TIMBER CONSTRUCTION: AN EXPERIMENTAL ASSESSMENT OF THE STRENGTH OF SCARF JOINTS AND THE EFFECTIVENESS OF VARIOUS ADHESIVES FOR LAMINATED WOOD

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SUMMARY

Timber construction has recently seen a significant regain of interest across a range of industries, owing to contemporary concerns for sustainability. In the marine industry, historic principles of traditional wooden boatbuilding remain present, with empirical rules still common practice, as is the case for scarf joints. Moreover, laminated wood is made more attractive and efficient thanks to modern adhesives. However, with the progresses made in structural analysis, these assemblies can now be refined based on scientifically informed evidence. Consequently, this paper will employ destructive testing to tackle two distinct cases. On the one hand, the strength of feathered (plain) scarf joints as a function of their slope will be evaluated. On the other hand, the effectiveness of a range of adhesives will be ascertained for the purpose of laminated manufacturing. Ultimately, the results will be compared to both the strength of solid wood and the mechanical properties assumed by modern scantling regulations, revealing significant differences. The research findings provide a better understanding of these fundamental timber construction principles, supporting designers and builders alike in making informed choices and promoting safer regulatory compliance. It is also anticipated these findings will impact structural design beyond the wooden boatbuilding field, with applications in sustainable buildings and architecture.

1. INTRODUCTION

Traditional timber construction has significantly impacted maritime transportation and yacht design, and some historical principles remain key elements of today's wooden boatbuilding. Despite the wealth of experience that originates from trial and error, limited scientific background dedicated to wooden boats exist. Consequently, this paper tackled two areas of particular interest, namely scarf joints and laminated timber, using destructive testing to quantify the mechanical properties. These are compared to experimental values for solid timber as well as the allowable regulatory properties. The aim is to provide scientific evidence to better support the use of timber construction in modern yacht design and construction. The experiments and analyses inherent to scarf joints are discussed in Section 2, while laminated timbers are discussed in Section 3. Ultimately, Section 4 summarises the findings and provides recommendations regarding the mechanical properties for safer and more reliable wooden yachts.

2. SCARF JOINTS

2.1 BACKGROUND

The use of scarf joints is a fundamental part of timber construction and traditional boatbuilding, allowing to overcome the natural restrictions in sizes to achieve components as large as necessary. Today, the use of scarf joints also extends into composites structures [1]. Nevertheless, modern advances in structural engineering leading to progressively lighter boats, coupled with significant progress in adhesives [2] and the contemporary regain of interest for wood as an engineering material [3; 4] call for a new understanding of the mechanical properties and strength of scarf joints compared to solid timber.

Scarf joints are characterised with a length-to-thickness ratio, and are further categorised by their various types, as depicted in Figure 1.

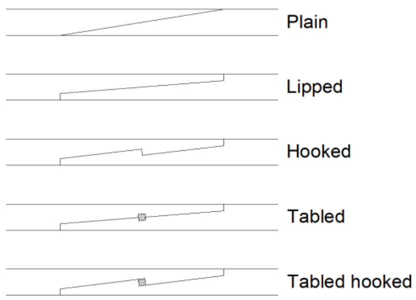

Figure 1: *Examples of scarf joints [5].*

While more complex joints have received more attention due to their use in civil engineering [6], plain scarfs remain the prevalent option in traditional boatbuilding, and thus will be the primary focus of this investigation.

Historically, scarf ratios have been driven by the location of the scarf on the vessel: 4:1 for planks, 6:1 (possibly 8:1) for keels, and 12:1 for spars. The Lloyd's rules [7] published in 1979, although no longer applicable, stated that plank scarfs should not have a length-to-thickness ratio less than 4 (rule 4707), adjacent planks shall not have scarfs within 1.2 m of each other, and a minimum of three complete planks shall separate scarfs in the same transverse plane. In addition, keel scarfs shall have a ratio no less than 6:1 (rule 4302), and the keel and hog scarfs should be spaced by at least 1.5 m (rule 4303), while being clear of engine bearers and maststeps. In those historical instances, it can be deduced that an increased scarf ratio leads to greater strength, though scarfs still represent weak spots that should be spaced out and not subjected to highly localized loads.

