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Regulatory Developments in Structural Keel Design: A Revised ISO 12215-9

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Abstract. The design of yacht keel structures is governed by the ISO 12215-9:2012, which is concerned with the loads and scantlings of monohull sailing craft appendages up to 24 m hull length. However, the significant advances in sailing yacht performance, appendages design, materials and manufacturing of the past decade now warrant a revision of this crucial international standard. Consequently, this paper presents the technical background and impending developments in regulatory yacht keel structures. The proposed revisions include (i) a new load case for lateral impact; (ii) compulsory and more stringent fatigue assessment; (iii) enhanced structural arrangements for bolts and backing plates; and (iv) informative guidelines regarding keel installation procedures. This is the first public introduction of the current developments inherent to the forthcoming ISO 12215-9:2025, which aims to support the design and manufacturing of safe and reliable keel structures for sailing yachts. Furthermore, it is envisaged this work may contribute to the development of future guidelines and regulations for the structural design of hydrofoils and internal supporting structure.

Keywords: ISO 12215; Small Craft, Yacht Keel, Yacht Design; Sailing Craft Appendages, Fatigue.

NOMENCLATURE

A	Planform area [m^2]
C_{MSF}	Miner's summation factor [-]
e	Proportion of total side force carried [-]
F	Load case force [N]
$F_{4,\mathrm{X}}$	Longitudinal component of load case 4 [N]
$F_{4,\mathrm{Y}}$	Transverse component of load case 4 [N]
F_{PS}	Bolt pre-stress force [N]
g	Gravitational acceleration [m s^{-2}]
h_{CE}	Centre of effort height [m]
m_K	Keel mass [kg]
m_{LDC}	Fully loaded vessel mass [kg]
M_R	Righting moment at 30° of heel [N m]
n_i	Number of cycles experienced [-]

N_i Number of cycles resulting in failure [-]
n_P Number of persons needed to recover capsized dinghy [-]
S_n Cross-sectional area of bolt neck [mm^2]
V Maximum boat speed [kn]

α Centreboard angle of attack [°]
λ Transverse load case 4 constant [-]
σ_y Yield stress [MPa]

ABS American bureau of shipping
ISO International organization for standardization
MSF Miner's summation factor

1. INTRODUCTION

The ISO 12215, published by the International Organization for Standardization (ISO), governs the structural design and scantlings of small crafts with a hull length up to 24 m. It is subdivided into 10 parts, with part 9 (ISO, 2012) being concerned with sailing craft appendages, namely fixed and canting keels, centreboards and daggerboards, and their attachments to the hull. The scope of the standard is limited to monohulls. Prior to the publication of the ISO 12215-9, keel structures were covered in the American Bureau of Shipping (ABS) Offshore Racing Yachts (ABS, 1994) rules, now superseded by the ABS Rules for Building and Classing Yachts (ABS, 2023), albeit to a lesser extent than in ISO regulations.

The motivation for the revision to the ISO 12215-9 is threefold. First, it follows significant regulatory advances in hull scantlings under the latest ISO 12215-5 (ISO, 2019, Souppez, 2018; Souppez & Ridley, 2019), and the launch of new parts governing multihulls (ISO, 2020a) and rig loads and attachments (ISO, 2020b). Then, while investigations did not yield any concerns on the suitability of the ISO 12215-9:2012, loss of keels leading to loss of lives, such as that of *Cheeki Rafiki* (MAIB, 2015), *Capella* (FEBIMA, 2017) and *Showtime* (Lyons, 2021), demonstrate the vital role of keel structures and the importance of fatigue life (Raju et al., 2010). This is also evidenced in offshore racing classes, with, for instance, the International Monohull Open Class Association moving to a standardized keel structure from 2013 in an effort to improve reliability. Lastly, improvements in yacht performance over the past decade, coupled advances in the understanding of welded joints fatigue (Grimm, 2016; Braun et al., 2018; Braun et al., 2021), flutter effects (Mouton and Finkelstein, 2015; Mouton et al., 2018), load monitoring (Russel et al., 2016) and the behaviour of centreboard and daggerboard for dinghies (Graf et al., 2020; Guida et al., 2020; Bagué et al., 2021) further motivate a revision of the 2012 standard.

