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A consideration of the ISO12215 Structural Rules and the Classification Rules for a Vessel Close to 24m in Waterline length

submitted on 1 August 2022

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I. CONTENT

II. ABSTRACT

Yachts and other recreational crafts are a growing market. Depending on the length, these vessels are subject to different rules and regulations. For scantling of boats with a length smaller than 24 m, ISO 12215 Structural Rules are applied. Above this length, yachts are designed following Classification society rules. Scantling by structural regulations, stipulated by both ISO and Classification societies, has a common pathway.

A high-speed motorboat was selected to assess the for impact of slamming load and acceleration of gravity on the design. The assessment of minimum design loads, computed by ISO and Classification societies' rules, is done by comparing the definition of design pressure, its longitudinal distribution, effect of gravity acceleration and effect of deadrise angle.

Afterwards, the scantling of a bottom plate is done by using the ISO and Classification societies' rules. The material of the motorboat is composite, with a sandwich structure. Minimum requirements demanded by the rules are assessed. Limitation criteria stemming from breaking strain or ultimate stress are evaluated parallelly with core check for shear.

Finally, the results are compared, with the purpose of verifying if there is a natural structural continuity between a 24m yacht designed with ISO and with another designed with Classification society; plating should be similar and there should not be and big jump in laminate thickness and strenght requirements, which was not the case. The inconsistencies between the results were analysed.

Keywords: Rules & Regulations, Scantling, Composite boats, Yachts

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V. LIST OF SYMBOLS AND ABBREVIATIONS

Latin symbols

A	Area
A, A_{ij}	Tensile rigidity matrix
A_D, A_d	Design area
A_R, A_r, A_{ref}	Reference area
AP	Aft perpendicular
B, B_{ij}	Tensile and bending coupling effect matrix
B_C	Chine beam
$BD+$	Biaxial
C_f	Craft type notation factor (LR)
D, D_{ij}	Bending rigidity matrix
$DB\times$	Double bias
E_{11}	Longitudinal Young's modulus of a single unidirectional ply
E_{22}	Transverse Young's modulus of a single unidirectional ply
E_C	Mean of compressive moduli
E_f	Elastic Modulus (// and ⊥)
E_T	Mean of tensile moduli
f	Freeboard
F_n	Froude Number
F_V	Vertical acceleration distribution factor
FP	Fore perpendicular
g	Acceleration due to gravity
G, G_f	Shear modulus
G_f	Service area notation factor (LR)
G_o	Support girth at LCG
G_S	Support girth
$H_{1/3}, H_S, h_{1/3}$	Significant wave hight
h_0	Vertical distance from waterline to the load point (DNV)
H_f	Hull notation factor (LR)
I	Moment of inertia
K_β	Correction factor for local deadrise angle (DNV)
k_{DYN}	Dynamic load factor
K_{red}	Reduction factor for design load area (DNV)
K_V	Vertical acceleration distribution factor
kt, kn	Knots
l, ℓ	Unsupported span, or length of a panel, or long span
L	Scantling length
L_{hull}	hull length
L_{LL}	load line

L_{WL}	Length at waterline
L_h	EC directive
LCB	Longitudinal centre of buoyancy
LCG	Longitudinal centre of gravity
m	Displacement (mass)
m_{LDC}	Mass in maximum loading condition
n_{CG}, a_{CG}	Vertical acceleration at LCG
nm, NM	Nautical miles
Q_{ij}, R_{ij}	Modulus components
$Q \times$	Quadriaxial
s, b	Spacing of longitudinal stiffeners, or width of a panel, or short span
S_a	Design area (BV)
S_f	Service type notation factor (LR)
S_r	Reference area (BV)
SM	Section modulus
SM_o, SM_i	Section modulus of outer, respectively inner skin
t	Thickness
t_{os}, t_{is}	Thickness of outer, respectively inner skin
T_C	Max depth of canoe body
V	Speed

Greek symbols

α_d	Deadrise angle at other locations (BV)
α_{dCG}	Deadrise angle (BV)
β_{CG}	Deadrise angle at LCG
β_{xx}	Deadrise angle at other locations
θ_B	Running trim angle (LR)
θ_D	Deadrise angle (LR)
σ_u	Ultimate stress
τ_u	Ultimate shear stress
Α	Flare angle
Γ	Taylor Quotient
Δ	Displacement (mass)
β	Deadrise angle
γ	Shear strain
ε	Strain
ν	Poisson’s ratio
σ	Stress
τ	Running trim angle (BV, ABS)
τ	Shear stress

Other symbols

//	Parallel
⊥	Perpendicular
℄	Centre line
°	Degree
®	Registered trademark
∇	Displacement (volume)

Abbreviations

ABS	American Bureau of Shipping
BV	Bureau Veritas
CFD	Computational Fluid Dynamics
CLT	Classical Lamination Theory
CS	Classification Society
CSM	Chopped strand mat
DNV	Det Norske Veritas
EU	European Union
FEM	Finite Element Analysis
FRP	Fibre Reinforced Plastics
GRP	Glass Reinforced Plastics
HSC	High-speed craft
IMO	International Maritime Organization
ISO	International Organization for Standardization
LR	Lloyd's Register
MY	Motor Yacht
SSC	Special Service Craft

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Ammar Tivari

Southampton, 1 August 2022

VII. DECLARATION OF AUTHORSHIP

I, Ammar Tivari, declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

I have acknowledged all main sources of help.

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

I cede the copyright of the thesis in favour of the University of Rostock and Solent University.

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1. INTRODUCTION

1.1. Background

In recent years the yacht and recreational crafts market has been growing. These boats are built in different lengths, with various materials and purposes. Humans have enacted rules that contain the safety and quality of these boats, some obligatory and some as recommendations. Naval architects or boatbuilders have to check and decide which rules and regulations are or are not binding to building a boat. In general, designing and building a boat with the purpose of selling it shall be accompanied by a guarantee of quality and safety.

In the European Economic Area and some other countries, the scantling of small boats is governed by the European Recreational Craft Directive 2013/53/EU. This directive recognizes the applicability of ISO 12215-5 Structural Rules to boats, including yachts, with a length smaller than 24 meters. These rules are used to determine the design loads and scantlings of boats built with steel, aluminium, or various composite materials. Above the 24-meter length, yachts are designed and built by following specific Classification Society rules.

1.2. Aim of the thesis

The length of 24 meters acts as the border between the application of ISO 12215-5 Structural rules and Classification Societies rules, although not exclusively. A vessel close to 24 meters, as shown in Figure 1, is expected to have similar scantling under the same operational conditions if designed with ISO 12215-5 Structural rules or Classification Societies rules. Additionally, as some Classification Societies propose unique rules for designing yachts, others include yachts in their more general rules.

The aim of this thesis is to evaluate the considerations, design loads and scantling determinations of ISO 12215 Structural rules and the rules of four Classification Societies related to a fast motor yacht with a length overall of 24 meters. The four Classification Societies rules can be grouped into two, those being unique for classification of only yachts, as are the rules of the American Bureau of Shipping, Bureau Veritas, DNV and those being more general, as are the rules proposed by Lloyd's Register. A small exception in this categorization might be DNV, which requires the usage of the rules for High-Speed crafts to determine the design loads of a fast motor yacht.

Figure 1 *Alchemist*, a 24-meter motor yacht with a maximum speed of 26 knots (80-foot motor yacht Alchemist photo D Ramey Logan.jpg from Wikimedia Commons by D Ramey Logan, CC-BY-SA 4.0)

The objectives of the thesis are to study the difference and similarities between the rules mentioned above, concentrating on the limitations, applicability, advantages, and disadvantages of their structural determination rules. A suitable vessel and a representative panel have been selected to achieve this goal.

For this study, a motor yacht navigating in a planing regime ($F_n > 0.8$) is considered, for which the design loads, including design vertical accelerations and design pressures, are to be defined. Different factors affecting the design loads and the effect of design vertical acceleration on design pressure acceleration are to be studied.

Secondly, the scantling of a plate in the bottom of the yacht is done in order to compare the structural requirements. The material selected to be studied is sandwich composite, for which the different failure criteria are to be checked and evaluated.

2. LITERATURE REVIEW

This chapter gives a brief review of design rules, vertical acceleration, slamming pressure and composite materials.

2.1. Design rules and regulations

Design rules play an important role in the boatbuilding and shipbuilding industry. From simple boats sold in the European market to transoceanic containerships, all are bound to specific sets of regulations. In contrast to regulations related to merchant ships or naval vessels, in which the buyer is well aware of what it is buying, in yachts industry (more so in the motor yachts industry), the buyer might not be fully aware of the details concerning the structure and safety of its yacht. In this aspect, design rules play their role as the certifier of safety and assurers of quality.

The design and manufacturing of small crafts (under 24 meters in length) in Europe is regulated by Directive 2013/53/EU of the European Parliament and of the Council of 20 November 2013 on Recreational Craft and Personal Watercraft [1], which repealed the EU Directive on recreational craft 94/25/EC and 2003/44/EC. As part of the harmonised standards for recreational craft, European Union recognises ISO 12215-5:2019 [2] as the standard that deals with structures of small boats, including design pressures, stresses, and scantling determinations.

According to Souppez, ISO 12215-5 is set to become a reference for the design and manufacturing of small crafts in the coming decade, especially in yacht design and manufacturing. [3] Per Souppez et al., the determination of design loads remains almost exclusively based on seminal work done in the 1960s and 1970s. [4] On the other hand, classification societies have their own rules regarding yacht design and construction. These rules are generally applicable to vessels over 24 meters in length, but sometimes they are utilised in vessels under this length. [5]

2.2. Prior studies

Previous work on the comparative assessment of ISO and classification societies rules has been done. Lee (2011) [6] evaluated the design slamming impact on an Open60' yacht with respect to ISO and classification rules. Coppola and De Santis (2011) [7] compared the differences between the structural scantling of an FRP boat using ISO12215 and four classification societies. Oh et al. (2014) [8] compared and analysed the design of a single-skin CFRP hull cruise motorboat by implementing ISO 12215 and RINA rules.

Souppez (2018) [9] evaluated the application of the new version of ISO 12215-5 on composite works boats, namely search and rescue vessels. Souppez (2018) [10] analysed the novelties of ISO 11215-5 and its relevance to high-performance composite yachts. Souppez et al. (2020) [4] made a comparative assessment of implementing ISO 12215-5 and six class rules on a high-speed aluminium power craft. Boote et al. (2022) [11] analysed the scantlings of a 25-meter motorboat using three different composite material configurations (glass, carbon, and hybrid) and further optimized the results with FEM.

2.3. Design vertical acceleration and pressure

Formulae for determination of the design vertical accelerations, subject to deadrise angle, speed, length, and significant wave height of all considered rules in this study, resemble the semi-empirical formula for determining the average impact acceleration at LCG, in g units, proposed by Stavisky et Brown (1976) [12], with the formula given in equation (1).

$$\tilde{n}_{\mathrm{CG}} = 0{,}0104 \left(\frac{H_{\frac{1}{3}}}{B_{WL}} + 0.084\right)\frac{\tau}{4}\left(\frac{5}{3} - \frac{\beta_{CG}}{30}\right)\left(\frac{V}{\sqrt{L_{WL}}}\right)^{2}\frac{\frac{L_{WL}}{B_{WL}}}{C_{\Delta}} \qquad (1)$$

The symbols in the formula are slightly modified to fit with the nomenclature used in this study.

Equation (1) is based on:

- The geometry of the vessel: breadth B_{WL}, deadrise angle β_{CG}, length L_{WL} and beam loading coefficient C_{Δ},
- The operation conditions: significant wave height $H_{1/3}$, running trim τ and speed V.

DNV HSCL, ABS Yachts, BV Yacht, LR SSC and ISO 12215-5 design slamming pressure formulae resemble the work of Allen and Jones [13], which proposed a semi-empirical method to calculate the design-limit impact pressures. It uses an impact reference area, defined by Spencer [14], as:

$$A_R[m^2] = 0.7\frac{\Delta}{d}; \tag{2}$$

Where d $[m]$ is the full load static draft, and Δ $[\text{tonnes}]$ is the full load displacement.

The average slamming pressure over the reference area can be determined by:

$$\overline{P} = \frac{impact\ induced\ load}{A_R} \tag{3}$$

The final form of the Allen and Jones design slamming pressure is described in eq. (4), taken from Razola et al. [15].

$$P_D = \frac{N_z\Delta}{0.14\ A_R}K_D F \tag{4}$$

Where:

N_z = global load factor (typically vertical acceleration)

Δ = craft mass

A_R = reference area, as defined in eq. (2

K_D = pressure reduction factor

F = longitudinal load reduction factor

Stemming from the same base does not necessarily lead to the same results, as some components of eq. (4) are highly modified or dropped, and different factors are introduced. Definition of the factors of DNV HSLC, ABS Yachts, BV Yachts, LR SSC and ISO 12215 rules are explained later in Chapter 4.

2.4. Composites

Composite materials are attractive to designers due to their excellent strength-to-weight ratio, low corrosion, and ability to be tailored to the application. [5] One of the composite materials are sandwich materials, which are widely used in marine structures. [16]

The selection of constituents and their combinations can be a hard equation to solve, considering a large amount of possibilities, or as Petras [17] notes that the catalogue of composite materials is of forbidding length. Composites have been growing since the early 1950s, especially with the introduction of Glass Reinforced Plastics (GRP), which have a low construction cost [17]. Sandwich materials are a subgroup of composite materials composed of a pair of strong and stiff skins (also known as faces) and a thick, lightweight core, which are widely used in the marine industry. [17].

Composite materials are a combination of materials with different compositions and forms, which retain their identities in the composite. Experimental testing of any given laminate is probably the best way to determine its strength. But, when the testing is not available or feasible, some reasonable methods to analyse the strength of laminates are available. These methods can be based on the level of detail of which the stress is being calculated, and in order from larger to smaller, they can be grouped into four: [18]

- Laminate level,
- Ply level,
- Constituent level,
- Micro-level.

In this study, the strength of the composites was analysed on laminate and ply levels, depending on the rules' requirements.

2.4.1. Mechanical properties of composites

The main mechanical properties of composite materials are processed in four steps:

- Constituent level: basic elastic engineering constants are defined, like longitudinal and transverse Young's modulus, shear modulus, and Poisson's ratio. ($E_{11}, E_{22}, G_{12}, \nu_{12}$)
- Local level of a single ply: the stiffness matrix of a single ply is defined in the local coordinate system. (Q_{ij})

- Global level of a single ply: the constituent level properties are converted into a global coordination system, depending on their direction, i.e., angle of rotation. (Q'_{ij})
- Global laminate level: the plies are stacked upon each other, and the global rigidity matrix can be found (ABD)

The basic elastic engineering constants are calculated based on the Rule of Mixture, which is based on the volume fraction, φ:

$$\varphi = \frac{\psi}{\psi + (1-\psi)\ \frac{\rho_f}{\rho_m}} \tag{5}$$

Where:

ψ = fibre mass fraction of a single ply,

ρ_f, ρ_m =specific gravity of fibre material and matrix material, respectively.

The minimum thickness of a single ply can be determined from:

$$t_{ply} = m_f \left(\frac{1}{\rho_f} + \frac{1-\psi}{\psi\ \rho_m} \right) \tag{6}$$

Where:

m_f = areal weight of fibre reinforcement (generally given in g/m^2)

In Table 1, the calculations of the longitudinal and transverse Young's modulus for a single unidirectional ply (with glass fibres) are given, depending on the rules. ABS rules do not give a specific way to calculate the fundamental engineering constants but require testing of the material to be performed, with some information given about the minimum mechanical properties, which are later analysed in chapter 5.

Table 1 Definition of longitudinal and transverse Young's modulus for a single unidirectional ply

Rules	Longitudinal Young's modulus	Transverse Young's modulus
DNV	$E_{11} = \varphi\, E_{fL} + (1-\varphi)\, E_m$	$E_{22} = \frac{E_m}{1-\nu_m^2} \frac{1+0.85\,\varphi^2}{(1-\varphi)^{1.25} + \varphi \frac{E_m}{E_{fT}(1-\nu_m^2)}}$
BV	$E_{UD1} = C_{UD1}\left[E_{f0^\circ}\, V_f + E_r(1 - V_f)\right]$	$E_{UD2} = C_{UD2}\left[\left(\frac{E_r}{1-\nu_r^2}\right)\frac{1+0.85\,V_f^2}{\left(1-V_f\right)^{1.25} + \frac{E_r}{E_{f90^\circ}}\frac{V_f}{(1-\nu_r^2)}}\right]$
ISO	$E_{UD1} = 0.975\left[E_{f1}\,\phi + E_m(1 - \phi)\right]$	$E_{UD2} = E_m \frac{1+\zeta\,\left[\frac{E_{f2}/E_m - 1}{E_{f2}/E_m + \zeta}\right]\phi}{1-\left[\frac{E_{f2}/E_m - 1}{E_{f2}/E_m + \zeta}\right]\phi}$
LR	$E_{0i} = E_F V_F + E_R(1-V_F)$	$E_{90i} = \frac{E_F E_R}{E_R V_F + E_F - E_F V_F}$

Where:

E_{11}, E_{UD1}, E_{0i}	=	longitudinal tensile modulus of single ply,
E_{22}, E_{UD2}, E_{90i}	=	transverse tensile modulus of single ply,
$E_{fL}, E_{f0^\circ}, E_{f1}, E_F$	=	tensile modulus of fibre in fibre direction,
$E_{fT}, E_{f90^\circ}, E_{f2}, E_F$	=	tensile modulus of fibre transverse to fibre direction,
E_m, E_r, E_R	=	tensile modulus of matrix,
φ, V_f, ϕ, V_F	=	volume content of reinforcement material in a laminate,
ν_m, ν_r	=	Poisson's ratio of resin.
C_{UD1}, C_{UD2}	=	experimental coefficients (for E-Glass: $C_{UD1} = 1$, $C_{UD2} = 0.8$)
ζ	=	1

In similar fashion, in Table 2, the shear modulus and longitudinal Poisson's ratio are given for a single ply. Only these components are necessary to compute the Q_{ij} matrix for a single ply in local coordinates, as shown in eq. (7).

Table 2 Shear modulus and Longitudinal Poisson's ratio for a single ply

Rules	Shear modulus	Longitudinal Poisson's ratio
DNV	$G_{12} = G_m \dfrac{1 + 0.8 \times \varphi^{0.8}}{(1-\varphi)^{1.25} + \dfrac{G_m}{G_{f12}}\varphi}$	$\nu_{12} = \varphi \nu_{f12} + (1-\varphi)\nu_m$
BV	$G_{UD12} = C_{UD12} G_r \dfrac{1 + \left(\dfrac{G_f}{G_r} - 1\right) V_f}{1 - \left(\dfrac{G_f}{G_r} + 1\right) V_f}$	$\nu_{UD12} = C_{UD_\nu}\left[\nu_f V_f + \nu_r (1 - V_f)\right]$
ISO	$G_{UD1} = G_m \dfrac{1 + \zeta \left(\dfrac{G_f/G_m - 1}{G_f/G_m + \zeta}\right)\phi}{1 - \left(\dfrac{G_f/G_m - 1}{G_f/G_m + \zeta}\right)\phi}$	$\nu_{UD} = \nu_f \phi + \nu_m (1 - \phi)$
LR	$G_{0/90i} = G_R \left(\dfrac{\dfrac{G_F}{G_R}(1 + V_F) + (1 - V_F)}{\dfrac{G_F}{G_R}(1 - V_F) + (1 + V_F)}\right)$	$\nu_{0/90} = V_F(\nu_F - \nu_R) + \nu_R$

Where:

$G_{12}, G_{UD12}, G_{UD1}, G_{0/90i}$ = shear modulus of single ply,

G_{f12}, G_f, G_F = shear modulus of fibre,

G_m, G_r, G_R = shear modulus of matrix,

C_{UD12}, $C_{UD\nu}$ = experimental coefficients (for E-Glass: $C_{UD12} = C_{UD\nu} = 0.9$),

$\nu_{12}, \nu_{UD12}, \nu_{UD}, \nu_{0/90}$ = Poisson's ratio of single ply,

ν_{f12}, ν_f, ν_F = Poisson's ratio of fibre.

2.4.2. Classical Lamination Theory

Classical Lamination Theory (CLT) is commonly used to determine stresses and strains for laminates. [19] The components of the stiffness or the rigidity matrix, $[Q]_k$, are given in eq. (7).

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \underbrace{\begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{bmatrix}}_{[Q]_k} \cdot \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{bmatrix} \tag{7}$$

Where:

$$Q_{11} = \frac{E_{11}}{(1 - \nu_{12}\nu_{21})} \qquad Q_{12} = Q_{21} = \frac{\nu_{21} \cdot E_{11}}{(1 - \nu_{12}\nu_{21})}$$

$$Q_{22} = \frac{E_{22}}{(1 - \nu_{12}\nu_{21})} \qquad Q_{33} = G_{12}$$

Note: DNV uses Q_{ij} notation, BV uses $\overline{R}_{ij}$ notation for the stiffness (or rigidity) matrix of a single ply in the local axes.

