Historic Ships Conference
28th-29th November 2023
London, United Kingdom

STRUCTURAL DESIGN OF WOODEN BOATS

J-B R G Souppez, Aston University, UK

SUMMARY

The contemporary environmental challenges faced by the maritime industry have triggered a regain of interest in wood as a sustainable material. Modern classics and replicas of historical vessels have been increasingly popular. However, owing to their historical nature and small market share, wooden yachts and small ships do not benefit from a robust and detailed regulatory framework. Instead, their structural design remains driven by designer and builder experience, historical scantlings and rules of thumb. As such, the lack of detailed regulations for the scantlings of traditional timber vessels has been identified as a limitation to their wider implementation in the maritime industry. Consequently, this paper explores existing regulations and recent experimental research to provide novel insights into wooden structures and their associated scantling rules. First, a classification of wooden boatbuilding techniques is offered. Then, the lower carbon footprint of traditional carvel construction compared to modern cold moulding, strip planking, and plywood construction is quantified. Finally, recommendations are provided regarding the remaining outstanding research questions that need to be addressed to ensure reliable traditional wooden boat scantlings in modern regulations. It is anticipated these findings will facilitate the wider adoption of wooden construction for small crafts, support the use of more sustainable materials, and may further contribute to the development of future regulations.

NOMENCLATURE

c	Curvature coefficient [-]
C_f	Carbon footprint of hull [kg kg^{-1} m^{-2}]
C_m	Carbon footprint of boatbuilding method [kg kg^{-1}]
k	Aspect ratio coefficient [-]
L	Rule length [m]
L_{OA}	Overall length of hull [m]
L_{WT}	Waterline length [m]
m	Mass of hull [kg m^{-2}]
P	Design pressure [kPa]
s	Short side of panel [mm]
t	Planking thickness [mm]
ρ	Density [kg m^{-3}]
σ_d	Design stress [MPa]
σ_{uf}	Ultimate flexural strength [MPa]
ABS	American Bureau of Shipping
GL	Germanischer Loyd
ISO	International Organization for Standardization

1. INTRODUCTION

Wooden boats have been predominant throughout history [1, 2, 3], prior to the advent of metal [4, 5] and, more recently, composite construction [6, 7]. The significant progress in adhesives associated with the latter [8] has led to the development of modern timber construction, namely cold moulding, strip planking and plywood, all relying on epoxy and modern adhesives for timber encapsulation. This alleviates the expansion of timber with increasing moisture content [9, 10] as found in traditional wooden construction, namely carvel and clinker (also known as lapstrake), where planks are left exposed to the environment. Carvel relies on caulked seams to cope with the swelling of planks with increasing moisture content, while clinker construction employs overlapping planks.

The past decade has seen a regain of interest in historical wooden boats and their analysis using modern naval architecture techniques [11, 12, 13, 14, 15]. This is further evidenced in the development of modern replicas [16, 17, 18, 19, 20, 21], new builds [22, 23] and wooden cargo vessels [24, 25, 26]. Yet, there remains a lack of regulations to support the adoption of traditional wooden boatbuilding techniques for sustainability purposes [27, 28, 29], leading to new considerations for the regulatory implications of timber constructions [30, 31] and regulatory compliance [32, 33]. Pre-1950 designs, whether original historical crafts or replicas built predominantly with the original materials, are beyond the scope of legislation [34, 35] and associated structural regulations (e.g. ISO 12215-5:2019 [36]). In fact, regulatory frameworks primarily focus on modern wooden construction [37, 38]. While plank thicknesses are provided for a given estimated shell area by Germanischer Lloyd (GL) [39], only the American Bureau of Shipping (ABS) [40] features traditional construction with dedicated scantling calculations.

Because clinker is less common than carvel, it has received comparatively less attention, but for the recent work of Loscombe [12, 41]. As a result, clinker scantlings are adjusted from carvel ones, instead of tackled in their own right. While ABS [40] does not cover clinker, GL [39] states that, for a given planking thickness, stiffener spacing can be increased by 65% for clinker compared to carvel. The guidelines of Gerr [42] also support the underlying assumption that greater strength is achieved with clinked construction thanks to the overlapping planks, recommending that, for a given stiffener spacing, clinker planking thickness can be reduced to 85% of that of carvel. Finally, the MGN 628 [43] gives, on average, plating thicknesses 24% thinner for clinker compared to carvel for a given vessel size.

Consequently, this paper focuses on carvel construction and further limits its scope to the shell planking thickness. The aim is to characterise the environmental benefits of traditional compared to modern timber construction, as well as identify critical areas currently overlooked by existing regulations in order to support its future wider implementation in small craft regulations. The remainder of this paper is structured as follows. Section 2 offers a classification of modern versus traditional wooden construction. Then, Section 3 tackles the current regulatory scantlings and identifies the benefits of traditional wooden boatbuilding. Subsequently, structural challenges beyond the scope of current regulatory bodies are discussed in Section 4 to provide novel insights into traditional wooden construction. Finally, the main findings are summarised in Section 5.

2. MODERN VERSUS TRADITIONAL TIMBER CONSTRUCTION

A simplified classification of the most commonly employed wooden boat construction methods is presented in Figure 1. A primary distinction is made between modern and traditional wooden boatbuilding. The former features a predominant use of modern adhesives (e.g. epoxy) to fully seal the timber from the outside environment, thereby maintaining a low moisture content. In addition, modern construction relies on machined timber, namely thin veneers, edge-machined strips and plywood, and commonly features a fibreglass sheathing. Three subcategories are presented here: cold moulding, strip planking and plywood (or plywood on frames), matching the options available for wooden construction under ISO 12215-5:2019 [36]. On the other hand, traditional boatbuilding requires the planking to absorb moisture and swell to yield a watertight hull. Planks are made from solid timber and mechanically fastened to transverse stiffeners. Planks may either be laid edge-to-edge, with a small seam later caulked (carvel construction) or overlapping edges (clinker construction).

