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STRUCTURAL DESIGN OF HIGH PERFORMANCE COMPOSITE SAILING YACHTS UNDER THE NEW BS EN ISO 12215-5

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Abstract: The forthcoming publication of the revised BS EN ISO 12215-5 is set to transform the structural design of most small crafts for the next decade, with the implementation of significant changes to the scope and underpinning theory, such as an applicability extended up to 24 m Load Line, and the use of finite element methods as part of the compliance assessment process. This paper represents the first public release of the major changes and novelty in the standard, with a strong emphasis on high performance composite sailing yachts. The aim is to provide designers and builders with an insight into the technical background and practical applications of the new regulation for structural optimization, and how the marine industry will be impacted.

Keywords: High Performance; Sailing Yachts; Composite; ISO 12215-5.

NOMENCLATURE

For the purpose of this paper, the following nomenclature applies, as defined in the BS EN ISO 8666 (ISO, 2016) and ISO 12215-5 (ISO, 2008) where relevant.

a_n	Proportion of overall fibre content
b	Short unsupported dimension of a panel (mm)
Cb/b	Transverse camber of a curved panel
Cl/l	Longitudinal camber of a curved panel
E	Young's modulus (GPa)
k_{10}	Sandwich outer skin coefficient
k_{2b}	Panel aspect ratio coefficient for bending moment
k_{AM}	Assessment method factor
k_{BB}	Boat building factor
k_c	Curvature correction factor for plating
k_{DC}	Design category factor
L_H	Hull length (m)
k_L	Longitudinal pressure distribution factor
L_{WL}	Length on waterline (m)
P	Pressure (kN.m^{-2})
S_{LR}	Speed length ratio
t	Thickness (mm)
V	Maximum speed at loaded displacement (kts)
V_F	Fibre volume fraction
η_θ	Krenchel factor
θ	Angle of fibre nominal to axis (°)
σ_{DES}	Design stress (N.mm^{-2})
$\omega_{\min}$	Minimum single skin reinforcement mass (kg.m^{-2})
$\omega_{OS\min}$	Outer skin minimum reinforcement mass (kg.m^{-2})

CLT	Classical Lamination Theory
FEM	Finite Element Methods
FRP	Fibre Reinforced Plastics
GRP	Grass Reinforced Plastics
IMO	International Maritime Organization
RCD	Recreational Craft Directive
SG	Specific Gravity
WG18	Woking Group 18

INTRODUCTION

Four years after the publication of the BS EN ISO 12215-5:2008 (ISO, 2008), the working group 18 (WG18), part of the ISO technical committee 188, began the work on the revision that will later lead to the latest BS EN ISO 12215-5 (ISO, 2018) standard. Despite not being intended for extreme racing yachts, the International Sailing Federation (ISAF), now World Sailing, made compliance with the ISO 12215-5 a requirement for racing crafts, without any prior consultation of the WG18. A similar issue arose with commercial vessels; a number of regulations, including the MGN 280 (M) (MCA, 2004) and the Brown Code (MCA, 2014) referred to ISO for the structure of commercial vessels, again without consultation with the WG18.

This prompted a reconsideration of the scope of the standard, with the development of a dedicated workboat annex (Souppez, 2018), and additional consideration for performance sailing yachts. Moreover, a number of additional factors will enable the users to refine and optimize the design of sailing vessels.

The background to the revision and the main modifications from the previous version will be introduced, together with the changes to the scope. Then, the new considerations made will be presented, with a strong emphasis on accounting for uncertainty in performance composite structures, and concluding on the applicability to performance sailboats. Throughout the paper, a number of industry best practices will be presented, thus providing relevant material for designers and builders alike.

Given the strong impact of the new regulation on industry, the traditional 6 months transition period between the withdrawn and new regulations will be extended to 24 months.

BACKGROUND TO THE REVISION

Building on the practical experience of the application of the standard, a number of improvements have been suggested by the industry, and various observations resulting from the use of the regulation were made, including:

- Large panels were penalized, notably when made in sandwich. Sandwich structures were further handicapped in terms of attached plating.
- Single curvature was considered, as per class regulations; however, for small crafts, accounting for double curvature would be very welcome.
- Vessels featuring a high freeboard appeared overly put at disadvantage compared to low freeboard crafts.
- The deflection criterion for sandwich panels and stiffeners was questioned.
- A more advanced analysis method of the quasi-isotropic laminates should be proposed. Furthermore, the simplified analysis for single skin was shown to sometimes give lower requirements than the ply-by-ply analysis. This was perceived as unfair by the industry, as a more advanced analysis method with less uncertainty gave higher structural requirements

- Advanced analytical design tools, such as Finite Element Methods (FEM), should be offered as an analysis method.
- Higher accelerations than the 6gs previously considered should be investigated for high speed and light crafts operating in professional use (workboats).

The overall philosophy for the new regulation was to widen the opportunities for more modern structural analysis, however not ruling out the possibility to use simplified methods, better suited to smaller yards. Additionally, the revision aimed to ensure a smooth transition; therefore, it was necessary for leisure vessels passing the 2008 standard to still pass the revised version.

CHANGES TO THE SCOPE

Maximum Length

A length of 24 m is absolutely critical to define the applicability of the regulatory framework; unfortunately, the definition of 24 m is inconsistent. On the one hand, the RCD II (European Parliament, 2013) and ISO standards are applicable only up to a hull length of 24 m. On the other hand, the next regulations (IMO, class society, etc.…) start at 24 m Load Line length (IMO, 2003), defined as the greatest of 96% of the L_{WL} at 85% of the moulded depth, or the length from the front of the stem to the rudder stock axis on that waterline. Consequently, vessels with large overhangs would typically be above the 24 m hull length, but below the 24 m Load Line, thus falling into a regulatory *'no man's land'* with no applicable regulation.

