# Real time structural loads monitoring for a large high-speed wave-piercing catamaran using numerical simulation and linear regression

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**ABSTRACT**

High-speed wave-piercing catamarans encounter several kinds of global loads; some are similar to those for traditional monohull sea going ships, such as longitudinal bending moment (LBM), shear, torsional and dynamic wave slamming loads. However, due to the twin-hull configuration of the catamaran, additional types of global load are introduced, such as pitch connecting moment (PCM) and transverse bending moment (TBM). This paper investigates the structural health monitoring (SHM) of a high-speed wave-piercing catamaran through prediction of global loads from real-time processing of signals from a large distributed network of strain and acceleration sensors. Finite element method (FEM) and computational fluid dynamic (CFD) analyses at full scale are deployed to simulate catamaran response to loading cases and sea waves. A transformation equation based on a linear regression of the FEA results is applied to measured signals to convert strain signals to global loads. Global loads are also estimated using rigid body dynamics alongside computational fluid dynamics (CFD) simulation of HSV2. Motion and strain data collected from sea trials runs of a 98m high-speed wave-piercing catamaran (HSV-2) are used to confirm the proposed method. The sea trials runs of HSV2 Incat catamaran have been carried out in 2004 in a wide range of sea states, ship speed, wave heights, wave periods and sea wave headings. Longitudinal bending moment (LBM) is estimated for headseas run at 20 knots using two methods based on CFD and FEM simulation.

*Figure 1 A Photograph of Incat HSV-2 Incat High-speed Wave-piercing catamaran [hull 061] during sea trials [1]*

**KEYWORDS:** Global wave loads, finite element method (FEM), computational fluid dynamic (CFD), Wave-piercing catamaran, Full-scale, High-speed vessel.

**NOMENCLATURE:**

| | | | |
|---|---|---|---|
| $M_y$ | Longitudinal bending moment, sagging positive (N.m) | $f_z$ | Vertical component of hydrodynamic force per unit length on the segment (positive up) (N/m) |
| $m_x$ | forward segment mass (kg) | $M_h$ | Hydrodynamic moment on the segment, evaluated at aft end of segment (N.m) |
| $\ddot{h}$ | Heave acceleration at centre of gravity (*CG*), positive up (m/s$^2$) | $I_y$ | Mass moment of inertia of the segment (kg.m$^2$) |
| $\ddot{p}$ | Pitch angular acceleration at CG, positive bow down (rad/s$^2$) | $\varepsilon_x$ | Strain |
| $x_G$ | Distance of segment *CG'* forward of ship's CG (m) | $z$ | Vertical height of neutral axis at the midship section (m) |
| $x'_G$ | Distance from aft end of segment to the segment's *CG'* | $I$ | Second moment of area of section about x-axis (m$^4$) |
| $L$ | Length of vessel (m) | $E$ | Young's modulus (Pa) |

## 1. INTRODUCTION

High-speed catamarans encounter various types of structural loads because of their hull shape and sea wave conditions and thus it is important to predict the vessel structural performance during the design stage. While longitudinal and transverse bending moments and shear forces acting on a catamaran hull can be important in all headings depending on speed and wave height, pitch connecting and torsional moments and splitting forces have their highest effects in oblique seas.

When strain gauge records are available from hull structural monitoring, the data can be used with comprehensive finite-element analyses (FEA) to estimate global loads, [2] and [3]. For example, in the study by Jensen et al. (2001) [4] fibre optic Bragg strain gauges were attached at a cross section near amidships to measure the maximum strain responses for global loads, and strain/load relations were used to measure the global load response continuously and in real-time during tests. The internal ship loads were obtained from strain measurements through data processing using either the method of distortion modes or the conversion matrix [5]. Kefal and Oterkus (2016) [6] also studied the inverse Finite Element Method (iFEM) for real-time reconstruction of full-field structural displacements and stresses in plate and shell structures that are instrumented with strain sensors.

In relation to wave piercing catamarans, the global and slamming loads have been studied previously through experimental tests of an elastic segmented model. The magnitude and location of the dynamic wave slam force and slam induced hull bending moments resulting from dynamic sea wave slamming were investigated by Lavroff et al. (2013) [7] and Shabani et al. (2019) [8]. Global and slam loads of a 112 m Incat wave piercing catamaran (WPC) design were presented [9]. The computed global loads were compared with DNV rule-based loads and empirically derived loads based on full-scale measurements undertaken on similar types of vessels.

