prevent the shear plane occurring on the threaded portion. The single bolt and the two bolt tests described in series one and two were arranged such that the failure of the bolt always occurred at the threaded portion. Therefore, to check the validity of the assumption in the theory that the linear load-deformation characteristics for the bolt is applicable, eighteen multi-bolt group tests were carried out. For the first nine tests, a four bolts configuration was considered, whereas for the remaining nine tests six bolts were used in each connection. The 20 mm diameter black bolts for these tests were taken from batch 1 and the 20 mm thick mild steel plate specimens were similar to the connection used for high strength bolts which is shown in Figure 3.12. The connections were tested on the large test rig and the procedure of testing was similar to that described in 3.3.2.1 and the loading span was varied to achieve a wide range of eccentricity. A spreader beam was used for tests labeled 4B1 and 6B1 to produce in-plane shear forces on the bolt group due to torsional moment only.

The applied failure load on the connection and the variation in spans are recorded in Table A.3.9. It is important to note

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	4B1	∞	34.65*	103.3
	4B2	4166	8.26	103.6
	4B3	2986	11.72	105.7
	4B4	1843	19.15	107.5
	4B5	1184	28.62	104.4
	4B6	878	39.91	109.3
	4B7	627	56.23	112.2
	4B8	289	110.07	109.9
	4B9	189	151.05	107.5
Mean F_{max}				107.0 ± 3.1
	6B1	∞	35.94*	96.7
	6B2	4210	7.58	87.1
	6B3	3169	11.14	96.6
	6B4	1824	18.72	94.0
	6B5	1265	27.78	97.4
	6B6	883	39.69	98.1
	6B7	651	52.94	97.7
	6B8	308	119.80	110.5
	6B9	209	164.70	108.5
Mean F_{max}				98.5 ± 7.1

i * Torsion moment in kNm
ii 20 mm diameter black bolts from batch 1
iii 20 mm thick plate from batch P1

TABLE 3.18: EXPERIMENTAL RESULTS BLACK BOLTS (Four and six bolts)

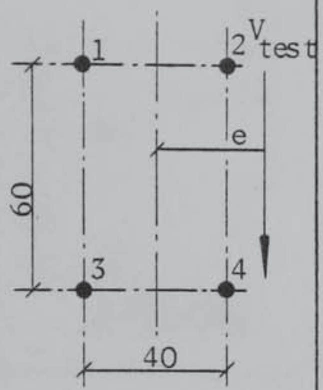
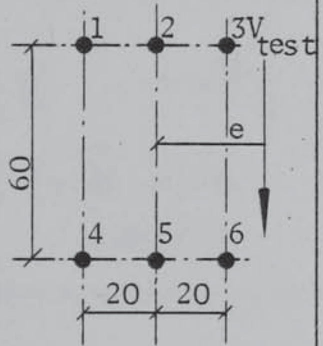
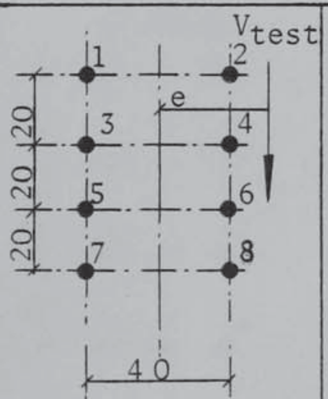
that with large eccentricity the furthest bolt from the centre of rotation failed first, whereas in test labeled 4B9 all the four bolts failed simultaneously as expected. Table 3.18 shows the calculated values of eccentricity, V_{test} and the maximum force F_{max} on the furthest bolt at failure. The mean F_{max} for eighteen tests is 102.77 ± 6.8 kN and the ratio F_{max}/F_t is 0.69 which agrees with F_v/F_t ratio for two bolt test.

3.3.3.3 Cheesehead Screws - Series 3

Although, in practice most of the connections are designed such that the bolts are arranged symmetrically about both axes, yet under the special circumstances it might be structurally advantageous to use unsymmetrical configuration. It appears that no experimental results exists for the behaviour of such connection and thus no design guidance had been given to steelwork designer. It was due to this lack of information why a number of unsymmetrical connections were included in this series. A wide range of joints, symmetrical and unsymmetrical, with three to twelve bolts per joint were considered. A total of fifty-nine multi-bolt tests were carried out on 5 mm cheesehead screws taken from both the batches 3a and 3b and the steel for the test plate was used from batch P2. It was the same small rig, the type of test specimen and method of testing as outlined previously in 3.3.2.3. The variations in span to produce different eccentricity in each test and the load at which the joint failed are recorded in Table A.3.10. The bolts in each group were numbered as shown in Table 3.19 and the last column in Table A.3.10 identifies the bolt or bolts that fractured first. Again, it is interesting to note that it was the bolt furthest from the centroid of the bolt group that failed first and in some cases the bolts nearest to the centroid were hardly damaged.

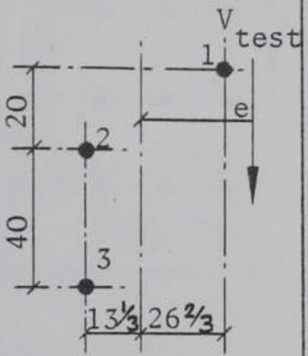
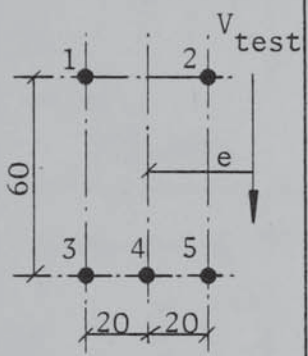
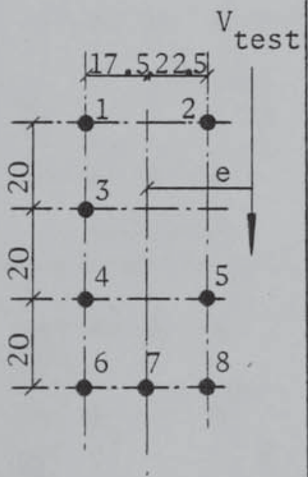
The calculated values of eccentricity e, V_{test} and the maximum force on the bolt at failure are presented in Table 3.19. The mean value of F_{max}/F_t for batch 3b is only 2.7% higher than the mean value for batch 3a.

The mean values of F_{max}/F_t for multi-bolt tests are summarised in Table 3.20. The mean value for the whole table is 0.71 which is greater than the single bolt value of 0.69 and the two bolt value of 0.68. This indicates that the linear load-deformation theory is conservative.

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	4C1	1007	0.709	5.054
	4C2	1000	0.758	5.361
	4C3	703	1.007	5.052
	4C4	701	1.038	5.195
	4C5	514	1.266	4.694
	4C6	296	2.444	5.377
	4C7	183	3.443	4.903
	4C8	109	6.222	5.713
Mean F_{max}				5.169 ± 0.316
	6C1	947	1.076	5.354
	6C2	686	1.484	5.384
	6C3	685	1.546	5.597
	6C4	514	1.930	5.294
	6C5	304	3.352	5.577
	6C6	193	4.953	5.438
	6C7	115	8.173	5.699
Mean F_{max}				5.478 ± 0.149
	8C1	948	1.078	5.194
	8C2	683	1.603	5.598
	8C3	683	1.641	5.724
	8C4	514	2.021	5.347
	8C5	302	3.039	4.814
	8C6	194	5.143	5.389
	8C7	115	8.387	5.489
Mean F_{max}				5.365 ± 0.298

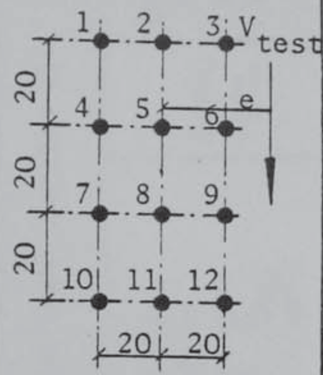
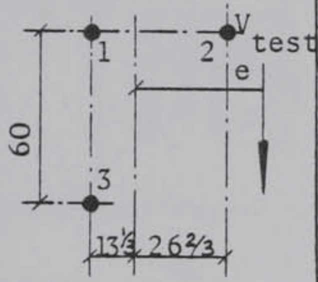
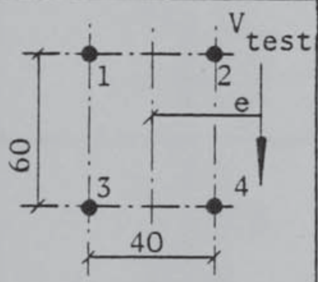
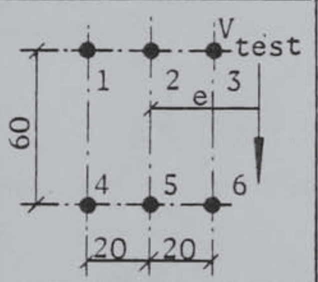
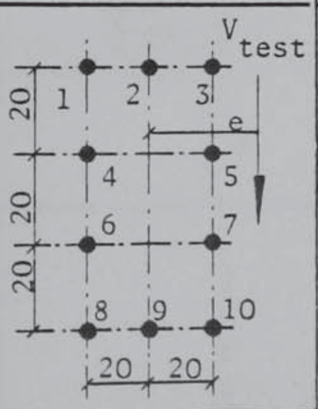
i 5 mm diameter cheese-head screws from batch 3a
ii 10 mm thick plate from batch P2

TABLE 3.19: EXPERIMENTAL RESULTS CHEESE-HEAD SCREWS
(Four, six and eight bolts)

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	3C1	∞	0.501*	6.438
	3C2	651	0.649	5.612
	3C3	654	0.696	5.993
	3C4	396	0.892	4.753
	3C5	265	1.376	5.028
	3C6	263	1.323	4.795
	3C7	164	2.316	5.445
	Mean F_{max}			5.438 ±0.631
	5C1	∞	0.845	5.876
	5C2	408	1.690	4.965
	5C3	283	2.461	5.109
	5C4	283	2.448	5.079
	5C5	179	4.104	5.560
	5C6	53	12.441	6.205
	Mean F_{max}			5.466 ±0.500
	8C1	∞	1.252*	6.596
	8C2	696	1.615	6.040
	8C3	691	1.627	6.040
	8C4	619	1.899	6.330
	8C5	522	2.149	6.065
	8C6	517	2.081	5.814
	8C7	417	2.516	5.710
	8C8	296	3.531	5.762
	8C9	295	3.488	5.688
	8C10	188	5.349	5.718
	8C11	64	15.199	6.428
	Mean F_{max}			6.017 ±0.317

i * Torsion moment in kNm
ii 5 mm diameter cheese head screws from batch 3b
iii 10 mm thick plate from batch P2

TABLE 3.19: EXPERIMENTAL RESULTS CHEESE HEAD SCREWS (Cont) (Three, five and eight bolts)

Arrangement and spacing of bolts	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	12C1	686	2.043	5.591
	12C2	612	2.492	6.097
	12C3	519	3.052	6.353
	12C4	417	3.189	5.366
	12C5	299	4.703	5.729
	12C6	191	7.053	5.633
	12C7	57	20.631	5.715
	Mean F_{max} kN			5.783 ± 0.333
	3C1	648	0.755	6.033
	4C1	∝	0.818*	5.675
	4C2	45	11.269	5.559
	4C3	44	11.086	5.451
	6C1	∝	1.154*	5.946
	10C1	∝	1.630*	6.528

i 5 mm dia cheese-head screws from batch 3b
ii 10 mm thick plate from batch P2

TABLE 3.19 (Cont) EXPERIMENTAL RESULTS CHEESE-HEAD SCREWS (Three, four, six, ten and twelve bolts)

Type of bolt	Length mm	Nominal Diameter of bolt/ hole in Plate mm	Tensile stress area of bolt mm^2	Nominal Thickness of plate mm	Yield Stress of plate N/mm^2	Multi-Bolt Tests (series 3)			
						Ultimate Tensile Strength $F_t (f_t)$ kN (N/mm^2)	Ultimate shear Strength $(F_t\ f_{max}$ kN (N/mm^2)	Ratio F_v/F_t	Ultimate Nominal Bearing Stress N/mm^2
Black Bolt (batch 1)	70	20/22	245	20 batch P1	271.7 ± 3.6	149.8 ± 2.2 (611.0 ± 9.0)	102.8 ± 6.7 (419.6 ± 27.3)	0.69	257.0
High Strength (batch 2b)	70	20/22	245	20 batch P1	271.7 ± 3.6	226.7 ± 8.5 (925.3 ± 38.7)	157.2 ± 5.1 (641.6 ± 20.8)	0.69	393.0
Cheese head (batch 3a)	30	5/5.1	15.77	10	256.4 ± 4.2	7.39 ± 0.89 (468.7 ± 56.6)	5.33 ± 0.28 (338.1 ± 17.8)	0.72	106.6
Cheese head (batch 3b)				batch P2		7.77 ± 0.25 (492.8 ± 15.9)	5.75 ± 0.47 (364.7 ± 29.8)	0.74	115.0

mean ratio $F_{max}/F_t = 0.71$

Notes: ultimate tensile and shear stresses calculated using tensile stress area, all holes in plates were drilled

TABLE 3.20: MULTI-BOLT PROPERTIES

CHAPTER FOUR

EXPERIMENTAL RESULTS FOR TENSIONED BOLTS

4.1 INTRODUCTION

High strength friction grip (HSFG) bolts subject to torsion and shear i.e. the in-plane forces in single shear at the serviceability limit state and the ultimate limit state, are considered in this chapter.

The introduction of limit state design in the draft steel code (56) requires that the strength of the bolt group having HSFG bolts, be determined at the serviceability and the ultimate limit states. When a "non slip" connection is required, the capacity of a "non slip" shear connection is to be determined from the slip resistance provided by the fasteners at each shear plane. In the case of a "normal" shear connection where slip does not represent failure and can be treated as a serviceability limit state, the capacity of the connection at the ultimate limit state is to be determined from normal shear capacity of the fasteners.

The parameters considered in this chapter are, the methods of tightening a bolt, the load-slip relationship of a pretensioned bolt in single shear, the effect of faying surfaces on the coefficient of slip resistance and its application to a group of bolts in a connection at the serviceability limit state. At the ultimate limit state the effect of pretension in the bolt was also investigated.

4.1.1 Referencing of Tests

The system of referencing outlined in Chapter three (3.1.1) is also applicable to the tests carried out in this section. In the direct tension calibration tests on the bolts to establish the Young's modulus and the applied verses bolt extension relationship, the test number is preceded by two letters DT (indicating direct tension), whereas for torqued tension tests the letters TT (torque tension) are used.

4.2 MATERIAL PROPERTIES

Included in this study were HSFG bolts from batch 2c and mild steel plates from batch P4, general properties of which were discussed in 3.2.1.2 and 3.2.2.3 respectively.

The load-slip relationship of a joint depends on the condition of the faying (contact) surfaces and the clamping force of the bolt. The load is transferred across the joint by the friction between the connected parts rather than through shear on the fasteners. To induce internal tension it is necessary to elongate the bolt in some way. This may be accomplished by subjecting the bolt to a direct axial load (direct tension) or, to extend the bolt by turning the nut (torqued tension). The direct tension method is more suitable for the laboratory conditions whereas turning the nut simulates site conditions. Tests were therefore carried out to establish the shank tension - elongation relationship caused by turning the nut and by pulling the bolt in direct tension.

The test specimens manufactured from the plates were similar to the specimen used in Chapter three but the faying surfaces of the plates were shot-blasted to achieve consistency in the slip resistance.

4.2.1 Direct Tensile Tests on Bolts

Nine full size HSFG bolts, together with nuts and washers, were selected from batch 2c and their physical properties such as diameter of the shank, length of unthreaded shank, thickness of nut, and washers etc were measured and are recorded in Table A.4.1. Holes were drilled in the head of bolts to pass electric resistance strain gauge wires. Four bolts were drilled with three holes in the head at 60°, whereas the remaining five bolts were drilled with two holes at 180° to economise on the number of strain gauges used. The centre of the head and the shank end of the bolt were cleaned and two demec spots, one on each end, were attached to accommodate the points of a C-frame extensometer. The demec spots provided a protected accurate measuring surface that could not be damaged during the bolting operation. FLA-3-11 strain gauges were attached to the unthreaded portion of the shank as shown in Figure 4.1b. One M20 flat round washer was used under the nut and a 24 mm diameter flat round washer was used under the head to provide a suitable clearance for the strain gauge wires. The bolt to be calibrated was inserted in the special tension jig shown in Plate 4.1, which was held in the hydraulic testing machine. The position of the testing machine head was set so that at a given distance between the washers, the nut was only finger tight and the bolt was unstressed. The distance between washers is also recorded in Table A.4.1.

Zero reading of the bolt length and strain gauges were taken with no load on the bolt. Bolt elongations were measured with the C-frame extensometer shown in Plate 4.1 . The device was capable of indicating changes in length of 0.002 mm. Accuracy of the device was assured by checking the measurements with slip gauges before and after testing. When measuring the initial, intermediate and final lengths of bolts, several readings were taken to establish the mean extension. Load was applied to the specimen at small

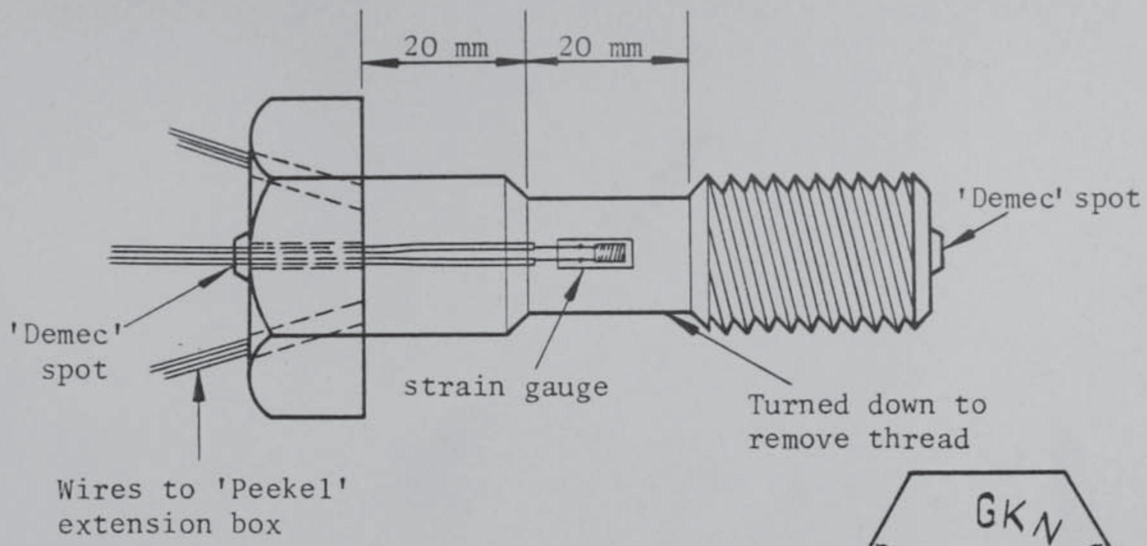
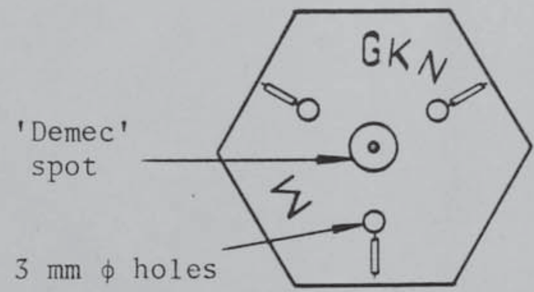


FIGURE 4.1a TURNED DOWN TEST SPECIMEN



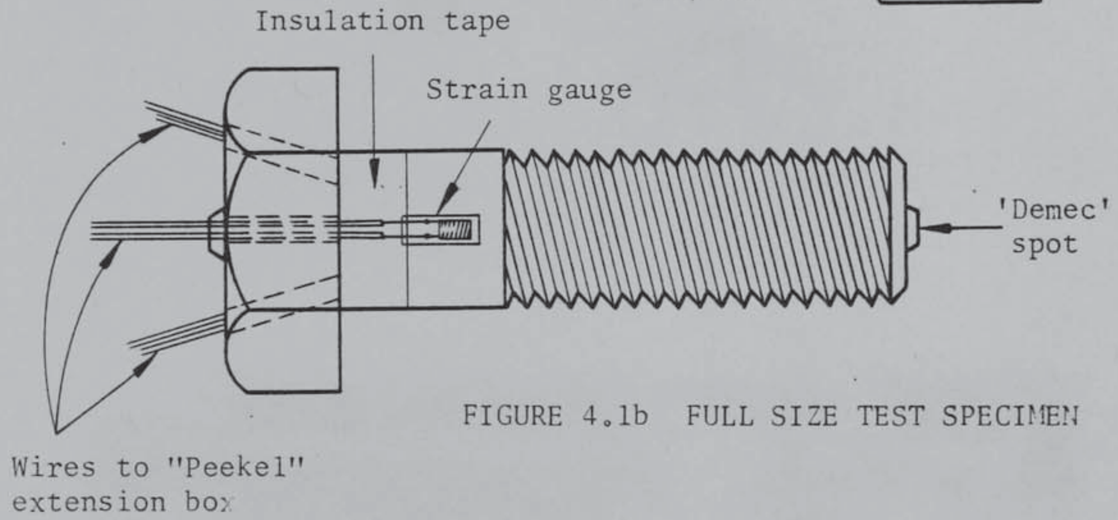


FIGURE 4.1b FULL SIZE TEST SPECIMEN

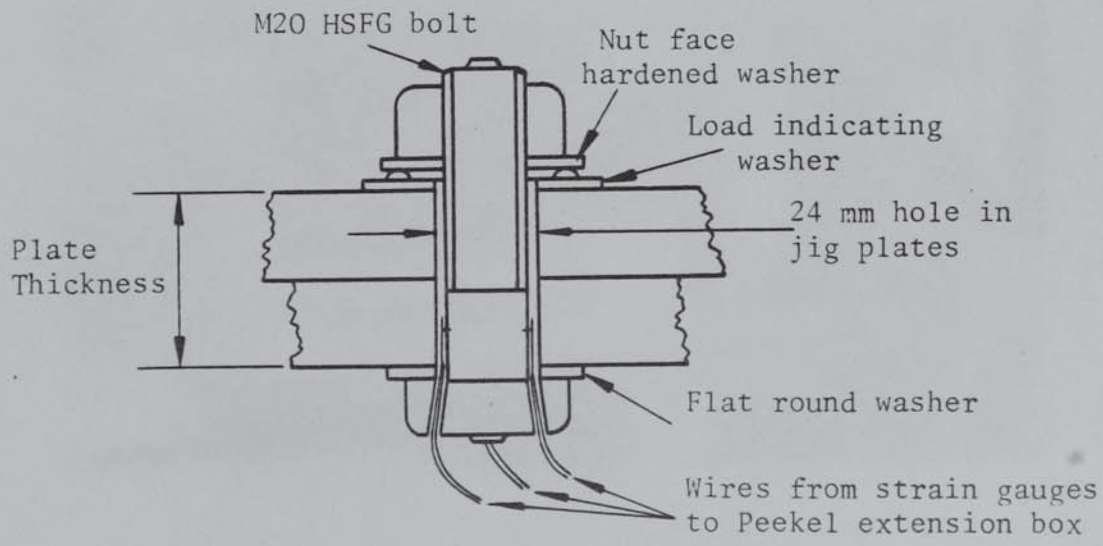
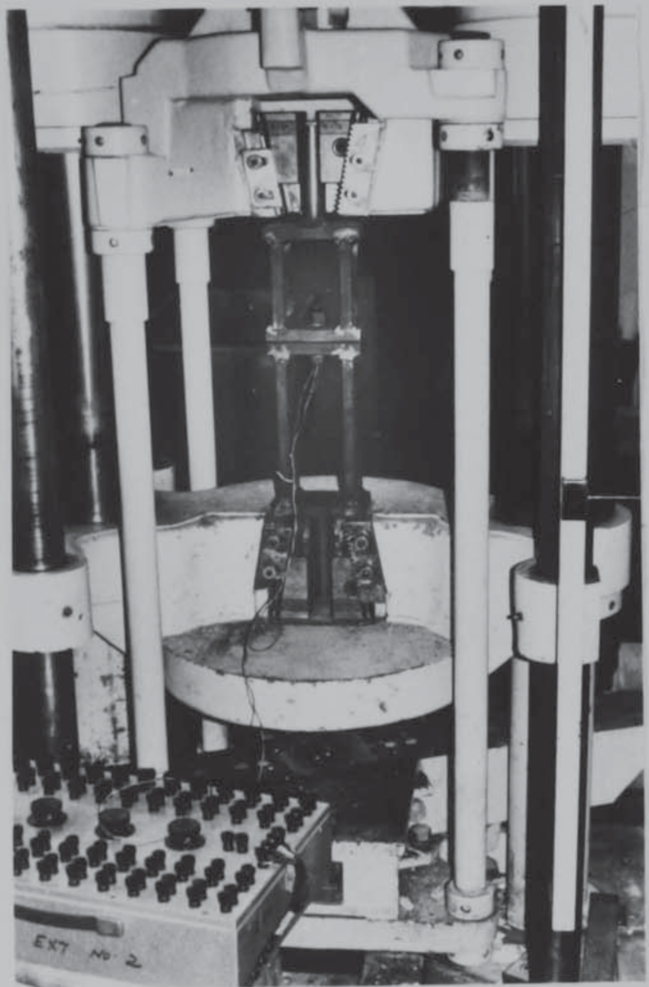
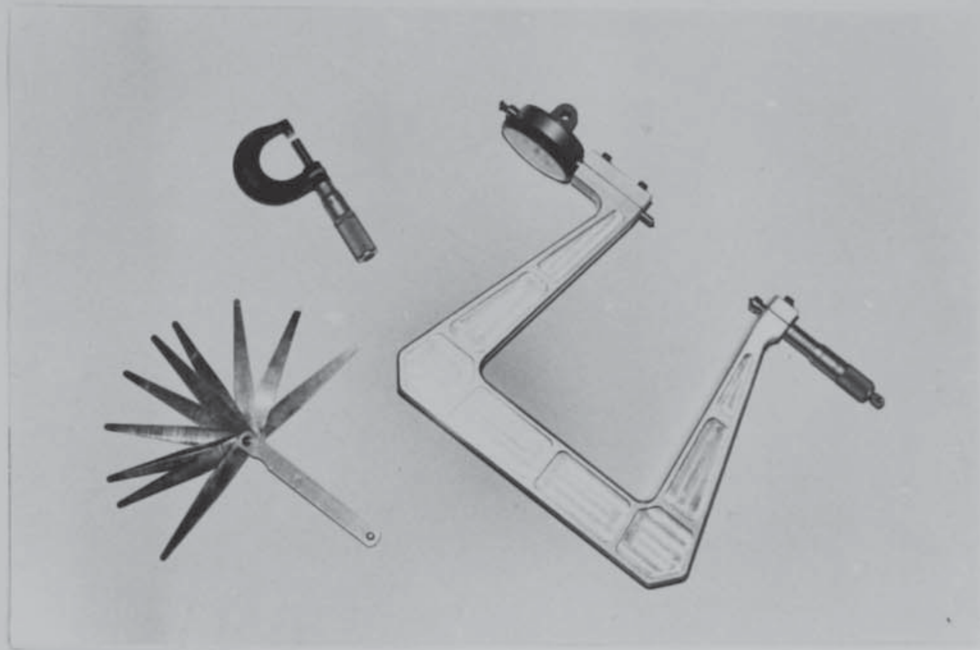


FIGURE 4.1c TORQUE TEST ARRANGEMENT

FIGURE 4.1 DIRECT AND TORQUE TENSION TEST SPECIMENS
(HSFG bolts)



DIRECT TENSION TEST



C-FRAME EXTENSOMETER

PLATE 4.1 EXTENSOMETER AND TENSION TEST JIG increments, mean extension and strain guage readings were taken until the bolt fractured. No readings were taken near to bolt failure because of the risk of being struck by pieces of fractured bolt. The shank tension (applied load) versus strain and bolt extension is recorded in Table A.4.2. The mean Young's modulus of the shank herein termed as apparent Young's modulus, calculated from the results of tests DT1 to DT9 inclusive, shown in Table 4.1, was 232.25 kN/mm^2 which is considerably higher than 210 kN/mm^2 normally taken for steel. It is evident from the test specimen examination that strain gauges attached to the shank were within the nominal diameter of bolt from the bolt head. The linear-elongation of the shank within this zone is partially restrained by the head of the nut. Therefore, for a given stress, the strain produced in this portion is small, which gives a higher value of the modulus of elasticity.

The total bolt extension for a given shank tension is the sum of extensions of unthreaded shank, threaded protion of the shank between the nut face and the thread-runout and the threaded part of the shank under the nut. The extension of the threaded portion will be greater than the unthreaded shank due to the reduced tensile area and it was therefore essential to establish the Young's modulus of elasticity of the bolt at the threaded portion. Six HSFG bolts were taken from batch 2c and their diameter was reduced approximately to the root of the threads. Electric strain gauges were attached to the reduced shank as shown in Figure 4.1a and bolts tested in the same manner as the full size bolts. The load-strain relationship of the test DT10 to DT15 inclusive are shown in Table A.4.3. The mean Young's modulus shown in Table 4.1 is 216.04 kN/mm^2, as expected, this value is lower than apparent Youngs modulus of

Type of tensile tests	Test No	Ultimate tensile stress N/mm^2	Young's modulus kN/mm^2
Full size bolt as supplied	DT 1	902.45	230.99*
	DT 2	974.98	232.17*
	DT 3	956.98	229.99*
	DT 4	914.89	229.61*
	DT 5	899.06	238.90*
	DT 6	956.04	232.70*
	DT 7	945.87	240.00*
	DT 8	931.63	229.10*
	DT 9	964.08	226.80*
mean		938.44 ±27.72	232.25 ±4.44
Turned-down diameter bolts	DT 10	948.15	215.77
	DT 11	963.72	215.66
	DT 12	1142.00	215.71
	DT 13	1143.44	218.60
	DT 14	955.31	217.10
	DT 15	978.90	213.43
mean		1021.92 ±94.13	216.04 ±1.72

i 20 mm dia HSFG bolts from batch 2C
ii *E_s apparent Young's modulus of elasticity of shank
iii Nominal tensile stress area for full size bolts 245 mm^2.

TABLE 4.1 MODULUS OF ELASTICITY
(HSFG Bolts)

the unthreaded shank.

4.2.2 Torqued Tension Test on Bolts

The object of this series of tests was to establish tension-elongation relationship caused by turning the nut, rather than by pulling the bolt in direct tension. Four separate methods of measuring the induced bolt tension were examined during these tests, these were torque control, load indicating washers, strain-gauges and C-frame extensometer. A brief description of each method is as follows:-

The torque control method of tightening involves the use of a calibrated tightening device (torque wrench) to tighten the nut and bolt to a predetermined torque; the pretension attained in the bolt being dependent upon the torque-tension relationship of the individual bolt. The torque required to overcome friction varies and there can be a wide variation in the pretension induced by a particular torque. With this method very careful control is required to achieve the correct pretension.

The load indicating washers is a device that provides a different means of evaluating the induced bolt tension during and after tightening. It is a hardened washer with a series of protrusions on one face. The protrusions are so designed that at the required minimum shank tension in the bolt the gap is reduced to a specified amount.

As the nut is tightened against the resistance of the gripped material, the bolt length within the grip is forced to elongate. If the gripped material and the threads are completely rigid, one complete turn of the nut would cause the bolt to elongate one pitch. Because the material in the joints pulls together and even compresses slightly and thread deformation does occur, the elongation of the bolt will not be one pitch. Controlling tension by turn-of-nut is primarily a strain control and the effectiveness of the method depends on the consistency of the starting point and the accuracy to which rotation increments are measured (17). FLA-3-11 electric strain gauges were used to measure the longitudinal strain in the bolt instead of turn-of-nut method.

Eleven HSFG bolts, together with nuts and washers were taken from batch 2c. Dimensions such as the diameter of the shank, length of the unthreaded shank, thickness of the nuts, washers and gripped plates were measured and recorded in Table A.4.4. Strain gauges and demec spots were attached to the bolt as described for the direct tension tests and initial lengths were measured with the C-frame extensometer. Bolts were inserted in 22 mm diameter drilled holes and assembled as shown in Figure 4.1.c. Zero readings of the bolt length, strain gauges and mean gap for load-indicating washers were taken with no load on the bolt. Closing of the gap was measured with feeler gauges shown in Plate 4.1. Five readings were taken to establish the mean extension and mean gap. Hand torque wrenches were used during the torqued tests. Two sizes of wrenches were used, the smaller wrench was capable of exerting a torque up to 50 Nm while the larger sized wrench was capable of exerting a torque between 400 to 1000 Nm. Initially with smaller torque wrench a torque of 50 Nm was applied then using the larger torque wrench, the nut was rotated 20 Nm increments of torque. Strain, gap and elongation readings were taken at each increment until failure was imminent. For safety reasons no readings were taken at failure. Since the readings were taken after the torque wrench was removed from the nut, dynamic effect were excluded.

Test results for eleven tests TT1 to TT11 inclusive are summarized in Table A.4.5. The shank tension in the bolt is calculated using the tensile stress area 305.424 mm^2 and the Young's modulus of the shank 232.25 kN/mm^2 from Table 4.1. The calculated shank tension verses torque, bolt extension and the gap for load indicating washers is shown in Figure A.4.6. These curves for eleven tests shows the variation that exist in each method of measuring the tensile force in the bolt. Specific values of bolt extension, torque and gap for shank tension 127 kN and 144 kN were read from these graphs and are recorded in Table 4.2. In these tests the load indicator washer was placed under the nut and a special nut face washer inserted between the nut and the load indicator. Results by J H A Struik and J W Fisher (48) on A325 bolts with load indicator inserted under the head were in reasonable agreement with the manufacturers recommendations.

In order to achieve the minimum required shank tension of 144 kN, the manufacturer recommends tightening until the minimum average gap is reduced to 0.25 mm. It is evident from Table 4.2 that the average gap required to achieve 144 kN shank tension is 0.138 mm with 65.9% coefficient of variation. Therefore further work may be necessary to establish the reliability of 'coronet' as a tension indicating device.

Although an experimental investiagtion by Gill (34) shows that for HSFG bolts the tightening must be at least 70% of the specified minimum ultimate tensile stress (144 kN) to use a bolt to its safe full economical strength, yet in this study of HSFG bolted connections a shank tension of 127 kN (62%) will be induced in each bolt. Table 4.2 shows that torque control and

Shank Tension	127 kN		
Test No	Bolt extension δ_b mm	Torque Nm	Gap mm
TT 1	0.130	535	0.140
TT 2	0.140	534	0.560
TT 3	0.150	540	0.375
TT 4	0.149	548	0.200
TT 5	0.143	608	0.325
TT 6	0.135	562	0.450
TT 7	0.140	525	0.400
TT 8	0.157	466	0.180
TT 9	0.132	504	-
TT 10	0.147	507	0.250
TT 11	0.123	542	0.540
mean	0.140 ±0.010	533 ±36	0.342 ±0.148
% coeff. of variation	7.1	6.7	43.3

i Extension, torque and gap values for 127 and 144 kN shank tension are taken from figure A.4.6

ii 20 mm HSFG bolts from batch 2C

TABLE 4.2 SHANK TENSION/TORQUE, GAP AND EXTENSION RELATIONSHIP

Shank Tension	144 kN		
Test No	Bolt extension δ_b mm	Torque Nm	Gap mm
TT 1	0.170	594	0.035
TT 2	0.160	598	0.250
TT 3	0.192	600	0.155
TT 4	0.167	584	0.060
TT 5	0.164	648	0.075
TT 6	0.157	614	0.185
TT 7	0.180	566	0.135
TT 8	0.175	516	0.055
TT 9	0.150	550	0.330
TT 10	0.173	575	0.085
TT 11	0.140	567	0.156
mean	0.166 ±0.014	583 ±34	0.138 ±0.091
% coeff of variation	8.4	5.8	65.9

i Extension, torque and gap values for 127 and 144 shank tension are taken from Figure A.4.6

ii 20 mm HSFG bolts from batch 2C

TABLE 4.2 SHANK TENSION/TORQUE, GAP AND EXTENSION RELATIONSHIP bolt extension methods of measuring the shank tension have a small percentage of coefficient of variation therefore both of these methods will be used in the single and multibolt tests.