In order to bridge this regulatory gap, the WG18 decided to extend the scope of the BS EN ISO 12215-5 up to 24 m Load Line. It is to be noted that, at present, this has only been adopted for the BS EN ISO 12215-5, and not for other standards or the RCD II. It is however hoped this will provide a precedent that would, in time, lead to a more harmonious definition of 24 m across regulatory bodies.

Workboats

The increasing recognition of the BS EN ISO 12215-5 by several countries as relevant to commercial vessels, despite the standard clearly not being intended to do so, led the WG18 to consider the addition of workboats as part of the new version, eventually taking the form of Annex J. This prompted further extension of the scope in terms of accelerations and maximum speeds, to better reflect the mode of operation of commercial vessels. Workboats are split between charter, light and heavy duty categories.

Charter

Rental and charter vessels do not have any environmental restriction with the exception of the design category conditions. As a commercial vessel, relevant maintenance and survey program are to be implemented.

Light Duty

A light duty workboat, is expected to operate in category D, or up to category C restricted to Beaufort 5 and a significant wave height of 1 m. The operating conditions for light duty workboats should not include rough seas, and the comfort of passengers should be paramount, leading to appropriate course and speeds at sea. Maintenance and surveying program shall be undertaken as appropriate, based on the usage and weather conditions experimented.

Heavy Duty

A heavy duty workboat is characterized as operating from the upper end of category C, up to category A, however restricted to Beaufort 9 and 5 m significant wave height. In this particular case, it is assumed that, due to the operating profile of vessels such as search and rescue crafts, the course would not be altered and the speed would not be reduced, and the boat would experience rough seas routinely. Consequently, the 50 knots top speed has been lifted, and accelerations up to 8gs may be considered on the structure; this represents another major change to the scope of the standard. This would obviously require special seating to be provided to the crew in order to remain in full ability to manoeuver the vessel and be comfortable, as well as imply additional structural requirements.

Racing Yachts

Following the publication of the 2008 version, the ISAF (International Sailing Federation), now World Sailing, made compliance with the 12215 compulsory for offshore races, without prior discussion with the WG18. While the standard is still not applicable for racing yachts designed for professional racing only, considerations for racing yachts have been made, including correction factors for sport sailing crafts. Note that, for professional racing crafts such as IMOCAs, the plating and stiffeners are to be assessed based on the unpublished working draft of the BS EN ISO 12215-5 (WD 12215-5: 2015-02-01) in which the WG18 made a proposal for fully racing yachts.

NEW CONSIDERATIONS

In addition to the changes to the scope, a number of new considerations and coefficients have been added (Souppez & Ridley, 2017); the most significant ones are presented in the following sub-sections.

Applicable Methods

To broaden the range of methods available to the industry, six will now be available to determine the scantlings.

Simplified Method

The simplified method provides an equation for strength-driven plating thickness, assuming a built-in beam (aspect ratio greater than 2) of span b, under a uniformly distributed load P. In those condition, the design stress can be found as the ratio of the maximum bending moment and the minimum section modulus per unit width; mathematically:

$$\sigma_{\mathrm{DES}} = \frac{M_{MAX}}{SM_{MIN}} = \frac{6\,P\,b^2}{12\,t^2} \tag{1}$$

Solving for the plate thickness yields:

$$t = b\sqrt{\frac{0.5\,P}{\sigma_{\mathrm{DES}}}} \tag{2}$$

Which is then implemented with a single curvature coefficient k_c and a unit conversion factor of 1000 to give the ISO single skin requirement as:

$$t = b\,k_c\sqrt{\frac{P\,k_{2b}}{1000\,\sigma_{\mathrm{DES}}}} \tag{3}$$

In which:

t	Thickness in mm.
b	Short side of the panel in mm.
k_c	Curvature coefficient.
P	Pressure in kN.m^{-2}.
k_{2b}	Panel aspect ratio coefficient for bending moment.
σ_{DES}	Design stress in N.mm^{-2}.

A similar set of assumption is made in order to develop the simplified requirements for stiffeners.

Enhanced Method

The enhanced method consist of a ply-by-ply analysis for quasi-isotropic and orthotropic materials, considering shear force and bending moment in both directions of the plates, and accounting for double curvature. While the simplified method is only applicable for GRP (Glass Reinforced Plastics), the enhanced method is intended for FRP (Fiber Reinforced Plastics), thus allowing more advanced materials, such as carbon and aramid, to be analyzed.

Developed Method

Extending the limitations of the enhanced method to all type of laminates (including non-balanced ones), the developed method relies on the principles of CLT (Classic Laminate Theory). This extends the ply-by-ply analysis, considering stress and strain in both direction, typically using the Tsai-Hill (Tsai, 1968) or Tsai-Wu (Tsai & Wu, 1971) criterion. This difference is the primary reason for the enhanced method having a lower assessment method factor, as later discussed. Note that CLT software users should ensure inner skin wrinkling and core shear stress are checked.

As an alternative to CLT, primarily aimed for boat builders or design offices not confident with CLT or unable to afford a CLT software, a simplified regression method (SRM) was developed. This offers a more practical and less numerical approach, although its application would be limited to balanced laminates, generally combining biaxial and quadraxial fabrics.

