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

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SUMMARY

Glass fibre reinforced polymer composites are the most common materials employed for the manufacturing of small crafts, with the scantlings governed by ISO 12215-5:2019. However, no validation data is available to ascertain the relevance of the default ultimate strengths provided by the standard. This paper experimentally characterises the ultimate flexural, tensile and compressive strength of hand laminated and vacuumed bagged quasi-isotropic glass-epoxy laminate. The results show that ISO 12215-5:2019 default ultimate strengths for the quasi-isotropic composite laminate tested are (i) conservative for the ultimate flexural strength, (ii) appropriate for the ultimate tensile strength, and (iii) optimistic for the ultimate compressive strength, especially for vacuum bagged samples, with the main cause identified as the value of the ultimate compressive breaking strain for chopped strand mat. These findings provide validation data for ISO12215-5:2019 and it is anticipated the results may contribute to future improvements in small craft regulations.

KEYWORDS

Composite Structures, Marine Composites, Experimental Testing, ISO 12215-5, Fibre Glass, Epoxy.

NOMENCLATURE

b	Width of test sample (mm)
B	Bias limit
b_{ISO}	Length of the short side of the panel (mm)
F	Force (N)
h	Thickness of test sample (mm)
k_{2b}	Panel aspect ratio factor for bending moment
k_{AM}	Assessment method factor
k_{BB}	Boatbuilding quality factor
k_C	Panel curvature coefficient
l	Length of test sample (mm)
n	Number of samples tested
P	Precision
P_{ISO}	Design pressure (kPa)
t	Thickness of the panel (mm)
t_{95}	t-value at the 95% confidence level
U	Uncertainty
w	Dry fibre mass (g.m^{-2})
ρ	Density (kg.m^{-3})
ρ_f	Fibre density (kg.m^{-3})
ρ_m	Matrix density (kg.m^{-3})
σ	Strength (MPa)
σ_d	Design strength (MPa)
σ_u	Ultimate strength (MPa)
$\sigma_{u\ t/c}$	Ultimate tensile or compressive strength (MPa)
σ_{uc}	Ultimate compressive strength (MPa)
σ_{uf}	Ultimate flexural strength (MPa)
σ_{ut}	Ultimate tensile strength (MPa)
Ψ	Fibre weight fraction
CSM	Chopped strand mat
DRE	Data reduction equation
GFRP	Glass fibre reinforced polymer
ISO	International organization for standardization
WR	Woven roving

1. INTRODUCTION

The hull construction and scantlings of small crafts is govern by ISO 12215-5:2019 (ISO, 2019a). To reflect the significant advances in marine composite materials and manufacturing over the last two decades, the previous ISO12215-5:2008 (ISO, 2008) was reviewed and updated in 2019. The revisions and improvements to the standard were first introduced by Souppez & Ridley (2017), and later detailed by Souppez (2018a; 2018b; 2019). Amongst the key changes between ISO 12215-5:2008 (ISO, 2008) and ISO 12215-5:2019 (ISO, 2019a) is the way the ultimate strengths of composite materials are assessed. Indeed, ISO 12215-5:2008 relied on simple regression equations, directly related to the fibre weight fraction, to yield the ultimate strengths (flexural, tensile and compressive) of given plies. In contrast, the more complex ISO 12215-5:2019 now employs a ply-by-ply analysis to yield more precise values for the considered ultimate strengths. This has resulted in higher ultimate strengths being assumed. Additionally, these now account for the analysis and manufacturing quality, thanks to an assessment method and a boatbuilding quality coefficient. The intension is to yield more conservative properties when simpler analysis methods and cruder boatbuilding techniques are employed.

The previous version of ISO 12215-5 has been compared to the requirements other regulatory bodies, such as the American Bureau of Shipping (Curry, 2005), and the Registro Italiano Navale (Oh, et al., 2014). No such comparisons have been undertaken for the mechanical properties under ISO 12215-5:2019. However, the recent work of Loscombe (2019), Begovic (2020) and Truelock, et al. (2022) have investigated the design pressures against industry practice for the former, and existing regulations for the latter two.