4.2.3 Surface Treatment of Plates

It has been shown (41) that relaxation of bolt tension due to applied joint load is produced by interface displacements and the plate thining which results from elastic and plastic-in-plane strains. The above effect, creep and other time dependent effects are small with bolts tensioned below their elastic limits. When the plate stresses are moderately low and the load is applied steadily the joint continues to carry the load without slip until the frictional resistance between the plates is overcome. Under these conditions the value of 'apparent' (41) coefficient of friction can be compared with coefficient of friction, μ and the factors effecting the strength of the joint are therefore the bolt tension at slip and the coefficient of friction, which is governed by the surface condition. The coefficient of friction for faying surfaces in this study is determined in 4.4.

Plates for HSFG bolted connections were taken from batch P4. To ensure that the experimental determination of the values of the displacement (including slip) and the coefficient of friction for these tests were consistent, faying surfaces of the specimens were shot blasted under controlled conditions. The range of surface roughness CLA values obtained using a Talysurf profilometer was 5 to 7.5 microns and a typical trace of the surface profile is shown in Figure 4.2 . All the specimens were prepared in one batch to achieve consistency and the surfaces were protected with a smear of grease which was removed using trichloroethylene prior to testing.

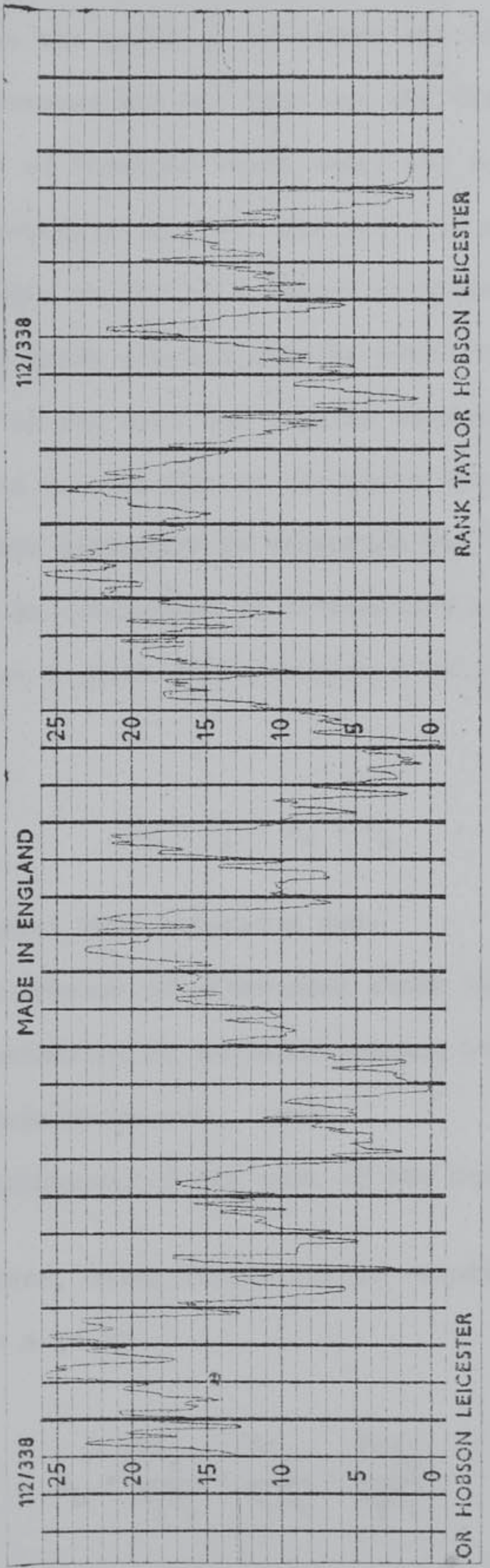


FIGURE 4.2 TYPICAL TRACE OF SURFACE PROFILE

4.3 DETERMINATION OF EFFECTIVE GAUGE LENGTH

The total extension of a bolt for direct and torque tension tests is the addition of extensions of unthreaded shank, threaded shank between the nut face and the thread-run-out and a certain portion of threaded shank under the nut. It has been confirmed experimentally in 4.2.1 and 4.2.2 by measuring the extension and the strain in the bolt that a relationship does exist between the induced shank tension and the total bolt extension. If the gauge length of the bolt for a given extension is known, it appears that, it is possible to calculate the force in the bolt. It is therefore necessary to establish the length of the bolt under the nut to be considered in determining the gauge length.

For a given shank tension P kN, the total extension of the bolt,

$$\delta_b = \delta_s + \delta_t + \delta_n \qquad (4.1)$$

δ_b = total bolt extension (mm)

δ_s = extension of unthreaded shank (mm)

δ_t = extension of threaded portion between the nut face and the thread-run-out. (mm)

δ_n = extension of the part of the bolt under the nut. (mm).

Therefore, using stress/strain relationship within elastic limits, from = n (4.1)

$$\delta_b = \frac{P\ell_s}{A_s E_s} + \frac{P\ell_t}{A_t E_t} + \frac{P\alpha\ell_n}{A_t E_t} \qquad (4.2)$$

where α is an arbitrary constant

A_s = tensile stress area of unthreaded shank. (mm^2)

A_t = specified tensile stress area of threaded shank. (mm^2)

E_s = apparent modulus of elasticity of unthreaded shank (kN/mm^2)

E_t = modulus of elasticity of threaded shank (kN/mm^2)

ℓ_s = length of unthreaded shank. (mm)

ℓ_t = length of threaded shank between nut face and thread-run-out. (mm)

ℓ_n = thickness of nut. (mm)

Therefore the value of α can be determined from equation (4.2) for direct or torque tension test.

From experimental data

E_s = 232.25 kN/mm^2	(Table 4.1)
E_t = 216.04 kN/mm^2	(Table 4.1)
A_s = 305.42 mm^2	(Table A.4.1)
A_t = 245 mm^2	BS 4395 (58)
ℓ_s = 20 mm	(Table A.4.1)

Substituting the above values in = n (4.2)

$$\delta_b = \frac{P}{245x216.04} \left(20 \times \frac{216.04}{232.25} \times \frac{245}{305.42} + \ell_t + \alpha\ell_n\right)$$

$$= \frac{P}{52930} (14.9 + \ell_t + \alpha\ell_n)$$

$$\therefore \quad \alpha = \frac{1}{\ell_n} \left(\frac{\delta_b x\ 52930}{P} - 14.9 - \ell_t\right) \qquad (4.3)$$

4.3.1 Value of α_D for Direct Tension Tests

In order to establish the value of constant α_D, the bolt extension δ_b are summarized in Table 4.3 for various applied loads (shank tension) and the mean extension for each load is calculated.

Applied load (kN)	99.7	119.6	129.6	139.5	144	149.5	159.5
Test No	BOLT EXTENSION δ_b						
	mm	mm	mm	mm	mm	mm	mm
DT 1	0.107*	0.127*	0.140*	0.154*	0.156*	0.160*	0.170*
DT 2	0.097*	0.124*	0.136*	0.148*	0.153*	0.158*	0.168*
DT 3	0.106*	0.130*	0.141*	0.156*	0.165*	0.173*	0.181*
DT 4	0.099*	0.124*	0.136*	0.149*	0.154*	0.159*	0.166*
DT 5	0.087	0.106	0.124	0.134	0.139*	0.145	0.156
DT 6	0.103	0.124	0.137	0.146	0.152*	0.160	0.174
DT 7	0.089	0.102	0.120	0.132	0.136*	0.142	0.155
DT 8	0.108	0.130	0.140	0.150	0.157*	0.166	0.178
DT 9	0.085	0.108	0.119	0.133	0.137*	0.142	0.154
mean	0.098 ±0.008	0.119 ±0.011	0.132 ±0.009	0.144 ±0.009	0.149 ±0.010	0.156 ±0.011	0.166 ±0.010

i Values of δ_b from Table A.4.2

ii * Intrapolated values of δ_b

iii 20 mm dia HSFG bolts from batch 2c

TABLE 4.3 APPLIED LOAD AND BOLT EXTENSION RELATIONSHIP

Applied load kN	Tensile stress N/mm^2	Mean ℓ_n mm	Mean ℓ_t mm	Mean δ_b mm	Constant α_D
99.7	406.9	18.06	28.32	0.098	0.457
119.6	488.2	18.06	28.32	0.119	0.522
129.6	528.9	18.06	28.32	0.132	0.591
139.5	569.4	18.06	28.32	0.144	0.631
144.0	587.7	18.06	28.32	0.149	0.654
149.5	610.2	18.06	28.32	0.156	0.663
159.5	651.0	18.06	28.32	0.166	0.656
Mean					0.596 ±0.08

i For value of ℓ_n and ℓ_t see Table A.4.1

ii For value of δ_b see Table 4.3

iii 20 mm dia bolts from batch 2c

iv Tensile stress based on an area of 245 mm^2

TABLE 4.4 TENSILE STRESS AND 'α_D' RELATIONSHIP

These mean values of extension, together with mean ℓ_n and ℓ_t are used in equation (4.3) to calculate constant α_D. The relationship between tensile shank stress and the constant α_D is shown in Table 4.4 and it appears that its value increases with the increase in tensile stress because no correction for the change in the cross-sectional area has been made in the equation. However, the mean value of $\alpha_D = 0.596$ shows that 6/10th of the bolt under the nut may be used in determining the effective length of the bolt in direct tension.

4.3.2 Value of α_T for Torque Tension Tests

The values of bolt extension for torqued tests TT1 and TT11 inclusive are summarized in Table 4.5. The mean bolt extension for a given shank tension was used to calculate constant α_T which is shown in Table 4.6. The mean α_T for torqued test is higher than direct tension test α_D due to the fact that the stresses induced are more complex and the extension produced during torqued test is smaller as expected.

4.3.3 Application of Theory

The simple elastic theory presented in 4.3 in the form of equation 4.2 can be rearranged to determine the force in the bolt. Therefore in practice, if the total extension of the bolt due to either direct tension or torque is known, the resulting shank tension in the bolt can be found using the appropriate values of α_D and α_T from Tables 4.4 and 4.6 respectively.

Experimental results on A325-7/8 in ϕ bolts are available for comparison by Rumpf and Fisher (17) to give confidence to the method. In Table A.4.7 the 75 experimental results for direct

Shank tension (kN)	100	110	120	127	130	140	144
Test No	BOLT EXTENSION δ_b						
	mm	mm	mm	mm	mm	mm	mm
TT 1	0.100	0.111	0.122	0.130	0.132	0.150	0.170
TT 2	0.110	0.123	0.133	0.140	0.145	0.155	0.160
TT 3	0.118	0.130	0.141	0.150	0.155	0.180	0.192
TT 4	0.116	0.127	0.140	0.149	0.152	0.163	0.167
TT 5	0.113	0.125	0.135	0.143	0.147	0.159	0.164
TT 6	0.105	0.115	0.125	0.135	0.137	0.150	0.157
TT 7	0.110	0.120	0.133	0.140	0.145	0.165	0.180
TT 8	0.123	0.135	0.148	0.157	0.160	0.172	0.175
TT 9	0.105	0.115	0.125	0.132	0.135	0.145	0.150
TT 10	0.115	0.127	0.140	0.147	0.150	0.164	0.173
TT 11	0.097	0.105	0.115	0.123	0.125	0.135	0.140
mean	0.110 ±0.007	0.121 ±0.009	0.132 ±0.009	0.140 ±0.101	0.144 ±0.010	0.158 ±0.012	0.116 ±0.014

i 20 mm dia HSFG bolts from batch 2c

ii values of δ_b from Fig A.4.6

TABLE 4.5 SHANK TENSION AND BOLT EXTENSION RELATIONSHIP

Applied load kN	Tensile stress N/mm^2	Mean ℓ_n mm	Mean ℓ_t mm	Mean δ_b mm	Constant α_T
100	408.2	17.97	28.20	0.110	0.843
110	448.9	17.79	28.20	0.121	0.843
120	489.8	17.97	28.20	0.132	0.843
127	518.4	17.97	28.20	0.140	0.850
130	530.6	17.97	28.20	0.144	0.866
140	571.4	17.97	28.20	0.158	0.927
144	587.7	17.97	28.20	0.166	0.999
Mean					0.881 ±0.059

i For values of ℓ_n and ℓ_t see Table A.4.4

ii For mean values of δ_b see Table 4.5

iii Equation (3) used to calculate α_T

iv Tensile stress based on 245 mm^2 c.s.a.

TABLE 4.6 SHANK STRESS AND α_T RELATIONSHIP tension tests and in Table A.4.8 the 62 results for torqued tests are compared with the theoretical results based on the values of α_D and α_T at the proof load. Only three test results were omitted due to unusually high extension reported by the authors. The last column in Tables A.4.7 and A.4.8 shows the accuracy of the method presented herein. The mean values of P_{theory}/P_{test} for direct tension tests of 1.05 and for torqued tests of 0.986, with small coefficients of variation, are acceptable.

4.4 SLIP RESISTANCE OF A JOINT

The theoretical analysis of a HSFG bolt group, where a 'non-slip' connection is required, depends on the load-slip resistance relationship of a single bolt. The slip resistance of a joint is related to the surface finish, number of faying surfaces, the clamping force in the bolt and the method in which the load is applied to the joint i.e. static or dynamic loading.

In this section joints are considered under the action of static loading and experiments are described which demonstrate the effect of bolt strength, initial bolt tension and the interface surface finish. An apparatus outlined in 4.4.1, permitted the study of the phenomenon of friction between surfaces, similar to those used in the two bolt and multi-bolt connections and the results for the coefficient of friction are presented. These results were used for a theoretical analysis of a joint at the limit state of slip.

4.4.1 Slip Resistance of a Single Bolt Series 1_t

Six tests were carried out to determine the load-slip relationship of a single bolted joint. The test rig was as shown in

Figure 3.3 except that the faying surfaces were treated as described in 4.2.3. One washer under the head and one under the nut were used and the bolt was tightened to a predetermined torque of 533 Nm using a calibrated torque wrench. The extension of the bolt was measured with a C-clamp extensometer. Although Table 4.2 shows that both the torque control and bolt extension methods of measuring shank tension are equally reliable, yet the latter method was preferred. The assembled specimen was placed in Denison Universal Testing Machines and a magnetic backed dial gauge capable of measuring 0.002 mm was attached to measure the slip. The load was applied at a constant rate of 0.25 kN/sec and the dial readings recorded at a suitable interval until a major slip occurred. At this stage, the bolt slipped into a bearing mode and the test was continued and the bolt finally fractured at threads in single shear. The results of these tests are recorded in Table A.4.9 and the load versus slip-deformation relationship is shown in Figure A.4.10. The slip of the joint was sudden and complete accompanied by some noise. In test No $1H_t2$ initially the faying surfaces slipped gradually, then followed by a sudden movement. In viewing Figure A.4.10 it should be noted that the relative movement of the gauge up to slip, includes plate strains. The load-deformation graph after the slip is similar to Figure 3.4 for bolts without induced shank tension. The load at which the bolt sheared has been recorded as the ultimate load.

The initial bolt tension P_i, major slip load P_s and ultimate shear strength F_v for each test is recorded in Table 4.7. The mean coefficient of friction μ was 0.360 with 7.7% coefficient of variation. The mean ultimate shear strength was 150.44 kN and the ratio of shear strength to tensile strength (F_v/F_t) was 0.66,

Test No	Initial bolt tension P_i kN	Slip load P_s kN	$\mu = P_s/P_i$	Ultimate shear strength F_v kN
$1H_t1$	122.686	44.85	0.365	151.50
$1H_t2$	138.139	50.83	0.368	148.31
$1H_t3$	147.994	46.25	0.313	143.53
$1H_t4$	140.813	49.84	0.354	160.27
$1H_t5$	124.771	44.85	0.359	148.51
$1H_t6$	121.206	48.64	0.401	150.51
mean	132.593 ±11.16	47.54 ±2.58	0.360 ±0.028	150.44 ±5.54

mean F_v/F_t = 0.66

i) 20 mm dia HSFG bolts from batch 2c
ii) Ultimate tensile strength of bolt F_t = 229.49 kN (Table 3.2)

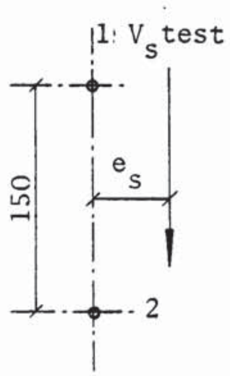
TABLE 4.7 COEFFICIENT OF FRICTION AND ULTIMATE SHEAR STRENGTH (Single HSFG bolt) whereas F_v/F_t ratio for un-stressed bolts was 0.67.

4.4.2 Two Bolt Tests Series 2_t

Seven tests were carried out as an alternative method of establishing the slip resistance of a bolted joint. The coefficient of friction μ and the ultimate strength F_v of the bolt obtained from two bolt tests was compared with single bolt test.

The test rig, specimens and method of testing were similar to unstressed bolt test described in 3.3.2.1. The faying surfaces of the test specimen were short blasted as 4.2.3. Each half of the test specimen was bolted to the main rig and the test bolts tightened to a torque of 533 Nm using a torque wrench. The extension of the bolts was measured with a C-clamp extensometer and average extension of the bolts recorded in Table 4.10. Two magnetic backed dial gauges were attached to the specimen similar to six bolts test shown in Plate 4.2. The load was applied in small increments and the dial reading recorded up to a major slip and until one of the bolts fractured. The variations in span, slip load, failure load and the bolt number which failed are given in Table A.4.11. The calculated force V_{test} and the corresponding amount of slip at both gauges is tabulated in Table A.4.12. From a typical load/slip-deformation for test No $2H_t6$, Figure A.4.13, it is evident that initially the relationship is linear until major slip occurred. At the major slip, large movement took place and the bolts slipped into bearing with the test plate. The load/deformation relationship after the slip is similar to unstressed bolted joints.

The forces on the bolts at the limit state (slip) and the ultimate limit state are shown in Tables 4.8 and 4.9 respectively.

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e_s mm	V_s test kN	Force on Bolt F_{vs} kN
	$2H_t1$	∞	6.534*	43.560
	$2H_t2$	∞	6.987*	46.582
	$2H_t3$	16143	0.333	35.826
	$2H_t4$	1352	3.992	36.030
	$2H_t5$	738	9.618	47.679
	$2H_t6$	476	16.341	52.48
	$2H_t7$	182	34.663	45.495
Mean F_{vs}				43.950±6.121

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

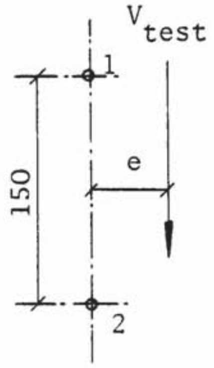
iii For loading system see Figure 3.9

iv For failure and slip loads see table A.4.11

v *Loading system produced torsion moment only

TABLE 4.8 EXPERIMENTAL RESULTS HSFG BOLTS AT SLIP

(Two HSFG bolts)

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_v kN
	$2H_t1$	∝	23.43*	156.200
	$2H_t2$	∝	24.03*	160.200
	$2H_t3$	2465	8.848	145.457
	$2H_t4$	1331	17.485	155.407
	$2H_t5$	898	26.419	158.786
	$2H_t6$	628	38.294	161.576
	$2H_t7$	298	80.382	164.694
Mean F_v				157.47 ± 6.2

Mean F_v/F_t = 0.69

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

iii For loading system see Figure 3.9

iv For failure and slip loads see Table A.4.11

v * Loading system produced torsion moment only

TABLE 4.9 EXPERIMENTAL RESULTS HSFG BOLTS AT FAILURE

(Two HSFG bolts)

Test No	Average bolt extension mm	Initial average bolt tension P_i (kN)	Force on bolt at slip F_{vs} (kN)	$\mu = F_{vs}/P_i$
$2H_t1$	0.140	127.00	43.560	0.343
$2H_t2$	0.146	132.44	46.582	0.351
$2H_t3$	0.135	122.46	35.826	0.292
$2H_t4$	0.130	117.92	36.030	0.305
$2H_t5$	0.146	132.44	47.679	0.360
$2H_t6$	0.136	123.37	52.480	0.425
$2H_t7$	0.130	117.92	45.495	0.386
Mean				0.352 ±0.045

i) 20 mm dia HSFG bolts from batch 2c
ii) Values of F_{vs} from Table 4.8

TABLE 4.10 COEFFICIENT OF FRICTION AND BOLT TENSION (Two HSFG bolts)

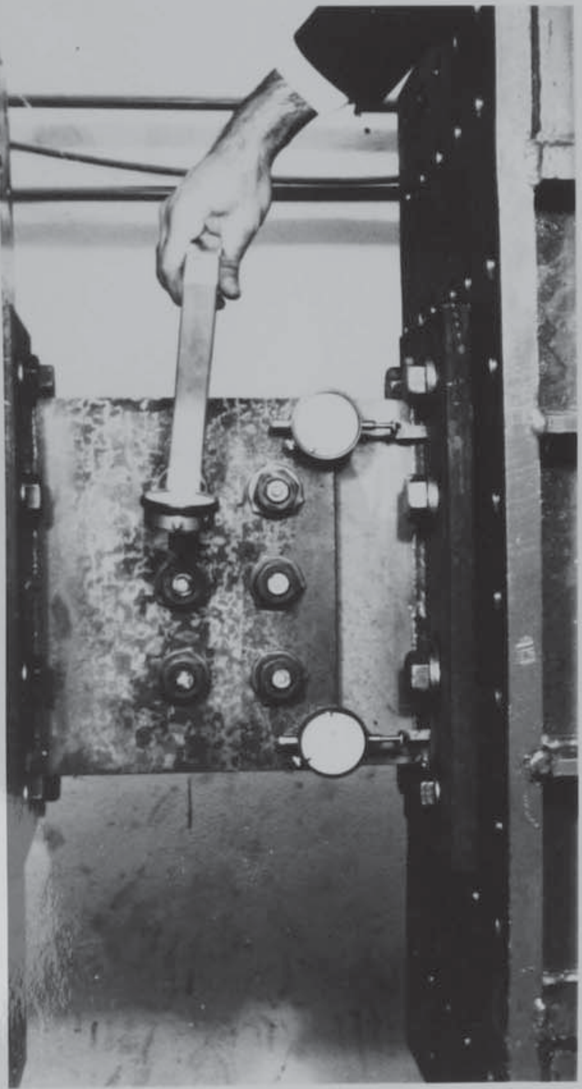
The ratio of F_v/F_t = 0.69 for these tests indicates that no detrimental shear behaviour of a connection occurred due to the initial shank tension in the bolts (28). The coefficient of friction μ (0.352) from Table 4.10 is only 2.2% lower than μ calculated for single bolt test and is acceptable.

4.4.3 Multi-Bolt Group Tests Series 3_t

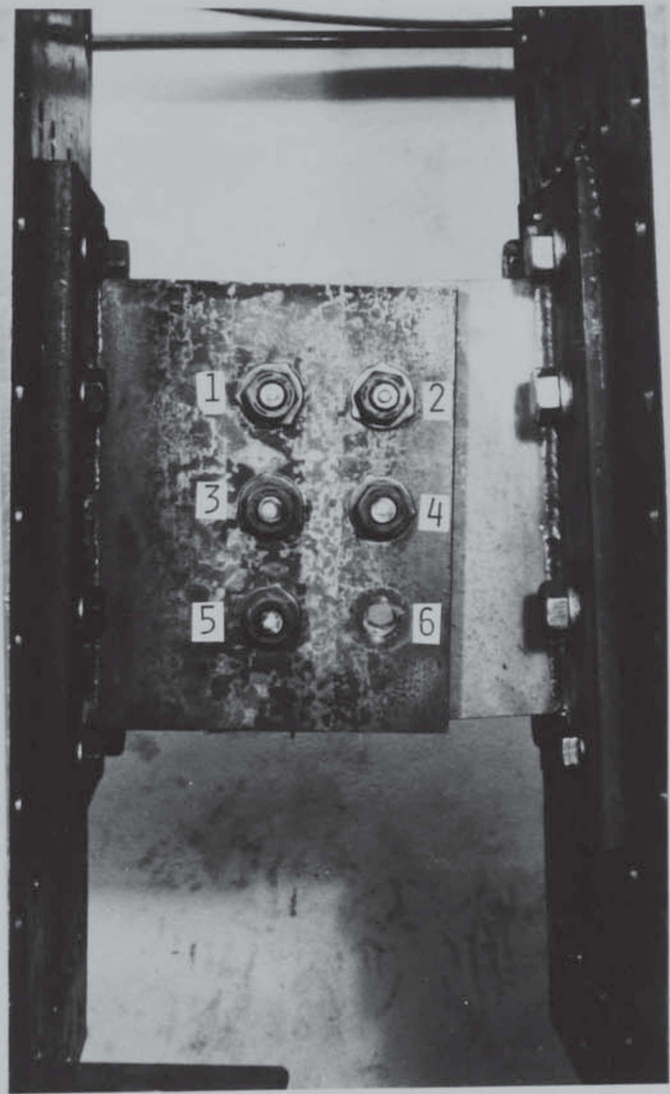
The main purpose of the tests was to check the adequacy of both rigid plate/elastic bolt and rigid plate/plastic bolt theories. The rigid plate/plastic bolt theory assumes that bolt forces are equalized at failure. For serviceability limit state (slip) failure was defined as the point at which static frictional resistance was overcome.

Control tests on a single bolt lap joint and two bolt main specimens produced a coefficient of friction (μ) of 0.36 and 0.352 respectively which indicated that the faying surface condition was reasonably consistant. A comparison between the above value and μ for the multi-bolt group will verify the theoretical assumptions.

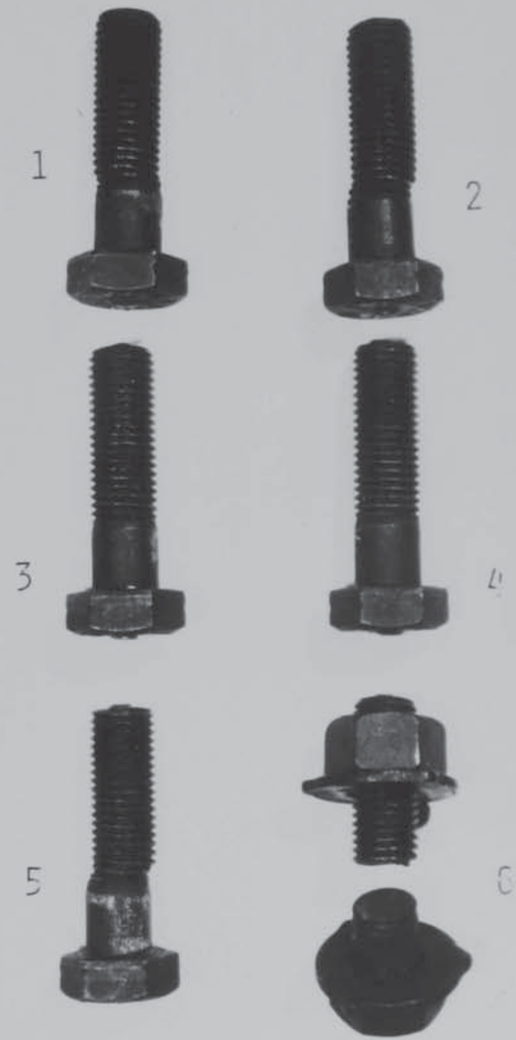
Five joints, containing four bolts and four joints with six bolts were tested in this series. Test specimens were similar to untensioned bolted specimens shown in Figure 3.12. The surface treatment, loading device, methods of testing etc was as stated in 4.4.2. Each bolt was centralized within the hole and its position marked on the plates. This procedure minimised the bearing effects before slip, although it was appreciated that such effects were inevitable in many practical applications. Plate 4.2a shows the assembled and fully instrumented specimen whereas Plate 4.2b exibits the specimen at failure of the bolt. All the bolts were carefully removed from the specimen and photographed. Plate 4.2c



4.2a



4.2b



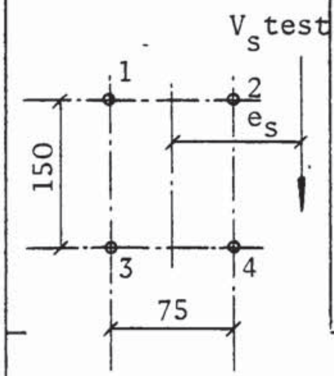
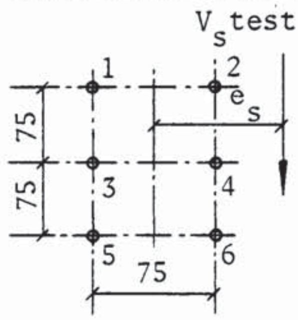
4.2c

PLATE 4.2 SIX HSFG BOLT TEST SPECIMEN

adequately clarifies the point that at ultimate limit state all the bolts do not deform by an equal amount. On the contrary it shows that the bolt furthest from the centre of rotation has suffered a large deformation compared to bolts nearer to the instantaneous centre of rotation.

The variations of loaded span, the corresponding slip loads, failure loads and the bolt number which fractured are recorded in Table A.4.14. The calculated V_{test} and the magnitude of slip at each dial gauge, for four and six bolted joints, are given in Tables A.4.15 and A.4.17 and typical V_{test} versus slip-deformation graphs are drawn in Figure A.4.16 and Figure A.4.18 respectively. In each case the slip-deformation at slip load was large compared to pre-slip deformation and the shape of the post slip graph was similar to untensioned bolts discussed in Chapter three.

The forces on the bolts, furthest from the centre of rotation, at the serviceability limit state (slip) $F_{s(max)}$ and ultimate limit state $F_{(max)}$, using rigid plate/elastic bolt theory were calculated and are shown in Table 4.11 and 4.12 respectively. The ratio of F_{max}/F_t for eight tests was 0.73, which was 5% higher than the ratio for untensioned bolts. This increase in strength maybe attributed to the residual frictional resistance at the ultimate limit state. The values of μ_E and μ_p, using elastic and fully plastic theories respectively are recorded in Table 4.13.

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e_s mm	V_s test kN	Force on Bolt $F_{s(max)}$ kN
	$4H_t1$	∝	19.596*	58.43
	$4H_t2$	1855	10.624	59.98
	$4H_t3$	1456	15.765	70.294
	$4H_t4$	925	18.839	54.218
	$4H_t5$	703	30.818	68.400
	Mean $F_{s(max)}$			62.26 ± 6.8
	$6H_t1$	1847	11.561	58.749
	$6H_t2$	1333	17.885	66.027
	$6H_t3$	919.5	28.933	74.390
	Mean $F_{s(max)}$			66.38 ± 7.8

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

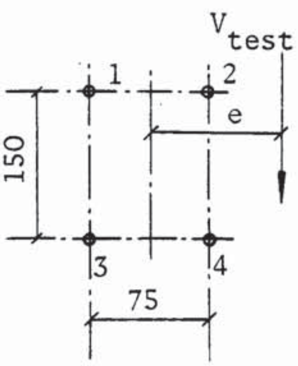
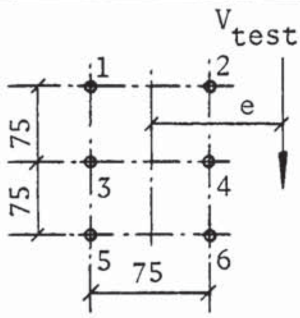
iii For loading system see Figure 3.12

iv For failure and slip loads see Table A.4.14

v * Loading system produced torsion moment only

TABLE 4.11 EXPERIMENTAL RESULTS HSFG BOLTS AT SLIP

(Four and six HSFG bolts)

Arrangement and spacing of bolts mm	Specimen label	Eccentricity e mm	V_{test} kN	Force on Bolt F_{max} kN
	$4H_t1$	∝	54.135*	161.404
	$4H_t2$	1692	31.944	164.903
	$4H_t3$	1420	39.522	172.003
	$4H_t4$	991	55.553	170.861
	$4H_t5$	769	72.719	175.493
	F_{max}			168.93 ± 5.7
	$6H_t1$	1697	33.560	156.947
	$6H_t2$	1323	44.49	162.950
	$6H_t3$	961	65.756	176.439
	F_{max}			165.44 ± 9.9

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

iii For loading system see Figure 3.12

iv For failure and slip loads see Table A.4.14

v * Load system produced torsion moment only

TABLE 4.12 EXPERIMENTAL RESULTS HSFG BOLTS AT FAILURE

(Four and Six HSFG bolts)

Test No	Average bolt extension mm	Initial Average bolt tension P_i kN	Force on bolt at slip $F_s(max)$ kN	Force on bolt at slip F_{sp} kN	$\mu_E = \frac{F_s(max)}{P_i}$	$\mu_p = \frac{F_{sp}}{P_i}$
$4H_t1$	0.139	126.09	58.43	58.43	0.463	0.463
$4H_t2$	0.139	126.09	59.98	59.15	0.475	0.469
$4H_t3$	0.146	132.44	70.294	68.93	0.530	0.520
$4H_t4$	0.141	127.91	54.218	52.71	0.423	0.412
$4H_t5$	0.142	128.81	68.400	65.54	0.531	0.508
	mean				0.484 ±0.046	0.474 ±0.042
$6H_t1$	0.140	127.00	58.739	52.31	0.462	0.412
$6H_t2$	0.160	145.14	66.027	58.28	0.454	0.401
$6H_t3$	0.158	143.33	74.390	65.23	0.519	0.455
	mean				0.478 ±0.035	0.422 ±0.028

i) 20 mm dia HSFG bolts from batch 2c
ii) $F_s(max)$ = force at bolt using elastic theory
iii) μ_E calculated for elastic theory
iv) $F_{sp(max)}$ = force at bolts using plastic theory
v) μ_p for plastic theory

TABLE 4.13 COEFFICIENT OF FRICTION AND BOLT TENSION (Four and six HSFG bolts)

CHAPTER FIVE

THEORETICAL ANALYSIS

5.1 INTRODUCTION

This chapter considers the theory associated with eccentrically loaded groups of bolts subjected to in plane shear forces, where failure is related to the bolts. These forces arise in situations such as brackets fastened to a column, beam to beam connections etc.

The analysis of the bolted joint at present is by elastic method which distributes the shear force equally between the bolts, and the torsional moment in proportion to the distance from the centroid of the group. The resultant force is the vector addition of these force.. This traditional linear load/deformation theory may be justified by the method of superposition but this approach provides no information on the position of the instantaneous centre of rotation. The theoretical proof in this chapter produces the same solution as the traditional method and defines the centre of rotation. The aim of this section is to produce an equation for use with a simple calculating machine to directly determine the size of bolt for the serviceability and ultimate limit state.