Direct Test

Rather than assuming the mechanical properties of a laminate as defined by the BS EN ISO 12215-5 and associated design assessment method, mechanical testing can be conducted to demonstrate that the bending moment and shear force of a panel or stiffener (with its attached plating) comply with the regulatory requirements.

The recommended test standards for each mechanical property are indicated below:

- Tensile properties: ISO 527-4 (ISO, 1997), ISO 527-5 (ISO, 2009)
- Flexural properties: ISO 178 (ISO, 2010)
- Compressive properties: ISO 14126 (ISO, 1999)
- In-plane shear properties: ISO 14129 (ISO, 1997)
- Interlaminar shear stress: ISO 14130 (ISO, 1997)
- Through-thickness tensile properties: ASTM D7291 (ASTM, 2015)

Should there not be an international standard for a given mechanical property, a recognized national regulation can be utilized as an alternative.

As it is common practice in structural testing, a minimum of 5 samples per property tested should be used, and the retained value should be the lesser of 90% of the mean, or the mean minus two standard deviations. The design values are then taken as $0.5 \times k_{BB}$ of the assessed value, i.e. applying a factor of safety of 2, and a consideration for the boat building quality, as later tackled.

It is to be noted that compressive properties under the ISO 14126 (ISO, 1999) have proven to be difficult to ascertain, especially for unidirectional (UD), that generally buckles as a result of the imposed test sample size, as opposed to failing in pure compression. It can therefore be seen relevant to assess this particular property using a four-point bending test, conducted under the ASTM D6272 standard (ASTM, 2017), and providing the sample failure occurs between the two load points on the upper face.

Finite Element Methods

Perhaps one of the most eagerly anticipated by industry, but also one of the most controversial addition to the revised standard is the use of FEM. Indeed, with the increasing computational power available and improving affordability of the software, designers now turn to FEM for a more realistic 3D analysis of structures.

Nevertheless, it is recommended good practice to compare the results of FEM with those of the enhanced method, and a technical explanation would be required should the FEM results appear to be considerably lower than those of the developed method. Indeed, the FEM analysis should be conducted using the ISO design pressures and relevant material properties, consequently vast discrepancies between FEM and the enhanced methods would not be expected.

Drop Test

Despite the novel considerations made for double curvature, subsequently discussed, the effect on small boats (hull length lesser than 6 m) cannot be properly quantified. Hence, the physical drop test is deemed a suitable method to demonstrate structural compliance. This is applicable only to FRP and non-reinforced plastics, where the thicknesses cannot be easily and reliably assessed, and where the large deflections are not covered under the BS EN ISO 12215-5. The drop test is also a very practical way to ensure compliance, and has therefore been employed primarily by boat builders, and as part of a self-certification process most typically.

Assessment Method Factor

As previously stated, one of the industry criticisms towards the previous version of the standard was that, in certain cases, simpler methods would give lower requirements than more advanced ones. To remedy this issue, and prevent it from happening with the larger number of methods available, an assessment method factor, k_{AM}, was introduced. The intention being to handicap cruder methods, and promote the use of more advanced ones, as reflected in the values of the coefficient shown in Table 1.

Table 1: Values of k_{AM}.

Assessment Method	Value of k_{AM} for FRP
Method 1: Simplified	0.90
Method 2: Enhanced	0.95
Method 3: Developed	1
Method 4: Direct Test	1
Method 5: FEM	1
Method 6: Drop Test	n/a

The more advanced methods, namely the developed one, direct test and FEM, benefit from a value of 1. The enhanced method is slightly penalized to reflect the absence of the Tsai-Hill or Tsai-Wu criterion, with a value of 0.95. Finally, the simplified method based on basic beam theory is set at a value of 0.90, which will prevent its thickness to be lower than the other methods.

Boat Building Quality Factor

In order to reflect the high impact of the build quality on the final mechanical properties of composite materials, a build quality coefficient, k_{BB}, has been developed. The aim is to reward both the higher manufacturing qualities and higher manufacturing processes, and consequently to penalize the mechanical properties for less advanced manufacturing methods.

Indeed, the mechanical properties of composites are primarily driven by the production, with the fiber weight fraction having a strong impact on the properties, while advanced quality control to minimize contamination, voids, dry patches and other defects should be enforced. The building qualities are classified as low, high and tested, with the characteristics and k_{BB} values presented in Table 2.

Table 2: Values of k_{BB}.

Quality	Builder Characteristics	Value of k_{BB}	
		Hand Laid	Infused / Prepreg
Low	No measurement or checking of fiber weight fraction. The volume fraction is taken as the ISO default value.	0.75	0.8
High	Measured fiber weight fraction resulting from a range of representative laminates, and high quality control.	0.95	1
Tested	Mechanical properties of the laminates are tested and high quality control.	1	1

This represents an incentive to upgrade production techniques from hand laid to infused for instance. In addition to the increase in mechanical properties and faster production times, infusion has strongly developed over the last decade for health and safety reasons. Indeed, although still debated, the role of styrene as a human carcinogen was recognized in 2011 (Gardiner, 2011). Infusion therefore provides a sensible alternative for polyester and vinylester yards, enabling to trap and extract the styrene, thus protecting the workforce's health.

Finally, a further improvement from the previous version is a clarification regarding how often the quality control and tests should be realized, which has now been fixed at a minimum of once a year. While manufacturers would be encouraged to conduct this as often as possible, this requirement is intended not to be too much of a burden for yards, particularly small ones with limited volume production.