In recent years, experimental data inherent to the tensile and flexural properties of fibreglass composites were presented by Jang, et al. (2019), with additional investigations into the effect of fibre weight fraction conducted by Oh & Han (2019) as well as Han, et al. (2020a). Experimental testing was also reported by Han, et al. (2020b) and Lee, et al. (2021) regarding the tensile and flexural properties of glass fibre composites, respectively. Data for carbon fibre composite was also provided by Han, et al. (2020c). However, all the above experiments were compared to the mechanical properties as defined in the former ISO 12215-5:2008 (ISO, 2008). The previously cited publications found the regulatory values to be pessimistic compared to experimental results, as would be expected of default regulatory properties. Whether this remains the case under the newer version of ISO 12215-5, which assumes greater mechanical properties, is unknown.

Experimental validation of the latest ISO12215-5:2019 would therefore be desirable, as the new default mechanical properties are yet to be compared to experimental results. This is also relevant as mechanical testing standards for flexural (ISO, 2019b) and tensile (ISO, 2021) properties have also recently been updated.

Composite materials, particularly glass fibre reinforced polymers, have long been established as the preferred material for small craft manufacturing (Shenoi, et al., 2011; Amirkhosravi, et al., 2017). Hand lamination has been the favoured manufacturing technique thanks to its low cost (Davies & Petton, 1999; Kolat, et al., 2007). More recently, however, health and safety concerns related to the styrene emissions associated with polyester and vinylester resins (Castillo, et al., 2001) have triggered a shift towards vacuum assisted manufacturing, such as vacuum bagging (Graham-Jones & Summerscales, 2015), as well as epoxy, albeit a higher cost option. The move towards vacuum bagging justifies the focus of the present work on glass fibre reinforced polymers (GFRP) manufactured using both hand lamination and vacuum bagging. This best represents the current manufacturing practices for small crafts.

In this paper, experimental destructive testing of a quasi-isotropic glass-epoxy composite laminate is undertaken for hand laminated and vacuum bagged samples. The ultimate flexural, tensile and compressive strength will be ascertained in accordance with their respective testing standards, namely ISO 178 (ISO, 2019b), ISO 527-4 (ISO, 2021) and ISO 14126 (ISO, 1999), respectively. Experimental results will be compared to the default properties of the 2008 and 2019 ISO 12215-5. For the latter, two assessment methods will be considered, namely the simplified (method 1) and enhanced (method 2) method. The aim of this work is to assess the reliability of the default ultimate strengths compared the default values of ISO 12215-5:2008 and ISO12215-5:2019. This would represent the first experimental validation of the latest ISO12215-5 standard, and would contribute to a better understanding of the relevance and validity of the regulatory mechanical properties for small crafts composite structures.

The remainder of the paper is structured as follows. Section 2 details the methodology employed in this study, including the destructive testing setup, uncertainty analysis, and underpinning ISO 12215-5 theory. Section 3 presents the results for the panel thickness, and ultimate flexural, tensile and compressive strengths. These are compared to the former (2008) and current (2019) ISO values. Finally, Section 4 summarises the main findings of this study and identifies areas worth of future investigations.

2. EXPERIMENTAL APPROACH

2.1 MANUFACTURING

A quasi-isotropic laminate was employed, by alternating E-Glass chopped strand mat (CSM) and woven roving (WR) plies. The laminate schedule is presented in Table 1, where ply 1 is the outer ply. The laminate consists of 8 plies, alternating between a WR and CSM, the latter being the inner ply. The CSM has a mass per square meter of 300 $g.m^{-2}$. The WR has a mass per square meter of 290 $g.m^{-2}$. The combination of these plies has been chosen as it is representative of a low technology and low cost laminate. Moreover, it can be analysed using the simplest ISO 12215-5 method for quasi-isotropic GFRP panels. A WR/CSM laminate was also investigate by Jang, et al. (2019) for the same reasons. In this study, epoxy resin (Ampreg 22) was used due to health and safety restrictions. Indeed, polyester or vinylester would yield harmful styrene emissions (Castillo, et al., 2001). The Ampreg 22 resin therefore enables to ensure a safer working environment, while being a common boatbuilding resin. Note that, under ISO 12215-5, the resin properties are considered identical for all resin systems (polyester, vinylester, epoxy).

Two manufacturing techniques were employed: hand lamination and vacuum bagging. In both cases, the manufactured panels were left to cure at room temperature and featured a peel-ply to remove excess resin and provide a consistent outer surface finish. Furthermore, samples

Table 1: Laminate schedule.