On the other hand, computational fluid dynamics (CFD) is considered to be a good tool to numerically study WPCs motions and loads if it is validated through towing-tank and full-scale tests, [10-12]. Centre bow slam loads of wave piercing catamarans can further be determined using computational fluid dynamics (CFD) simulation and compared with model tests for validation [13] whilst slam-induced bending of wave-piercing catamarans in head seas has also been investigated through fluid–structure interaction CFD simulations as reported by McVicar et al. (2018) [14]. Based on using Reynolds-Averaged Navier-Stokes Equations (RANSE), further CFD simulations were done to identify transient slam loads on a 112 m catamaran based on its hydroelastic motion response [15].

In the present study, the global longitudinal bending moment is estimated for a high-speed wave-piercing catamaran. Data records collected in sea trials of Incat catamaran HSV-2 Swift (Figure 1) are studied for this purpose. Results collected from FEA were used as input to the transformation matrix. This is achieved using finite element models provided by the Incat design office, Revolution Design. Load cases applied in the FEA were based on the Det Norske Veritas DNV (2011) [16] code rules for design loads.

## 2. METHOD

Catamaran global loads include longitudinal bending moment, transverse bending moment, pitch connecting moment, shear and splitting forces. The value of these loads depend on relative sea wave heading angle, wave characteristics and ship speed. The longitudinal bending moment (LBM) is one of the main global loads occurring at all heading angles and is investigated in the current work presented. The chart in Figure 2 represents the work process conducted in this study. Catamaran global loads are estimated by applying the load transfer matrix to strain gauge records from sea trials runs. This transformation is based on linear regression of DNV load cases applied in several FEA analyses. Catamaran global loads are also estimated through CFD simulation. Wave characteristics are determined directly from sea trial runs and applied to the CFD run.

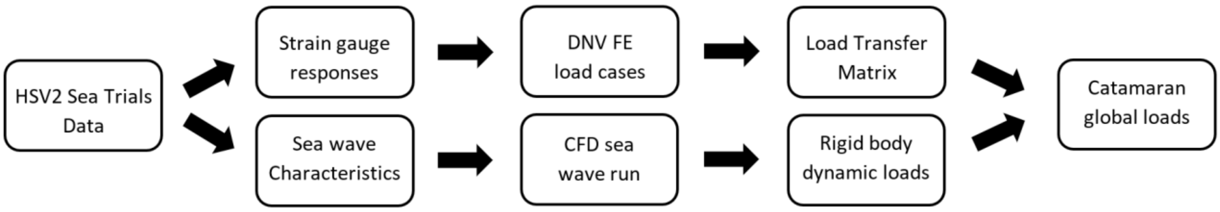



*Figure 2 Process of work based on the development of load prediction using FE transformation matrix and CFD analyses*

### 2.1 Rigid body dynamics

Catamaran internal global loads were estimated through motion and inertia responses using sea trials full-scale strain and motion data [17]. The vertical longitudinal bending moment is estimated using equation (1) which is derived by summing forces and moments about the selected section and eliminating the shear force $V_x$. Positive bending moments correspond to sagging moment and negative to hogging. Figure 3 shows the main forces and moments essential for calculation of internal bending moment at a specified section at distance *x* measured from the forward end of the catamaran.

$$M_y = M_h - m_x x'_G \left( g + \ddot{h} - \ddot{p}\, x_G \right) - I_y \ddot{p} \qquad (1)$$

The hydrodynamic moment term, $M_h$, is the moment calculated about the aft end of the forward segment of $f_z$, the vertical component of the hydrodynamic force acting on the segment (clockwise positive in Figure 3).

## 2.2 Structural model

Global loads can be estimated through strain responses at specific determined positions within the WPC hull. Strain to load conversion is a well-known method to define global bending moment. The strain signal record at strain gauge G5 is used for estimating the longitudinal bending moment (LBM). Strain gauge G5, located on the port keel at frame 26 (details are given in Figure 5 of Section 3), was the most responsive to longitudinal bending moment based on finite element (FE) runs that were undertaken by the design office Revolution Design prior to the sea trials.