Very few instances of guidelines regarding the effectiveness of scarfs for boatbuilding applications are present in the literature. Birmingham [8] suggests that the efficiency of scarfs ranges from 65 percent of the strength of solid timber for a 4:1 ratio and up to 95 percent for a 20:1 ratio. On the other hand, Gerr [9] recommends a 12:1 ratio that will achieve 90 percent of the strength of solid timber. Lastly, an 8:1 ratio is advised for greater strength, with a 12:1 ratio being recommended for spars [10], with additional rules of thumbs regarding spacing and slope suggested [11]. The origin of these various values is however not clear, nor is their accuracy when utilizing different glues and wood species, and no underpinning scientific data is presented to support the claims made.

Consequently, in order to provide a detailed analysis of how scarf ratios affect the strength of timber components, destructive structural testing was undertaken on European oak samples (*Quercus spp*, having a density no less than 690 kg.m^{-3} at 12% moisture content), joined together with feathered scarfs glued with epoxy. In order to faithfully replicate a typical boatyard scenario, the samples were manufactured from different quarter sawn boards, never joining samples from the same board. Ratios of 4:1, 8:1, 12:1, 16:1, and 20:1 were tested, comparing all of them to solid samples. The aim was to ascertain the relative strengths of the various scarf ratios, for the wood species and adhesive utilised in this instance, both prominent in the boatbuilding industry, to provide designers and builders with relevant and reliable information; and an evaluation of regulatory default values.

2.2 EXPERIMENTAL TESTING

2.2 (a) Manufacturing

The samples sizes were 400 mm long, by 20 mm wide, by 20 mm thick, with in excess of 5 samples per tested configuration, in accordance with the relevant standard [12]. An example of joints prior to gluing is shown in Figure 2, with the adhesion process being conducted under camping pressure for the duration of the epoxy's cure.

Figure 2: *Samples machined prior to gluing [4].*

2.2 (b) Method

To assess the strength and mechanical properties of samples, a number of destructive tests can be employed; for timber, four-point bending is preferred, as it allows one to establish the ultimate flexural strength and elastic modulus (also known as Young's modulus). In four-point bending tests, the sample is simply supported at each extremity, while the load is applied evenly at two locations equidistant from the center, as depicted in Figure 3. In this instance, all tests were conducted on a Lloyds Instruments LR 30k tensile machine. To ensure the reliability, accuracy, and repeatability of the results obtained, the BS EN 408 standard [12] was applies.

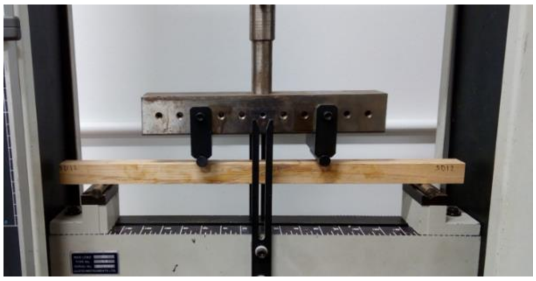

Figure 3: *Experimental setup [4].*

2.3 QUALITATIVE RESULTS

From the experimental testing, typical load-deflection curves for the various scarf ratios compared to solid timber were obtained, see Figure 4, yielding three main findings.

