DISCUSSION

ULTIMATE STRENGTH OF QUASI-ISOTROPIC COMPOSITES: ISO 12215-5:2019 VALIDATION

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COMMENT

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With the incorporation of the International Journal of Small Craft Technology into the IJME, it is always good to see papers of direct concern to the small craft design community. The process of on-going validation of scantling rule formulae is also to be welcomed. The authors are to be commended on both counts. Word count restricts comments/questions to the ultimate flexural strength of hand-laminated panels (Table 5).

The ISO (2008) thickness and ultimate flexural strength are given as 4.311mm and 174.69 MPa respectively. The contributor obtained *4.302mm* and *174.91* MPa using Southampton University's Wolfson unit HullScant (ISO 2008 version) with Evaluation level "B" (Table C.1 of Ref 14.). Evaluation level "B" requires that *fibre content by mass be determined by measurement and spot checks are to be carried out using recognised test standards for samples that are representative of the product as manufactured to ensure the product meets or exceeds the default values*, i.e. equation (8) in this case. Equation (8) was not developed by the ISO working group, but was taken from classification society rules, notably those of Lloyd's Register of Shipping and of Germanischer Lloyd. If memory serves, the formula dates from around the late 1970's and may still be found, unamended in current rule issues.

The ISO (2019) thickness and ultimate flexural strength are given as 4.311mm and 183.05 MPa respectively. The contributor obtained *4.302mm* and *182.87** MPa using HullScant's laminate stack option with "HIGH" build quality (Table 15 of Ref 15.). "HIGH" (k_{BB} = 0.95) requires that the *fibre mass content be monitored, obtained either from sample thickness with theoretical approach or ashing test.* Note; there does not *appear* to be any requirement to carry out spot-checks on *mechanical* properties. Is this the case? If so, how can manufacturing defects such as fibre misalignment be identified?

On page A-241, the authors mention the k_{AM} factor of 0.95. Should this be also included to be compatible with the ISO (2008)? If so then the figure of ≈ 183 MPa becomes 174 MPa, i.e. virtually identical to the ISO (2008) value.

As an aside, users have the option to employ the "Developed method (classical lamination theory) introduced in ISO (2019) method, notwithstanding that for this type of layup, one would expect very similar results to the stack analysis. This was checked out using version 4.1 of the Laminate Analysis program (LAP) by Anaglyph Ltd (UK). The results were virtually identical. As k_{BB} is taken as 1.0 in this case (rather than 0.95), a rather artificial, though admittedly small increase in allowable strength is obtained!

The mean measured thickness and ultimate flexural strength is given as 4.065mm and 298.33 MPa respectively in Table 5. The variation in flexural strength is tiny at around 3%. This value *could* be entered into equation (11) on page A-241 after derating by 10% (as required in both ISO versions). It also requires the application of k_{AM} = 0.9. The value of 298.33 MPa is obtained (presumably) using the measured thickness of 4.065mm. If used unamended to find the required laminate thickness from equation (11) and subsequently converted to fibre areal density using equation (7) (which overestimates the measured thickness by 4.311mm v 4.065mm), is this not a case of "having your cake and eating it"? It *may* be prudent to correct for this giving a resulting ultimate flexural strength of 214 MPa (from 298.33 x 0.9 x 0.9 x $(4.065/4.311)^2$).

* Obviously HullScant (2008) cannot calculate ISO (2019) rule-of-mixtures based elastic constants or use the failure strains given in Annex C of Ref 14, but these may be calculated manually and entered as "TEST" values. The program provides the permissible applied between moment/unit width to just comply with the safety factor of 2 (296.93 N) and this may be easily converted to an effective flexural strength if multiplied by $12/t^2$ giving 192.49 MPa. Including the factor k_{BB} = 0.95 yields 182.87 MPa.

This, the contributor would suggest, is a decent enough margin to serve as an indicator that the default values (both ISO versions) are good enough to be considered reasonably safe. Whether this value could be used with confidence to *supersede* the default values for scantling determination is another matter. It seems difficult to argue convincingly that such "lab-samples" are truly representative of those cut from various locations of a craft (some areas more difficult to access than others), built by various workers with differing skill levels and loaded by a huge variety of static and dynamic loads over its twenty year service life. This is not a critical comment of the authors' approach in any sense – the contributor faced similar concerns when using a near identical approach to investigate ISO (2008) properties v experimental results for glass, carbon and aramid cross-ply layups in various permutations – limited resources preclude any other approach (Loscombe, 2008).