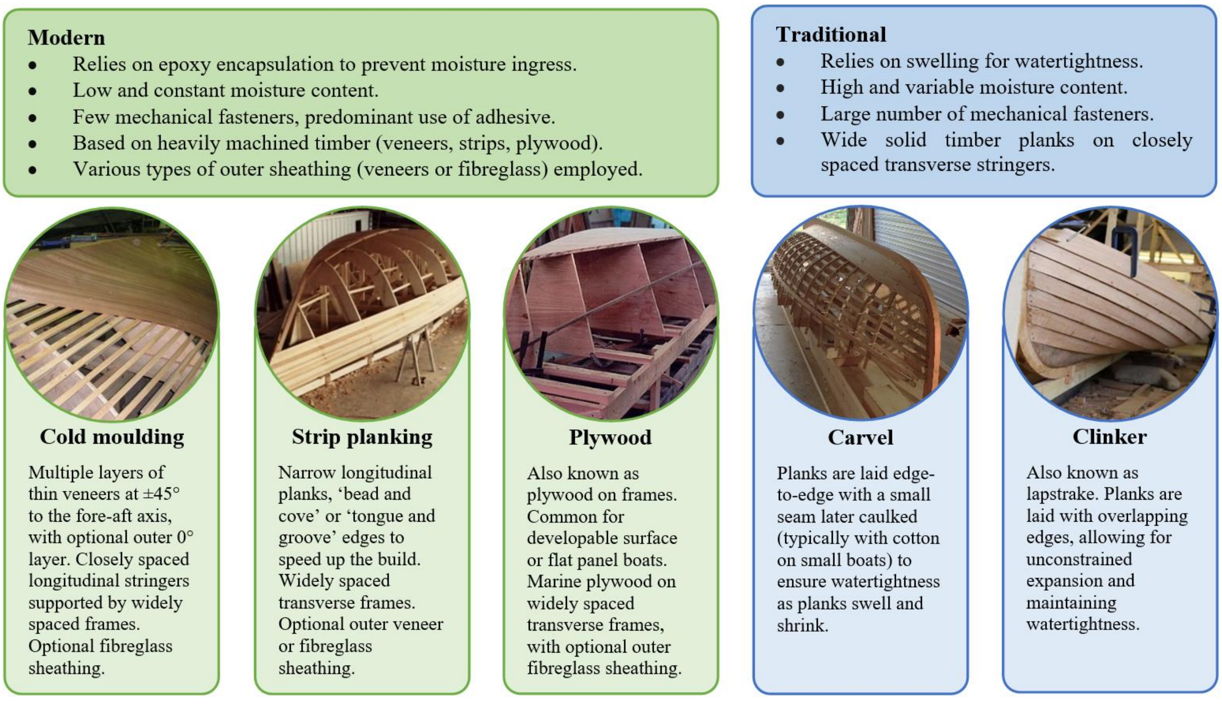

Figure 1. Classification of the main wooden boatbuilding methods for small crafts. Illustrations taken from [44] for cold moulding, [45] for strip planking, [46] for plywood on frames, [47] for carvel and [48] for clinker.

First, the application of existing regulations for small wooden crafts will be investigated in Section 3. Then, the specifics of traditional boatbuilding and associated challenges will be detailed in Section 4, with the intention to identify outstanding research questions and provide an overview of the limitations that may be associated with regulatory scantlings for carvel and clinker vessels.

3. CONTENPORARY SCANTLINGS FOR STRUCTURAL DESIGN

The planking thickness t of modern wooden boats is given in both ISO [36] and ABS [40] by an equation of the form

$$t = c\, s \sqrt{\frac{P\, k}{\sigma_d}}, \tag{1}$$

where c is a curvature correction coefficient taken as 1 (i.e. no curvature), s is the short side of the panel, P is the design pressure, k is an aspect ratio coefficient taken as 0.5 for panel with an aspect ratio greater than or equal to 2, and σ_d is the design stress, based on the ultimate flexural strength, σ_{uf}. Equation (1) assumes a built-in beam a under uniformly distributed load [49].

For carvel, ABS [40] gives the planking thickness as

$$t = 1.09\left(4.2 - 0.84\sqrt[4]{L}\right) s \sqrt{\frac{P}{\sigma_d}}, \tag{2}$$

where L is

$$L = \frac{L_{\text{OA}} + L_{\text{WL}}}{2}, \tag{3}$$

and L_{OA} and L_{WL} are the overall hull length and waterline length, respectively.

Despite varying pressure and material properties, rules and regulations have been shown to yield consistent scantlings [50]. To avoid bias in the subsequent analysis, a pressure range $0\,\text{kPa} \leq P \leq 150\,\text{kPa}$ is adopted, representing small craft pressures [51]. It is noted that longitudinal pressure distributions vary between ISO [36], ABS [40] and GL [39], and thus could impact scantlings for individual panels under different regulations. In this work, the mechanical properties are taken as defined by ISO 12215-5:2019 [36] and the short side of the panel is constrained to the practical ranges employed in small wooden boat building (see Table 1). Note that ISO [36] does not provide scantlings for carvel construction, while ABS [40] does not cover strip planking.

For the purpose of the paper, the assumptions inherent to the materials and associated properties for each boatbuilding technique are detailed in Table 1. Eco-properties, in the form of the carbon footprint C_f are provided [52], and account for the timber used, necessary machining, and epoxy (cold moulding and strip planking), phenol-formaldehyde (plywood) or copper nails (carvel and clinker), as relevant.

Table 1. Boatbuilding techniques, assumed construction material [10, 42, 53] and material properties [36, 52].

Construction Method	Cold moulding	String Planking	Plywood	Carvel
Stiffener spacing, s [mm]	$0 \leq s \leq 360$	$0 \leq s \leq 1200$	$0 \leq s \leq 900$	$0 \leq s \leq 360$
Wood species (common name)	African mahogany	Western red cedar	9 ply marine plywood	European Oak
Wood species (latin name)	*Khaya anthotheca*	*Thuja plicata*	*n/a*	*Quercus spp.*
Wood density, ρ [kg m^{-3}]	514	368	500	689
Ultimate flexural strength, σ_{uf} [MPa]	67	52	32	77
Design stress, σ_d [MPa]	10	26	16	38.5
Carbon footprint, C_m [kg kg^{-1}]	1.942	1.301	1.133	0.602

The regulatory thicknesses, calculated according to ISO 12215-5:2019 [36] for cold moulding, strip planking and plywood, and based on ABS [40] for carvel are presented in Figure 2. Cold moulding yields significantly lower thicknesses than the other boatbuilding methods under consideration. This may be expected given the original use of hot moulding for lightweight aircraft [54], before being adapted to yachts [55]. Note the difference in terminology between hot moulding and cold moulding, the former required the application of heat for the resin to cure, while advances in adhesives later enabled the curing process to take place at room temperature (cold moulding).