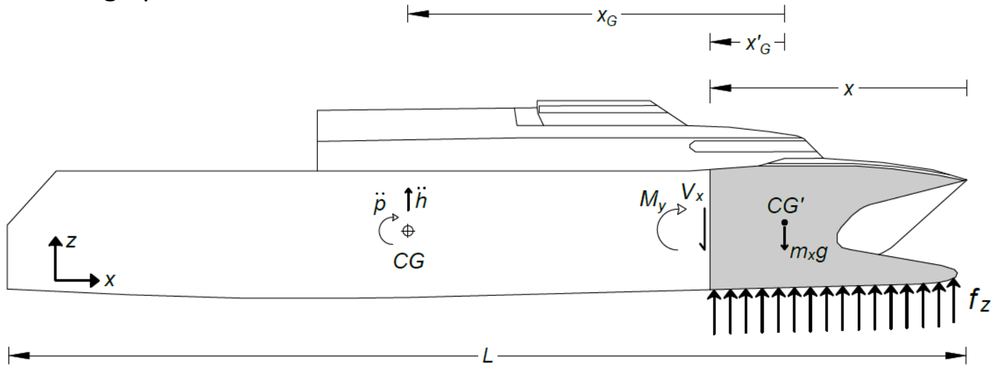



*Figure 3 Rigid body dynamic internal bending load of HSV-2 high-speed catamaran*

A conversion formulation is required in order to convert from strain to global bending moment. Several finite-element runs were performed to estimate the relation between strain response to applied bending load, [18]. The distribution of nodal forces in the FEA model is aimed at replicating the same method of loads application as set by the DNV code rules [16]. Figure 4 shows forces and exaggerated deflection for the longitudinal bending moment case.

Based on the principle of beam analysis there is a one-to-one correspondence between strain and global load, as presented in equation (2). Strain values depend on the applied load value and material and sectional properties *E*, *I* and *z*, which has a constant value for the same location. Consequently, the constant relation *C* between the applied load and corresponding strain is determined through these finite element (FE) cases at the location of strain gauge. It is important to note that this concept would not be valid in the event of slamming and whipping of the catamaran structure. A slamming load is a dynamic impulse load that occurs in a relatively small time period.

$$\varepsilon_x = \frac{M_y \times z}{I \times E} = C\, M_y \qquad (2)$$

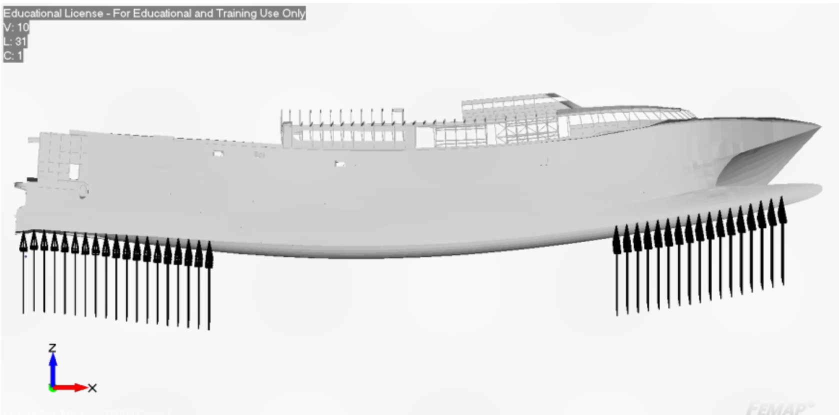



*Figure 4 FE Longitudinal bending FE case [18]*

## 3. HSV-2 SWIFT SEA TRIALS PROGRAMME

Incat catamaran HSV-2 Swift was extensively tested through a large number of sea trial runs by the US Navy and the Naval Surface Warfare Centre Carderock Division (NSWCCD) to assess motion and structural responses of the vessel over a wide range of wave heights, wave periods, wave headings and ship speeds [19]. The sea trials consisted of 22 octagons, each undertaken in a specific sea state, wave height and period, vessel speed and ride control setting. Each octagon consisted of five runs at different heading angles (the three remaining sides of the octagon were assumed to be equivalent by symmetry).