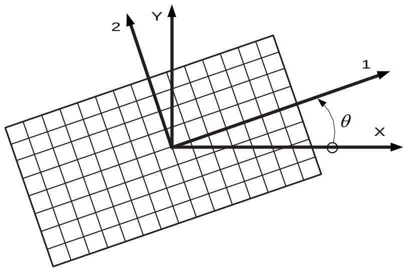

Figure 2 Local single ply axis about the laminate global axes [20]

The local single ply stiffness matrix shall be transformed into the laminate global axes, as shown in Figure 2. This is done for each individual ply k by the following equation, using the transfer matrices T and T':

$$[Q']_k = \begin{bmatrix} Q'_{11} & Q'_{12} & Q'_{13} \\ Q'_{21} & Q'_{22} & Q'_{23} \\ Q'_{31} & Q'_{32} & Q'_{33} \end{bmatrix} = T[Q]_k T'^{-1} \tag{8}$$

Note: DNV uses Q'_{ij} notation, BV uses R_{ij} notation for the stiffness (or rigidity) matrix of a single ply in the global axes. Transfer matrices T and T' are defined in eq. (9) and eq. (10)respectively.

$$T = \begin{bmatrix} (cos\theta)^2 & (sin\theta)^2 & -2(cos\theta sin\theta) \\ (sin\theta)^2 & (cos\theta)^2 & 2(cos\theta sin\theta) \\ (cos\theta sin\theta) & -(cos\theta sin\theta) & ((cos\theta)^2 - (sin\theta)^2) \end{bmatrix} \tag{9}$$

$$T = \begin{bmatrix} (cos\theta)^2 & (sin\theta)^2 & -(cos\theta sin\theta) \\ (sin\theta)^2 & (cos\theta)^2 & (cos\theta sin\theta) \\ 2(cos\theta sin\theta) & -2(cos\theta sin\theta) & ((cos\theta)^2 - (sin\theta)^2) \end{bmatrix} \tag{10}$$

The global multiply stiffness matrix (also noted as ABD matrix) is defined as:

$$\begin{bmatrix} A & B \\ B & D \end{bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} \tag{11}$$

Where:

A_{ij} = tensile rigidity (extension) matrix, as defined in eq. (12)

B_{ij} = tensile and bending coupling matrix, as defined in eq. (13)

D_{ij} = bending rigidity matrix, as defined in eq. (14)

$$A_{ij} = \sum_{k=1}^{n} (Q'_{ij})_k \cdot t_k \tag{12}$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} (Q'_{ij})_k \cdot (z_k^2 - z^2{}_{k-1}) \tag{13}$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} (Q'_{ij})_k \cdot (z_k^3 - z^3{}_{k-1}) \tag{14}$$

The inverse of the ABD matrix is defined as:

$$\begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} = \begin{bmatrix} A' & B' \\ B' & D' \end{bmatrix} = \begin{bmatrix} a & b \\ b & d \end{bmatrix} \tag{15}$$

Using the inverse ABD matrix, the in-plane engineering constants of a multiply laminate can be calculated as in the following equations (with t_M being the thickness of the whole laminate):

$$E_X = \frac{1}{A'_{11} t_M}; E_Y = \frac{1}{A'_{22} t_M}; G_{XY} = \frac{1}{A'_{33} t_M}; \nu_X = \frac{A_{21}}{A_{22}}; \nu_Y = \frac{A_{12}}{A_{11}} \tag{16}$$

3. CONSIDERATIONS

This chapter defines the main parameters of the vessel and the selected panel, including the limitations, applications, and considerations of ISO 12215 and four class rules.

3.1. Vessel

In this study, a motor yacht with a length overall of 24 meters is considered. The maximum speed, and thus the *scantling speed*, is taken as 25 knots. The hull is based on Naples warped hard chine hulls systematic series, which includes five models with different depth and breadth ratios [21].

This hull series allows the evaluation of the effect of the planing regime. The selected hull for this thesis is the C1 model, i.e., the parent hull, with its 3D model given in Figure 3 and plans in Figure 4, Figure 5 and Figure 6. This hull has a variable deadrise angle, starting from 14.4 degrees at the transom to 37.4 degrees at 0.7 L_{WL}. The main particulars of the full-scaled boat are shown in Table 3.

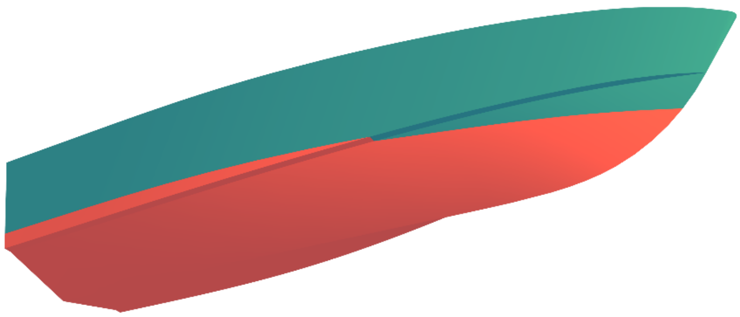

Figure 3 Perspective view of Naples warped chine hull C1 model

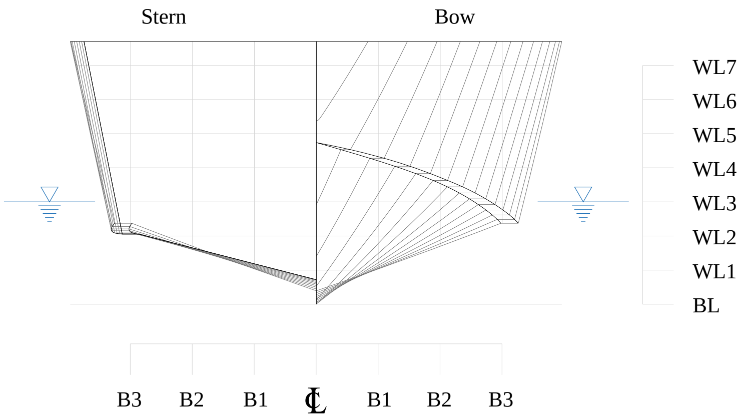

Figure 4 Body Plan

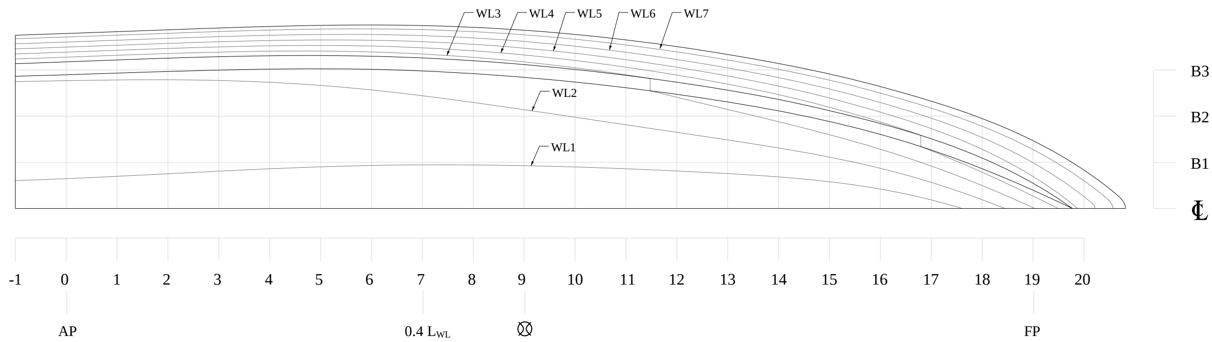

Figure 5 Half Breadth Plan

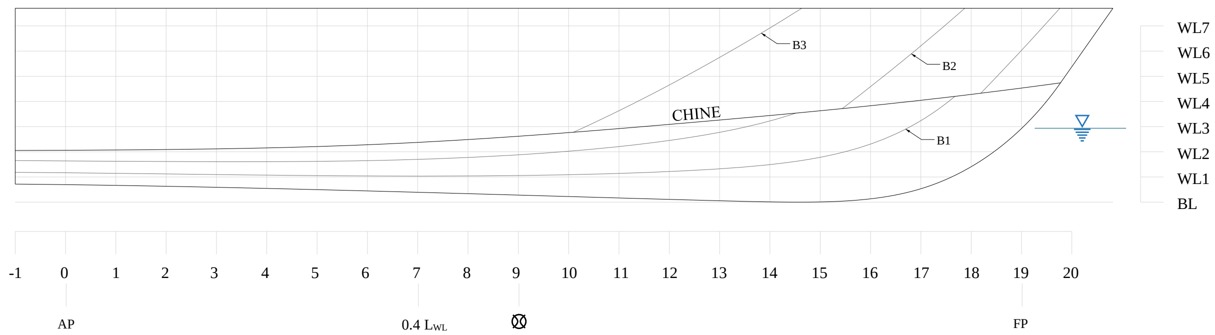

Figure 6 Profile Plan

Table 3 Main particulars of the boat

Particular		Value
Length overall	L_{OA}	24 m
Length on waterline	L_{WL}	22.06 m
Length between perpendiculars	L_{PP}	20.9 m
Beam overall	B_{OA}	7.94 m
Beam on waterline	B_{WL}	6.83 m
Beam on chine at LCG	B_c	6.52 m
Longitudinal centre of buoyancy	L_{CB}	8.69 m (0.39· L_{WL})
Draft	T	1.65 m
Depth	D	4.24 m
Submerged volume	∇	93 m^3
Displacement	Δ	95.4 t
Wetted are	S_W	143.6 m^2
Block coefficient	C_B	0.37
Deadrise angle at transom	$\beta_{transom}$	14.4 deg
Deadrise angle at 0.4 · L_{WL}	$\beta_{0.4}$	20.1 deg
Deadrise angle at 0.5 · L_{WL}	$\beta_{0.5}$	24.3 deg
Deadrise angle at 0.7· L_{WL}	$\beta_{0.7}$	37.4 deg
Top Speed	V_{max}	25 kts

Deadrise angles are calculated according to the definitions by the classification societies, as represented with β in Figure 7, while ISO 12215-5 defines deadrise angle as shown as β_{ISO} in the same figure. Support girth (G_S), as defined in LR SSC, is the girth distance measured around the circumference of the shell plate between chines for vessels having a chine.

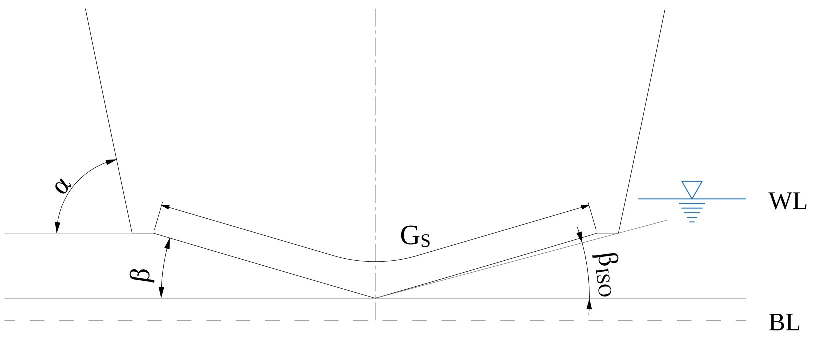

Figure 7 Definition of deadrise angle (β; β_{ISO}), flare angle (α) and support girth (G_S)

Table 4 Deadrise angles, flare angles and support girths at different sections

x/L	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
β [°]	14.4	14.8	15.6	17.3	20.1	24.3	30.1	37.4	46.6	56.8	65.9
β_{ISO} [°]	13.2	13.5	14.3	15.9	18.5	22.4	27.7	34.5	43.2	52.0	58.2
α [°]	78.8	78.8	78.6	77.8	76.5	75.1	73.7	72.4	70.5	68.0	62.2
G_S [m]	5.91	6.06	6.22	6.34	6.34	6.23	6.05	5.81	5.49	4.62	1.94

3.2. Limitations

Each rule or guide has its applicability range, subject to certain limitations. One of the main limiting factors is length, which is defined differently for different sets of rules. As this boat is intended to navigate in a planing regime, the high-speed craft definition is checked.

3.2.1. DNV

DNV rules have been known before as Det Norske Veritas Germanischer Lloyds (DNV GL) rules and Det Norske Veritas (DNV) rules, but as of 1 January 2022, all rules are rebranded and unified under DNV. The DNV rules for the classification of yachts (hereinafter “DNV Yachts”) [22] apply to yachts powered by sail or motor with a minimum length of 24 meters. Motor yacht scantling shall comply with Part 3 or these rules, except for high-speed motor yachts, which shall comply with the DNV rules for classification of High speed and light craft (hereinafter “DNV HSLC”) [23]. Yachts with speed higher than $V \geq 7.16\, \Delta^{1/6} (knots)$ are considered according to DNV HSLC rules.

The main class notation is **1A Yacht**, which can have three ship type notations: Motor, Sail or Passenger. The interest of this study is the Motor notation, which is defined as yachts propelled mainly by engine(s) with a maximum of 12 passengers and a length of over 24 m. Additionally, there are four service area notations assigned, which affect the design pressures, among others.

Table 5 DNV Yachts service area restrictions

Service area notations	**Seasonal zones (nautical miles)**		
	Winter	**Summer**	**Tropical**
R0	250	No restrictions	No restrictions
R1	100	200	300
R3	20	50	100
RE	Enclosed water		

3.2.2. Bureau Veritas

Bureau Veritas Rules for the Classification and the Certification of Yachts (hereinafter "BV Yachts") [24] are applicable to sailing and motor yachts made of steel, aluminium, composite materials, or wood. Yachts smaller than 24 m can be classified with BV Yachts rules, while the upper limit is 90 m, after which BV Rules for the Classification of Steel Ships [25] shall be used.

The main service notations are **yacht** and **charter yacht**. For the scope of this study, only yacht service notation is considered, with the additional service feature **motor**, which is defined for ships propelled by a propulsion engine, and **C** for hull made of composite material. High speed yachts are considered for which $V \geq 7{,}16\ \Delta^{1/6}$.

Table 6 BV Yachts navigation notations

Navigation notation	Restriction
unrestricted navigation	any area, any period of year
navigation limited to 60 nautical miles	60 NM, 300 UMS (only for charter yachts)
coastal area	20 NM, max 6 h from a port of refuge or safe sheltered anchorage
sheltered	sheltered waters, wind < 6 Beaufort scale

3.2.3. Lloyd's Register

Lloyd's Register Rules and Regulations for the Classification of Special Service Craft (hereinafter "LR SSC") [26] apply to a range of vessels: high-speed crafts, light displacement crafts, multihulls, yachts of overall length $L_{OA} \geq 24$ m, made of steel, aluminium, or composite materials, which do not exceed 150 meters.

A service type notation **Yacht** is assigned to all yachts. A high-speed craft is defined as having a minimum speed of at least $V = 7.19\ \nabla^{1/6}$ knots, while a craft operating in non-displacement mode typically applies to a craft with a Taylor Quotient, $\Gamma \geq 3$, which can be expressed as:

$$\Gamma = \frac{V}{\sqrt{L_{WL}}} \geq 3 \rightarrow V \geq 3\sqrt{L_{WL}} \tag{17}$$

Table 7 LR SSC service area notations

Service area notations	Restriction
Zone 1	Inland waters, wave up to 0.5 m
Zone 2	Inland waters, wave up to 1.0 m
Zone 3	Inland waters, wave up to 1.6 m
G1	Coastal waters, up to 5 nm
G2	20 nm
G2A	60 nm
G3	150 nm
G4	250 nm
G5	350 nm
G6	Unrestricted

3.2.4. International Organisation for Standardization

International Organisation for Standardization (ISO) published the newer standard for hull construction and scantling of small crafts 12215-5:2019 in 2019. This standard defines the dimensions, design local pressures, mechanical properties, and design stresses for the scantling determination of monohull small craft with hull length (L_H) or a load line length of up to 24 m. [2]

ISO 12215-5 definition of planing and displacement craft (or mode) is based on the waterline length of the boat at maximum loading condition and forces by which is supported. A planing craft is considered if the maximum speed is:

$$V \geq 5\sqrt{L_{WL}} \qquad (18)$$

If the boat is mainly supported by buoyancy forces it is considered in displacement mode, while if the boat is significantly supported by forces coming from dynamic lift due to speed in the water, then it is considered in planing mode.

ISO 12215 recognizes four design categories, which are based on the wind force and significant wave hight, as defined in Table 8. The selection of the design category affects the pressure by introducing a design category factor (k_{DC}), which is 1 for A category and it reduces by 20% for each ascending category.

Table 8 ISO Design categories

Design Category	Wind force [Beaufort scale]	Significant wave height [m]	k_{DC}
A	> 8	> 4	1.0
B	≤ 8	≤ 4	0.8
C	≤ 6	≤ 2	0.6
D	≤ 4	≤ 0.3	0.4

Except its applicability to recreational crafts, ISO 12215-5:2019 is also applicable to workboats.

3.2.5. American Bureau of Shipping

American Bureau of Shipping Guide for Building and Classing Yachts (hereinafter "ABS Yachts") [27] are dedicated explicitly to classing yachts with length $L \geq 24\ m$ and $L \leq 90\ m$. ABS Yachts assigns four yacht classifications: Yachting Service, Yachting Service R[es-tricted], Commercial Yachting Service, and Passenger Yachting Service.

For this study, only the **Yachting Service** classification is considered, which applies to yachts designed for pleasure. Semi-planing and planing motor yachts are considered those having a maximum speed greater than $2.36\sqrt{L}$ knots.

3.2.6. High-speed overview

Various definitions of high-speed crafts are given by different regulations. The rules considered in this study define the high-speed based on displacement (∇ in m^3) or waterline length (L_{WL} in m), as shown in Table 9.

Table 9 Minimum required speed for high-speed crafts and selected vessel

Organization	Formula [knots; otherwise noted]	Required speed [knots]
ABS	$2.36\sqrt{L_{WL}}$	11.08
BV	$7.16\ \nabla^{1/6}$	15.24
DNV	$7.16\ \nabla^{1/6}$	15.24
IMO	$3.7\ \nabla^{0.1667}\ [m/s]$	15.31
ISO	$5\sqrt{L_{WL}}$	23.48
LR	$7.19\ \nabla^{1/6}$	15.30

BV, DNV, and LR follow the definition of high-speed crafts given by IMO [28]. ISO and ABS base their required speed on waterline length, which for ISO gives a high minimum speed. This is explained by the fact that ISO is limited to 24-meter small boats.

3.3. Panel and materials

A specific panel has been selected to compare the loads, design accelerations and scantling determinations over several rules. The panel is in the slamming area of the bottom, as depicted in Figure 8, and its specifications are given in Table 10.

Table 10 Panel specifications

Panel length	2000 mm
Panel breadth	1000 mm
Longitudinal curvature	0 mm
Transverse curvature	0 mm
Distance from aft of centroid	15.4 m (0.7 · L_{WL})
Freeboard height	0.144 m
Local deadrise	37.4 deg
Construction material	Composite sandwich: E-Glass (fibres) Polyester (resin) PVC (core)

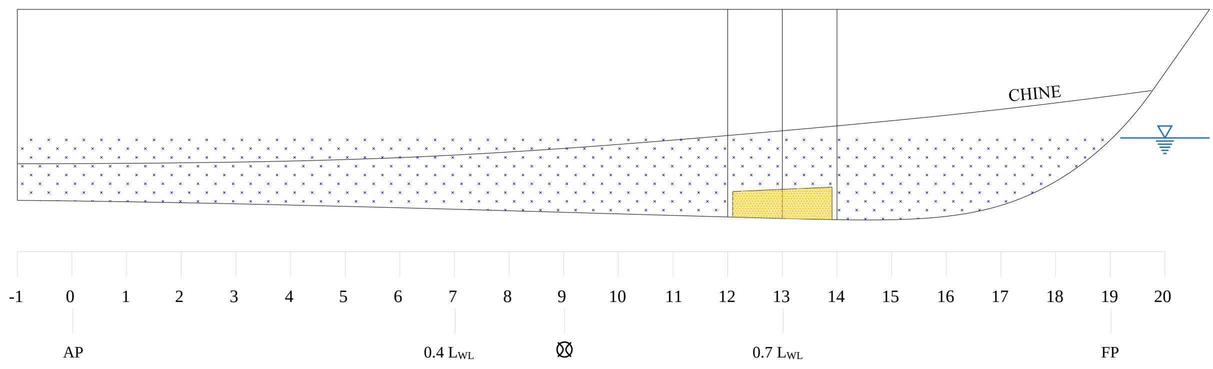

Figure 8 Location of the selected panel

The materials selected to evaluate the scantlings of this panel are picked among the most used composites in the boat industry. With the aim of selecting the cheapest materials among those, the following materials were selected:

- E-Glass for the fibres,
- Polyester for the resin,
- PVC for the core.

E-Glass is a relatively cheaper fibre than its peers, usually Kevlar, and carbon fibres, while having good overall performance. [29] Generally, E-glass is combined with polyester, vinyl ester or epoxy in the marine industry. The properties of the selected E-Glass fibres are given Table 11. Additionally, because of its wide usage, all considered rules have formulae for calculation of main mechanical properties and limits for E-Glass reinforced laminates, allowing even-handed comparison of the scantling determinations.

Table 11 Physical and mechanical properties of E-glass fibre [2]

Specific gravity	ρ	2.56 t/m^3
Elastic Modulus (// and ⊥)	E_f	73 000 N/mm^2
Shear Modulus	G_f	30 000 N/mm^2
Poisson's ratio	ν	0.22
Ultimate Elongation [29]		4.8 %

The selected resin is polyester, the most commonly used in boatbuilding today and the cheapest material among its two main peers, epoxy and vinyl ester [30]. The properties of the selected polyester are properties given in Table 12.

Table 12 Physical and mechanical properties of polyester matrix [2]

Specific gravity	ρ	1.2 t/m^3
Elastic Modulus (// and ⊥)	E_f	3300 N/mm^2
Shear Modulus	G_f	1222 N/mm^2
Poisson's ratio	ν	0.32

The combinations considered for E-Glass/polyester composites have been limited to Four types of fibre and resin combinations proposed by ISO 12215, excluding unidirectional plies. The four combinations are given in Table 13 and Figure 9.

Table 13 Fibre combinations

Type	Combination	ISO Abbreviation [2]
Chopped strand mat		CSM
Bidirectional	0°/90°	BD+
Double bias	±45°	DB×
Quadriaxial	0°/+45°/90°/-45°	Q×

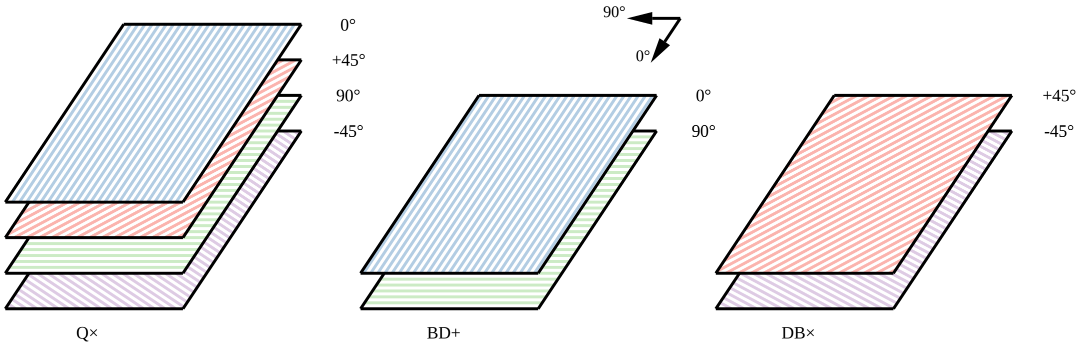

Figure 9 Used ply combinations

To have a thorough application of failure modes given by the rules, the selected panel shall be made of sandwich construction. The selected core for the sandwich construction is made of PVC, with the properties of the selected PVC130 given in Table 14. Additional cores used during scantling determination and laminate definition are given in Appendix A. The final sandwich construction is defined and analysed in chapter 5.

