

Validation of Practical Approaches for the Strength Evaluation of High-speed Catamaran under Beam and Quartering Seas

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Abstract

The structural scantling of High Speed Craft (HSC) of length less than 50 m is mostly driven by the local scantling requirements related to the design pressure and acceleration. However, for the case of catamaran-type HSC such as the two passenger ships considered in this study, the Class rules require also to assess the Cross-deck structural strength under Beam and Quartering Seas. For that purpose, this study employed simplified approaches which the most common consist in (1) a Cross-deck girder undergoing the Beam Sea induced transverse bending moment and (2) a system of longitudinal and transverse Finite Elements beams to reproduce the interaction between the Floats and the Cross-deck subjected to the Quartering Sea induced pitch connection moment. This study validated then the accuracy of the stresses predicted by the simplified methods by comparison with detailed finite element analysis results. However, limitations were also identified regarding the effect of the stiffness of the Float to Cross-deck connection, the consideration of the longitudinal component of stress and the superstructure additional strength. This study also conducted Seakeeping analyses for comparison with the rules design vertical acceleration.

Keyword: Catamaran, Strength, Beam & Quartering Sea.

1. INTRODUCTION

The structural scantling of High Speed Craft (HSC) of length less than 50 m is mostly driven by the local scantling requirements related to the design pressure and acceleration. However, for the case of catamaran-type HSC, the rules require also to assess the Cross-deck structural strength under Beam and Quartering Seas. The most precise approach consists in a detailed finite element analysis entailing a full ship FE model that at the least must reproduce the primary support members of the ship structure using Shell elements, whereas the stiffeners can be represented through Beam elements. However, such an approach is very time consuming in terms of modeling. Simplified approaches are often proposed by Class that neglects the superstructure effect (e.g. passenger ships) and the longitudinal component of stress in the Cross-deck. Those methods are very practical especially for the early stage of design, but they might not be accurate enough for final strength verification. The detailed FE model of the ship might thus still need to be produced upon Class request, but the extent of required structural changes and consecutive remodeling will be limited since the structure will already conform to the first principles of the structural response as ensured by the simplified approaches, and the FE modeling process would thus be optimized.

This study evaluated the Cross-deck structural strength of two passenger high-speed catamarans hereafter referred as HSC1 and HSC2. Tables 1 and 2 list the main particulars and the Cross deck structural arrangement of the two investigated ships. In a first section, rules loads are calculated and Seakeeping analyses are conducted for comparison with the rules design vertical acceleration. The second section compares the Cross-deck stresses obtained by the simplified methods to those produced by detailed finite element analyses. The third section discusses on the simplified approaches limitations and possible ameliorations.

Table 1. Ships main particulars.

	HSC1	HSC2
Length at the water line, L_{wl}	39.5 m	31.6 m
Breadth, B	10.0 m	8.2 m
Float width amidship, B_W	2.6 m	2.5 m
Depth, D	3.4 m	2.9 m
Draft amidship, T	1.3 m	1.3 m
Service speed, V_s	29.2 knt	15.0 knt
Design vertical acceleration, a_c	0.925 g's	0.403 g's

Table 2. Design loads and Cross-deck structural arrangement.

	HSC1	HSC2
Rules transverse bending moment, M_{bt}	4482 kN.m	1750 kN.m
Rules pitch connection moment, M_{tt}	15173 kN.m	6522 kN.m
Cross-deck height, H_{CD}	0.8 m	0.3 m
Cross deck width between Floats, S	3.4 m	2.7 m
Transverse frame spacing (avg.), w	1.0 m	0.8 m
Strength deck thickness, t_{s-deck}	2 mm	6 mm
Wet deck thickness, t_{w-deck}	6 mm	6 mm

2. RULES LOADS AND SEAKEEPING COMPUTATIONS

It is known that ship motion in waves is one of the major source of structural loads, especially vertical accelerations are directly related to ships loads for high speed crafts. Typically there are two approaches to determine accelerations: direct numerical simulation, shown in Figure 1, and rule calculation. The former is based on potential flow theory, while the latter in the present study is according to CR Rules^[1]. The direct numerical method usually has higher accuracy as considering full hull geometry descriptions, but suffers theoretical limitations, which are 3D panel method by using zero-forward speed Green function in frequency domain, with encounter-frequency correction for forward speed effect. The solution is linearized about mean water level and only calculates submerged hull surface under this level. It should be recognized that solutions become unrealistic as the wave height increasing or too high forward speeds.

Figure 2 shows seakeeping results of HSC1, vertical acceleration at center of gravity at different ship speeds were obtained by the two aforementioned methods. The red line was evaluated by direct numerical simulation and the blue one is by rule calculation. Sea condition was set at 2 m significant wave height condition to meet the linear wave assumption. The two methods match each other at low speed, but obviously the direct simulation significantly underpredicted than rule values and is incapable in the high speed range. As a consequence, it is recommended and conducted to apply rule calculation to determine vertical accelerations and hence ship loads for high speed crafts.