In 1966 Abolitz (35) produced a theoretical solution for the ultimate load.based on rigid plate and fully plastic behaviour of the bolts. This theory postulates that under heavy stress each fastener will exert its full resistance, irrespective of its location. This method was basically the same as applied by Koenigsberger (36) in 1951 to eccentrically loaded welded joints where the concept of instantaneous centre of rotation was applied to this type of problems. Abolitz presented his solution finally in a graphical non-dimensional form plotting shear resistance against torsional resistance. The main criticism of the plastic method is the assumption of full plasticity.

The above stated methods represent simple extremes of bolt behaviour. Crawford and Kulak (46) in 1971 considered the bolts as discrete elements and used a nonlinear load-deformation characteristic derived from double shear tests. This combined with equilibrium of forces, compatability of rotation about an instantaneous centre of rotation produced an iterative solution using the computer. The solution for design purposes was presented in a tabular form. These tables could not be applied to bolts other than A325 due to the empirical parameters used for the load deformation curve. The load-deformation graph is dependent on factors such as the type of bolts, yield strength of connecting material, location of shear plane and the type of shear mode i.e. single or double shear. Therefore for each type of bolt and connecting material a separate load-deformation relationship in single shear and double shear will be required to apply this method.

For comparison of simple elastic and fully plastic analysis, the plastic theory is expressed in the general form in this chapter. An exact theoretical solution to the plastic analysis of a four bolt group is also given.

5.2 ELASTIC ANALYSIS

This theoretical approach is based on the following five assumptions:

1 Each fastener of the bolt group carries an equal share of the direct load plus an additional load due to the couple.

2 The load due to couple is taken to be proportional to the distance of the fastener from the centre of rotation, implying that the fastener behaves elastically.

3 The connected plates remain "rigid" during rotation (i.e. their deformation is regarded as negligible compared to that of the fasteners.

4 The load on each fastener due to the couple is taken as acting perpendicular to a line joining the fastener to the centre of rotation.

5 The forces act in one plane and no prying action occurs.

Consider a given configuration of n fasteners and an external force P_a applied at an angle θ as shown in figure 5.1 such that the vertical and horizontal components of P_a are $V = P_a \sin\theta$ and $H = P_a \cos\theta$ respectively. The component V is acting at an eccentricity e to the centroid of the bolt group. The axes x-x and y-y are two convenient perpendicular axes which pass through the centroid G. It is assumed that the centre of rotation I_E is at a distance $\bar{x}_E$ and $\bar{y}_E$ from the centroid of bolt group. The nth bolt is furthest from the centre of rotation at a radius r_n and has a resistance F_{max}. In the linear-elastic stage of the bolt behaviour the shear resistance is porportional to shear deformation, and thus the force on the bolt is proportional to the distance from the centre of rotation i.e. $(r_i/r_n)\ F_{max}$.

Let F_{max} for elastic theory be equal to F_E, therefore the components of the forces on the bolts are:

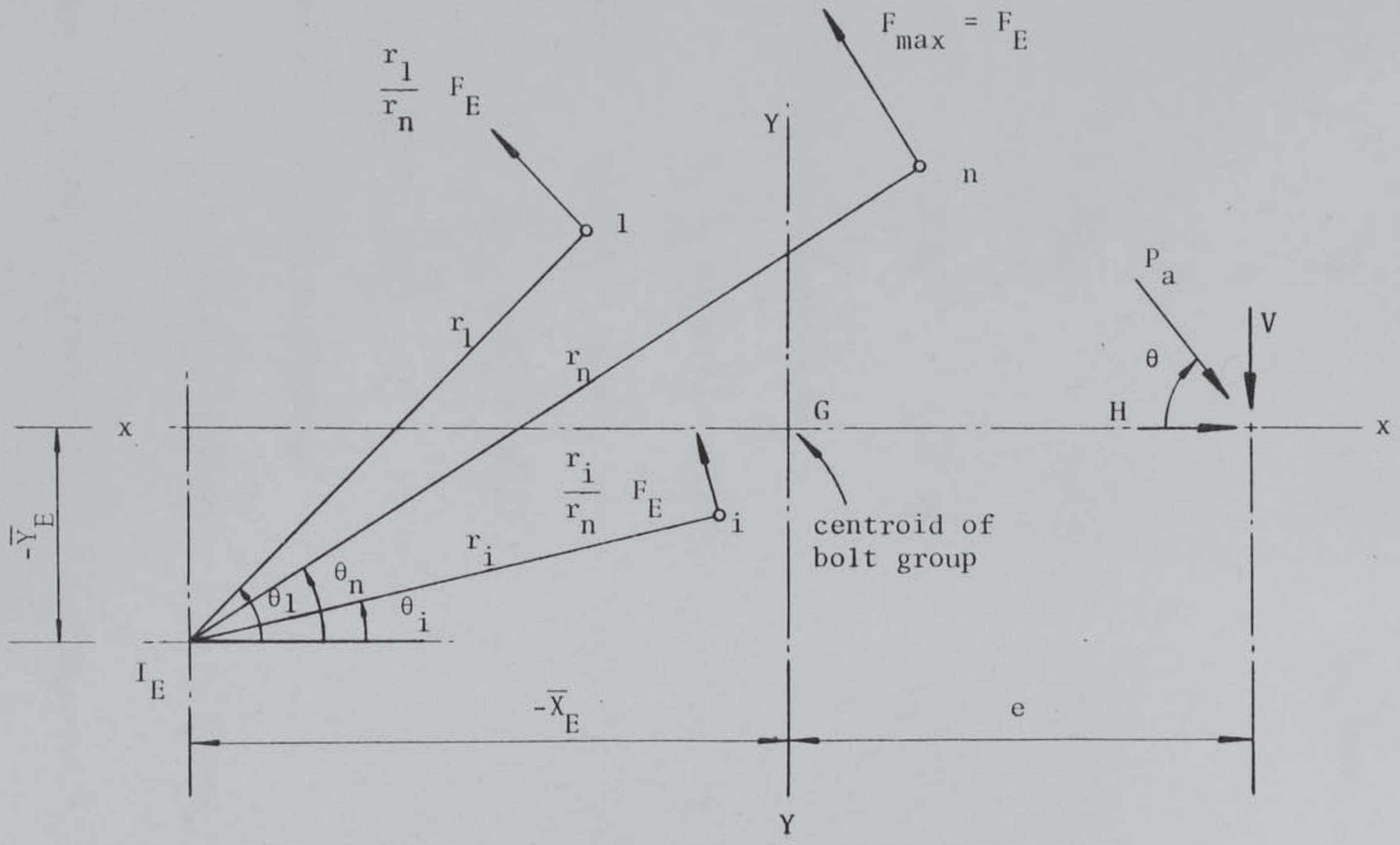


FIGURE 5.1 DIAGRAM FOR GENERAL ELASTIC THEORY

Bolt No	Distance from I_E to each bolt	Force on each bolt	Horizontal component	Vertical component
1	r_1	$F_E \frac{r_1}{r_n}$	$F_E \frac{r_1}{r_n}\sin\theta_1$	$F_E \frac{r_1}{r_n}\cos\theta_1$
2	r_2	$F_E \frac{r_2}{r_n}$	$F_E \frac{r_2}{r_n}\sin\theta_2$	$F_E \frac{r_2}{r_n}\cos\theta_2$
-	-	-	-	-
-	-	-	-	-
n-1	r_{n-1}	$F_E \frac{r_{n-1}}{r_n}$	$F_E \frac{r_{n-1}}{r_n}\sin\theta_{n-1}$	$F_E \frac{r_{n-1}}{r_n}\cos\theta_{n-1}$
n	r_n	$F_E \frac{r_n}{r_n}$	$F_E \frac{r_n}{r_n}\sin\theta_n$	$F_E \frac{r_n}{r_n}\cos\theta_n$

Resolving forces vertically

$$F_E \frac{1}{r_n} [r_1\cos\theta_1 + r_2\cos\theta_2 + \ldots\ldots\ldots + r_n \cos\theta_n] = V$$

But $\quad r_1\cos\theta_1 + r_2\cos\theta_2 + \ldots\ldots + r_n\cos\theta_n = -n.\overline{X}_E$

i.e. $\quad \sum_{i=1}^{n} r_i \cos\theta_i = -n\overline{X}_E$

$$\therefore \quad \overline{X}_E = - \frac{V\, r_n}{n\, F_E} \qquad (5.2.1)$$

Resolving forces horizontally

$$F_E \cdot \frac{1}{r_n} [r_1 \sin\theta_1 + r_2\sin\theta_2 + \ldots\ldots + r_n\sin\theta_n] = H$$

But $\quad r_1\sin\theta_1 + r_2\sin\theta_2 + \ldots\ldots + r_n\sin\theta_n = -n\, \overline{Y}_E$

i.e. $\quad \sum_{i=1}^{n} r_i\sin\theta_i = -n\overline{Y}_E$

$$\therefore \quad \overline{Y}_E = - \frac{H}{n} \cdot \frac{r_n}{F_E} \qquad (5.2.2)$$

Taking moments of forces about the instantaneous centre of rotation I_E.

$$V(e-\overline{X}_E) - H\,\overline{Y}_E = F_E \frac{r_1^2}{r_n} + F_E \frac{r_2^2}{r_n} + \ldots\ldots\ldots + F_E \frac{r_n^2}{r_n}$$

$$= F_E \cdot \frac{1}{r_n} (r_1^2 + r_2^2 + \ldots\ldots\ldots + r_n^2)$$

$$= F_E \frac{1}{r_n} \sum_{i=1}^{n} r_i^2 \qquad (5.2.3)$$

where

$$\sum_{i=1}^{n} r_i^2 = \sum_{i=1}^{n} [(-\overline{X}_E + x_i)^2 + (-\overline{Y}_E + y_i)^2] = n[\overline{X}_E^2 + \overline{Y}_E^2 + r_{OE}^2]$$

$$r_{OE}^2 = \sum_{i=1}^{n} (x_i^2 + y_i^2)/n$$

Therefore from (5.2.3)

$$Ve - V\overline{X}_E - H\overline{Y}_E = F_E \frac{n}{r_n} [\overline{X}_E^2 + \overline{Y}_E^2 + r_{OE}^2] \qquad (5.2.4)$$

Substituting values from equations (5.2.1) and (5.2.2) for V/F_E and H/F_E in equation (5.2.4).

$$-\frac{n\overline{X}_E e}{r_n} + \frac{n\overline{X}_E^2}{r_n} + \frac{n\overline{Y}_E^2}{r_n} = \frac{n\overline{X}_E^2}{r_n} + \frac{n\overline{Y}_E^2}{r_n} + \frac{n r_{OE}^2}{r_n}$$

$$\therefore \quad \overline{X}_E = -\frac{r_{OE}^2}{e} \qquad (5.2.5)$$

i.e. $\overline{X}_E = -\sum_{i=1}^{n} (x_i^2 + y_i^2)/ne$

Dividing equation (5.2.2) by (5.2.1)

$$\frac{\overline{Y}_E}{\overline{X}_E} = \frac{H}{V}$$

$$\therefore \quad \overline{Y}_E = -\frac{H}{V} \cdot \frac{r_{OE}^2}{e} \qquad (5.2.6)$$

i.e. $\overline{Y}_E = -\left(\frac{H}{V}\right) \cdot \sum_{i=1}^{n} (x_i^2 + y_i^2)/n\,e$

Substituting values of $\overline{X}_E$ and $\overline{Y}_E$ from equation (5.2.5) and (5.2.6) respectively in equation (5.2.4).

$$Ve + V\frac{r_{OE}^2}{e} + \frac{H^2}{V} \cdot \frac{r_{OE}^2}{e} = \frac{n\,F_E}{r_n}\left(\frac{r_{OE}^4}{e} + \frac{H^2}{V^2}\frac{r_{OE}^4}{e^2} + r_{OE}^2\right)$$

$$Ve\left(1 + \frac{r_{OE}^2}{e^2} + \frac{H^2}{V^2} \cdot \frac{r_{OE}^2}{e^2}\right) = \frac{n\,F_E\,r_{OE}^2}{r_n}\left(\frac{r_{OE}^2}{e^2} + \frac{H^2}{V^2} \cdot \frac{r_{OE}^2}{e^2} + 1\right)$$

$$\therefore \quad F_E = \frac{V}{n} \times \frac{e}{r_{OE}^2} \cdot r_n \tag{5.2.7}$$

but $r_n = [(-\overline{X}_E + x_n)^2 + (-\overline{Y}_E + y_n)^2]^{\frac{1}{2}}$

$$= (\overline{X}_E^2 + x_n^2 - 2\overline{X}_E \cdot x_n + \overline{Y}_E^2 + y_n^2 - 2\overline{Y}_E\,y_n)^{\frac{1}{2}}$$

Substituting values of $\overline{X}_E$ and $\overline{Y}_E$

$$r_n = \left[\frac{r_{OE}^4}{e^2} + x_n^2 + 2 \cdot x_n\frac{r_{OE}^2}{e} + \frac{H^2}{V^2} \cdot \frac{r_{OE}^4}{e^2} + y_n^2 + 2y_n\frac{r_{OE}^2}{e}\frac{H}{V}\right]^{\frac{1}{2}}$$

$$= \frac{r_{OE}^2}{e}\left[1 + \frac{e^2x_n^2}{r_{OE}^4} + \frac{2ex_n}{r_{OE}^2} + \frac{H^2}{V^2} + \frac{e^2y_n^2}{r_{OE}^4} + \frac{2ey_n}{r_{OE}^2} \cdot \frac{H}{V}\right]^{\frac{1}{2}}$$

$$= \frac{r_{OE}^2}{e}\left[\left(1 + \frac{ex_n}{r_{OE}^2}\right)^2 + \left(\frac{H}{V} + \frac{ey_n}{r_{OE}^2}\right)^2\right]^{\frac{1}{2}} \tag{5.2.8}$$

Substituting value of r_n from equation (5.2.8) in equation (5.2.7)

$$F_E = \frac{V}{n}\left[\left(1 + \frac{ex_n}{r_{OE}^2}\right)^2 + \left(\frac{H}{V} + \frac{ey_n}{r_{OE}^2}\right)^2\right]^{\frac{1}{2}}$$

Therefore the maximum shear force on a bolt

$$F_{max} = \frac{V}{n} [\{1 + \frac{n\,e\,x_n}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}\}^2 + \{\frac{H}{V} + \frac{n\,e\,y_n}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}\}^2]^{\frac{1}{2}} \qquad (5.2.9)$$

V and H are positive in the direction shown in figure 5.1. The values of x_i and y_i are determined by the standard cartisian convension with the origin at the centroid of a bolt group.

For the case of pure torsion

$$F_{max} = M_T \frac{\sqrt{x_n^2 + y_n^2}}{\sum_{i=1}^{n} (x_i^2 + y_i^2)} \qquad (5.2.10)$$

Equations (5.2.9) and (5.2.10) may be modified for design purposes in the following form:-

$$F_D = \gamma_E \frac{V}{n} [\{1 + \frac{n\,e\,x_n}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}\}^2 + \{\frac{H}{V} + \frac{n\,e\,y_n}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}\}^2]^{\frac{1}{2}} \qquad (5.2.9a)$$

and

$$F_D = \gamma_E M_T \frac{\sqrt{x_n^2 + y_n^2}}{\sum_{i=1}^{n} (x_i^2 + y_i^2)} \qquad (5.2.10a)$$

where γ_E is the partial safety factor for an applied load and F_D is the design force in a bolt. A suitable bolt may be selected from allowable load tables related to single shear and bearing values.

5.3 PLASTIC ANALYSIS

In rigid plate/plastic bolt behaviour, the following assumptions are considered in establishing a theoretical model:-

1 Each fastener of the bolt group exerts its full resistance, irrespective of its location.

2 The connected plates remain "rigid" during rotation (i.e. their deformation is regarded as negligible compared to that of the fasteners.

3 The load on each fastener is taken as acting perpendicular to a line joining the fastener to the centre of rotation.

4 The forces act in one plane and no prying action occurs.

Figure 5.2 shows an eccentrically loaded bolt group defined with respect to cartesian axes x and y passing through I_p, the instantaneous centre of rotation. As the connecting plates are assumed to be rigid, all bolt displacements must be compatible with rigid body movement, it is assumed that all deformation are in the plastic range, therefore the resistance of each bolt is the same. This is not true for a bolt close to the centre of rotation.

Let F_p be the maximum shear force acting on a bolt in a bolt group at failure. Resolving forces vertically

$$V = F_p \sum_{i=1}^{n} \cos \theta_i \tag{5.3.1}$$

Resolving horizontally

$$H = F_p \sum_{i=1}^{n} \sin \theta_i \tag{5.3.2}$$

Taking moments about I_p

$$V (\overline{X} + e) + H \overline{Y} = F_p \sum_{i=1}^{n} r_i \tag{5.3.3}$$

Substituting the value of V and H from equations (5.3.1) and (5.3.2) in (5.3.3)

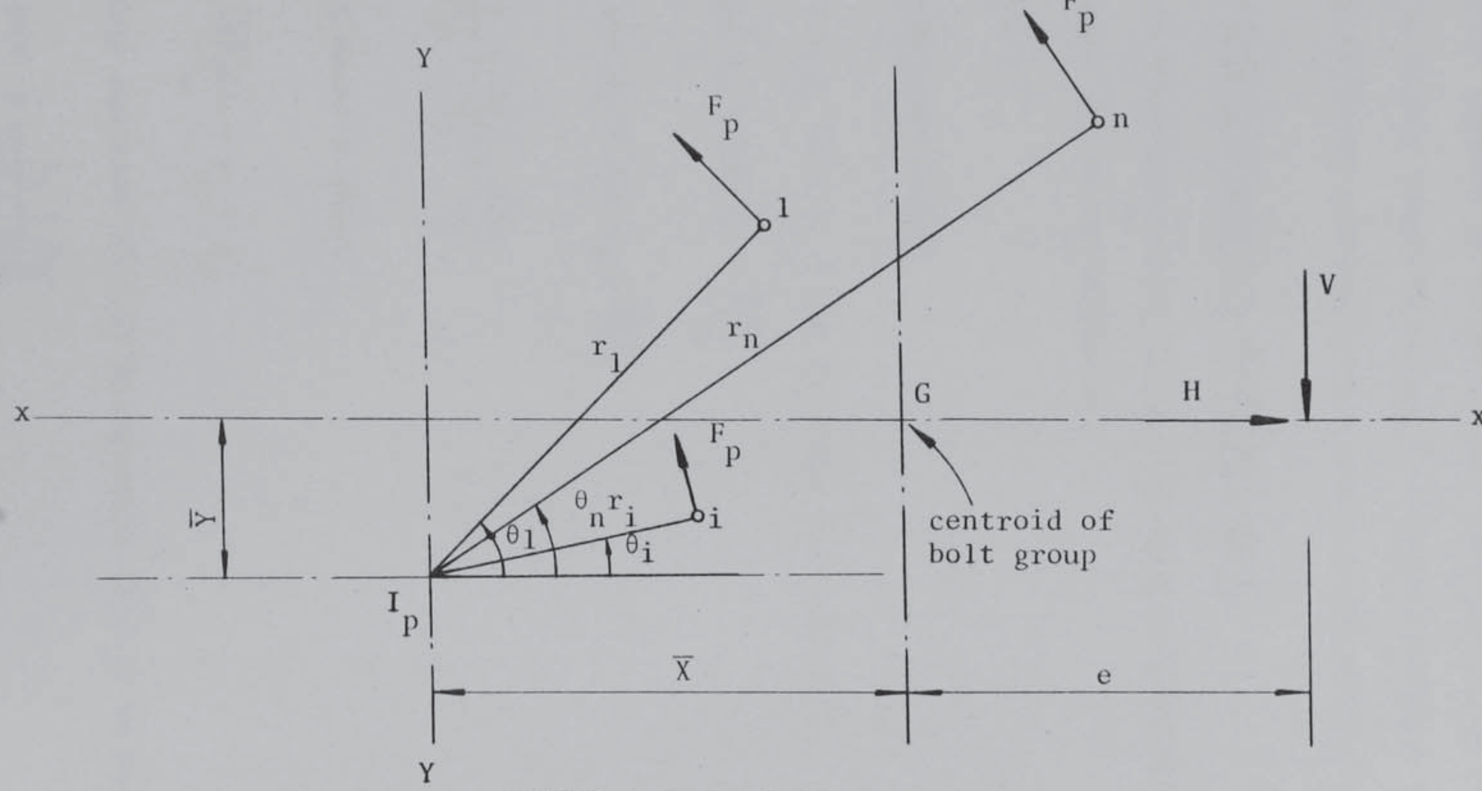


FIGURE 5.2 DIAGRAM FOR GENERAL PLASTIC THEORY

$$(\overline{X} + e) \sum_{i=1}^{n} \cos \theta_i + \overline{Y} \sum_{i=1}^{n} \sin \theta_i = \sum_{i=1}^{n} r_i \qquad (5.3.4)$$

Equation (5.3.4) shows that the location of the instantaneous centre of rotation I_p is independent of the applied force, but is a function of eccentricity e and bolts configuration. These equations appears to be simple but their solution in the general form is highly complicated and is of the iterative nature. Therefore a desk top computer can be used to solve this problem.

5.4 PLASTIC ANALYSIS OF FOUR BOLT GROUP

An analytical solution to a special case of four bolts shown in figure 5.3 is as follows:-

Let $\overline{X} = X$

Resolving vertically

$$V = F_p (\cos \theta_1 + \cos \theta_2 + \cos \theta_3 + \cos \theta_4)$$

but $\cos \theta_1 = \cos \theta_3 = \frac{X-b}{r_1}$

$$\cos \theta_2 = \cos \theta_4 = \frac{X+b}{r_2}$$

$$\therefore \quad \frac{V}{2F_p} = \frac{X-b}{r_1} + \frac{X+b}{r_2} \qquad (5.4.1)$$

taking moments about I_p

$$\frac{V(e+X)}{2F_p} = r_1 + r_2 \qquad (5.4.2)$$

Dividing equation (5.4.2) by equation (5.4.1) we have

$$(e+X) = \frac{r_1 + r_2}{\frac{X-b}{r_1} + \frac{X+b}{r_2}}$$

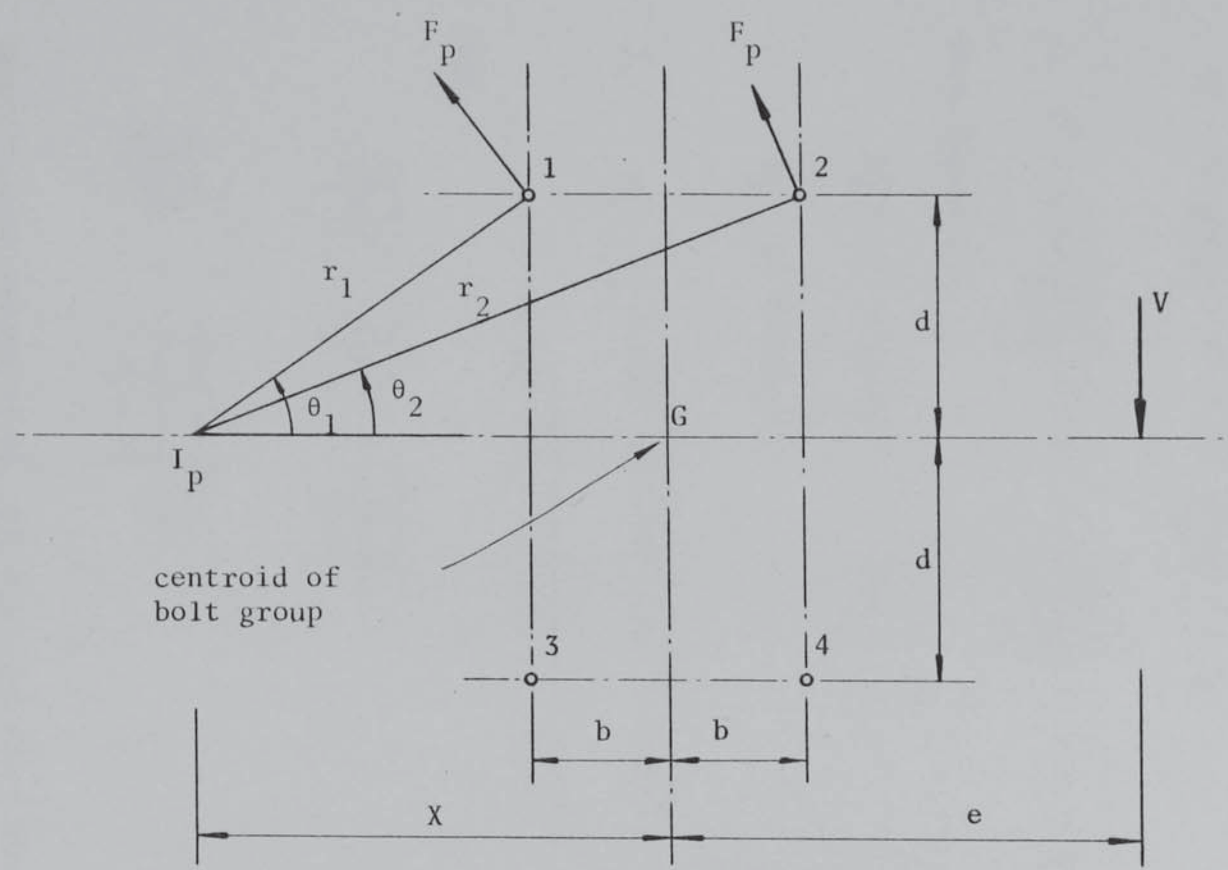


FIGURE 5.3 DIAGRAM FOR FOUR BOLT PLASTIC THEORY

$$(e + X) = \frac{(r_1 + r_2)\, r_1 r_2}{r_2\,(X-b) + r_1\,(X+b)} = \frac{(r_1+r_2)\, r_1 r_2}{X\,(r_2+r_1) - b\,(r_2-r_1)}$$

$$\therefore\; eX(r_2+r_1) - eb(r_2-r_1) + X^2\,(r_2+r_1) - Xb(r_2-r_1) = (r_1+r_2)\, r_1 r_2$$

Dividing both sides by $(r_1 + r_2)$ we have

$$eX - eb\,\frac{r_2-r_1}{r_2+r_1} + X^2 - Xb\,\frac{r_2-r_1}{r_2+r_1} = r_1 r_2$$

$$\therefore\; X^2 + X\,\{\frac{-b(r_2-r_1)}{r_1+r_2} + e\} - be\,\frac{r_2-r_1}{r_1+r_2} - r_1 r_2 = 0 \qquad (5.4.3)$$

From figure 5.3

$$r_1^2 = d^2 + (X-b)^2 \qquad \text{and}$$

$$r_2^2 = d^2 + (X+b)^2$$

$$\therefore\; r_1 \cdot r_2 = \sqrt{\{d^2 + (X-b)^2\} \times \{d^2 + (X+b)^2\}}$$

$$= \sqrt{d^4 + 2d^2\,(X^2+b^2) + (X^2-b^2)^2} \qquad (5.4.4)$$

but

$$\frac{r_2-r_1}{r_2+r_1}\;\frac{r_2-r_1}{r_2-r_1} = \frac{(r_2-r_1)^2}{r_2^2-r_1^2}$$

$$\therefore\; \frac{r_2-r_1}{r_2+r_1} = \frac{r_2^2+r_1^2 - 2r_1 r_2}{r_2^2 - r_1^2} \qquad (5.4.5)$$

Substituting values of r_1^2, r_2^2, $r_1 r_2$ and $r_2^2-r_1^2$ from above in equation (5.4.5).

$$\frac{r_2-r_1}{r_2+r_1} = \frac{d^2+X^2+b^2- 2Xb+d^2+X^2+b^2+2Xb - 2\sqrt{d^4+2d^2(X^2+b^2)+(X^2-b^2)^2}}{d^2 + X^2 + b^2 + 2Xb - d^2 - X^2 - b^2 + 2Xb}$$

$$= \frac{d^2 + X^2 + b^2 - \sqrt{d^4 + 2d^2 (X^2 + b^2) + (X^2 - b^2)^2}}{2 X b} \qquad (5.4.6)$$

Now substituting values of $r_1 r_2$ and $\frac{r_2 - r_1}{r_2 + r_1}$ from equation (5.4.4) and (5.4.6) in equation (5.4.3).

$$X^2 + X \left[-b \left\{\frac{d^2 + X^2 + b^2 - \sqrt{d^4 + 2d^2 (X^2 + b^2) + (X^2-b^2)^2}}{2 X b}\right\} + e\right]$$

$$- \frac{b\ e\ [d^2 + X^2 + b^2 - \sqrt{d^4 + 2d^2 (X^2 + b^2) + (X^2-b^2)^2}]}{2 X b}$$

$$- \sqrt{d^4 + 2d^2 (X^2+b^2) + (X^2-b^2)^2} = 0 \qquad (5.4.7)$$

Let $\sqrt{d^4 + 2d^2 (X^2+b^2) + (X^2-b^2)^2} = K$

∴ Simplifying (5.4.7)

$$X^2 + ex - d^2 (1 + \frac{e}{X}) - b^2 (1 + \frac{e}{x}) = K (1 - \frac{e}{X})$$

Squaring both sides and substituting value of K. We have:-

$$X^4 [1 - (1 - \frac{e}{X})^2] + X^3 (2e) + X^2 [e^2 - 2d^2 (1 + \frac{e}{X}) - 2b^2 (1 + \frac{e}{X})$$

$$- 2d^2 (1 - \frac{e}{X})^2 + 2b^2 (1 - \frac{e}{X})^2] -$$

$$X[2 e d^2 (1 + \frac{e}{X}) + 2 e b^2(1 + \frac{e}{X})] +$$

$$d^4 (1 + \frac{e}{X})^2 + b^4 (1 + \frac{e}{X})^2 + 2 b^2 d^2 (1 + \frac{e}{X})^2 -$$

$$d^4 (1 - \frac{e}{X})^2 - 2 d^2 b^2 (1 - \frac{e}{X})^2 - b^4 (1 - \frac{e}{X})^2 - \qquad (5.4.8)$$

Simplifying further

$$4\ e\ X^4 - 4\ d^2\ X^3 - 8\ eb^2\ X^2 - 4\ e^2d^2\ X + 4\ ed^4 + 4\ eb^4 + 8eb^2d^2 = 0$$

$$\therefore\quad X^4 - \frac{X^3}{e}d^2 - 2\ X^2b^2 - X\ ed^2 + d^4 + b^4 + 2\ b^2d^2 = 0$$

Now let $b = \frac{B}{2}$ and $d = \frac{D}{2}$

$$\therefore\quad X^4 - \frac{X^3}{e}\left(\frac{D}{2}\right)^2 - 2\left(\frac{B}{2}\right)^2 X^2 - \left(\frac{D}{2}\right)^2 eX + \left[\left(\frac{D}{2}\right)^2 + \left(\frac{B}{2}\right)^2\right]^2 = 0 \qquad (5.4.9)$$

The values of X can be calculated using the method outlined in appendix A.5.1.

CHAPTER SIX

DISCUSSIONS AND CONCLUSIONS

6.1 INTRODUCTION

Bolted connections subject to in-plane forces in single shear have been divided for the purpose of this investigation into two separate categories i.e. un-tensioned bolted joints and tensioned bolted joints. This distinction will be maintained throughout this chapter in order to compare test results reported by other authors and to judge the accuracy of available theories.

6.2 UN-TENSIONED BOLTED JOINTS

It has been stated in Chapter three that the behaviour of such joints may be considered at the ultimate limit state 'failure of a bolt'. The factors affecting the strength are therefore the load-deformation relationship of the bolt in single shear and the relationship of deformation and bearing stress on the bolt and plate. It is evident from the literature review that the experimental result of eccentrically loaded joints subject to shear forces are scarce. Only 28 experimental results, for rivets and bolts in double shear, are available for comparison.

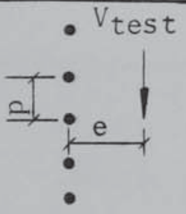
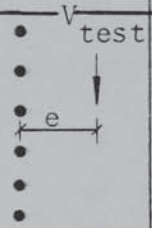
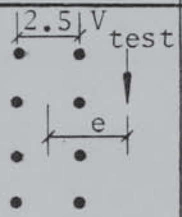
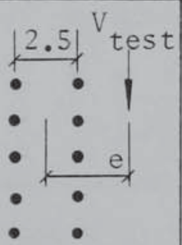
In 1971 Crawford and Kulak (46) produced eight results of eccentrically loaded bolted joints in double shear. The test bolts in all specimens were 3/4" diameter A 325 bolts and the holes were 3/4" diameter match drilled. Although these bolts were tightened to a snug position and an additional one-half turn of the nut in accordance with the standard installation proceedure, yet it has been shown (29) that the initial induced shank tension does not affect the load carrying capacity of a joint at the ultimate limit state of failure.

It is also recognised that the shear capacity of a fastener is not directly proportional to the number of shear planes (37). The results of eight tests are listed in Table 6.1 for comparison. The values of F_{max} for each result and the mean values have been calculated using equation 5.2.9 where v is equal to the test load. The mean value of F_{max} = 78.5 kips may be divided by F_v = 74 kips from single bolt tests to produce a value of F_{max}/F_v = 1.06. This is greater than one and indicates that the linear load deformation theory is conservative.

In 1953 Francis (7) gave details of 10 eccentrically loaded aluminium rivetted joints in double shear, whereas Yarimci and Slutter (18) published a further 10 results on steel rivetted joints subject to in-plane forces in double shear. Despite the fact that the load deformation graph of rivets vary considerably from that of the bolts (29), it may be considered that they behave in a similar manner to unstressed bolts. Experimental results by Francis (7) are given in Table 6.2 and by Yarimci and Slutter (18) are shown in Table 6.3. The same procedure as for bolts has been followed and produced values of F_{max}/F_v = 1.23 for steel rivets and 1.15 for aluminium rivets for the results by Francis, and 1.12 for the results by Yarimci and Slutter.