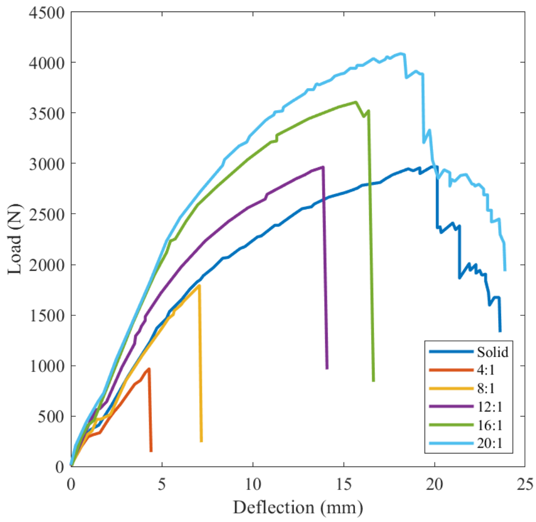

Figure 4: *Typical load-deflection curves [4].*

First, the results clearly demonstrate that the small scarf ratios (4:1 and 8:1) have a lesser resistance compared to solid timber, whereas the opposite is true for the higher ratios (12:1, 16:1, 20:1). Practically, this means that higher scarf ratios have a higher modulus of elasticity than the solid timber and will be able to carry more load for a given deflection.

The second important result is that solid timber withstands the most deflection before ultimate failure; in other words, despite not carrying as much load as a high-ratio scarf, solid timber is able to deflect much farther than scarfed samples.

Finally, there is an interesting shift in the failure mechanisms, shown in the fracture behavior. For ratios ranging from 4:1 to 16:1, the fracture is sudden and abrupt, with no strength left. In these cases, it was the epoxy bond that failed. Conversely, solid timber and the 20:1 scarf do retain some strength, as it is the timber and not the adhesive that failed in those instances. The two failure modes are presented in Figure 5. This proved true for all samples tested with the exception of a single 16:1 ratio where a combination of timber and glue failure (attributed to a weak spot in the timber) was noticed. It is to be noted that these findings will be affected by the adhesive employed, and could vary for alternative glues, as well as timber species.

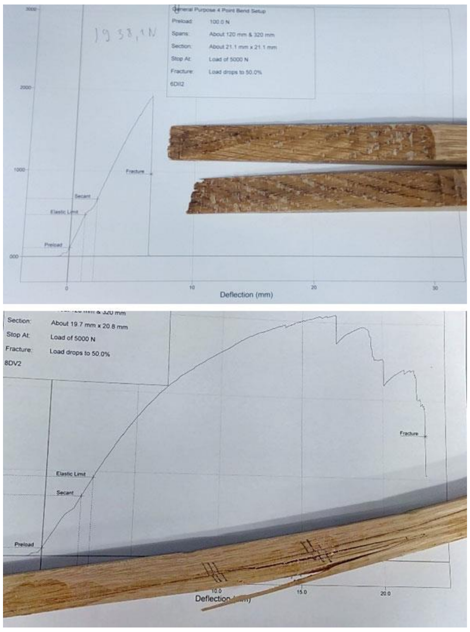

Figure 5: *Comparison of failure mechanisms [4].*

Further inspection of the samples revealed the presence of micro wood failures, specifically localized on the annual rings, as shown in Figure 6. It is hypothesized that the higher density of annual rings made for a lower resin absorption and therefore better bond.

Figure 6: *Localized micro wood failure [4].*

2.4 QUANTITATIVE RESULTS

Amongst the many mechanical properties that can be ascertained from this experiment, the two of primary importance here are the modulus of elasticity and ultimate flexural stress, respectively labelled as $E_{//}$ and $\sigma_{uf//}$, where the subscript '//' specifies that those properties are given parallel to the grain.

In the absence of mechanical testing, default values would be provided by the relevant rules and regulations. For small craft scantlings, Annex F of the ISO 12215–5 [13], specifies the default mechanical properties of typical wood species. Despite the recent revision of the standard [14], with updates on composites [15; 16] and commercial crafts [17], only minor changes were made to the default properties, and no modifications to the theory underpinning atypical species were implemented. Ultimately, regulatory bodies do not account for the presence of scarf joints or their ratios.

For a strength-driven design, where the primary concern is to ensure stresses remain below an acceptable level, the ultimate flexural strength will be utilized. Note that, in this instance, a safety factor would be employed to ensure added reliability, and that the material does not suffer from permanent deformation under normal loading. As a minimum requirement, the ISO 12215–5 imposes a factor of safety of 2 on the ultimate flexural strength, which leads to the design stress value, ultimately employed is the calculation of thickness calculation for panels, and section modulus for stiffeners. On the other hand, the modulus of elasticity comes into play for stiffness-driven designs, where the primary intent is to limit deflection to a comfortable level.