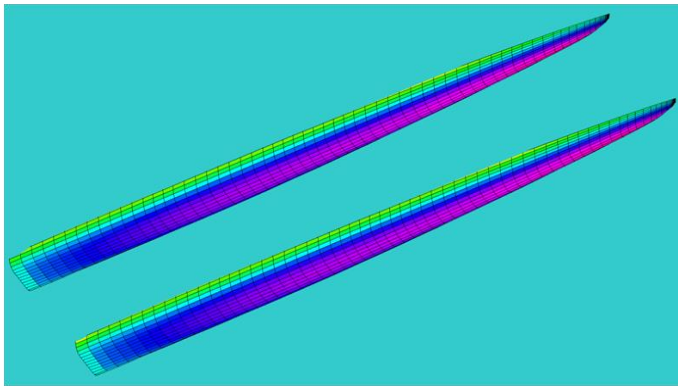


Fig.1 Illustration of ship hydrodynamic pressure by using direct numerical method.

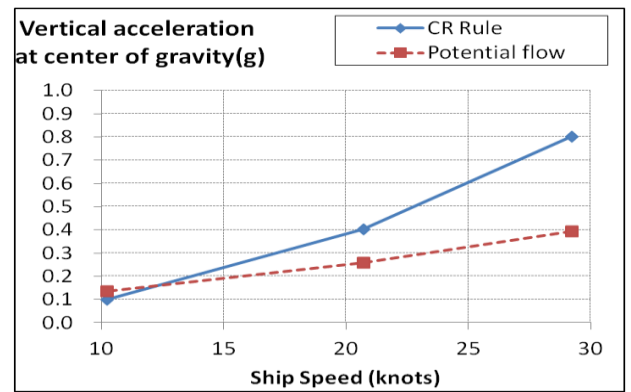


Fig.2 Vertical acceleration at center of gravity at different ship speeds.

3. STRUCTURAL RESPONSE EVALUATION

For both target ships, HSC1 and HSC2, the structural response evaluation was conducted using simplified approaches and, for validation, was also produced by detailed Finite Element Analyses (FEA).

Detailed Finite Element Analyses

Both ship FE models were made of Shell elements with a global mesh size of one tenth of frame spacing \times one half of stiffener spacing for HSC1, and of one half of frame spacing \times one half of stiffener spacing for HSC2. It worth being noted that the coarser mesh adopted for HSC2 is sufficient to evaluate the global strength of the ship, whereas the finer mesh used for HSC1 enables also to evaluate the local yielding in way of stress concentration. The aluminum material was set as isotropic linear with a Young's modulus of 69000 N/mm² and a Poisson ratio of 0.33.

Figure 3 and Table 3 present the boundary conditions applied for the Beam and Quartering Seas load cases. For the Beam Sea, the rules design transverse bending moment M_{bt} in the Cross-deck was reproduced by applying nodal forces at the mid-draft in way of the transverse web frames. Figure 4 shows the load application on the FE model with the horizontal nodal forces taken Y-negative for the starboard float and Y-positive for the port-side float. The uniform horizontal line pressure in force per unit length was calculated using Eq.(1).

$$q_y = [M_{bt} / (z_{NA} - T/2)] / L_{wl} \quad (1)$$

where z_{NA} is the vertical coordinate of the Cross-deck's neutral axis.

For the Quartering Sea, the rules design pitch connection moment M_{tt} in the Cross-deck was reproduced by applying nodal forces at the keel line in way of the transverse web frames. Figure 5 shows the load application on the FE model with the nodal forces taken upwards for the aft half of starboard float and the fore half of port-side float, and downwards for the fore half of starboard float and the aft half of port-side float. The uniform line pressure in force per unit length was calculated using Eq.(2).

$$q_z = 4M_{tt} / L_{wl}^2 \quad (2)$$

For both load cases, the applied forces were balanced, so that the reaction forces at the boundary conditions were negligible. Figures 6 and 7 show the FE results of HSC1 under both load cases.

Table 3. Boundary condition settings.

Beam Sea						
#	UX	UY	UZ	RX	RY	RZ
CL _A						
CL _B						
SB						
PS						
Quartering Sea						
#	UX	UY	UZ	RX	RY	RZ
CL _A						
CL _B						
SB						
PS						

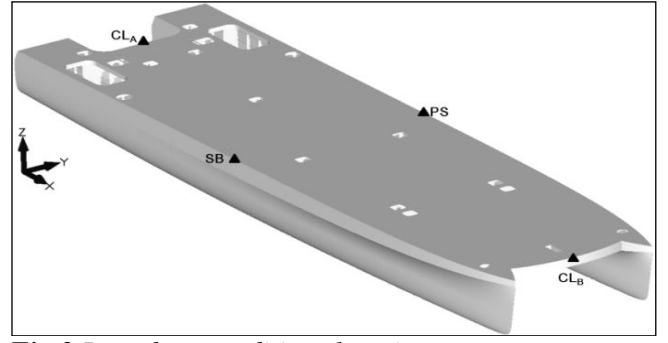


Fig.3 Boundary conditions location.

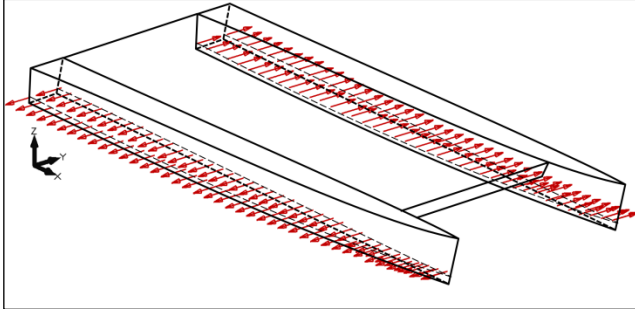


Fig.4 Beam Sea load application.