HSV-2 Swift catamaran was equipped with a large number of sensors to record all motions and structural responses. A TSK wave radar was placed on the bow of the forward deck to measure relative wave height during the sea trials. 53 strain gauges were installed on the catamaran to measure structural responses; these gauges were divided into groups, each group relating mainly to a particular global load. Each strain gauge was positioned at the appropriate location to pick up a specific dominant loading response of the vessel. Strain gauge G5 was located at frame number 26, in the X - axis direction at approximately 31.2 m from the stern at the keel level to pick up primarily the longitudinal bending response of the ship, whether for sagging or hogging. Figure 5 shows the locations of strain gauge G5 and the TSK wave radar.

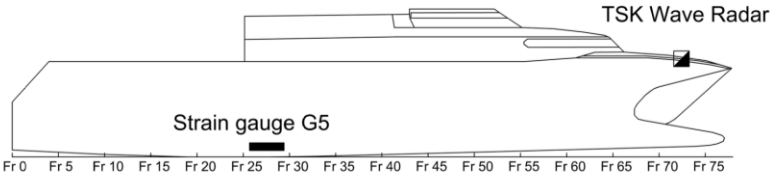



*Figure 5 The location of strain gauge G5 and TSK wave height meter on HSV-2 Swift during sea trials*

One run is selected from sea trials for the present analysis for prediction of the global load. It has been conducted in head seas at a speed of 20 knots for 20 minutes with significant wave height of 2.59 m in low sea state 5. A time record of 30 seconds was selected from the 20 minute run to represent wave loading on the HSV-2 without slamming events and as close as possible to a regular sea wave. This is because slamming events involve shock load and subsequent whipping response, and these effects are not accounted for in the present quasi-static finite element analysis. Figure 6 shows time records of wave height, pitch angle, heave acceleration and strain gauge G5.

## 4. CFD SIMULATION

Computational fluid dynamics (CFD) analysis was undertaken at full-scale to simulate the sea trial run 163 in order to investigate prediction of the global longitudinal bending moment. As mentioned above, the time record selected from run 163 has a wave profile close to a regular wave. Wave characteristics are identified from the 30-sec record. The wave height is set to be 1.7 m and the encounter wave period is taken to be 3.75 seconds peak to peak in this CFD simulation to closely match the data in Figure 6. Since the sea trials were in quasi-regular but random waves no attempt was made to match the phase of the incoming wave with that in the sea trials results.

The flow type of sea water waves used in this simulation is VOF inviscid fluid flow as it provides accurate results in comparatively less running time in full scale simulations. Separate CFD runs were developed to investigate the best flow type that should be used in the current simulation. Viscous laminar, viscous K-Omega turbulent and inviscid VOF fluid flows of sea water were used and compared. Inviscid flow is considered to be most efficient for simulating the full-scale WPC, as it gave comparable accuracy to viscous K-Omega turbulent flow but for significantly less running time. This is because the oscillatory nature of motion in waves is dominated by inertia effects over viscosity effects of water flow [10 and 12]. The overset mesh technique is used in CFD to simulate motions of the catamaran. Figure 7 shows pitch angle motion responses of these three fluid flow simulation types during the initial transient phase as steady-state is approached. It is noted that the amplitudes of pitch motion have less than 10% variation between the three simulations. However, as expected, the viscous turbulent and inviscid solutions are in closer agreement than the viscous laminar solution. This strongly supports the use of the inviscid simulation in the present work since the Reynolds number for the full-scale ship will be very high and the flow will be fully turbulent.

The mesh is refined near the hull and gradually increased towards the domain boundaries [14]. Figure 8 shows the mesh for the fluid surrounding the demihulls in the midship area. The smallest size of fluid mesh element close to hull is set to be 0.3125 m and the largest size of the mesh is 5 m.

Wave damping is applied near the outlet CFD boundary to prevent any wave reflection from the outlet surface back to the model. The domain block size is 4 times the length of the catamaran, 10 times the breadth, and the water depth is 15 times the catamaran draught. These domain dimensions assure that the developed motions of the catamaran in waves is free from any significant reflections that might occur at the boundaries.