In structural testing, the final values for the mechanical properties are typically the lesser of either 90% of the average across all samples, or the average value achieved to which two standard deviations are subtracted, thus accounting for the scatter in the data. In all cases, the average minus two standard deviation proved to be the most pessimistic case, and thus was retained. Table 1 presents the average variation in two principal quantities of interest here, and demonstrates the conclusiveness of the results obtained.

Table 1: *Variance in the quantitative results.*

Samples	$\sigma_{uf//}$ **(MPa)**	$E_{//}$ **(MPa)**
Solid	7.88%	3.07%
4:1	8.66%	7.44%
8:1	7.07%	7.22%
12:1	5.74%	8.02%
16:1	1.70%	2.51%
20:1	3.73%	3.96%

The flexural strength and modulus of elasticity can then be plotted against the increasing scarf ratios of the samples, and compared to standard values given by structural regulations. Here, both the International Organisation for Standardization (ISO) [13] and the American Bureau of Shipping (ABS) [18] are considered, together with solid timber and published rule of thumb [8; 9].

The results are presented in Figure 7 as scarf efficiency, where 100% represents the strengths of the solid timber as determined experimentally, for the ultimate flexural strength and modulus of elasticity.

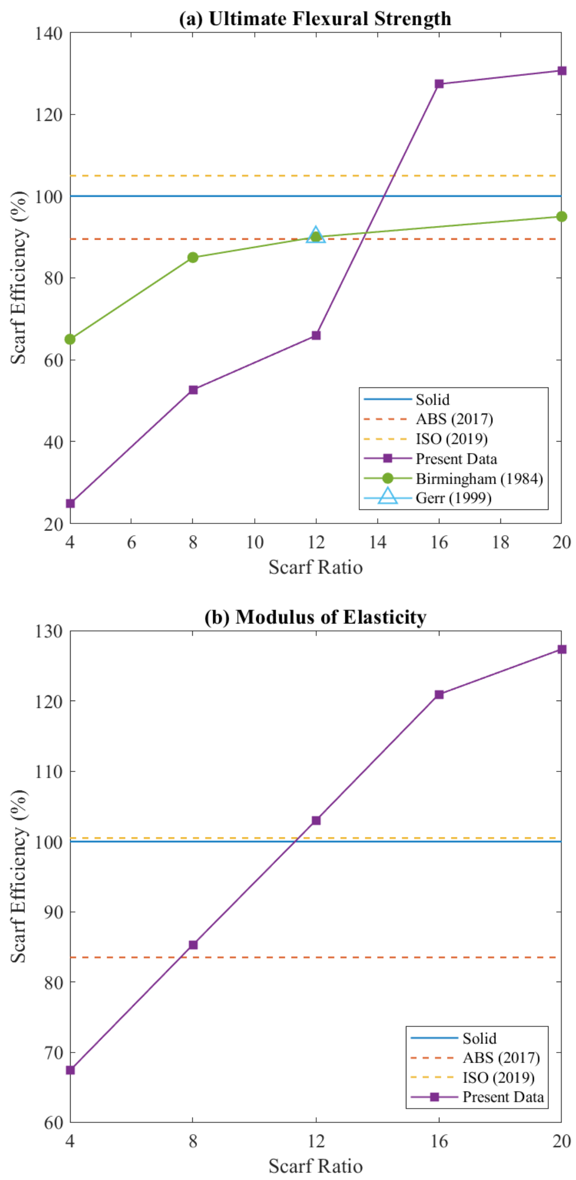

Figure 7: *Scarf efficiency compared to solid timber and typical regulatory values.*

The results reveal striking differences between the experimental data and both solid timber and the previously existing guidance. This implies that greater care should be taken in the design of structural components with a low scarf ratio, and thus a higher factor of safety should be used. Loss of strength was also noticed for small (6:1) Iroko samples [19], further confirming the present study. Conversely, the higher end of scarf ratios showed a significant improvement in mechanical properties, which could therefore be strategically utilized, particularly for weight-critical components, thus justifying the requirement for high ratios on spars.