Ply	Fibre	Cloth	Dry mass	Orientation
1	E-Glass	WR	290 g.m^{-2}	0°/90°
2	E-Glass	CSM	300 g.m^{-2}	n/a
3	E-Glass	WR	290 g.m^{-2}	0°/90°
4	E-Glass	CSM	300 g.m^{-2}	n/a
5	E-Glass	WR	290 g.m^{-2}	0°/90°
6	E-Glass	CSM	300 g.m^{-2}	n/a
7	E-Glass	WR	290 g.m^{-2}	0°/90°
8	E-Glass	CSM	300 g.m^{-2}	n/a

were visually checked for delamination and any defects that may influence the results.

Samples were manufactured in accordance with the following international standards, as recommended by Souppez (2018a) for the assessment of the mechanical properties of composite materials for small crafts:

- ISO 178:2019 (ISO, 2019) for the determination of flexural properties,
- ISO 527-4:1997 (ISO, 2021b) for the determination of tensile properties, and
- ISO 14126:1999 (ISO, 1999) for the determination of compressive properties in the in-plane direction.

The geometric definition of the rectangular sample compared to their respective ISO requirements are presented in Table 2. For flexural samples, the width is a function of the nominal thickness. A 10 mm width is required for samples thicknesses h between 3 and 5 mm. This is met for the hand laminated samples, but for the vacuum bagged ones h = 2.82 mm. For consistency and to avoid introducing a bias due to varying sample widths, the same 10 mm width as the hand laminated samples was adopted for the vacuumed bagged ones.

2.2 DESTRICTUVE TESTING

Experiments were conducted on a Lloyd Instruments LR 30K, as depicted in Figure 1. This mechanical testing equipment enables forces up to 30 kN to be applied to test samples, and forces are recorded thanks to a loadcell. Ten samples were tested for each mechanical property and manufacturing method. This is twice the minimum number (five samples) specified in all ISO standards.

All tests were conducted at a fixed displacement-driven test speed. This was 1 mm/min for flexural and compressive tests, and 2 mm/min for tensile samples. All test speeds were as specified in their relevant standards. The maximum standard deviation of the displacement rate recorded was 1.2905×10^{-7} mm, i.e. far below the required accuracy of ±1%/min (ISO 178) and ±0.5 mm/min (ISO 14126). Note that no test speed accuracy is specified in ISO 527-4.

Figure 1. Experimental setup (compressive test) on a Lloyd Instruments LR30K (Wiszniewski, 2019).

Table 2: Geometrical definition of the samples.

Flexural Samples		
Dimensions	ISO 178 requirements	Samples size
Length, l	80 ± 2 mm	80 ± 0.1 mm
Width, b	10 ± 0.2 mm	10 ± 0.1 mm
Thickness, h - Hand Laminated	4 ± 0.2 mm	4.15 ± 0.08 mm
Thickness, h - Vacuum Bagged	4 ± 0.2 mm	2.82 ± 0.13mm
Tensile Samples		
Dimensions	ISO 527-4 requirements	Samples size
Length, l	≥ 250 mm	250 ± 0.1 mm
Width, b	25 ± 0.5 mm	25 ± 0.1 mm
Thickness, h - Hand Laminated	$2 \leq h \leq 10$ mm	3.98 ± 0.14 mm
Thickness, h - Vacuum Bagged	$2 \leq h \leq 10$ mm	2.79 ± 0.10mm
Compressive Samples		
Dimensions	ISO 14126 requirements	Samples size
Length, l	110 ± 1 mm	110 ± 0.1 mm
Width, b	10 ± 0.5 mm	10 ± 0.1 mm
Thickness, h - Hand Laminated	$2 \leq h \leq 10 \pm 0.2$ mm	4.09 ± 0.10 mm
Thickness, h - Vacuum Bagged	$2 \leq h \leq 10 \pm 0.2$ mm	2.73 ± 0.11 mm

2.3 UNCERTAINTY ANALYSIS

Two types of errors are considered in this paper: the bias limit and the precision. The bias limit is a fixed error associated with the experimental setup. The precision is a random error. The overall uncertainty U is defined as the root sum of the bias limit B and the precision P.

$$U^2 = B^2 + P^2 \quad (1)$$

As the strength σ is not directly measured, its data reduction equation (DRE) is considered (Coleman & Steel, 1995). The DRE for the ultimate flexural and for the ultimate tensile and compressive strengths are given is Equation 2 and Equation 3, respectively.