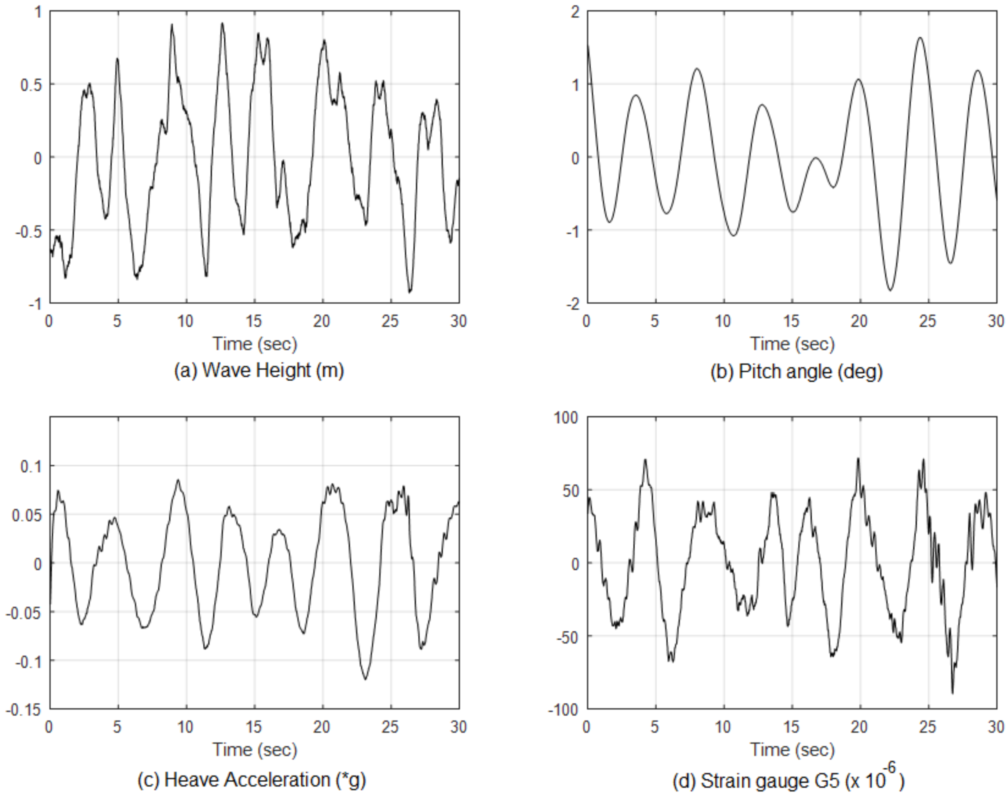



*Figure 6 Sample wave and motion records of run 163 at a speed of 20 knot in head seas with wave height of 1.7m (Data Source : HSV 2 sea trials data [19])*

The CFD simulation is set to run for 60 seconds and after the stabilization of motion responses and after the flow has reached steady state, a 30 seconds period is extracted for validation. A screenshot of the CFD model during bow entry in a wave is shown in Figure 9. This simulation is undertaken using High-performance computing (HPC) with 22 cores at 2.1 GHz and 6 GB RAM. About 48 hours was required for CPU time to run this simulation.

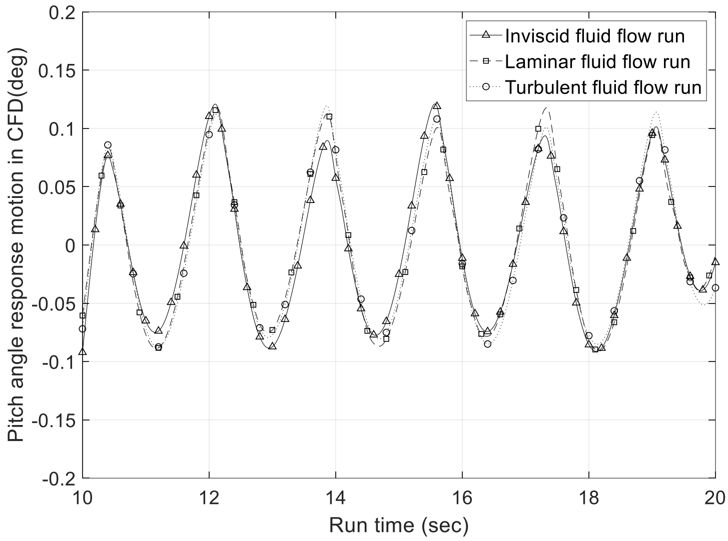



*Figure 7 Pitch motion responses in CFD simulations undertaken with different fluid flow models in 2.44 m wave height of regular wave sea at 20 knots of forward speed*