Table 14 Physical and mechanical properties of PVC130

Density	ρ	100 kg/m^3
Compressive strength	$\sigma_{c,co}$	2.05 MPa
Compressive modulus	$E_{c,co}$	95 MPa
Shear strength	τ_{co}	1.48 MPa
Shear modulus	G_{co}	36 MPa
Shear elongation at breaking		25%
Tensile strength	$\sigma_{t,co}$	3.18 MPa
Tensile modulus	$E_{t,co}$	162 MPa

4. DESIGN LOAD ASSESSMENT

In this chapter, the design loads are investigated. These loads are based on different parameters, from geometric to operational. The first step after defining the hull geometry and the vessel's operation limits is to determine the design loads, i.e., the design pressures. Then, the pressure on the bottom, and specifically on the selected panel, is determined using the rules and regulations mentioned in Chapter 3. Commonly, the pressure definitions depend on many factors, but the main types of pressure can be described by location or regime:

- Location: Bottom, Side, Deck, Superstructure
- Regime: Static vs Dynamic
    - Static: Sea pressure, internal tank pressure
    - Dynamic: Slamming, side impact

4.1. Considerations

The input data for the calculation of the design loads on the yacht are those presented in Table 3. The yacht was considered fully loaded. As explained in the Limitations, the formulae for the calculations of design loads are all applicable to the current yacht.

The yacht is considered to be a non-charted one, with her operating in the open ocean. As rules require different limiting operational factors (like service area/navigation restrictions and wave heights), the largest of the minimums are considered, where applicable. This results in applying a minimum significant wave height of $H_{1/3} = 4\ m$, while the selected service area/navigation notations are represented in Table 15.

Table 15 Comparison of selected service area/navigation notations

Rules	**ABS Yacht**	**BV Yachts**	**DNV Yachts**	**LR SSC**	**ISO 12215**
Notations	Yachting Service	Unrestricted navigation	R0	G4	A
Restrictions	$H_{1/3} \geq 4\ m$	any area, any period of year $H_s \geq 4\ m$	250 nm (winter) $H_s \geq 0.25\ m$	250 nm $H_s \geq 4\ m$	$H_{1/3} > 4\ m$

DNV Yachts requires the utilization of the DNV HSLC rules when the vessel is considered high speed, with the type of yacht being considered as crew boat during design loads calculations.

ISO 12215-5 recalls ISO 12217, [31] which is in line with European Recreational Craft Directive 2013/53/EU [1], in which the watercraft design category B is considered to be designed for a wind force up to, and including, wind force 8 (Beaufort scale) and significant wave height up to, and including, 4 m, while design category A is considered to be designed above these requirements.

4.2. Design vertical acceleration

The design vertical acceleration at LCG, a_{CG} (in terms of g), is to be defined by the designer and corresponds to the average of the 1 per cent highest accelerations in the most severe sea conditions expected, in addition to the gravity acceleration. [24]

ABS Yachts uses a formula which is based on significant wave height, running trim angle and deadrise angle at LCG, which is limited between 10 and 30 degrees. Compared to ABS HSC, ABS Yachts does not consider vertical accelerations at sections clear of LCG. Maximum design vertical acceleration, according to ABS Yachts is $n_{cg,max} = 7\ g$.

BV Yachts gives two formulae for calculating the design vertical acceleration, one based on type design and the sea conditions (row 2 of Table 16), and the other based on the relation between the instantaneous speed and associated wave heights (row 3 of Table 16). BV Yachts limit the upper value of $a_{cg}$to 1 g for cruise motor yachts, 1.5 g for sport motor yachts, 2.0 g for offshore racing motor yachts and 2.5 g for motor yachts with specific equipment, like safety belts or shock mitigation seats.

LR SSC requires a minimum design vertical acceleration $a_v \geq 1\ g$, while it does not set an upper limit. DNV HSCL sets the limit at $a_{cg,max} = 6\ g$, and requires a minimum design vertical acceleration of 1 g.

Table 16 Acceleration definition formulae

Rules	**Formula [g, if not specified]**	**Constraints**
ABS Yachts	$n_{cg} = N_2\left[\frac{12h_{1/3}}{B_w} + 1.0\right]\tau[50-\beta_{cg}]\frac{v^2(B_w)^2}{\Delta}$	$n_{cg} < 7\ g$
BV Yachts	$a_{cg} = foc \cdot soc \frac{V}{\sqrt{L_{wl}}} \leq a_{CG_{max}}$	Max values for Cruise MY: 1 g Sport MY: 1.5 g Racing MY: 2 g MY with specific equipment: 2.5 g
	$a_{cg} = \frac{(50-\alpha_{dCG})\left(\frac{\tau}{16}+0.75\right)}{3555 * C_B}\left(\frac{H_S}{T} + 0.084\frac{B_W}{T}\right)K_{FR}K_{HS}$	
DNV HSLC [m/s2]	When $\frac{V}{\sqrt{L}} \geq 10.86$ $a_{cgi} = \frac{8.38 g_0 k_\tau}{\left(\frac{L}{\Delta^{\frac{1}{3}}}\right)^{0.35}}\left(\frac{H_{si}}{B_{WL2}} + 0.084\right)(50 - \beta_{cg})Ln(F_{Nv})V_i\sqrt{L}\frac{B_{WL2}^2}{1000 * \Delta}$	$a_{cg} \geq 1\ g$ for R0-R4 $a_{cg} \geq 0.5\ g$ for R5-R6 $a_{cg,max} < 6\ g$
	When $\frac{V}{\sqrt{L}} \geq 3$ $a_{cgi} = \frac{k_h g_0}{1650}\left(\frac{H_{si}}{B_{WL2}} + 0.084\right)(50-\beta_{cg})\left(\frac{V_i}{\sqrt{L}}\right)^2\frac{LB_{WL2}^2}{\Delta}$	
	When $\frac{V}{\sqrt{L}} < 3$ $a_{cgi} = 6\frac{H_{si}}{L}\left(0.85 + 0.35\frac{V_i}{\sqrt{L}}\right)g_0$	
DNV Yachts	$a_0 = \frac{c_0\ c_b}{L^2}\left(0.6\ v_0 + 2.3\sqrt{L}\right)^2$ (Unitless acceleration parameter)	Non stated
ISO 12215-5	Lesser of $k_{DYN1} = 0.32\left(\frac{L_{WL}}{10B_C} + 0.084\right)(50-\beta_{0.4})\frac{V^2B_C^2}{m_{LDC}}$ $k_{DYN2} = \frac{0.5V}{m_{LDC}^{0.17}}$	$3 \leq k_{DYN2} < 6$
LR SSC	$a_v = 1.5\theta_B L_1(H_1 + 0.084)(5-0.1\theta_D)\Gamma^2 \times 10^{-3}$	$a_v > 1\ g$

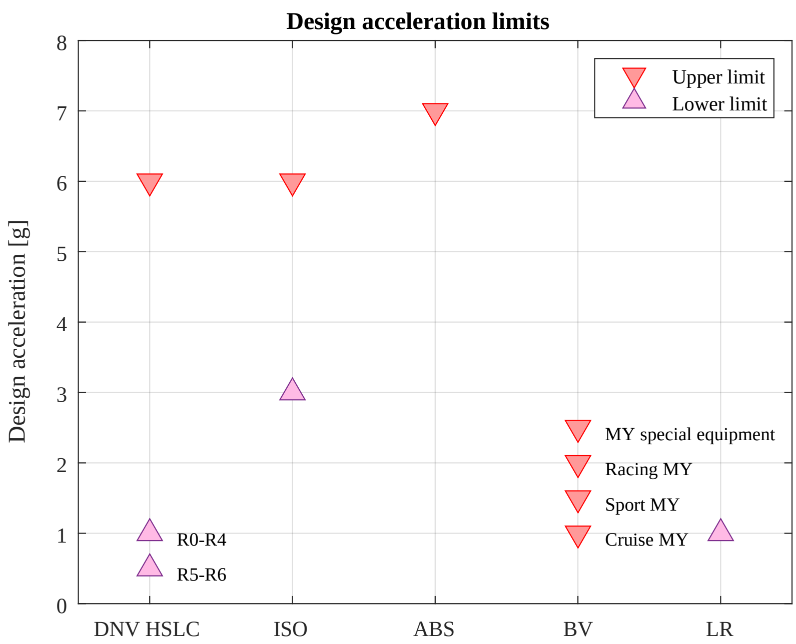

Figure 10 Limits of design vertical accelerations (n_{cg}), expressed in g's

4.2.1. Results and longitudinal distribution

A spreadsheet was created to calculate the vertical accelerations according to the procedures given by the rules. Each Classification Societies' rule starts with the calculation of the design vertical acceleration at LCG, which for this boat is at around 0.39 L_{WL}~0.4 L_{WL}. Factors affecting the value of vertical acceleration are deadrise angle, speed, significant wave height, running trim, waterline breadth and displacement. This study describes the effects of deadrise angle, speed, and running trim in the following subsections. In Table 17, the calculated design vertical acceleration (n_{cg}) is calculated, including the value at 0.4 L_{WL} and 0.7 L_{WL}. The difference between the value of n_{cg} and $n_{0.4L_{WL}}$is due to rules applying different distribution factors. Figure 11 shows the results of design vertical accelerations for each rule.

Table 17 Design vertical acceleration n_{cg} and distribution at 0.4 L_{WL} and 0.7 L_{WL}

Rules		**ABS**	**BV**	**DNV**	**LR**	**ISO**
n_{cg}	[g]	2.29	1.00	3.71	2.44	1.19
0.4 L_{WL}		1.81	1.20	3.71	2.44	
0.7 L_{WL}		2.29	1.55	5.19	3.62	

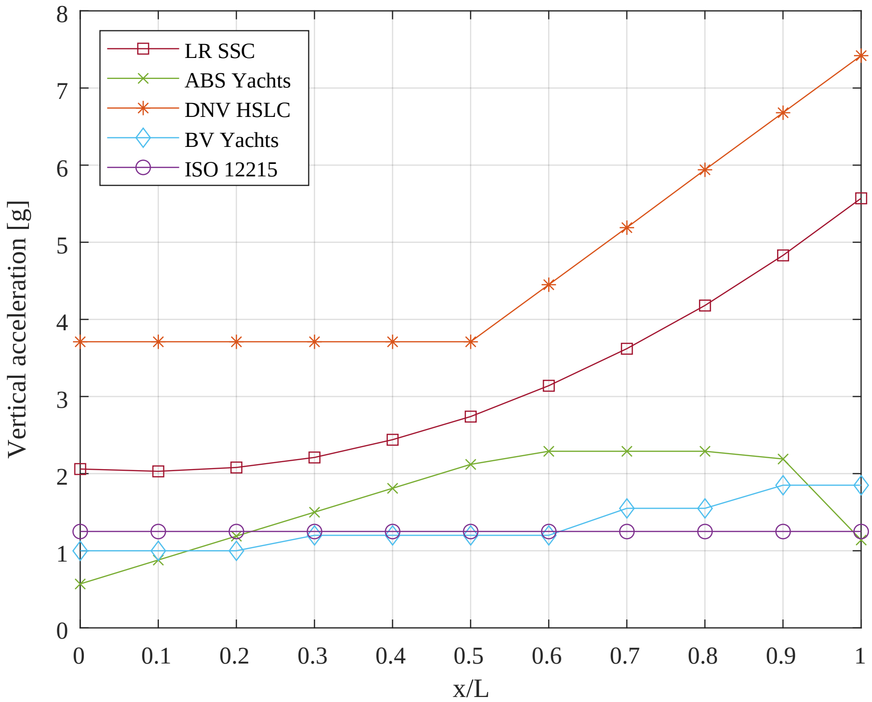

Figure 11 Longitudinal distribution of vertical accelerations [in g's]

Quantitatively, there are differences in the calculated accelerations at LCG and $0.4L_{WL}$, with a 45.2%, respectively 52.4%, of variation from the mean. BV and ABS rules, made only for yacht result in fairly lower accelerations than the more general rules of LR SSC and DNV HSLC, which are applicable for a large scope of fast boats and ships of different purposes. It shall be noted that DNV HSLC requires a minimum significant wave height of 0.25 meters to be considered, independent of the service area notation thus leaving in th designer hand to dedice the significant wave height. In this study, to make a fair comparison, the wave height was considered 4 meters, the minimum significant wave height considered by other rules.

Nevertheless, it is the designer's duty to specify the vessel's operation limits in terms of speeds and significant wave heights, which allows combinations to result in a preferred maximum acceleration. Similarly, LR SSC allows for assignment of an operational envelope, which shall be based on allowable speeds, significant wave heights and corresponding displacements. An example of an envelope for this yacht, by considering a maximum $n_{cg} = 2.5\ g$, and using DNV HSLC rules is given in Table 18.

Table 18 Operation envelope for the selected vessel, with a $n_{cg} = 2.5\ g's$ limit (using DNV HSLC)

Significant wave height $H_{1/3}$ [m]	**Highest allowable speed V [knots]**
1	35.0
2	27.4
3	23.2
4	20.5

ISO 12215-5 does not consider a longitudinal vertical acceleration distribution factor, and its pressure distribution factor is a function of k_{DYN}, which is explained in the Design pressure subsection.

4.2.2. Effect of deadrise angle

The deadrise is the angle between the bottom of the hull with respect to a horizontal plane as depicted in Figure 7. The deadrise angles of the boat are given in Table 4, while four characteristics stations, in which the change of the angles is visible, are depicted in Figure 12.

Kim et al. explain the general effect of deadrise angles as follows: "In general, when deadrise angles of a planing hull with vee-bottom get smaller, trim angle is decreased and the hull rises up higher so that it shows good resistance performance. But its vertical motion amplitude in rough water becomes larger, and the course-keeping ability gets worse. On the other hand, when deadrise angles are larger, the seakeeping performance and course-keeping ability of the planing hull improve, but its resistance performance worsens." [32] But in this study, only the effect of the deadrise angle located in LCG on the vertical acceleration results is considered. Even though there is a difference in the definition of deadrise angle between the classification societies' rules and ISO, the input angle was considered the same for the comparison of its effect, as shown in Figure 13.The computation was done at a speed of V = 25 knots, and a running trim of 4 ° (where applicable) and a significant wave height of 4 m (also where applicable).

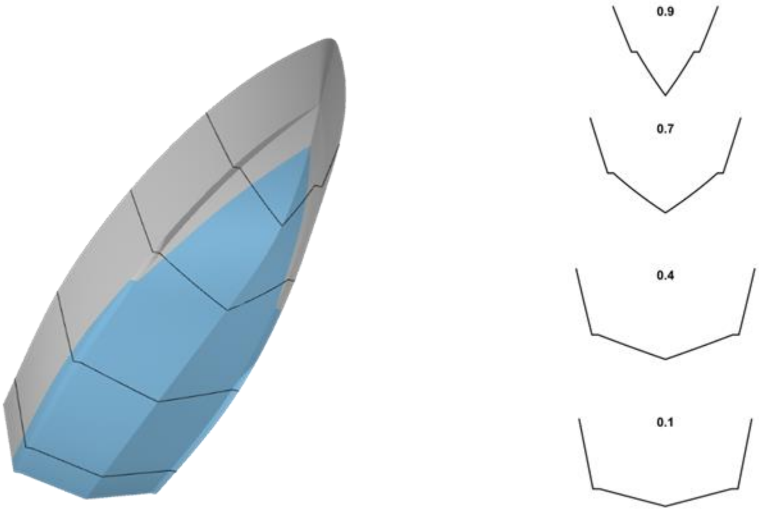

Figure 12 Characteristic cross sections expressed as % L_{WL}

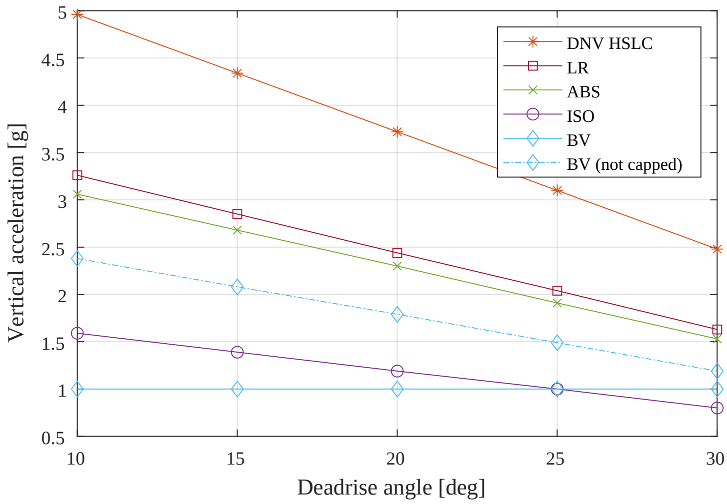

Figure 13 Comparison of vertical acceleration due to deadrise angle (at LCG) change

From the results, it is concluded that smaller deadrise angles will produce higher vertical accelerations. This is noticeable when a boat navigates through rough waters, in which the bottom is prone to slamming. As the deadrise angle of a V-shaped boat increases, she can break the water and move more smoothly, considerably reducing the slamming effect. [33] This reduction is enacted in the vertical acceleration formulae in the term $(50 - \beta)$, which comes from equation (1).

4.2.3. *Effect of speed*

The speed of the vessel is an essential factor on its overall performance and operation. With a higher speed, a higher design acceleration is expected. LR SSC and ABS Yachts propose similar values, but at 45 knots, the cap of 7 g proposed by ABS is reached. DNV HSLC starts conservatively and at 45 knots, the boats reach the proposed 6 g cap. BV Yachts caps the acceleration for cruse motor yachts at 1 g, considering that a cruise yacht, in reality, will be cruising in low speeds; thus, the limitation is wise. The information formula of BV Yachts (2nd formula of BV in Table 16) proposes a similar pattern to LR and ABS, with BV value being 73% of LR and 78% of ABS value in each speed if ABS cap is not considered. In a similar pattern, ISO gives a value of around 50% of LR.

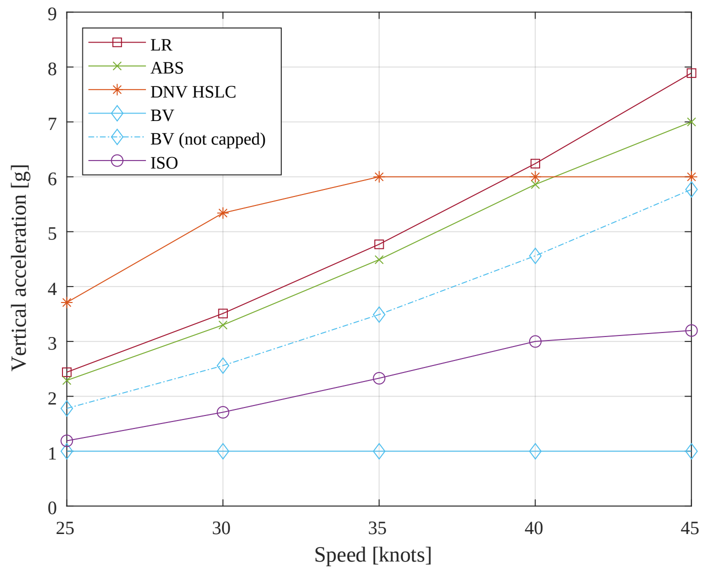

Figure 14 Comparison of vertical acceleration due to change in speed

4.2.4. *Effect of running trim angle*

Running (or dynamic) trim (τ) as expressed in degree is also part of the vertical design acceleration formulae. The effect of running trim is important on the magnitude of resistance component of high-speed crafts, and the running time itself is influenced by the deadrise angle. [34]

This study observed the effect of changing the running trim during a constant speed and deadrise angle at LCG. From the considered rules, only LR SSC, BV Yachts and ABS Yachts consider the running trim in the formula.

The minimum value for running trim is 3 degrees for LR SSC and 4 degrees for BV Yachts and ABS Yachts (for yachts with L>50 m, it shall be 3 degrees).

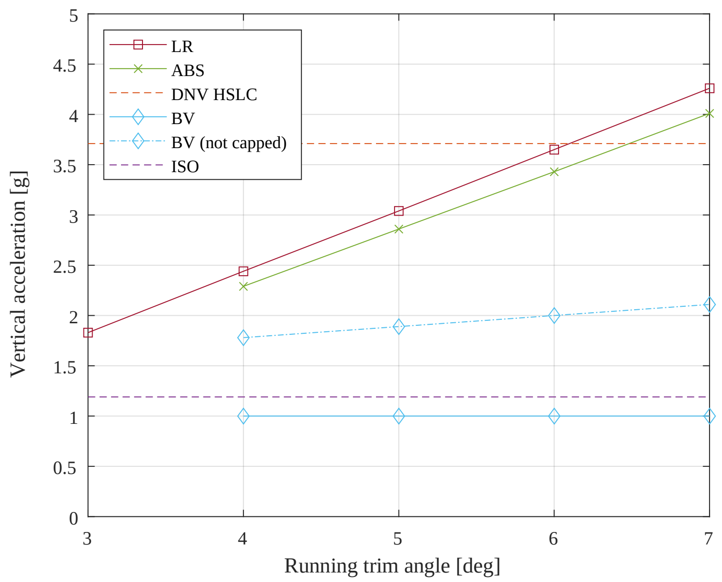

Figure 15 Running trim angle effect on vertical acceleration

In Figure 15, the comparison of the results due to different running trim angles is shown. The values from 3 to 7 degrees are taken as the limitations of equation (1). [12] The results presented by LR SSC, and ABS Yachts are similar and follow each other, while DNV HSLC comes close to them at running trim angles of 6 and 6.5 to LR, respectively, ABS. This means that the DNV HSLC rules have incorporated the upper limit of the effect of running trim angle in the formula. On the other hand, BV is capped at 1 g for a cruise motorboat, but the information about the relation between instantaneous speed and wave height gives an acceleration value of roughly half that given by LR and ABS.