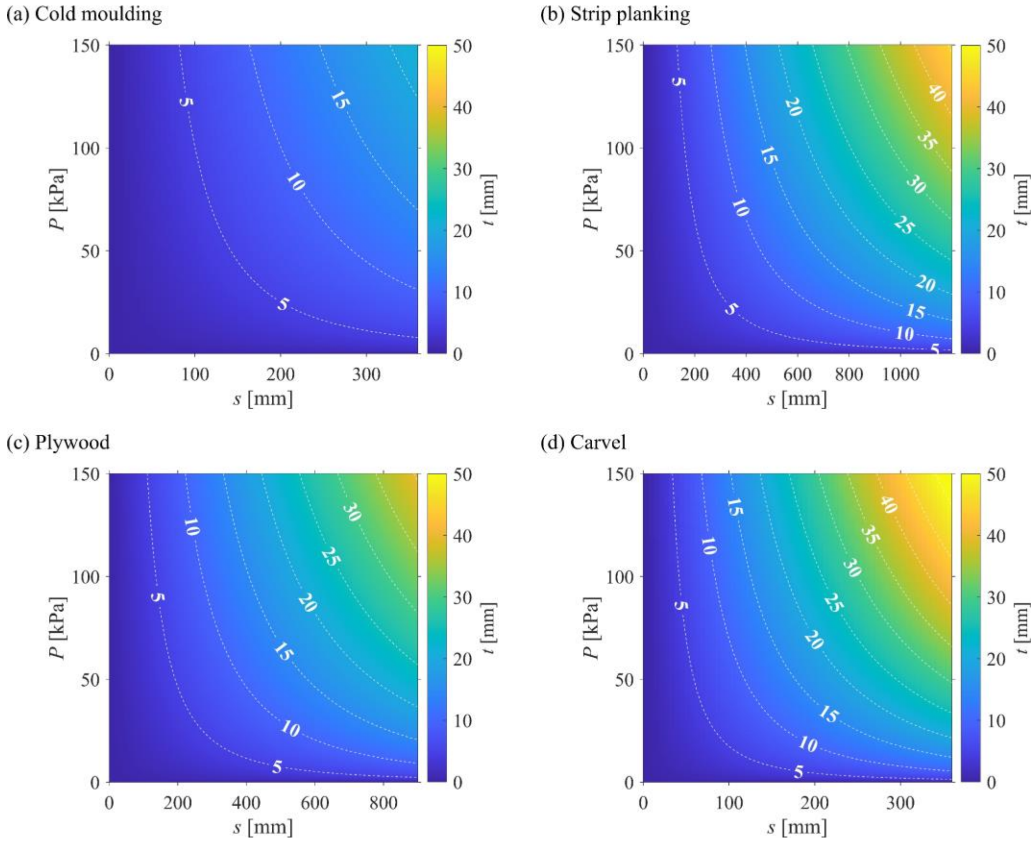

Figure 2. Required planking thickness for (a) cold moulding [36], (b) strip planking [36], (c) plywood [36], and (d) carvel (and clinker) [40].

In Figure 2, the carvel scantlings are given for $L = 15$ m, i.e. in the middle of the range where ABS [40] applies ($6\text{ m} \leq L \leq 24$ m). This is compared to the upper bound (minimum length $L = 6$ m, maximum pressure $P = 150$ kPa) and lower bound (maximum length $L = 24$ m, minimum pressure $P = 10$ kPa) of ABS [40] (Equation (2)), as well as the discrete values provided by GL [39], and the guidelines of Gerr [42] in Figure 3. There is a clear common trend across all three methods, despite their quantitative differences, which may be explained by their varied input parameters and associated assumptions.

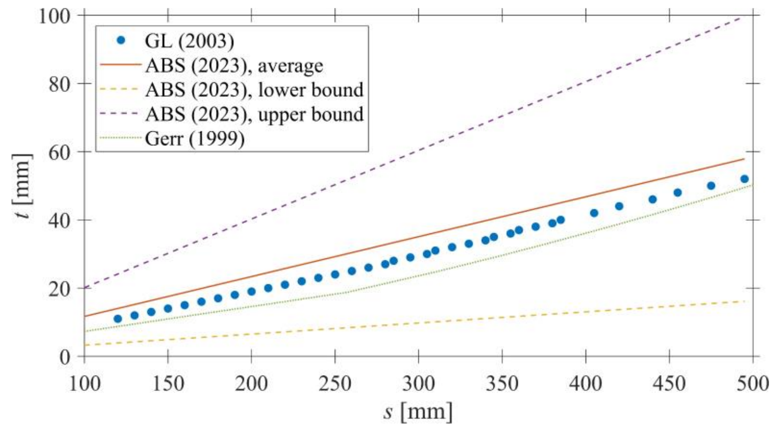

Figure 3. Comparison of the GL [39], ABS [40] and Gerr [42] carvel planking thickness.

Because different construction methods are associated with different timber species (see Table 1), with varying densities ρ, the resulting hull mass per square meter m can be computed as

$$m = t\rho. \tag{4}$$

The results are presented in Figure 4, further revealing the potential for cold moulding to achieve the lightest hull weights. Additionally, despite initially high thicknesses, the relatively low densities of western red cedar for strip planking ($\rho = 368$ kg m^{-3} [36]) and the marine plywood assumed ($\rho = 500$ kg m^{-3} [36, 53]) compared to that of oak for carvel ($\rho = 689$ kg m^{-3} [36]) makes the latter a much heavier option. Note that this finding remains valid for all species of timber commonly employed for carvel planking (e.g. larch, Douglas fir, mahogany, etc).

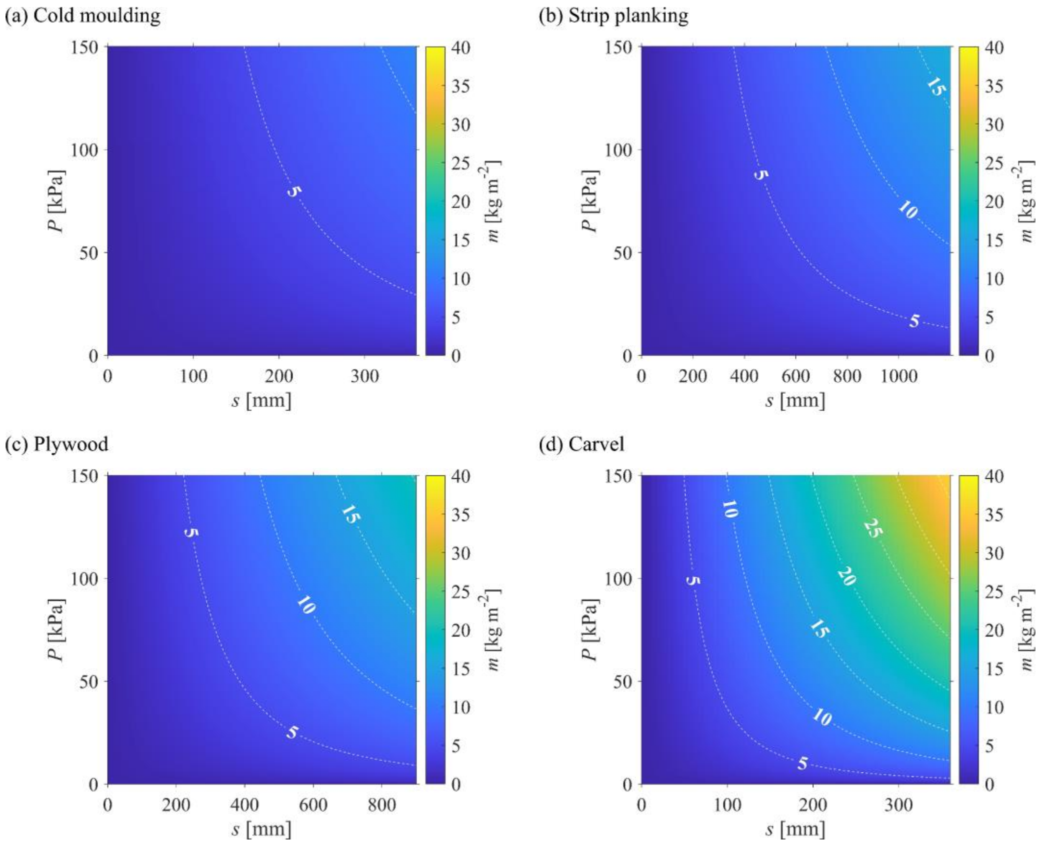

Figure 4. Planking mass based on required thickness for (a) cold moulding [36], (b) strip planking [36], (c) plywood [36], and (d) carvel (and clinker) [40].