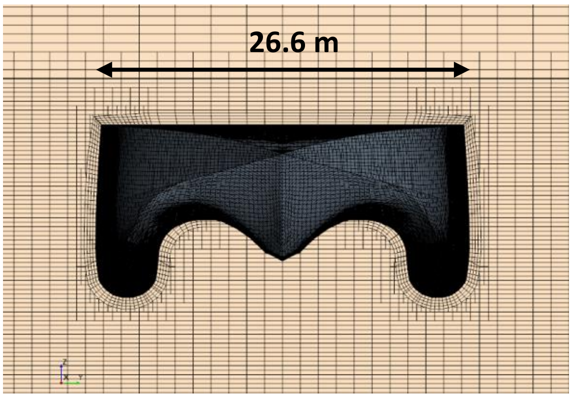



*Figure 8 CFD Model of HSV-2 with mesh*

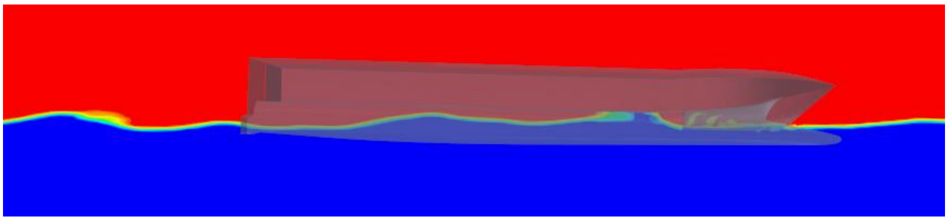
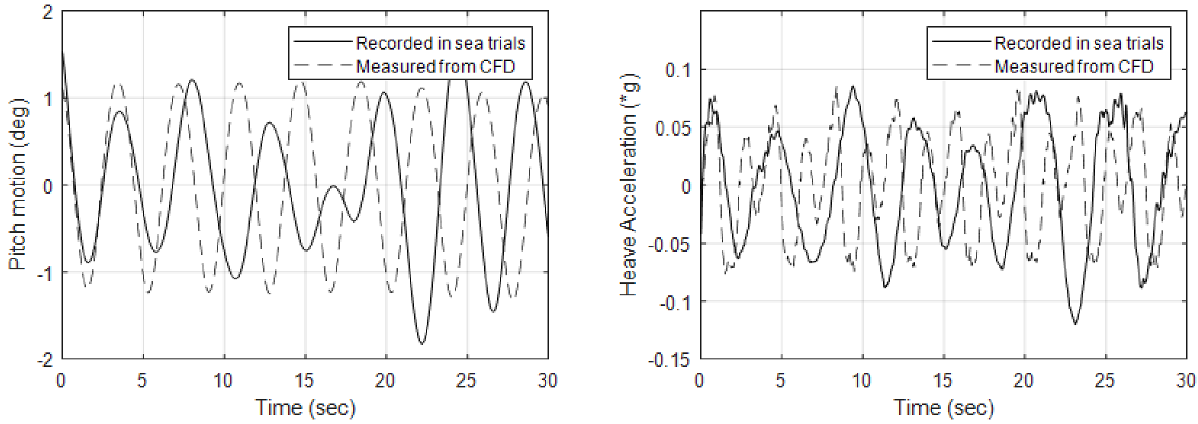


*Figure 9 Wave and motion scene of HSV-2 in regular wave CFD simulation at 20 knots forward speed*

Motion responses are compared between CFD simulation and sea trial records, as shown in figure 10. It is observed that there is agreement between the amplitudes of pitch angle and heave acceleration with those from sea trial run. However, a phase shift is also seen between motion records. As explained above, the CFD simulation assumes a regular wave with specific wave period, whereas the sea trial record has some small irregularities in the wave period and amplitude due to the random nature of sea waves as expected. In the CFD simulation it is difficult to set the same wave profile as in the sea trials runs, so it has been approximated to a degree where comparisons and validation between simulation and real sea trial run are attained.