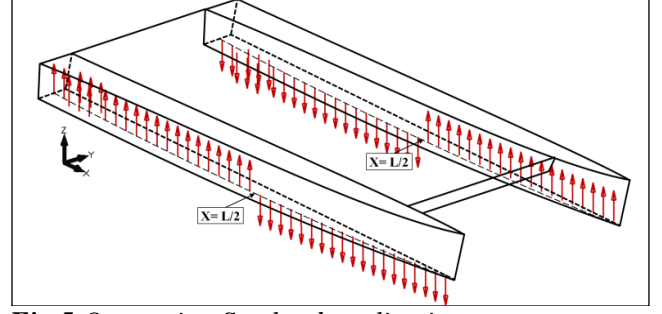


Fig.5 Quartering Sea load application.

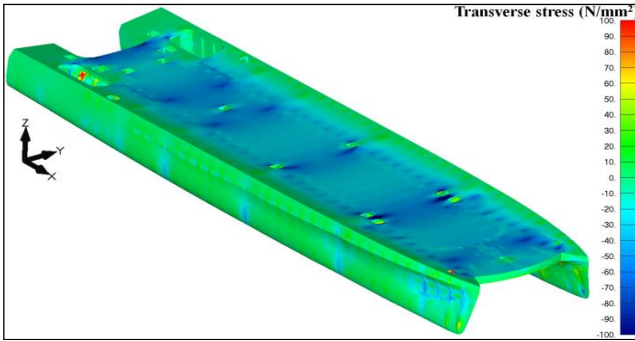


Fig.6 Detailed FEA results for HSC1 under Beam Sea.

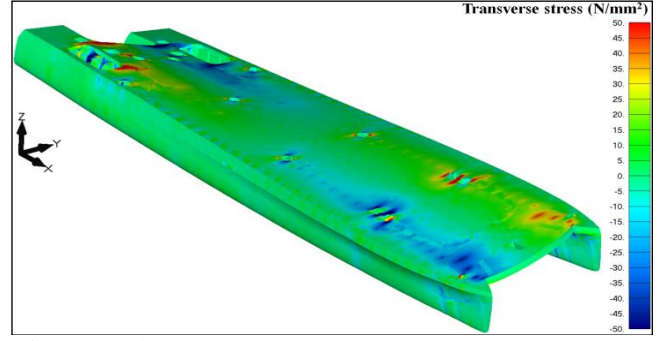


Fig.7 Detailed FEA results for HSC1 under Quartering Sea.

Simplified 'Cross-deck girder' approach for Beam Sea

This approach is commonly used in CR Rules^[1] to evaluate the bending stress on the strength deck and the wet deck, while neglecting the superstructure effect. This approach considers that the transverse bending distribution is constant though the Cross-deck width and that the Cross-deck girder section is symmetric. This last assumption is valid for Cross-deck arrangement such as those of HSC1 and HSC2 where only the deck thickness slightly changes along the ship. However, for catamaran's Cross-deck arrangement that significantly differs along the ship (e.g. higher strength deck at the bow), the non negligible asymmetry of the section would result in the rotation of the section's principal axes that, in view of the structure, would decompose the external vertical bending moment into a vertical and a horizontal internal bending component as shown in Figure 8 For HSC1 and HSC2, the bending stress at the vertical coordinate z of the strength deck and wet deck amidship was calculated using Eq.(3) derived from the Beam theory.

$$\sigma_{yy} = M_{bt}(z_{NA} - z)/I_{yy} \quad (3)$$

where z_{NA} is the Cross-deck neutral axis vertical coordinate from the base line, z is the vertical coordinate of the point on the structure at which the stress is calculated and I_{yy} is the vertical sectional moment inertia.

Figures 11 and 15 present the transverse bending results of HSC1 and HSC2 respectively. It can be observed that the transverse stress distribution along the Cross-deck was fluctuating to values close to those obtained by the Cross-deck girder approach. The stress peaks corresponded to the transverse bulkheads location that are stiffer area in the Floats and thus that transmit more transverse bending loads to the Cross-deck. For HSC1, the fluctuations were very large with stresses at the bulkheads that were approximately two times and three times higher than stresses between bulkheads for the strength deck and the wet deck respectively. Table 4 presents the transverse stresses averaged over the length of the Cross-deck produced by detailed FEA and those obtained by the Cross-deck girder approach that cannot reproduce the stress concentrations at the bulkhead. It can be observed that the averaged stresses were relatively close to the Cross-deck girders values, except for the HSC1's wet deck which the stress was significantly (-

38%) underestimated by the Cross-deck girder approach. To determine the cause of those discrepancies, the FE model section properties were compared to those calculated for the Cross-deck girder method, the results are listed in the Table 4. The FE model cross section area of the Cross-deck was directly read-out from the FE model, while its neutral axis and moment of inertia were deduced from the FE stress at the strength deck ($z_{strength\ deck}$) and on the wet deck ($z_{wet\ deck}$) using the Eq.(4) and (5) that are derived from Eq.(3).

