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Investigation into Wave Loads and Catamarans

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SUMMARY

Catamaran designs, whilst fundamentally unchanged from their historic predecessors, have developed rapidly over the last decade. As these vessels become larger and faster, accurate prediction of hull loads becomes increasingly important. Unlike more traditional vessels, high speed craft must have efficient, light-weight structures to maximise their payload and/or operating speed; however, the safety and structural integrity of the vessel must not be compromised.

To obtain a better understanding of the behaviour and response of a catamaran in a seaway, an eight metre research catamaran, "Educat", has been built and instrumented with strain gauges and motion sensors. The research and findings to-date are presented in this paper, including: calibration of "Educat"; results of the sea trials and towing tank tests; and correlation with the numerical models.

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Stephen Cook graduated with a Bachelor of Engineering (Naval Architecture) from the Australian Maritime College in 1996. He is currently working towards his PhD at the Curtin University of Technology, on the topic of global wave loads and catamarans.

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Kim Klaka is a naval architect with particular interests in hydrodynamics and small craft. He joined the Centre for Marine Science and Technology at Curtin University, Perth, in 1985 and is currently the Director of the Centre. He is the “Seakeeping of Catamarans” Task Leader for AME CRC.

NOMENCLATURE

AME CRC	Australian Maritime Engineering Co-operative Research Centre
BOA	Vessel Beam Over All
CMST	Centre for Marine Science and Technology
Fn	Froude Number
g	Acceleration due to gravity
L	Length of Vessel
LOA	Length Over All
LWL	Length on Water Line
o/b	Outboard
RMS	Root Mean Square
Δ	Displacement of Vessel
∇	Immersed Underwater Volume of Vessel

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* now employed by Formation Design Systems

1. INTRODUCTION

1.1. BACKGROUND

Loads imposed on a monohull operating in a seaway have been the topic of much research and are relatively well understood compared with catamaran loading. With a catamaran a whole new series of structural problems arise. The primary additional problem is related to predicting the size of the loads acting on the structure connecting the two hulls.

In the past cross-structure loads have been predicted mainly from experience with similar vessels with inbuilt safety factors or error margins. Classification society rules have for the most part been empirically derived from structural designs that have stood the test of time. The work of Disenbacher (1970) is still the basis for obtaining most operational design loads for catamarans.

Smaller catamarans, less than 50 m, are essentially designed to satisfy local load conditions, Fan & Pinchin (1997). With these smaller catamarans it is inherent in the design that they will be able to withstand the global loads applied to them if they satisfy local load conditions. As the size of catamarans increase the global loads will tend to dominate the design of the overall structure, Speer (1996).

The primary global loads that are being investigated in this research, under guidance from industry, are listed below in order of priority.

1. Longitudinal bending moment of demihulls, Figure 1-1.

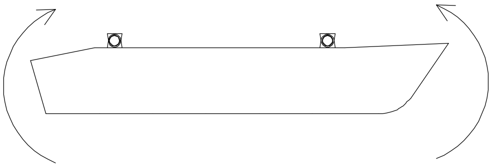

Figure 1-1: Longitudinal Bending Moment

2. Transverse vertical bending moment in cross-structure, Figure 1-2.

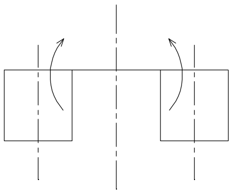

Figure 1-2: Transverse Vertical Bending Moment

3. Torsional moment in cross-structure (Pitch connecting moment), Figure 1-3.

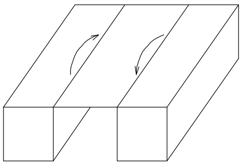

Figure 1-3: Pitch Connecting Moment

For the transverse vertical bending moment the most severe condition has been found to be at zero speed in beam seas. Lankford (1967) was the first to discover this somewhat surprising result with his work on the ASR catamaran.

Faltinsen et al. (1992) presented numerical and experimental results of global wave loads at a Froude number of 0.49. The results showed satisfactory agreement except for transverse vertical shear. At high vessel speeds, the numerical model shows that the transverse vertical bending moments and shear force are generally largest in beam seas, while the largest value for pitch connecting moment occurs at a wave heading angle of 60 degrees for most wave periods. Roll motion is important for vertical shear and pitch connecting moment, while heave and pitch acceleration influence the vertical bending moment.

1.2. METHODOLOGY

The aim of this project is to develop an improved understanding of wave induced loads on catamarans by developing techniques for their prediction and investigation.

To achieve this overall aim various tools are available. They are outlined in Figure 1-4 along with their associated contributions.