(a) Pitch motion angle (b) Heave Acceleration

*Figure 10 Motion of sea trial run compared with inviscid CFD simulation run undertaken at 20 knots of forward speed and 1.7m wave height.*

Longitudinal bending moment (LBM) is estimated through a CFD simulation and rigid body dynamics formulation as discussed in section 2.1. This LBM is calculated at the sectional location of frame 26. It is compared with the longitudinal bending moment that is estimated based on strain gauge G5 record, through the strain-load conversion matrix. The still-water bending moment is subtracted from both load predictions (in the case of the sea trials by subtracting the mean from the strain gauges since it is impossible to quantify a true zero as there will always be some stress in the hull when the gauges are zeroed). Thus, the dynamic component of the load is investigated. Figure 11 compares the two longitudinal bending moment predictions. Although there is again a phase shift between the two load predictions, the load amplitudes agree well: longitudinal bending moment (LBM) values range between peaks of +/- 32 MN.m in sagging and hogging repetitively.

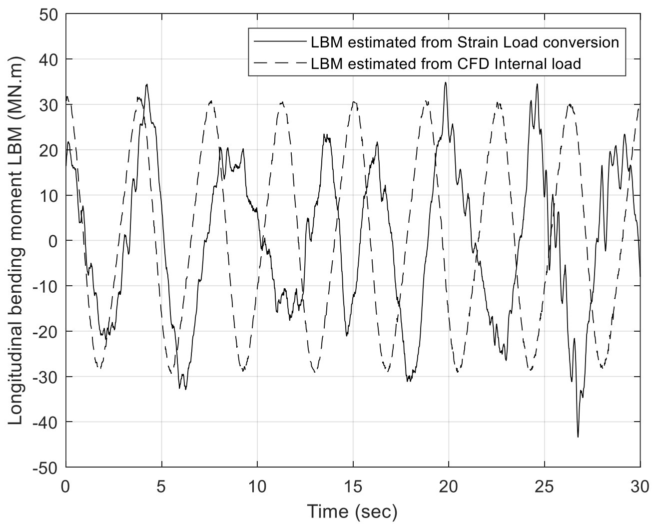



*Figure 11 Predicted value of Longitudinal bending moment (LBM) of run 163 records based on CFD compared with FE conversion load at 20 knots of forward speed and 1.7m wave height.*

The strong magnitude correlation between the motion and load responses of sea trial run records with the simulated CFD run implies that the applied methods in this study are reliable for prediction of global loads, despite minor deviation of the computed results due to the approximation of the random wave sea trial conditions with a near equivalent regular wave in the CFD simulation. It is recommended to apply this method to investigate further types of internal global loads of WPCs, such as torsional moments, transverse bending and splitting forces, and in different sailing conditions. This will assist in prediction of structural integrity at a future time and allows operators to respond to sea conditions to improve safety and increase the operating range. Consequently, the future design of new high-speed wave-piercing catamaran will be based on better understanding of motions and dynamic structural responses.

## 5. CONCLUSIONS

Sea trial records have been used to estimate the global longitudinal bending moment on HSV-2 high-speed wave-piercing catamaran. Two different methods are applied to calculate the longitudinal bending moment. Computational fluid dynamics (CFD) is combined with basic rigid body dynamics to estimate the internal bending moment. Then, strain records collected from a sea trial run are used with a finite element (FE) based matrix to convert to longitudinal bending moment.

The finite element method (FEM) using quasi-static loading is found to be sufficient for determining the trend of strain gauge responses observed in the sea trials runs in absence of slamming [18]. Furthermore, the conversion of strain data collected to corresponding global loads is achievable using linear regression of finite element analyses FEA. However, in order to estimate wave slamming loads, a transient finite element analysis is recommended of course.

Inviscid computational fluid dynamics (CFD) combined with a rigid body dynamics formulation is found to be a reliable method to study motion and loads associated with high-speed catamarans. CFD simulation has been validated on a broad basis with motion responses undertaken in full-scale sea trials tests, and the additional computational cost of a turbulent simulation was shown not to be warranted for this type of analysis. Longitudinal bending moment (LBM) estimated from FE and CFD based approaches showed good agreement of load value prediction. Loads within CFD simulations are estimated from accumulative addition of fluid element forces acting on the WPC hull. It is important to note that the CFD based approach is also effective especially when considering wave slamming loads occurring at higher range of speed [14].

The CFD simulation approach adopted in this study is beneficial for load estimation purposes for future high-speed catamarans during early design stages. The future research work of this project will be to identify further types of global loads, such as transverse bending moment, using the adopted methods. Both regular and irregular sea wave profile will be considered, and as well, headings other than headseas should be investigated to generate torsional loads of larger magnitude important for ship design.

## 6. ACKNOWLEDGEMENTS

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