Longitudinal Pressure Distribution Factor

The longitudinal pressure distribution coefficient has been modified, following industry feedback, to reduce the requirements in the aft section, but also extended beyond the Aft Perpendicular (AP) where x/L_{WL} is 0, and the Forward Perpendicular (FP) where x/L_{WL} is 1. A comparison of the longitudinal pressure distribution coefficients at accelerations of 3gs and 6gs is depicted in Figure 1.

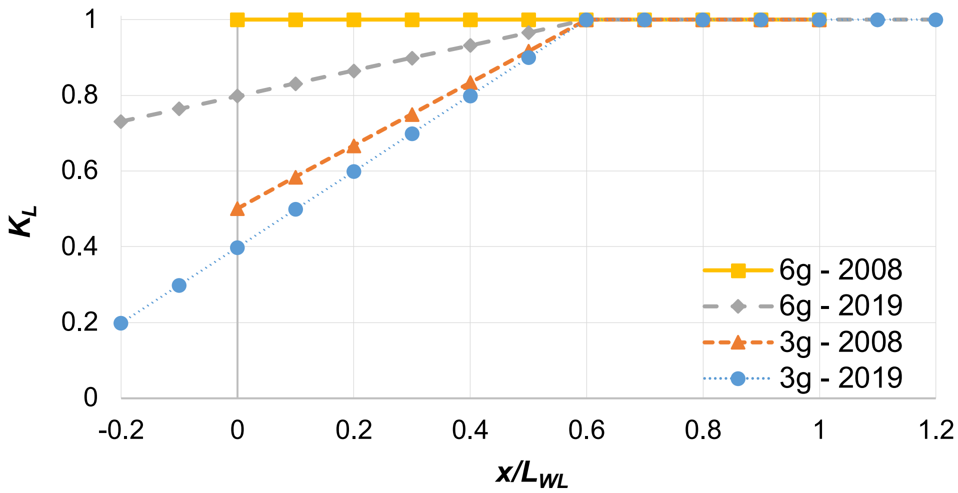

Figure 1: Values of k_L.

While the pressure remained constant aft of the AP in the previous version, the revised standard will consider a more realistic decrease in pressure over the aft overhang. Moreover, coupled with the new definition for natural stiffeners on round bilge hulls, presented in the following section, the lower pressure aft will allow to lighten the structure.

Natural Stiffeners for Round Bilge Hulls

Natural stiffeners for hard chine sections have long been established, and featured in the previous version of the BS EN ISO 12215. In the newer version, a criterion for natural stiffeners on round bilge will be introduced. This will be particularly significant for virtually all sailing yachts, and will prove helpful in reducing the number of stiffeners, notably in the aft sections of vessels, often deemed 'over-structured' by the industry.

Furthermore, this may also turn out to be very valuable for the next generation of high performance racing yachts. Indeed, the very latest offshore racing vessels, such as the IMOCAs, are now reverting back to more round bilge hull shapes with much softer chines. This is a direct consequence of the use of hydrofoils; these provide the necessary power to carry sails, meaning wide hard chine hulls are not necessary anymore, and the designers now focus on minimizing the hull drag (Beyou, 2017).

Two definition for natural stiffeners are provided, one for circular center panels, typically found in the forward section of sailing yachts, and one for curved sections, more representative of the middle to aft sections.

Circular Centre Panel

Where a circle can be inscribed in the center bottom panel, it may be considered as a natural stiffener provided the chord length between tangent points is greater than 80% of the radius of the circle. This is shown in Figure 2.

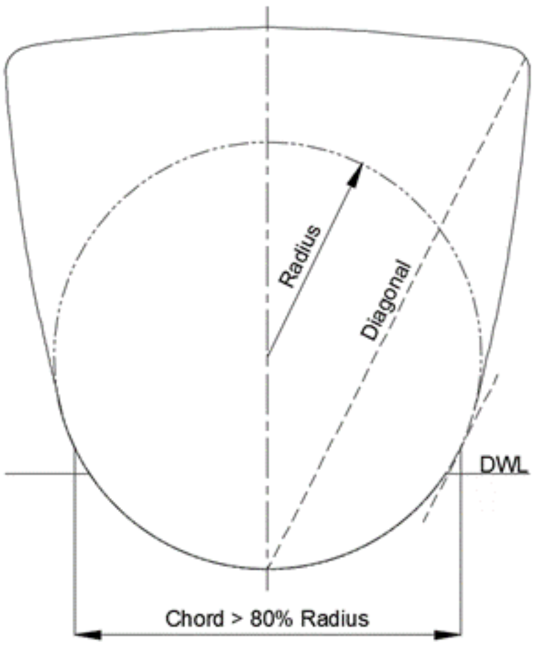

Figure 2: Natural stiffener criterion for circular center panel.

Curved Panel

For curved panel, a circle that represents the shape of the hull (see Figure 3) shall be defined and connected to the hull at the tangent point with a line parallel to the diagonal between the centerline and deck edge. Under those conditions, a natural stiffener maybe be defined, provided the following are satisfied:

- The radius of the circle is lesser than or equal to 40% of the length of the diagonal.
- The intersection with the hull is greater than 80% of the radius of the circle.

This is depicted in Figure 3.

