Extreme Asymmetric Slam Loads On Large High Speed Catamarans

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Summary

In order to optimise the structural design of lightweight high speed vessels knowledge is required of the effect of sea loads on their structure. During the full scale monitoring of a 96m Incat high speed catamaran the vessel experienced an extreme slam event when operating in severe sea conditions. The extensive hull stress, motion and wave measurements, in conjunction with a refined finite element model, enabled the development of a realistic asymmetric slam loading scenario for structural design purposes. This slam load case has been compared with Det Norske Veritas classification rules and a method for scaling the load case for use with other large wave-piercer catamaran designs is proposed.

1. Introduction

High speed sea transportation requirements for both commercial and military applications have evolved rapidly leading to the development of large, fast, lightweight vessels. In order to optimise the structural design of lightweight high speed vessels knowledge is required of the effect of sea loads on their structure [1, 2, 3, 4]. Severe wet deck slam events, which occur when the vessel's motion causes an impact between the cross deck structure and the water surface when operating in large waves, are of particular importance for high speed catamarans, [5], since such a slam can impart a large global load onto a vessel's structure. Naval architects have adopted finite element modelling as a standard tool for the structural analysis of ships' structures [6, 7] and studies have been conducted seeking to relate the measured stresses on board vessels with those predicted by finite element analysis [8, 9].

Previously, full scale measurements have been conducted on-board Incat catamarans with the primary aim of characterising the global loads experienced by large high speed catamarans [10, 11]. However, as well as defining the global loads, the analysis of this data also led to development of preliminary slam load cases to be used in the design process [11, 12].

This paper reports on an investigation into the response of a 96m Incat high speed catamaran to an extreme slam event which occurred whilst extensive full scale hull stress, motion and wave measurements were being conducted on the vessel during regular ferry services. The strain gauge data from the full scale slam events has been used, in conjunction with a refined finite element model, to develop a realistic asymmetric slam loading scenario for structural design purposes. This slam load case has been compared with Det Norske Veritas (DNV) classification rules and a method for scaling the load case for use with other large wave-piercer catamaran designs is proposed.

2. Extreme Slam Event

In order to investigate the dynamic loads experienced by a high speed catamaran during a slam event, a series of full scale trials was undertaken on a 96m Incat high speed catamaran ferry, Incat Hull 050. This ferry is a wave-piercer catamaran with a prominent centre bow, the principal parameters of the vessel are shown in Table 1.

Parameter	Dimension
Length overall	96.0m
Length waterline	86.0m
Beam overall	26.0m
Draft	3.7m
Hull beam	4.5m
Lightship	860 tonnes
Deadweight	840 tonnes
Speed, fully loaded condition	38+ knots

Table 1: Hull 050 Principal Parameters

Full scale wave, motion and hull stress measurements were taken on board the vessel during regular service crossings across Cook Strait in New Zealand. The measurement system comprised 8 strain gauges located throughout the vessel, see Fig. 1 and Table 2. A TSK on board radar based wave sensor was utilised to give readings of instantaneous wave height. A tri-axial accelerometer was fitted close to the centre of gravity of the vessel to measure heave, surge and sway accelerations. The speed of the vessel was also measured using an on board GPS. Further details of the on board data acquisition system may be found in Thomas et al. [11].

On the 21st of November 1999 the vessel was travelling from Picton to Wellington into a large southerly swell. The vessel experienced an extreme slam event which caused some external plate buckling and distortion to several internal frames as shown in Fig. 2. On board weather observations were recorded at the time of the slam and are given in Table 3. The structural stresses were measured, along with the incident wave details and the vessel accelerations.

The rapid application of load on the vessel due to centrebow archway impact with the water may be clearly seen in the extreme slam event strain gauge raw data in Fig. 3.