$$z_{NA} = \frac{\sigma_{wet\ deck} \cdot z_{strength\ deck} - \sigma_{strength\ deck} \cdot z_{wet\ deck}}{\sigma_{wet\ deck} - \sigma_{strength\ deck}} \quad (4)$$

$$I_{yy} = \frac{M_{bt} (z_{NA} - z_{strength\ deck})}{\sigma_{strength\ deck}} \quad (5)$$

It appeared that the section areas produced by both methods were similar for both ships. However, the neutral axis vertical coordinate z_{NA} and the sectional vertical moment of inertia I_{yy} deviated between both approaches. Especially, HSC1's moment of inertia produced by the Cross-deck girder approach was 88% of that derived from the detailed FEA results. Therefore, the Cross-deck girder approach can slightly overestimate the transverse bending strength of the structure.

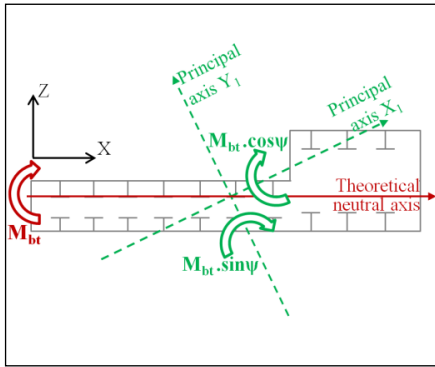


Fig.8 Asymmetric Cross-deck girder.

Table 4. Comparison between detailed FEA and Cross-deck girder methods.

		HSC1			HSC2		
		Cross-deck girder	FEA ^a	CDgir./ FEA	Cross-deck girder	FEA ^a	CDgir./ FEA
$\sigma_{strength\ deck}$	N/mm ²	-43.7	-38.4	114%	-32.9	-28.1	117%
$\sigma_{wet\ deck}$	N/mm ²	23.7	38.0	62%	28.9	30.5	95%
$z_{strength\ deck}$	mm	3400 ^b		-	2859 ^b		-
$z_{wet\ deck}$	mm	2618 ^b		-	2500 ^b		-
A	mm ²	402.3×10 ³	399.0×10 ³	101%	370.9×10 ³	370.9×10 ³	100%
z_{NA}	mm	2893	3007	96%	2668	2687	99%
I_{yy}	mm ⁴	5.19×10 ¹⁰	5.92×10 ¹⁰	88%	1.02×10 ¹⁰	1.07×10 ¹⁰	95%

a) FEA stresses are averaged over the Cross-deck length
b) Decks coordinate from base line at the midship

Simplified approach for Quartering Sea assuming a Cross-deck structure connected to rigid Floats

This simplified approach is proposed by Class^[2] for single plating transversely framed Cross-deck arrangement. However, this study evaluated its validity for the double plating transversely framed Cross-deck arrangement of HSC1 and HSC2. This simplified approach assumes that the Cross-deck structure is connected to rigid Floats, which is similar to consider that the Cross-deck structure is very soft compare to the Float stiffness. This assumption leads to a linear distribution of the Cross-deck vertical deformation along the Float connection that originates from the center of the stiffnesses r_i of the Cross-deck structure located at the abscissa a_r defined using Eq.(6) and that propagates with a slope ω calculated using Eq.(8). Those equations are formulated for a Cross-deck structural modeling that consists in independent parallel transverse beams located at each transverse frame and for which a typical cross-section is shown in Figure 9.

$$a_r = \frac{\sum r_i \cdot x_i}{\sum r_i} \quad (6)$$

with the beam bending stiffness expression assuming restrained beam ends deformation,

$$r_i = \frac{12E \cdot I_{yy,i}}{S_i^3} \quad (7)$$

where x_i is the X-coordinate of the beam i , E is the Young's modulus, $I_{yy,i}$ is the beam sectional vertical moment of inertia and S_i is the beam span or the Cross-deck width taken between the inner hull of each float.

$$\omega = \frac{M_{tt}}{\sum r_i \cdot d_i^2} \quad (8)$$

with

$$d_i = x_i - a_r \quad (9)$$

Eventually, the beams sectional shear force and vertical bending moment at the Float connection can be calculated using Eq.(10) and Eq.(11), respectively. This approach is thus very practical since the bending and shear stress at the end of each beam can be analytically determined.

$$F_i = d_i \cdot \omega \cdot r_i \quad (10)$$

$$M_i = F_i \cdot S_i / 2 \quad (11)$$

Figures 12 to 14 and 16 to 18 present the Cross-deck torsion results of HSC1 and HSC2 respectively. It can be observed that except for the Cross-deck ends, the simplified approach, referred as 'rigid Float' in the Figures, resulted in transverse and shear stress values greater than the detailed FEA results for HSC1, whereas the stress predictions were very similar by both approaches for HSC2. At the Cross-deck ends, the stresses were often largely underestimated by this simplified method. In addition, especially for HSC1, the simplified approach significantly underpredicted the stresses in way of the transverse bulkheads. Finally, it worth being noted that this approach ignores the axial torsion of the beam induced by the vertical deflection at the Float connection whereas Zheng et al (2010)^[3] highlighted that this effect on the stress might not be negligible especially at the Cross-deck ends.