Carvel planking may, therefore, not appear as an obvious choice for contemporary wooden boatbuilding. However, carvel differs from modern wooden boatbuilding methods in its absence of adhesives, which have a high environmental impact. Indeed, the regain of interest for wooden boats has been driven by sustainability considerations, which has yielded investigation into the life cycle assessment of vessels [56, 57], including wooden boats [58], albeit with high uncertainty as life cycle assessments for small crafts remain to be improved [59]. Nevertheless, assessing the carbon footprint per meter squared of hull shell C_f for the four construction methods under consideration using Equation (5) shows carvel to have the lowest carbon footprint, as evidenced in Figure 5.

$$C_f = m\, C_m \tag{5}$$

The benefits of carvel construction from an environmental point of view demonstrated in this section justify the increasing need for its inclusion in rules and regulations to support sustainable developments in small craft design and construction. Recent work [33], however, has highlighted the difficulty in achieving a reliable rule-based thickness equation for traditional wooden boatbuilding owing to some specific structural features and considerations not accounted for by regulatory bodies, and for which a thorough understanding remains lacking. Consequently, Section 4 tackles the challenges associated with traditional construction to identify the outstanding research questions to be answered in order to include traditional wooden construction methods in modern structural regulations.

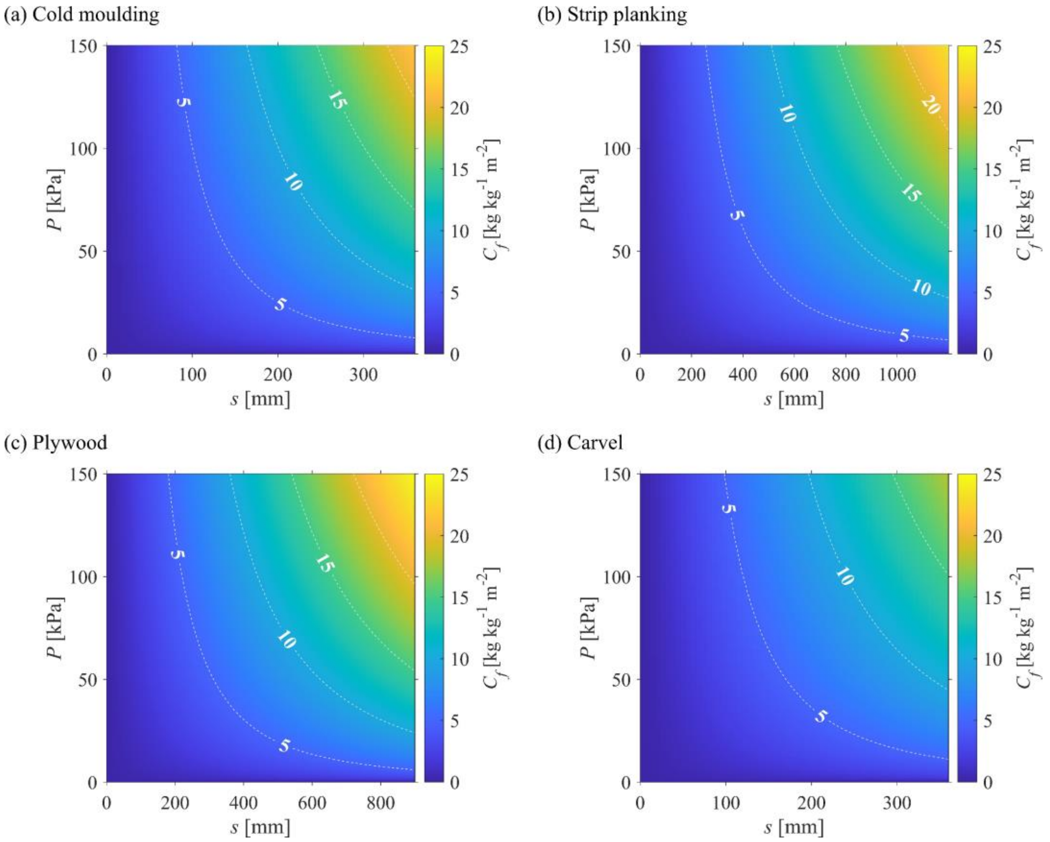

Figure 5. Carbon footprint for planking based on required thickness for (a) cold moulding [36], (b) strip planking [36], (c) plywood [36], and (d) carvel (and clinker) [40].

4. RECOMMENDATIONS FOR FUTURE CONSIDERATIONS

4.1 MOISTURE CONTENT

Moisture content is defined as the mass of water in timber compared to the dry mass of the timber. For boatbuilding applications, moisture content ranges from 7% (kiln-dried) to 14% (air-dried) [60] (7% to 16% allowed in ABS [40]; 8% to 14% in GL [39]). For modern boatbuilding, the epoxy encapsulation means the timber will remain within this moisture content throughout the operating life of the vessel. For traditional construction, however, the moisture content would increase to 28%-30%, also known as the fibre saturation point [60, 61], while in the water. This increase in moisture content is associated with a sharp reduction in material properties [62, 63, 64], as evidenced in Figure 6.

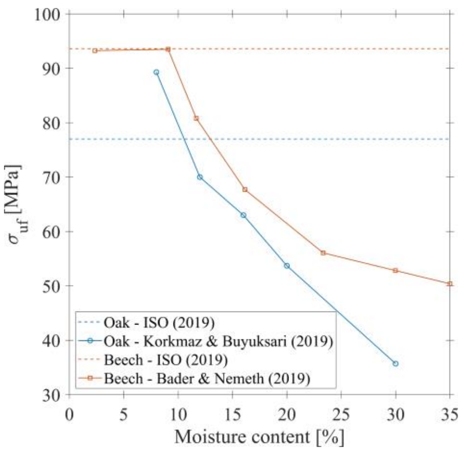

Figure 6. Variations in ultimate flexural strength with moisture content. Includes data from [62] for Oak and [63] for Beech, both compared to the default ISO properties [36].

Mechanical properties for timber are typically given at 12% moisture content [36, 39, 40]. Comparing σ_{uf} at 12% moisture content with 30% (fibre saturation point), the values are halved: 46% and 56% for oak and beech, respectively. This would imply that the factor of safety on the mechanical properties of timber for traditional construction needs to be at least doubled compared to current regulations.