4.3. Design Pressure

In this study, the local loads on the bottom of the vessel were considered. The rules propose that hydrostatic, hydrodynamic, and slamming loads to be calculated for planing hull motor yacht. The design pressures are calculated for the panel defined in Chapter 3, which is located at 0.7 L_{WL}, where the effect of the slamming is high. Additionally, the longitudinal distribution of design pressures along the ships is computed.

4.3.1. Design pressure formulae

A summary of the design pressure formulae for the bottom shell is presented in Table 19, with the type of pressure.

Table 19 Pressure definitions formula for bottom

Rules	Type	Formula (kN/m²)	#
ABS Yachts	Slamming	$p_b = \frac{N_1\, \Delta}{L_w B_w}\left[1 + n_{cg}\right] F_D F_v$	1
	Hydrostatic	$p_d = N_3(0.64H + d)$	2
ISO 12215	Displacement mode	$P_{BMD\ BASE} = 2.4\, m_{LDC}^{0.33} + 20$	3
		$P_{BMD} = \max(P_{BMD\ BASE} * k_{AR} * k_{DC} * k_L; P_{BM\ MIN})$ $P_{BM\ MIN\ PLT} = \max\left[\left(0.45 * m_{LDC}^{0.33} + 0.9L_{WL} * k_{DC}\right) * k_L; 10T_c; 7\right]$ $P_{BM\ MIN\ STF} = \max[0.85\ P_{BM\ MIN\ PLT}; 7]$	4
	Planing mode	$P_{BMP\ BASE} = \frac{0.1\, m_{LDC}}{L_{WL} * B_C} * \left(1 + k_{DC}^{0.5} * k_{DYN}\right)$	5
		$P_{BMP} = \max(P_{BMP\ BASE} * k_{AR} * k_L; P_{BM\ MIN})$ $P_{BM\ MIN\ PLT} = \max\left[\left(0.45 * m_{LDC}^{0.33} + 0.9L_{WL} * k_{DC}\right) * k_L; 10T_c; 7\right]$ $P_{BM\ MIN\ STF} = \max[0.85\ P_{BM\ MIN\ PLT}; 7]$	6
DNV Yachts	Sea pressure	$p_{S_{stat}} = 10\,(T - z)$ $p_{S_{dyn}} = p_0 * K_F * C_p * \left[1 + \left(\frac{z}{T}\right)^{0.75}\right]$	7
DNV HSLC	Slamming pressure on bottom	$p_{sl} = \frac{a_{CG} * \Delta}{0.14\, A_{ref}} K_{red} K_l K_\beta$	8

	Pitching slamming pressure on bottom	$p_{sl} = \frac{21}{\tan(\beta_x)} k_a k_b C_w \left(1 - \frac{20T_{FP}}{L}\right)\left(\frac{0.3}{A}\right)^{0.3}$	9
	Sea pressure	$p = a\left(10h_0 + \left(k_s - 1.5\frac{h_0}{T}\right)C_w\right)$ $p_{min} = 6.5$ (R0)	10
BV Yachts	Sea pressure	$P_s = \rho g\left[T + \left(\frac{nC_w}{X_i} + h_2\right) - z\right] \geq P_{dmin}$	11
	Slamming	$P_{sl} = P_{sl_1} K_2$ $(P_{sl_1} = 70 * \frac{\Delta}{S_r} * K_1 * K_3 * a_{CG})$	12
LR SSC	Hydrostatic	$P_h = 10(T_x - (z - z_k))$	13
	Hydrodynamic wave	Greater of $P_m = 10 f_z H_{rm}$ $P_p = 10 H_{pm}$	14
	Design load criteria	Greater of $H_f S_f P_s$ $H_f S_f C_f P_{d/}$ $H_f S_f G_f C_f P_f$	15
	Combined hydrostatic and hydrodynamic pressure	$P_s = P_h + P_w$	16
	Bottom impact pressure	$P_{d/b} = \frac{f_d \Delta\Phi(1 + a_v)}{L_{WL} G_O}$	17
	Local design loads	P_f = the greater of $P_{d/s}$ or $f_f L_{WL}(0.8 + 0.15\Gamma)^2$ at FP $= P_{d/s}$ at 0.75 L_{WL} $= P_m$ at 0.5 L_{WL}	18

DNV Yachts proposes only sea pressure to be calculated for motor (not high-speed) yachts and refers to DNV HSLC calculations for high-speed motor yachts. Thus, in calculating the design pressures, only DNV HSLC is considered of the two. DNV HSLC considers slamming pressure when $\frac{V}{\sqrt{L}} \geq 3$ knots, with the slamming pressure being a function of design vertical acceleration (a_{cg}), reference area (A_{ref}) from impact loads, as defined in eq. (19, reduction factor (K_{red}) as defined in eq. (20, longitudinal distribution factor (K_l), and correction factor for local deadrise angle (K_β), as defined in eq. (21.

$$A_{ref} = 0.7\frac{\Delta}{T} \tag{19}$$

$$K_{red} = 0.445 - 0.35\left(\frac{u^{0.75} - 1.7}{u^{0.75} + 1.7}\right); u = 100\ \frac{n\,A}{A_{ref}} \tag{20}$$

$$K_{beta} = \frac{50 - \beta_x}{50 - \beta_{cg}} \tag{21}$$

Pitching slamming pressure on the bottom shall also be considered per DNV HSLC for all crafts. This pressure is based on the design area, deadrise angle, draft vs length ratio, and two coefficients related to the type of structural member being investigated. Pitching slamming pressure shall be considered for a length $\left(0.1 + 0.15\ \frac{V}{\sqrt{L}}\right)L$ from FP, with $\frac{V}{\sqrt{L}} < 3$, as shown in Figure 16. Bottom slamming pressures, according to DNV HSLC, shall be applied up to the chine or upper turn of the bilge.

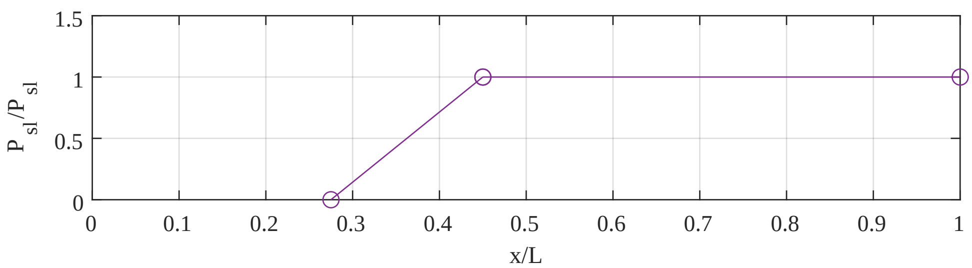

Figure 16 Pitching slamming pressure distribution for $V/\sqrt{L} > 3$

BV Yachts recognized two types of local external loads to be considered for bottom plating:

- Sea pressure: still water loads and wave loads,
- Dynamic sea pressures: bottom slamming pressure.

Bottom pressures, according to BV Yachts, shall be applied in the bottom area, which is defined as the submerged part of the hull. Similar to DNV, the slamming pressure is a function of the area factor (K_2), as defined in eq. 58, distribution factor (K_1) and bottom shape factor (K_3), as defined in eq. (24.

$$\mathrm{K}_2 = 0.455 - 0.35\frac{u^{0.75} - 1.7}{u^{0.75} + 1.7} \geq K_{2min} \tag{22}$$

Where:

$$\mathrm{u} = 100\frac{S_a}{S_r} \text{ and } S_r = 0.7\frac{\Delta}{T} \tag{23}$$

The limiting factor K_{2min} is dependent on the material of the structure and the element being considered (plating, secondary stiffener, and primary stiffener).

$$\mathrm{K}_3 = \frac{50 - \alpha_d}{50 - \alpha_{dCG}} \leq 1 \tag{24}$$

BV employs a limit of $\alpha_d \leq 50°$, which for stations with angles larger than that will reduce the effect of design slamming pressure to zero.

ISO 12215-5 gives a base formula for determination of the pressure at the bottom when a motor craft is in displacement or planning mode, where the greater of the two shall be considered. For both modes, three minimum design pressures are present. Base pressure at the bottom in displacement mode ($P_{BMD\ BASE}$) for a motor craft is dependent on the mass of the boat only, with the area pressure reduction factor k_{AR}, as defined in eq. 58, design category factor k_{DC} (c.f. Table 8), and longitudinal pressure distribution factor k_L coming in the max function for the bottom pressure P_{BMD}.

$$\mathrm{k}_{AR} = \frac{0.1\ k_R m_{LDC}^{0.15}}{A_D^{0.3}} \tag{25}$$

Where, k_R is a factor which depends on the location of the considered panel, craft type and regime.

When the motor craft is in planing mode, the base pressure is calculated using a formula, which resembles slightly Allen and Jones formula, eq. (4. In the max function for determination of the final bottom pressure in planing mode (P_{BMP}), the same three minimum design pressure, as in the displacement mode are given. Furthermore, the paling base pressure is multiplied with the k_{AR} and k_L factor. The final formula is depicted in eq. 58, as P'_{BMP}.

$$P'_{BMP} = \frac{0.1\, m_{LDC}}{L_{WL} * B_C} * (1 + k_{DC}^{0.5} * k_{DYN}) * k_{AR} * k_L \tag{26}$$

From the above formula, it can be deduced that the design category factor effects the magnitude of the dynamic load factor.

ABS Yachts considers two factors in the formula: design area factor (F_D) and vertical acceleration distribution factor (F_v). F_D is based on a graph (c.f. ABS Yachts 3-2-2, Figure 2), which is dependent on the ratio A_d/A_r, with A_r calculated as in eq. (27.

$$A_r = 6.95 \frac{\Delta}{d} \tag{27}$$

LR SCC proposes extensive local design criteria for crafts operating in displacement and non-displacement modes. The rules introduce four design factors:

- H_f = hull notation factor, depending on if the craft is notated as HSC or LDC,
- G_f = service area notation factor, depending on the selected service area restriction,
- S_f = service type notation factor, depending on the selected service type, which for yachts is given as 1.1,
- C_f = craft type notation factor, depending on the selected craft type restriction, which for monohulls is 1.0.

For the bottom shell of a basic craft in non-displacement mode, the greater of the following shall be selected according to LR SSC:

- $H_f S_f P_s$, with P_s being the shell envelope pressure,
- $H_f S_f C_f P_{d/}$, with $P_{d/}$ being the impact pressure,
- $H_f S_f G_f C_f P_f$, with P_f being the forebody impact pressure.

Pressure P_s is a combined hydrostatic and hydrodynamic pressure on the shell plating, which is related by its hydrodynamic component with the relative vertical motion. The impact pressure $P_{d/}$ is given for the bottom and side. The bottom impact pressure due to slamming $P_{d/b}$, as given in Table 19, row 17 resembles Allen and Jones formula, eq. (4., but with the introduction of two new terms:

- Hull form pressure factor f_d, which is 54 for mono-hull crafts and $81/N_H$ for multi-hull crafts, where N_H is the number of hulls, limited to four.
- Support girth G_o, which is defined as in Figure 7.

The magnitude of the support girth plays an important role, with a smaller girth leading to a larger impact pressure. For

4.3.2. Longitudinal distribution factor

Each rule proposes a distribution factor to define the slamming pressure at a specific section. Figure 17 shows the comparison between the different slamming pressure distributions. As expected, the fore of a vessel is subject to higher slamming pressures, with the location of the selected panel at $0.7\ L_{WL}$ being under the full slamming load per all rules.

ISO 12215-5 longitudinal pressure distribution factor k_L, which are valid for both planing and displacement pressures, and is dependent on the dynamic load factor k_{DYN}. k_{DYN} shall be 3 for displacement pressure distribution, while for planing motor crafts, the calculated k_{DYN} shall be used with limits $3 \leq k_{DYN} < 6$ thus the distribution in the figure represents the limits of the distribution factor.

Table 20 Design pressure distribution factor notations

LR	ABS	DNV	BV	ISO
Φ	F_D	K_l	K_i	k_L

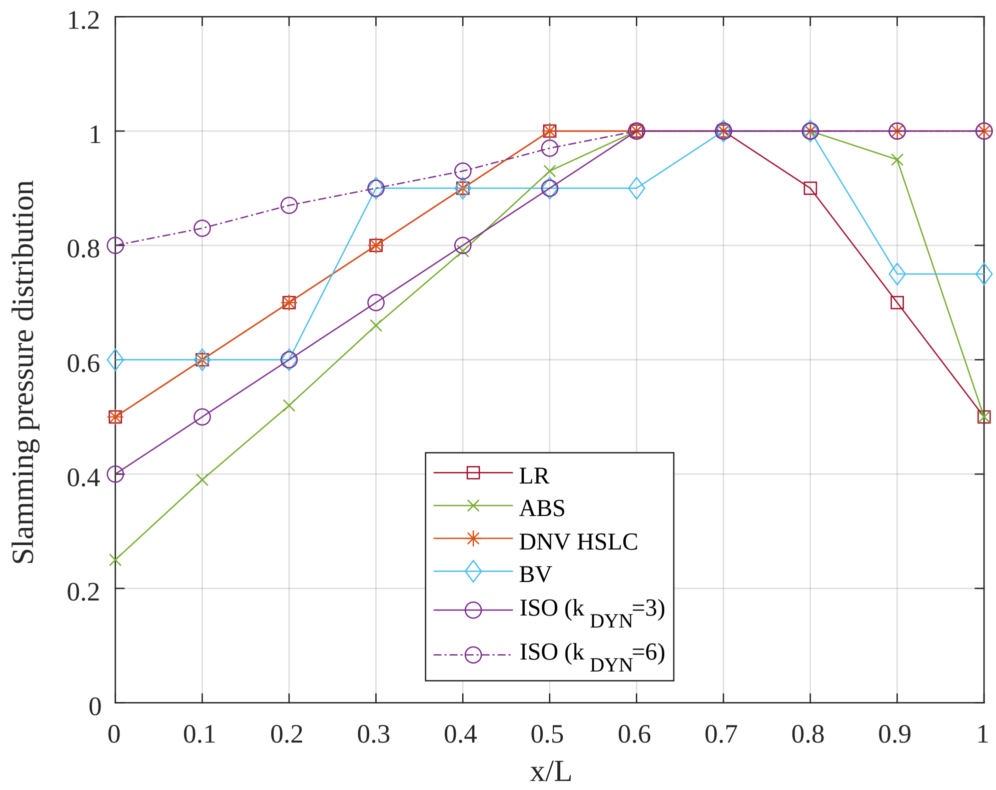

Figure 17 Slamming pressure distribution

4.3.3. *Effect of the design area*

Except for LR SSC, all other considered rules include an area factor, being the design area alone or the ratio of design area over the reference area, which is generally calculated as in equations (19 and (27. As expected, the design pressure will be higher for smaller panels, as shown in Figure 18. LR does not consider design ratio at the design load stage but later at scantling.

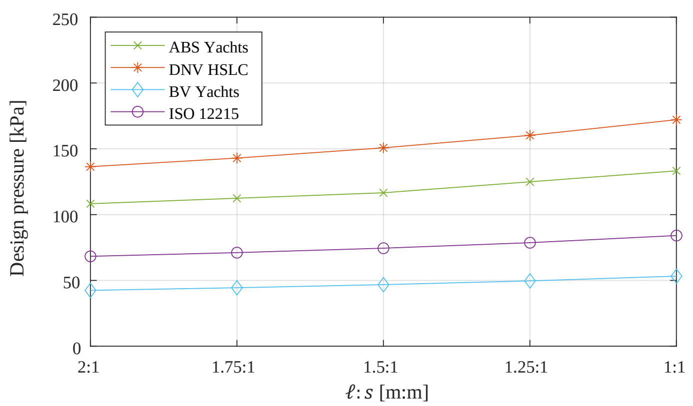

Figure 18 Design pressure with different panel dimensions

4.3.4. Results and comparison

The final design pressures calculated for the selected panel, when the yacht is going at 25 knots, are given in Figure 19 and Figure 20, and the numerical values can be found in Appendix C.2. Similarly, with the design vertical acceleration results, a 38.45% variance from mean can found in the final results at the considered selected panel. By comparing Figure 20 and Figure 17, the effect of different factors included in the design slamming pressure formulae can be seen.

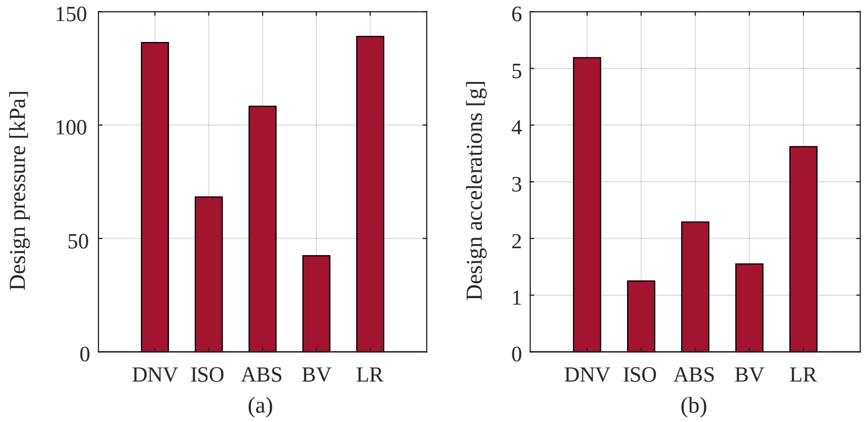

Figure 19 (a) Design pressure and (b) design vertical acceleration at 0.7 L_{WL}

ABS, ISO and LR results completely follow their distribution factors for this speed. On the other hand, BV shows higher pressure at LCG than at the front. This comes from the fact that for deadrise angles more than 50° BV considers the slamming pressure 0 because $K_3 = 0$ if $\alpha_d \geq 50°$. A slightly similar issue is noted on the distribution of DNV HSALC results from 0.6 L_{WL}, where the effect of the deadrise angles over 30° gives a factor of $K_\beta = 0.67$ for this case.

The broader rules of DNV and LR give in general higher design pressures than the two yacht dedicated rules of BV and ABS and small craft rules of ISO. At the considered panel, the design pressure trends follow the trends of the design vertical acceleration, except with the design pressure of DNV and BV, which are penalized by the deadrise angle factor.

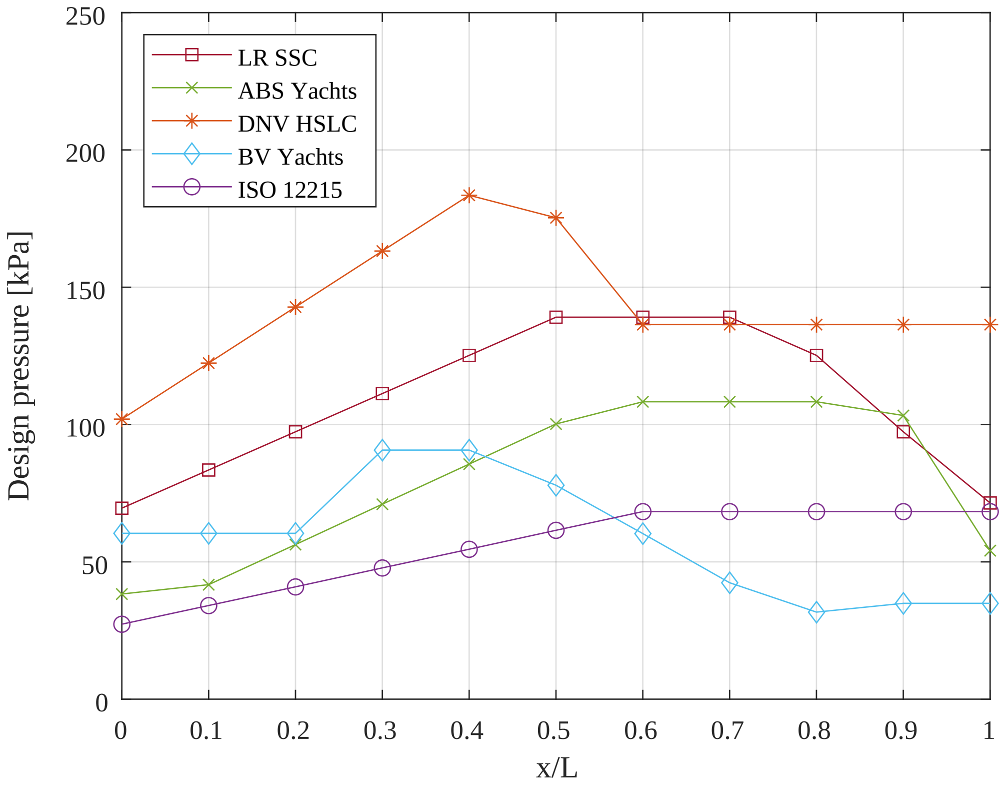

Figure 20 Design pressures

5. SCANTLINGS

This chapter defines the final panel configuration, and the scantling procedures and requirements of ISO 12215-5 and class rules are explained.

5.1. Panel laminate

A sandwich laminate is created to be the material of the selected panel to compare the rules. After iterative work, a panel made of the laminate shown in Table 21 is considered. The iterative process stopped when all scantling checks of the ISO 12215 Simplified method were passed.