6.2.1 Discussion

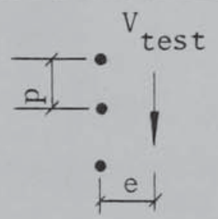
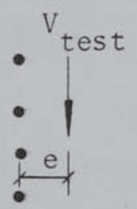
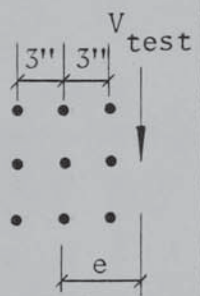
The average values of F_v/F_t for single and two bolt tests from Tables 3.12 and 3.16 respectively are in reasonable agreement at approximately 0.69. This result agrees with a few results obtained by Chesson et al (30). The average value of F_v/F_t is greater for the large diameter bolts than for the small diameter bolts. This may be because the large size bolts failed on the first thread close

Arrangement of bolts	Specimen label	Pitch P in	Eccentricity e in	V_{test} kips	Force on bolt (equn. 5.2.9) F_{max} kips
	B1	2.5	8	225	75.4
	B2	3.0	10	230	80.0
	B3	3.0	12	190	78.3
	B4	3.0	13	251	80.5
	B5	3.0	15	221	81.1
	B6	3.0	12	264	78.2
	B7	3.0	15	212	77.1
	B8	2.5	15	266	77.4
Mean F_{max}					78.5 ± 1.9

1 3/4 in diameter A325 bolts
2 Tensile strength 40.2 kips
3 3/4 in diameter of holes
4 Bolts bearing on two 1/2 inch and one 3/4 inch thick plates
5 Double shear strength of single bolt 74 kips

TABLE 6.1 EXPERIMENTAL RESULTS BY CRAWFORD AND KULAK (46)

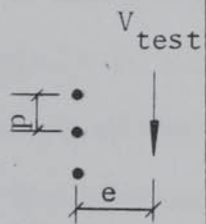
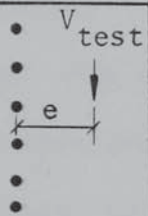
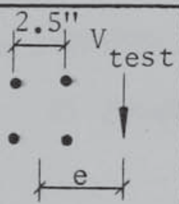
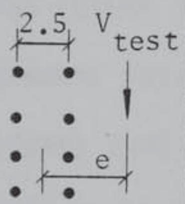
(Bolts in double shear)

Arrangement of rivets	Specimen label	Pitch P in	Eccentricity e in	V_{test} kips	Force on rivet (equn 5.2.9) F_{max} kips
	3A3 3A6 3S1½	3 3 3	2.10 4.51 0.47	30.91 17.70 85.12	14.94 14.54 29.16
	4A1½ 4A3	3 3	0.88 1.38	51.52 49.28	13.66 14.07
	9A1½ 9A3 9A6 9S1½ 9S3	3 3 3 3 3	1.37 2.81 5.58 1.08 2.40	101.36 79.52 53.76 199.36 120.06	15.61 16.27 16.56 28.77 31.35
Mean F_{max} steel rivets					29.76 ± 1.14
Mean F_{max} aluminium rivets					15.09 ± 1.02

1 1/2 in diameter steel and aluminium rivets
2 Double shear strength steel(s) 24.19 kips
3 Double shear strength aluminium 13.15 kips
4 Rivets bearing on 3/4 in thick aluminium plates

TABLE 6.2 EXPERIMENTAL RESULTS BY FRANCIS (7)

(Rivets in double shear)

Arrangement of rivets	Specimen label	Pitch P in	Eccentricity e in	V_{test} kips	Force on rivet (equn. 5.2.9) F_{max} Kips
	TP1 TP2 TP3	3 3 3	2.5 3.5 6.5	217 161 100	57.9 54.1 56.7
	TP4 TP5 TP6	3 3 3	2.5 4.5 6.5	550 440 362	56.3 59.7 63.6
	TP7 TP8	3 3	3.5 6.5	222 120	70.8 60.6
	TP9 TP10	3 3	3.5 6.5	568 354	72.6 62.1
Mean F_{max}					61.4±5.8

1 3/4 in diameter steel rivets
2 Double shear strength 55 kips
3 Rivets bearing an 7/16 in and 1/2 in plates

TABLE 6.3 EXPERIMENTAL RESULTS BY YARIMCI AND SLUTTER (18)

(Rivets in double shear)

to the shank where the area of steel available is slightly higher than that at the fully threaded portion, whereas the small diameter bolts were threaded for the whole length.

The average value of F_{max}/F_t for multibolt group from Table 3.20 is 0.71 and if this is divided by the mean value of F_v/F_t = 0.69, the result is 1.04. Therefore the linear load deformation theory may be described as approximately 4% conservative. The reason is that the load-deformation relationship is slightly non-linear at the ultimate limit state. However, a 4% error is not considered to be excessive. The comparable figure for the experimental results by Crawford and Kulak (46) is 1.06, and therefore approximately 6% conservative; the load-deformation curve is therefore more non-linear, probably because of the higher bearing stresses on the plates. It should be remembered that these tests were in double shear.

For rivets in double shear comparable figures are 1.17 from experimental results by Francis (7) and 1.12 for results by Yarimci and Slutter (18). The linear load-deformation theory may therefore be judged to be 17% and 12% conservative. The higher values for rivets are because the load-deformation relationship is more non-linear than it is for bolts. Many previous investigators have used the arguement that the linear load-deformation theory is excessively conservative, and that plastic or elastic-plastic methods should be developed. The experiment results on bolts in single shear in this study do not confirm this. The linear load-deformation theory has the advantage of simplicity; rigid plate/plastic bolt and non-linear load-deformation methods are iterative and time consuming, or require the extensive use of tables.

The characteristic plate bearing stress specified for grade 43 steel in the draft code for steel (56) is 400 N/mm^2. This is approximately the value attained in the tests on high strength bolts for a 20 mm thick plate. The specified shear stress of a bolt is 0.36 times the ultimate tensile stress. The results of these two restraints is that the load-deformation relationship is likely to be almost linear, and the linear load-deformation theory will therefore be a satisfactory method of analysis at the ultimate limit state 'failure of a bolt'.

In general in this thesis the linear load-deformation relationship has been applied to theoretical calculations. However, a rigid plate/plastic bolt theory shown in Chapter five is compared with a linear load-deformation theory and experimental results in Figure 6.1 for the four black bolt group. The differences between the position of the centre of rotation and the values of v are not excessive. The values of v for the two methods will agree only when the eccentricity is infinite.

6.2.2 Conclusions

The following conclusions are based on the analysis of available experimental results of untensioned bolted joints subject to torsion and shear at ultimate load where the bolts are in single shear.

1 The load-deformation relationship for a single bolt is dependent on the shear deformation of the bolt, the bending of the bolt and, in particular, the plate bearing stresses.

2 The ultimate shear strength of a single bolt is independent of the plate thickness.

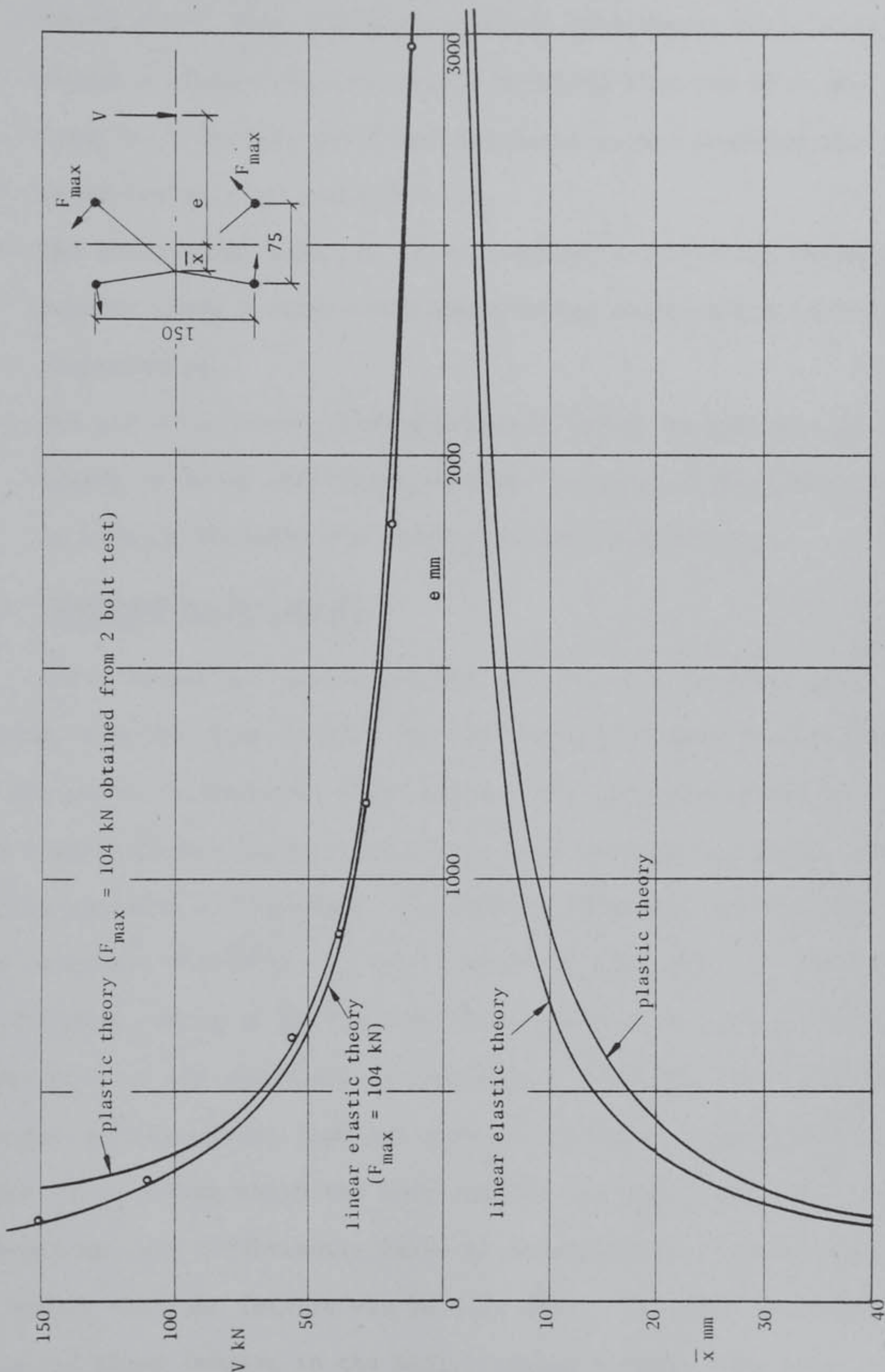


FIGURE 6.1 COMPARISON OF ELASTIC AND PLASTIC THEORIES FOR A FOUR BLACK BOLT GROUP

3 The total deformation of a bolt at ultimate load is directly related to the bearing and shearing stresses.

4 The ultimate shear strength obtained from single bolt tests is directly comparable with values obtained from two bolt tests.

5 Group bolt failure loads are dependent on the load-deformation characteristic of a single bolt.

6 The theoretical analysis of all available bolted experimental results using a linear load-deformation relationship is slightly conservative.

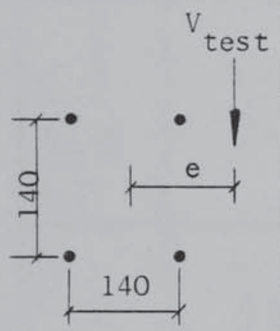
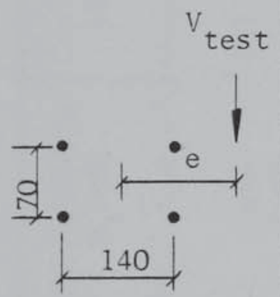
7 The use of a linear load-deformation theory in practice is likely to be of sufficient accuracy because of the limits placed on bearing stresses and shear stresses in the bolt.

6.3 TENSIONED BOLTED JOINTS

For a 'non-slip' connection the failure of a friction grip bolted joint has been defined for the purpose of this investigation as the point at which the joint slips. The joint continues to carry the load without slip until the frictional resistance between the faying surfaces is overcome. The factors affecting the strength of the joint are therefore the bolt tension at slip and the coefficient of friction, which is governed by the condition of faying surfaces. Therefore, it was necessary to determine the coefficient of friction for the surface finish used and this was obtained experimentally by joint tests during which the bolt tension was monitored. The joint dimensions were sufficiently large to maintain low plate stresses and to ensure that the failure was by slip only. In order to induce the required shank tension in the bolt, various methods were investigated and it was found that torque control and direct measurement of bolt extension methods produced a small percentage coefficient of variation and compared favourably with strain gauge readings.

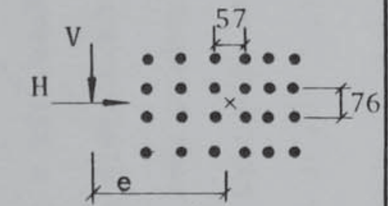
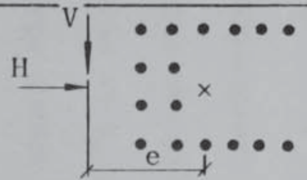
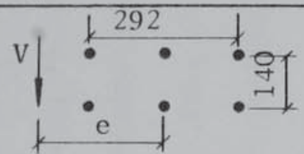
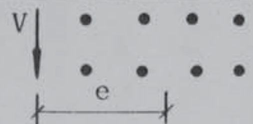
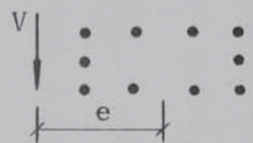
Experimental results of eccentrically loaded joints subject to in-plane shear forces in single shear, where slip of the joint was considered as failure, are rare. In 1976 Purkiss (53) reported 11 results of eccentrically loaded joints in single shear. High strength friction grip bolts, 20 mm diameter, were used twice before discarding and the faying surfaces of test plates were blast cleaned after each use. Bolts were tightened until the gap in the load indicating washer were reduced to 0.015" and it was assumed that a minimum shank tension of 144 kN was induced in each bolt. The results of these tests have been recorded in Table 6.4 for comparison. The value of maximum force $F_{s(max)}$ at slip was calculated using equation 5.2.9, where v_s is equal to the applied load to the joint at the limit state of slip. The writer is aware of the fact that the induced shank tension in the bolt employing 'coronet' load indicating method can vary considerably. It has been shown (48) that for 7/8", A325 bolts, an induced bolt tension varied between 37 kips and 46 kips for a specified gap of 0.015". However in the absence of exact shank tension value for each test, a value of 144 kN has been adopted. The mean value of μ from Table 6.4 is 0.68 with 2.9% coefficient of variation. This is greater than μ value for a single bolt test. This indicates that the mean induced shank tension was higher and of the order of 166 kN, which is well within the variation reported (48).

A series of nine tests were published by Surtees and Pape (54) in 1979, on eccentrically loaded friction grip bolted joints, where bolts were in single shear. The failure was defined at the point at which the static frictional resistance was overcome. The results of nine tests are shown in Table 6.5 and the vlaue of $F_{s(max)}$ was

Arrangement of bolts	Specimen label	Eccentricity e_s mm	$V_{s\,test}$ kN	$F_{s\,(max)}$ kN	μ
	T19	50	276	97	0.67
		100	210	98	0.68
		150	182	106	0.73
		200	133	94	0.65
		250	120	100	0.69
		300	95	91	0.63
	T19	50	246	98	0.68
		100	182	101	0.70
		150	142	101	0.70
		200	116	101	0.70
		250	93	96	0.66
Mean μ					0.68 ±.02

1 Blast cleaned faying surface
2 20 mm dia HSFG bolts
2 Minimum shank tension 144 kN
4 μ for single bolt test 0.587
5 L.I. washers used to specified gap 0.015 in

TABLE 6.4 EXPERIMENTAL RESULTS BY PURKISS (53)
(Bolts in single shear major slip)

Arrangement and spacing of bolts mm	Specimen label	Bolt dia. / Plate thickness mm	Eccentricity e_s mm	V_s test kN	H_s test kN	Force on bolt $F_{s(max)}$ kN	P_i kN	μ
	E1 E3 E5	22/12 22/12 22/12	255 1546 1546	668.5 116.3 100.2	333.3 58.0 50.0	108.26 87.18 75.11	160.0 146.6 126.6	0.67 0.59 0.59
	E2 E4 E6	22/12 22/12 22/12	227 1518 1518	641.7 100.2 114.5	319.9 50.0 57.1	117.28 83.85 95.82	162.0 144.4 148.9	0.72 0.58 0.64
	E7	16/10	203	120.0	-	53.14	84	0.63
	E8	16/10	203	165.0	-	59.76	84	0.71
	E9	16/10	203	179.0	-	50.06	84	0.59
							Mean	0.63 ±0.05

1 Faying surfaces as rolled condition

TABLE 6.5 EXPERIMENTAL RESULTS BY SURTEES AND PAPE (54)

(Bolts in single shear - initial slip)

calculated using equation 5.2.9. The mean value of $\mu = 0.63$ is higher than the value of μ for single bolt test. This indicates that either the rigid plate/elastic bolt theory is conservative or the average induced shank tension in the bolts were higher than recorded value. It is to be noted that several bolts in large joints were ungauged and were tensioned by a turn-of-nut procedure.

In the case of a 'normal' shear connection where slip is permitted, two limit states will be considered for such a joint. A serviceability limit state is defined as the point at which the joints slips and the capacity of the connection at the ultimate limit state is found from the failure of a fastener in single shear. The results of the untensioned bolted joints will be compared with results from tensioned bolted joint at the ultimate limit state.

6.3.1 Discussion

Table 4.2 shows that for a shank tension of 127 kN and 144 kN, the mean gap closure for load indicating washers was 0.342 mm with 43.4% coefficient of variation and 0.138 mm with 65.9% coefficient of variation respectively. The load indicating washers were used under the nut together with a hardened washer. The recommended gap for a minimum shank tension of 144 kN is 0.25 mm. This correspond to an induced shank tension smaller than that specified.

The results obtained from torque control and a direct measurement of bolt extension methods, with 5.8 and 8.4 percentage coefficient of variation, are in reasonable agreement with strain gauge readings. In the case of direct measurement of bolt extension, it has been shown in Chapter four that the shank tension can be easily calculated using an appropriate value of α_D or α_T from Table 4.4 and 4.6. These results agree with a large number of test results reported by

Rumpf and Fisher (17). The mean value of P_{theory}/P_{test} for direct tension tests was 1.05 and for torqued test was 0.986. This indicates that the direct tension method overestimates the force by 5% and torque tension method underestimates by 1.4%, which is well within the acceptable experimental error.

The average value of μ = 0.36 for a single bolt is only 2.2 percent higher than a value of μ = 0.352 for two bolt tests and are in reasonable agreement.

The average value of μ_E = 0.481 and μ_p = 0.448, using elastic and plastic theories respectively, for multibolt groups are also in reasonable agreement. However, the value of μ_p suggests that plastic theory is slightly more accurate than elastic theory for an ultimate limit state in a 'non slip' joint. The values of μ_E and μ_p for multibolt joints are greater than value of μ for one or two bolt connection. A similar trend is observed from the experimental results reported by Purkiss (53) and Surtees and Pape (54). This variance indicates that the value of μ increases from single bolt test to multibolt test. Therefore if the value of μ from single bolt test is used for the analysis of multibolt group the error induced will be on the safe side.

For 'normal' joint at an ultimate limit state of failure of fastener, the average value of F_v/F_t for stressed bolt is in close agreement with similar value of unstressed bolts. The average value of F_{max}/F_t for stressed multibolt group from Table 4.12 is 0.73, whereas the value of F_{max}/F_t for unstressed bolts is 0.71. If average value for unstressed bolts is divided by the average value for stressed bolts the result is 1.03. Therefore the load carrying capacity of stressed bolted joint is 3% higher than unstressed bolted connection. This increase in strength may be attributed to residual frictional resistance at the ultimate limit state. The European recommendations state that large proportion of frictional resistance is available after slip, this does not agree with the finding of this investigation and other researchers (41, 29).

6.3.2 Conclusions

The following conclusions has been reached as a result of this investigation of stresses bolted connections subject to in-plane shear forces in single shear.

1 The experiments on load indicating washers, when placed under the nut, indicate that the average induced shank tension reached at a gap of 0.25 mm was always less than the specified minimum shank tension.

2 The average measured gap at the specified minimum shank tension of 144 kN was 0.138 mm with a 65.9% coefficient of variation.

3 The use of strain gauges to measure the tension induced in a bolt on tightening is the most reliable method.

4 Torque control and direct measurement of bolt extension methods are of comparable accuracy in establishing the shank tension.

5 The location of strain gauges on the unthreaded shank within twice the bolt diameter from the head affects the measurement of the modulus of elasticity.

6 The mean value of $\alpha_T = 0.881$ with 6.7% coefficient of variation suggests that approximately 9/10th of the bolt under the nut may be used in determining the effective length of a bolt in torque tension test as shown from the tests in this thesis.

7 The load/slip deformation relationship for a single bolt is dependent on the faying surfaces and the induced shank tension.

8 The value of μ obtained from single bolt test is directly comparable with value arrived from two bolt test.

9 For 'non' slip connections, the elastic theory is slightly more conservative than rigid plate/plastic bolt theory.

10 The initial shank tension in the bolt has no adverse effect on the shear capacity of a connection at the ultimate limit state of failure of bolt.

11 The load carrying capacity of a 'normal' joint at the ultimate limit state of failure of a fastener is considerably greater than the load carrying capacity at the limit state of slip.

The literature review and the extensive experimental investigation by the writer suggest that rigid plate/plastic bolt theory predicts the load carrying capacity of a 'non' slip and 'normal' joint more reliably than does rigid plate/elastic bolt theory. However, it also indicates that the application of rigid plate/plastic bolt theory is more complex for all but the simplest configuration. The rigid plate/elastic bolt theory is simple to use and is likely to be of sufficient accuracy for design purpose for 'non' slip and 'normal' joints.

6.4 RECOMMENDATIONS FOR FURTHER RESEARCH

It is evident from the tests on load indicating washer that the shank tension induced varies considerably at the specified gap, when these washers are used under the nut, therefore, further detailed investigation should be carried out.

This research has shown that for unstressed bolts, the distribution of the intensity of pressure on the bolt shank due to the shearing force varies with the thickness of plate. The bending stress produced thus, when combined with shear stress, may significantly influence the load carrying capacity of a fastener. Therefore, to establish the effect of bending stress on the fastener, further extensive experimental and theoretical work could be undertaken.

Further research into the load/deformation behaviour of eccentrically loaded bolt in single shear is required in order to understand the effect of plate thickness on the shear strength of a non slip joint.

In practice, due to misalignment of holes, it is inevitable in large 'non' slip joints that some of the bolts may be in bearing from the onset, which could affect the load/deformation relationship. Thus useful experimental work could be carried out in this area.

Test results from Chapter four suggests that the coefficient of friction of an interface may increase with the increased number of bolts in a given configuration. Although, a considerable research into the surface treatment and its effects on the coefficient of friction has been already carried out, further work is necessary.

APPENDIX A.3

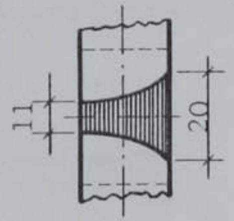
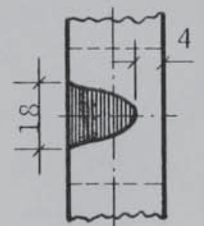
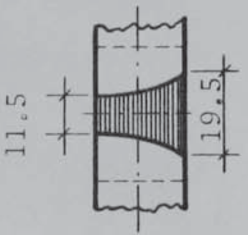
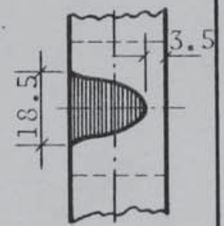
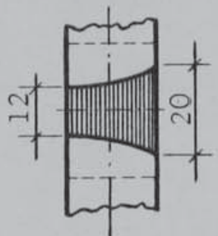
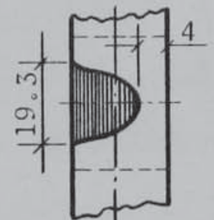
Test No	Projected deformed shape of holes at faces (mm) A B	C D	Plate thickness mm	Maximum deformed dia. of holes at faces (mm) A	B	C	D	dia. of holes before def'n mm	Max def'n of holes mm
1			20.00	22.10	22.92	22.75	22.00	22.00	1.67
2			20.00	22.10	22.70	22.80	22.00	22.00	1.50
3			20.00	22.15	23.00	23.00	22.00	22.00	2.00

TABLE A.3.1 DEFORMATION OF HOLES (BLACK BOLTS)

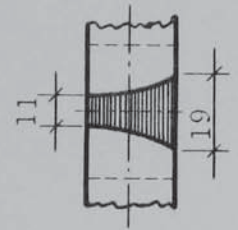
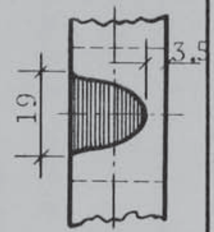
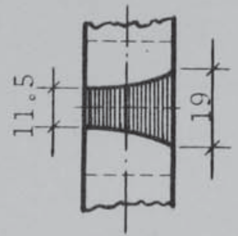
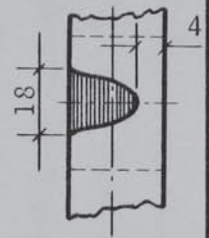
Test No	Projected deformed shape of holes at faces (mm) A B	C D	Plate thickness mm	Maximum deformed dia. of holes at faces (mm) A	B	C	D	dia. of holes before defn. mm	Max. defn of holes mm
4			20.00	22.05	22.77	22.65	22.00	22.00	1.42
5			20.00	22.10	22.50	22.70	22.00	22.00	1.2

Table A.3.1 (Cont.) DEFORMATION OF HOLES (BLACK BOLTS)

Test No	Batch 3a		Batch 3b	
	1	2	3	4
Load (kN)	Deformation mm	Deformation mm	Deformation mm	Deformation mm
0	0	0	0	0
0.5	0.05	0.09	0.116	0.106
1.0	0.106	0.146	0.160	0.120
1.5	0.148	0.178	0.206	0.162
2.0	0.202	0.242	0.246	0.218
2.5	0.236	0.268	0.290	0.294
3.0	0.290	0.330	0.330	0.354
3.5	0.350	0.388	0.374	0.426
4.0	0.438	0.475	0.420	0.532
4.1	0.512	0.552	0.431	0.546
4.4	0.752*	0.786	0.465	0.589
4.5		0.798*	0.476	0.604
4.7			0.510	0.651
4.8			0.550*	0.674
4.85				0.738*

* Indicates the deformation at which the load started reducing

TABLE A.3.2 SHEAR STRENGTH OF CHEESE HEAD SCREWS

(Batches 3a and 3b)

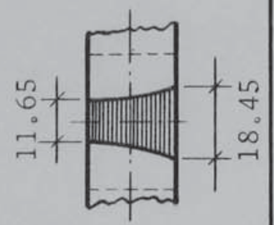
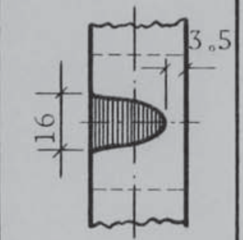
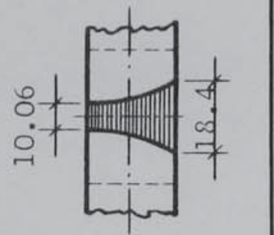
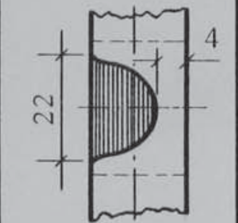
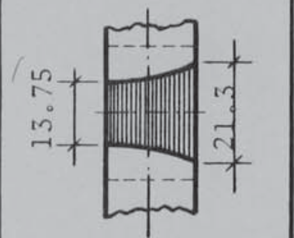
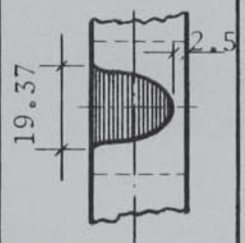
Test No	Projected deformed shape of holes at faces (mm) A B	C D	Plate thickness mm	Maximum deformed dia. of holes at faces (mm) A	B	C	D	dia. of holes before def'n mm	Max def'n of holes mm
1			20.00	22.33	22.75	22.56	22.25	22.25	0.81
2			20.00	22.26	22.67	22.52	22.25	22.25	0.69
3			20.15	22.01	22.80	22.80	22.00	22.00	1.6

TABLE A.3.3 DEFORMATION OF HOLES (HIGH STRENGTH BOLTS)

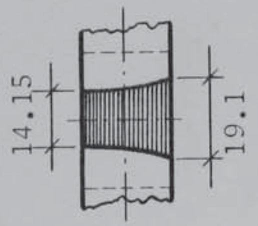
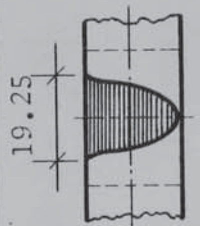
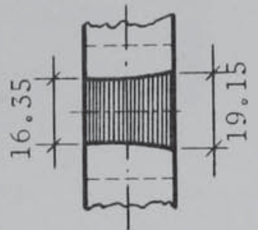
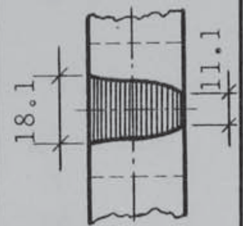
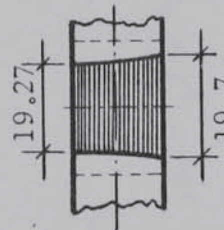
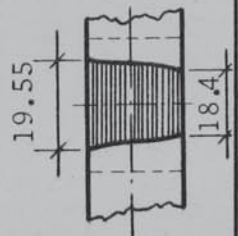
Test No	Projected deformed shape of holes at faces (mm) A B	C D	Plate thickness mm	Maximum deformed dia. of holes at faces (mm) A	B	C	D	dia. of holes before def'n mm	Max def'n of holes mm
4			17.10	22.20	23.15	23.25	22.03	22.00	2.40
5			14.10	22.60	23.65	23.65	22.55	22.00	3.30
6			12.07	23.2	24.4	24.35	23.65	22.00	4.75

TABLE A.3.3 (Cont.) DEFORMATION OF HOLES (HIGH STRENGTH BOLTS)

A.3.4 TYPICAL DATA RECORDED DURING TEST AND CALCULATIONS SHOWING THE EFFECT OF NON-VERTICAL LOAD. FOR SPECIMEN LABEL 2H10.

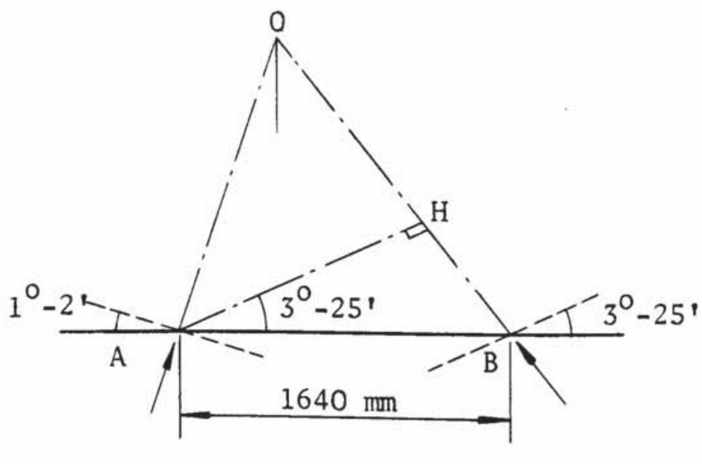
The following calculations were carried out to check the error associated with the rotation of rig from the horizontal position due to clearance in holes, bolt shear deformation and yield bearing stresses. The figure A.3.4.1 shows the loading system and the position of dial gauges marked D1, D2, D3 etc. In addition to the dial gauges, a biaxial travelling telescope was also used to find the position of bolts near failure. Table A.3.4.1 shows the deflection of the rig with respect to the horizontal position where as the Table A.3.4.2 indicates the horizontal and vertical movement of the bolts marked 1 and 2. It was not possible to record any deflection reading at failure due to the large rate of increase and dangerous situation. Therefore the comparison for correction was made for an applied load of 129.57 kN.

From Table A.3.4.1 and Figure A.3.4.1

$$\tan \theta_1 = \frac{27.15}{1500} = 0.0181 \qquad \therefore \quad \theta_1 = 1^o - 2'$$

$$\tan \theta_2 = \frac{58.15}{971} = 0.0598 \qquad \therefore \theta_2 = 3^o - 25'$$

$$\tan \theta_3 = \frac{7.8 - 3.5}{149.4} = 0.02878 \qquad \therefore \quad \theta_3 = 1^o - 39'$$



$\therefore$ AH = 1640 x cos 3^{o} - 25'

= 1640 x 0.998 = 1637 .08 mm

$\therefore$ Reaction at B

$$R_B = \frac{129.57 \times 987 + 7.643 \times 2609 - 7.985 \times 7}{1637.08} = 90.264 \text{ kN}$$

To find P_{test} take moments about C.G. of bolt group

$$90.264 \times (342 - \frac{3.5 + 7.8}{2}) = 30360.296 \text{ kN mm}$$

$$-7.643 \times 1311 = -10019.973 \text{ kN mm}$$

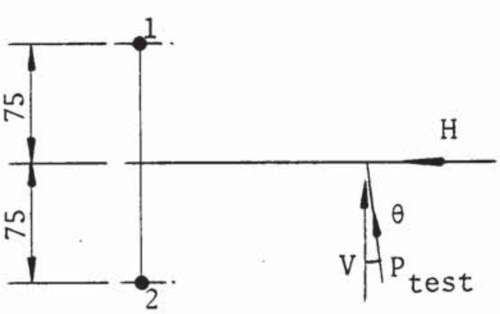
$$82.621 \text{ kN} \qquad = 20340.323 \text{ kN mm}$$

$\therefore$ P_{test} = 82.621 kN

eccentricity e = 246.18 mm

This force P_{test} is acting at an angle of $(\theta_2-\theta_3) = 1^{o} - 46'$ with respect the centroid of the bolt group and therefore the maximum force on the bolt at an applied load of 129.57 kN is calculated using the following = n.

$$F_v = \frac{V}{n}\left[\left[1 + \frac{n\, x_n\, e}{\Sigma_1^n(x_i^2 + y_i^{\,2})}\right]^2 + \left[\frac{H}{V} + \frac{n\, y_n\, e}{\Sigma_1^n\,(x_i^2 + y_i^2)}\right]^2\right]^{\frac{1}{2}}$$



$\theta = 1^{o}46'$

$\therefore$ V = P cos θ = 82.621 x 0.9995 = 82.579 kN

H = P sin θ = 82.621 x 0.030829 = 2.547 kN

$$\therefore \quad F_v = \frac{82.579}{2}\left[1 + (0.03084 + \frac{2 \times 75 \times 246.18}{11250})^2\right]^{\frac{1}{2}}$$

$$= 142.897 \text{ kN} \qquad -(1)$$

Now check the maximum force on the bolt for the same applied load without considering the effect of rotation of the rig.

The reaction at B

$$R_B = \frac{129.57 \times 987 + 7.643 \times 2609 - 7.985 \times 7}{1640}$$

$$= 90.103 \text{ kN}$$

To find V_{test} take moments about CG of bolt group

90.103 x 342	= 30815.226 kNmm
-7.643 x 1311	= -10019.973 kNmm
82.46 kN	20795.253 kNmm

$\therefore V_{test} = 82.46$ kN

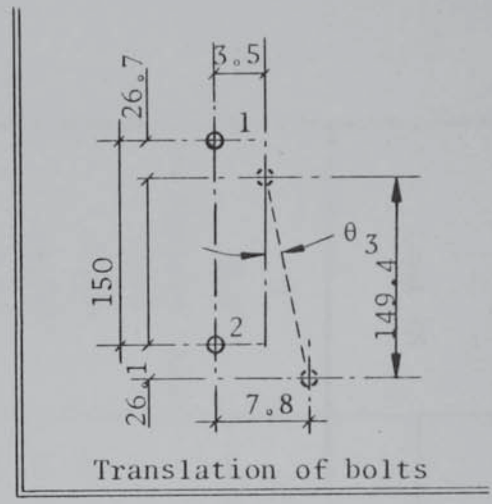
$e = 252.186$ mm

$$\therefore \quad F_v = \frac{82.46}{2}\left[1 + (\frac{252.186}{75})^2\right]^{\frac{1}{2}}$$

$$= 144.636 \text{ kN} \qquad -(2)$$

From (1) and (2) it is evident that the error, in ignoring the effect of rotation, is only 1.2 per cent.. Therefore no correction will be made in the calculations to determine the ultimate strength of the bolt group.