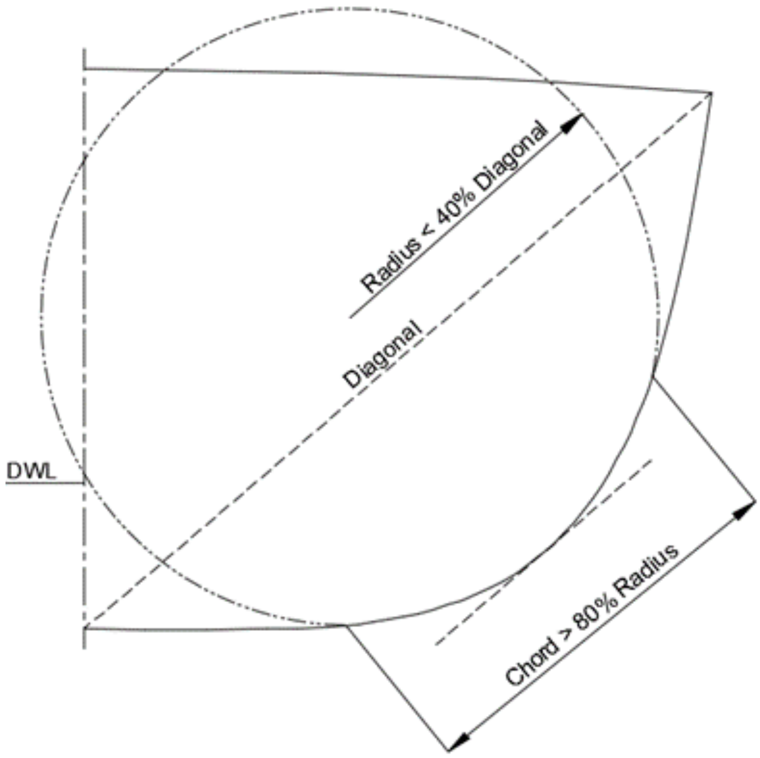

Figure 3: Natural stiffener criterion for curved panel.

Double Curvature

Single curvature has long been considered (Hildebrand, 1991), and features in all class regulations. In addition, it has been acknowledged that the double curvature on small crafts would also have a strong impact, although this was never quantitatively ascertained, and could only be demonstrated via the use of a drop test for very small vessel ($L_H < 6\ m$).

It was therefore sensible for a small craft regulation such as ISO to introduce a correction factor for double curvature; this represents one of the novelties of the revised standard. Indeed, building on Timoshenko's theory of shells and plates (Timoshenko, 1959) and after FEM validation, a curvature correction for up to 22.5% camber in the transverse direction and 10% camber in the longitudinal direction was implemented. It is to be noted that the 22.5% camber in the transverse direction extends further than the original 18% maximum in the previous version, which appears more consistent with other class rules.

The values of the curvature coefficient factor, k_C, for a range of transverse curvatures Cb/b and longitudinal curvatures Cl/l is presented in Figure 4, and compared to the single curvature coefficient of the 2008 version.

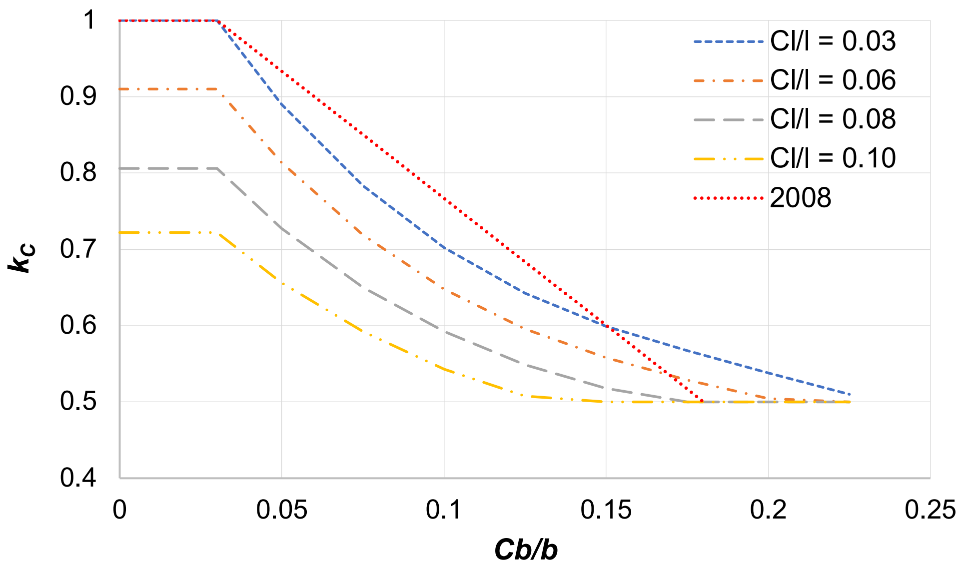

Figure 4: Curvature correction coefficients.

In most cases, a much lower requirement will be achieved thanks to the lower values of k_C, the only exception being highly curved panels in the transverse direction with very little curvature in the longitudinal direction, that will see a slight increase compared to the previous version.

It is to be noted that the above values only apply for fully fixed panels; should this not be the case, the users should either employ FEM, or refer to the values provided by Timoshenko (1959) for other end fixities

Analysis of Bulking Material

A number of bulking materials, whether resin-rich felts, syntactic foams, of thick fabrics, are very common in the production of sailing yachts. On the one hand, they can be used as a print-through barrier on lower level production. On the other hand, they can be employed on high performance small sailing yachts as a thinner alternative to a core, or on superstructure to achieve stiffer panels by increasing the thickness. This prompted further regulatory considerations in order for those materials to be analyzed properly. Indeed, as a print-though barrier, the bulking material would be considered as part of the laminate, thus working in both shear transmission and bending. Conversely, when used as a thin core, it would only be carrying shear. Care should therefore be taken by the designers or builders to clearly define whether the bulking material is considered part of the laminate or acting as a core.