Table 21 Selected laminate

Layer	Material		Mass of fibre [g/m^2]	Thickness [mm]
Inner	E-Glass	BD+	1200	1.031
9	E-Glass	Q×	900	0.773
8	E-Glass	Q×	800	0.688
7	E-Glass	DB×	800	0.688
6	Gurit PVC130			30.000
5	E-Glass	DB×	800	0.688
4	E-Glass	Q×	800	0.688
3	E-Glass	Q×	900	0.773
2	E-Glass	BD+	1200	1.031
Outer	E-Glass	CSM	300	0.562

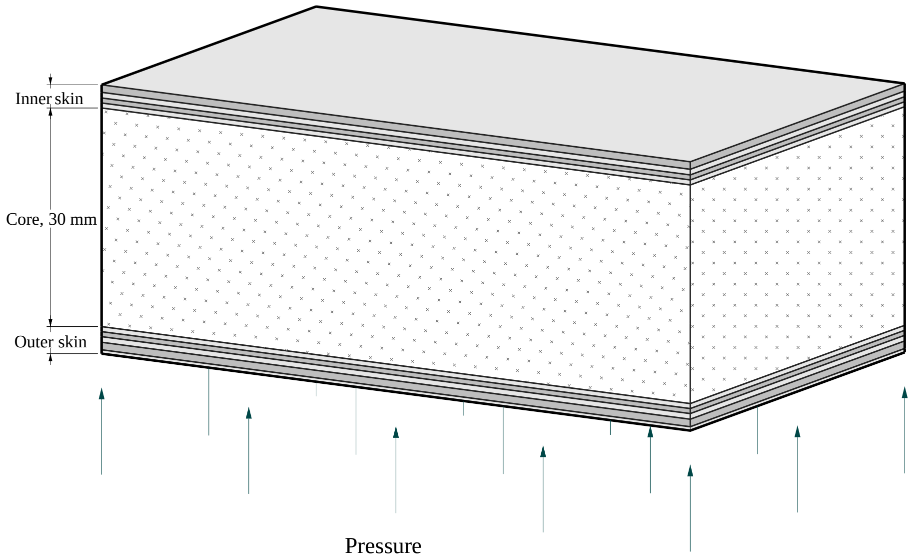

Figure 21 Selected sandwich laminate

5.2. Scantling rules

In this section, the rules regarding the scantling of sandwich panels are explained. Except for main rules for determining the loads, scantlings, and stresses of yacht structures, some classification societies propose additional but obligatory rules regarding the materials and scantlings. ABS has the Rules for Materials and Welding (hereinafter "ABS Materials") [35], which deals with applicable materials and its accompanying processes. BV has the Rule Note for Hull in Composite Materials (hereinafter "BV Composite") [20].

5.2.1. ABS formulation

ABS Guide for Building and Classing Yachts in its Part 3 about Hull Construction and Equipment deals separately with scantling of displacement, semi-planing and planing, and sailing yachts. There are given guides for aluminium and steel, fibre reinforced plastic, wood, cold-moulded laminate, and carvel. For this thesis, same as for the design pressures, the guides for semi-planing and planing yacht are used. The rules for hull materials are given in a separate set of rules, with Chapter 6 dealing with–Fibre Reinforced Plastics. [35]

Two sets of rules are given based on single skin or sandwich configuration. The limiting criteria for plating are:

- Required section modulus of inertia (for outer and inner skin separately)
- Required moment of inertia
- Minimum core thickness (based on shear strength)
- Minimum skin buckling stress
- Minimum skin thickness

Table 22 Minimum requirements for core (ABS Materials)

Material	Density [kg/m^3]	Minimum Shear Strength [MPa]
PVC, crosslinked	80	2.5
PVC, crosslinked	100	1.4

Table 23 Minimum FRP laminate properties (ABS Materials) in [N/mm^2]

Flexural Strength, F	172
Flexural Modulus, E_f	7580

Tensile Strength, T	124
Tensile Modulus, E_t	6890
Compressive Strength, C	117
Compressive Modulus, E_c	6890

Additional requirement is given for PVC foam cores, in which the minimum density at bottom forward of 0.4 L_{WL} shall be $120\ kg/m^3$ for $V \geq 25\ kts$ and $100\ kg/m^3$ for $V < 25\ kts$, requiring a minimum thickness of 30 mm for PVC core for selected panel, as calculated below:

$$4 \times d_c \geq 120 \frac{kg}{m^3} \rightarrow d_c \geq 30\ mm \tag{28}$$

ABS for sandwich laminate with essentially the same properties in 0° and 90° direction, calculated for a strip of sandwich panel 1 cm wide.

$$SM_{o,i} \geq \frac{(sc)^2 pk}{6 \times 10^5 \sigma_{a_{o,i}}}\ [cm^3] \tag{29}$$

$$I \geq \frac{(sc)^3 pk_1}{120 \times 10^5 k_2 E_{tc}} \tag{30}$$

Design stress σ_a for the bottom shell made of FRP is given as 0.33 σ_u, with σ_u being minimum tensile strength for the outer skin and minimum compressive strengths for the inner skin.

Skin buckling stress σ_c is given by eq. 58, and is generally not to be less than $2.0\sigma_{ao}$ and $2\sigma_{ai}$.

$$\sigma_c = 0.6\ \sqrt[3]{E_s\ E_{cc} G_{cc}} \tag{31}$$

Minimum skin thicknesses shall not be less than given by the following equations:

$$t_{os} = 0.35 k_3 (C_1 + 0.26L)\ [mm]$$
$$t_{is} = 0.25 k_3 (C_1 + 0.26L)\ [mm] \tag{32}$$

Where:

k_3 = location factor (1.2 for bottom, 1.0 for side and deck)

C_1 = 5.7 mm

For this yachts, the minimum skin thicknesses for bottom shell required by ABS rules are: $t_{os} = 4.91\ mm$ and $t_{is} = 3.51\ mm$.

5.2.2. BV formulation

BV Composite (NR546) gives some typical values of mechanical characteristics of resins and E-Glass fibres, among others, as shown in Table 24.

Table 24 Mechanical characteristics of resins (BV)

	Polyester	**Vinyl ester**	**Epoxy**
Density ρ_r	1.2	1.1	1.25
Poisson coefficient ν_r	0.38	0.26	0.39
Tensile Young modulus E_r (N/mm^2)	3550	3350	3100
Tensile or compression breaking stress (N/mm^2)	55	75	75
Tensile or compression breaking strain (%)	1.8	2.2	2.5
Shear modulus G_r (N/mm^2)	1350	1400	1500
Shear breaking strain (%)	3.8	3.7	5.0

Table 25 Mechanical properties of E-glass fibre (BV)

Mechanical property	**Unit**	**Value**
Density ρ_f		2.57
Poisson coefficient ν_f		0.238
Tensile Young modulus E_{f0}° and$E_{f90°}$	N/mm^2	73100
Tensile breaking strain (//)	%	3.8
Tensile breaking stress (//)	N/mm^2	2750
Tensile breaking strain (⊥)	%	2.4
Tensile breaking stress (⊥)	N/mm^2	1750
Compressive breaking strain (//)	%	2.4
Compressive breaking stress (//)	N/mm^2	1750
Shear Modulus G_f	N/mm^2	30000
Shear breaking strain	%	5.6
Shear breaking stress	N/mm^2	1700

The geometrical and physical properties of an individual layer are calculated by CLT, as shown in 2.4.1 and 2.4.2. BV Composite requires the computation of the stresses on a ply-by-ply basis, and those stresses are to be smaller than the theoretical braking stresses, which are to be calculated using the theoretical breaking strains given in Appendix E.2, in the following manner:

$$\sigma_{\mathrm{br}} = \varepsilon_{br} \times E_{ij} \times Coef_{res} \quad (33)$$

Where:

σ_{br} = theoretical breaking stress

ε_{br} = theoretical breaking strain (see Appendix E.2)

E_{ij} = Elastic coefficient

$Coef_{res}$= coefficient taking in the account the adhesive quality of the resin system (0.8 for polyester, 0.9 for vinyl ester, 1 for epoxy)

BV requires the calculation of these stresses due to bending moments, shear forces and in-plane forces in two locations in the middle of the boundary of the panel at each side, named A and B, as shown in Figure 22.

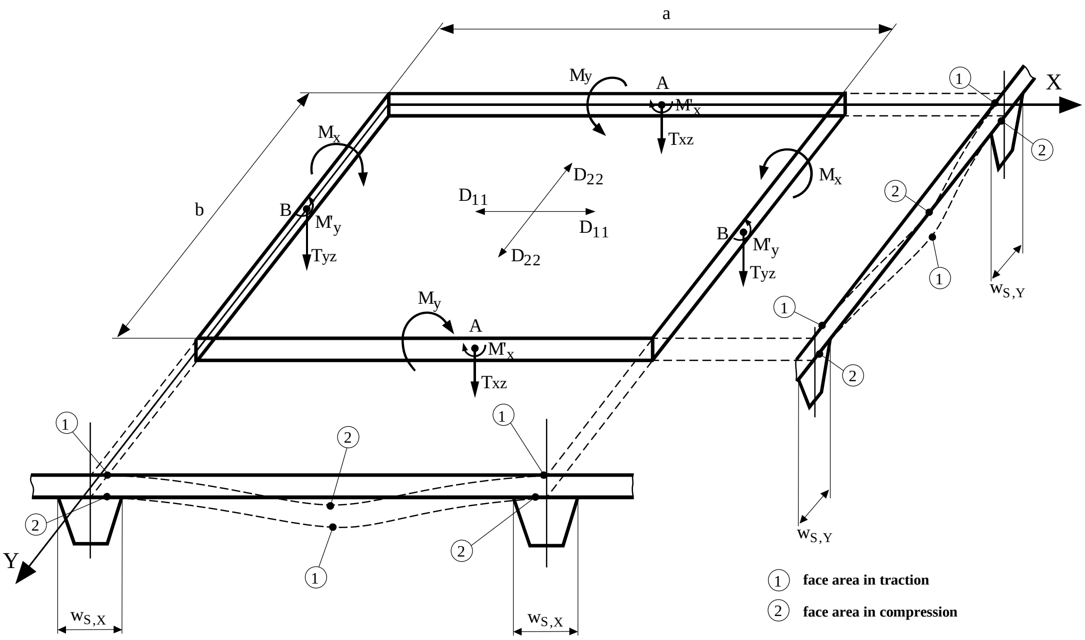

Figure 22 BV Moments [20]

At location A, the primary local bending moment M_y, secondary local bending moment M_x' and main local shear force T_{xz} are applied, while in location B, the local bending moment M_x, secondary local bending moment M_y' and main local shear force T_{yz} are applied. The bending moments and the shear force are calculated in Table 26. The rules give two options for calculating the moments and shear depending on the panel length and the panel's orientation.

Table 26 Bending moment and shear force calculation by BV

Bending moment and α_0	$a_0. \geq b_0$	$a_0. \leq b_0$
M_x	$F_1\ p_S\ b_0^2\ k_{S,X}$	$F_1\ p_S\ a_0^2\ k_{S,X}$
M_y	$F_2\ p_S\ b_0^2\ k_{S,Y}$	$F_2\ p_S\ a_0^2\ k_{S,Y}$
M'_x	$\nu_y\ E_x\ M_y/E_y$	
M'_y	$\nu_x\ E_y\ M_x/E_x$	
α_o	$(a_0/b_0) \leq 2$	$(b_0/a_0) \leq 2$

Where:

F_1, F_2 = Coefficients equal to:

$$F_1 = 0{,}0343\,\alpha_o^2 - 0{,}1333\,\alpha_o + 0{,}0471$$

$$F_2 = 0{,}0113\,\alpha_o^2 - 0{,}0382\,\alpha_o - 0{,}0251$$

a_0, b_0 = Panel dimensions

$k_{s,x}, k_{s,y}$ = Reduction factor for wide base of stiffeners

E_x, E_y, ν_x, ν_y = Moduli and Poisson's ratio as

p_S = Local pressure

Shear force andα_0	$(a_0 - w_{s,x}) \geq (b_0 - w_{s,y})$	$(a_0 - w_{s,x}) \leq (b_0 - w_{s,y})$
T_{yz}	$F'_1(b_0 - w_{s,y})P_S$	$F'_2(b_0 - w_{s,x})P_S$
T_{yz}	$F'_2(b_0 - w_{s,y})P_S$	$F'_1(b_0 - w_{s,x})P_S$
α_o	$\frac{a_0 - w_{s,x}}{b_0 - w_{s,y}} \leq 2$	$\frac{b_0 - w_{s,y}}{a_0 - w_{s,x}} \leq 2$

Where:

F'_1 =0.5 $\alpha_0/(1+\alpha_0^4)$

F'_2 =0.5 $\alpha_0^4/(1+\alpha_0^4)$

a_0, b_0 = Panel dimensions

$k_{s,x}, k_{s,y}$ = Equivalent dimensions of the panel

p_S = Local pressure

The maximum stresses of each individual ply due to the bending moments and shear forces are to be smaller than the value of the breaking stress over the safety factor SF, as shown below:

$$\sigma \leq \frac{\sigma_{br}}{SF} \text{ and } \tau = \frac{\tau_{br}}{SF} \quad (34)$$

The panel analysis considers six stresses (or criteria), including the combined stress according to Hoffman criteria. Failure of one fibre is considered failure of one ply on the "first ply failure" basis.

Table 27 BV six stresses

σ_1	Local stress in axis 1	τ_{12}	Local stress in plane 12	τ_{IL1}	Interlaminar local stress in axis 1
σ_2	Local stress in axis 2	σ_{comb}	Combined Hoffman stress	τ_{IL2}	Interlaminar local stress in axis 2

The minimum safety factor in each layer is a function of partial safety factors:

$$\mathrm{SF} \geq \mathrm{C_V} C_F C_R C_i \tag{35}$$

Where:

C_V = partial safety factor depending on the laminate ageing effect

C_F = partial safety factor depending on the fabrication process

C_R = partial safety factor depending on the type of fibre and the direction of stress

C_i = partial safety factor depending on the load type

There is no minimum requirement of thickness or fibre weight by BV. Additionally, there is no specific formula for minimum core thickness, but the core is analysed using the six stresses, in which the interlaminar local shear stress due to in-plane force is the main factor in checking if the core complies with the load.

5.2.3. DNV formulation

DNV Yachts and DNV HSLC have the same rules concerning the scantlings of hulls made of fibre composites and sandwich constructions (c.f. DNV Yachts Part 3 Chapter 5 and DNV HSLC Part 3 Chapter 4).

Table 28 Generic material properties (DNV)

	SG	**Young's Modulus**		**Shear Modulus**	**Poisson's ratio**
		//	⊥		
	[g/m^3]	[MPa]		[MPa]	[-]
E-Glass fibres	2.54	73000		30000	0.18
Polyester matrix	1.20	3000		1140	0.316

Scantling using DNV Yacht is based on the failure ratio concepts:

- Maximum strain criteria
- Maximum stress criteria

Maximum strain to failure in fibre direction is defined as:

. $$\varepsilon_{uf} = \frac{\sigma_u}{E_r} \quad (36)$$

Where:

σ_u = ultimate tensile or compressive strength

E_r = representative E modulus for laminate in range of allowable stresses (defined at secant modulus at $0.3\sigma_u$)

For this study, the representative modulus were selected as E_{11}, E_{22} and G_{12} to calculate the ultimate stresses by considering a 1.2% breaking strain.

The reaction bending moment is calculated using the following equation:

$$M_{b-max} = \frac{\beta p_d s_{eff}^2}{6} r_c \quad (37)$$

Where:

β = factor depending on ar_{eff} and panel connection (simply supported, partially clamped, or clamped)

p_d = lateral design pressure

s_{eff} = effective span (depends on aspect ratio $ar_g = S_x/S_y$)

r_c = curvature correction coefficient

$$F_{q-max} = \gamma p_d s_{eff} \quad (38)$$

Where:

γ = factor depending on ar_{eff} and panel connection (simply supported, partially clamped, or clamped)

The mass of reinforcement in skin laminates in sandwich construction shall not be less than:

. $$W \geq w_o(1 + k(L - 20)) \text{ for } L > 20\ m$$
$$W = W_o \text{ for } L \leq 20\ m \quad (39)$$

Where, W_0 is the minimum requirement for the mass of reinforcement, which is:

- $2400\ g/m^2$ for hull bottom outer skin made of Glass reinforcement, with k given as 0.025.

- $1600\ g/m^2$ for hull bottom inner skin made of Glass reinforcement, with k given as 0.013.

For the selected panel, the minimum mass of reinforcement shall be $2523.6\ g/m^2$ and $1642.8\ g/m^2$ for outer and inner skins, respectively. Maximum deflection is a function of design pressure and effective panel span over the plate bending stiffness, as given below.

$$z_{max} = \frac{\alpha p_d s^4{}_{eff}}{12\ D_{eff}} \tag{40}$$

Allowable deflection for a sandwich panel is given as $\frac{z_{max}}{s_{eff}} = 1.5\%$, and for this panel is 1.02%, which complies with the rule. The maximum allowable stress or strains shall not exceed the following formulation:

$$\sigma, \tau, \varepsilon, \gamma = \frac{F_r}{R\ c_c\ c_{rm}} \tag{41}$$

Where:

F_r = reference mechanical strength/resistance

R = reserve factor (3 for laminates and stability issues, 2.5 for cores)

c_c = structural coefficient (0.8 for watertight bulkheads, 1.0 otherwise)

c_{rm} = manufacturing coefficient (0.95 for vacuum assisted, 1.0 otherwise)

5.2.4. ISO formulation

ISO 12215-5 allows six methods to be used to determine the scantling of composite hulls: [10]

- Simplified method: based on a simple thickness equation for a single skin of quasi-isotropic Glass Reinforced Plastics (GRP).
- Enhanced method: ply-by-ply analysis for quasi-isotropic GRP.
- Developed method: application of Classical Laminate Theory (CLT) to all FRP structures.
- Direct test: relying on mechanical testing, primarily intended for FRP.
- FEM: finite element methods using the ISO design pressures and properties, also mostly aimed at FRP.
- Drop test: applicable to vessels less than 6 m hull length.

The selection of the assessment method will affect the definition of the design direct and shear stresses, by an assessment method factor k_{AM}, given in Table 29.

Table 29 Assessment method factor

Determination of k_{AM}		
Assessment method	Value of k_{AM}	
	FRP & wood	Metal
Simplified	0,9	1
Enhanced	0,95	1
Developed and FEM	1	1
Direct test	1	1

ISO 12215 gives the design bending moment, in the b direction, as in eq. (42), and in the l direction, as in eq. (43). In the Enhanced method, the corrected design bending moments shall be used, as shown in eq. (44).

$$M_{dl} = -1/6 \times k_{2b} \times P \times b \times 10^{-3} \tag{42}$$

$$M_{dl} = -1/6 \times k_{2l} \times P \times b^2 \times (EI_l/EI_b) \times 10^{-3} \tag{43}$$

$$M_{db_{corr}} = M_{db} \times k_c; M_{dl_{corr}} = M_{dl} \times k_c \tag{44}$$

Where:

k_c = curvature correction factor

$k_{2_{b,l}}$ = bending moment factors related to aspect ratio, given in Appendix D.3

P = design pressure

b = short unsupported dimension of the panel

ISO gives two design shear forces, in the b direction, given in eq. (45) and in the l direction, given in eq. (46).

$$F_{db} = k_c \times k_{SHb} \times P \times b \times 10^{-3} \tag{45}$$

$$F_{dl} = k_c \times k_{SHl} \times P \times b \times (EI_l/EI_b) \times 10^{-3} \tag{46}$$

Where:

k_c = curvature correction factor

$k_{SH_{b,l}}$ = shear force factors related to aspect ratio, given in Appendix D.3

Section modulus, simplified ISO:

$$SM_{o,i} \geq \frac{P \times b^2 \times k_{2b} \times k_c \times 10^{-5}}{6\sigma_{d_{0,i}}} = \frac{M_{db}}{\sigma_{d_{o,i}}} \left[\frac{cm^3}{cm}\right] \quad (47)$$

Where:

$\sigma_{d_{o,i}}$ = design direct stress (c.f. ISO 12215-5 Table 17)

For sandwich skins, the design direct stresses are defined as:

$$\sigma_d = 0.5\sigma_{ut}\ k_{BB}\ k_{AM} \text{ (outer)}$$
$$\sigma_d = \min\left[0.5\sigma_{uc}; 0.3(E_c\ E_{CO}\ G_{CO})^{0.33}\right] k_{BB}\ k_{AM} \text{ (inner)} \quad (48)$$

Where:

$\sigma_{u_{t,c}}$ = ultimate tensile and compressive stress, respectively

k_{BB} = built quality factor (c.f. ISO 12215-5 Table 15)

E_c = compressive modulus of the inner skin

E_{CO} = compressive modulus of core perpendicular to skins

G_{CO} = shear modulus of core parallel to load direction

The additional requirement of $0.3(E_c\ E_{CO}\ G_{CO})^{0.33}$ is added to prevent wrinkling stress from occurring.

5.2.5. LR formulation

Lloyd Register SSC rules give the typical minimum properties for E-Glass and polyester, as depicted in Table 30.

Table 30 Typical minimum fibre and reinforcement properties (LR)

	Specific gravity	**Tensile modulus**	**Shear modulus**	**Poisson's ratio**
	[g/m^3]	[MPa]	[MPa]	[-]
E-Glass	2.56	69000	28000	0.22
Polyester	1.20	3400	1300	0.36

Table 31 Mechanical properties of CSM and cross-plied glass reinforced polyester resin laminate

Mechanical property	**CSM**	**WR/CP**	**UD**	
	$[N/mm^2]$			
Ultimate tensile strength	$200f_c + 25$	$400f_c - 10$	//	$656f_c - 89.3$
			⊥	$68.4f_c^2 - 55f_c + 23$
Tensile modulus	$(15f_c + 2) \times 10^3$	$(30f_c - 0.5) \times 10^3$	//	$(50.5f_c - 6.87) \times 10^3$
			⊥	$(19.6f_c^2 - 15.7f_c + 6.6) \times 10^{-3}$
Ultimate compressive strength	$150f_c + 72$	$150f_c + 72$	//	$530f_c - 72.1$
			⊥	$196f_c^2 - 157f_c + 65.6$
Compressive modulus	$(40f_c - 6) \times 10^3$	$(40f_c - 6) \times 10^3$	—	
Ultimate shear strength	$80f_c + 38$	$80f_c + 38$	IP	$73.4f_c^2 - 59.2f_c + 24.5$
Shear modulus	$(1.7f_c + 2.24) \times 10^3$	$(1.7f_c + 2.24) \times 10^3$	IP	$(7.3f_c^2 - 5.9f_c + 2.4) \times 10^3$
Ultimate flexural strength	$502f_c^2 + 106.8$	$502f_c^2 + 106.8$	—	
Flexural modulus	$(33.4f_c + 2.2) \times 10^3$	$(33.4f_c + 2.2) \times 10^3$	—	
f_c: Fibre percentage by weight. IP: In-plane.				