W = applied load kN
W_1 = self weight of R.H.S. beam and specimen = 7.643 kN
W_2 = self weight of L.H.S. beam and specimen = 7.985 kN
D_1 = No 1 dial gauge



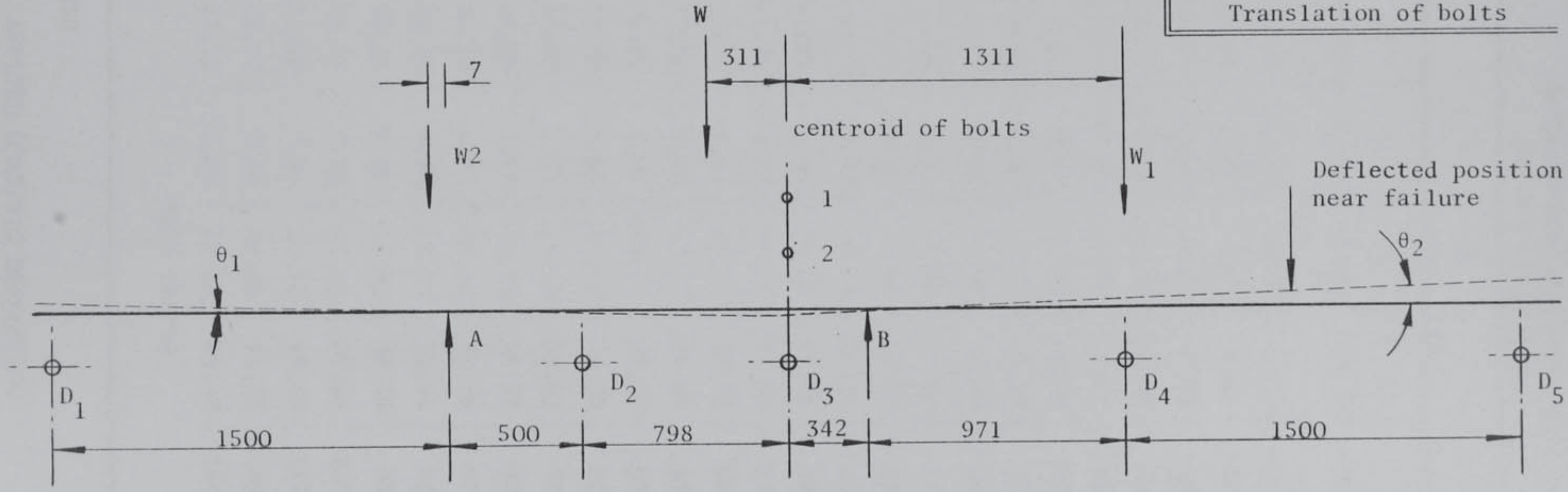


FIG. A.3.4.1 LOADING DIAG. FOR SPECIMEN LABEL 2H10

Load kN	Deflection dial gauges and deflection in (mm)				
	1	2	3	4	5
0	0	0	0	0	0
S.W	-4.69	-1.55	-4.08	-10.98	-27.95
+ Applied load 4.98	-4.27	-1.29	-3.45	-10.06	-26.10
9.96	-3.94	-1.09	-3.05	-8.65	-22.02
14.95	-3.61	-0.91	-2.56	-7.28	-18.53
19.93	-3.32	-0.76	-2.15	-6.09	-15.50
24.92	-3.07	-0.64	-1.80	-5.12	-12.03
29.90	-2.87	-0.51	-1.43	-4.07	-10.46
34.88	-2.10	-0.20	-0.77	-2.19	-5.57
39.86	2.4	0.86	2.08	5.91	16.01
44.85	5.10	2.21	5.49	6.82	17.36
49.83	7.44	2.89	7.63	11.27	28.69
54.82	9.17	3.53	9.27	15.93	40.52
59.80	10.46	4.06	10.56	19.51	49.64
64.79	11.20	4.37	11.34	21.54	54.81
69.77	12.01	4.67	12.22	23.75	60.43
74.75	12.34	4.83	12.65	24.84	63.21
79.74	13.38	5.15	14.11	27.35	69.61
84.72	13.71	5.31	14.99	28.39	72.26
89.71	14.63	5.71	15.46	30.63	77.95
94.69	14.96	5.87	16.95	31.57	80.34
99.67	16.13	6.12	17.12	34.26	87.19
104.65	16.54	6.30	18.73	35.41	90.10
109.64	18.24	6.86	19.85	39.26	99.93
114.63	19.41	7.28	21.38	42.04	107.85
119.60	21.08	7.84	22.56	45.69	117.72
124.59	23.72	8.86	24.36	51.25	133.37
129.57	27.15	10.05	27.58	58.49	150.12
142.50	Bolt failed				

Specimen label 2H10

TABLE A.3.4.1 APPLIED LOAD/RIG DEFLECTION

Load kN	Horizontal and vertical translation of bolts using telescope			
	Bolt No 1		Bolt No 2	
	x mm	y mm	x mm	y mm
0	0	0	0	0
S.W.	-3.7	-4.1	-3.3	-4.4
+ Applied load 4.98	-5.8	-3.8	-4.8	-4.1
9.96	-5.3	-3.2	-5.4	-3.4
14.95	-5.2	-2.8	-5.5	-3.1
19.93	-5.4	-2.5	-5.4	-2.6
24.92	-5.3	-2.2	-4.6	-2.5
29.90	-5.3	-2.0	-5.3	-1.9
34.88	-4.9	-1.0	-4.9	-1.6
39.86	-3.8	1.7	-2.8	1.3
44.85	-3.2	5.5	-1.4	4.6
49.83	-1.7	7.5	-1.2	7.1
54.82	-1.0	9.3	-0.4	8.9
59.80	-1.0	10.5	0.7	10.1
64.79	-0.2	11.3	0.9	10.8
69.77	-0.6	12.2	1.3	11.6
74.75	-0.6	12.6	1.3	11.9
79.74	-1.2	13.6	1.5	13.0
84.72	-1.2	14.0	1.9	13.4
89.71	-0.6	14.8	2.3	14.2
94.69	-0.9	15.2	2.5	14.5
99.67	-0.1	16.2	3.4	15.8
104.65	0.1	16.8	3.5	16.2
109.64	0.6	18.4	4.5	17.9
114.63	1.6	19.6	4.7	19.1
119.60	1.6	21.1	5.1	20.5
124.59	2.8	23.6	6.6	23.1
129.57	3.5	26.7	7.8	26.1
142.50	Bolt failed			

Specimen label 2H10

TABLE A.3.4.2 APPLIED LOAD/TRANSLATION OF BOLTS

Specimen label	L_1 mm	L_2 mm	L_3 mm	W failure load kN	Bolt No which fractured
2H1*	1245	1245	-60	53.82	1
2H2*	1245	1245	-60	52.83	1
2H3	1302	2401	-3	28.91	2
2H4	1305	2025	0	38.87	2
2H5	1295	1930	-10	37.87	1
2H6	1302	1695	-3	40.87	2
2H7	1302	990	-3	63.79	2
2H8	1302	740	-3	74.75	2
2H9	1305	385	0	133.56	1
2H10	1298	342	-7	142.50	1
2H11	1290	280	-15	165.96	1
2H12	1325	96	20	342.1	2

i 20 mm diameter H.S. bolts from batch 2b

ii 20 mm thick plate from batch P1

iii For loading system sec fig. 3.9

iv *Loading system produced torsion moment only

TABLE A.3.5: SPAN VARIATIONS AND FAILURE LOAD

(Two H.S. Bolts)

Specimen lable	L_1 mm	L_2 mm	L_3 mm	W failure load kN	Bolt No which fractured
2B1*	Torsion moment only			31.19	1
2B2	1340	2795	90	14.95	1
2B3	1299	2440	49	17.44	1
2B4	1287	1697	37	23.42	1
2B5	1266	1310	16	30.89	1
2B6	1283	996	33	40.87	1
2B7	1337	769	87	42.86	1

i 20 mm diameter black bolts from batch 1b

ii 20 mm thick plate from batch P1

iii For loading system see Figure 3.9

iv * loading system produced torsion moment only

TABLE A.3.6: SPAN VARIATIONS AND FAILURE LOAD

(Two black bolts)

Specimen label	L_1 mm	L_2 mm	L_3 mm	L_4 mm	L_5 mm	W failure load kN	Bolt(s) which fractured
2C1	513	832	0	158	514	1.274	2
2C2	513	650	0	167	514	1.414	2
2C3	513	514	0	167	514	1.685	2
2C4	513	326	0	167	514	2.514	2
2C5	513	217	0	167	514	3.257	2
2C6	513	133	0	167	514	5.328	2
Batch 3a							
2C7	513	830	0	160	514	1.088	2
2C8	513	650	0	160	514	1.360	2
2C9	513	514	0	160	514	1.703	2
2C10	513	326	0	162	514	2.474	2
2C11	513	223	0	162	514	3.574	2
2C12	513	143	0	162	514	5.303	2
Batch 3b							

i 5 mm diameter cheese-head screws from batch 3a and 3b

ii 10 mm thick plate from batch P2

iii For loading system see figure 3.11

TABLE A.3.7: SPAN VARIATIONS AND FAILURE LOAD
(Two cheese-head screws)

Specimen label	L_1 mm	L_2 mm	L_3 mm	W failure load kN	Bolt(s) which fractured
6H1*	1299	1298	12	116.92	2
6H2	1326	2775	39	74.75	5
6H3	1325	2375	38	78.24	5,6
6H4	1287	1599	0	100.17	5,6
6H5	1327	1322	40	112.13	5
6H6	1336	1321	49	109.64	6
6H7	1291	939	4	142.03	6
6H8	1290	718	3	157.48	1,2
6H9	1282	363	-5	259.15	4,5,6
6H10	1287	245	0	338.89	2,4,5,6

i 20 mm diameter H.S.F.G. Bolts from batch 2b

ii 20 mm thick plate from batch P1

iii For loading system see figure 3.12

iv * Loading system produced torsion moment only

TABLE A.3.8: SPAN VARIATIONS AND FAILURE LOAD (six bolts)

Specimen label	L_1 mm	L_2 mm	L_3 mm	W failure load kN	Bolt(s) which fractured
4B1	1267*	1307	-20	68.07	1,2
4B2	1298	2788	11	44.35	1,2
4B3	1287	2320	0	49.84	1,2
4B4	1305	1688	18	58.81	1,2
4B5	1331	1208	44	68.27	1,2
4B6	1331	946	44	83.73	1,2
4B7	1350	708	63	103.66	1,2
4B8	1335	355	48	169.44	1,2
4B9	1322	243	35	219.28	1,2,3,4
6B1	1267*	1307	-20	70.08	1,2
6B2	1367	2748	80	38.37	1,2
6B3	1334	2408	47	47.34	1,2
6B4	1312	1672	25	56.81	1,2
6B5	1303	1272	16	69.77	1,2
6B6	1321	950	34	83.92	1,2
6B7	1382	733	95	97.18	1,2
6B8	1282	368	-5	190.62	1,2,6
6B9	1300	258	13	244.20	1,2,4,6

i 20 mm diameter black bolts from batch 1

ii 20 mm thick plate from batch P1

iii For loading system see figure 3.12

iv * Loading system produced torsion moment only

TABLE A.3.9: SPAN VARIATIONS AND FAILURE LOAD (four and six bolts)

Specimen label	L_1 mm	L_2 mm	L_3 mm	L_4 mm	L_5 mm	W failure load kN	Bolt(s) which fractured
12C1	520	660	9	190	519	7.46	1,2,3,10,11,12
12C2	750	600	239	190	519	5.90	3
12C3	520	519	9	190	519	9.60	3
12C4	721	428	210	190	519	6.68	1,12
12C5	518	315	7	190	519	11.70	1,2,3,10,11,12
12C6	518	208	7	190	519	15.24	1, 3
12C7	713	65	202	190	519	30.21	all
3C1	743	607	239	183	526	1.71	3
4C1	*520	520	-	-	-	4.454	1,2
4C2	693	60	182	190	519	16.38	
4C3	705	60	194	190	519	15.98	
6C1	*520	520	-	-	-	6.282	1,6
10C1	*520	520	-	-	-	8.868	7,8,9,10

i 5 mm dia cheese-head screws from batch 3b

ii 10 mm thick plate from batch P2

iii For loading system see figure 3.11

iv * Loading system produced torsion moment only

TABLE A.3.10 SPAN VARIATION AND FAILURE LOAD (Cont)

Specimen label	L_1 mm	L_2 mm	L_3 mm	L_4 mm	L_5 mm	W failure load kN	Bolt(s) which fractured
3C1	*520	520	-	-	-	2.725	1
3C2	743	607	239	183	526	1.45	1
3C3	743	607	239	183	526	1.57	1
3C4	714	435	210	183	526	1.71	1
3C5	715	322	211	183	526	2.38	1
3C6	511	322	7	183	526	3.11	1
3C7	511	215	7	183	526	4.76	1,3
5C1	*520	520	-	-	-	4.596	1,2
5C2	721	428	210	190	519	3.44	1,2
5C3	722	315	211	190	519	4.50	1,2
5C4	518	315	7	190	519	5.97	1,2
5C5	518	208	7	190	519	8.71	1,2
5C6	715	67	204	190	519	18.06	all
8C1	*520	520	-	-	-	6.811	2
8C2	517	633	9	187	522	5.93	2
8C3	522	658	9	192	517	5.97	8
8C4	747	603	239	187	522	4.47	8
8C5	517	522	9	187	522	6.76	2
8C6	522	517	5	192	517	6.54	1
8C7	718	431	210	187	522	5.22	2,8
8C8	719	318	211	187	522	6.58	1,2
8C9	515	318	7	187	522	8.61	8
8C10	515	211	7	187	522	11.47	1,2
8C11	713	76	205	187	522	22.33	all

i 5 mm diameter cheese-head screws from batch 3b

ii 10 mm thick plate from batch P2

iii For loading system see figure 3.11

iv *Loading system produced torsion moment only

TABLE A.3.10 SPAN VARIATIONS AND FAILURE LOAD (Cont)

Specimen label	L_1 mm	L_2 mm	L_3 mm	L_4 mm	L_5 mm	W failure load kN	Bolt(s) which fractured
4C1	513	832	0	164	514	3.089	1,2
4C2	513	834	0	108	514	2.831	1,2
4C3	513	650	0	162	514	3.488	1,2,3
4C4	513	650	0	167	514	3.642	1,2,4
4C5	513	514	0	167	514	3.757	1,3,4
4C6	513	326	0	167	514	5.714	2,3,4
4C7	513	217	0	167	514	6.928	2,3,4
4C8	513	133	0	167	514	11.185	1,2,4
6C1	513	832	0	164	514	4.503	4,5,6
6C2	513	650	0	167	514	5.142	1,2,3,4
6C3	513	650	0	162	514	5.274	1,2,3
6C4	513	514	0	167	514	5.728	4,5
6C5	513	326	0	167	514	7.914	1,2,3,5,6
6C6	513	217	0	167	514	10.114	1,2,3
6C7	513	133	0	167	514	14.828	2,3,4,5,6
8C1	513	832	0	162	514	4.488	1,2,7,8
8C2	513	650	0	167	514	5.542	1,8
8C3	513	650	0	162	514	5.588	1
8C4	513	514	0	167	514	5.999	1,2,7,8
8C5	513	326	0	167	514	7.157	1,8
8C6	513	217	0	167	514	10.514	1,2,8
8C7	513	133	0	167	514	15.288	1,2

i 5 mm diameter cheese-head screws from batch 3a

ii 10 mm thick plate from batch P2

iii For loading system see figure 3.11

TABLE A.3.10 SPAN VARIATIONS AND FAILURE LOAD

APPENDIX A.4

Test No	Thicknesses of Nut ℓ_n (mm)	Nut washer t_1 (mm)	Headwasher t_2 (mm)	Distance between washers ℓ_w mm	ℓ_t mm
DT 1	18.10	3.60	3.90	40.76	28.26
DT 2	18.07	3.63	3.92	40.66	28.21
DT 3	18.03	3.59	3.91	40.91	28.41
DT 4	18.05	3.61	3.95	41.35	28.91
DT 5	17.95	3.64	3.93	40.66	28.23
DT 6	18.17	3.59	3.89	40.66	28.14
DT 7	18.02	3.64	3.91	40.66	28.21
DT 8	18.05	3.65	3.99	40.66	28.30
DT 9	18.08	3.70	3.93	40.66	28.29
Mean	18.06 ±0.06	3.63 ±0.04	3.93 ±0.03	40.77 ±0.23	28.32 ±0.23

i Shank dia of HSFG bolts = 19.72 mm

ii Length of unthreaded shank ℓ_s = 20 mm

iii $\ell_t = \ell_w + t_1 - \ell_s + t_2$

TABLE A.4.1 PHYSICAL PROPERTIES OF BOLTS, NUTS AND WASHERS

Test No	DT1				
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Mean extension mm
0	0	0	0	0	0
19.62	620	171	17	269	0.021
39.24	1077	305	226	536	0.040
58.86	1355	561	525	814	0.061
78.48	1617	809	845	1090	0.077
98.10	1858	1090	1146	1365	0.106
117.72	2093	1393	1434	1640	0.125
127.53	2221	1556	1588	1788	0.138
137.34	2335	1704	1729	1923	0.152
147.15	2461	1858	1877	2065	0.158
159.96	2581	2016	2028	2208	0.171
166.77	2689	2162	2191	2347	0.183
176.58	2788	2319	2348	2485	0.195
186.39	2856	2499	2537	2631	0.217
196.20	2802	2796	2734	2777	0.248
221.10	Bolt fractured at threads				

i 20 mm dia HSFG bolts, batch 2C

TABLE A.4.2 LOAD/STRAIN AND EXTENSION REPATIONSHIP

Test No	DT2				
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Mean extension mm
0	0	0	0	0	0
19.62	117	221	501	280	0.021
39.24	194	437	1041	558	0.040
58.86	416	767	1310	832	0.059
78.48	708	1080	1548	1113	0.077
98.10	1000	1404	1761	1389	0.096
117.72	1271	1720	1971	1655	0.122
127.53	1407	1871	2068	1783	0.134
137.34	1563	2026	2194	1928	0.146
147.15	1707	2159	2329	2066	0.156
159.96	1876	2313	2449	2213	0.169
166.77	2045	2447	2572	2357	0.181
176.58	2217	2580	2673	2490	0.197
186.39	2416	2736	2751	2635	0.215
196.20	2636	2874	2833	2781	0.231
238.87	Bolt fractured at threads				

i 20 mm dia HSFG bolts batch 2C

TABLE A.4.2 (Cont) LOAD/STRAIN AND EXTENSION RELATIONSHIP

Test No	DT3				
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Mean extension mm
0	0	0	0	0	0
19.62	444	40	361	282	0.019
39.24	746	298	685	577	0.039
58.86	1007	541	1018	856	0.061
78.48	1252	793	1355	1134	0.083
98.10	1525	1037	1661	1408	0.105
117.72	1817	1302	1955	1692	0.128
127.53	1966	1418	2090	1825	0.139
137.34	2088	1555	2236	1950	0.154
147.15	2238	1699	2366	2101	0.171
159.96	2366	1850	2509	2242	0.182
166.77	2512	1997	2656	2389	0.193
176.58	2643	2177	2790	2537	0.207
186.39	2745	2350	2892	2663	0.221
196.20	2818	2604	2959	2794	0.245
234.46	Bolt fractured at threads				

i 20 mm dia HSFG bolts, batch 2C

TABLE A.4.2 (Cont) LOAD/STRAIN AND EXTENSION RELATIONSHIP

Test No	DT4				
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Mean extension mm
0	0	0	0	0	0
19.62	261	301	278	280	0.017
39.24	605	599	501	568	0.037
58.86	913	935	734	861	0.058
78.48	1160	1240	960	1120	0.076
98.10	1419	1588	1220	1409	0.098
117.72	1655	1895	1492	1681	0.122
127.53	1777	2069	1652	1833	0.134
137.34	1915	2244	1788	1982	0.147
147.15	2019	2399	1926	2115	0.157
159.96	2144	2564	2065	2258	0.167
166.77	2256	2719	2222	2399	0.182
176.58	2376	2865	2356	2532	0.192
186.39	2495	2990	2523	2669	0.206
196.20	2673	3007	2777	2819	0.245
224.15	Bolt fractured at threads				

i 20 mm dia HSFG bolt batch 2C

TABLE A.4.2 (Cont) LOAD/STRAIN AND EXTENSION RELATIONSHIP

Test No	DT5				DT6				DT7			
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	Average	Mean extension mm	Strain x 10^{-6} Strain gauges 1	2	Average	Mean extension mm	Strain x 10^{-6} Strain gauges 1	2	Average	Mean extension mm
0	0	0	0	0	0	0	0	0	0	0	0	0
19.9	454	53	254	0.003	255	296	276	0.025	580	-54	263	0.018
39.9	750	264	507	0.021	528	551	540	0.043	1101	-7	547	0.037
59.8	1030	540	785	0.040	872	805	839	0.068	1417	190	804	0.051
79.7	1284	806	1045	0.061	1174	1070	1122	0.086	1740	435	1088	0.068
99.7	1570	1109	1340	0.087	1418	1373	1396	0.103	2025	690	1358	0.089
119.6	1818	1388	1603	0.106	1668	1689	1679	0.124	2285	890	1588	0.102
129.6	1946	1530	1738	0.124	1792	1845	1819	0.137	2409	1099	1754	0.120
139.5	2074	1675	1875	0.134	1913	1994	1954	0.146	2531	1253	1892	0.132
149.5	2210	1819	2015	0.145	2043	2158	2101	0.160	2658	1421	2040	0.142
159.5	2329	1948	2139	0.156	2164	2311	2238	0.174	2747	1565	2156	0.155
169.4	2463	2111	2287	0.171	2288	2474	2381	0.188	2825	1749	2287	0.174
179.4	2584	2264	2424	0.183	2407	2610	2509	0.204	2874	1972	2423	0.192
189.4	2629	2444	2537	0.211	2515	2785	2650	0.224	2827	2316	2572	0.226
199.3	2820	2656	2738	0.399	2630	2895	2763	0.278	2779	2664	2722	0.306
220.27	Bolt fractured at threads											
231.74									Bolt fractured at threads			
234.23					Bolt fractured at threads							

i 20 mm dia HSFG bolts, batch 2C

TABLE A.4.2(Cont) LOAD/STRAIN; EXTENSION RELATIONSHIP

Test No	DT8				DT9			
Applied load kN	Strain $\times 10^{-6}$ Strain gauges 1	2	Average	Mean extension mm	Strain $\times 10^{-6}$ Strain gauges 1	2	Average	Mean extension mm
0	0	0	0	0	0	0	0	0
19.9	-79	576	249	0.024	42	449	246	0.012
39.9	79	974	527	0.046	160	899	530	0.031
59.8	329	1286	808	0.065	307	1324	816	0.054
79.7	646	1550	1098	0.088	456	1711	1084	0.064
99.7	990	1778	1384	0.108	666	2100	1383	0.085
119.6	1336	2005	1671	0.130	869	2453	1661	0.108
129.6	1497	2097	1797	0.140	994	2612	1803	0.119
139.5	1678	2207	1943	0.150	1108	2786	1947	0.133
149.5	1875	2335	2105	0.166	1231	2907	2069	0.142
159.5	2046	2433	2240	0.178	1387	3046	2217	0.154
169.4	2244	2527	2386	0.189	1566	3144	2355	0.170
179.4	2420	2623	2522	0.204	1805	3198	2502	0.188
189.4	2644	2692	2668	0.220	2103	3223	2663	0.217
199.3	2993	2623	2808	0.264	2410	3228	2819	0.259
228.25	Bolt fractured at threads							
236.2					Bolt fractured at threads			

i 20 mm dia HSFG bolts batch 2C

TABLE A.4.2 (Cont) LOAD/STRAIN; EXTENSION RELATIONSHIP

Test No	DT10					
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Tensile stress N/mm^2	Mean extension mm
0	0	0	0	0	0	0
19.62	632	435	435	501	91	0.027
39.24	924	827	975	909	181	0.049
58.86	1211	1269	1523	1335	272	0.076
78.48	1448	1681	2119	1750	362	0.093
98.10	1785	2039	2680	2168	453	0.117
117.72	2153	2451	3197	2601	544	0.140
127.53	2333	2651	3404	2796	598	0.155
137.34	2513	2875	3643	3011	635	0.168
147.15	2715	3084	3827	3209	680	0.178
156.96	2916	3315	4034	3422	726	0.191
166.77	3307	3596	4273	3726	771	0.213
176.58	3182	4021	7385	4863	816	0.243
186.39	3781					0.539
196.20	3869					1.018
205.03	Bolt fractured at reduced dia					

i 20 mm dia HSFG bolt from batch 2C

ii Turned-down dia of the bolt 16.593 mm

TABLE A.4.3 LOAD/STRAIN RELATIONSHIP

Test No	DT11					
Applied load kN	Strain x 10^{-6} Strain gauges 1	2	3	mean	Tensile stress N/mm^2	Mean extension mm
0	0	0	0	0	0	0
19.62	-358	1005	619	422	90	0.008
39.24	186	1067	1274	842	180	0.041
58.86	715	1077	1957	1250	270	0.061
78.48	1145	1122	2689	1652	360	0.082
98.10	1588	1199	3401	2062	450	0.103
117.72	2057	1370	4043	2490	540	0.125
127.53	2305	1482	4309	2698	585	0.136
137.34	2560	1615	4609	2928	630	0.151
147.15	2814	1672	5191	3225	675	0.175
156.96	3161	1626	7415	4067	720	0.189
166.77	4555	1661	10521	5579	765	0.227
176.58	6090	2141	13598	7276	810	0.266
186.39	11636	6637	18369	12214	855	0.367
196.20	3850	20782	9169	11267	900	0.478
209.93		Bolt fractured at reduced dia				

i 20 mm dia HSFG bolt from batch 2C

ii Turned-down dia of the bolt 16.654 mm

TABLE A.4.3 (Cont) LOAD/STRAIN RELATIONSHIP

Test No	DT12			DT13			DT14			DT15		
Reduced bolt dia	16.5 mm			16.15 mm			16.3 mm			16.5 mm		
Applied load	Strain x 10^{-6} Strain gauges			Strain x 10^{-6} Strain gauges			Strain x 10^{-6} Strain gauges			Strain x 10^{-6} Strain gauges		
	1	2	Average	1	2	Average	1	2	Average	1	2	Average
0	0	0	0	0	0	0	0	0	0	0	0	0
19.9	333	543	438	934	-39	448	704	215	459	639	333	486
39.9	782	962	872	1469	304	887	1100	684	892	1189	620	904
59.8	1295	1330	1313	1956	730	1343	1521	1164	1342	1695	990	1343
79.7	1797	1682	1730	2402	1173	1788	1891	1591	1741	2171	1365	1768
99.7	2258	2052	2155	2808	1610	2209	2271	2116	2193	2675	1738	2207
119.6	2737	2424	2581	3247	2079	2663	2642	2611	2626	3131	2139	2635
129.6	2969	2600	2784	3471	2330	2901	2823	2863	2843	3331	2322	2826
139.5	3214	2830	3022	3666	2552	3109	2995	3141	3068	3568	2540	3054
149.5	3452	3002	3227	3891	2808	3350	3197	3371	3284	3798	2764	3279
159.5	3707	3223	3465	4107	3063	3585	3414	3675	3544	4030	2994	3512
169.4	3909	3414	3662	4301	3301	3801	3810	4127	3969	4220	3206	3713
179.4	4145	3650	3897	4520	3566	4043	17221	19472	18346	6850	3321	5085
189.4	4412	3875	4143	4715	3815	4265						
199.3	4721	4115	4418	4940	4067	4504		Bolt fractured				
209.3	5885	4652	5268								Bolt fractured	
234.2					Bolt fractured							
244.2		Bolt fractured										

TABLE A.4.3 (Cont) LOAD/STRAIN RELATIONSHIP (Turned-down bolts batch 2c)

Test No	Thicknesses of						ℓ_t mm
	Nut ℓ_n (mm)	Nut washer t_1 (mm)	Hardened washer t_2 (mm)	L.I.W and protrusions t_3 (mm)	L.I. washer t_4 (mm)	Flange and Plate T (mm)	
1	17.81	3.69	3.93	5.51	3.78	36.19	28.45
2	18.01	3.66	4.00	5.47	3.73	36.37	28.63
3	18.09	3.68	3.90	5.58	3.78	36.43	28.69
4	17.85	3.66	3.90	5.60	3.84	35.35	27.63
5	18.28	3.60	3.91	5.53	3.77	35.46	27.62
6	18.08	3.64	3.96	5.59	3.76	35.48	27.75
7	17.92	3.64	3.88	5.58	3.81	36.37	28.58
8	18.24	3.66	3.90	5.51	3.72	36.61	28.78
9	18.03	3.71	3.88	5.52	3.76	36.55	28.78
10	17.64	3.65	3.95	5.58	3.77	35.41	27.68
11	17.79	3.63	3.78	5.49	3.79	35.59	27.64
mean	17.97	3.65	3.91	5.54	3.77	35.98	28.20
	±0.19	±0.03	±0.05	±0.04	±0.03	±0.52	±0.52

i Shank dia of HSF bolts = 19.72 mm

ii Length of unthreaded shank ℓ_s = 20 mm

iii $\ell_t = t_1 + t_2 + T + \frac{t_3 - t_4}{2} + t_3 - \ell_s$

TABLE A.4.4 PROPERTIES OF BOLTS, NUTS AND L.I. WASHERS

TEST NO TT 1

Applied Torque Nm	Strain x 10^{-6} strain gauges			Average gap mm	Mean extension mm	Shank tension kN
	1	2	mean			
0	0	0	0	1.73	0	
50	208	65	136	-	0.004	9.6
400	1296	1367	1331	0.925	0.107	94.4
420	1422	1555	1488	0.588	0.116	105.5
440	1419	1625	1522	0.575	0.113	107.9
460	1405	1694	1549	0.493	0.112	109.8
480	1358	1846	1602	0.388	0.112	113.6
500	1423	1854	1638	0.338	0.115	116.2
520	1575	1885	1730	0.213	0.120	122.7
540	1782	1916	1849	0.100	0.132	131.1
560	1850	1975	1912	0.081	0.136	135.6
580	1942	1977	1959	0.050	0.143	138.9
600	2118	1994	2056	0.030	0.184	145.8
620	2212	2039	2125	0.012	0.235	150.7
640	2556	2385	2470	0	0.586	175.2
660	2556	2385	2470	0	0.586	175.2
680	2864	2634	2749	0	0.768	194.9
700	3249	2864	3056	0	0.951	216.8
720	2966	2714	2840	0	-	201.4
780	2658	2427	2542	0	-	180.3

i 20 mm dia HSFG bolts from batch 2c
ii Tensile stress area for shank tension 305.424 mm^2
iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 SHANK TENSION / TORQUE; STRAIN; GAP AND EXTENSION

Test No TT2

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	1.74	0	0
50	178	200	189	-	-	13.4
400	1234	1400	1317	1.06	0.098	93.4
420	1380	1384	1382	1.03	0.106	98.0
440	1381	1324	1353	1.03	0.104	95.9
460	1509	1332	1421	1.01	0.110	100.8
480	1789	1348	1568	0.81	0.130	111.2
500	1896	1499	1698	0.69	0.134	120.4
520	1992	1548	1770	0.60	0.138	125.5
540	2013	1617	1815	0.51	0.144	128.7
560	2162	1635	1899	0.43	0.148	134.7
580	2329	1639	1984	0.33	0.156	140.7
600	2442	1670	2056	0.24	0.164	145.8
620	2509	1705	2107	0.21	0.164	149.4
640	2545	1841	2193	0.13	0.194	155.5
660	3115	2547	2831	0	0.930	200.8
680	3604	2885	3244	0	1.204	230.1
700	488	3298	1893	0	1.824	134.2

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 SHANK TENSION / TORQUE; STRAIN: GAP AND EXTENSION (Cont)

Test No TT3

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	1.80	0	0
50	187	9	98	-	0.002	6.9
400	1385	1360	1373	0.90	0.117	97.4
420	1457	1410	1434	0.84	0.122	101.7
440	1492	1441	1467	0.84	0.122	104.0
460	1540	1502	1521	0.75	0.127	107.9
480	1601	1587	1594	0.62	0.133	113.1
500	1712	1529	1621	0.56	0.137	114.9
520	1767	1598	1683	0.46	0.143	119.4
540	1831	1885	1858	0.31	0.158	131.8
560	1874	1984	1929	0.25	0.166	136.8
580	1890	2050	1970	0.24	0.175	139.7
600	1922	2172	2047	0.14	0.207	145.2
620	1952	2260	2106	0.11	0.229	149.4
640	2090	2383	2236	0.05	0.330	158.6
660	2941	2519	2730	0	0.740	193.6
680	3703	3879	3791	0	1.907	268.9
700	3817	3980	3899	0	2.140	276.6

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE; STRAIN, GAP AND EXTENSION

Test No TT4

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	1.75	0	0
50	-129	363	117	-	0.007	8.3
400	1490	1068	1279	0.75	0.113	90.7
420	1502	1114	1308	0.74	0.112	92.8
440	1529	1243	1386	0.65	0.120	98.3
460	1569	1274	1422	0.63	0.121	100.8
480	1677	1348	1513	0.51	0.124	107.3
500	1724	1404	1564	0.44	0.132	110.9
520	1813	1453	1633	0.33	0.135	115.8
540	1977	1549	1763	0.19	0.144	125.0
560	1957	1862	1910	0.11	0.156	135.5
580	2019	2090	2055	0.05	0.172	145.8
600	2117	2177	2147	0.03	0.192	152.3
620	2195	2263	2229	0.01	0.219	158.1
640	2446	2439	2443	0	0.471	173.3
660	2932	3131	3032	0	0.959	215.1
680	3029	3250	3140	0	1.017	222.7
700	3110	3518	3311	0	1.119	234.8

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A 4.5 (Cont) SHANK TENSION / TORQUE; STRAIN, GAP AND EXTENSION

Test No TT5

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	mean	Average gap mm	mean extension mm	Shank tension kN
0	0	0	0	1.76	0	0
50	-31	266	117	-	0.006	8.3
400	1013	1180	1096	1.35	0.084	77.7
420	1110	1326	1217	1.03	0.100	86.3
440	1185	1401	1293	0.95	0.101	91.7
460	1101	1538	1320	0.91	0.106	93.6
480	1129	1720	1425	0.80	0.113	101.1
500	1113	1806	1460	0.76	0.116	103.6
520	1158	1823	1491	0.74	0.117	105.7
540	1229	1836	1532	0.67	0.118	108.6
560	1315	1869	1592	0.57	0.121	112.9
580	1441	1846	1644	0.51	0.123	116.6
600	1803	1715	1759	0.37	0.143	124.7
620	2026	1664	1845	0.29	0.153	130.8
640	2383	1606	1995	0.11	0.165	141.5
660	2432	1737	2085	0.04	0.171	147.9
680	2356	2136	2246	0.01	0.344	159.3
700	2391	2305	2348	0	0.463	166.5

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE: STRAIN, GAP AND EXTENSION