Simplified approach for Quartering Sea assuming a Cross-deck structure connected to deformable Floats

This simplified approach is proposed by EEIG UNITAS^[4] for catamaran and it includes the Float deformation effect. Compared to the simplified method assuming rigid Floats, this method is a bit more complex to conduct since it entails the use of FEA, but the FE model remains very simple to build as shown in Figure 10. The model consists in a system of transverse FE Cross-deck beams with span and sectional properties identical to the rigid Float approach, that are attached at one end to the longitudinal FE Float beam model while the other end is set as fixed. Two opposite concentrated nodal forces, as calculated by Eq.(12), are applied at each end of the Float beam to reproduce the pitch connection moment. The Float beam deformation are then imposed to the Cross-deck beams using rigid connections, which would induce a more realistic load distribution of the pitch connection moment M_{tt} through the Cross-deck.

$$F = M_{tt} / L_{wl} \quad (12)$$

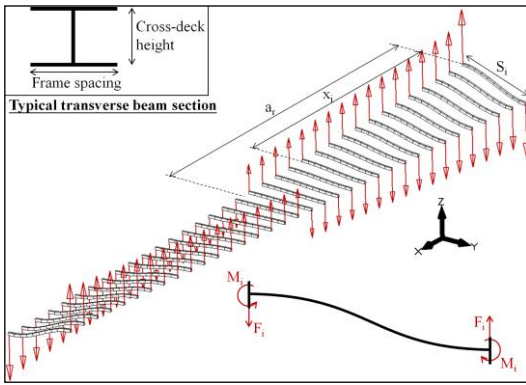


Fig.9 Cross-deck connected to rigid Floats.

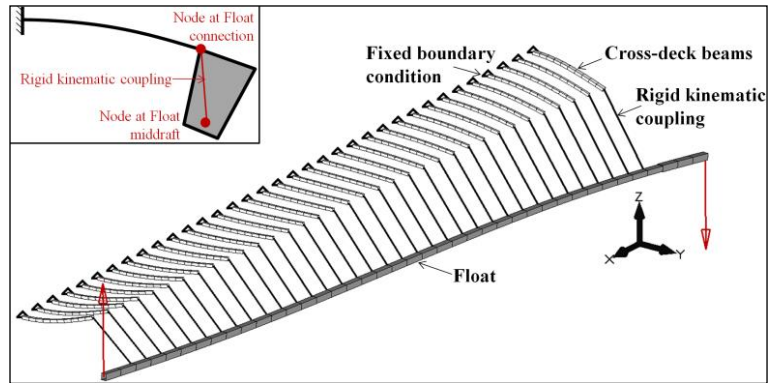


Fig.10 Cross-deck connected to a deformable Float.

Figures 12 to 14 and 16 to 18 present the Cross-deck torsion results of HSC1 and HSC2 respectively. It can be observed that at the Cross-deck ends, the transverse and shear stress distribution, referred as 'deformable Float' in the Figures, was very similar to those produced by the detailed FEA. However, in the remaining of the Cross-deck, the stresses were significantly underestimated for HSC1 and very similar for HSC2. Finally, especially for HSC1 the stresses in way of the bulkhead were underestimated since this simplified approach cannot reproduce their stress concentration effect. In the future, a similar modeling with two deformable Floats connected to the Cross-deck could be considered.

4. DISCUSSION OF THE RESULTS

Float to Cross-deck connection stiffness

The HSC1's deck transverse stresses obtained by the detailed FEA showed very large stress fluctuations along the Cross-deck with peaks at the transverse bulkheads, whereas the stress variations were much smaller for HSC2. This difference would directly be linked to the stiffness of the connection between the Float where the load is applied and the Cross-deck where the stress was read-out. Table 5 presents the Float and Cross-deck bending stiffness r calculated using Eq.(7) for a piece of the Cross-deck (see Figure 19) located amidship and extending over the average transverse bulkheads spacing. It appeared that the Float bending stiffness of HSC1 was about 70% higher than that of the Cross-deck structure, whereas for HSC2 that bending stiffness ratio reached 633%. Therefore, HSC2's Float to Cross-deck connection relative stiffness was significantly higher than the one of HSC1.

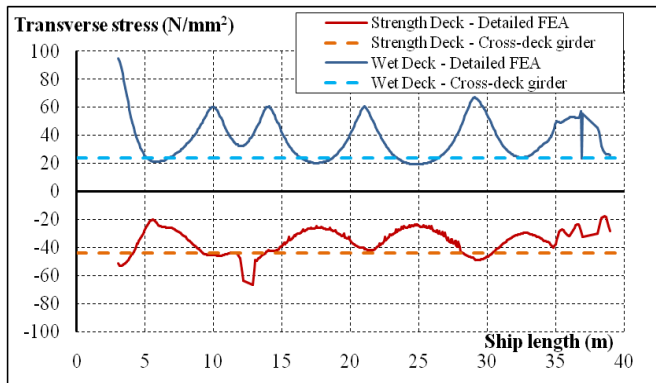


Fig.11 Transverse stress on the Cross-deck structure at the Centerline for the HSC1 under Beam Sea.