Consequently, this paper presents an insight into the current developments of the revision to the ISO 12215-9:2012, and will adopt the same scope, namely focusing on the appendages of monohull sailing craft with a hull length up to 24 m but excluding hydrofoils and craft intended solely for the purpose of racing. Indeed, these are excluded from the scope of the Recreational Craft Directive (European Parliament, 2013) and Recreation Craft Regulations (Office for Product Safety and Standards, 2017). A draft international standard is due to be released for comments by June 2024, with the revised standard published by June 2025. As such, this paper presents current developments and intended updates to the structural regulations governing sailing craft appendages but does not represent formal regulatory requirements. Future regulatory requirements are pending further developments and the publication of the revised standard. Nevertheless, the present work provides the motivations behind the proposed changes and informs the reader on the areas likely to be amended in the forthcoming ISO 12215-9:2025.

The remainder of this paper is structured as follows. Section 2 introduces the proposed combined longitudinal and lateral impact load case for keels. Section 3 presents the fatigue strength assessments, while Section 4 discusses keel bolts and backing plates. Section 5 discusses the guidelines associated with the keel installation procedure. Ultimately, Section 6 summarizes the main intended changes to the forthcoming ISO 12215-9 revision and future prospects.

2. COMBINED LONGITUDINAL AND LATERAL IMPACT LOAD CASE

A total of six load cases are considered by the ISO 12215-9:2012, as outlined hereafter.

(1) Fixed keel at 90° knockdown, where the force applied F_1 is the product of the gravitation acceleration g and the keel mass m_K such that

$$F_1 = g\, m_K. \tag{1}$$

(2) Canted keel under steady load at 30° heel with a 40% dynamic overload factor, yielding a force

$$F_2 = 1.4\, g\, m_K. \tag{2}$$

(3) Keelboat vertical pounding, where the force is taken as acting purely vertically upwards, such that

$$F_3 = g\, (m_{\mathrm{LDC}} - m_K), \tag{3}$$

where m_{LDC} is the fully loaded mass of the vessel.

(4) Keel boat longitudinal impact, assuming a longitudinal and horizontal force only, giving

$$F_4 = 1.2\, g\, (m_{\mathrm{LDC}} - m_K). \tag{4}$$

(5) Centreboard on capsize recoverable dinghies, assuming a minimum number of persons for recovery n_P, each with a mass of 80 kg, so that the force to be withstood is

$$F_5 = 80\, g\, n_P. \tag{5}$$

(6) Centreboard or daggerboard upwind, which considers the hydrodynamic lift exerted, given as either

$$F_{6.1} = 136\, (0.075\, \alpha)\, A\, V^2, \tag{6}$$

or

$$F_{6.2} = e\, \frac{M_R}{h_{\mathrm{CE}}}, \tag{7}$$

where the constant 0.075 is only valid for symmetric foil sections, α is the angle of attack (with $\alpha \geq 5°$), A is the planform area, V is the maximum speed, e is the proportion of total side force carried by the appendage, M_R is the righting moment at 30° of heel, and h_{CE} is the height of the centre of effort of the nominal sail area.

The assumptions inherent to load case 4, namely that the longitudinal impact acts purely longitudinally and horizontally, may be seen as optimistic, and a transverse horizontal component would be expected. Consequently, it is prosed the force is considered in both longitudinal ($F_{4,\mathrm{X}}$) and transverse ($F_{4,\mathrm{Y}}$) directions, such that

$$F_{4,\mathrm{X}} = 1.2\ g\ (m_{\mathrm{LDC}} - m_K), \tag{8}$$

and

$$F_{4,\mathrm{Y}} = \lambda\ F_{4,\mathrm{X}}, \tag{9}$$

where values $0.17 \le \lambda \le 0.375$ are currently being investigated, with the intention for the final standard to provide a single constant.

3. FATIGUE

3.1 Compulsory Fatigue Assessment

Annex A of the ISO 12215-9 contains the application declaration, where users specify their approach to demonstrating compliance. This may involve (i) complying with all relevant requirements of the standard; (ii) complying with selected requirements of the standard, with full background, description and validation of alternative methods used; or (iii) solely relying on alternative methods, again with full background, description and validation provided. Here, *alternative methods* refer to more advanced structural assessment methods, including numerical methods such a finite element analysis, commonly applied to yacht keels (Raju et al., 2010; Mouton and Finkelstein, 2015).