Test No TT6

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0		1.83	0	0
50	213	361	-214	120	-	0.003	8.5
400	1318	1021	796	1045	1.42	0.077	74.1
420	1167	1421	702	1096	1.31	0.081	77.7
440	1639	1646	416	1291	1.05	0.093	91.5
460	1652	1686	454	1331	1.02	0.097	94.4
480	1811	1757	407	1402	0.95	0.107	99.4
500	2162	1970	492	1541	0.76	0.115	109.3
520	2309	1989	799	1668	0.60	0.123	118.3
540	2320	1910	863	1697	0.60	0.125	120.3
560	2370	1818	1187	1791	0.45	0.130	127.0
580	2425	1718	1490	1877	0.34	0.142	133.1
600	2380	1694	1696	1923	0.30	0.149	136.4
620	2377	1712	1988	2025	0.18	0.159	143.6
640	2435	1778	2183	2152	0.14	0.173	152.6
660	2366	1876	2443	2228	0.08	0.221	158.0
680	2272	2059	2735	2355	0.03	0.394	167.0
700	2337	2543	3002	2627	0	0.647	186.3

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION/TORQUE: STRAIN, GAP AND EXTENSION

Test No TT7

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	0	1.82	0	0
50	41	70	280	130		0.007	9.2
400	988	1241	1738	1322	0.94	0.103	93.7
420	988	1241	1738	1322	0.94	0.103	93.7
440	1064	1277	1776	1372	0.92	0.106	97.3
460	1104	1288	1811	1401	0.88	0.107	99.3
480	1099	1421	2095	1538	0.75	0.117	109.1
500	1165	1427	2240	1611	0.61	0.122	114.2
520	1255	1475	2356	1695	0.53	0.130	120.2
540	1446	2085	2386	1972	0.19	0.167	139.8
560	1522	2088	2425	2012	0.14	0.171	142.7
580	2007	2317	2345	2223	0.06	0.376	157.7
600	2007	2317	2345	2223	0.06	0.376	157.7
620	2274	2478	2492	2415	0.03	0.538	171.3
640	2274	2478	2492	2415	0.03	0.538	171.3
660	3003	3031	2981	3005	0	0.922	213.1
680	3266	3132	3203	3194	0	1.004	226.6
700	3904	3315	3468	3562	0	1.229	252.6

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE; STRAIN, GAP AND EXTENSION

Test No TT8

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	0	1.79	0	0
50	199	51	216	155		0.011	11.0
400	1184	1365	1893	1480	0.62	0.132	104.9
420	1307	1479	2131	1639	0.38	0.144	116.2
440	1313	1534	2241	1696	0.30	0.148	120.3
460	1408	1665	2277	1783	0.19	0.160	126.4
480	1777	1895	2254	1975	0.08	0.172	140.1
500	1892	1936	2324	2050	0.05	0.179	145.4
520	1990	1964	2330	2089	0.04	0.188	148.2
540	1977	1949	2285	2070	0.02	0.186	146.8
560	2057	2044	2297	2132	0	0.204	151.2
580	2301	2458	2332	2363	0	0.549	167.6
600	2979	3036	2692	2902	0	0.999	205.8
620	3100	3078	2753	2977	0	1.027	211.1
640	3260	3134	2893	3095	0	1.114	219.5
660	3260	3134	2893	3095	0	1.114	219.5
680	3374	3177	2964	3171	0	1.163	224.9
700	3771	3961	3738	3823	0	2.535	271.2

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE: STRAIN, GAP AND EXTENSION

Test No TT9

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	0		0	0
50	253	-54	707	302		0.002	21.4
400	1670	723	1831	1408	1.22	.099	99.8
440	1723	760	1988	1490	1.09	0.106	105.7
480	1680	975	2365	1674	0.77	0.121	118.7
520	1913	1023	2721	1886	0.53	0.134	133.7
540	2024	1115	2839	1993	0.43	0.147	141.3
560	2158	1186	2872	2072	0.28	0.163	146.9
580	2278	1420	2863	2187	0.16	0.176	155.1
600	2356	1795	2803	2318	0.08	0.195	164.4
620	2463	2225	2839	2509	0.02	0.453	177.9
640		2480			0		

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE: STRAIN, GAP AND EXTENSION

Test No TT10

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	0		0	0
400	1414	982	2207	1534	0.72	0.123	108.8
440	1575	872	2345	1597	0.65	0.130	113.3
480	1691	964	2469	1708	0.32	0.140	121.1
520	1922	1325	2257	1834	0.23	0.150	130.1
540	2010	1502	2126	1879	0.20	0.154	133.2
560	2201	1794	1943	1979	0.12	0.166	140.3
580	2350	2012	1804	2055	0.08	0.176	145.7
600	2434	2195	1723	2117	0.04	0.189	150.1
620	2458	2348	1816	2207	0	0.216	156.5
640	2490	2404	1873	2255	0	0.232	159.9
660	2539	2504	2238	2427	0	0.366	172.1
680	2673	2619	2507	2599	0	0.515	184.3

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE: STRAIN, GAP AND EXTENSION

Test No TT11

Applied Torque Nm	Strain x 10^{-6} strain gauges 1	2	3	mean	Average gap mm	Mean extension mm	Shank tension kN
0	0	0	0	0		0	0
400	1764	1479	829	1357	1.09	0.099	96.2
440	1820	1505	945	1423	1.00	0.100	100.9
480	1934	1580	955	1490	0.94	0.102	105.7
520	2174	1785	898	1619	0.78	0.110	114.8
540	2366	2004	930	1767	0.61	0.123	125.3
560	2446	2080	1291	1939	0.27	0.134	137.5
580	2796	2029	1834	2220	0.06	0.165	157.4
600	2854	2107	2104	2355	0.02	0.228	167.1
620	3078	2340	2504	2641	0	0.546	187.3
640	3561	2762	3068	3130	0	0.849	222.0