With respect to the default properties provided by rules and regulations, that can be found in Table 2, there is a large difference in the actual values, with ABS [18] specifying more pessimistic mechanical properties and imposing a larger factor of safety than the ISO standard [13]. The latter also proved to be more in line with the results for solid timber.

Table 2: *Comparison of the experimental mechanical properties with solid timber and typical regulatory values.*

	Mechanical Properties	$\sigma_{uf//}$ **(MPa)**	$E_{//}$ **(MPa)**
	ABS (2017)	66.00	10 000
	ISO (2019)	77.00	12 060
Experimental	Solid Timber	73.51	11 980
	4:1 Scarf	18.28	8 045
	8:1 Scarf	38.86	10 270
	12:1 Scarf	48.72	12 379
	16:1 Scarf	93.43	14 486
	20:1 Scarf	96.11	15 250

2.5 CONCLUSIONS

When looking at an actual design, these research findings should be kept in mind. The examples here demonstrate that, in considering either ABS or ISO default ultimate flexural strength and inherent factor of safety, the design stress would have been over-estimated and thus would not have prevented failure of the 4:1 scarf ratio. Structural testing is a time-consuming and expensive approach; it is therefore hoped the results provided in this paper offer an efficient alternative and will allow designers and builders to adjust safety margins where necessary or help justify the need for an increased scarf ratio. This is particularly pertinent when tackling scantling determination for wooden boats [20].

The fact that these findings are specific to the timber species and adhesive tested here should be reiterated, and while qualitative similarities can be expected, quantitative results will require further research. Furthermore, it is vital to point out that the mechanical properties of wood can vary greatly and be affected by a wide range of parameters, including density, moisture content, grain orientation and straightness, defects, and so on, eventually leading to higher factors of safety when designing wooden boats.

The factor of safety adopted is also influenced by the thickness of wood: large sections carry greater uncertainty as to grain orientation and the presence of defects, which means they generally require an increased factor of safety. On the other hand, it is easy to spot any defect in thin pieces of wood. As a result, laminated components made of thin veneers generally permit reduced safety margins, allowing lighter and stronger structures. Consequently, laminated timber is a very attractive technique for modern construction, therefore calling for further experimental research in this field.

3. LAMINATED WOOD

3.1 BACKGROUND

The primary aim of this experiment was to characterize the mechanical properties of three species of timber present in Costa Rica, in order to support the current build of a wooden cargo sailing vessel, as well as providing the necessary data for new designs [21]. The three species under investigation are:

- *Cedrela Odorata*, $\rho \approx 548$ kg.m^{-3}
- *Cordia Gerascanthus*, $\rho \approx 661$ kg.m^{-3}
- *Dialium Guianense*, $\rho \approx 987$ kg.m^{-3}

In addition to solid samples, various adhesives will be employed for the laminated ones, namely:

- Epoxy (Ampreg 22)
- Resorcinol (Dynea Prefere 4050)
- Polyurethane (Geocel Joiner's Mater)

This will be compared to the values for solid timber. In the case of epoxy, two test batches will also be investigated, a standard one glued using clamps, and a more advanced manufacturing method, namely vacuum bagging.

From a regulatory perspective, both ISO [13] and ABS [18] assume greater overall properties for laminated timber. The former considering 50% of a timber's ultimate flexural strength when laminated (40% for solid), while the latter employs 42% of the modulus of rupture when laminated (37.5% for solid). This however does not account for the number of plies, adhesive or manufacturing method used. Hence the interest in performing destructive testing. Furthermore, previous work highlighted the need to treat laminated timber as composite laminates [22], contrary to the current regulatory process.