$$\sigma_{uf} = \frac{3Fl}{2bh^2} \quad (2)$$

$$\sigma_{ut/c} = \frac{F}{bh} \quad (3)$$

The total bias limit of the ultimate strength $B(\sigma_u)$ will therefore be a function of the magnitude of the bias limits associated with the force *B(F)*, the width *B(b)*, thickness *B(h)* and length *B(l)* of the sample; the latter being relevant to the ultimate flexural strength only. These are multiplied by their respective sensitivity coefficient (partial differentials). Because the magnitude of the bias limits may either be positive of negative, it is seen as unreasonable to consider them as cumulative (Abernethy & Thompson, 1973). Therefore, a root sum approach is preferred.

$$B(\sigma_{uf})^2 = \left(\frac{\partial\sigma}{\partial F}B(F)\right)^2 + \left(\frac{\partial\sigma}{\partial l}B(l)\right)^2 + \left(\frac{\partial\sigma}{\partial b}B(b)\right)^2 + \left(\frac{\partial\sigma}{\partial h}B(h)\right)^2 \quad (4)$$

$$B(\sigma_{ut/c})^2 = \left(\frac{\partial\sigma}{\partial F}B(F)\right)^2 + \left(\frac{\partial\sigma}{\partial b}B(b)\right)^2 + \left(\frac{\partial\sigma}{\partial h}B(h)\right)^2 \quad (5)$$

The magnitude of the force bias limit is taken as the manufacturer's specification for the load resolution, so that $B(F)$ = 0.0001 N. On the other hand, for the linear measurements of l, b and h, the magnitude of the bias limit as taken as half of the smallest measuring division, i.e. 0.005 mm.

The precision P is given in this paper at the 95% confidence level, and is defined as

$$P = \frac{t_{95}S}{\sqrt{n}} \quad (6)$$

where t_{95} is the -value at the 95% confidence level, S is the standard deviation of the results and n the number of tests performed. Here, n = 10 for all cases, which yield t_{95} = 2.228 (Coleman & Steele, 1995).

The combination of the total bias limit and the precision associated with each experiment yields the overall uncertainty. This will be graphically represented with red vertical error bars for the experimental results presented in the Section 3.

2.4 ISO 12215-5 THEORY

2.4 (a) Thickness

Under ISO 12215-5, both 2008 and 2019, the thickness t of a laminate is given as

$$t = \frac{w}{\rho_f \rho_m}\left(\frac{\rho_f}{\Psi} + \rho_m - \rho_f\right) \quad (7)$$

where w is the dry fibre mass (for the laminate considered in this study, this is 2360 g.m^{-2}); ρ_f is the fibre density, assumed as 2560 kg.m^{-3} for fibreglass by ISO 12215-5:2019, which matches the manufacturer specification for the cloths employed; ρ_m is the matrix density, given as 1200 kg.m^{-3} for all resin systems in ISO 12215-5:2019 (note that, in this work, the Ampreg 22 epoxy resin employed has a density of 1187 kg.m^{-3}, but the former default value will be assumed for the purpose of the theoretical calculations); and Ψ is the fibre weight fraction. This is defined as the ratio of the dry fibre mass to the total laminate mass. It is a function of the type of fibre and type of cloth employed, and the manufacturing technique.

For vacuum bagged cloths, ISO 12215-5:2019 provides a range of fibre weight fractions, listed under the *infusion* umbrella term. For the purpose of this paper, the average value of Ψ will be employed in the calculation process. This applies to both CSM and WR. Black error bars will be employed in Section 3 to depict the range of properties that could be achieved by using the extreme values of the ranges provided. Note that ISO 12215-5:2019 does not provide any recommendation as to which fibre weight fraction to adopt for vacuumed bagged samples, but only an advised range of values.

A comparison between the values of Ψ under ISO 12215-5:2008 and ISO 12215-5:2019 is presented in Table 3. This also features the values achieved for individual plies and the whole laminate considered in this studies. The values of Ψ were assessed using direct measurements of volume and mass, one of the four methods to determine fibre weight fraction, as presented by Han, et al. (2020a).