i 20 mm dia HSFG bolts from batch 2c

ii Tensile stress area for shank tension 305.424 mm^2

iii E_a for shank 232.25 kN/mm^2

TABLE A.4.5 (Cont) SHANK TENSION / TORQUE: STRAIN, GAP AND EXTENSION

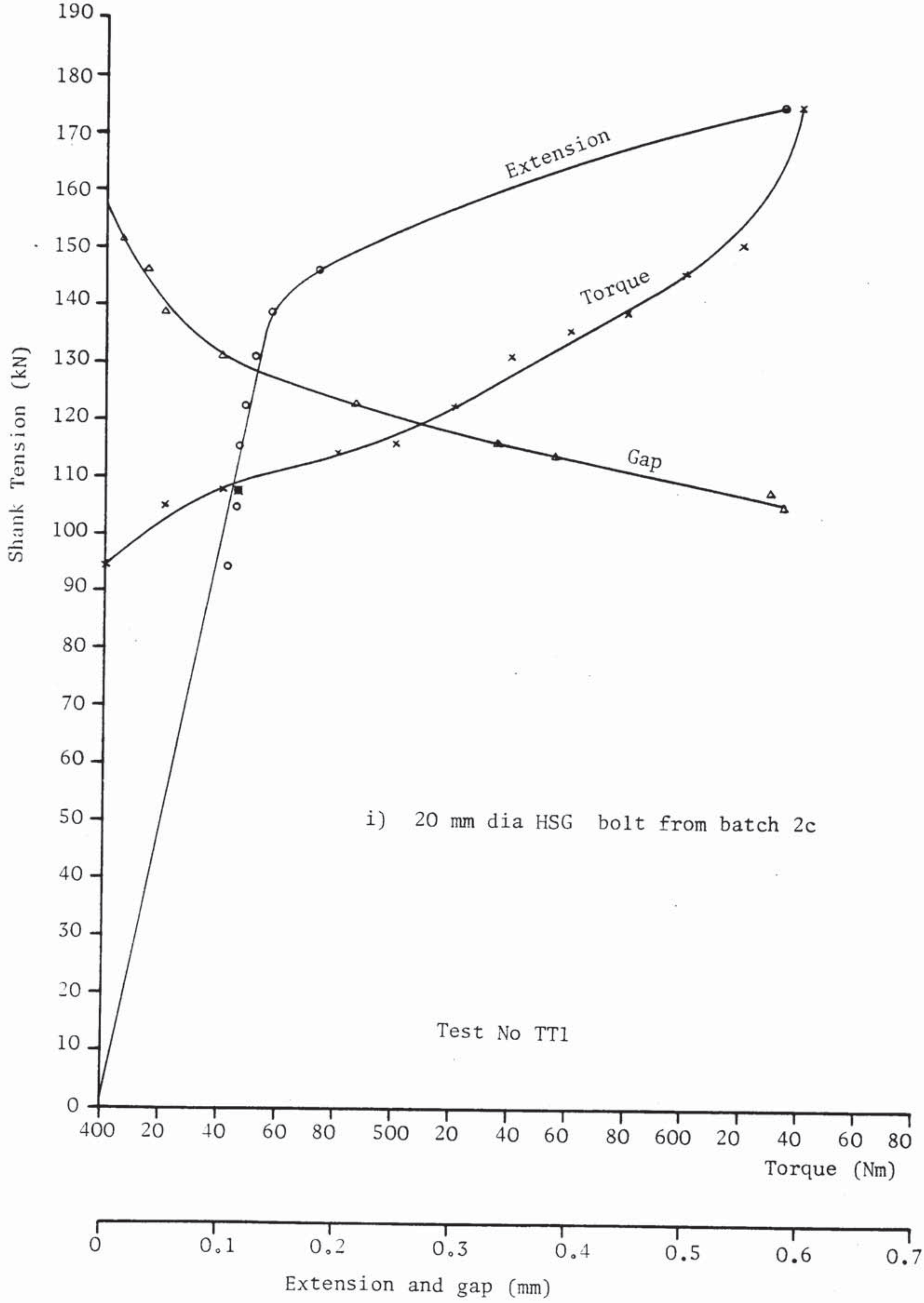


FIGURE A.4.6 SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

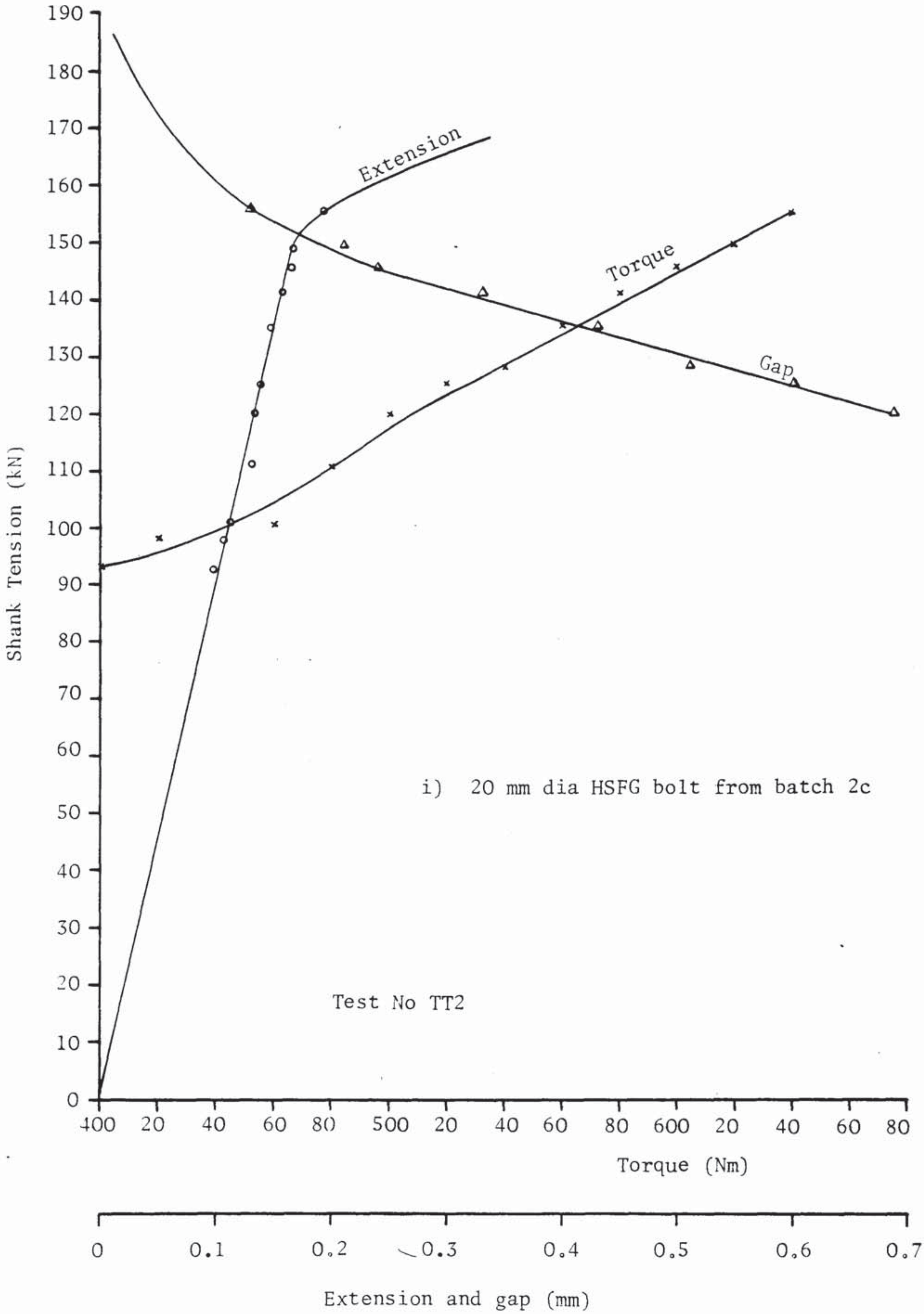


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

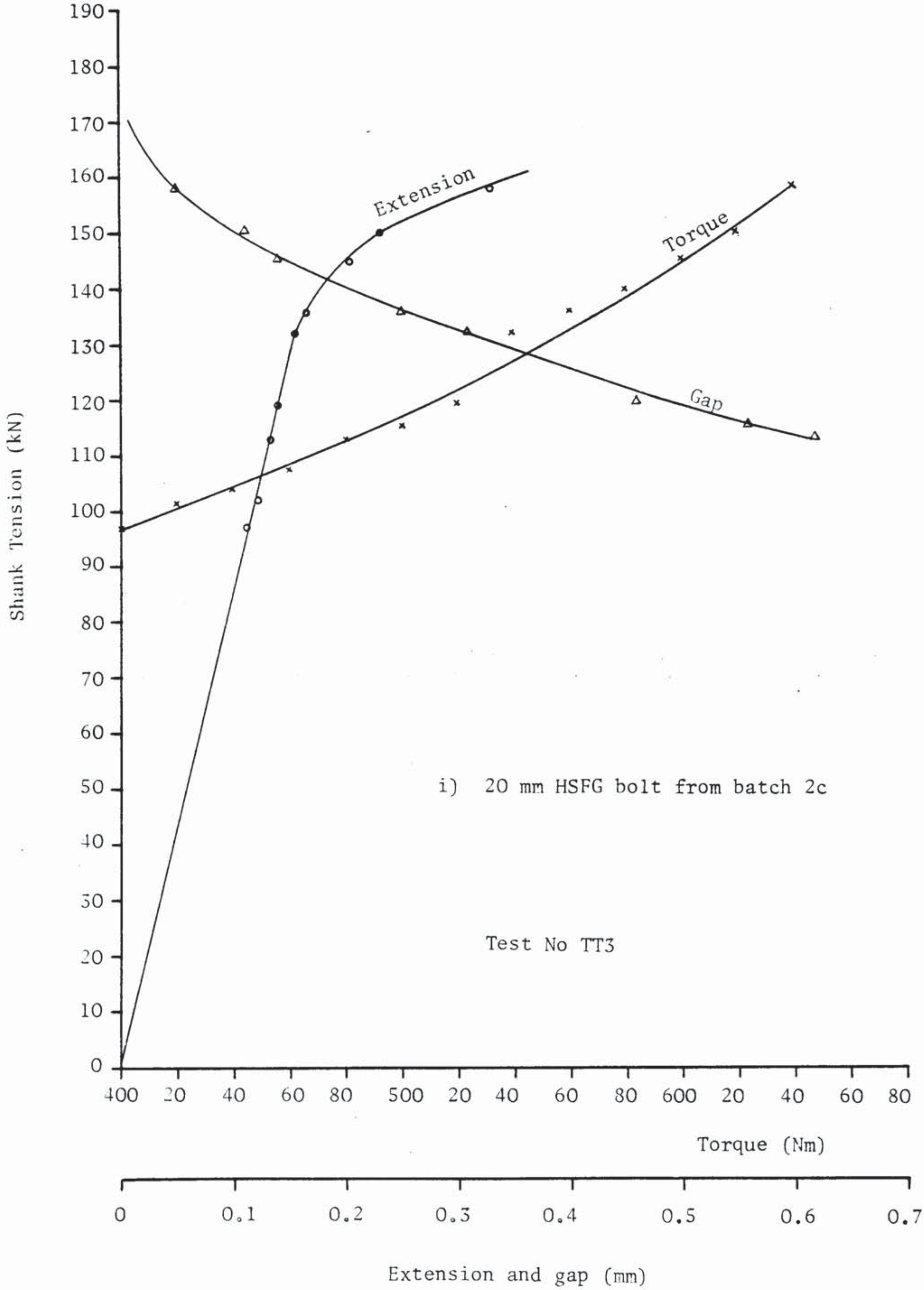


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

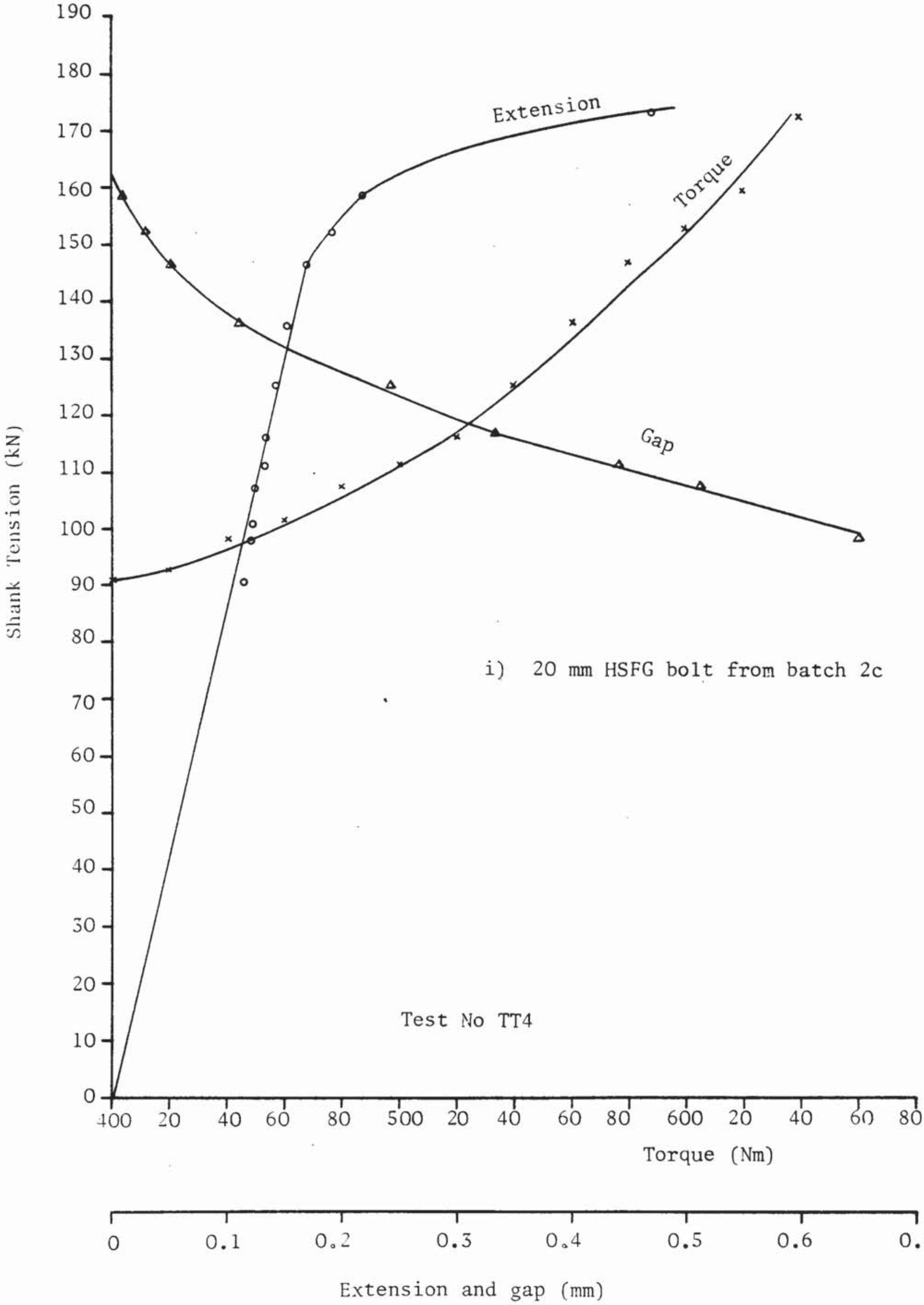


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

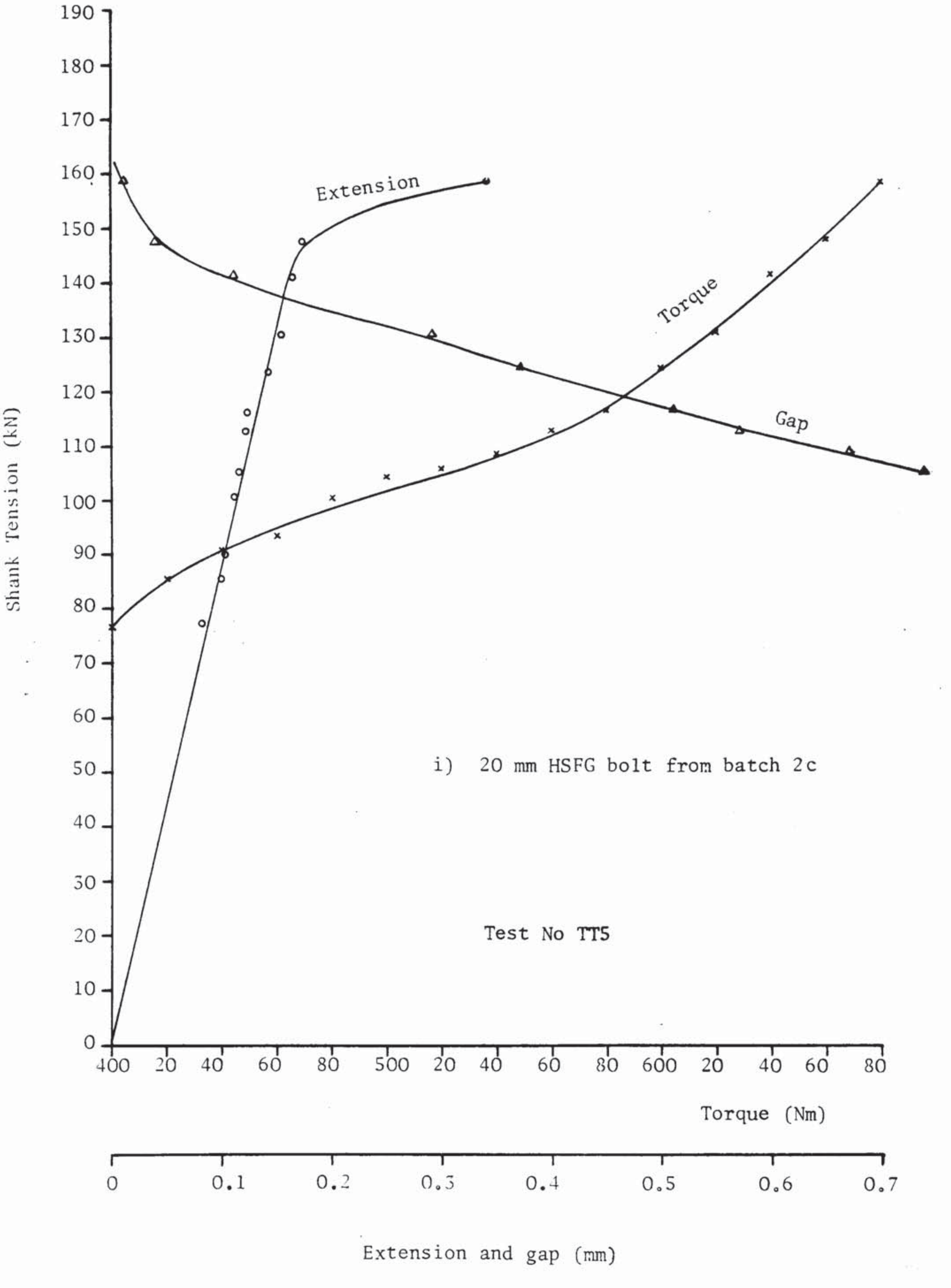


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

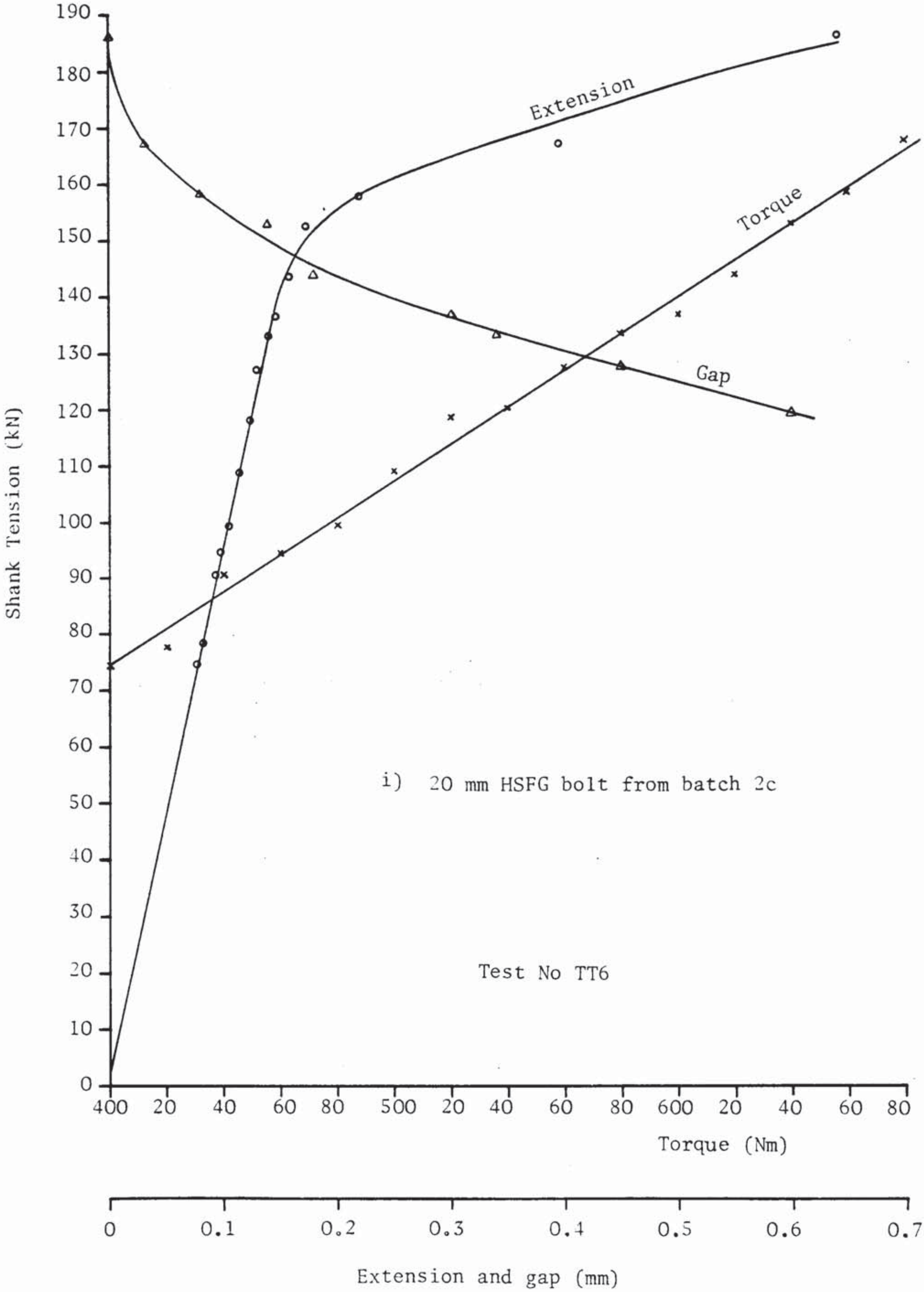


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

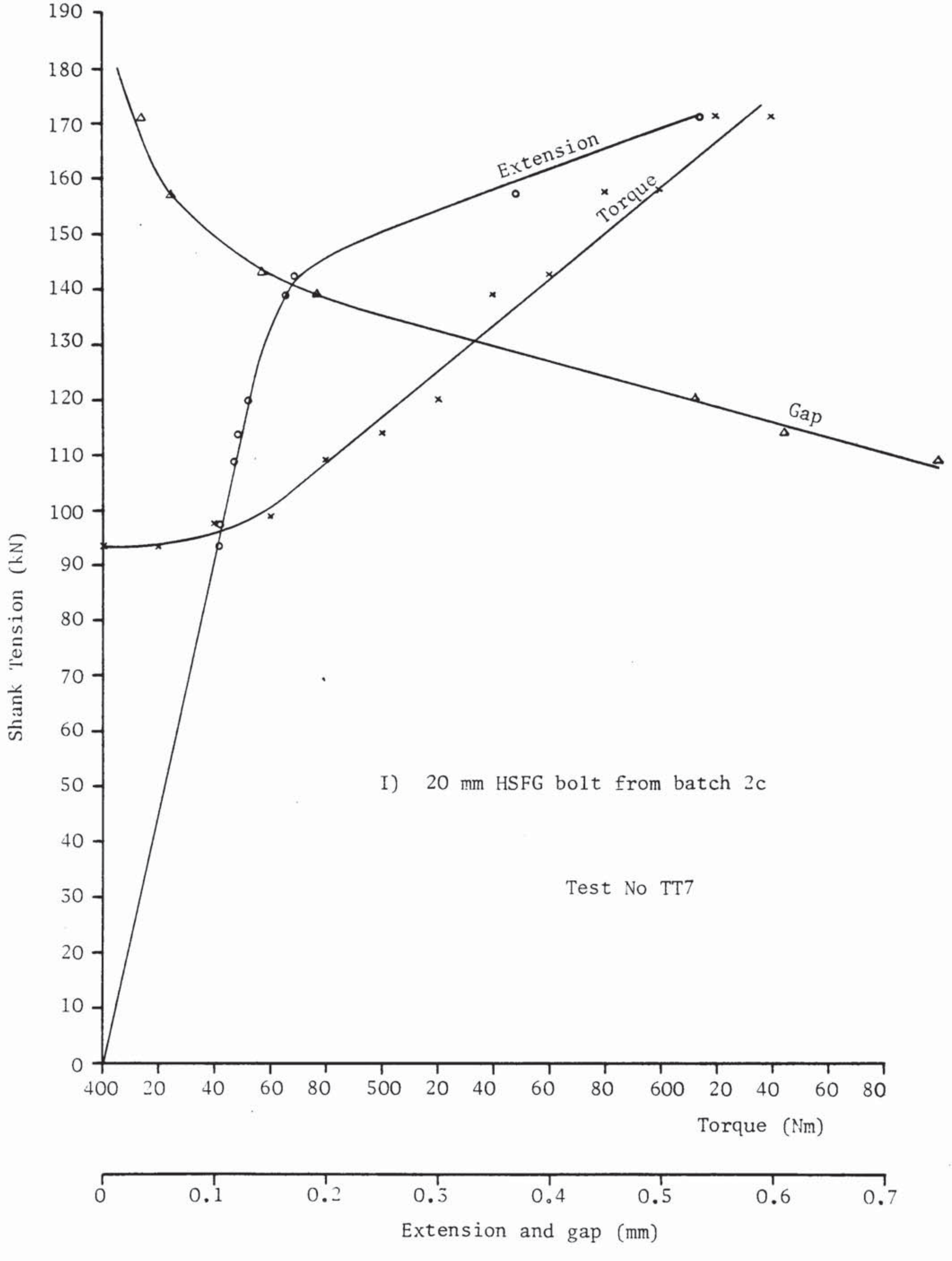


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

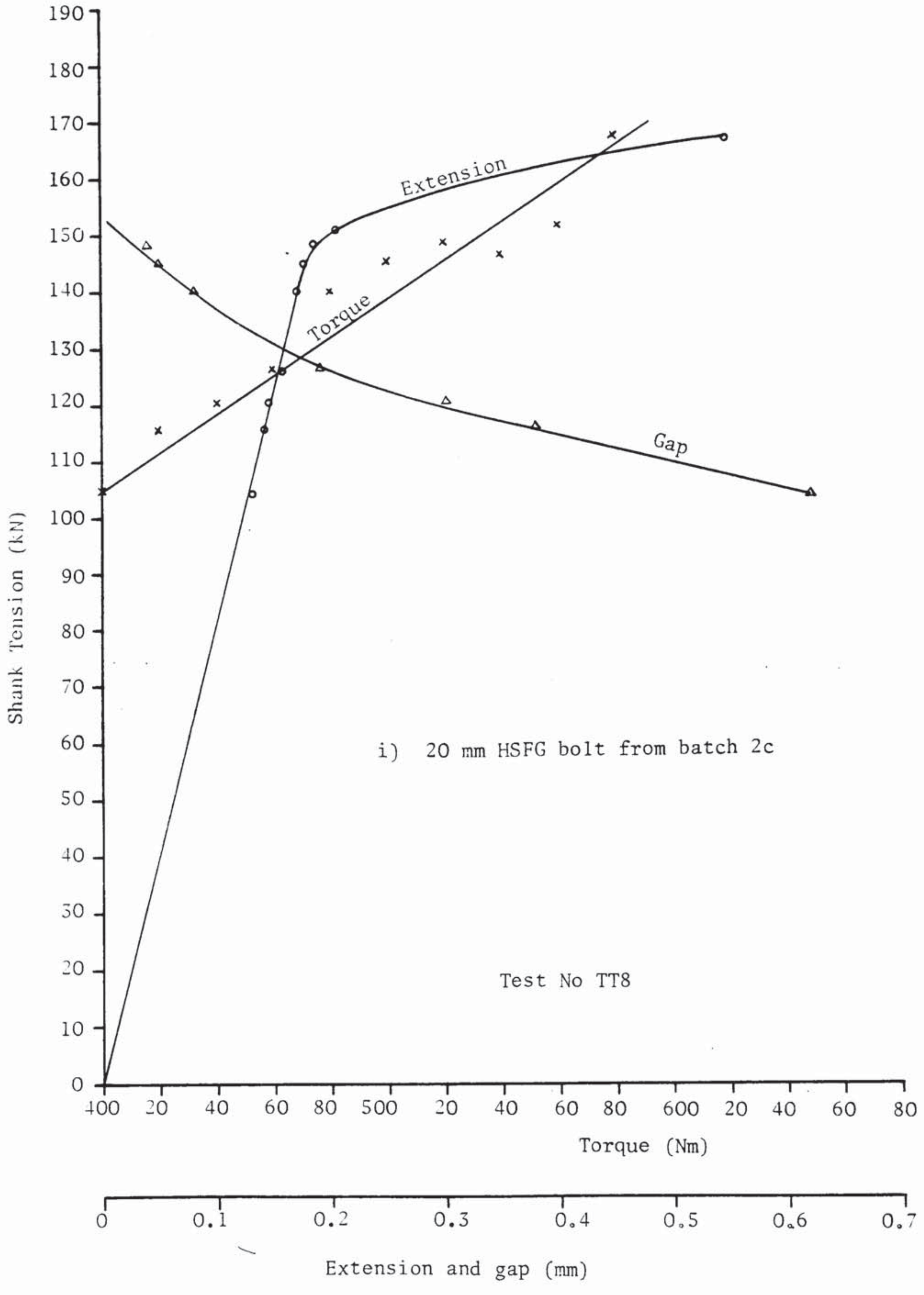


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

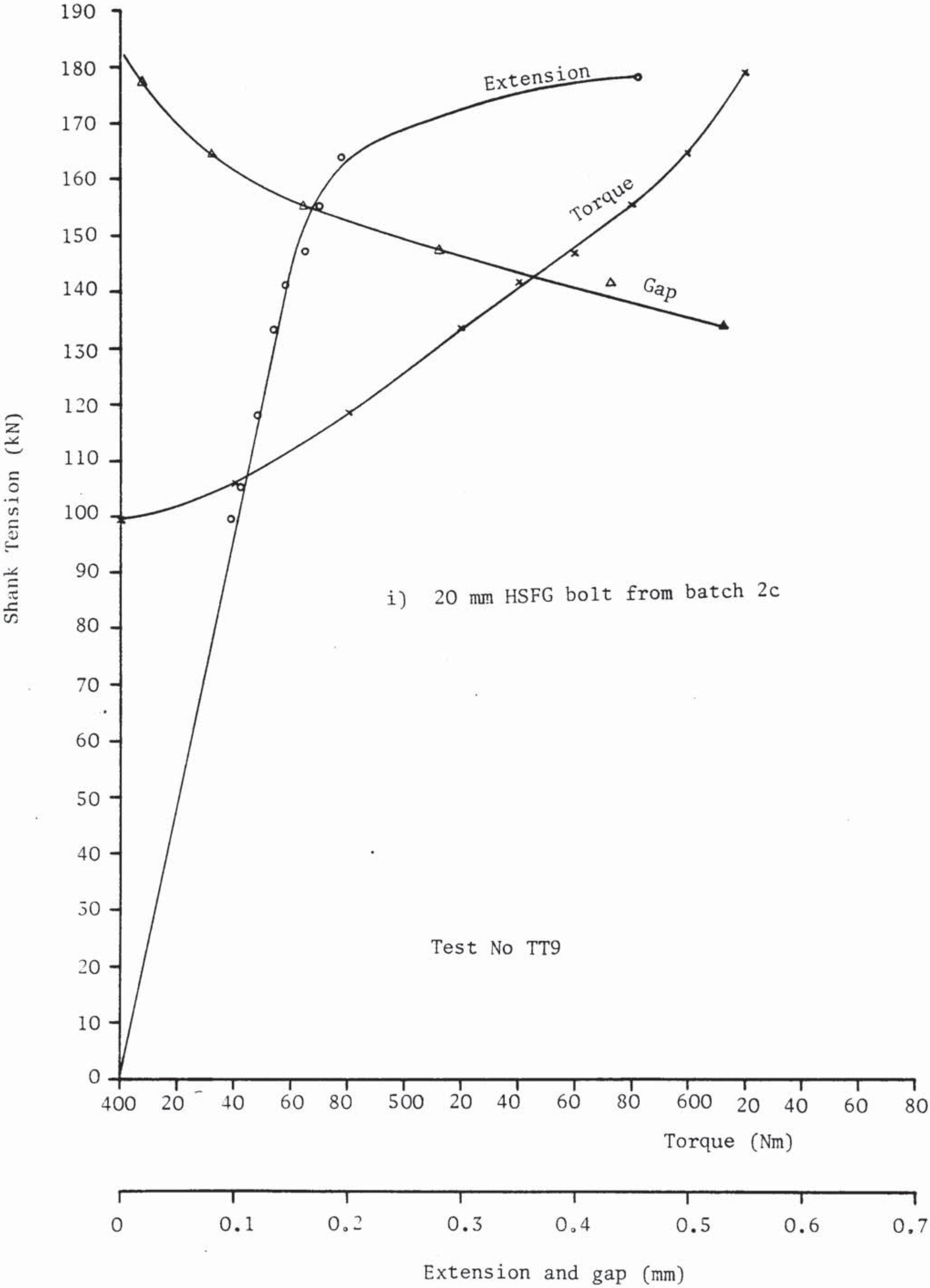


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

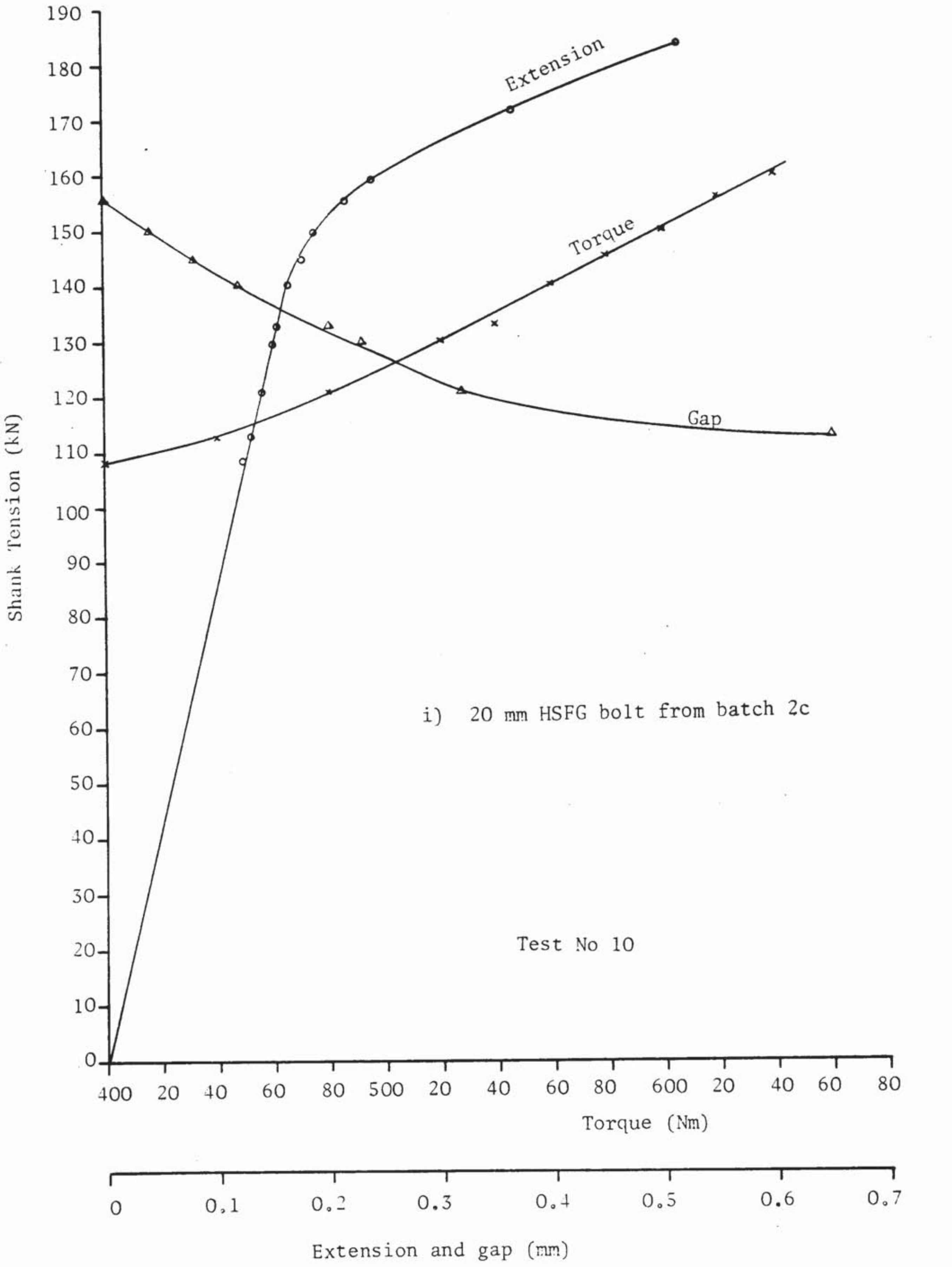


FIGURE A.4.6 (Cont) SHANK TENSION/TORQUE; EXTENSION AND GAP RELATIONSHIP

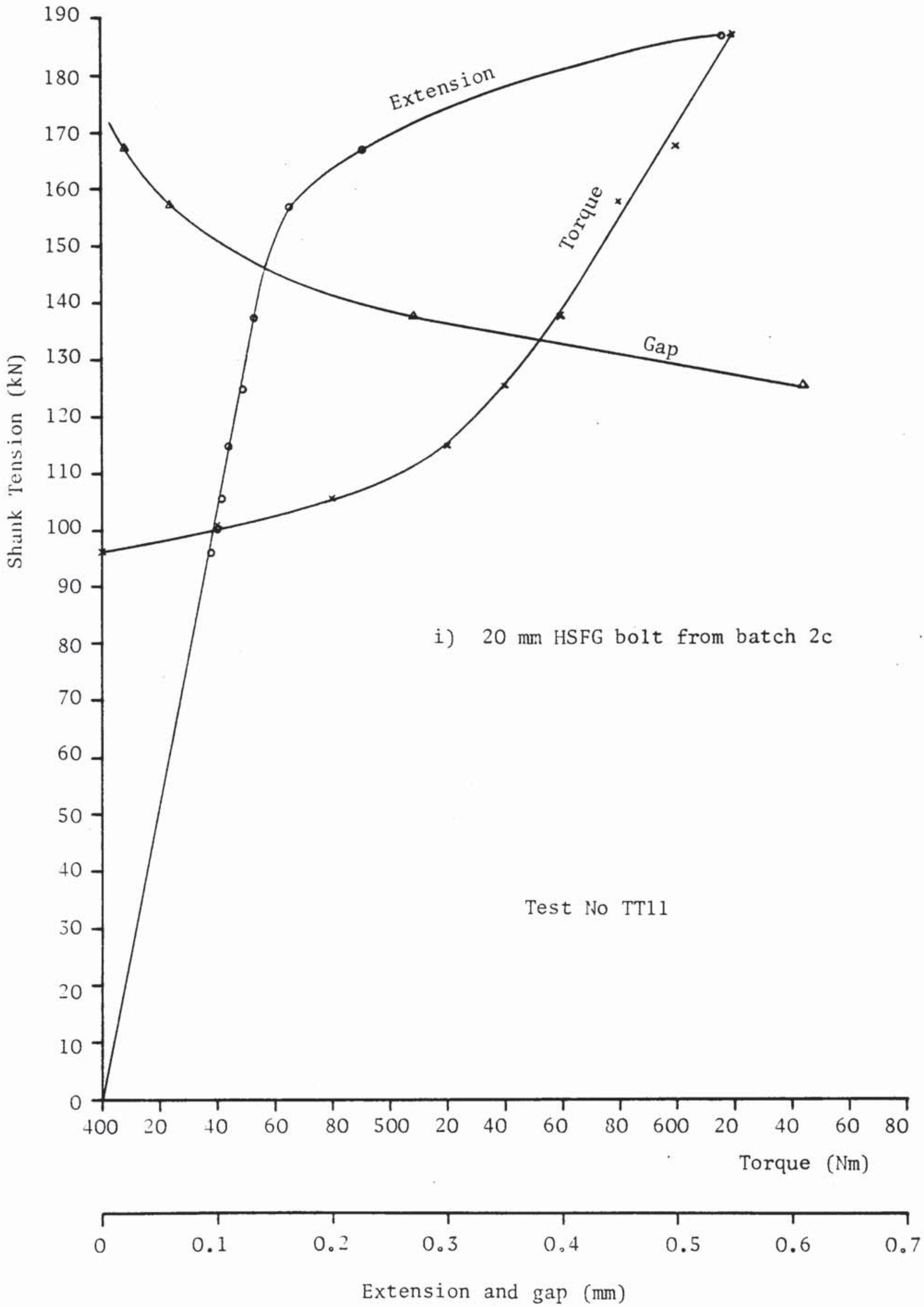


FIGURE A.4.6 (Cont) SHANK TENSION TORQUE; EXTENSION AND GAP RELATIONSHIP

Lot*	No of specimen tested	ℓ_s* (in)	ℓ_t* (in)	δ_b* (in)	P_{theory} = n(4.2) (kips)	P_{theory}/P_{test}*
B	5	3.50	0.75	0.010	33.4	0.92
C	5	7.25	1.00	0.023	43.1	1.19
D	5.	3.50	0.75	0.010	33.4	0.92
Z	8	3.50	0.75	0.010	33.4	0.92
Q	3	3.25	1.00	0.012	39.6	1.09
R	3	2.25	2.00	0.010	31.2	0.86
S	3	0	4.25	0.021	58.5	1.62
T	3	4.25	0.75	0.014	40.9	1.13
U	3	4.75	0.75	0.015	40.4	1.12
V	3	5.25	1.00	0.016	38.3	1.06
W	3	6.25	0.75	0.017	37.2	1.03
H	7	7.75	0.375	0.018	34.9	0.97
E	4	4.00	0.250	0.011	37.9	1.05
E	5	4.00	0.125	0.010	35.6	0.98
8A	5	3.75	0.25	0.010	36.2	1.00
8B	5	4.00	0.125	0.010	35.6	0.98
8B	5	4.00	0.25	0.011	37.9	1.05
Total 75			Mean and Standard Deviation			1.05 ±0.17

i 7/8" ϕ A325 bolts; $A_t = 0.462$ in^2 and $A_t/A_s = 0.77$

ii $E_s = E_t = 29 \times 10^3$ Kips/in^2

iii $\ell_n = 0.859$ in

iv $\alpha_D = 0.654$ at proof load from Table 4.4

v $P_{test} = 36$ Kips

vi * Rumpf and Fisher (17)

TABLE A.4.7 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS (Direct tension tests)

Lot*	No of specimen tested	ℓ_s* (in)	ℓ_t* (in)	δ_b* (in)	P_{theory} = n(4.2) (Kips)	P_{theory}/P_{test}*
B	3	3.5	0.75	0.009	28.0	0.77
D	4	3.5	0.75	0.010	31.1	0.86
D	4	3.5	0.30	0.009	31.3	0.86
Z	8	3.5	0.75	0.009	28.0	0.77
Q	3	3.25	1.00	0.014	43.0	1.19
T	3	4.25	0.75	0.015	41.2	1.14
U	3	4.75	0.75	0.015	38.2	1.06
V	3	5.25	1.00	0.017	38.6	1.07
W	3	6.25	0.75	0.018	37.6	1.04
H	6	7.75	0.375	0.019	35.4	0.98
E	3	4.00	0.250	0.012	38.4	1.06
E	3	4.00	0.125	0.011	36.3	1.00
8A	5	3.75	0.25	0.010	33.5	0.93
8A	3	3.75	0.75	0.010	29.8	0.82
8B	5	4.00	0.125	0.012	39.6	1.09
8B	4	4.00	0.25	0.013	41.6	1.15
Total 62				Mean and Standard deviation		0.986 ±0.136

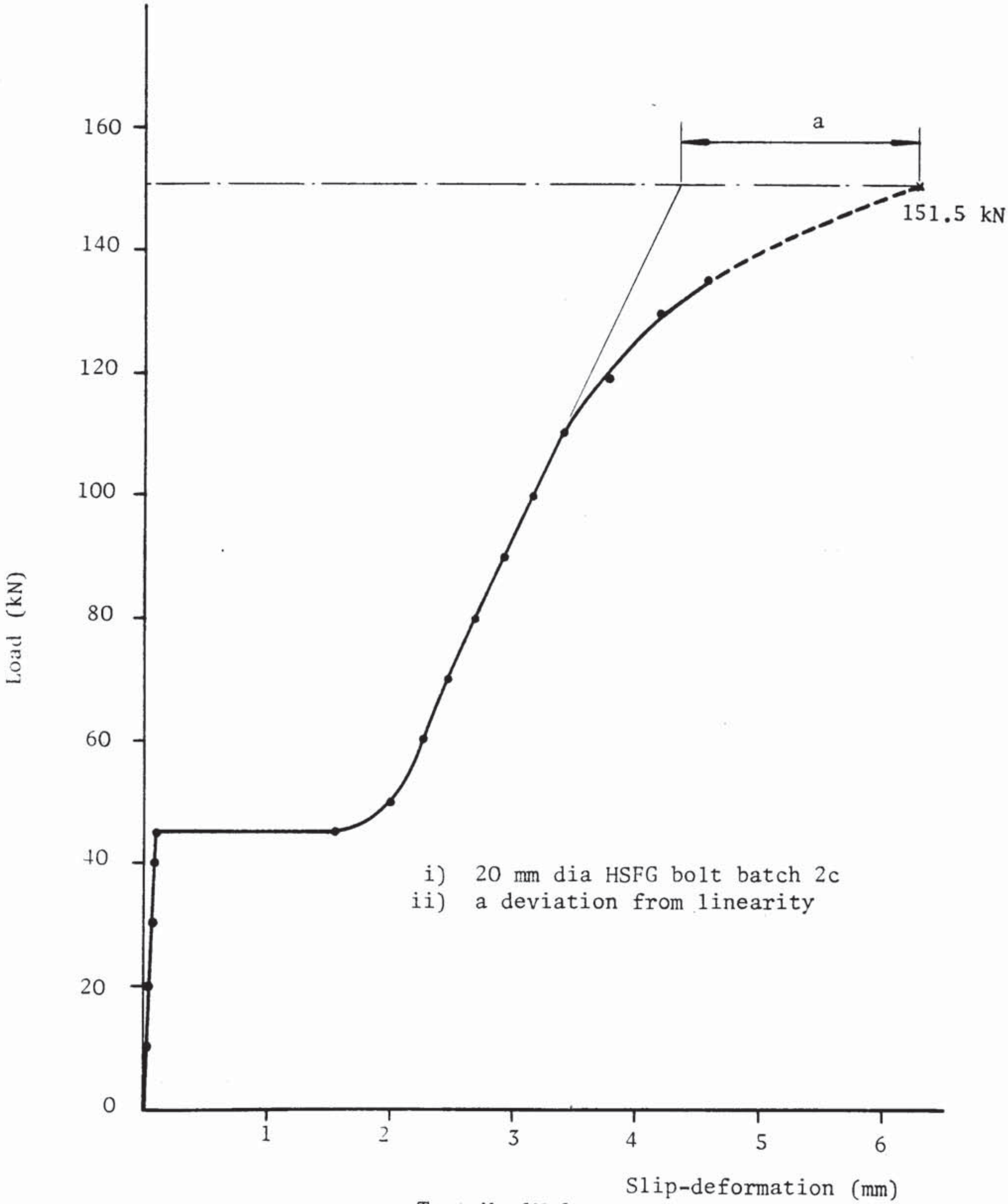
i) 7/8" ϕ A325 bolts $A_t = 0.462\ in^2$ and $A_t/A_s = 0.77$
ii) $E_s = E_t = 29 \times 10^3\ Kips/in^2$
iii) $\ell_n = 0.859$ in
iv) $\alpha_T = 0.999$ at proof load from Table 4.6
v) $P_{test} = 36$ Kips
vi) * Rumpf and Fisher (17)

TABLE A.4.8 COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS (Torque Test)

Test No	$1H_t1$	$1H_t2$	$1H_t3$	$1H_t4$	$1H_t5$	$1H_t6$
Load (kN)	Amount of slip-deformation (mm)					
0	0	0	0	0	0	0
9.96	0.025	0.029	0.026	0.011	0.040	0.062
19.93	0.046	0.050	0.044	0.034	0.068	0.093
29.90	0.064	0.070	0.064	0.050	0.094	0.118
31.89	0.068	0.075	0.069	0.053	0.100	0.124
33.89	0.072	0.079	0.075	0.056	0.107	0.128
35.88	0.077	0.089	0.078	0.059	0.110	0.132
37.87	0.082	0.123	0.083	0.066	0.114	0.138
39.87	0.087	0.291	0.087	0.072	0.123	0.143
41.86	0.093	0.335	0.092	0.076	0.132	0.147
43.86	0.106	0.631	0.098	0.082	0.165	0.153
44.85	1.547*	0.752	0.121	0.084	1.891*	0.155
46.25	1.581	0.823	1.678*	0.087	1.973	0.163
47.84	1.927	1.079	1.701	0.094	2.056	0.170
48.64	-	-	-	-	-	2.386*
49.84	2.092	1.223	1.728	2.237*	2.133	2.388
50.83	-	2.306*	-	-	-	-
51.83	2.116	2.335	1.775	2.266	2.219	2.419
53.82	2.165	2.389	1.831	2.304	2.250	2.450
55.82	2.203	2.445	1.884	2.345	2.281	2.481
57.81	2.262	2.495	1.939	2.389	2.420	2.512
59.80	2.288	2.566	1.975	2.430	2.470	2.543
69.77	2.493	2.814	2.275	2.628	2.790	2.743
79.73	2.691	2.985	2.493	2.836	3.101	2.866
89.70	2.909	3.075	2.739	3.073	3.256	3.065
99.67	3.144	3.255	2.982	4.278	3.669	3.247
109.64	3.428	3.479	3.276	4.532	3.863	3.487
119.60	3.803	3.771	3.658	3.832	4.373	3.877
129.57	4.265	4.186	4.137	4.214	4.795	4.029
135.55	4.630	-	4.482	-	5.020	-
139.54	-	4.85	4.903	4.73	-	-
143.53	-	-	failed	-	-	-
148.31	-	failed		-	-	-
148.51	-			-	failed	-
150.51	-			-		failed
151.50	failed			-		
160.27				failed		

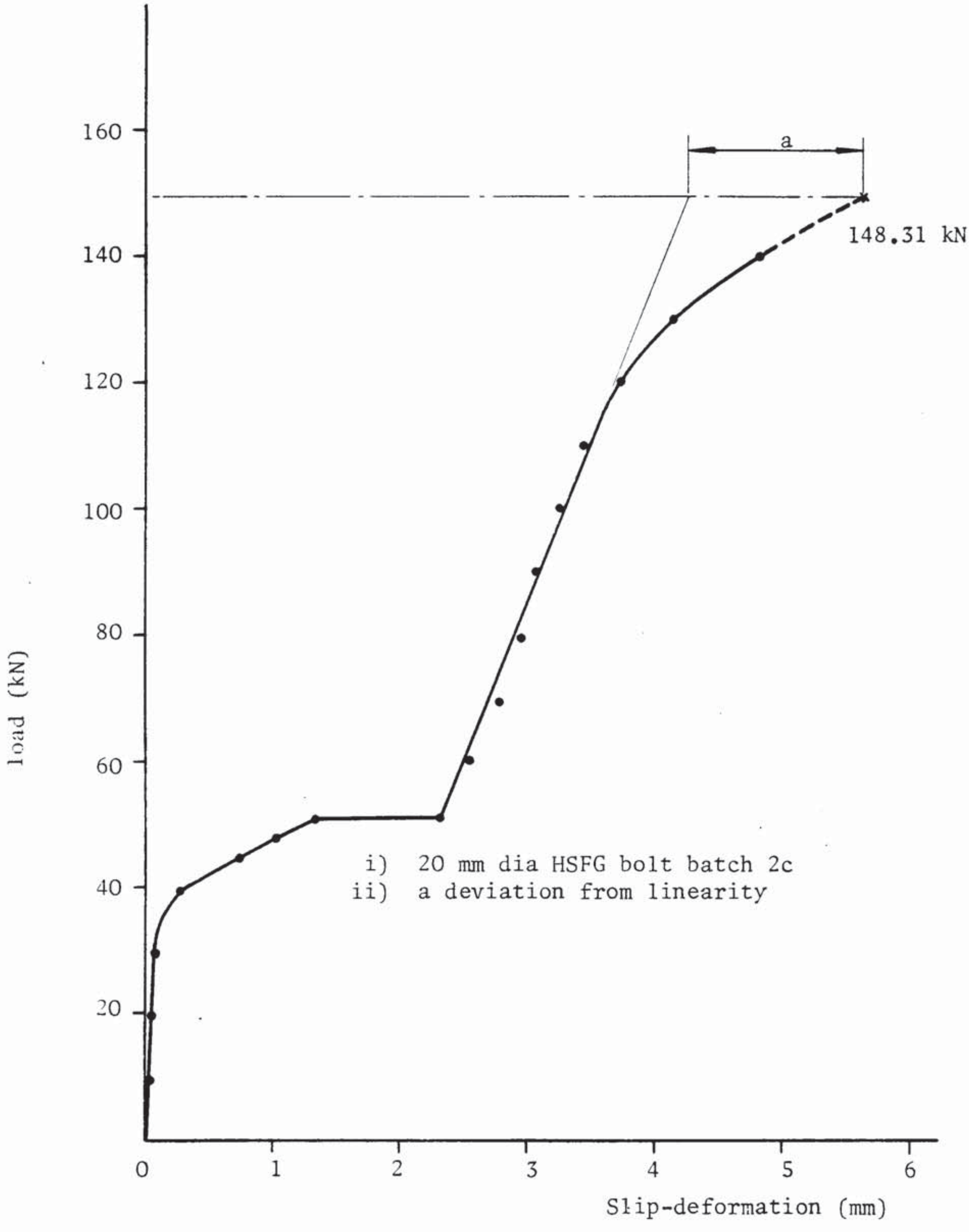
i) 20 mm dia HSFG bolts from batch 2c
ii) Indicates the area at which major slip occurred

TABLE A.4.9 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Series 1_t single bolt)



Test No $1H_t1$

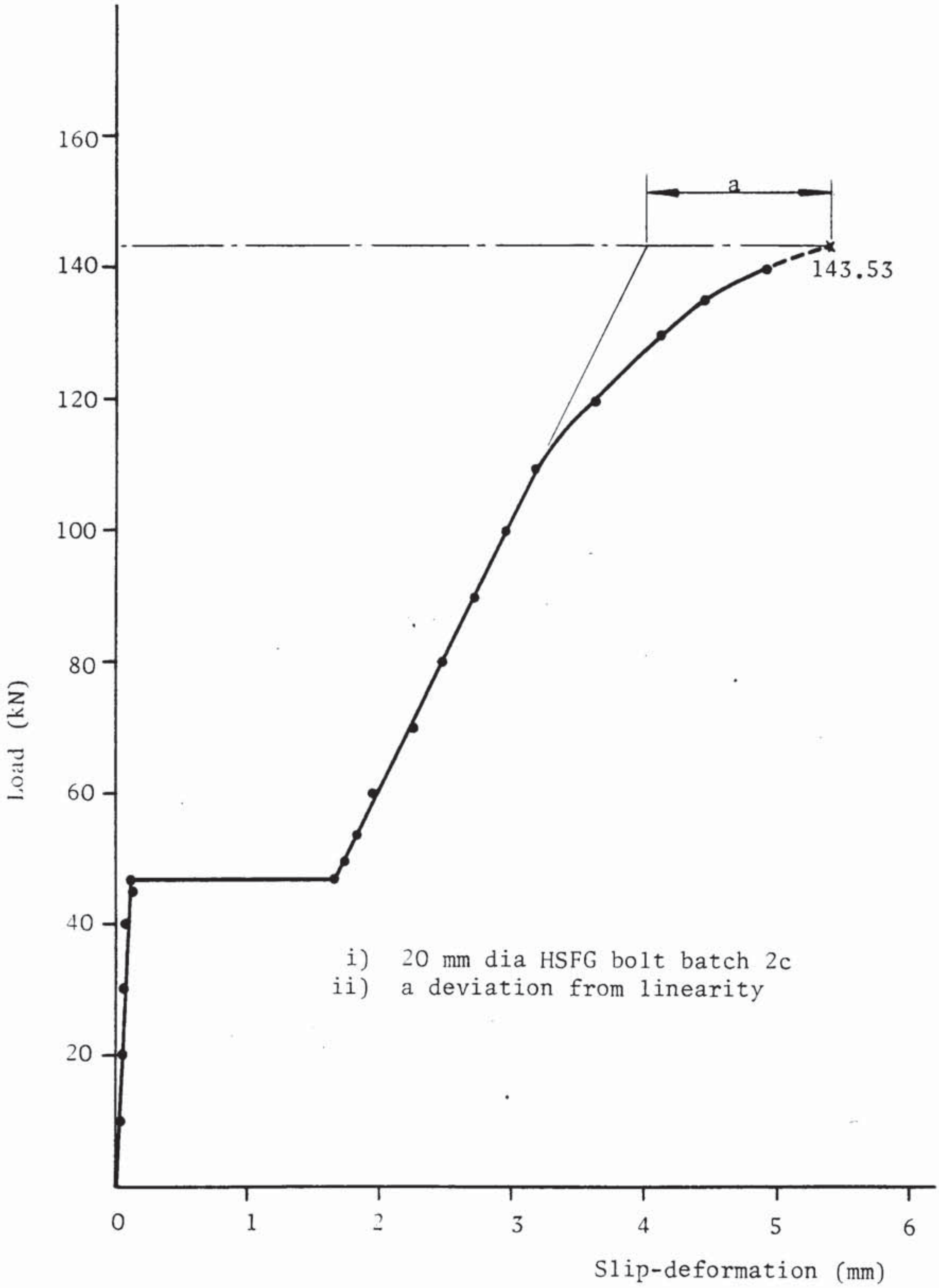
FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Single bolt)



Test No $1H_t2$

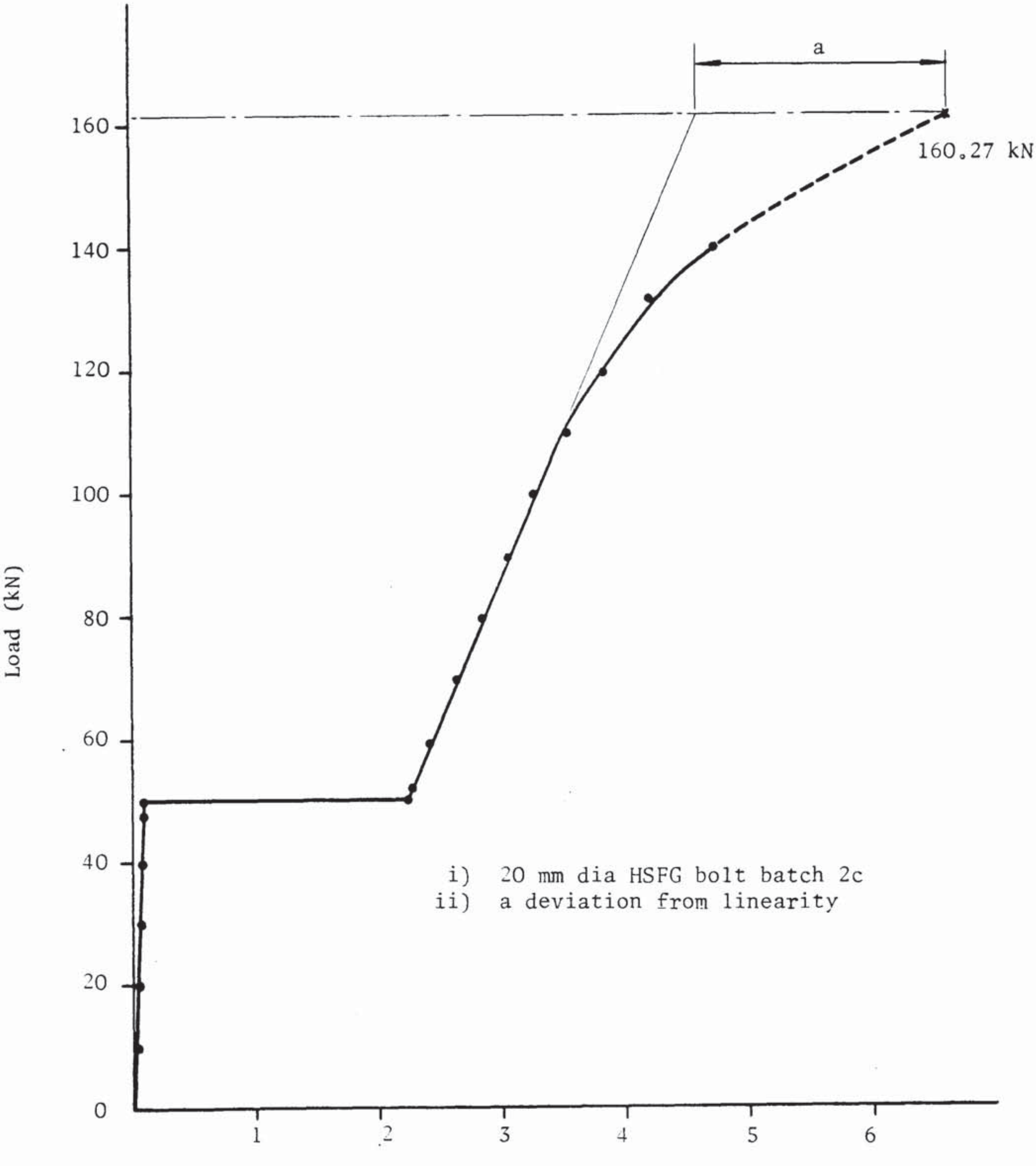
FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP

(Single bolt) (Cont)



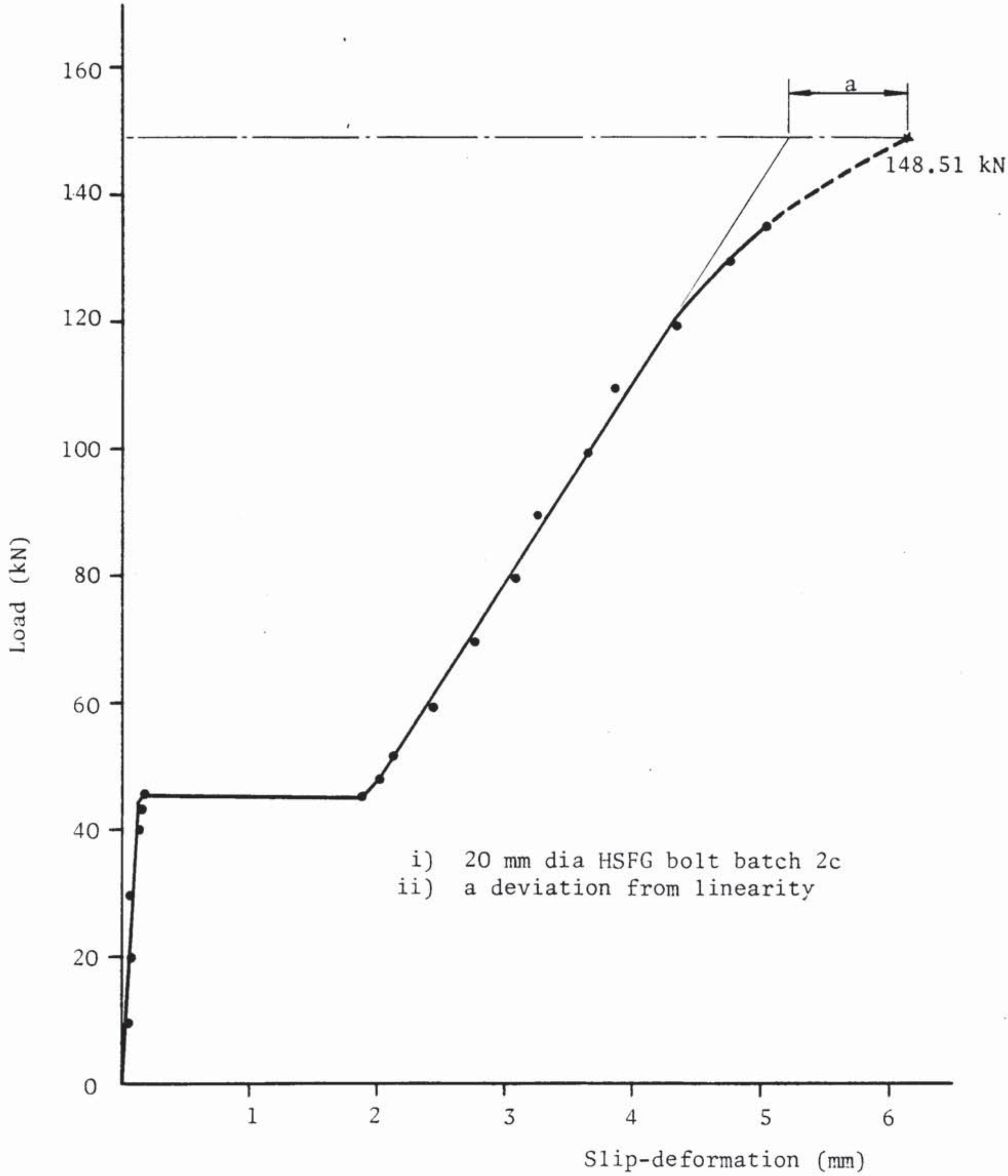
Test No $1H_t3$

FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Single bolt) (Cont)