4.2 STEAM BENDING

Steam bending allows to form timber into complex curved shapes, which is particularly appealing to boatbuilding. While suggestions for more effective application of steam bending in other fields have been made [65, 66], boatbuilding retains the rule of thumb that timber should be steamed for an hour per inch of thickness to bend [9]. Steam bending increases compressibility while having little effect on tensile properties [67]. However, under-streaming will not achieve the desired curvature, and over-streaming can lead to compressive fracture.

Studies have focused on the ability of timber species to bend following exposure to steam, investigating the effect of timber moisture content, steam time and breakage [68, 69, 70]. However, the material properties remain uncharacterised. The curvature of the timber thanks to stream bending provides better grain orientation. Whether the resulting mechanical properties deviate from that of solid timber assumed by regulatory bodies is unknown. As such, this may be an area of future research to quantify the effect of steam bending on traditional wooden boat scantlings.

4.3 MECHANICAL FASTENING

Both carvel and clinker planks rely on a large number of mechanical fasteners, typically riveted copper nails [9]. These require the use of a pilot hole and are counterbored, thereby introducing both a loss of mechanical properties, and a stress concentration, none of which is currently accounted for despite empirical methods available for their analysis [71]. Additionally, the pull force (or withdrawal force) exerted on a nail can be computed [60, 72], though it is unlikely to be of concern [73]. However, because the built-in end fixity of traditional construction may be questioned and simply supported seen as more suitable, as later detailed in Section 4.7, the prying action may be critical. Indeed, contrarily to built-in beams, simply supported ones experience a slope at their support. This would cause a prying moment on nails, the study of which requires further research [74].

4.4 SOLID TIMBER DEFECTS

Traditional construction methods are characterised by the use of thick solid timber, as previously evidenced in Figure 2. This leads to a high uncertainty associated with individual components, which may be affected by the grain orientation (further influenced by the slab or quarter-sawn nature of the timber [42]), deviation from straightness (cupping, bowing, twisting, diamonding, etc… [60]), or natural flaws (knots, sap pockets, etc…).

This renders default regulatory mechanical properties and the result of mechanical tests on small samples too optimistic. Indeed, while experimental testing of timber samples displays values close to that of ISO [23, 33, 75], lower values are achieved for larger timber components [76]. As such, higher factors of safety would be necessary. Conversely, modern construction techniques, such as cold-moulding, relying on thin, straight-grain veneers, where any defect would be visible, yield much more reliable structures. This justifies their lower thickness requirement (Figure 2), inclusion in scantling regulations [36], and lightweight, high-performance applications [10, 55, 77, 78]. While composite reinforcement of timber beams has been shown to alleviate the uncertainty inherent to timber defects [76], this would defy the environmental benefits associated with traditional construction.

4.5 PROPERTIES PERPENDICULAR TO THE GRAIN

Both carvel and clinker feature wide planks, meaning the properties perpendicular to the grain may become relevant. While properties perpendicular to the grain for plywood, and perpendicular to unidirectional fibre orientation for composite, are covered in ISO [36], this is not the case for solid timber. For the purpose of the application of ISO standards, flexural properties perpendicular to the grain may be taken as 7% and 9% of the flexural properties parallel to the grain for softwood and hardwood, respectively. There remains a lack of experimental data for timber perpendicular to the grain for boatbuilding applications. Moreover, any mechanical test would be affected by the limitations detailed in Section 4.4, and would further be affected by joint efficiency, tackled in Section 4.6, which has solely been investigated parallel to the grain.

4.6 JOINT EFFICIENCY

The finite size of timber planks requires the use of scarf joints. For plain scarfs, the length-to-thickness ratio drives the resulting strength, leading to higher scarf ratios being recommended for structurally critical applications. For instance, historical rules by Lloyds register of shipping [79] recommended ratios 4:1 for planks, 6:1 (possibly 8:1) for keels, and 12:1 for spars. In contemporary regulations, ratios of at least 10:1 for $t < 10$ mm and at least 8:1 for $t > 10$ mm are required by GL [39]. While both Birmingham [9] and Gerr [42] suggested scarfs are always weaker than solid timber, recent work by Souppez [33] has demonstrated that, thanks to modern adhesives, joints stronger than solid timber may be achieved for scarf ratios of 16:1 and higher. This is depicted in Figure 7.

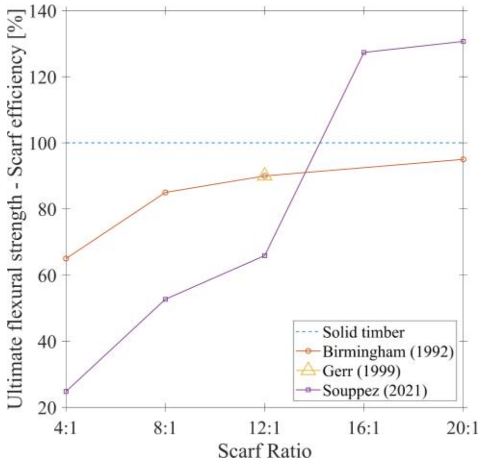

Figure 7. Scarf efficiency (ultimate flexural strength) compared to solid timber, represented by 100% efficiency. Includes data from [9], [33] and [42].

There is, therefore, a concern that, for commonly employed and recommended scarf ratios [9, 39, 42], flexural properties significantly lower than those assumed for solid timber may be achieved. Consequently, the scantlings of traditional crafts may be driven by the effectiveness of joints, as opposed to the mechanical properties of solid timber, an approach currently overlooked by rules and regulations.

4.7 STRUCTURAL ANALYSIS AND FAILURE MODE

Structural regulations are based on two assumptions: panels are treated as built-in beams (100% end fixity), and the load is considered uniformly distributed [80]. The first assumption may not be relevant to traditional construction, which features closely spaced small stringers, and thus a lower end fixity. Interestingly, recent developments in carbon fibre racing yachts have developed similar structures: small, closely spaces stringer, where panels have been assumed to be simply supported [81, 82]. Secondly, with short panels, a robustness criterion may be relevant [73], which would lead to a point load instead of a uniformly distributed load. The combination of both changes to the regulatory assumption would result in a change in the maximum bending moment from $Ps^2/12$ for a built-in beam under uniformly distributed load, to $Ps^2/4$ for a simply supported beam subject to a central point load assumed a Ps. The new plating thickness would, therefore, become

$$t = s\sqrt{\frac{1.5P}{\sigma_d}}, \tag{6}$$

in lieu of the current

$$t = s\sqrt{\frac{0.5P}{\sigma_d}}. \tag{7}$$

A thickness increase of $\sqrt{3}$ would therefore result from a change in underpinning assumptions. However, an additional failure mode may also need to be considered, namely shear. Indeed, given the high thickness and short span, panels with a thickness-to-span ratio up to 0.097 would be achieved for carvel, based on the parameter space considered in Figure 2. This compares to 0.031 for cold moulding, 0.013 for strip planking and 0.022 for plywood. The mechanical testing of samples to determine shear properties under ISO 14130:1998 [83] is to be performed for $t/s = 0.100$. Conversely, flexural tests under ISO 178:2019 [84] are to be performed at $t/s = 0.050$. Carvel planking is, therefore, most likely to fail under shear, which is overlooked by current regulations.