2.4 (b) Strength

Under the previous ISO 12215-5:2008, the ultimate flexural (σ_{uf}), tensile (σ_{ut}) and compressive (σ_{uc}) strengths were assessed using regression equations based on Ψ. These are presented for fibreglass CSM and WR in Equations 8, 9 and 10, respectively.

Table 3: Values of Ψ for hand laminated and vacuum bagged plies and laminate.

Hand Laminated			
Ψ	**ISO 12215-5:2008**	**ISO 12215-5:2019**	**Samples**
CSM	0.300	0.300	0.296
WR	0.480	0.478	0.473
Laminate	0.367	0.367	0.363
Vacuum Bagged			
Ψ	**ISO 12215-5:2008**	**ISO 12215-5:2019**	**Samples**
CSM	0.36	0.36 - 0.48	0.419
WR	0.58	0.61 - 0.68	0.670
Laminate	0.443	0.451 - 0.561	0.513

$$\sigma_{uf} = 502\Psi^2 + 107 \quad (8)$$

$$\sigma_{ut} = 800\Psi^2 - 80\Psi + 37 \quad (9)$$

$$\sigma_{uc} = 150\Psi + 72 \quad (10)$$

The latest ISO 12215-5:2019 offers six methods to demonstrate compliance. This work is concerns with methods 1 and method 2 only, respectively known as the *simplified* and *enhanced* methods.

Method 1 (simplified) applies to quasi-isotropic fibreglass composites. This is based on simple beam theory, as often employed in small craft design (Ocera, et al. 2017). The required thickness is ascertained based on a strength driven criterion, the derivation of which was provided by Souppez (2021a), and is given as

$$t = b_{ISO} k_c \sqrt{\frac{P_{ISO} k_{2b}}{1000\sigma_d}} \quad (11)$$

where t is the required thickness, b_{ISO} is the short side of the panel, k_c is the curvature coefficient, P_{ISO} is the design pressure, k_{2b} is the panel aspect ratio factor for bending moment, taken as 0.5 for aspect ratios greater or equal to 2, and σ_d is the design strength.

The design strength is based on the ultimate strength, to which a factor of safety of 2 is applied. This may differ from ship scantlings as small crafts employ different limit states (Rizzo & Boote, 2010). The design strength, σ_d, is

$$\sigma_d = 0.5\sigma_u k_{AM} k_{BB} \quad (12)$$

where k_{AM} is the assessment method factor, k_{BB} is the boatbuilding quality factor, and σ_u is the ultimate strength. This would be σ_{uf} for a single skin panel, σ_{ut} for the outer skin of a sandwich panel, and σ_{uc} for the inner skin of a sandwich panel.

In this paper, k_{BB} = 0.95 for hand laminated laminates, and k_{BB} = 1 for vacuum bagged laminates, as in ISO definition. Furthermore, k_{AM} = 0.9 for σ_{uf} as its use is intended for method 1, and k_{AM} =0.95 for $\sigma_{u\ t/c}$, most commonly used as part of method 2. While the value of k_{BB} is intended to account for the defects inherent to manufacturing, these are not required to be assessed as part of the standard. This represents a limitation of the regulation, as void content can negatively affect the properties of a laminate, even if the fibre weight fraction target is met (Han, et al. 2020a).

Method 2 (enhanced) is a ply-by-ply analysis with a first-ply-to-fail criterion. This method is intended for quasi-isotropic and orthotropic materials, considering shear force and bending moment in both directions. While the simplified method (method 1) is only applicable for GFRP, the enhanced method (method 2) can be applied to any type of fibre. This allows more advanced materials, such as carbon and aramid, to be analysed.

A greater level of theoretical analysis may be achieved with method 3 (developed), which would yield k_{AM} = 1. This relies on the application of classical laminate theory. A failure criterion such as that of Tsai-Hill (1968) or Tsai-Wu (1971) would be employed. However, this is beyond the scope of the present work.

In the next section, the results for the laminate thickness (Sec. 3.1), ultimate flexural (Sec. 3.2), tensile (sec. 3.3) and compressive (Sec. 3.4) strengths will be presented. The experimental results will be compared to the default values assessed using ISO 12215-5:2008 and ISO 12215-5:2019 (Laci, 2022) using the theory presented in this section.