For single skin composite laminates, LR offer a minimum thickness formula, while for sandwich laminates a minimum amount of reinforcement in the facing is given, as in eq. (49).

$$W_T = \omega K_L K_V W_{min} \tag{49}$$

Where:

ω = Service Type Correction Factor, which for yachts is 1.00

K_L = Craft Length Correction Factor, calculated as 0.79 for the selected vessel and panel

K_V = Fibre Volume Correction Factor

A minimum amount of reinforcement (W_T) for a panel located in hull bottom is $3650\ g/m^2$ for outer skin, and $2850\ g/m^2$ for inner skin (c.f. LR SSC Table 3.2.2). The outer skin's thickness shall not be greater than 1.33 times that of inner skin, while core thickness shall be 5.77 times or greater than mean facing thickness. An estimated required thickness of the sandwich skins and core is given by eq. 50, which shall be tested against other criteria.

$$t_s = \phi_1 k_s b \sqrt[3]{\frac{p}{E_{tps}}} \tag{50}$$

Where:

ϕ_1 = 0.0214 (for inner skins), 0.0286 (for outer skins), 0.1440 (for core)

k_S = aspect ratio correction factor = $\begin{cases} A_R \leq 2 & 0.32\, A_R + 0.36 \\ A_R > 2 & 1.0 \end{cases}$

E_{tps} = tensile modulus of a plate laminate which forms a skin of a sandwich laminate subject to tensile loading = $\Sigma\,(E_{ti}/t_i)\,/\Sigma t_i$

p = design pressure

Additionally, core thickness is required to be 5.77 times greater than the mean of the skin thicknesses:

$$\frac{t_c}{0.5\,(t_o + t_s)} \geq 5.77 \tag{51}$$

To calculate the stresses, the bending moments M_b and M_c are calculated, which are defined as the bending moment at panel boundary and under stiffener base and bending moment at centre of panel respectively. Both bending moments are to be applied to a 1 cm length of panel, and the following formulae determine them:

$$M_b = \frac{kpv^2}{12} \times 10^{-5}\ [Nm] \tag{52}$$

$$M_c = \frac{(1.5 - k)pb^2}{12} \times 10^{-5}\ [Nm] \tag{53}$$

Where:

k = bending moment influence coefficient, based on the panel breadth and base width of the stiffener

Additionally, if the panel aspect ratio (A_R) is less than two, LR allows the reduction of the rule bending by the following factor:

$$\mathrm{K_{AR}} = 0.56 + 0.63 \ln(A_R) \geq 0.56 \tag{54}$$

While missing in the design pressure definition, LR SSC allows the reduction of slamming pressure by introducing the factor K_i, which is defined as:

$$K_i = 0.18 + \frac{1.8}{16\left(\frac{A_{pn}}{A_{rf}}\right) + 1.1}, 0.7 \leq K_i \leq 1 \quad (55)$$

Where:

A_{pn} = area of plate laminate = $s \times l \leq 2(s/1000)^2$

A_{rf} = reference impact pressure area, = $0.7\Delta/T$

The tensile stress, σ_{ti}, and the compressive stress, σ_{ci} at the outer fibre of a single ply are calculated using eq. (56) and (57).

$$\sigma_{ti} = \frac{0.1\, E_{ti} y_i M}{\Sigma(E_i I_i)} \quad (56)$$

$$\sigma_{ci} = \frac{0.1\, E_{ci} y_i M}{\Sigma(E_i I_i)} \quad (57)$$

The resulting tensile and compressive stresses shall comply with the limiting stress criteria. The limiting stress criteria for local loading for the bottom shell envelope are given in Table 32.

Table 32 Limiting stress criteria for local loading

Item	**Limiting stress fraction**		
Bottom shell laminate	Tensile	Compressive	Shear
Slamming zone	0.28	0.28	—
elsewhere	0.25	0.25	
PVC	—		0.45

Deflection control of a shell sandwich construction is to be checked by the span/deflection ratio being not less than $f_\delta = 100$. The deflection for a known Poisson's ratio for a facing laminate is calculated as:

$$\delta = \frac{pb^2}{8}\left(\frac{b^2(1-\nu_f^2)}{48 D_s} k_{db} + \frac{1}{G\, t_c} k_{ds}\right) \times 10^{-3} \text{ [mm]} \quad (58)$$

Where:

k_{db} = bending deflection aspect ratio factor = $1.5 - 1/A_R$ ($A_R \leq 2$)

k_{ds} = shear deflection aspect ratio factor = $1.2 - 0.6/A_R$ ($A_R \leq 3$)

D_s = flexural rigidity of the sandwich panel per unit mm width

$= \frac{E_{pi} t_{inner} E_{po} t_{outer}}{E_{pi} t_{inner} + E_{po} t_{outer}} (t_c + t_s)^2 \; Nmm$

For this panel, the span/deflection ratio is $f_\delta = 51.6$, which means that the panel does not pass this check. If the Poisson's ratio is not known, the following formula shall be used:

$$\delta = \frac{pb^2}{8}\left(\frac{b^2}{48\, D_s} k_{db} + \frac{1}{G\, t_c} k_{ds}\right) \times 10^{-3} [\text{mm}] \quad (59)$$

5.3. Comparison of the formulations

In this section, the comparison of some considerations of the above-stated formulations are compared.

5.3.1. Minimum thickness requirements

In the world of aluminium and steel scantling, it is of major importance to determine the minimum thickness requirements. Meanwhile, for composites, the importance is not at that same level. In the considered rules, only ABS and LR have given minimum thickness requirements for sandwich panels, while ISO gives a minimum thickness for single-skin hulls.

Table 33 Minimum skin thickness requirements

	Outer skin	**Inner skin**
ABS	4.91	3.51
LR	5.58	4.18
Offered	3.74	3.81

The two formulas are inherently different. On the one hand, the ABS formula is wholly based on possible experience and empirical studies, while the formula offered by LR includes the effect of pressure, aspect ratio and tensile elastic modulus.

5.3.2. Minimum skin mass requirements

Three of the five considered rules give a minimum mass requirement for the skins of sandwich constructions, ISO giving it as a “good practice” and not a requirement for vessels other than “heavy duty.” The minimum mass requirements checks for the selected panel are given in Table 34.

Table 34 Minimum required mass [g/m^2] for sandwich skins

		ISO	DNV	LR
Inner skin	Required	*1725.9* or *2416.3*	1642.8	2850
	Offered	3700		
Outer skin	Required	3451.9	2523.6	3650
	Offered	4000		

DNV only considers the panel's location and the boat's length in the formulation, which is similar to LR SSC, with the exception of boat type and fibre volume content. On the other hand, it considers several unnamed factors, which are the results of the empirical analysis, but it includes the mass of the whole boat, the speed of the vessel, the longitudinal location of the panel, the vertical location of the panel, fibre mass, design category and type of craft. There is no formula to calculate the inner skin’s required mass, but it gives a recommendation stating that the weight might be taken as 50% to 70% of that of the outer skin.

5.3.3. Core shear check

One of the main properties of using a core is its capability to carry the shear load for the panel, while the skins carry the bending loads (tension and compression). [36]

ISO requirements for the shear check, both for Simplified and Enhanced, are technically the same, except with the value of the safety factor. The shear force capacity is calculated as in eq. (60), and the minimum design shear stress is defined in (61). These requirements

$$t_s = t_c + \frac{t_o + t_i}{2} \geq \frac{F_d}{\tau_{dco}} \tag{60}$$

Where:

t_i, t_o, t_c = thicknesses of the inner skin, outer skin, and core, respectively

F_d = design shear force, defined in eq. (45) and (46)

τ_{dco} = design shear stress of the core (c.f. ISO 12215-5 Table 17)

$$\tau_{dco} \geq \min[\max(0.7 - 0.12 \times L_{WL}\,; 0.3); 0.58] \quad (61)$$

ABS, except for the minimum thickness requirement for the core as shown in the section above, has a shear core check, which is similar to ISO's formula and is given in the equation below:

$$\frac{d_o + d_c}{2} \geq \frac{vps}{1000\,\tau} \quad (62)$$

Where:

v = coefficient varying with plate panel ratio

τ = design shear stress, taken as $0.4\tau_u$ for cross-linked PVC, or $0.55\tau_u$ when sheer elongation is more than 40%

p = design pressure

d_o = overall thickness of the sandwich

d_c = thickness of the core

DNV considers the maximum core shear stress and compressive stress as the failure criteria for core materials. The design core shear stress is to be greater than t_c, given in eq. (63).

.

$$\tau_c = \frac{F_q}{t_c + \frac{t_{s1}}{2} + \frac{t_{s_2}}{2}} \quad (63)$$

According to LR, the direct core shear stress, τ_c, at the edges of a sandwich panel subjected to lateral pressure is to be determined from:

$$\tau_c = \frac{p\,b\,k_s}{2\,(t_s + t_c)} \times 10^{-3} \quad (64)$$

BV on the other hand, does not give a simple formula for core shear check, but requires the core to be analysed under the laminate theory. In Table 35, the comparison of the core shear check is given. The main factors affecting these results are the design load, which determines the shear force, and the safety factor of the design shear stress, which are given in the next section.

Table 35 Core shear check comparison [mm]

	Offered $t_c + \frac{t_o+t_i}{2}$	**Required F/τ**	**Ratio**	**Comply?**
ABS		55.46	0.60	No
ISO		29.14	1.15	Yes
DNV	33.46	58.48	0.57	No
LR		63.34	0.53	No
BV		19.81	1.69	Yes

5.3.4. Safety factors

The safety factors for the design stresses in the laminates and the core of the selected panel are given in Table 36. The lower the safety factor is, more conservative it is, thus leading to lower design stresses.

Table 36 Safety factors for the selected panel components

<table>
<tr><th rowspan="2">Rule</th><th colspan="3">Laminate</th><th colspan="3">Core</th></tr>
<tr><th>Compressive</th><th>Tensile</th><th>Shear</th><th>Compressive</th><th>Tensile</th><th>Shear</th></tr>
<tr><td>ISO Simplified</td><td colspan="3">0.45</td><td>0.45</td><td>0.495</td><td>0.495</td></tr>
<tr><td>ISO Enhanced</td><td colspan="3">0.475</td><td>0.475</td><td>0.5225</td><td>0.5225</td></tr>
<tr><td>BV (//)</td><td colspan="2">0.43</td><td rowspan="2">0.56</td><td colspan="2" rowspan="2">0.54</td><td rowspan="2">0.36</td></tr>
<tr><td>BV (⊥)</td><td colspan="2">0.72</td></tr>
<tr><td>DNV</td><td colspan="3">0.351</td><td colspan="3">0.478</td></tr>
<tr><td>ABS</td><td colspan="3">0.33</td><td>—</td><td>—</td><td>0.40</td></tr>
<tr><td>LR</td><td>0.28</td><td>0.28</td><td>—</td><td>—</td><td>—</td><td>0.45</td></tr>
</table>

These safety factor, or better saying reduction factors, are to be multiplied with the stress or the strain and are considered for this specific case. The formulations are different, thus resulting in different factors:

- ISO safety factor formula includes the method factor, fabrication factor and a 0.5 fixed factor for direct stress and 0.55 fixed factor for core (with elongation at break $\leq 35\%$) shear stress. Additional fixed factors are given for other material types or structural elements.
- BV safety factor formula includes four partial safety factors, which are related to the laminate ageing effect, fabrication process, type of fibre and the direction of stress, and load type.
- DNV safety factor formula includes a 0.33 reserve factor (0.4 for cores), structural coefficient and a manufacturing coefficient.
- ABS gives fixed factors depending on the location of the panel, stress being evaluated (direct or shear) and material (for cores).
- LR gives fixed factors depending on the location of the panel, type of structural element, stress being evaluated (tensile, compressive or shear).

6. RESULTS

This chapter presents the scantling check of the panel laminate, which passed the check using ISO 12215-5 Simplified and Enhanced method. Spreadsheets were created to calculate the mechanical properties and scantling checks. Furthermore, the results from ISO have been cross-checked with Wolfson Hull Scant 2 software, while the results from BV have been cross-checked with StarBoat and ComposeIT software. Notable differences were spotted in the calculations. This is explained by the fact that some properties of user-defined materials have been differently recognized by the software, resulting in the application of slightly different safety factors or related factors.

6.1. ISO panel analysis

Using the formulae presented in the previous chapter, the selected panel was checked using ISO 12215-5 Simplified and Enhanced methods. The main inputs are given in Table 37.

Table 37 Panel specification

$l\ (mm)$	2000	$A_D\ (m^2)$	2
$b\ (mm)$	1000	k_{AR}	0.454
Aspect ratio	2	k_C	1
Pressure (kN/m^2)	68.3	k_{2b}	0.492
k_L	1	k_{2l}	0.338

ISO 12215-5 Simplified method requires the laminate to comply with three conditions. The skins shall pass the minimum section modulus, and the core shall pass the core shear check. Simplified method results are given in Table 38.

Table 38 Panel analysis according to ISO 12215-5 Simplified method

	Core shear	SM_O	SM_i
	[mm]	[cm^3]	[cm^3]
Requirements	29.14	0.67	0.59
Offered	33.46	1.12	0.98
Results	1.15	1.68	1.65
Comply?	Yes	Yes	Yes

More checks are required when the Enhanced method is used. As given in Table 39, ISO Enhanced method requires the panel to comply with seven checks. Four of them require a minimum shear force and bending moment capacity in both panel directions, which is to be checked for each ply, and the ply with the lowest load capacity is considered the offered value. Additionally, the core is checked against shear, strength and compressive stress. As Seen from the value, the lowest bending moment capacity is at layer 7, which is expected considering that the layer is made of a double biaxial configuration.

Table 39 Panel analysis according to ISO 12215-5 Enhanced method

	F_{db}	F_{dl}	M_{db}	M_{dl}	**Core shear**	**Core strength**	**Core comp. stress**
	[N/mm]	[N/mm]	[Nm/mm]	[Nm/mm]	[mm]	[N/mm^2]	[N/mm^2]
Require-ments	35.20	31.43	5693.33	3837.31	29.14	0.30	0.55
Offered	40.41	40.41	9232.55 (Layer 7)	9232.55 (Layer 7)	33.46	1.21	1.45
Results	1.15	1.29	1.62	2.41	1.15	4.03	2.64
Comply?	Yes	Yes	Yes	Yes	Yes	Yes	Yes

6.2. ABS panel analysis

Results and checks for a 1 cm wide strip of the selected sandwich panel according to ABS are given in Table 40. Similarly, to ISO, ABS requires checking for minimum section modulus and core check, in addition to the moment of inertia and minimum skin thicknesses. Skin stability is considered separately, contrary to ISO, which includes the minimum wrinkling stress as part of design compressive stress.

Table 40 Panel analysis according to ABS Yachts

	Section modulus		**I**	**Shear strength**	**Skin stability**	**Skin thickness**	
	Outer	Inner				Outer	Inner
	[cm^3]	[cm^3]	[cm^4]	[mm]	[N/mm^2]	[mm]	[mm]
Require-ments	1.44	1.28	1.59	55.46	140.53	4.91	3.51
Offered	1.12	0.98	1.93	33.46	224.37	3.74	3.18
Results	0.778	0.766	1.214	0.6	2.74	0.76	0.91
Comply?	No	No	Yes	No	Yes	No	No

The selected panel laminate does not comply with ABS rules, which is expected to be, as the pressure given by ABS is higher than the one given by ISO. Even so, it shall be noted that ABS is applicable to much larger yachts, and thus considers higher scantling requirements.

6.3. BV panel analysis

BV requires the plies to comply in two locations: A and B, as mentioned in the previous chapter. The results for locations A and B are depicted in Appendix G.1 and Appendix G.2, respectively. In Table 41, the main results of each individual ply are given. In the columns σ_1, σ_2 and τ_{12} the value of SF over σ_{br}/σ_{act} or τ_{br}/τ_{act}.is given, which shows the capacity used by the actual ply. The letters A and B beside the values represent where most of this capacity was used.

Table 41 Panel analysis according to BV Yachts and BV Composite rules

Layer	**Ply**		**Angle**	$\boldsymbol{\sigma_1}$		$\boldsymbol{\sigma_2}$		$\boldsymbol{\tau_{12}}$	
Inner	1	UD 600	0	B	0.231	A	0.237	A	0.001
	2	UD 600	90	A	0.332	B	0.156	A	0.001
8	3	UD 225	0	B	0.22	A	0.226	A	0.001
	4	UD 225	45	B	0.171	B	0.142	A	0.238
	5	UD 225	90	A	0.319	B	0.15	A	0.001
	6	UD 225	-45	B	0.169	B	0.138	A	0.233
7	7	UD 200	0	B	0.211	A	0.217	A	0.001
	8	UD 200	45	B	0.164	B	0.136	A	0.228
	9	UD 200	90	A	0.306	B	0.143	A	0.001
	10	UD 200	-45	B	0.162	B	0.132	A	0.224
6	11	UD 400	45	B	0.158	B	0.131	A	0.22
	12	UD 400	-45	B	0.157	B	0.127	A	0.216
5	13 Top	PVC130	0	B	0.103	A	0.149	A	0
	13 Bot	PVC130	0	B	0.068	A	0.098	A	0
4	14	UD 400	45	B	0.092	B	0.33	A	0.191
	15	UD 400	-45	B	0.094	B	0.34	A	0.196
3	16	UD 200	0	B	0.124	B	0.546	A	0.001
	17	UD 200	45	A	0.097	B	0.348	A	0.202
	18	UD 200	90	B	0.184	B	0.387	A	0.001
	19	UD 200	-45	B	0.099	A	0.358	A	0.206
2	20	UD 225	0	B	0.13	B	0.574	A	0.001
	21	UD 225	45	A	0.102	B	0.365	A	0.211
	22	UD 225	90	B	0.193	B	0.405	A	0.001
	23	UD 225	-45	B	0.104	A	0.376	A	0.216
1	24	UD 600	0	A	0.138	A	0.607	A	0.001
	25	UD 600	90	B	0.206	B	0.432	A	0.001
Outer	26	CSM 300	0	B	0.279	A	0.24	A	0.001

From the results using BV rules, it is noticeable that the low design pressure will lead to lower requirements, and thus to compete compliance of the laminate. Additionally, the core is checked by the ratio of the largest of the two permissible interlaminar shear stresses τ_{IL1} and τ_{IL2}, as shown below:

$$\tau_{\mathrm{IL2}_{act}} = 0.65\ MPa < \frac{\tau_{IL2_{rule}}}{SF} = \frac{2.44}{2.20} = 1.109\ MPa \tag{65}$$

6.4. LR panel analysis

Using eq. (57), the minimum required thicknesses are found, which do not comply with ISO results, except the core.

Table 42 Thicknesses, in [mm]

	Outer skin	**Core**	**Inner skin**
Required	5.68	28.37	4.18
Offered	3.74	30	3.18
Comply?	No	Yes	No

The formulae given by LR SSC, as shown in Table 43 were used for calculating the mechanical properties. Table 43 shows the check of tensile and compressive stresses, where a value of more than one means the ply failed, which is the case for all plies. The complete results are given in Appendix G.4.

Table 43 Panel analysis according to LR SSC rules

Layer	**Ply**	$\boldsymbol{\sigma_{c,t}}$ check
Inner	BD+ 1200	2.53
9	Q× 900	2.39
8	Q× 800	2.29
7	DB× 800	2.20
6	PVC130	0.81
5	DB× 800	1.39
4	Q× 800	1.46
3	Q× 900	1.53
2	BD+ 1200	1.63
Outer	CSM 300	1.61

6.5. DNV panel analysis

In similar manner to BV calculations, DNV requires the usage of CLT to calculate the stresses on each ply. The maximum moment and in-plane shear force, given by the rules and explained din the previous chapter, are applied to compute the strains, which bring us to the final stresses. Each ply has a failure, which is explained by the high applied bending moment which can be seen in Table 44.

Table 44 Panel analysis according to DNV rules

Layer	Ply		Angle	σ_1	σ_2	τ_{12}
Inner	1	UD 600	0	0.07	1.50	0.01
	2	UD 600	90	1.46	0.35	0.01
8	3	UD 225	0	0.07	1.43	0.01
	4	UD 225	45	0.73	0.88	1.41
	5	UD 225	90	1.40	0.34	0.01
	6	UD 225	-45	0.73	0.86	1.37
7	7	UD 200	0	0.06	1.37	0.01
	8	UD 200	45	0.71	0.84	1.34
	9	UD 200	90	1.34	0.33	0.01
	10	UD 200	-45	0.70	0.82	1.32
6	11	UD 400	45	0.68	0.81	1.30
	12	UD 400	-45	0.67	0.79	1.27
5	13 Top	PVC130	0	0.29	1.12	0.00
	13 Bot	PVC130	0	0.24	0.99	0.00
4	14	UD 400	45	0.60	0.70	1.13
	15	UD 400	-45	0.60	0.72	1.16
3	16	UD 200	0	0.05	1.18	0.01
	17	UD 200	45	0.63	0.74	1.18
	18	UD 200	90	1.21	0.29	0.01
	19	UD 200	-45	0.64	0.76	1.22
2	20	UD 225	0	0.05	1.24	0.01
	21	UD 225	45	0.66	0.78	1.25
	22	UD 225	90	1.27	0.31	0.01
	23	UD 225	-45	0.67	0.80	1.27
1	24	UD 600	0	0.06	1.31	0.01
	25	UD 600	90	1.35	0.33	0.01
Outer	26	CSM 300	0	0.45	1.51	0.01
	Represents failing plies					

To ease the checking of the failing plies, they have been coloured in light orange, and the extended values are given in Appendix G.3.

6.6. Comparison

Results of the selected panel analysis show a large variety of differences. Initial differences can be traced to the definition of the materials and their mechanical properties, as well as the breaking strains or stresses. Two of the considered rules, BV and DNV, utilize the Classical Lamination Theory to define the material and laminate characteristics and to calculate the strains. The computation procedures are the same, including the definition of bending moment and shear force. There is one difference as DNV considers one maximum bending moment to be considered on the calculation, while BV requires two, one primary and one secondary for each middle point of the panel boundary. Results between BV and DNV are expectedly different, as DNV required a 3-times higher design slamming pressure.

On the other hand, ISO Simplified method is similar to ABS. Both do not require ply-by-ply check, but ISO Enhanced method in the other hand is more similar to LR SSC, which includes ply-by-ply computation, but without CLT. Considering that the selected panel was an iterative work of complying with ISO Simplified method, it is expected that it will fail with ABS, as ABS required a 1.6 times higher design pressure and ISO safety factors (in the inverse scale) for the design stresses are higher: 0.45 to 0.33 for laminate, and 0.495 to 0.40 for core. LR panel analysis shows that all the plies will fail, except the core for bending, but not against shear. This is expected for the selected panel because of the high input slamming pressure and much higher safety factors than ISO.