5. CONCLUSIONS

Modern timber construction is thoroughly addressed in contemporary structural regulations. However, traditional construction is only rarely accounted for, despite benefits that have led to a recent regain of interest in their design and construction for small crafts and wind-assisted ships alike. The comparative plating scantlings have been assessed for cold moulding, strip planking, plywood on frame and carvel planking. The latter, despite its higher thickness and mass, was shown to yield a much lower carbon footprint, demonstrating its relevance to sustainable boatbuilding.

To facilitate the development of structural regulations for traditional wooden construction, the key specificities of this construction method have been reviewed. These include high moisture content, the use of steam bending and mechanical fastener, the effect of natural defects and orientation perpendicular to the grain on the mechanical properties, the efficiency of scarf joint, and limitations to the regulatory assumptions for traditional construction. Areas of future research have been identified where knowledge currently is not available to affect scantling calculations.

This paper focused on carvel construction; however, clinker may be of further interest. Indeed, despite a lack of research, clinker planking is consistently taken as lesser than that of carvel owing to the overlapping planks. This would enable to achieve lighter hull shells than carvel and further reduce the environmental impact, which would warrant future work tackling clinker. Additionally, while planking has been detailed, the internal structure of traditional wooden boats would also benefit from further research to support the future development of thorough scantling rules for traditional wooden boats. Nevertheless, it is acknowledged that there remain numerous challenges associated with regulatory scantling rules for traditional boats, which may also prove overly conservative and discourage its adoption.

6. ACKNOWLEDGEMENTS

The valuable discussions and advice provided by Robin Loscombe is greatly acknowledge by the author.

7. REFERENCES

1. PARK, G., KIM, J.-C., YOUN, M., YUN, C., KANG, J., SONG, Y.-M., SONG, S.-J., NOH, H.-J., KIM, D.-K., and IM, H.-J., 'Dating the Bibong-ri Neolithic site in Korea: Excavating the Oldest Ancient Boat', *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 268, no. 7-8, pp. 1003-1007, 2010.
2. WARD, C., 'Boat-building and its Social Context in Early Egypt: Interpretations from the First Dynasty Boat-grave Cemetery at Abydos', *Antiquity*, vol. 80, no. 307, pp. 118-129, 2006.
3. MCGRAIL, S., 'Ancient Boats in North-West Europe: The Archaeology of Water Transport to AD 1500', *Routledge*, Milton Park, 2014.
4. FAIRBAIRN, W., 'Treatise on Iron Ship Building: Its History and Progress as Comprised in a Series of Experimental Researches on the Laws of Strain', *Longmans, Green & Company*, 1865.
5. BAXTER, J. P., 'The Introduction of the Iron-clad Warship', *Harvard University Press*: Harvard, US, 1933.
6. GREENE, E., 'Use of Fiber Reinforced Plastics in the Marine Industry', *Ship Structure Committee, National Academy of Science*, Washington, DC United States, 1990.
7. SOUPPEZ, J.-B. R. G., 'Structural Assessment and Scantlings of Traditional Small Crafts', *RINA Historic Ships*, London, UK, 2020.
8. BECK, R., BOOTE, D., DAVIES, P., HAGE, A., HUDSON, D., KAGEYAMA, K., KEUNING, J.A. and MILLER, P., 'Sailing Yacht Design', *17th International Ship and Offshore Structures Congress*, Seoul, Korea, 2009.
9. BIRMINGHAM, R., 'Boat Building Techniques Illustrated', London, UK: *Adlard Coles Nautical*; 2nd edition, 1992.
10. GOUGEON, M., 'The Gougeon Brothers on Boat Construction', Bay City, Michigan, US: *Gougeon Brothers Incorporated*, 2005.
11. SOUPPEZ, J.-B. R. G., 'On the Applications of Modern Naval Architecture Techniques to Historical Crafts', *RINA Historic Ships*, London, UK, 2016.
12. LOSCOMBE, P. R., 'Analysing Ancient (Viking) Longship Structure', *International Journal of Maritime Engineering*, vol. 164, no. A2, pp. 207-220, 2022.
13. ROSE, K. J., 'The Naval Architecture of Vasa, a 17th-Century Swedish Warship', *Doctoral Thesis*, *Texas A & M University*, Colle Station, Texas, US, 2014.