3. RESULTS

3.1 LAMINATE THICKNESS

The laminate thickness for the laminate under study is presented in Table 4, and depicted in Figure 2. Hand laminated values have remained consistent between the 2008 and 2019 version of ISO standard, as the fibre weight fractions were unchanged. Conversely, for vacuum bagged construction, the range provided by the 2019 version always yields a thinner panel. This is due to the higher fibre weight fractions recommended compared to the 2008 edition.

The hand laminated panel is thinner than ISO 12215-5:2019 calculation would suggest, and thus could be reviewed in the future. On the other hand, the vacuum bagged panel appears to be within the range covered by the standard. This suggests the changes made in the 2019 version are relevant and reflect current manufacturing

Table 4: Panel thickness.

Panel thickness - Hand Laminated		
ISO 12215-5 2008	ISO 12215-5 2019	Experimental Results
4.311 mm	4.311 mm	4.065 ± 0.05 mm
Panel thickness - Vacuum Bagged		
ISO 12215-5 2008	ISO 12215-5 2019	Experimental Results
3.399 mm	3.318 mm - 2.460 mm	2.783 ± 0.05 mm

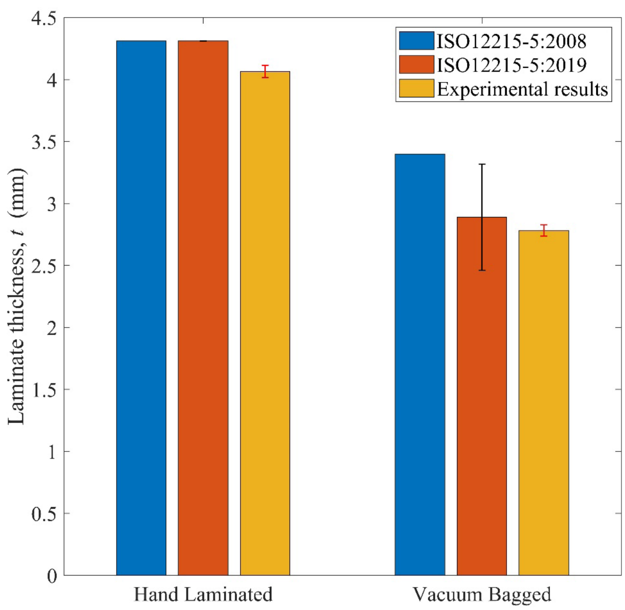

Figure 2. Panel thickness.

capabilities in term of the fibre weight fractions that can be achieved under vacuum.

The effect of thickness on composite panels is two folds. First, a thinner laminate will yield a reduced stiffness. This could prove critical on single skin panels that are stiffness driven. Secondly, a thinner panel implies a higher fibre weight fraction, and therefore greater strength. This may therefore influence the flexural, tensile and compressive strengths of the tested samples, detailed in the following subsections.

3.2 ULTIMATE FLEXURAL STRENGTH

The increase in the default mechanical properties from the 2008 to the 2019 version of the standard appears justified, and may be seen as still being on the pessimistic side. Indeed, the experimental results reveal a much higher ultimate flexural strength than suggested by both versions of the standard. The numerical values are provided in Table 5, and represented in Figure 3.

In this instance, the default ultimate flexural strength appears to be overly safe for the laminate tested. This is similar to the findings of Han, et al. (2020a), who reported a much higher experimental ultimate flexural strength for fibreglass compared to ISO 12215-5:2008, provided $\Psi > 0.33$.

Table 5: Ultimate flexural strength.

σ_{uf}	Hand laminated	Vacuum Bagged
ISO 12215-5 2008	174.69 MPa	205.29 MPa
ISO 12215-5 2019	183.05 MPa	250.82 ± 26.62 MPa
Experimental Results	298.33 ± 9.64 MPa	391.11 ± 13.71 MPa