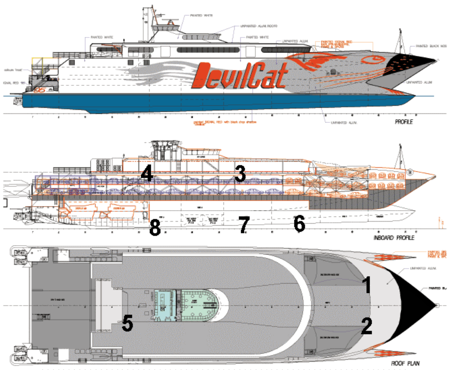

Figure 1: Strain Gauge Locations

	Location
1	Port lower steel post at frame 63
2	Starboard lower steel post at frame 63
3	Starboard portal top cross brace at frame 41
4	Starboard portal top cross brace at frame 23
5	Starboard steel post on vehicle deck
6	Starboard keel at frame 49.5
7	Starboard keel at frame 40.5
8	Starboard keel at frame 24.5
Note: There are 75 frames in total, numbered from the transom at a spacing of 1200mm	

Table 2: Strain Gauge Locations

Figure 2: Hull 050 Damage from Extreme Slam Event - External Plating at Frame 51. View showing Buckled External Plating and Sponson

This fast increase in load is more visible on the structural members closer to the bow of the vessel and hence closer to the point of slam impact; the asymmetric nature of the slam event can be seen with the forward starboard steel post experiencing significantly larger stresses than the port forward steel post. The structural members with a transverse orientation, i.e. portal top cross bracing at frames 23 and 41, show the least influence of the slam event. It was determined from the data records that the wave height for the extreme slam event was approximately 5m and the encounter wave length 80m.

Parameter	Observed Value
Beaufort Sea Scale	4
Beaufort Swell Scale	SSE 5
Heading Direction	Waves 40 degrees on std bow
Significant Wave Height	3.7m
Vessel Speed	Engine 700rpm and 15 knots

Table 3: Slam Event On-board Observations

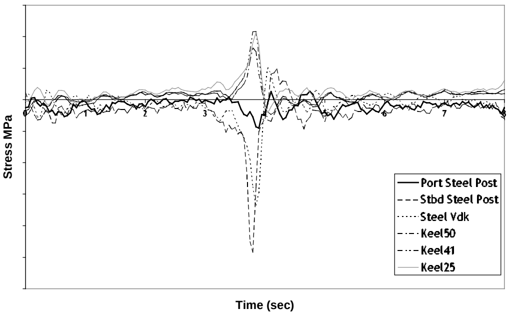

Figure 3: Extreme Slam Event
Raw Strain Gauge Data

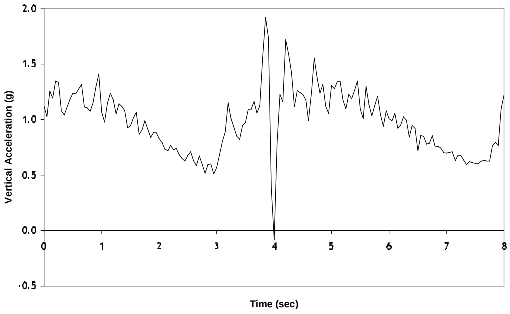

Figure 4: Extreme Slam Event
Vertical Acceleration at LCG

The average steady state value of g was 1.0, whilst the vertical acceleration at the LCG during the slam was 1.9g, and at the bow it was 3.0g (although no dedicated accelerometer was fitted to the bow, the TSK wave sensor readings allowed the vertical acceleration at the bow to be calculated). Whilst these values of vertical acceleration are high the vessel was only subjected to them for a short instant of time as is shown in Fig. 4.

3. Asymmetric Slam Load Case Development

An asymmetric sag load case, equivalent to the load experienced during the extreme slam event, was developed by correlating the measured stress levels during the slam event with those predicted by a Finite Element (FE) model.

The first stage of the load case development consisted of correlating the FE model with a typical asymmetric longitudinal bending scenario without a slam impact force. Then the extreme slam impact event was simulated by the FE model to produce a realistic asymmetric slam load case for this vessel.

3.1. Finite Element Model

The PATRAN/NASTRAN FE model of Hull 050 was constructed by importing the geometry from CADKEY.

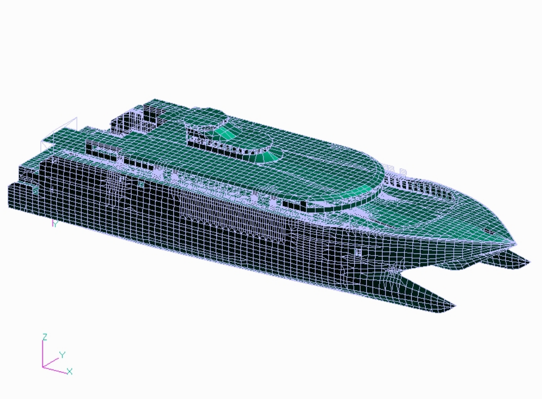

Figure 5: Finite Element Model of Hull 050

The model consisted of predominantly plate and bar elements with the exception of laminate elements used to model the honeycomb material in the mezzanine ramps. The model included the superstructure which was connected to the main hull via elements modelling the connecting rubber mountings.