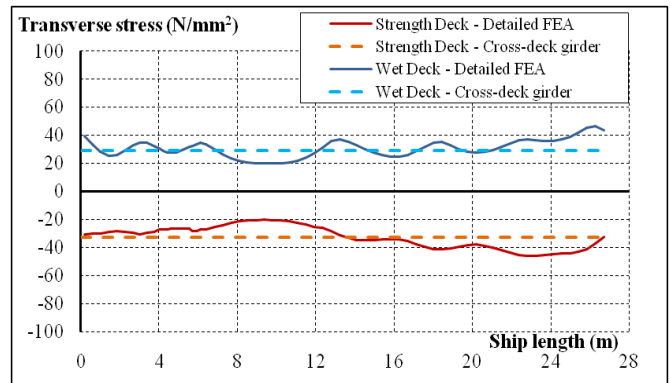


Fig.15 Transverse stress on the Cross-deck structure at the Centerline for the HSC2 under Beam Sea.

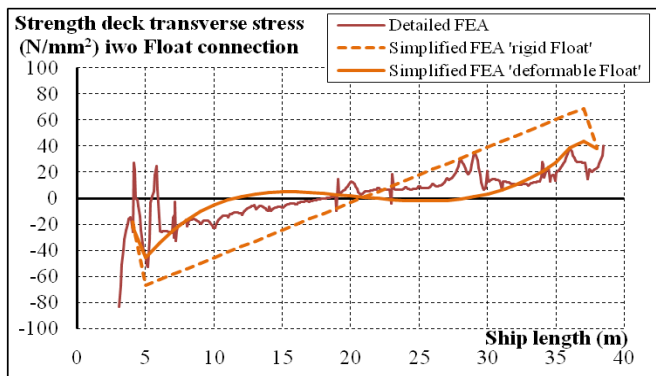


Fig.12 Transverse stress on the Cross-deck's strength deck at the float connection for the HSC1 under Quartering Sea.

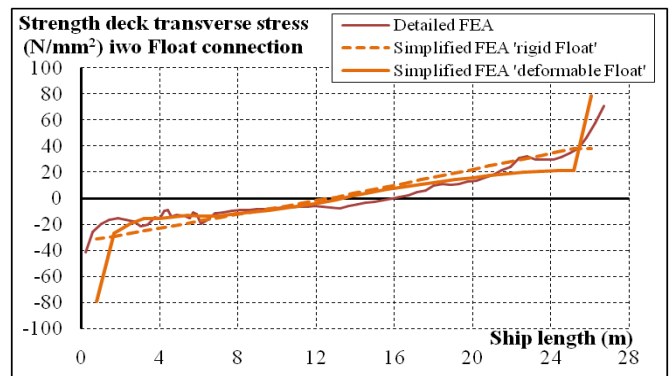


Fig.16 Transverse stress on the Cross-deck's strength deck at the float connection for the HSC2 under Quartering Sea.

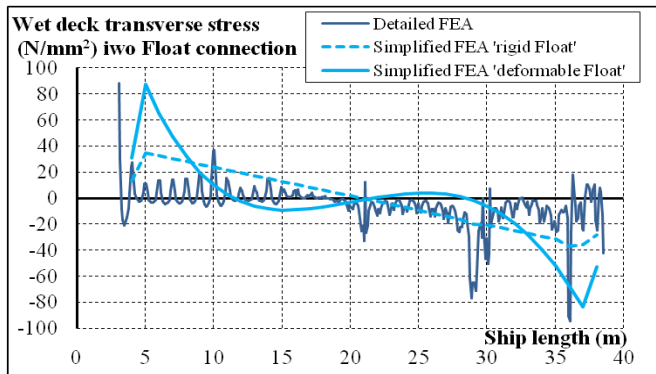


Fig.13 Transverse stress on the Cross-deck's wet deck at the float connection for the HSC1 under Quartering Sea.

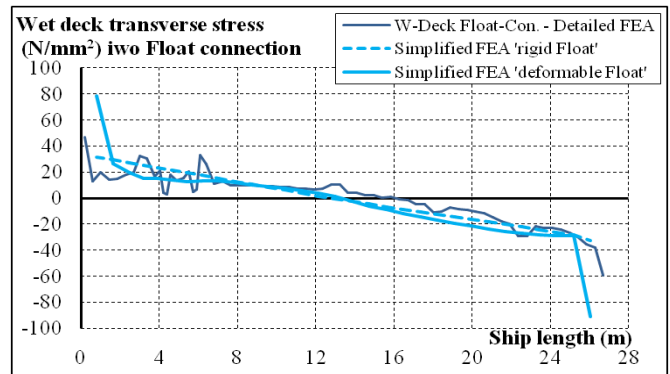


Fig.17 Transverse stress on the Cross-deck's wet deck at the float connection for the HSC2 under Quartering Sea.

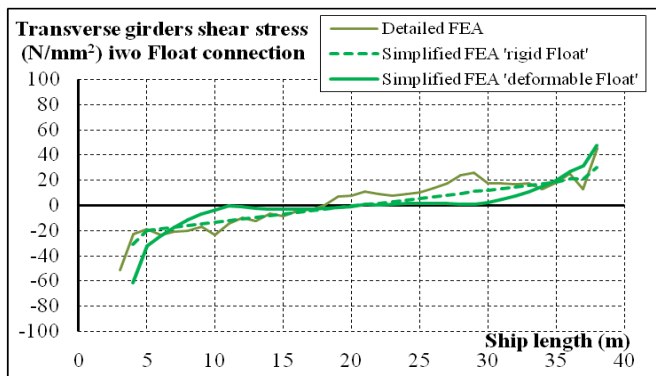


Fig.14 Shear stress on the Cross-deck's transverse structure at the float connection for the HSC1 under Quartering Sea.