Sport / Flat-Out Racing Crafts

Due to the increasing use of the BS EN ISO 12215-5 for the design of high performance sailing yachts, labelled as 'sport' or 'flat-out' crafts in the regulation, appropriate modifications had to be made to accommodate the competitive nature of those. The opportunity for high performance composite sailing yachts to reduce their scantlings under the previous standard were essentially limited to the use of the sandwich minimum skin care factor, that could be decreased from a value of 1 to 0.9 for crafts where the outer skin of the sandwich could be expected to be punctured. This was however not deemed satisfactory to achieve light weight structures for application where a lower factor of safety is acceptable.

To remedy this, the new BS EN ISO 12215-5 made a stronger case for sport boats, with more flexibility to reduce the regulatory requirements. For single skin structures, the minimum recommended mass of reinforcement $\omega_{\min}$ can be reduced by up to 30% for flat-out racing crafts; this also applies to sandwich constructions.

Moreover, the recommended minimum mass of reinforcement for sandwich outer skin, $\omega_{OS\ \min}$, is given as:

$$\omega_{OS\ \min} = k_{10}\ \omega_{\min} \tag{4}$$

In which:

$\omega_{OS\ \min}$	Sandwich outer skin minimum reinforcement mass in kg.m^{-2}.
k_{10}	Coefficient taken as: • 0.6 for recreational crafts. • $k_{DC} \times (0.5\ to\ 0.4)$ or less for sport racing boats, with k_{DC} being the design category factor (see Table 3).
$\omega_{\min}$	Minimum single skin reinforcement mass in kg.m^{-2}.

Although there is no formal criterion for the inner skin of sandwich panels anymore, industry practice is to typically use between 50% and 70% of the outer skin reinforcement mass.

Those modifications will substantially impact the design of high performance racing crafts, by allowing to achieve lighter structures and lower factors of safety.

Some racing class rules refer to the BS EN ISO 12215-5 in terms of structural compliance. This is the case of the Mini 6.50 class, which despite racing across the Atlantic Ocean single handed on a 6.5m yacht, only requires compliance with category C, i.e. inshore crafts. In this particular case, the outer skin mass could be reduced by 30% in the $\omega_{\min}$ calculation, and values of k_{10} lower than 0.24 (k_{DC} of 0.6 for category C multiplied by 0.4 for sport crafts) could be used. As a result, only 28% of the equivalent offshore recreational craft outer skin mass would be used, thus allowing for tremendous weight savings under the new regulations. It is however strongly advised that designers of such racing crafts consider the actual loads the vessel would encounter to ensure a safe and sound structure is achieved, and remember that the standard was not intended for professionally raced yachts.

Other ISO 12215 Developments

In parallel to the revision of the BS EN ISO 12215-5, Part 7 for multihull scantlings and Part 10 for rig loads and rig attachment have been finalized.

BS EN ISO 12215-7: Scantlings Determination of Multihulls

Long awaited by industry, and after more than a decade of development, the recent regain of interest in multihulls prompted by the America's Cup allowed to finally publish a regulation for the structure of multihulls. The scope however excludes foiling catamarans, small waterplane area twin-hull ships (SWATHS) and surface effect ships.

The standard will not only feature local load analysis, but a number of global load cases are also considered, such as quartering sea, rig loads, asymmetric broaching, pitchpoling, shock, and bending loads on beams for power multihulls. In addition, specificities for racing multihulls and racing dinghies have been incorporated.

BS EN ISO 12215-10: Rig Loads and Rig Attachment

The last part of the BS EN ISO 12215 series enables to assess the loads in the various rig elements, and the resulting scantlings for rig attachments and mast steps for both monohulls and multihulls, again excluding craft intended solely for professional racing. The primary aim of the standard is not to provide a rig design procedure, but to contribute to the assessment of the rig attachments scantlings and consider the rig loads transferred in the hull as well as global loads.

The regulation was developed in close relation with the industry, and represents the established practice in rig load design, with a large number of useful good practice guidance. A simplified and a developed method are available, once again to widen the range of users and allow further design analysis and optimization.

The standard distinguishes between righting moment driven and heeling moment driven designs:

- For most monohulls and sport multihulls that will heel significantly before the maximum wind forces are applied, the design is driven by the righting moment of the vessel.
- For cruising catamarans, the tremendous stability of the vessels mean the maximum righting moment will most likely not be reached; and consequently the heeling moment will drive the design.

A key part of the BS EN ISO 12215-10 (ISO, 2018) is the attention to safety, a prime example is maintaining the watertight integrity of the hull in the event of the vessel dismasting. It is therefore required for the connection between the rig attachment and hull to be stronger than the rig attachment itself, implying a rig failure will not induce a breach of the hull structural integrity.

UNCERTAINTY IN COMPOSITE YACHTS

The uncertainty inherent to composite structure for sailing yachts is split into five main parameters (Belgrano & McEwan, 2002), tackled in the following sub-sections, in order to demonstrate how the new BS EN ISO 12215-5 accounts for each.

Loads

Probably the most critical source of uncertainty in marine designs is the accuracy (or lack of) of the loads. Under the RCD II, a category A vessel is expected to withstand a significant wave height, $H_{1/3}$, defined as the average wave height of the highest third of waves, exceeding 4 m, and a wind speed exceeding Beaufort 8. This does not however define the wave height and wind speed the vessel should be designed to. For the purpose of the BS EN ISO 12215-5 (both the previous and forthcoming version), values of 7 m for the wave height and Beaufort 10 for the wind speed have been retained. Nevertheless, it is probable an offshore vessel will, at some point during its service life, encounter harsher conditions.