14. CANNON, S. BOYD, S. and WHITEWRIGHT, J., ‘Development of a Quantitative Method for the Assessment of Historic Ship Performance’, *14th International Symposium*, PRADS 2019, Yokohama, Japan, 2021.
15. THOMAS, J. and SOUPPEZ, J.-B. R. G., ‘Comparative Performance Prediction of Historical Thames A Rater Class Designs’, *RINA Historic Ships*, London, UK, 2018.
16. ALESSIO, L., SOUPPEZ, J.-B. R. G., and HAGE, A., ‘Design Evaluation and Alteration of the Dark Harbor 17.5: Case Study of a Modern Replica’, *RINA Historic Ships*, London, UK, 2016.
17. ALESSIO, L. G., ‘Redesign of a Classic Sailboat with FEA Investigation of the Plate Curvature’, *MSc Thesis, University of Liege*, Liege, Belgium, 2017.
18. SOUPPEZ, J.-B. R. G., ‘Design and Production of a Wooden Thames A Rater Class Sailing Yacht’, *MEng Thesis*, *The University of Auckland*, Auckland, New Zealand, 2015.
19. MARTUS, V., ‘Major Refit of a Sailing Replica of the 18th Century Frigate Experience and Traditional Skills Obtained by a Team of Volunteers’, *RINA Historic Ships*, London, UK, 2018.
20. CASTRO RUIZ, M., and PEREZ FERNANDEZ, R., ‘Galatea II: Reborn of a Classic’, *RINA Historic Ships*, London, UK, 2020.
21. WHITE, R. G., and PEREIRA, R. S., ‘Lilian: From Gentleman's Yacht to Scrap and Back’, *RINA Historic Ships*, London, UK, 2016.
22. GUELL, A. and SOUPPEZ, J.-B. R. G., ‘Combining Modern Hydrofoils with Wooden Classic’, *British Conference of Undergraduate Research*, Sheffield, UK, 2018.
23. SCEKIC, S., ‘Design of a 23 m Modern-Classic Wooden Sailing Yacht with Timber Investigation’, *MSc Thesis, University of Liege*, Liege, Belgium, 2018.
24. LINDEN, V. and SOUPPEZ, J.-B. R. G., ‘Sailing Towards Sustainable Trading with Wooden Cargo Schooner’, *British Conference of Undergraduate Research*, Sheffield, UK, 2018.
25. DE BEUKELAER, C., ‘Plain Sailing: How Traditional Methods could Deliver Zero-Emission Shipping’, *The Conversation*, 2018.
26. ARMANTO, J., ‘The Future of Sailing Cargo’, *Thesis, University of Turku*, Turku, Finland, 2019.
27. WANG, X. and PEGG, N., ‘Proceedings of the 21st International Ship and Offshore Structures Congress VOLUME 2 Specialist Committee Reports’, *21st International Ship and Offshore Structures Congress*, Volume 2, Vancouver, Canada, 2022.
28. TRUELOCK, D., LAVROFF, J., PEARSON, D., CZABAN, Z., LUO, H., WANG, F., CATIPOVIC, I., BEGOVIC, E., TAKAOKA, Y., LOUREIRO, C., SONG, C. Y., GARCIA, E., EGOROV, A., SOUPPEZ, J.-B. R. G., SENSHARMA, P., and NICHOLS-LEE, R., ‘Committee V. 5: Special Vessels’, *21st International Ship and Offshore Structures Congress*, Vancouver, Canada, 2022.
29. SOUPPEZ, J.-B. R. G., ‘Structural Challenges of Low-Emission Vessels: A Review’, *International Journal of Maritime Engineering*, vol. 165, no. A2, 2023.
30. MEULEMEESTER, D., ‘The Classification of Historic(al) Vessels and their Replicas’, *RINA Historic Ships*, London, UK, 2018.
31. SOUPPEZ, J.-B. R. G., ‘Timber Construction: An Experimental Assessment of the Strength of Scarf Joints and the Effectiveness of Various Adhesives for Laminated Wood’, *RINA Historic Ships*, London, UK, 2020.
32. BUCCI, V., CORIGALIANO, P., EPASTO, G., GUGLIELMINO E. and MARINO, A., ‘Experimental Investigation on Iroko Wood used in Shipbuilding’, *Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science*, vol. 231, no. 1, pp. 128-139, 2017.
33. SOUPPEZ, J.-B. R. G., ‘Experimental Testing of Scarf Joints and Laminated Timber for Wooden Boatbuilding Applications’, *International Journal of Maritime Engineering*, vol. 163, no. A3, 2021.
34. EUROPEAN PARLIAMENT, ‘Directive 2013/53/EU on Recreational Craft and Personal Watercraft’, *Official Journal of the European Union*, Luxembourg, Luxembourg, 2013.
35. UK GOVERNMENT, ‘The Recreational Craft Regulations 2017’, *UK Government*, London, UK, 2017.
36. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ‘ISO 12215-5:2019 Small Craft - Hull Construction and Scantlings - Part 5: Design Pressures for Monohulls, Design Stresses, Scantlings Determination’, *International Organization for Standardization*, Geneva, Switzerland, 2019.
37. LOSCOMBE, P. R., ‘Structural Design Considerations for Laminated Wood Yachts’, *International Conference on the Modern Yacht*, Portsmouth, UK, 1998.
38. LOSCOMBE, P. R., ‘Developing an ISO Scantling Standard for Recreational Craft of Laminated Wood Construction’, *The Modern Yacht Conference*, Southampton, UK, 2003.
39. GERMANISCHER LLOYD, ‘Rules for Classification and Construction - I Ship Technology - 3 Special Craft - 3 Yachts and boats up to 24 m’, *Germanischer Lloyd*, Hamburg, Germany, 2003.
40. AMERICAN BUREAU OF SHIPPING, ‘Rules for Building and Classing - Yachts - Part 3 Hull Construction and Equipment’, *American Bureau of Shipping*, Spring, Texas, US, 2023.
41. LOSCOMBE, P. R., ‘Some Observations on the Strength of Viking Ship Rudders’, *International Journal of Maritime Engineering*, vol. 165, no. A2, 2023.

42. GERR, D., 'The Elements of Boat Strength: for Builders, Designers, and Owners', *International Marine/McGraw-Hill*, 2000.
43. MARITIME AND COASTGUARD AGENCY, 'MGN 628 (M+F) Construction and outfit standards for fishing vessels of less than 15m length overall', *Maritime and Coastguard Agency*, Southampton, UK, 2020.
44. ROXANE & ROMILLY, '*Cold molded Romilly*,' 23 08 2023. [Online]. *Available: https://www.roxane-romilly.co.uk/romilly-spv/cold-molded-romilly*, 2023.
45. VAN DE STADT DESIGN, 'Glass-Fibre Wood Core', 23 08 2023. [Online]. *Available: https://www.stadtdesign.com/pages/woodcore*, 2023.
46. NEXUS MARINE CORPORATION, 'Building a Custom Wood Fly Fishing Boat', 23 08 2023. [Online]. *Available: https://www.nexusmarine.com/flyfisher_construction.html*, 2023.
47. SMALL BOAT NATION, 'Parker Dinghy', 23 08 2023. [Online]. *Available: https://smallboatsmonthly.com/article-tags/plank-on-frame/*, 2023.
48. SUTTON TIMBER, 'Clinker Boat for Burnham Overy Staithe', 23 08 2023. [Online]. *Available: https://www.suttontimber.co.uk/blog/clinker-boat-burnham-overy-staithe/*, 2023.
49. SOUPPEZ, J.-B. R. G., 'Structural Design of High Performance Composite Sailing Yachts under The New BS EN ISO 12215-5', *Journal of Sailing Technology*, vol. 3, no. 1, pp. 1-18, 2018.
50. SOUPPEZ, J.-B. R. G., BEGOVIC, E., SENSHARMA, P., WANG F., and ROSÉN, A., 'Comparative Assessment of Rule-Based Design on the Pressures and Resulting Scantlings of High Speed Powercrafts', *HSMV - High Speed Marine Vehicles*, Naples, Italy, 2020.
51. NIKFARJAM, M., YAAKOB, O., SEIF, M. S., and KOTO, J., 'Investigation of Wedge Water-Entry Under Symmetric Impact Loads by Experimental Tests', *Latin American Journal of Solids and Structures*, vol. 14, no. 5, pp. 861-873, 2017.
52. ANSYS, 'Ansys Granta EduPack', *Ansys*, Canonsburg, Pennsylvania, US: Ansys, 2023.
53. BRITISH STANDARDS INSTITUTION, 'BS 1088:2018 Marine Plywood. Requirements', *British Standards Institution*, Chiswick, UK, 2018.
54. BLUNDEL, R., 'Little Ships: The Co-evolution of Technological Capabilities and Industrial Dynamics in Competing Innovation Networks', *Industry and Innovation*, vol. 13, no. 3, pp. 313-334, 2006.
55. BARRY, C. D., 'CNC Enabled Wood/Metal Composite Construction of (Relatively) High Performance Sailing Yachts', *Journal of Sailing Technology*, vol. 7, no. 1, pp. 152-185, 2022.
56. MIO, A., FERMEGLIA, M. and FAVI, C., 'A Critical Review and Normalization of the Life Cycle Assessment Outcomes in the Naval Sector', *Journal of Cleaner Production*, p. 133476, 2022.
57. TUAN, D. D., and WEI, C., 'Cradle-to-Gate Life Cycle Assessment of Ships: A Case Study of Panamax Bulk Carrier', *Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, vol. 2, pp. 670-683, 2019.
58. POMMIER, R., GRIMAUD, G., PRINÇAUD, M., PERRY N., and SONNEMANN, G., 'Comparative Environmental Life Cycle Assessment of Materials in Wooden Boat Ecodesign', *The International Journal of Life Cycle Assessment*, vol. 21, pp. 265-275, 2016.
59. JACQUET, L., DUIGOU, A. L., and KERBRAT, O., 'Holistic Lifecycle Assessments Made in Maritime Industry: A Systematic Review and Proposals for Future Research Directions in Racing Boats Eco-Design', *6th International Conference on Innovation in High Performance Sailing Yachts and Wind-Assisted Ships*, Lorient, France, 2023.
60. HOADLEY, R. B., 'Understanding Wood: A Craftsman's Guide to Wood Technology', Newtown, Connecticut, United States: *Taunton Press*, 2000.
61. BARKAS, W. W., 'Fibre Saturation Point of Wood', *Nature*, vol. 135, p. 545, 1935.
62. KORKMAZ, O., and BÜYÜKSARI, Ü., 'Effects of Moisture Content on Mechanical Properties of Micro-Size Oak Wood', *BioResources*, vol. 14, no. 4, pp. 7655-7663, 2019.
63. BÁDER, M., and NÉMETH, R., 'Moisture-Dependent Mechanical Properties of Longitudinally Compressed Wood', *European Journal of Wood and Wood Products*, vol. 77, pp. 1009-1019, 2019.
64. FU, W.-L., GUAN, H.-Y. and KEI, S., 'Effects of Moisture Content and Grain Direction on the Elastic Properties of Beech Wood Based on Experiment and Finite Element Method', *Forests*, vol. 5, p. 610, 2021.
65. WRIGHT, R. S., BOND, B. H., and CHEN, Z., 'Steam Bending of Wood; Embellishments to an Ancient Technique', *BioResources*, vol. 8, no. 4, pp. 4793-4796, 2013.
66. STEVENS, W. C., and TURNER, N., 'A Method of Improving the Steam Bending Properties of Certain Timbers', *Wood*, vol. 15, no. 3, pp. 79-84, 1950.
67. WANGAARD, F. F., 'The Steam Bending of Beech', *Journal of the Forest Products*, vol. 2, pp. 35-41, 1952.
68. RATNASINGAM, J., LATIB, H. A., LIAT, L. C., and FARROKHPAYAM, S. R., 'Comparative Steam Bending Characteristics of some Planted Forest Wood Species in Malaysia', *BioResources*, vol. 17, no. 3, p. 4937, 2022.
69. KULJICH, S., CÁCERES, C. B., and HERNÁNDEZ, R. E., 'Steam-Bending Properties of Seven Poplar Hybrid Clones', *International Journal of Material Forming*, vol. 8, pp. 67-72, 2015.