Under the 2012 version, the above options apply to all regulatory requirements but the simplified fatigue strength assessment, where a technical justification for not undertaking fatigue assessment may be provided. Given the importance of fatigue on keel structures and the strong emphasis on the present revision on fatigue life, users of the standard would no longer be able to provide a justification for the absence of fatigue assessment, thereby making it compulsory. Instead, as for other requirements, fully detailed alternative methods would need to be used should the assessment not be undertaken based on the simplified method featured in the standard.

3.2 Updated Fatigue Strength Assessment

The ISO fatigue assessment is based on the total Miner's summation factor (MSF) (Miner, 1945), denoted C_{MSF} in this paper, such that

$$C_{\mathrm{MSF}} = \sum\nolimits_1^n \frac{n_i}{N_i} \tag{10}$$

where, for a load case i, n_i is the number of cycles experienced and N_i is the number of cycles to result in failure, where *failure* is defined as through-thickness cracking at the 95% confidence level.

The calculation process for C_{MSF} is detailed in Annex F of the ISO 12215-9. Both the 2012 and revised versions consider three scenarios, namely:

(i) $C_{\mathrm{MSF}} < 0.5$, meaning the fatigue life should exceed the design life by a factor of 2. This should be the intended outcome, though consideration for stress concentration and welding are necessary for the result to be relevant.

(ii) $0.5 \le C_{\mathrm{MSF}} \le 1$, where the fatigue life should still exceed the design life, but by a factor ranging from 1 to 2. Under the 2012 version, $0.7 \le C_{\mathrm{MSF}} \le 1$ would yield a recommendation for further investigation using more advanced methods than the simplified ISO approach. Under the forthcoming revision, $0.5 \le C_{\mathrm{MSF}} \le 1$ will require further investigation.

(iii) $C_{\mathrm{MSF}} > 1$, which implies the fatigue life is less than the design life. While the 2012 version requires further analysis in this case, the forthcoming revision will not accept this outcome and will require a redesign.

The proposed changes are summarized in Table 1.

Table 1. Proposed changes to the ISO 12215-9 for fatigue assessment based on the C_{MSF} value.

C_{MSF} value		Current ISO 12215-9:2012	Proposed ISO 12215-9:2025
$C_{\mathrm{MSF}} < 0.5$		Intended outcome	Intended outcome
$0.5 \leq C_{\mathrm{MSF}} \leq 1$	$0.5 \leq C_{\mathrm{MSF}} < 0.7$	No recommendation	Further investigation required
	$0.7 \leq C_{\mathrm{MSF}} \leq 1$	Further investigation recommended	
$C_{\mathrm{MSF}} > 1$		Further investigation required	Outcome not accepted

The ISO 12215-9 takes the *design life* of a sailing craft as circa 30 000 nautical miles or 25-30 years of recreational sailing, estimated to correspond to 3-5 years of offshore racing. While crafts solely intended for racing are beyond the scope of all ISO standards, it is acknowledged that recreational crafts may engaged in offshore racing. As such, the adoption of the ISO 12215-9 minimum safety requirements by racing rules is discouraged and deemed dangerous: further safety margins would be necessary. Lastly, the number of stress cycles associated with the design lift has doubled, from 8 million under the 2012 version to 16 million in the forthcoming revision.

4. KEEL BOLTS AND BACKING PLATES

4.1 Keel Bolts

The tightening of bolts is crucial to ensure pre-stressing, thereby avoiding fatigue, gaps opening under load, and potentially nuts working loose. However, excessive tightening may result in stripping the bolts' thread or added stress on components, including the hull. As such, the pre-stress force F_{PS} applied should be

$$F_{\mathrm{PS}} = 0.7\, \sigma_y\, S_n, \tag{11}$$

where σ_y is the yield stress of the bolts, and S_n is the cross-sectional area of the bolt's neck. Users of the standard are also referred to national regulations, such as the VDI 2230-1 (VDI, 1984) and NF E25 030-1 (AFNOR, 2014), for further details on bolt pre-stressing.