Ensuring a vessel is able to withstand some of the most extreme weather conditions recorded would be impractical, and yachts are consequently designed for the statistically most probable conditions.

For lower categories, namely B, C and D, a 20%, 40% and 60% reduction is applied respectively, through the use of the k_{DC} factor, presented in Table 3.

Table 3: Design category coefficients.

Category	A	B	C	D
k_{DC}	1	0.8	0.6	0.4

To account for the greater uncertainty in category A, the unofficial category A* is often informally used by designers, and signifies a 20% compliance margin has been applied on top of the category A requirement.

Nevertheless, the factor of safety embedded in the ISO rules, namely 2 for composites, contributes to alleviate the uncertainty of the loads.

Mechanical Properties

Assessing mechanical properties, even with structural testing, will reveal a spread in the data, thus implying a certain level of uncertainty regarding the actual values for a given material. This is magnified with composites, where the large number of manufacturing variables can heavily alter the overall properties of the laminate. The properties of a composite laminate are primarily driven by: the fibers properties, the resin properties, the ratio of fiber to resin, and the alignment of the fibers (Gurit, 2017).

Properties of the Fibers

The properties of the fibers are vital to the overall properties of the final laminate; the values presented in the BS EN ISO 12215-5 have therefore been updated to reflect the improvements in manufacturing that have taken place over the last decade. The default values however remain on the pessimistic side.

This is the reason behind the direct test analysis method, which allows, upon completion of satisfactory structural testing, to upgrade the mechanical properties of the fibers.

Properties of the Resin

Regarding the mechanical properties of the resin, the BS EN ISO 12215-5 does not distinguish between resin types, and upgrading from polyester to vinylester or epoxy will not impact the regulatory requirements. The properties also neglect the presence of voids and contaminants, hence the importance of the manufacturing process, reflected in the boat building quality factor.

Furthermore, the properties are only valid for fully solidified resins. In the case of polyester and vinylester, the resin cure is accelerated by the use of a catalyst (that speeds up a reaction that would take place anyway, simply at a much slower rate). Consequently, those resins will eventually cure. With epoxy however, the crucial ratio of the resin and hardener (that triggers a reaction that would otherwise not take place) must be accurately respected; failure to do so will result in improper cure and soft patches.

Ratio of Fiber to Resin

Either expressed in terms of mass ratio (fiber weight fraction) for design and production applications, or volume ratio (fiber volume fraction) for structural theory, those ratios govern the properties of composites. A higher fiber content will lead to higher properties; care should however be taken to ensure fibers are properly encapsulated, as well as considering laminate thickness and resulting stiffness, since a higher fiber weight fraction will result in a thinner laminate.

At a low quality control level, where the values are based on the ISO default ones, the k_{BB} value will penalise the properties to account for the uncertainty. However, when fiber weight fraction control is realized (normally with a burn-off test) much higher k_{BB} values can be used to reflect the reduced uncertainty.

As an indication for designer and builders, guidance values for fiber weight fractions for E-Glass and Carbon HR (High Resistance) are given in Table 4.

Table 4: Guideline values for fiber volume and weight fractions.

Manufacturing Process	Cloth	Fiber Volume Fraction	Fiber Weight Fraction	
			E-Glass SG = 2.56	**Carbon** SG = 1.78
Hand Laminated Simple Surface	CSM	0.167	0.300	n/a
	WR	0.300	0.478	0.406
	RVM	0.246	0.410	n/a
	MD	0.319	0.500	0.406
	UD	0.364	0.550	0.455
Hand Laminated Complex Surface	CSM	0.134	0.248	n/a
	WR	0.240	0.403	0.315
	RVM	0.197	0.343	n/a
	MX	0.255	0.422	0.333
	UD	0.291	0.467	0.374
Infused	CSM	0.21-0.30	0.36-0.48	n/a
	WR	0.42-0.50	0.61-0.68	0.51-0.59
	MD/UD	0.45-0.53	0.64-0.71	0.54-0.63
Prepreg	MD/UD	0.530	0.706	0.630
Note: CSM = Chopped Strand Mat, WR = Woven Roving, RVM = Rovimat, MD = Multidirectional, UD = Unidirectional.				

Alignment of Fibers

The beauty of composites is the ability to tailor the properties to the loads, thanks to the fiber orientation. However, misalignment can result in a large change in the expected properties. From a design perspective, the Krenchel factor (Krenchel, 1964) can be employed to assess the change in mechanical properties with the change in orientation; mathematically:

$$\eta_\theta = \sum (a_n \cos^4\theta) \tag{5}$$

In which:

η_θ	Krenchel factor.
a_n	Proportion of overall fiber content.
θ	Angle of fiber to nominal axis.

The Young's modulus of the composite laminate can then be found based on the fiber volume fraction V_F and the matrix volume fraction V_M, where $V_M = 1 - V_F$.

$$E_C = \eta_\theta \, E_F \, V_F + E_M \, V_M \tag{6}$$

In which:

E_C	Laminate Young's modulus in GPa.
η_θ	Krenchel factor.
E_F	Fiber Young's modulus in GPa.
V_F	Fiber volume fraction.
E_M	Matrix Young's modulus in GPa.
V_M	Matrix volume fraction.

For a single ply of prepreg carbon UD (E_F = 235 000 GPa) and epoxy (E_F = 3 300 GPa), having a fibre volume fraction V_F = 0.530, the variation of the overall Young's modulus from 0 ° (parallel to fibers) to 90 ° (perpendicular to fibers) according to the Krenchel theory is shown in Figure 5.