70. NIEMIEC, S. S., and BROWN, T. D., ‘Steam Bending Red Alder’, *Western Hardwoods*, vol. 12, 1995.
71. YOUNG, W. C., BUDYNAS, R. G., and SADEGH, A. M., ‘Roark's Formulas for Stress and Strain’, New York, US: *McGraw-Hill Education*, 2012.
72. JONES, T. H., ‘The Encyclopedia of Wood’, New York, US: *Sterling Publishing Co INC International Concepts,* 1989.
73. LOSCOMBE, P. R., ‘Remarks Related to Scantling Formulae for Wooden Craft’, *Personal Conversation*, 2023.
74. VAN DE LINDT, J. W. and DAO, T. N., ‘Performance-Based Wind Engineering for Wood-Frame Buildings’, *Journal of Structural Engineering*, vol. 135, no. 2, pp. 169-177, 2009.
75. LINDEN, V., ‘Wooden Cargo Schooner for Sustainable Trading Initiatives’, *Dissertation, Solent University*, Southampton, UK, 2018.
76. CORRADI, M., BORRI, A., RIGHETTI, L. and SPERANZINI, E. ‘Uncertainty Analysis of FRP Reinforced Timber Beams’, *Composites Part B: Engineering*, vol. 113, pp. 174-184, 2017.
77. MILLER, P. H., and DILLON, D. L., ‘The International Sailing Canoe: A Technical Review’, *Marine Technology and SNAME News*, vol. 31, no. 4, pp. 296-304, 1994.
78. PARKER, R. B., ‘The New Cold-Molded Boatbuilding: from Lofting to Launching’, Brooklin, Maine, US: *WoodenBoat Books*, 2005.
79. LLOYD'S REGISTER OF SHIPPING, ‘Rules and Regulations for the Classification of Yachts and Small Craft, Part 2, Hull Construction’, *Lloyd's Register of Shipping*, London, UK, 1970.
80. SOUPPEZ, J.-B. R. G., ‘Ships and Maritime Transportation’, in *Springer Handbook of Mechanical Engineering*, Springer, Berlin, Germany, pp. 1139-1164, 2021.
81. LORIMER, T. and T. ALLEN, ‘Concurrent Multi-Component Optimization of Stiffened-Plate Yacht Structures’, *Journal of Sailing Technology*, vol. 7, no. 1, pp. 203-227, 2022.
82. HARRIS, S. P. H., ‘Structural Design, Sizing and Optimisation for a Foiling Monohull’, *Thesis, The University of Auckland*, Auckland, New Zealand, 2020.
83. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ‘ISO 14130:1998 - Fibre-reinforced Plastic Composites - Determination of Apparent Interlaminar Shear Strength by Short-Beam Method’, *International Organization for Standardization*, Geneva, Switzerland, 1998.
84 INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, ‘ISO 178:2019 - Plastics - Determination of Flexural Properties’, *International Organization for Standardization*, Geneva, Switzerland, 2019.

8. AUTHORS BIOGRAPHY

Jean-Baptiste R. G. Souppez is a Senior Teaching Fellow in Mechanical, Biomedical and Design Engineering at Aston University, and contributes to the Erasmus Mundus Masters in Advanced Design of Ship and Offshore Structures (EMship+) and Sustainable Ships and Shipping 4.0 (Seas 4.0) as a Visiting Professor at the University of Liege and Naples Federico II, respectively. He was awarded a National Teaching Fellowship for outstanding impact on student outcomes and the teaching profession in higher education. He is also the Deputy Editor-in-Chief of the Society of Naval Architects & Marine Engineers (SNAME) Journal of Sailing Technology, the world's leading peer-reviewed journal for sailing research. His work in fluid dynamics features a wide range of experimental techniques, supporting his expertise in hydrofoils and award-winning research on the aerodynamics of yacht sails. As the UK Principal Expert in Small Craft Structures, he represents the interests of the British Marine Industry in the development of international structural regulations (ISO 12215) thanks to his extensive knowledge of composites and structural design and analysis, for which he was awarded a Medal of Distinction by the Royal Institution of Naval Architects (RINA). Recognised as an international leader in yacht design and marine engineering, he sits on several prestigious and influential international committees, and oversees all small craft regulatory developments on behalf of the Institute of Marine Science, Engineering and Technology (IMarEST).