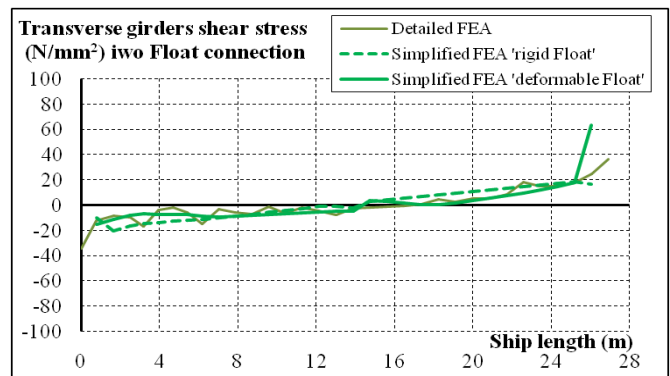


Fig.18 Shear stress on the Cross-deck's transverse structure at the float connection for the HSC2 under Quartering Sea.

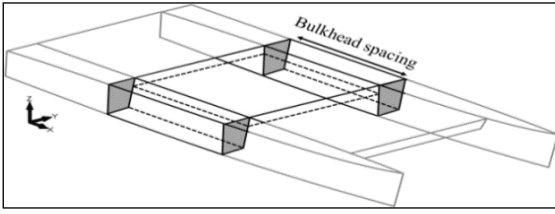


Fig.19 Local Float to Cross-deck model extent.

Table 5. Float and Cross-deck structure stiffness amidship.

		HSC1	HSC2
Cross-deck vertical flexural stiffness over average bulkhead spacing, $r_{Crossdeck}$	N/m	217	79.3
Float vertical flexural stiffness amidship with S = average bulkhead spacing, r_{Float}	N/m	368	502
$r_{Float} / r_{Crossdeck}$	-	170%	633%

The Floats' stiffness and transverse bulkhead spacing effects were already identified by Yasuhira and Hiroyasu (2002)^[5] when they compared the results of an idealized 'box-type catamaran' under Quartering Sea produced through detailed FEA. One might anticipate that a Float to Cross-deck connection rigidity criterion (K_r) satisfying Eq.(13) could be extracted from a sensitivity analysis based on detailed FEA of such simplified 'box-type catamaran' models. Applying this criterion would ensure minimizing the stress concentrations at the transverse bulkheads and would also make the simplified approaches stress predictions reliable.

$$\frac{r_{Float}}{r_{Crossdeck}} = \frac{I_{yy,Float} \cdot S^3 \cdot w}{I_{yy,CDbeam} \cdot L_{bhd}^4} > K_r \quad (13)$$

where w is the average frame spacing, L_{bhd} is the average bulkhead spacing, and $I_{yy,CDbeam}$ is the vertical sectional moment inertia of the Cross-deck transverse beam element as shown in Fig.18.

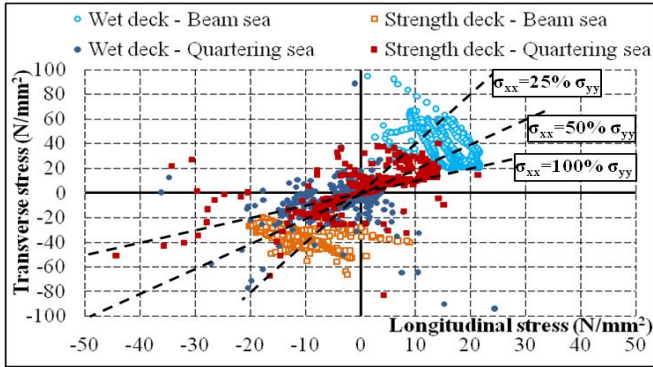


Fig.20 Cross-deck transverse stress vs. longitudinal stress for HSC1.

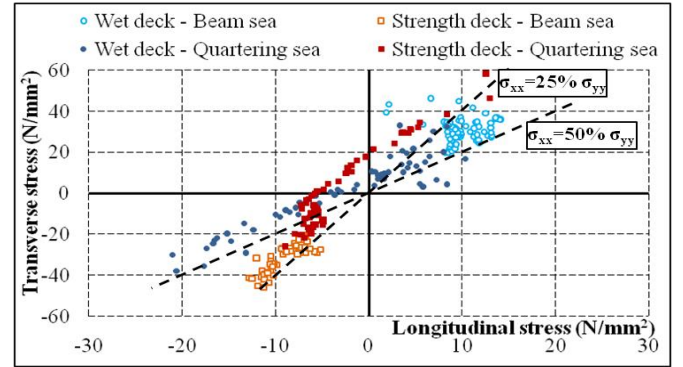


Fig.21 Cross-deck transverse stress vs. longitudinal stress for HSC2.