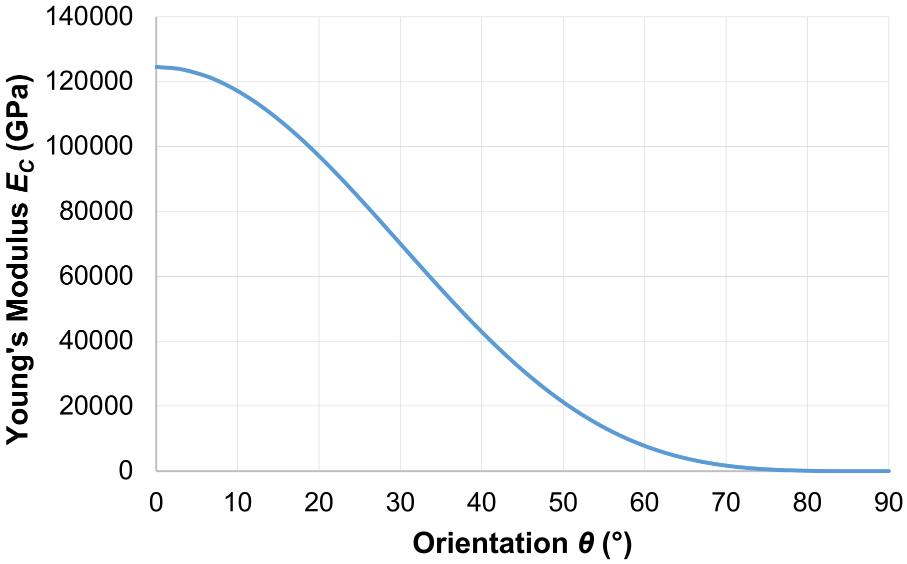

Figure 5: Variation in Young's modulus of a prepreg carbon UD with misalignment.

The properties can be seen to vary from the maximum parallel to the fiber, down to only the properties of the resin once the UD is at 90 °.

From an uncertainty analysis perspective, the BS EN ISO 12215-10 provides a relevant guideline, which is to assume a misalignment of 5 degrees (ISO, 2018). Consequently, a Krenchel factor of 0.985 would be achieved, which in this case translates to a reduction in Young's modulus of 2.7%.

While this particularly small value would largely be covered by the factor of safety of 2 applied to composite materials, and the smaller k_{BB} for lower level production, designers of highly optimized structures aiming to decrease the scantlings as much as allowed by the rule may want to consider the uncertainty due to fiber alignment. Furthermore, it is to be noted that vessels with complex shapes will almost certainly experience misalignments greater than the 5 degrees suggested, after which the mechanical properties start falling much rapidly.

Geometry

The geometry being analyzed can introduce a high uncertainty if it differs from the actual one. When dealing with the simpler methods for structural analysis in the BS EN ISO 12215-5, the panels are converted into a rectangular equivalent, with an account for curvature. The revised standard bringing in the longitudinal curvature contributes to modelling a closer geometry. However, the most relevant step forward is the use of FEM with the ISO pressures and ISO mechanical properties, so that the actual geometry can be analyzed.

Analysis Method

The newly implemented k_{AM} coefficient for analysis method allows to much better capture the uncertainty of the analysis method. Traditional calculations, derived from beam theory, are prone to large errors, but are also blind to certain structural details, such as cut-outs and fastening holes. In that respect, and particularly for the high performance yacht design industry, the opportunity to demonstrate compliance with FEM contributes to reduce the inaccuracies.

Additional Effects

Lastly, a vast number of additional factors are left out of rules-based structural design. For instance, in the case of the BS EN ISO 12215-5, deflection under operation is neglected, so is fatigue, aging, pre-stress due to manufacturing or resin shrinkage, and a vast array of more advanced failure mechanisms than the strength and robustness criteria of the standard.

It is often those more advanced failure mechanisms that lead to structural failure on performance yachts. Those are left beyond the scope of the BS EN ISO 12215-5, which focusses on the essential minimum requirements, but still represent a predominant part of the development of high performance sailing yachts and their structural design. This is where further considerations should be applied by the designer of the structure to maximize its reliability in service and over its operating life.

Furthermore, the BS EN ISO 12215-5 is solely based on local loads. The BS EN ISO 12215-6 (ISO, 2008) makes a recommendation for the longitudinal strength of sailing crafts; this would be a primary concern for racing yachts with extreme rig loads and high ballast ratios and keel loads.

CONCLUSIONS

The background to the revision of the BS EN ISO 12215-5 and its impact on the design of high performance composite sailing yachts have been detailed. Building on the motivations behind the revision, the main changes to the scope have been introduced, together with a number of new features, aimed at enhancing the structural analysis options and offer more flexibility in the compliance assessment. Particular emphasis on how the revisions of the standard responds to the need for a refined uncertainty analysis in composite structures has been provided, thus offering an insight into the applied safety considerations and inherent limitations. In addition, a number of guidelines to help both designers and builders in the structural analysis and production process have been incorporated, including values for fiber volume and weight fractions. Furthermore, a number of established industry practices have been featured, thus providing a suitable starting point for the structural optimization of high performance yachts, and how to achieve lighter structures under the forthcoming BS EN

ISO 12215-5 to ensure competitiveness, with lower factors of safety when acceptable while still providing a sound engineering analysis.

DISCLAIMER

The views expressed in this paper are those of the author only and do not necessarily reflect those of the ISO/TC188/WG18. All information presented are subject to changes, approval of the final standard and its publication.

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