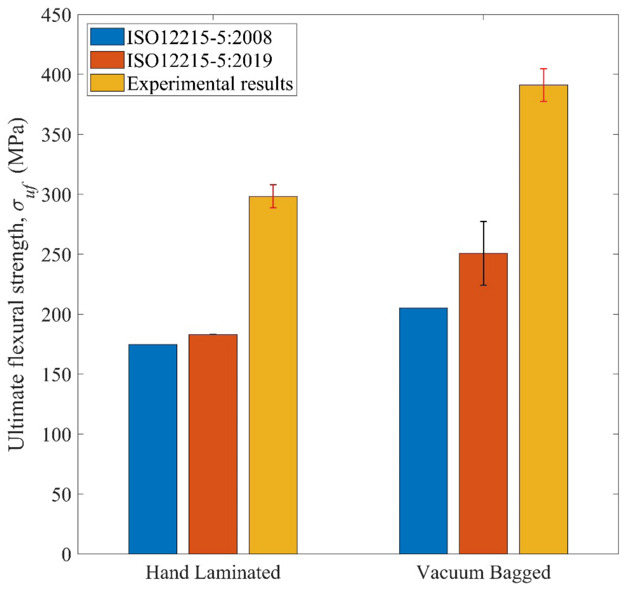

Figure 3. Ultimate flexural strength.

3.3 ULTIMATE TENSILE STRENGTH

A noticeable increase in the ultimate tensile strength of both the hand laminated and vacuum bagged laminates can be seen between the 2008 and 2019 versions of ISO standards. The values are compared to experimental results in Table 6 and visually represented in Figure 4.

The experimental results for the vacuum bagged laminate yield a comfortable margin above the most optimistic ISO value (highest fibre weight fraction). The standard therefore provides a safe ultimate tensile strength for the vacuum bagged samples tested in this study, and the increase in default ultimate tensile strength appears suitable.

The hand laminated results prove to be very close to the ultimate tensile strength estimated by ISO 12215-5:2019. Nevertheless, the experimental results prove superior to the default values, even when accounting for the experimental uncertainty. The hand laminated ultimate tensile strength is therefore found to be suitable for the samples tested in this work. However, any further increase in default values would be discouraged, as the standard would risk providing values superior to those achieved in the present experiments.

Table 6: Ultimate tensile strength.

σ_{ut}	**Hand laminated**	**Vacuum Bagged**
ISO 12215-5 2008	115.50 MPa	158.25 MPa
ISO 12215-5 2019	141.76 MPa	194.25 ± 20.62 MPa
Experimental Results	151.98 ± 4.35 MPa	241.18 ± 5.03 MPa

Table 7: Ultimate compressive strength.

σ_{uc}	**Hand laminated**	**Vacuum Bagged**
ISO 12215-5 2008	127.08 MPa	138.38 MPa
ISO 12215-5 2019	147.01 MPa	201.44 ± 21.38 MPa
Experimental Results	141.81 ± 6.42 MPa	141.01 ± 4.01 MPa

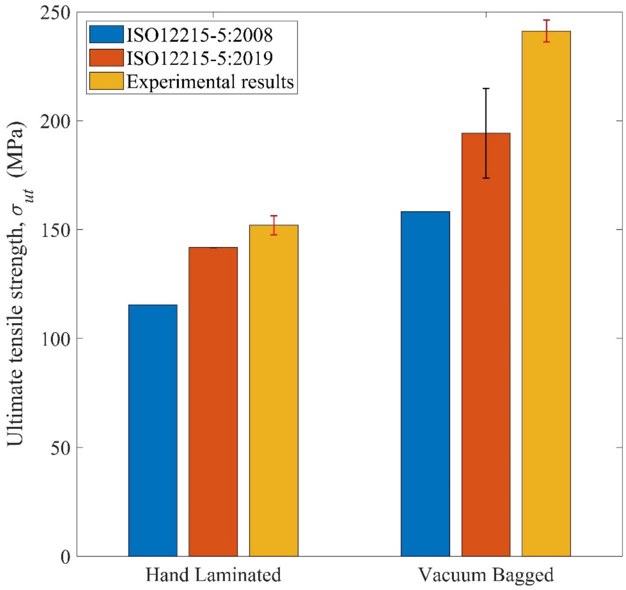

Figure 4. Ultimate tensile strength.