3.2 Hydrostatic Load Model

A simplified model was set up for the evaluation of the global wave loads based on a quasi-static approach. The model was originally developed to consider regular sinusoidal waves at a heading angle of 0 or 180 degrees, however it was extended to account for asymmetric wave headings. The vessel’s hulls were modelled through Bonjean curves representing the immersed area of each transverse section for the local draft. The moment generated in the single hulls by the asymmetry of the wetted transverse area was neglected and the draft was considered to be equal on both sides of the same hull. However, for a non-head or non-following sea condition the draft at the same longitudinal position on each hull was different. The vessel is balanced on the wave, for a given wave length, wave height and heading angle, with the vessel’s weight forces and moments balanced by the vessel’s buoyancy forces and moments. The sinkage and trim of the vessel are iteratively varied until the equilibrium position is determined. The vessel is assumed to maintain a zero heeling angle in the wave environment. Although in oblique seas a catamaran would be expected to exhibit an angle of heel, the effect on the buoyancy forces was assumed to be small. It should be noted that the weight force may contain an additional dynamic acceleration component which is given for the longitudinal centre of gravity position and the forward perpendicular.

3.3 Global Loads Correlation

The FE model was simulated in typical asymmetric longitudinal bending conditions in order to gain confidence in the correlation technique. If this correlation proved satisfactory the method may then be extended to simulate an asymmetric impact slam event.

The wave loadings were determined by the hydrostatic load model utilising the wave details (wave height = 2.2m, wave length = 90m) and mass distribution from the full scale measurements. The vertical acceleration of the vessel was also utilised to develop the wave loading using the acceleration levels measured during the full scale trials, the vertical acceleration at the LCG was 1.2g, whilst at the bow it was 2.0g. The vessel was travelling at 19 knots at a wave heading of 140 degrees.

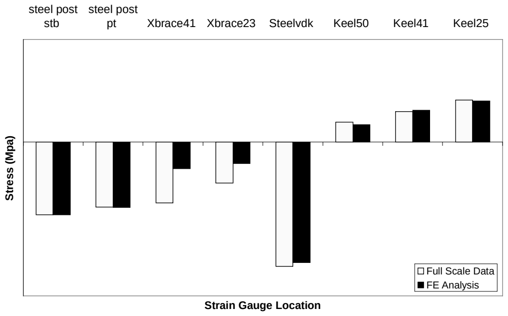

Figure 6: Comparison of FE Analysis and Full Scale Data for Asymmetric Sag Longitudinal Bending Scenario

The results for the sag condition are shown in Fig. 6. The results show that good correlation was achieved for all the strain gauges except for those situated on the portal top crossbracing. For these two gauges the FE analysis under predicts the stress as measured in full scale. This may be due to the presence of some split hull loading which was not included in the FE loading condition adopted. It was concluded that these results showed acceptable levels of correlation between the full scale results and the FE analysis to proceed with developing a realistic load case of the extreme slam event.

3.3 Asymmetric Slam

The underlying wave loading was determined by utilising the hydrostatic load model for a wave of length 80m, height 5m and heading angle 140 degrees. It is interesting to note that the wave length of the wave is close to the vessel length and hence near to the worst sagging case. The vertical acceleration of the vessel was also taken into account when calculating the buoyancy forces using the acceleration levels of 1.9g measured at the LCG and 3.0g measured at the bow during the slam event.