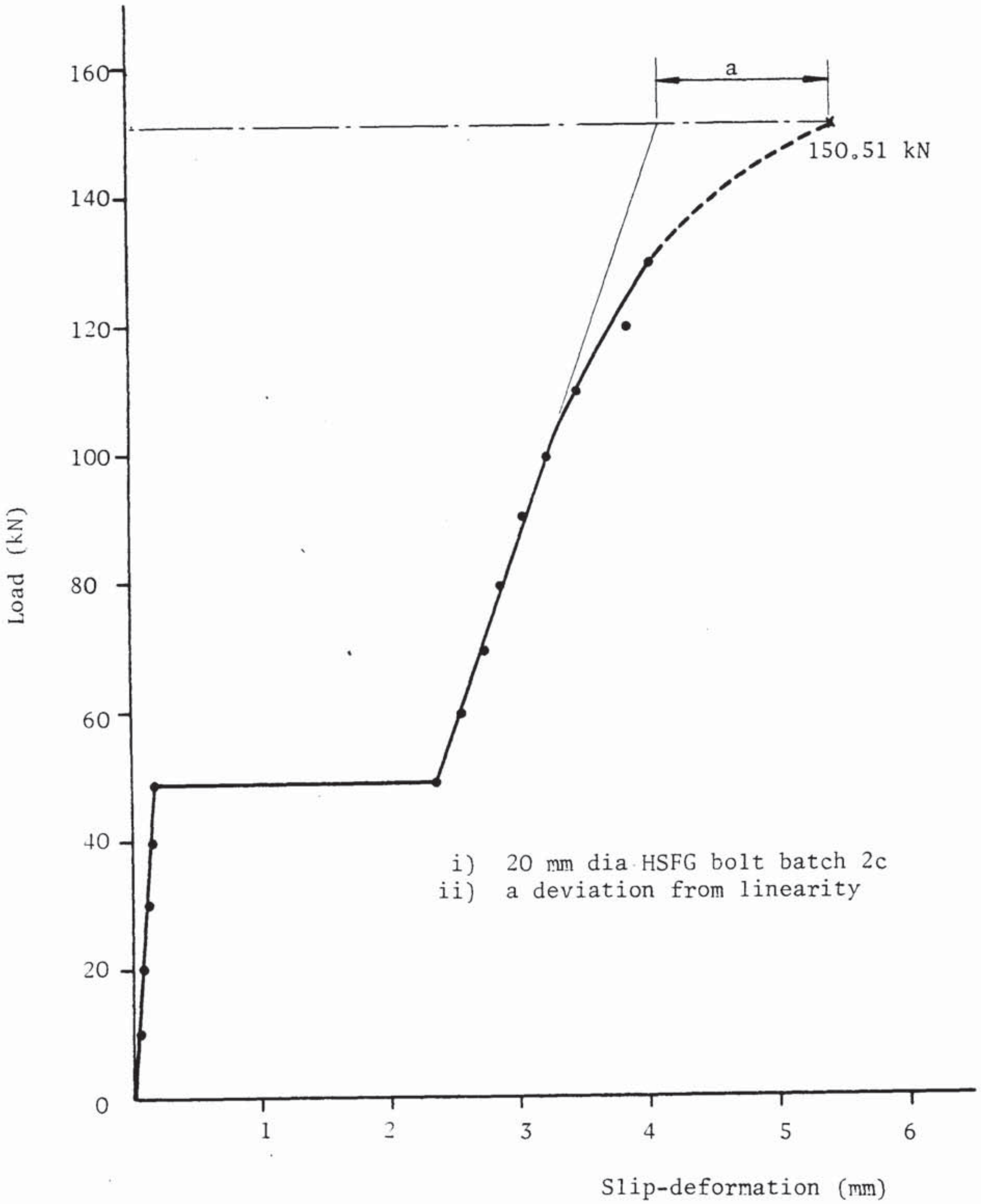
Test No $1H_t4$

FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Single bolt) (Cont)



Test No $1H_t5$

FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP (Single bolt) (Cont)



Test No $1H_t6$

FIGURE A.4.10 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Single bolt) (Cont)

Specimen label	L_1 mm	L_2 mm	L_3 mm	W_s slip load kN	W failure load kN	Bolt No which fractured
$2H_t1$*		Torsion moment only				1
$2H_t2$*		Torsion moment only				1
$2H_t3$	1295	1930	-10	5.98	33.89	2
$2H_t4$	1355	1325	50	9.97	44.61	2
$2H_t5$	1299	991	-6	19.93	58.81	1
$2H_t6$	1299	742	-6	29.40	74.75	2
$2H_t7$	1306	386	1	51.83	129.58	2

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

iii For loading system see Figure 3.9

iv *Loading system produced torsion moment only

TABLE A4.11 SPAN VARIATIONS/SLIP AND FAILURE LOADS

(Two HSFG bolts)

Test No $2H_t3$			Test No $2H_t4$			Test No $2H_t5$		
Calculated V_{test} kN	slip at dial 1 mm	slip at dial 2 mm	Calculated V_{test} kN	slip at dial 1 mm	slip at dial 2 mm	Calculated V_{test} kN	slip at dial 1 mm	slip at dial 2 mm
0	0	0	0	0	0	0	0	0
-0.883	0.020	0.016	1.080	0.045	0.012	1.047	-0.022	0.002
-0.579	0.030	0.018	2.050	0.056	0.015	2.122	0.005	-0.001
-0.275	0.032	0.020	3.021	0.072	0.028	3.197	0.010	0.001
0.287	0.040	0.038	3.990*	0.370	0.139	4.272	0.026	-0.001
0.333*	2.944	3.290	5.933	0.750	0.418	5.347	0.039	-0.001
0.941	3.052	3.420	6.904	1.043	0.623	6.422	0.049	0.002
1.549	3.164	3.564	7.874	1.312	0.873	7.497	0.062	0.007
2.157	3.260	3.704	8.845	1.580	1.205	8.573	0.088	0.020
2.759	3.376	3.856	9.816	1.882	1.334	9.618*	3.027	2.907
3.374	3.482	3.970	10.787	2.100	1.538	10.723	3.083	dial
3.982	3.624	4.114	11.757	-	1.825	11.798	3.323	damaged
4.591	3.766	4.264	12.728	-	2.234	12.873	3.451	
5.199	4.016	4.496	13.699	-	2.672	13.948	3.594	
5.807	4.136	4.618	17.485	Bolt	failed	15.023	3.753	
6.415	4.452	4.902				16.098	3.886	
7.023	4.800	5.200				17.173	4.059	
7.632	5.434	5.694				18.248	4.053	
8.848	Bolt	failed				26.419	Bolt	failed

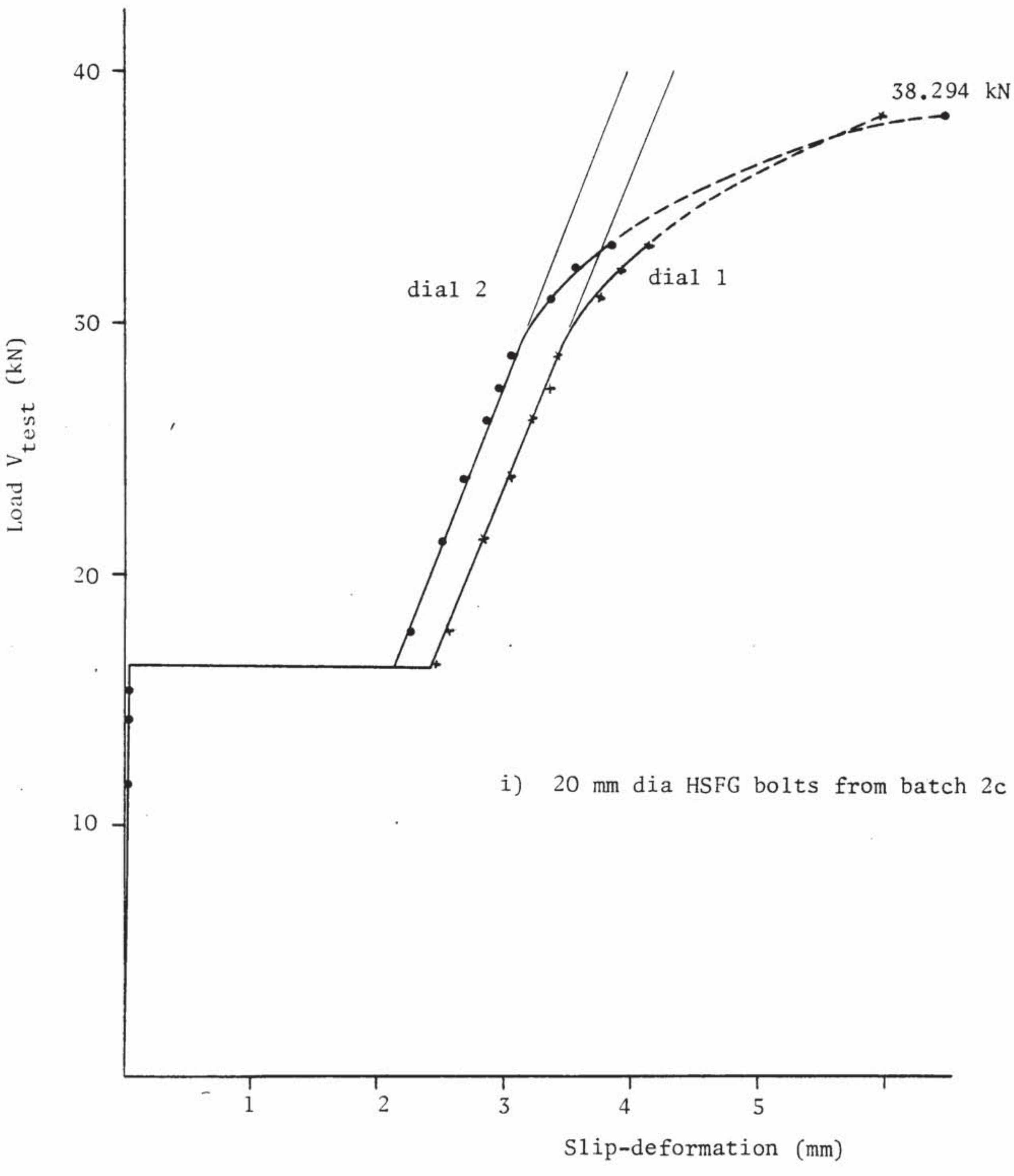
i *Load at which the major slip occurred
ii 20 mm dia HSFG bolts from batch 2C
iii For position of dials see Plate 4.2

TABLE A4.12 CALCULATED TEST LOAD AND SLIP RELATIONSHIP
(Two HSFG bolts)

Test No $2H_t6$			Test No $2H_t7$		
Calculated V_{test} kN	slip at dial 1 mm	slip at dial 2 mm	Calculated V_{test} kN	slip at dial 1 mm	slip at dial 2 mm
0	0	0	0	0	0
3.314	-0.026	0.006	10.045	0	0.002
4.520	-0.024	0.006	15.906	0	0.004
6.932	-0.016	0.006	18.251	0.006	0.004
9.345	-0.012	0.006	21.767	0.018	0.004
11.757	-0.008	0.008	24.112	0.040	0.114
14.169	0	0.020	27.629	0.078	0.216
15.376	0.010	0.042	31.146	0.118	0.308
16.341*	2.486	2.362	32.318	0.134	0.352
17.788	2.546	2.374	33.491	0.346	0.952
18.995	2.650	2.396	34.663*	0.534	1.300
21.407	2.832	2.510	35.835	0.570	1.356
23.820	3.030	2.686	37.007	0.668	1.460
26.232	3.218	2.866	39.352	1.552	1.746
27.438	3.338	2.972	45.213	1.842	1.822
28.645	3.436	3.086	51.074	2.130	2.064
31.057	3.732	3.384	56.936	2.418	2.298
32.263	3.922	3.578	62.797	2.716	2.568
33.469	4.156	3.838	65.728	2.914	2.742
38.294	Bolt failed		80.382	Bolt failed	

i *Load at which the major slip occurred
ii 20 mm dia HSFG bolts from batch 2C
iii For position of dials see Plate 4.2

TABLE A4.12 CALCULATED TEST LOAD AND SLIP RELATIONSHIP (Two HSFG bolts) (Cont)



Test No $2H_t6$

FIGURE A.4.13 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Two bolts)

Specimen label	L_1 mm	L_2 mm	L_3 mm	W_s slip load kN	W failure load kN	Bolt numbers which fractured
$4H_t1$*		Torsion moment only				3, 4
$4H_t2$	1345	1612	78	31.397	90.703	1, 2
$4H_t3$	1317	1397	50	41.863	104.159	1, 2
$4H_t4$	1337	1026	70	39.869	122.101	1, 2
$4H_t5$	1345	817	78	58.807	144.029	1, 2
$6H_t1$	1357	1619	90	33.789	94.690	2
$6H_t2$	1381	1316	114	43.355	108.644	5, 6
$6H_t3$	1352	994	85	60.801	141.537	6

i 20 mm dia HSFG bolts from batch 2C

ii 20 mm thick plate from batch P4

iii For loading system see Figure 3.12

iv * Loading system produced torsion moment only

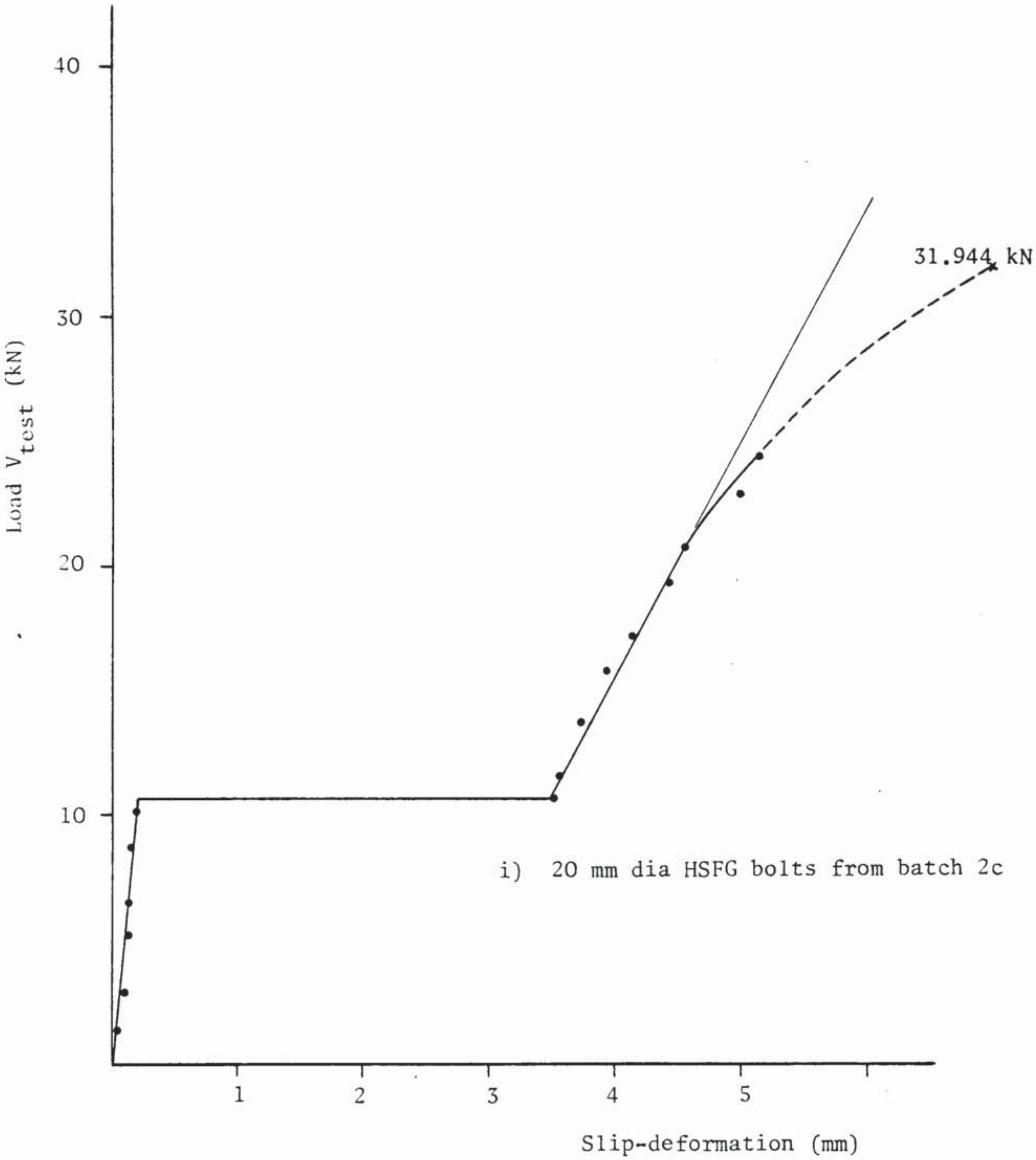
TABLE A4.14 SPAN VARIATIONS/SLIP AND FAILURE LOADS

(Four and six HSFG bolts)

Test No 4 $H_t 2$			Test No 4 $H_t 3$			Test No 4 $H_t 4$			Test No 4 $H_t 5$		
Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm	Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm	Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm	Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm
0	0	0	0	0	0	0	0	0	0	0	0
0.053	0.044	0.004	2.081	0.038	0.006	1.038	-0.032	0.022	1.904	-0.004	-0.024
1.486	0.080	-0.010	3.601	0.064	-0.004	1.928	-0.020	0.036	2.884	0.020	-0.024
2.203	0.100	-0.022	7.403	0.110	-0.022	5.489	0.014	0.024	5.824	0.056	-0.052
2.920	0.106	-0.024	9.683	0.138	-0.016	9.939	0.048	0.030	6.804	0.068	-0.060
5.070	0.140	-0.016	11.204	0.148	-0.014	11.719	0.068	0.034	11.705	0.098	-0.056
6.503	0.150	-0.012	13.485	0.180	0.006	14.389	0.096	0.046	14.645	0.112	-0.054
8.653	0.184	0.010	15.005	0.204	0.026	17.059	0.122	0.056	16.606	0.124	-0.050
10.086	0.208	0.030	15.765*	2.406	2.156	18.839*	2.920	2.730	19.546	0.140	-0.040
10.624*	3.526	3.624	16.525	2.484	2.224	21.509	3.000	2.828	21.506	0.150	-0.034
11.519	3.590	3.680	17.286	2.556	2.298	22.399	3.076	2.942	22.487	0.158	-0.030
13.669	3.770	3.848	18.046	2.646	2.388	23.289	3.152	3.060	24.447	0.168	-0.024
15.819	3.974	4.054	18.806	2.700	2.452	25.069	3.348	3.366	26.407	0.182	-0.010
17.252	4.160	4.228	21.087	2.936	2.718	27.739	3.56	3.692	28.367	0.202	0.004
19.402	4.456	4.492	24.128	3.236	3.064	55.553	Bolt	failed	30.818*	3.626	3.106
20.835	4.590	4.616	26.408	3.428	3.318				31.308	3.660	3.126
22.985	5.010	4.976	27.929	3.606	3.530				33.268	3.790	3.210
24.418	5.168	5.13	30.209	3.852	3.806				35.228	3.892	3.274
31.944	Bolt	failed	31.730	4.098	4.086				36.208	3.956	3.322
			32.251	4.398	4.386				39.149	4.368	3.480
			39.522	Bolt	failed				72.719	Bolt	failed

i *Load at which the major slip occurred
ii 20 mm dia HSFG bolts from batch 2C
iii For position of dials see Plate 4.2

TABLE A4.15 CALCULATED TEST LOAD AND SLIP RELATIONSHIP
(Four HSFG bolts)



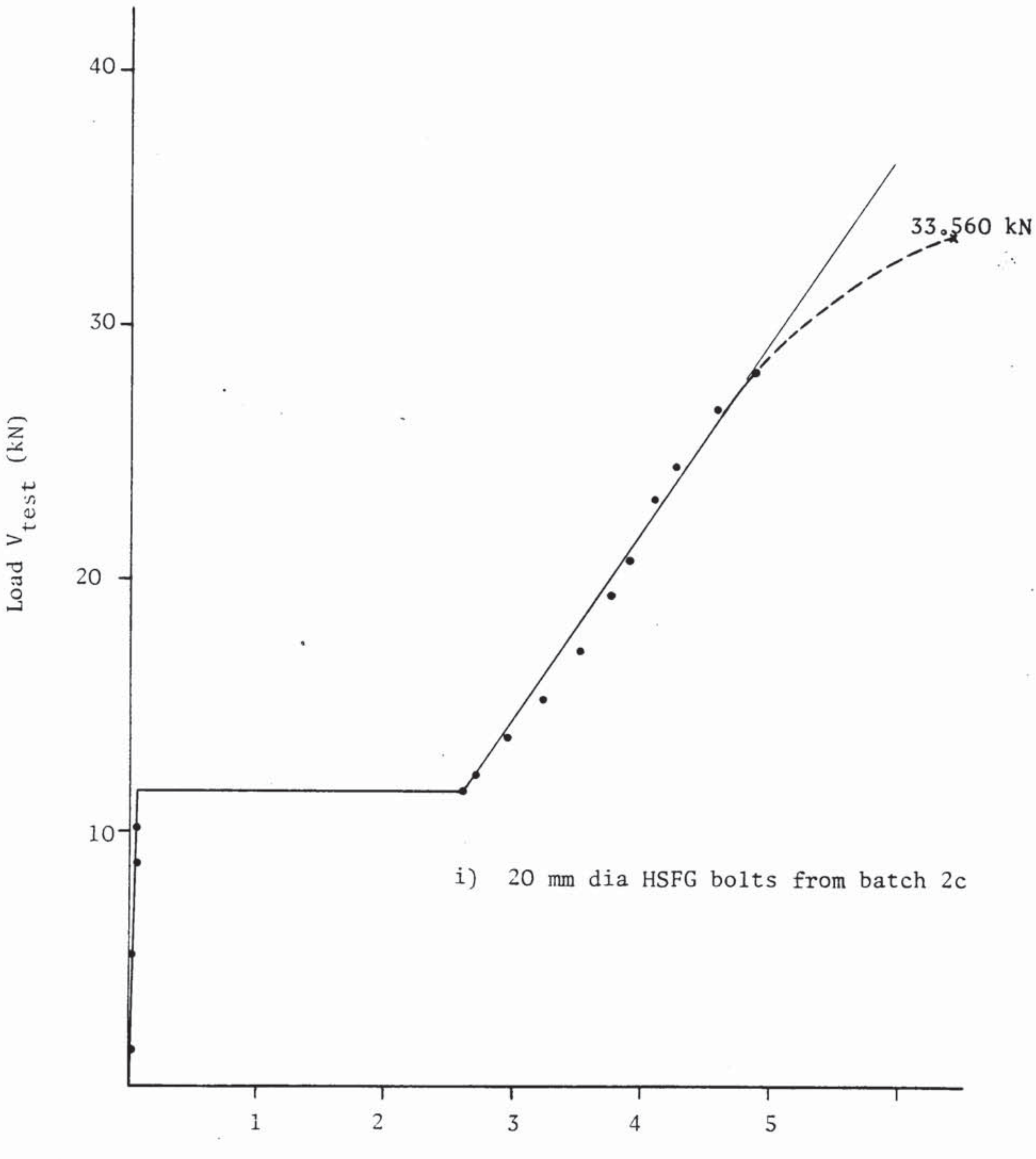
Test No $4H_t2$

FIGURE A.4.16 LAOD/SLIP-DEFORMATION RELATIONSHIP
(Four bolts)

Test No $6H_t1$			Test No $6H_t2$			Test No $6H_t3$		
Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm	Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm	Calculated V_{test} kN	Slip at dial 1 mm	Slip at dial 2 mm
0	0	0	0	0	0	0	0	0
0.075	0.004	0.052	0.218	0.002	0	2.111	0.006	0.006
1.515	0.004	0.066	1.031	0.040	-0.002	3.929	0.002	0
2.956	0.008	0.082	4.280	0.086	-0.014	5.747	0.058	-0.014
5.116	0.022	0.112	8.342	0.130	0.004	10.294	0.086	-0.012
6.556	0.034	0.128	10.778	0.160	0.010	14.839	0.122	-0.004
8.716	0.056	0.156	12.403	0.182	0.014	19.386	0.156	0.016
10.157	0.076	0.184	16.465	0.246	0.042	23.932	0.188	0.044
11.561*	2.602	3.018	17.277	0.272	0.058	28.478	0.258	0.118
12.317	2.706	3.156	17.886*	3.100	2.828	28.933*	2.802	3.154
13.757	2.980	3.544	18.902	3.176	2.918	29.387	2.828	3.172
15.197	3.234	3.956	20.526	3.294	3.048	31.205	2.960	3.310
15.917	3.316	4.100	22.963	3.520	3.286	33.024	3.038	3.388
16.637	3.418	4.274	24.588	3.668	3.450	37.570	3.336	3.704
17.357	3.514	4.432	28.649	4.058	3.886	42.116	3.608	3.978
19.518	3.746	4.812	32.711	4.490	4.330	46.662	3.952	4.326
20.958	3.878	5.035	36.773	5.168	5.024	51.208	4.362	4.716
23.118	4.094	5.370	38.397	5.508	5.376	55.754	4.866	5.286
24.558	4.264	5.610	39.210	5.694	5.556	60.300	5.562	6.018
26.718	4.592	6.078	40.834	6.24	6.076	63.028	6.144	6.586
28.159	4.882	7.178	41.647	6.318	6.188			
33.560	Bolt	failed	44.490	Bolt	failed	65.756	Bolt	failed

i * Load at which the major slip occurred
ii 20 mm dia HSFG bolts from batch 2C
iii For position of dials see Plate 4.2

TABLE A.4.17 CALCULATED TEST LOAD AND SLIP RELATIONSHIP
(Six HSFG bolts)



Test No $6H_t1$

FIGURE A.4.18 LOAD/SLIP-DEFORMATION RELATIONSHIP
(Six bolts)

APPENDIX A.5

A.5.1 Solution of Equation (5.4.9).

$$X^4 - \frac{X^3}{e}(\frac{D}{2})^2 - 2(\frac{B}{2})^2 X^2 - (\frac{D}{2})^2 eX + [(\frac{D}{2})^2 + (\frac{B}{2})^2]^2 \qquad (5.4.9)$$

Let

$$-\frac{1}{e}(\frac{D}{2})^2 = k_1$$

$$-2(\frac{B}{2})^2 = k_2$$

$$-e(\frac{D}{2})^2 = k_3$$

and

$$[(\frac{D}{2})^2 + (\frac{B}{2})^2]^2 = k_4$$

Then equation (5.4.9) becomes

$$X^4 + k_1 X^3 + k_2 X^2 + k_3 X + k_4 = 0$$

$$\therefore \quad X^4 + k_1 X^3 = -k_2 X^2 - k_3 X - k_4$$

To complete square on L.H.S. introduce another unknown λ

$$\therefore (X^2 + \frac{k_1}{2} X + \lambda)^2 = X^2 (2\lambda + \frac{k_1^2}{4} - k_2) + X(\lambda k_1 - k_3) + (\lambda^2 - k_4) \qquad (5.4.10)$$

The R.H.S. of equation (5.4.10) can be written as $(MX + N)^2$ i.e. by expanding $(MX + N)^2$ we have $M^2 X^2 + 2MNX + N^2$.

$\therefore$ by comparing with equation (5.4.10) we have

$$M^2 = 2\lambda + \frac{k_1^2}{4} - k_2$$

$$MN = \frac{1}{2}(\lambda k_1 - k_3)$$

$$N^2 = \lambda^2 - k_4$$

For these equations to be consistant we must have

$$M^2N^2 = (MN)^2$$

So λ must satisfy these equations

$$(2\lambda + \frac{k_1^2}{4} - k_2)(\lambda^2 - k_4) = [\frac{1}{2}(\lambda k_1 - k_3)]^2$$

$$\therefore \quad 2\lambda^3 + \lambda^2 \frac{k_1^2}{4} - \lambda^2 k_2 - 2\lambda k_4 - \frac{k_1^2}{4} k_4 + k_2 k_4$$

$$= \frac{1}{4}(\lambda^2 k_1^2 + k_3^2 - 2\lambda k_1 k_3)$$

$$\therefore \quad 2\lambda^3 - \lambda^2 k_2 - 2\lambda k_4 + \lambda \frac{k_1 k_3}{2} - \frac{k_1^2}{4} k_4 + k_2 k_4 - \frac{k_3^2}{4} = 0$$

$$\therefore \quad 2\lambda^3 - k_2\lambda^2 + (\frac{k_1 k_3}{2} - 2k_4)\lambda + (k_2 k_4 - \frac{k_1^2}{4} k_4 - \frac{k_3^2}{4}) = 0 \qquad (5.4.11)$$

Now let

$$a_0 = 2$$

$$3a_1 = -k_2$$

$$3a_2 = \frac{k_1 k_3}{2} - 2k_4$$

$$a_3 = -\frac{k_1^2}{4} k_4 + k_2 k_4 - \frac{k_3^2}{4}$$

$\therefore$ equation (5.4.11) becomes

$$a_0\lambda^3 + 3a_1\lambda^2 + 3a_2\lambda + a_3 = 0 \qquad (5.4.12)$$

Now put $a_0\lambda = (Z - a_1)$. The resulting equation in Z reduces to

$$Z^3 + 3Z(a_0a_2 - a_1^2) + (a_0^2a_3 - 3a_0a_1a_2 + 2a_1^3) = 0 \qquad (5.4.13)$$

Put $a_0a_2 - a_1^2 = H$ and $a_0^2a_3 - 3a_0a_1a_2 + 2a_1^3 = G$

$\therefore$ equation (5.4.13) becomes

$$Z^3 + 3HZ + G = 0 \tag{5.4.14}$$

Considering H and G are real numbers. Now using Cardan's solution

Put $Z = p + q$

$\therefore \quad Z^3 = p^3 + q^3 + 3pq\,(p + q)$

Hence $Z = p + q$ is a solution of

$$Z^3 - 3pq\,(p + q) - (p^3 + q^3) = 0$$

Therefore we obtain a solution of equation (5.4.14) if we choose p and q so that $p^3 + q^3 = -G$ and $pq = -H$ when above statement holds p^3 and q^3 are roots of equation:-

$$t^2 + Gt - H^3 = 0 \tag{5.4.15}$$

Since Z is symmetrical in p and q, we may take either root of this quadratic, for p^3 take

$$p^3 = \frac{1}{2}\,[-G + \sqrt{G^2 + 4H^3}] \tag{5.4.16}$$

Now in complex algebra, p^3 has three cube roots and if p is one of them, the three roots are

$$p,\ pw,\ pw^2 \text{ where } w = e^{2\pi i/3}$$

The corresponding values of q are

$$q,\ q\,w^{-1},\ q\,w^{-2}$$

where $pq = -H$, we cannot combine any cube root of q^3 with any cube root of p^3 since previous statement determines not p^3q^3 but pq. Hence the three roots of equation (5.4.12) are given by

$$Z = p + q; \; Z = pw + qw^{-1}; \; Z = pw^2 - qw^{-2}$$

where p is the cube root of

$$\frac{1}{2} [-G + \sqrt{G^2 + 4H^3}]$$

q is given by $q = - \frac{H}{p}$

Limitation of Cardan's Solution

The nature of the calculations to be carried out in order to solve any cubic will depend on the value of $G^2 + 4H^3$ (see equation 5.4.16). When $G^2 + 4H^3 > 0$ Cardan's formula presents no difficulty as a table of square roots or of logrithms will give $(G^2 + 4H^3)^{\frac{1}{2}}$ and on taking the cube root of $\frac{1}{2} [-G + \sqrt{G^2 + 4H^3}]$ a real value of p is obtained. The cubic has a real root given by $p - (\frac{H}{p})$.

To calculate the value of X use the following procedure:-

$$k_1 = -\left(\frac{D}{2}\right)^2 \times \frac{1}{e}$$

$$k_2 = -2\left(\frac{B}{2}\right)^2$$

$$k_3 = -\left(\frac{D}{2}\right)^2 e$$

$$k_4 = \left[\left(\frac{B}{2}\right)^2 + \left(\frac{D}{2}\right)^2\right]^2$$

$$a_0 = 2$$

$$a_1 = -\frac{k_2}{3}$$

$$a_2 = \frac{1}{3}\left(\frac{k_1 k_3}{2} - 2\,k_4\right)$$

$$a_3 = -\frac{k_1^2}{4} k_4 + k_2 k_4 - \frac{k_3^2}{4}$$

$$G = a_0^2 a_3 - 3a_0 a_1 a_2 + 2\,a_1^3$$

$$H = a_0 a_2 - a_1^2$$

$$p^3 = \frac{-G + \sqrt{G^2 + 4H^3}}{2}$$

$$\therefore \quad p = \left[\frac{-G + \sqrt{G^2 + 4H^3}}{2}\right]^{1/3}$$

$$q = -\frac{H}{p}$$

$$Z = p + q$$

$$\lambda = \frac{Z - a_1}{a_0}$$

$$M^2 = 2\lambda + \frac{k_1^2}{4} - k_2$$

$$M = (2\lambda + \frac{k_1^2}{4} - k_2)^{\frac{1}{2}}$$

$$MN = \frac{1}{2}(\lambda k_1 - k_3)$$

$$\therefore \quad N = \frac{1}{2M}(\lambda k_1 - k_3)$$

$$\therefore \quad X^2 + \frac{k_1}{2} X + \lambda = MX + N$$

$$\therefore \quad X^2 - (M - \frac{k_1}{2}) X + (\lambda - N) = 0$$

$$X = \frac{(M - \frac{k_1}{2}) \pm \sqrt{(M - \frac{k_1}{2})^2 - 4(\lambda - N)}}{2}$$

The solution outlined above shows the complication involved in the analysis of a four bolt group and therefore an iterative procedure is used in general to compare the position of instantaneous centre of rotation of elastic and plastic methods.

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