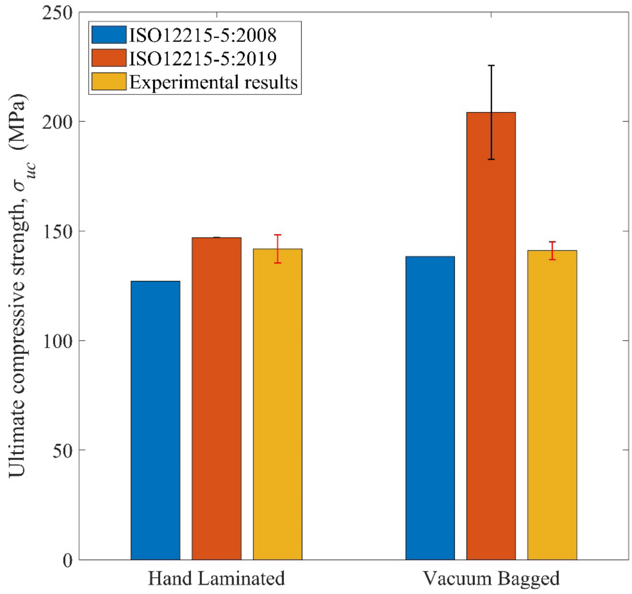

Figure 5. Ultimate compressive strength.

3.4 UTIMATE COMPRESSIVE STRENGTH

The experimental results for the ultimate compressive strength are detailed in Table 7 and shown in Figure 5. For hand laminated samples, ISO 15512-5:2019 values are in line with the upper end of the uncertainty of the present results. This may be seen as slightly optimistic, and thus caution should be used. It would also appear that the previous regression equations in ISO 12215-5:2018 yielded more suitable values, being just lower than the present experimental results.

Similarly, the experimental results for vacuum bagged samples are in agreement with ISO 12215-5:2008. In stark contrast, however, the latest ISO 12215-5:2019 values appear significantly greater than both the previous standard and the present experimental results. This may not be attributed to the uncertainty inherent to the fibre weight fraction, as the lower end of the black error bar in Figure 5 remains largely above the experiment results. This suggests a largely over-estimated ultimate compressive strength, the value of which does not appear relevant.

The discrepancy was identified as the value of ultimate compressive breaking strain for CSM in ISO 12215-5:2019. Indeed, while the value of the ultimate compressive breaking strain is always lesser than the value of the ultimate tensile breaking strain for all other cloths, it is higher for CSM in compression (1.70) compared to tension (1.35). In comparison, the same breaking strain is adopted in both tension and compression for E-Glass by Bureau Veritas NR546 rules (Bureau Vertias, 2021). The ultimate compressive breaking strain of CSM would therefore appear a relevant area of future work.

It should be noted that, as a first-ply-to-fail criterion is applies, quasi-isotropic laminates with a neutral axis virtually mid-way through the panel would remain safe under the new regulation. Indeed, as the ultimate tensile strength is lower than the ultimate compressive strength, for an identical distance away from the neutral axis, failure would occur in one of the plies in tension first. Nevertheless, this section highlighted clear limitations for quasi-isotropic single skin composite panels working in compression, under the latest ISO 12215-5:2019. Additional limitations to the latest ISO 12215-5 were also identified by Souppez (2021b) for timber structures. Structural designers, compliance assessors and policy makers may therefore need to consider the implications of the present results for the design small craft structures.

4. CONCLUSIONS

Destructive testing was undertaken to experimentally characterise the ultimate flexural, tensile and compressive strength of quasi-isotropic glass-epoxy panels. Hand laminated and vacuum bagged samples were tested in accordance with ISO 178 for flexural properties, ISO 527-4 for tensile properties, and ISO 14126 for compressive properties.

For the tested samples, and accounting for the uncertainty of the results, the following conclusions on ISO12215-5:2019 have been drawn.

- The updated range of fibre weight fractions provided for vacuum bagging are suitable, as demonstrated by the thickness measurements.
- The ultimate flexural strength is conservative for both manufacturing techniques. This justifies the increase in default properties from ISO 12215-5:2008 to ISO 12215-5:2019, and the default values may be seen as safe.
- Suitable values for the ultimate tensile strength are found, in line with the experimental results for hand laminated samples, and lower than the vacuum bagged default values.
- While the ultimate compressive strength may be seen as slightly optimistic for hand laminated samples, it appears vastly overestimated for vacuum bagged samples. As such, the increase in the default ultimate compressive strength of vacuum bagged panels should be considered extremely cautiously.
- The origin of the discrepancy for the ultimate compressive strength was pinpointed as the value of the ultimate breaking compressive strain for chopped strand mat.

These findings provide validation data for the latest ISO12215-5:2019, while also suggesting areas of future improvements. These results may further inform designers, compliance assessors and policy makers in the selection of relevant factors of safety for composite structures, and it is anticipated they may contribute to future improvements in small craft structural regulations.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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