It is noted that the plies failing with higher stress are in the inner skin due to compressive strength, which is lower than the tensile one. Additionally, as expected from theory, Double biaxial ($\pm 45°$) plies are prone to higher shear stress due to bending but give good results in direct stresses. Moreover, all rules require specific material test to be made, which might differ from the estimated values given by the rules, thus leading in different but realistic results.

6.7. Discussion

The objective of this study was verifying if there is a natural structural continuity between a 24m yacht designed with ISO and other ones designed with Classification society rules by considering comparable operation conditions. This verification partially failed to be proven, as the bottom panel designed with ISO did not pass nor it was close to pass when considered under class rules.

The influence stemming from the definition of design vertical acceleration largely affects the value of the design pressure for planing crafts. Thus, the design vertical acceleration, in the context of operational limits, could be supressed by introducing navigation envelopes, which combine vessel speed and significant wave heights.

This design pressure is the main factor influencing the compliance of a selected panel under the considered structural rules. In the context of scantling definitions, rules which have less complex calculation require higher safety factors compared to rules with more complex calculations. This might be an important point for the designer to decide which rule to use for classification, especially for small boatyards.

In the context of bottom scantling, sandwich panel might not be the perfect choice for high load cases, considering that the skins are far from each other, and higher bending stress might be expected. Achieving optimum load resistance is closely related to the placing of different ply configurations on the skins. As the number of configurations is high, coupled with different materials for fibres and resins, and the combination fractions with the two, a designer has to choose wisely, by introducing specific objective and constraints.

In general, scantling a yacht with composite shall be a compromise between objectives and constraints, like minimizing weight and cost, but maximizing stiffness, strength and toughness of the hull, under the constraints imposed by rules and by the environment itself.

7. CONCLUSION

Nowadays, a particular yacht can be classified according to multiple class rules. For example, a designer might classify and certify a yacht with a rule length of around the 24-meter using ISO 12215-5 rules (as part of the EU recreational craft directive) or Classification Societies rules. In today's competitive market, using rules which give a lighter structure can be an advantage. The lower structural requirement means lower weight, which indeed means lower construction costs. Additionally, a lightweight yacht consumes less fuel, lowering operational costs.

A test case was used to determine the differences and similarities to examine if a designer designing a yacht around a rule of 24 meters shall use Classification Societies rules or ISO 1221-5 Structural rules. In this test case, a bottom panel made of a sandwich composite was checked to see if it complies with scantling rules of ISO and class rules. In this study, the limits of the application of ISO structural rules and four class rules, namely ABS Yachts, BV Yachts, DNV Yachts (and DNV HSLC), and LR SSC, were studied and compared.

As this yacht was considered navigation in planing regime and without restriction, different rules resulted in different slamming design pressures. Slamming pressure is closely related to vertical acceleration. Therefore, even though the design acceleration formula of all the considered rules resembles a semi-empirical 70s procedure, the results were quite different. Generally, ISO, BV Yachts, and ABS Yachts rules resulted in lower design vertical accelerations, while DNV HSLC and LR SSC rules gave much higher values. This is explained by the fact that the two later rules apply to many boats and ship types, while BV and ABS rules are limited to yachts, and ISO is limited to small crafts.

Similarly to the definition of vertical design acceleration, design pressure calculation formulae due to impact loads are based on previous literature. Vertical design acceleration is the main factor in calculating design slamming pressure, followed by the longitudinal distribution factor, design area factor, and deadrise angle. The longitudinal distribution factor and area factor follow similar trends. Deadrise angle affects the design pressure more if it is considered locally, like in the case of DNV HSLC and BV Yachts. In the case of BV rules, slamming pressure is nullified for angles over 50 degrees, and in the case of DNV rules, the value of design slamming pressure gets lowered by a third when angles are over 30 degrees.

Contrary to other rules, LR SSC considers support girth at LCG to calculate the design slamming pressure. As a result, DNV and LR require higher design pressure for the selected speed than the other three rules. Conversely, ISO and BV require the lowest pressures, while ABS is midway between the two.

To check the scantling requirements, a sandwich panel was defined. Initially, a sandwich construction consisting of E-glass and polyester plies of different combinations and a PVC core was checked against ISO 12215-5 Simplified and Enhanced scantling rules until a passing laminate was constructed. After that, this laminate was tested against the scantling rules of the four classification societies. There is a wider variety in scantling definitions than design loads definitions. ISO 12215, on the one hand, proposes five different methods to determine the scantlings, starting from more straightforward methods but more conservative ones to more complex (like CLT and FEM) and less conservative ones. On the other hand, BV Yachts and DNV Yachts require the usage of Laminate Theory to calculate ply-by-ply the strains and stresses against breaking strains and stresses restricted by safety factors. LR SSC also requires checking for each ply but does not give CLT as a requirement. ABS Yachts do not require ply-by-ply analysis but similarly to ISO require the check for skins and core separately.

The results conclude that the sandwich laminate constructed to pass ISO 12215-5 Simplified and Enhanced scantling methods easily complies with BV rules due to the lower design pressure definition, which is the result of the vertical acceleration cap. Checking with ABS rules, which is similar to the ISO Simplified method, fails the laminate. As with ABS, the higher design pressure fails the selected laminate in DNV and LR calculations. These results shall be taken with reserves, as the operational inputs, like significant wave height and vertical accelerations, and the practical nature of scantling, like testing the materials for lower safety factors, are subject to the designer’s decision.

To conclude, a fast motor yacht with a length of around 24 meters, considering unrestricted service, should be designed according to ISO 12215-5 Structural rules or unique class rules for classifications of yachts. More general rules have higher requirements, but the designer is allowed to define the operational limits. Thus, the vertical acceleration might be suppressed, leading to lower design pressure and scantling requirements.

As this study was limited to evaluating the rules only for the bottom plating of a monohull motor yacht, the thesis can be expanded. This could be accomplished through the evaluation of plating at sides, decks, and superstructures, and the scantling of stiffeners, which would lead to the study of the differences in the weight of the vessel.

Additionally, factors like the effect of change in fibre content in the overall scantling were not considered. In this context, alternative fibre materials and combinations could be utilized. A more thorough study on the effects of the methods used to construct the composites, like vacuum-assisted resin transfer moulding, could be done.

To advance the general scope of this study, it is recommended the use of FEM to evaluate the safety factors being utilized on the panel. Likewise, CFD could be utilized to estimate the actual vertical acceleration and design pressure, which could be further used in the calculations.

8. REFERENCES

[1] European Parliament, Council of the European Union, *Directive 2013/53/EU of 20 November 2013 on Recreational Craft and Personal Watercraft,* vol. L 354/90, Official Journal of the European Union, 2013.

[2] ISO, *ISO 12215-5: 2019 Small Craft - Hull construction and scantlings. Part 5: Design pressures for monohulls, design stresses, scantlings determination,* International Organisation for Standardization, 2019.

[3] J.-B. R. G. Souppez, "Designing the Next Generation of Small Pleasure and Commercial Powerboats with the Latest ISO 12215-5 for Hull Construction and Scantlings," in *SNAME / IBEX 2019 Symposium*, 2019.

[4] J.-B. R. G. Souppez, E. Begovic, P. Sensharma, F. Wang and A. Rosen, "Comparative Assessment of Rule-Based Design on the Pressures and Resulting Scantlings of High Speed Powercrafts," *Progress in Marine Science and Technology,* vol. 5, p. 263–275, 2020.

[5] A. J. Sobey, J. I. Blake and R. A. Shenoi, "Optimisation of composite boat hulls using first principles and design rules," *Ocean Engineering*, vol. 65, pp. 62-70, 2013.

[6] J. Lee, "On the Design Impact Pressure in the Rules and Regulations of ISO and Classification Societies," *Journal of Korea Ship Safrty Technology Authority,* vol. 31, pp. 60-70, 2011.

[7] T. Coppola and F. De Santis, "On the comparison between the ISO Norm and the independent private companies: the expression of the demand," in *9th Symposium on High Speed Marine Vehicles*, Naples, 2011.

[8] D. Oh, D. K. Lee, G.-M. Kang and C. Ryu, "Comparative Study of Rules of ISO 12215 and International Classification Society for Structural Design of CFRP Cruise Boat," *Journal of Ocean Engineering and Technology*, vol. 28, no. 1, pp. 77-84, 2014.

[9] J.-B. R. G. Souppez, “Structural Analysis of Composite Search and Rescue Vessels under the New BS EN ISO 12215-5,” in *SURV9 – Surveillance, Search and Rescue Craft*, London, UK, 2018.

[10] J.-B. R. G. Souppez, “Structural Design of High Performance Composite Sailing Yachts Under the New BS EN ISO 12215-5,” *Journal of Sailing Technology,* vol. 3, no. 01, p. 1–18, 2018.

[11] D. Boote, G. Vergassola, V. Hydar and S. Mitolo, “Structural re-design of a composite pleasure craft with direct and numerical calculations,” in *Developments in the Analysis and Design of Marine Structures,* Trondheim, 2021.

[12] D. Savitsky and P. W. Brown, “Procedures for Hydrodynamic Evaluation of Planing Hulls in Smooth and Rough Water,” *Marine Technology and SNAME News,* vol. 13, no. 04, pp. 381-400, 1976.

[13] R. Allen, R. Jones and D. Taylor, “A Simplified Method for Determining Structural Design-Limit Pressures on High Performance Marine Vehicles,” in *Advanced Marine Vehicles Conference,* San Diego, CA, USA, 1978.

[14] J. S. Spencer, Structural Design of Aluminum Crewboats, Society of Naval Architects and Marine Engineers, 1974.

[15] M. Razola, A. Rosén and K. Garme, “Allen and Jones revisited,” *Ocean Engineering,* vol. 89, pp. 119-133, 2014.

[16] N. Baral, D. D. R. Cartié, I. K. Partridge, C. Baley and P. Davies, “Improved impact performance of marine sandwich panels using through-thickness reinforcement: Experimental results,” *Composites Part B: Engineering,* vol. 41, no. 2, pp. 117-123, 2010.

[17] A. Petras, Design of Sandwich Structures, Cambridge: Cambridge University Engineering Department, 1998.

[18] U.S. Department of Defense, “Composite Materials Handbook, Volume 3 - Polymer Matrix Composites Materials Usage, Design, and Analysis,” U.S. Department of Defense, 2002.

[19] S. W. Tsai and H. T. Hahn, Introduction to Composite Materials, New York: Routledge, 1980.

[20] BV, *BV NR 546 Rule Note on Hull in Composite Materials and Plywood*, Bureau Veritas, 2021.

[21] F. De Luca and C. Pensa, "The Naples warped hard chine hulls systematic series," *Ocean Engineering*, vol. 139, pp. 205-236, 2017.

[22] DNV, *DNV Rules for classification: Yachts, Part 3 Hull,* DNV, 2021.

[23] DNV, *DNV Rules for classification: High speed and light craft, Part 3 Structures, equipment,* DNV, 2021.

[24] BV, *BV NR500 Rules for the Classification and the Certification of Yachts*, Bureau Veritas, 2021.

[25] BV, *BV NR467 Rules for the Classification of Steel Ships*, Bureau Veritas, 2022.

[26] LR, *LR Rules and Regulations for the Classification of Special Service Craft,* Lloyd's Register, 2021.

[27] ABS, *ABS Guide for Building and Classing Yachts Part 3 Hull Construction and Equipment,* American Bureau of Shipping, 2022.

[28] IMO Maritime Safety Committee, *Resolution MSC.97(73) - 200 HSC Code,* International Maritime Organization, 2000.

[29] E. Greene, Marine Composites, Annapolis, Maryland: Eric Greene Associates, Inc., 1999.

[30] E. Greene, Design Guide for Marine Applications of Composites, Ship Structure Committee, 1997.

[31] ISO, *ISO 12217:1:2017 Small craft - Stability and buoyancy assessment and categorization,* International Organization for Standardization, 2017.

[32] D. J. Kim, S. Y. Kim, Y. J. You, K. P. Rhee, S. H. Kim and Y. G. Kim, Design of high-speed planing hulls for the improvement of resistance and seakeeping performance, vol. 5, Elsevier, 2013, pp. 161-177.

[33] R. Yousefi, R. Shafaghat and M. Shaker, "Hydrodynamic analysis techniques for high-speed planing hulls," *Applied Ocean Research,* vol. 42, pp. 105-113, 2013.

[34] E. Begovic and C. Bertorello, "Resistance assessment of warped hullform," *Ocean Engineering,* vol. 56, pp. 28-42, 2012.

[35] ABS, *ABS Rules for Materials and Welding*, American Bureau of Shipping, 2022.

[36] F. Campbell, “Adhesive Bonding and Integrally Cocured Structure: A Way to Reduce Assembly Costs through Parts Integration,” in *Manufacturing Processes for Advanced Composites*, Elsevier Science, 2003, pp. 241-301.

[37] A. K. Kaw, Mechanics of composite materials, Boca Raton, FL: CRC Press, 2006.

9. APPENDICES

Appendix A. Physical and mechanical properties of PVC materials

Reference: Gurit PVC

Cores	**Density**	**Compressive strength (ASTM D1621-10)**	**Compressive modu-lus (ASTM D1621-10)**	**Shear Strength**	**Shear Modulus**	**Shear elon-gation at break**	**Tensile Strength**	**Tensile Modulus**
Units	*Kg/m^3*	*MPa*	*MPa*	*MPa*	*MPa*	*%*	*MPa*	*MPa*
PVC40	40	0.52	29	0.47	15	6.00%	0.71	68
PVC48	48	0.62	34	0.52	16	7.00%	0.98	71
PVC60	60	0.98	48	0.79	21	18.00%	1.82	100
PVC80	80	1.6	74	1.2	30	19.00%	2.74	146
PVC100	100.00	2.05	95.00	1.48	36.00	25.00%	3.18	162.00
PVC130	130	3.22	138	2.44	55	32.00%	4.35	227
PVC200	200	5.07	234	3.44	77	35.00%	6.26	358
PVC250	250	6.88	296	4.37	98	35.00%	7.19	439

Appendix B. Vertical acceleration values

Appendix B.1. Vertical acceleration due to deadrise angle (at LCG) change

Deadrise angle at LCG	**[deg]**	**10**	**15**	**20**	**25**	**30**
DNV	[g]	4.96	4.34	3.72	3.1	2.48
ISO		1.51	1.32	1.13	0.94	0.75
ABS		3.06	2.68	2.30	1.91	1.53
BV (information)		2.38	2.08	1.79	1.49	1.19
BV (capped)		1	1	1	1	1
LR		3.26	2.85	2.44	2.04	1.63

Appendix B.2. Comparison of vertical acceleration due to change in speed

Speed	**[knots]**	**25**	**30**	**35**	**40**	**45**
DNV	[g]	3.71	5.34	6.00	6.00	6.00
ISO		1.19	1.71	2.32	3.00	3.20
ABS		2.29	3.30	4.49	5.86	7.00
BV (information)		1.78	2.56	3.49	4.56	5.77
BV (capped)		1.00	1.00	1.00	1.00	1.00
LR		2.44	3.51	4.77	6.24	7.89
Note: Underlined values show the capped values.						

Appendix B.3. Running trim angle effect on vertical acceleration

Running trim	**[deg]**	**3**	**4**	**5**	**6**	**7**
ABS	[g]		2.29	2.86	3.43	4.01
BV (information)		2.38	1.78	1.89	2.00	2.11
BV (capped)		1	1	1	1	1
LR		1.83	2.44	3.04	3.65	4.26

Appendix C. Design pressures

Appendix C.1. Slamming distribution factor

x/L	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
ABS	0.25	0.39	0.52	0.66	0.79	0.93	1.00	1.00	1.00	0.95	0.50
BV	0.60	0.60	0.60	0.90	0.90	0.90	0.90	1.00	1.00	0.75	0.75
DNV HSLC	0.50	0.60	0.70	0.80	0.90	1.00	1.00	1.00	1.00	1.00	1.00
ISO ($k_{DYN} = 3$)	0.40	0.50	0.60	0.70	0.80	0.90	1.00	1.00	1.00	1.00	1.00
ISO ($k_{DYN} = 3$)	0.80	0.83	0.87	0.90	0.93	0.97	1.00	1.00	1.00	1.00	1.00
LR	0.50	0.60	0.70	0.80	0.90	1.00	1.00	1.00	0.90	0.70	0.50

Appendix C.2. Design pressures

x/L	**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
DNV	102.0	122.4	142.8	163.2	183.5	175.3	136.4	**136.4**	136.4	136.4	136.4
ISO	27.3	34.1	40.9	47.8	54.6	61.5	68.3	**68.3**	68.3	68.3	68.3
ABS	38.3	41.7	56.3	71.0	85.6	100.2	108.3	**108.3**	108.3	103.3	54.1
BV	60.4	60.4	60.4	90.7	90.7	77.9	60.3	**42.4**	31.7	34.9	34.9
LR	69.6	83.5	97.4	111.3	125.2	139.1	139.1	**139.1**	125.2	97.4	71.5

Values are in kPa.

Appendix D. Panel aspect ratio factors and coefficients

Appendix D.1. ABS panel aspect ratio coefficient (for sandwich constructions)

Plate Panel Aspect Ratio ℓ/s	**v**
>2.0	0.500
2.0	0.500
1.9	0.499
1.8	0.499
1.7	0.494
1.6	0.490
1.5	0.484
1.4	0.478
1.3	0.466
1.2	0.455
1.1	0.437
1.0	0.420

Appendix D.2. ISO panel aspect ratio factors

Panel effective aspect ratio A_{RE} [a]	**Transverse factor $k2b$ for transverse bending moment**	**Longitudinal factor $k2l$ for longitudinal bending moment**	**Factor $kSHb$ for shear force in b direction (in middle of side l)**	**Factor $kSHl$ for shear force in l direction (in middle of side b**
>2,0	0,500	0,337	0,520	0,460
2,0	0,494	0,337	0,516	0,460
1,9	0,490	0,339	0,516	0,459
1,8	0,484	0,339	0,516	0,459
1,7	0,476	0,339	0,515	0,458
1,6	0,465	0,339	0,515	0,458
1,5	0,451	0,339	0,512	0,458
1,4	0,432	0,337	0,506	0,457
1,3	0,409	0,335	0,496	0,457
1,2	0,380	0,329	0,482	0,454 7
1,1	0,345	0,320	0,462	0,447
1,0	0,305	0,305	0,436	0,436
a $ARE = (l/b) \times (EI_b/EI_l)^{0.25}$				

Appendix D.3. ISO approached panel aspect ratio factors

Approached value of these factors with formula:							
$ki = A(l/b)5 + B(l/b)4 + C(l/b)3 + D(l/b)2 + E(l/b) + F$							
	A	B	C	D	E	F	
k_{2b}	−0,0103	0,0790	−0,1441	−0,2780	1,1645	−0,5065	with k_{2b} = 0,5 for l/b>2
k_{2l}	0,0227	−0,2497	1,0846	−2,3255	2,4592	−0,6860	with k_{2l}= 0,337 for l/b>2
k_{SHb}	−0,0032	−0,0194	0,3325	−1,2586	1,9183	−0,5339	with k_{SHb}= 0,52 for l/b>2
k_{SHl}	0,0372	−0,3841	1,5530	−3,0725	2,9792	−0,6767	with k_{SHl}= 0,46 for l/b>2

Appendix E. Theoretical breaking strains

Appendix E.1. Theoretical breaking strains – ISO [%]

Breaking strains (ultimate strength/initial E modulus) in %			
Type of fibre & resin		E Glass & polyester	HS Carbon & epoxy
Unidirectional UD	εut1	1.9	1
	εut2	0.5	0.5
	εuc1	1.4	0.7
	εuc2	1.4	1.9
	εuf1	2.02	1.21
	εuf2	0.92	1.16
	γu12	1.7	1.5
Chopped strand mat CSM	εut	1.35	Not applicable
	εuc	1.7	
	εuf	1.88	
	γu12	2	
WR/bidirectional 0/90° BD+	εut	1.55	1
	εuc	1.4	0.7
	εuf	1.84	1.21
	γu	1.7	1.4
Double bias ±45° DB×	εut	1.06	0.77
	εuc	1.02	0.75
	εuf	1.3	1.12
	γu	1.8	1.02
Quadriaxial 0/45/90/-45° Q×	εut	1.3	0.92
	εut	1.2	0.74
	εuf	1.56	1.21
	γu	1.7	1.02

Appendix E.2. Theoretical breaking strains – BV [%]

Reinforcement fabric type		Strains		Reinforcement fibre type					
				E Glass	R Glass	HS Carbon	IM Carbon	HM Carbon	Para-aramid
Reinforcement fabric type	Unidirectional	Tensile	ε_{brt1}	2,70	3,10	1,20	1,15	0,70	1,70
			ε_{brt2}	0,53	0,44	1,00	0,80	0,50	0,80
		Compression	ε_{brc1}	1,80	1,80	0,85	0,65	0,45	0,35
			ε_{brc2}	1,55	1,10	2,30	2,30	2,10	2,00
		Shear	γ_{br12}	1,80	1,50	1,60	1,70	1,80	2,00
			γ_{br13}, γ_{brIL2}	1,80	1,50	1,60	1,70	1,80	2,00
			γ_{br23}, γ_{brIL1}	2,50	1,80	1,90	1,85	1,80	2,90
	Woven roving	Tensile	ε_{brt1}	1,80	2,30	1,00	0,80	0,45	1,40
			ε_{brt2}	1,80	2,30	1,00	0,80	0,45	1,40
		Compression	ε_{brc1}	1,80	2,50	0,85	0,80	0,50	0,42
			ε_{brc2}	1,80	2,50	0,85	0,80	0,50	0,42
		Shear	γ_{br12}	1,50	1,50	1,55	1,60	1,85	2,30
			γ_{br13}, γ_{brIL2}	1,80	1,80	1,55	1,60	1,85	2,90
			γ_{br23}, γ_{brIL1}	1,80	1,80	1,55	1,60	1,85	2,90
	Chopped strand mats	Tensile	ε_{brt1}	1,55	NA	NA	NA	NA	NA
			ε_{brt2}	1,55	NA	NA	NA	NA	NA
		Compression	ε_{brc1}	1,55	NA	NA	NA	NA	NA
			ε_{brc2}	1,55	NA	NA	NA	NA	NA
		Shear	γ_{br12}	2,00	NA	NA	NA	NA	NA
			γ_{br13}, γ_{brIL2}	2,15	NA	NA	NA	NA	NA
			γ_{br23}, γ_{brIL1}	2,15	NA	NA	NA	NA	NA

Note 1:
NA = Not applicable.