As an aside, it is interesting to note that the laminated wood annex of ISO (2008) appears in ISO (2019) largely unchanged. In 2005, the default property data required a lot of "scratching around" but subsequently Lloyd's Register has presented similar equations for plywood. These yield rather more conservative values than ISO 2008/19. Perhaps Lloyd's Register has applied additional factors? Have the authors come across this?

There may be no (cost-effective) definitive/scientific answer but the contributor would be most interested to learn the authors' views on the matter, especially in the light of the much lower factor of safety of 2 used in both ISO versions compared with 3 or more as highlighted in the authors' paper. This may be even more of a problem for more complex layups which feature unidirectional plies, where the calculated "first-ply-to-failure" moment may be significantly smaller than the ultimate bending moment capacity.

Finally, the contributor would like to thank the authors for this and numerous other papers on the ISO-12215 theme. If some presumption may be forgiven, another topic worthy of their attention is the design bending moment $[EI_l/EI_b]^{0.5}$ factor in Table A.4 ISO (2019) which is only valid for 0/90 layups and those where the Poisson's ratio and shear modulus possess characteristics which are not generally met in marine composites. Given that one major benefit of moving away from the 2008 version (for single skin layups) to the new release is to better accommodate the increasingly prevalent double-bias plies into the laminate stack, it is important that designers, rather than rely exclusively on Table A.4, consider using 8-noded shell elements within simple FEA rectangular panel models or consider some further modifying factors be adopted as was explored by the contributor (Loscombe, 2017).

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AUTHORS' RESPONSE

Firstly, the authors are very thankful for **Dr Robin Loscombe's** pertinent and insightful comments, particularly given his seminal and influential work on small craft structural regulations – much of today's structural regulatory landscape has been shaped by his original work. It is also hoped that the IJME will indeed provide a platform for the publication and discussion of small craft related research.

Under the ISO12215-5:2019, the requirements for a 'high' boatbuilding quality factor are, indeed, limited to the monitoring of the fibre weight fraction. Assessment of the mechanical properties of the laminate, as built, become a requirement for a 'tested' boatbuilding quality factor. Manufacturing defects such as misalignment have, until recently, not been explicitly considered. A first step towards addressing this issue was taken with the publication of the ISO 12215-10 (ISO, 2020), which acknowledges misalignment, and suggest a value of 5 degrees is assumed in the absence of better information. Previous work by the author (Souppez, 2018) discussed this further, and employed the Krenchel factor (Krenchel, 1964) to compute losses in mechanical properties due to misalignment. Additional consideration for defects in small craft structures may be found in Han *et al.* (2020) and Oh *et al.* (2022), some of the many publications from Mokpo National Maritime University, South Korea, in the field of composite materials for small craft applications.

Because the boatbuilding quality factor was introduced in the 2019 version of the ISO 12215-5, it was not retrospectively applied to the 2008 calculations, the latter being developed under the (no longer existing) evaluation level b. While parallels can be drawn between the 2008 evaluation levels (a, b and c) and the 2019 boatbuilding quality factors (tested, high, low), direct comparisons and application in subsequent/previous versions are not deemed suitable.

The mechanical properties experimentally assessed in laboratory setting fall under specific ISO standards, with recommendations made by the ISO 12215-5 for composite material properties (e.g. ISO 178 for flexural properties (ISO, 2019), ISO 527-4 for tensile properties (ISO, 2021), ISO 14126 for compressive properties (ISO, 1999), etc…). As rightly pointed out, these yield vast areas of uncertainty with respect to the shape of the vessel or the various skill levels of the workers. While the ISO 12215-5:2019 attempts to capture these, with a distinction between simple and complex surfaces (the latter yielding a reduction in fibre volume fraction) and a boatbuilding quality factor, these remain generic. The former does not capture the accessibility of a panel, while the latter targets manufacturing processes, and not individual skill level. These, therefore, remain limitations. The effect of static and dynamic loads over the service life is a further excellent point raised. This has historically been beyond the scope of the ISO 12215s. However, current work on the revision of the sailing craft appendages standard (ISO 12215-9) is tackling the Miner's summation factor (MSF), which may pave the way for greater consideration for fatigue and service life. Returning to the limitations of testing sample for small craft applications, the work carried out by the Centre for Advanced Composite Materials, part of the University of Auckland, New Zealand is to be mentioned, and includes (among various research areas) whole panel testing over slamming events (Battley and Allen, 2019), and novel structural arrangements for small crafts (Lorimer and Allen, 2022).