3.2 EXPERIMENTAL TESTING

3.2 (a) Manufacturing

All sample were manufactured from timber directly supplied by the Costa Rican shipyard to a final size of 400 mm long, by 20 mm wide, by 20 mm thick. In the case of the laminated samples, 5 layers of 4 mm were employed, glued with either epoxy, resorcinol or polyurethane, and clamped for the duration of the curing process. To replicate a more advance manufacturing process, laminated samples were also glued using epoxy under vacuum, as depicted in Figure 8.

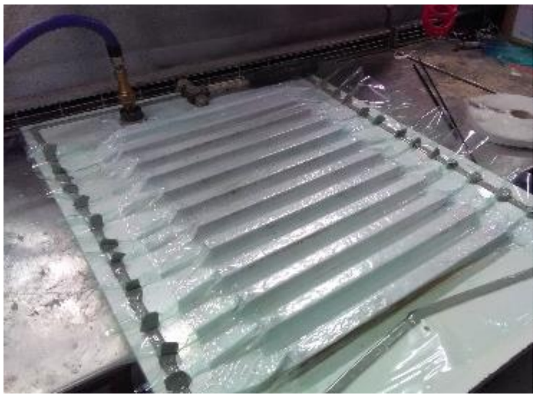

Figure 8: *Laminated samples under vacuum bagging consolidation [23].*

3.2 (b) Method

The experimental campaign was undertaken under the specifications of the BS EN 408 standard [12], with the notable exception of a reduced number of samples. Indeed, due to the restricted supply of timber, only 4 samples were tested for each combination of the timber, glue and manufacturing method, thereby falling just short of the minimum 5 samples required. The four-point bending test employed on a Lloyds Instruments LR 30k tensile machine is depicted in Figure 9.

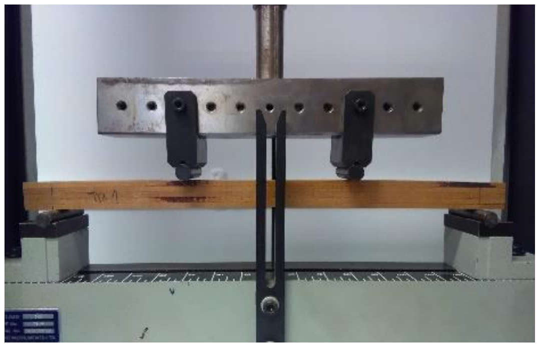

Figure 9: *Experimental setup [23].*

3.3 QUALITATIVE RESULTS

A comparison of the load-deflection curves for all three species, either solid timber or clamped epoxy laminated, are presented in Figure 10. The difference in behaviour between spices can immediately be identified, and is closely related to their respective density. Indeed, *Cedrela Odorata* is marginally less dense than *Cordia Gerascanthus*, with *Dialium Guianense* being far denser. In the case of *Cedrela Odorata* and *Cordia Gerascanthus*, the laminated sampled proved to reach failure at much lower deflections, though at virtually identical load for the latter. *Cordia Gerascanthus* also proved able to withstand a much higher level of deformation prior to rupture. Lastly, while comparable loads could be reached in the case of *Dialium Guianense*, the laminated samples proved more flexible, thereby allowing for greater deformation.