Appendix F. Selected laminated exploded into single plies

Layer	Type	Label	Angle	Thickness
1	Unidirectional	UD600 @64%(M) E Glass Polyester	0.00	0.51
2	Unidirectional	UD600 @64%(M) E Glass Polyester	90.00	0.51
3	Unidirectional	UD225 @64%(M) E Glass Polyester	0.00	0.19
4	Unidirectional	UD225 @64%(M) E Glass Polyester	45.00	0.19
5	Unidirectional	UD225 @64%(M) E Glass Polyester	90.00	0.19
6	Unidirectional	UD225 @64%(M) E Glass Polyester	-45.00	0.19
7	Unidirectional	UD200 @64%(M) E Glass Polyester	0.00	0.17
8	Unidirectional	UD200 @64%(M) E Glass Polyester	45.00	0.17
9	Unidirectional	UD200 @64%(M) E Glass Polyester	90.00	0.17
10	Unidirectional	UD200 @64%(M) E Glass Polyester	-45.00	0.17
11	Unidirectional	UD400 @64%(M) E Glass Polyester	45.00	0.34
12	Unidirectional	UD400 @64%(M) E Glass Polyester	-45.00	0.34
13	Core	Foam PVC Cross Linked, 130 kg/m^3	0.00	30.00
14	Unidirectional	UD400 @64%(M) E Glass Polyester	-45.00	0.34
15	Unidirectional	UD400 @64%(M) E Glass Polyester	45.00	0.34
16	Unidirectional	UD200 @64%(M) E Glass Polyester	-45.00	0.17
17	Unidirectional	UD200 @64%(M) E Glass Polyester	90.00	0.17
18	Unidirectional	UD200 @64%(M) E Glass Polyester	45.00	0.17
19	Unidirectional	UD200 @64%(M) E Glass Polyester	0.00	0.17
20	Unidirectional	UD225 @64%(M) E Glass Polyester	-45.00	0.19
21	Unidirectional	UD225 @64%(M) E Glass Polyester	90.00	0.19
22	Unidirectional	UD225 @64%(M) E Glass Polyester	45.00	0.19
23	Unidirectional	UD225 @64%(M) E Glass Polyester	0.00	0.19
24	Unidirectional	UD600 @64%(M) E Glass Polyester	90.00	0.51
25	Unidirectional	UD600 @64%(M) E Glass Polyester	0.00	0.51
26	Mat	Mat300 @36%(M) E Glass Polyester		0.56

Appendix G. Panel analysis

Appendix G.1. BV panel analysis for location A

Layer			σ 1				σ 2				τ 12				Combined		τ IL1				τ IL2			
			Act	Rule	Ratio	SF	Act	Rule	Ratio	SF	Act	Rule	Ratio	SF	Ratio	SF	Act	Rule	Ratio	SF	Act	Rule	Ratio	SF
1	UD 600	0	-5.04	-504	>20	2.32	-15	-87.2	5.81	1.38	0.03	38.7	>20	1.77	5.8	1.88	0	-37.6	>20	1.77	0.23	38.7	>20	1.77
2	UD 600	90	-72.2	-504	7.0	2.32	-3.84	-87.2	>20	1.38	-0.03	-38.7	>20	1.77	8.39	1.88	0.27	37.6	>20	1.77	0	38.7	>20	1.77
3	UD 225	0	-4.81	-504	>20	2.32	-14.3	-87.2	6.11	1.38	0.03	38.7	>20	1.77	6.08	1.88	0	-37.6	>20	1.77	0.35	38.7	>20	1.77
4	UD 225	45	-37.2	-504	13.5	2.32	-8.96	-87.2	9.74	1.38	-5.21	-38.7	7.42	1.77	6.37	1.88	0.3	37.6	>20	1.77	0.25	38.7	>20	1.77
5	UD 225	90	-69.3	-504	7.3	2.32	-3.69	-87.2	>20	1.38	-0.03	-38.7	>20	1.77	8.74	1.88	0.4	37.6	>20	1.77	-0.05	-38.7	>20	1.77
6	UD 225	-45	-36.8	-504	13.7	2.32	-8.7	-87.2	10	1.38	5.1	38.7	7.59	1.77	6.52	1.88	-0.3	-37.6	>20	1.77	0.31	38.7	>20	1.77
7	UD 200	0	-4.61	-504	>20	2.32	-13.7	-87.2	6.38	1.38	0.03	38.7	>20	1.77	6.35	1.88	0	-37.6	>20	1.77	0.49	38.7	>20	1.77
8	UD 200	45	-35.6	-504	14.2	2.32	-8.59	-87.2	10.2	1.38	-4.99	-38.7	7.75	1.77	6.65	1.88	0.4	37.6	>20	1.77	0.35	38.7	>20	1.77
9	UD 200	90	-66.4	-504	7.6	2.32	-3.54	-87.2	>20	1.38	-0.03	-38.7	>20	1.77	9.11	1.88	0.53	37.6	>20	1.77	-0.04	-38.7	>20	1.77
10	UD 200	-45	-35.3	-504	14.3	2.32	-8.35	-87.2	10.4	1.38	4.89	38.7	7.91	1.77	6.8	1.88	-0.39	-37.6	>20	1.77	0.4	38.7	>20	1.77
11	UD 400	45	-34.4	-504	14.7	2.32	-8.28	-87.2	10.5	1.38	-4.82	-38.7	8.03	1.77	6.9	1.88	0.48	37.6	>20	1.77	0.39	38.7	>20	1.77
12	UD 400	-45	-34	-504	14.8	2.32	-8.05	-87.2	10.8	1.38	4.72	38.7	8.2	1.77	7.05	1.88	-0.45	-37.6	>20	1.77	0.48	38.7	>20	1.77
13 Top	PVC130	0	-0.07	-3.22	>20	1.85	-0.26	-3.22	12.3	1.85	0	2.44	>20	2.20	12.9	1.88	0	-2.44	>20	2.20	0.64	2.44	3.79	2.20
13 Bot	PVC130	0	0.06	4.35	>20	1.85	0.23	4.35	18.8	1.85	0	2.44	>20	2.20	>20	1.88	0	-2.44	>20	2.20	0.65	2.44	3.78	2.20
14	UD 400	45	30.1	756	>20	2.32	7.13	29.8	4.18	1.38	4.18	38.7	9.25	1.77	3.8	1.88	0.46	37.6	>20	1.77	0.48	38.7	>20	1.77
15	UD 400	-45	30.5	756	>20	2.32	7.35	29.8	4.06	1.38	-4.28	-38.7	9.03	1.77	3.69	1.88	-0.48	-37.6	>20	1.77	0.4	38.7	>20	1.77
16	UD 200	0	3.94	756	>20	2.32	11.8	29.8	2.53	1.38	0.02	38.7	>20	1.77	2.54	1.88	0	37.6	>20	1.77	0.56	38.7	>20	1.77
17	UD 200	45	31.7	756	>20	2.32	7.52	29.8	3.97	1.38	4.41	38.7	8.78	1.77	3.61	1.88	0.36	37.6	>20	1.77	0.37	38.7	>20	1.77
18	UD 200	90	59.9	756	12.6	2.32	3.18	29.8	9.38	1.38	-0.02	-38.7	>20	1.77	7.73	1.88	0.48	37.6	>20	1.77	0.04	38.7	>20	1.77
19	UD 200	-45	32.2	756	>20	2.32	7.74	29.8	3.85	1.38	-4.51	-38.7	8.58	1.77	3.51	1.88	-0.36	-37.6	>20	1.77	0.32	38.7	>20	1.77

20	UD 225	0	4.12	756	>20	2.32	12.4	29.8	2.41	1.38	0.02	38.7	>20	1.77	2.43	1.88	0	37.6	>20	1.77	0.45	38.7	>20	1.77
21	UD 225	45	33.2	756	>20	2.32	7.88	29.8	3.78	1.38	4.62	38.7	8.38	1.77	3.44	1.88	0.27	37.6	>20	1.77	0.28	38.7	>20	1.77
22	UD 225	90	62.8	756	12.0	2.32	3.33	29.8	8.94	1.38	-0.02	-38.7	>20	1.77	7.37	1.88	0.35	37.6	>20	1.77	0.04	38.7	>20	1.77
23	UD 225	-45	33.8	756	>20	2.32	8.12	29.8	3.67	1.38	-4.73	-38.7	8.17	1.77	3.34	1.88	-0.27	-37.6	>20	1.77	0.22	38.7	>20	1.77
24	UD 600	0	4.37	756	>20	2.32	13.1	29.8	2.28	1.38	0.02	38.7	>20	1.77	2.29	1.88	0	37.6	>20	1.77	0.31	38.7	>20	1.77
25	UD 600	90	67	756	11.3	2.32	3.56	29.8	8.38	1.38	-0.02	-38.7	>20	1.77	6.9	1.88	0.1	37.6	>20	1.77	0	-38.7	>20	1.77
26	CSM 300	0	6.26	114	18.2	2.32	19.8	114	5.76	1.38	0.03	56.7	>20	1.77	6.5	1.88	0	19.5	>20	1.77	0.06	19.5	>20	1.77

Appendix G.2. BV panel analysis for location B

Layer			σ 1				σ 2				τ 12				Combined		τ IL1				τ IL2			
			Act	Rule	Ratio	SF	Act	Rule	Ratio	SF	Act	Rule	Ratio	SF	Ratio	SF	Act	Rule	Ratio	SF	Act	Rule	Ratio	SF
1	UD 600	0	-50.2	-504	10.0	2.32	-2.7	-87.2	>20	1.38	0.02	38.7	>20	1.77	12.1	1.88	0.01	37.6	>20	1.77	0	-38.7	>20	1.77
2	UD 600	90	-3.47	-504	>20	2.32	-9.85	-87.2	8.85	1.38	-0.02	-38.7	>20	1.77	8.81	1.88	0	-37.6	>20	1.77	-0.03	-38.7	>20	1.77
3	UD 225	0	-47.9	-504	10.5	2.32	-2.58	-87.2	>20	1.38	0.02	38.7	>20	1.77	12.6	1.88	0.04	37.6	>20	1.77	0	-38.7	>20	1.77
4	UD 225	45	-25.2	-504	20.0	2.32	-6.07	-87.2	14.4	1.38	3.51	38.7	11	1.77	9.43	1.88	0.03	37.6	>20	1.77	-0.03	-38.7	>20	1.77
5	UD 225	90	-3.34	-504	>20	2.32	-9.45	-87.2	9.23	1.38	-0.02	-38.7	>20	1.77	9.19	1.88	0.01	37.6	>20	1.77	-0.05	-38.7	>20	1.77
6	UD 225	-45	-24.9	-504	>20	2.32	-5.9	-87.2	14.8	1.38	-3.43	-38.7	11.3	1.77	9.66	1.88	0.04	37.6	>20	1.77	0.04	38.7	>20	1.77
7	UD 200	0	-45.8	-504	11.0	2.32	-2.47	-87.2	>20	1.38	0.02	38.7	>20	1.77	13.2	1.88	0.05	37.6	>20	1.77	0	-38.7	>20	1.77
8	UD 200	45	-24.2	-504	>20	2.32	-5.82	-87.2	15	1.38	3.36	38.7	11.5	1.77	9.85	1.88	0.04	37.6	>20	1.77	-0.04	-38.7	>20	1.77
9	UD 200	90	-3.21	-504	>20	2.32	-9.06	-87.2	9.63	1.38	-0.02	-38.7	>20	1.77	9.59	1.88	0.01	37.6	>20	1.77	-0.07	-38.7	>20	1.77
10	UD 200	-45	-23.9	-504	>20	2.32	-5.66	-87.2	15.4	1.38	-3.29	-38.7	11.8	1.77	10.1	1.88	0.05	37.6	>20	1.77	0.05	38.7	>20	1.77
11	UD 400	45	-23.3	-504	>20	2.32	-5.61	-87.2	15.5	1.38	3.24	38.7	11.9	1.77	10.2	1.88	0.06	37.6	>20	1.77	-0.05	-38.7	>20	1.77
12	UD 400	-45	-23.1	-504	>20	2.32	-5.45	-87.2	16	1.38	-3.17	-38.7	12.2	1.77	10.4	1.88	0.06	37.6	>20	1.77	0.06	38.7	>20	1.77
13 Top	PVC130	0	-0.18	-3.22	18.2	1.85	-0.05	-3.22	>20	1.85	0	2.44	>20	2.20	19.1	1.88	0.08	2.44	>20	2.20	0	-2.44	>20	2.20

13 Bot	PVC130	0	0.16	4.35	>20	1.85	0.04	4.35	>20	1.85	0	2.44	>20	2.20	>20	1.88	0.08	2.44	>20	2.20	0	-2.44	>20	2.20
14	UD 400	45	20.8	756	>20	2.32	4.92	29.8	6.06	1.38	-2.91	-38.7	13.3	1.77	5.5	1.88	0.06	37.6	>20	1.77	-0.06	-38.7	>20	1.77
15	UD 400	-45	21.1	756	>20	2.32	5.07	29.8	5.88	1.38	2.98	38.7	13	1.77	5.34	1.88	0.06	37.6	>20	1.77	0.05	38.7	>20	1.77
16	UD 200	0	40.5	756	18.7	2.32	2.12	29.8	14.1	1.38	0.02	38.7	>20	1.77	11.5	1.88	0.07	37.6	>20	1.77	0	38.7	>20	1.77
17	UD 200	45	21.9	756	>20	2.32	5.18	29.8	5.75	1.38	-3.06	-38.7	12.6	1.77	5.22	1.88	0.05	37.6	>20	1.77	-0.05	-38.7	>20	1.77
18	UD 200	90	2.62	756	>20	2.32	8.35	29.8	3.57	1.38	-0.02	-38.7	>20	1.77	3.59	1.88	0	-37.6	>20	1.77	-0.07	-38.7	>20	1.77
19	UD 200	-45	22.2	756	>20	2.32	5.33	29.8	5.59	1.38	3.13	38.7	12.3	1.77	5.08	1.88	0.04	37.6	>20	1.77	0.04	38.7	>20	1.77
20	UD 225	0	42.4	756	17.8	2.32	2.22	29.8	13.4	1.38	0.02	38.7	>20	1.77	11	1.88	0.06	37.6	>20	1.77	0	38.7	>20	1.77
21	UD 225	45	22.9	756	>20	2.32	5.43	29.8	5.49	1.38	-3.21	-38.7	12.1	1.77	4.98	1.88	0.04	37.6	>20	1.77	-0.04	-38.7	>20	1.77
22	UD 225	90	2.76	756	>20	2.32	8.75	29.8	3.41	1.38	-0.02	-38.7	>20	1.77	3.42	1.88	0	-37.6	>20	1.77	-0.05	-38.7	>20	1.77
23	UD 225	-45	23.3	756	>20	2.32	5.6	29.8	5.33	1.38	3.28	38.7	11.8	1.77	4.84	1.88	0.03	37.6	>20	1.77	0.03	38.7	>20	1.77
24	UD 600	0	44.9	756	16.8	2.32	2.35	29.8	12.7	1.38	0.02	38.7	>20	1.77	10.4	1.88	0.04	37.6	>20	1.77	0	38.7	>20	1.77
25	UD 600	90	2.95	756	>20	2.32	9.33	29.8	3.2	1.38	-0.02	-38.7	>20	1.77	3.21	1.88	0	37.6	>20	1.77	-0.03	-38.7	>20	1.77
26	CSM 300	0	13.7	114	8.3	2.32	4.28	114	>20	1.38	0.02	56.7	>20	1.77	9.42	1.88	0.01	19.5	>20	1.77	0	19.5	>20	1.77

Appendix G.3. DNV panel analysis

Layer			σ 1				σ 2				τ 12			
			Act	Rule	Ratio	SF	Act	Rule	Ratio	SF	Act	Rule	Ratio	SF
1	UD 600	0	-10.1	419.784	>20	2.85	-44.4	84.396	1.90081081	2.85	0.09	32.232	>20	2.85
2	UD 600	90	-215	419.784	1.952483721	2.85	-10.5	84.396	8.03771429	2.85	-0.09	32.232	>20	2.85
3	UD 225	0	-9.61	419.784	>20	2.85	-42.3	84.396	1.9951773	2.85	0.09	32.232	>20	2.85
4	UD 225	45	-108	419.784	3.886888889	2.85	-26.1	84.396	3.23356322	2.85	-15.9	32.232	2.02717	2.85
5	UD 225	90	-206	419.784	2.037786408	2.85	-10.1	84.396	8.3560396	2.85	-0.09	32.232	>20	2.85
6	UD 225	-45	-107	419.784	3.923214953	2.85	-25.4	84.396	3.32267717	2.85	15.5	32.232	2.079484	2.85
7	UD 200	0	-9.2	419.784	>20	2.85	-40.5	84.396	2.08385185	2.85	0.09	32.232	>20	2.85

8	UD 200	45	-104	419.784	4.036384615	2.85	-25	84.396	3.37584	2.85	-15.2	32.232	2.120526	2.85
9	UD 200	90	-198	419.784	2.120121212	2.85	-9.65	84.396	8.74569948	2.85	-0.09	32.232	>20	2.85
10	UD 200	-45	-103	419.784	4.075572816	2.85	-24.3	84.396	3.47308642	2.85	14.9	32.232	2.163221	2.85
11	UD 400	45	-100	419.784	4.19784	2.85	-24.1	84.396	3.50190871	2.85	-14.7	32.232	2.192653	2.85
12	UD 400	-45	-99.2	419.784	4.231693548	2.85	-23.5	84.396	3.59131915	2.85	14.4	32.232	2.238333	2.85
13 Top	PVC130	0	-0.2	1.656	8.28	2.375	-0.78	1.656	2.12307692	2.375	0.0001	0.66	>20	2.375
13 Bot	PVC130	0	0.17	1.656	9.741176471	2.375	0.69	1.656	2.4	2.375	0.00001	0.66	>20	2.375
14	UD 400	45	87.7	419.784	4.78659065	2.85	20.8	84.396	4.0575	2.85	12.8	32.232	2.518125	2.85
15	UD 400	-45	89	419.784	4.716674157	2.85	21.4	84.396	3.94373832	2.85	-13.1	32.232	2.460458	2.85
16	UD 200	0	7.73	419.784	>20	2.85	35	84.396	2.41131429	2.85	0.07	32.232	>20	2.85
17	UD 200	45	92.5	419.784	4.538205405	2.85	21.9	84.396	3.85369863	2.85	13.4	32.232	2.405373	2.85
18	UD 200	90	178	419.784	2.358337079	2.85	8.65	84.396	9.75676301	2.85	-0.07	32.232	>20	2.85
19	UD 200	-45	93.7	419.784	4.480085379	2.85	22.5	84.396	3.75093333	2.85	-13.8	32.232	2.335652	2.85
20	UD 225	0	8.1	419.784	>20	2.85	36.6	84.396	2.30590164	2.85	0.07	32.232	>20	2.85
21	UD 225	45	96.9	419.784	4.332136223	2.85	23	84.396	3.6693913	2.85	14.1	32.232	2.285957	2.85
22	UD 225	90	187	419.784	2.244834225	2.85	9.08	84.396	9.29471366	2.85	-0.07	32.232	>20	2.85
23	UD 225	-45	98.4	419.784	4.266097561	2.85	23.7	84.396	3.56101266	2.85	-14.4	32.232	2.238333	2.85
24	UD 600	0	8.59	419.784	>20	2.85	38.8	84.396	2.17515464	2.85	0.07	32.232	>20	2.85
25	UD 600	90	199	419.784	2.109467337	2.85	9.68	84.396	8.71859504	2.85	-0.07	32.232	>20	2.85
26	CSM 300	0	17.3	110.52	6.388439306	2.85	58.7	110.52	1.88279387	2.85	0.09	42.504	>20	2.85

Appendix G.4. LR panel analysis

No	Ply	f_c	t (mm)	Lever @ base, x (mm)	E (N/mm^2)	E t (N/mm^2)	E t x	I @ base	EI @ base	Lever @ NA, x (mm)	Act σ	Rule σ	Check
1	BIAXIAL 1200	0.64	1.031	36.41	18700.00	1.93E+04	7.02E+05	13668	2.56E+08	19.13	118.81	47.0	2.53
2	QUAD 900	0.64	0.773	35.50	18700.00	1.45E+04	5.13E+05	9749	1.82E+08	18.10	112.41	47.0	2.39
3	QUAD 800	0.64	0.687	34.77	18700.00	1.29E+04	4.47E+05	8313	1.55E+08	17.33	107.60	47.0	2.29
4	DB 800	0.64	0.687	34.09	18700.00	1.29E+04	4.38E+05	7987	1.49E+08	16.64	103.34	47.0	2.20
6	PVC130	–	30	18.74	138.00	4.14E+03	7.76E+04	105371	1.45E+07	15.95	0.73	0.9	0.81
7	DB 800	0.64	0.687	3.40	19600.00	1.35E+04	4.58E+04	79	1.56E+06	-14.73	-95.88	68.9	1.39
8	QUAD 800	0.64	0.687	2.71	19600.00	1.35E+04	3.65E+04	50	9.90E+05	-15.42	-100.36	68.9	1.46
9	QUAD 900	0.64	0.773	1.98	19600.00	1.52E+04	3.00E+04	30	5.94E+05	-16.19	-105.39	68.9	1.53
10	BIAXIAL 1200	0.64	1.031	1.08	19600.00	2.02E+04	2.18E+04	12	2.35E+05	-17.22	-112.10	68.9	1.63
11	CSM 300	0.36	0.561631682	0.28	7400.00	4.16E+03	1.17E+03	0	3.28E+03	-17.79	-43.70	27.2	1.61
Sum:			36.92			1.30E+05	2.31E+06		7.61E+08				

Inner skin in compression/outer skin in tension.

Position of neutral axis above base = 17.79 mm

Tensile modulus of elasticity of section = 18196.50 N/mm^2

Stiffness EI about neutral axis = 34910.50 $N\ cm^4/mm^2$ per 1 cm wide strip