In addition to the underlying global load, a load was required to simulate the slam impact force on the bow of the vessel. Unfortunately the size and distribution, both longitudinally and transversely, of this load were unknown. Therefore the load magnitude and distribution were systematically altered until an acceptable correlation with the full scale strain gauge data was achieved. The only port/starboard asymmetry in the strain gauge results was the data for the forward port and starboard steel posts, which were located towards the bow of the vessel at frame 63. These gauge locations were very sensitive to the slam load magnitude and distribution, and were therefore helpful guides for determining the impact force. The other gauges along the vessel were more sensitive to the slam load magnitude than its distribution, although the gauges on the portal top cross bracing gave guidance on the transverse distribution of the load. The result of the sensitivity study was that an additional load in excess of 1000 tonnes was distributed over the starboard side of the centrebow and arch to account for the impact force. The longitudinal distribution of the buoyancy forces for each hull and centrebow plus the slam impact applied forces are shown in Fig. 7. Note that the frames are numbered from the transom.

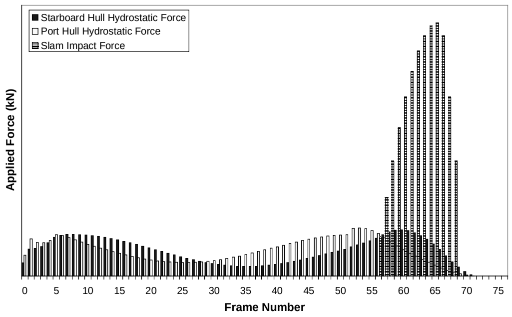

Figure 7: Longitudinal Distribution of Applied Force for Extreme Slam Event

Examples of the output from the FE analysis are shown in Figs. 8 and 9. The exaggerated plot of the deflection of the hull in Fig. 8 shows the dominance of distortion in the starboard bow region due to the slamming impact force. The image showing Von Mises stress, Fig. 9, illustrates the concentration of stress in the region where damage was experienced by the vessel following the extreme slam event (compare with the photograph of the damage in Fig. 2).

Fig. 10 shows that good correlation was achieved for the strain gauges when compared with the FE analysis for the extreme asymmetric slam event with the strain gauge readings during the extreme slam event, being within 17.7 % of the full scale measurements except for the gauge on the port steel post.

The major discrepancy in the results is the level of stress in the port steel post. It was difficult to reduce the level of stress in this structure whilst maintaining sufficient load to retain the required stress levels at the other strain gauge locations and the steel posts were very susceptible to the localised slam loading.

Figure 8: Exaggerated Deflection Plot for Extreme Asymmetric Slam Load Case

Figure 9: Stress Plot for Extreme Asymmetric Slam Load Case.
The zone identified by the circle highlights the area of external damage in Fig. 2.

The slam loading increased in magnitude very rapidly during a slam event, particularly in the forward region of the vessel, and since the sampling rate for these strain gauges was only 20 Hz the peak for the port steel post may have been missed which could account for the disparity in results for this location. The accuracy of the heading angle, which was an on board visual observation, may have affected the results and account for disparity in the correlation with the strain gauge results. Also the wave data recorded gave no information on wave spreading which may have been present.

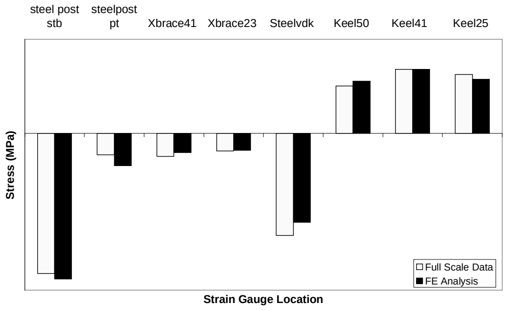

Figure 10: Comparison of FE Analysis and Full Scale Data for Extreme Asymmetric Slam Load Case

4. Comparison with Det Norske Veritas Class Rules

The extreme asymmetric slam load case was compared with the DNV sag rule moment as prescribed by their Classification Rules [13]. Fig. 11 shows the comparison of the full scale and FE analysis results for the extreme slam load case with the stress levels obtained through applying the DNV sag rule moment load case to the same vessel.

The vessel was at full design load for the sag moment load case with a complete complement of trucks, cars and passengers along with full fuel tanks. To achieve the required DNV bending moment the vessel was hydrostatically balanced on a wave of length 81.5m and height 9m with an LCG acceleration of 2.1g. The comparison of stress results shows that the stress levels, for both the full scale results and the slam load case FE analysis, were greater than the DNV sag rule moment for every location, except the steel vehicle deck bracing and port steel post. This is borne out by the bending moment curves shown in Fig. 12, where the bending moment curves have been normalised by the maximum values determined from the DNV sag rule moment.