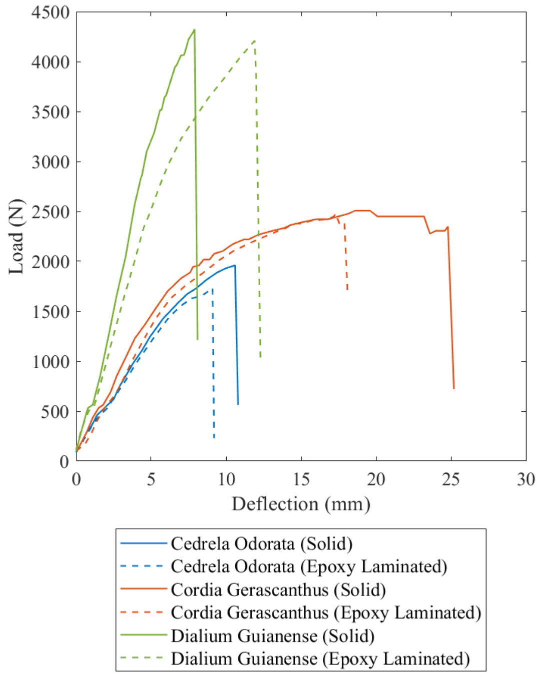

Figure 10: *Typical load-deflection curves [23].*

3.4 QUANTITATIVE RESULTS

The experimental data gathered allowed to characterise the two fundamental mechanical properties for strength and stiffness design, namely the ultimate flexural stress and modulus of elasticity respectively. As per Section 2.4, the final retained values are the lesser of either 90% of the average across all samples, or the average value achieved to which two standard deviations are subtracted.

In addition, the estimation of mechanical properties for rarer timber species provided in the ISO 12215-5:2019 [13] was implemented. Indeed, for unconventional species, the mechanical properties can be derived as a direct function of the density of the wood. Hence, the ultimate flexural strength ($\sigma_{uf//}$) and modulus of elasticity ($E_{//}$) of a hardwood of density ρ can be approximated as:

$$\sigma_{uf//} = 0.137\rho \tag{1}$$

$$E_{//} = 19.5\rho \tag{2}$$

The equations are slightly adjusted for softwood, and respectively given as:

$$\sigma_{uf//} = 0.130\rho \tag{3}$$

$$E_{//} = 17.5\rho \tag{4}$$

These estimates should however be treated very carefully, and mechanical testing should always be conducted to ensure the most suitable properties are employed as part of the structural design. The importance of this is demonstrated in the results for all three timber species depicted in Figure 11, with the numerical values summarised in Table 3, revealing extremely significant divergence in the actual and estimated properties for solid timber. The effect of the various adhesives and associated manufacturing techniques can also be observed.