With the above clarifications and elements of discussion, perhaps the most significant discussion points can now be tackled, namely the thickness and ultimate strength. While the full commercial version of the HullScant software is not available to the authors, the demonstration version was employed (Wolfson Unit, 2022) for the hand laminated and vacuum bagged laminates, assuming the lowest fibre weight fraction within the ISO range given for the latter. The thicknesses appeared consistent with the published values based ISO 12215-5:2019 equations, within 0.001 mm and 0.002 mm for the hand laminated and vacuum bagged panels, respectively, likely arising from rounding. Further comparison with the software, however, could not be undertaken, owing to the limitations of the demonstration version. As pointed out, ultimate strengths (extrapolating here beyond the comments on the ultimate flexural strength to also include tensile and compressive ones) are indeed reported as the average experimental values plus/minus the uncertainty, as defined in Section 2.3 of the paper under discussion (Souppez & Laci, 2022), an approach similar to that of Oh *et al.* (2022), for instance. For design purposes, experimental values are indeed taken as the lesser of 90% of the average or the average minus two standard deviation, a requirement of the ISO 12215-5, also shared by ISO standards inherent to the determination of mechanical properties. It should be noted that, while 10 samples are employed in the paper under discussion, ISO standards only require a minimum of 5 samples to be tested. A higher standard deviation could therefore be expected with a lower number of test samples. Particular attention was also paid to providing a methodology to assess the bias in the paper under discussion (see Section 2.3), a factor currently not accounted for by ISO standards. For the design strengths, this time from a regulatory point of view under the ISO 12215-5, additional factors are indeed to be considered, including the assessment method and boatbuilding quality factor. Designers may also wish to consider other sources of uncertainty, which may include that related to thickness (with the paper under discussion showing an overestimation by the ISO thickness equation compared to experimental values), as well as other sources tackled in this discussion (misalignment, defects, factor of safety, etc…). For the purpose of this study, which was not intended to provide a comparative, applied design case study, this was therefore not fully explored. However, part of this approach is being implemented in current work (a collaboration between Aston University and the University of Edinburgh) investigating virgin versus pyrolysis-recycled carbon fibre, looking at added thickness, added mass, cost savings and reduction in environmental impact when employing pyrolysis-recycled carbon fibre over virgin one, the former achieving lower mechanical properties than the latter.

Regarding laminated wood, while the authors are unaware of whether additional factors are applied by Lloyd's Register, it is also an area of particular research interest. Experimental work investigating the validity of ISO and ABS mechanical properties, and limitation arising from the presence of scarf joints and lamination using various adhesives, has been undertaken (Souppez, 2021). It is hoped that further work will be conducted to support the next revision of the ISO 12215-5.

This leads to the factors of safety considered in the ISO 12215-5. The paper under discussion does indeed identify this as a crucial area. The ISO 12215-5 has, typically, employed lower factors of safety than other regulations. The revision of the 2008 version of the standard, however, did not identify any cause for concern regarding the values employed based on the service history of the vessels built to the 2008 version. These have, however, not yet reach their full lifespan, and an increase in factor of safety was implemented for commercial crafts given their expected use compared to recreational ones. Future work expanding the experimental approach employed in the paper under discussion to more complex laminate is envisaged, and it is hoped it will provide further elements of discussion, in the absence of a definite answer or solution.

Lastly, the recommendations regarding the design bending moment, Table A.4 of the ISO 12215-5:2019 and the application of 8-noded shell elements are well noted, and provide valuable direction for future revisions to the standard. A further area of interest, which bring together the points about the uncertainty associated experimental data and factors of safety, previously discussed, is the increasing use of biocomposites and recycled composites in small crafts. These vessels do not yet benefit from the same service history a fiberglass, aramid and carbon ones, and properties remain solely based on laboratory testing, limitations of which have been identified in this discussion. This is deemed a vital step to support developments in sustainable small craft design and manufacture.

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