Moreover, the inclusion of a stress modifier to account for the proximity of adjacent bolts is being investigated. Indeed, the proximity of keel bolts has been associated with additional stress concentration. This may range from 10% to 20% more than estimated by the current ISO 12215-9:2012 for typical keel design and may negatively influence the fatigue life of the bolts.

4.2 Backing Plates

Backing plates, together with the hull shell, enable to transfer the keel loads into the internal supporting structure (e.g. floors, girders). Because of the requirement for sandwich composite vessels to transition to single-skin laminate in way of the keel, too thin a hull shell in way of the backing plate may result in failure (ISO, 2012). As such, thicker backing plates have been employed in combination with a thinner hull shell. The proposed revision issues a clear warning that such an arrangement should be treated with caution. Yet, because this trade-off between the backing plate and hull shell thickness is common practice, the possibility of a simplified equation to safely reduce hull thickness thanks to a thicker backing plate is under consideration.

5. KEEL INSTALLATION PROCEDURE

Through-life monitoring is vital to ensure the reliability and longevity of the keel structure. However, because the scope of ISO standards is to ensure product compliance when placed on the market, this is not straightforward to implement. Consequently, it is proposed an informative annex presenting keel installation guidelines is provided. A similar 'checklist' approach has been implemented in other small craft standards (ISO, 2022), and is deemed a suitable approach for yacht keels, thereby leading to a proposal for an informative annex on keel installation procedures.

The annex aims to ensure good practice is promoted in crucial area, including: (i) keel geometry, maximum allowable design component weights, component centre of gravities and fastening layout; (ii) foil geometry at multiple spanwise sections; (iii) material specification and minimum required mechanical properties of all components; (iv) weld specification and reference to any relevant welding standards; (v) mechanical fastening specifications and required assembly torque settings; and (vi) installation notes, particularly where novel assembly details are required.

6. CONCLUSIONS

6.1 Proposed Revisions and Future Work

After over a decade since its publication, the ISO 12215-9:2012 governing sailing yacht appendages is undergoing a review, with the final publication intended in 2025. While the formal revision will not be official until publication, this paper provides the first insight into the proposed changes and current areas of revision.

First, a more thorough definition of the longitudinal impact load case, including a transverse component, is being developed. Then, because of the critical importance of fatigue, its assessment is intended to become compulsory, with more stringent fatigue strength requirements, based on the Miner's summation factor. Keel boats pre-stressing and the trade-off between single-skin hull plating in way of the keel and backing place thickness are also being considered. Additionally, the introduction of an informative annex on keel installation procedure is envisaged. Finally, further minor modifications to enhance the readability and applicability of the standard for designers and builders alike are being implemented.

While not currently considered as part of the present revision, the addition of a dedicated multihull scantling standard (ISO, 2020a) could warrant an expansion of the scope of the ISO 12215-9 to also include multihull appendages in the next revision cycle, as it is beyond the remit of the current one. Whether the addition of hydrofoils to the standard could then be considered is still hypothetical.

6.2 Towards the Inclusion of Hydrofoils

Hydrofoils remain excluded from the scope of the Recreational Craft Directive (European Parliament, 2013) and Recreation Craft Regulations (Office for Product Safety and Standards, 2017) and thus may not be included in ISO standard. However, the undeniable growth in hydrofoiling technology, not only for racing yachts (also excluded from the scope of the directives and ISO standards) but also for recreational crafts, may lead to their eventual inclusion in small craft regulations, which would further support their wider adoption (Truelock et al., 2022).

The scope of the ISO 12215-9, namely sailing craft appendages and their supporting structure, would make it an obvious regulation to include hydrofoils in a simplified manner, with load cases including hydrodynamic loads and impact scenarios (akin to the keel load cases presented in Section 2) and their effect on the foil itself and its internal support structure. Any future inclusion of hydrofoil in ISO standards may also yield new load cases for hull structure, to be tackled in the ISO 12215-5, for instance, due to slamming loads arising from a yacht crashing off the foils (Battley et al., 2020).

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