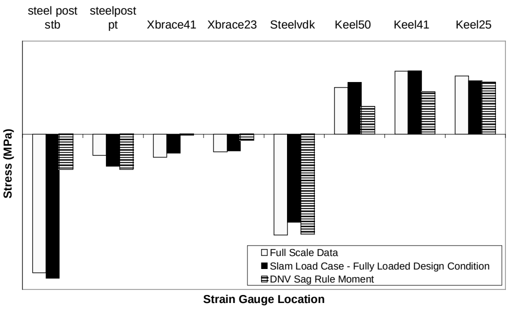

Figure 11: Comparison of FE Analysis and Full Scale Data for Extreme Slam Load Case and DNV Sag Rule Moment

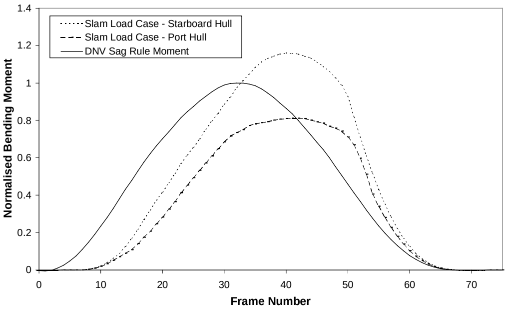

Figure 12: Comparison of Bending Moment Curves for Extreme Slam FE Load Case and DNV Sag Rule Moment for Hull 050

It can be seen that the maximum bending moment for the extreme slam load case has a greater maximum value and its peak is further forward than for the DNV sag rule moment. The reduction in the bending moment for the port hull compared to the starboard hull may be clearly seen.

5. Slam Load Case Application

The extreme asymmetric slam event that was experienced by Incat Hull 050 provided an effective design load case for that particular design of vessel. However, in order to utilise the slam load case successfully with other wave piercing catamaran designs a method for scaling the loads would be required. Such a method for scaling the slam load case is proposed.

The data required by the hydrostatic model is scaled utilising Froude scaling based on a scale factor *R*. If the new design is not a geosim of Hull 050 this scale factor may be derived by averaging the scaling factor of a number of principal parameters, i.e. overall length, waterline length, displacement, hull beam, overall beam and design draft.

$$\lambda_{des} = \lambda_{050} R \qquad (3)$$

$$h_{des} = h_{050} R \qquad (4)$$

$$\ddot{z}_{des} = \ddot{z}_{050} \qquad (5)$$

Where the subscripts *des* and *050* denote the new design and Hull 050 respectively. The slam impact force is determined by scaling the slam load case force as follows:

$$F_{des} = F_{050}\left[\left(\frac{L_{des}}{L_{050}}\right)\times\left(\frac{B_{des}}{B_{050}}\right)\times\left(\frac{T_{des}/TH_{des}}{T_{050}/TH_{050}}\right)\right] \qquad (6)$$

where L is the waterline length, B is the overall beam, T is the design draft and TH is the tunnel height. The tunnel height is defined as the vertical distance between the design waterline and the top of the centrebow archway. This formulation was adopted because whilst it utilises the correct Froude scaling $F_{des} = F_{050} \times R^3$, instead of using the average scale factor, *R*, it makes use of parameters which are likely to have an influence on the slam impact magnitude. The scaling factors for waterline length and overall beam were included since they are guides to the overall change in vessel size. The ratio of draft to tunnel height was included as an indication of susceptibility to slamming; if this ratio reduces it is proposed that archway closure slams are less likely to occur. This method was utilised to develop a slam load case for a new 112m Incat wave-piercer catamaran design A comparison of the bending moment curves for the new slam load case and the DNV sag rule moment is shown in Fig. 13.

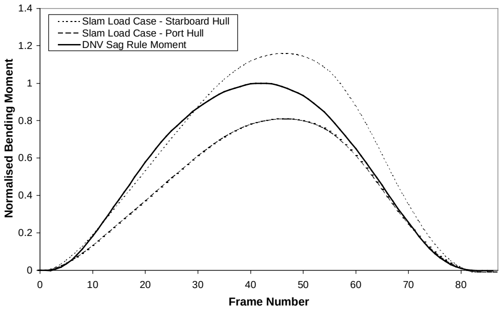

Figure 13: Comparison of Bending Moment Curves for Extreme Slam FE Load Case and DNV Sag Rule Moment for 112m Design

This plot, where the bending moment curves have been normalised by the maximum values determined from the DNV sag rule moment, shows that the maximum bending moment for the extreme slam load case has a greater maximum value and its peak is further forward than for the DNV sag rule moment due to the slam impact load on the centrebow and archway region.