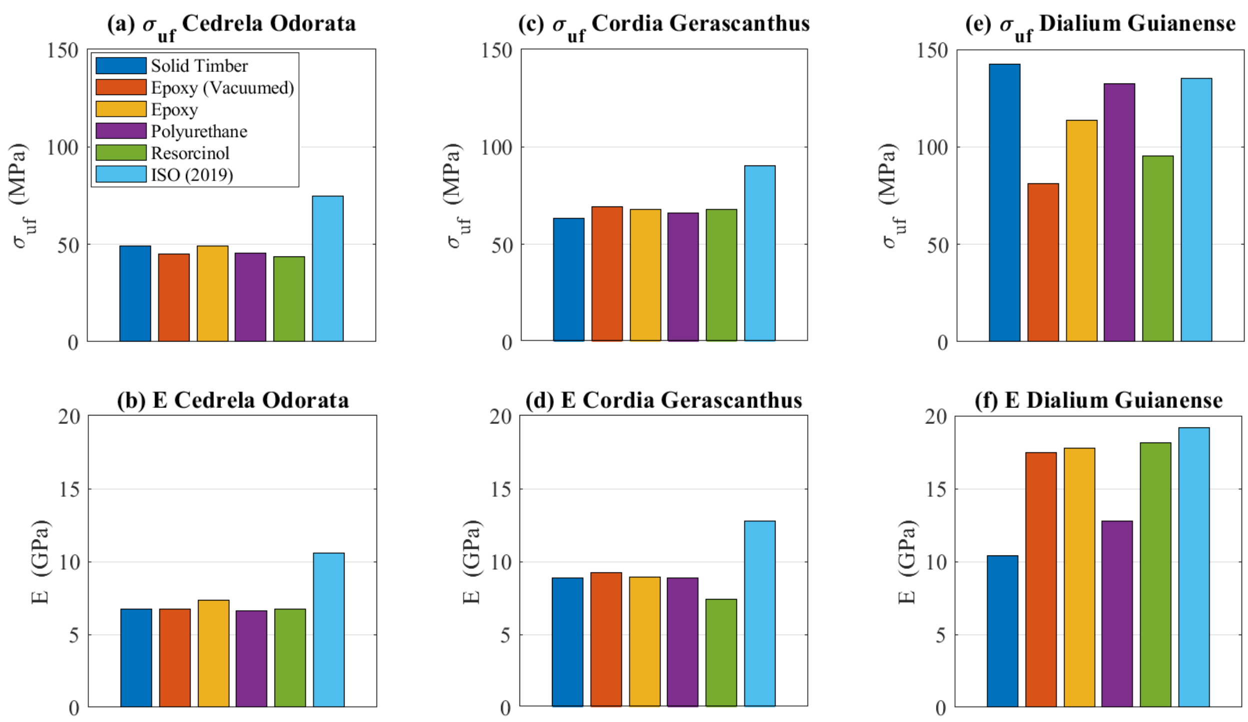

Figure 11: *Comparison of the ultimate flexural strengths and moduli of elasticity.*

Table 3: *Comparison of the experimental mechanical properties with solid timber and regulatory values.*

		Mechanical Properties	$\sigma_{uf//}$ **(MPa)**	$E_{//}$ **(MPa)**
Cedrela Odorata		**ISO (2019)**	75.01	10 686
	Experimental	Solid Timber	48.20	8 510
		Epoxy (Vac.)	44.66	8 523
		Epoxy	48.68	9 340
		Polyurethane	44.58	8 474
		Resorcinol	42.93	8535
Cordia Gerascanthus		**ISO (2019)**	90.56	12 889
	Experimental	Solid Timber	62.16	11 135
		Epoxy (Vac.)	67.97	11 579
		Epoxy	66.67	11 370
		Polyurethane	64.61	11 316
		Resorcinol	66.96	12 414
Dialium Guianense		**ISO (2019)**	135.22	19 246
	Experimental	Solid Timber	107.48	19 695
		Epoxy (Vac.)	41.18	24 532
		Epoxy	85.12	24 837
		Polyurethane	100.11	21333
		Resorcinol	71.88	25 085

3.5 CONCLUSIONS

In terms of the ultimate flexural stress, the results demonstrate that improvements can be achieved with laminated timber in the case of *Cordia Gerascanthus* (Figure 11 (c) and (d)), with further enhancement thanks to the vacuum bagging. These results are however very specific to each species, with *Cedrela Odorata* (Figure 11 (a) and (b)) displaying a loss of strength as a result on the lamination process (with the notable exception of clamped epoxy). Further and more significant loss of strength was noticed for *Dialium Guianense* (Figure 11 (e) and (f)), and is attributed to the extreme density of timber, that does not allow for suitable adhesive penetration and bonding.

The variations in stiffeness for both *Cordia Gerascanthus* and *Cedrela Odorata* remained minimal. However, strong improvements were revealed for *Dialium Guianense*, where the lamination process greatly enhanced the modulus of elasticity.

The present results clearly highlights that no generalisation can be made regarding the use of laminated timber, or adhesive type, as there is a crucial dependency on the actual timber species considered. In addition, care should be taken when looking at approximations for regulatory properties of unconventional timber species, as these proved too optimistic, and therefore unsafe, in all tested cases.

4. CONCLUSIONS

Timber construction remains strongly rooted in historical developments, with many traditional features still present in modern construction. Nevertheless, as more advanced wooden boats are designed and built, in line with relevant rules, it is critical to appraise the reliability of such regulations. This is particularly vital considering the complex nature of wooden designs, and comparatively lesser research undertaken compared to composites.

This paper presents the results of two experimental campaigns, the first focussed on the effect of scarf ratios, and the second tackling the effect of various adhesives for laminated unconventional timber species. The results show stark disparities with small craft regulations, and highlight the importance of undertaking destructive testing to characterize the mechanical properties, eventually feeding into the structural design process. Furthermore, it should be noted that extrapolation to other timber species did not prove straight forward, and thus care should be taken when dealing with different ones, particularly unconventional ones.

Ultimately, destructive testing would be strongly advised to support the structural design of wooden boats. Should this not prove feasible, additional factor of safety compared to that of regulatory bodies would be advised, as this paper demonstrated a number of limitations, where regulatory properties would appear far greater than the tested ones.

5. ACKNOWLEDGEMENTS

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