Longitudinal component of stress

The simplified approaches presented in this study neglects the longitudinal stress in the Cross-deck structure. Figures 20 and 21 relate the transverse stress to the longitudinal stress in the Cross-deck structure obtained by detailed FEA for Beam and Quartering Seas, of HSC1 and HSC2 respectively. As for Figures 11 to 18, the stresses were extracted from the elements along the Cross-deck centerline for the Beam Sea and along the Float connection for the Quartering Sea. It appeared that the relation between the two stress components was much more scattered for HSC1 than for HSC2. As a rough estimate, it can be concluded that, the longitudinal stresses were mostly comprised between 25% and 50% of the transverse stresses, with peaks at 100% for the HSC1 in way of the transverse bulkheads. The longitudinal stresses would thus be non negligible for strength verifications using stress combination criteria e.g. Von Mises stress or buckling ratio. Therefore, a reasonable approach for safe strength evaluation through simplified methods would consist in including longitudinal stresses corresponding to 50% the evaluated transverse stresses.

Superstructure additional strength

The HSC1 is a 2-deck passenger ship which the superstructure extends over the full ship breadth and over 80% the ship length. Therefore, the detailed FEAs of HSC1 including the superstructure were conducted for both load cases in order to evaluate the beneficial effect of the superstructure on the Cross-deck stresses. Figures 22 and 23 present the transverse stress results obtained by detailed FEA with and without the superstructure for both load cases. It can be observed that the contribution of the superstructure decreased the transverse stress by more than 50%. The strength margin provided by omitting the superstructure from the calculations would thus be sufficient to cover the uncertainties of the simplified methods such as the stress concentrations due to soft Float to Cross-deck connection or the omission of the longitudinal stress component as discussed above.

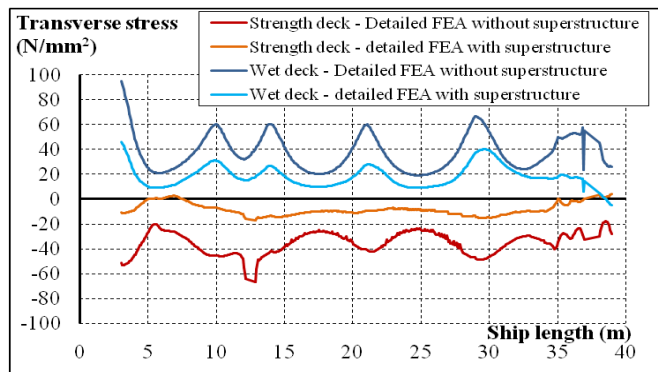


Fig.22 Transverse stress on the Cross-deck structure at the Centerline from detailed FEA with and without superstructure for HSC1 under Beam Sea.

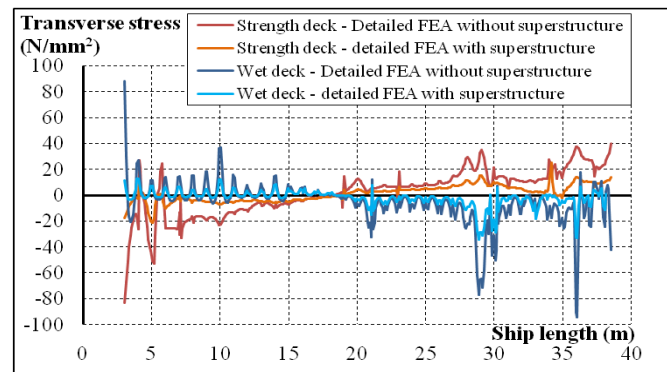


Fig.23 Transverse stress on the Cross-deck structure at the float connection from detailed FEA with and without superstructure for HSC1 under Quartering Sea.

CONCLUSIONS

This study evaluated the validity of simplified approaches for the Cross-deck structural strength evaluation of two passenger high speed catamarans under Beam and Quartering Seas by comparison with detailed Finite Element Analyses. The design loads were calculated accordingly to the rules, and the design accelerations were compared to the results of direct Seakeeping analyses for the design sea state. For the Beam Sea, the Cross-deck girder approach enabled satisfactory assessment of the transverse bending stress on the strength deck and wet deck compared to the detailed FEA stresses averaged along the Cross-deck centerline. For the Quartering Sea, the simplified approach assuming the Cross-deck connected to rigid Floats resulted in safe stress predictions in view of the strength, at the exception of the Cross-deck ends. However, when considering deformable Floats, the simplified approach Cross-deck ends' critical stresses became very close to the detailed FEA results.

This study provided also a discussion about the limitations and possible ameliorations of the simplified approaches by the observation of the detailed FEA results. First, large stress fluctuations were observed along the Cross-deck of HSC1 that would be consistent with the softer Float to Cross-deck connection of HSC1 compared to that of HSC2 which would result in significant stress concentrations in way of the stiffer transverse bulkheads. Such 'soft' design should be avoided and a possible Float to Cross-deck connection rigidity criterion formulation was provided. Then, the detailed FEA showed that the longitudinal stresses should not be omitted by the simplified approaches. For those two ships, a reasonable estimate would consist in taking the longitudinal stresses as 50% the transverse stresses obtained by the simplified methods. Finally, the extended superstructures of passenger ships would result in significant additional strength that makes the simplified approach very conservative. However, for new types of high speed catamarans such as the Offshore Wind Farm Support Vessels, such additional strength margin cannot be considered with regard to the limited extent of the superstructure.

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