The extreme slam event that was experienced by Hull 050 has therefore provided an effective design load case that may be applied in future design scenarios.

6. Conclusions

A realistic load case for an asymmetric extreme slam event has been developed for Hull 050, a 96m Incat catamaran. This was achieved by correlating the measured strain gauge readings measured during an extreme slam event with predictions from a refined FE model. This design load case is a significant improvement on the current DNV sag load case design rule for this type of vessel.

The slam load case identified for the vessel studied is for a wave length of 80m, wave height of 5m and wave heading of 140 degrees with a vertical acceleration at the LCG of 1.9g. An additional slam impact force in excess of 1000 tonnes was spread over the starboard centrebow and arch region. This load case gave good correlation with the strain gauge readings during the extreme slam event, being within 17.7 % of the full scale measurements except for the gauge on the port steel post.

When compared with the DNV design sag rule, the maximum bending moment for the extreme slam load case, applied to the vessel in the design condition, has a greater maximum value on the critical hull and its peak is further forward than for the DNV sag rule moment. The shear force curve for the extreme slam load case has a strong forward bias due to the slam impact load on the centrebow and archway region.

A method for scaling this realistic asymmetric load case for other catamaran designs has been proposed. This technique was utilised successfully to develop an extreme asymmetric slam load case for a 112m design Incat catamaran.

7. Nomenclature

B	Overall beam
F	Force
h	Wave height
L	Waterline length
R	Scale factor
T	Design draft
TH	Tunnel height
$\ddot{z}$	Vertical acceleration
λ	Wave length

8. Acknowledgements

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9. References

1. Morris, J.A., ‘A Three Dimensional Structural Analysis of a Large Wave Piercing Catamaran Design’, IMAS 91 High Speed Marine Transportation, 1991.

2. Hughes, O.F., McNatt, T., Spradbrow, B.J., ‘Structural Design of Large, Fast Marine Vehicles Based on First Principles’, FAST ’93, 1993.

3. Pettersen, O., Wiklund, K.M., ‘Det Norske Veritas Requirements for Direct Calculation of High Speed and Light Craft’, FAST ’99, 1999.

4. Humphrey, R., Nybø, T.., ‘Det Norske Veritas - Direct Calculation Methods for High Speed, Light Craft and Naval Surface Craft.’, Pacific 2002, 2002.

5. Faltinsen, O., ‘Slamming’, Advances in Ship and Offshore Hydrodynamics, 1996.

6. Yakimoff, P., ‘State-of-the-Art Computer Simulation for Structural Analysis of High Speed Catamarans’, FAST ‘97, 1997.

7. Tulk, R.J., ‘The BC Ferries’ Catamarans’, Trans IMarE, Vol. 111, Part 3, 1999.

8. Pegg, N.G., Vernon, T.A., Wegner, L., Nethercote, W.C.E., ‘Finite Element Prediction of Measured Bow Flare Plate Stresses under Dynamic Wave Loading’, Trans RINA, 1988.

9. Stredulinsky, D.C, Pegg, N.G., Gilroy, L.E., ‘Motion, Load and Structural Response Predictions and Measurements on CFAV Quest’, Trans SNAME, 1999.

10. Roberts, T.J., Watson, N.L., Davis, M.R., ‘Evaluation of Sea Loads in High Speed Catamarans’, FAST ‘97, 1997.

11. Thomas, G., Davis, M.R., Whelan, J., Roberts, T.J., ‘Dynamic Response of Large High Speed Catamarans’, FAST ’01, 2001.

12. Roberts, T., Yakimoff, P., ‘Adequate Global Design Loads for Fast Ferry Vessels’, 14th Fast Ferry International Conference, 1998.

13. Det Norske Veritas, ‘Rules for Classification of High Speed and Light Craft: Design Principles, Design Loads’, Part 3 Chapter 1, DNV, 1996.