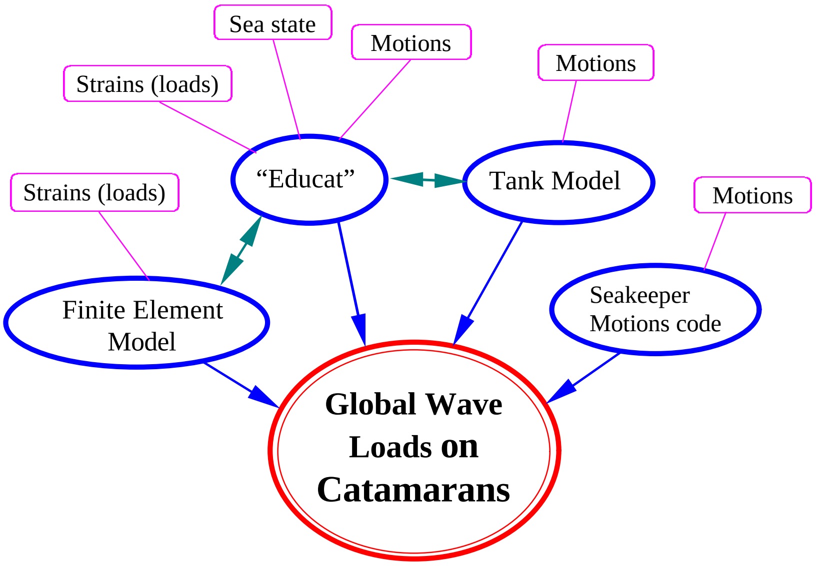

Figure 1-4: Overview of Project

The 8m research vessel "Educat", described in detail in Section 2.1, is central to the goals of this research. It is able to operate in real ocean waves at specified heading and speed. The sea state, vessel motions and loads can be measured simultaneously. It is common practice for regulatory bodies to associate their design loads with a maximum expected value of vertical acceleration, which can be obtained from motion spectra. Thus evaluating the motions of the "Educat" is an important step in understanding and developing a link to the global loads. Comparing motions between the tank, "Educat" and full scale will also establish the validity of comparing loads determined from these methods. Due to the small physical size, and relatively simple construction of "Educat", the strain gauges have been calibrated by applying known loads to the vessel while out of the water. This procedure is outlined in Section 2.3. These known load conditions are then applied to the finite element model to correlate the predicted strains with those measured on the "Educat". This will allow the global loads experienced during operation to be determined more accurately. The "Educat" has a very simple structure and thus the combination of load cases which can produce a given strain combination is greatly reduced. This is a distinct advantage over strain gauging full scale vessels in which local strains can be easily obtained, however relating these strains to a global load requires an in depth knowledge of how the structure reacts to different load case combinations. It is also logistically difficult to obtain wave magnitude and direction, motions, and loads data simultaneously for full scale vessels, thus only statistical predictions can be derived rather than establishing transfer functions which will allow different operational conditions to be tested and to evaluate the most severe load conditions.

Finite element modelling is currently commonplace in high speed vessel design. The fundamental problem with finite element modelling is knowledge of the loads to be applied. Classification Societies impose loading conditions which they feel are representative cases which will allow for safe operation of the vessel. These load cases while providing a structurally sound design are not necessarily representative of real operational conditions experienced in a seaway and thus may produce a somewhat conservative design. By comparing the strains predicted by finite element modelling of these imposed load cases with those measured on the "Educat" during operation it will be possible to establish if these load cases are realistic and representative of real wave induced loadings.

The towing tank model gives comparison of motions results between the tank model and full scale tests and an insight into scale effects. Measuring loads on the model was not an available option in this project.

The strip theory based Seakeeper motions prediction program, outlined in Section 4, provides another tool for validating the motions of the "Educat".

All of these tools mentioned provide input to the overall goal of further understanding global loads on catamarans.

2. SEA TRIALS AND THE "EDUCAT"

2.1. VESSEL DESCRIPTION

The "Educat" is an 8m research vessel, the hulls constructed of aluminium with a plywood/fibre glass accommodation pod. It is shown below in Figure 2-1. It essentially consists of two hulls joined by two tubular beams. The accommodation pod is resiliently mounted to the top of these beams to reduce the dynamic loads transferred to the hulls. This practice is used in various catamaran designs to isolate the accommodation decks from the main structure. A system of cables is used to reduce the lateral motion of the pod.

Figure 2-1: "Educat" Research Vessel

The cross-structure is shown below in Figure 2-2.

Figure 2-2: "Educat" Cross-structure

Particulars of the "Educat" are shown below in Table 2-1.

LOA	7.80m
LWL	6.80m
BOA	2.79m
Demi-Hull Beam	0.74m
Draught	0.28m
Separation between centre lines	2.05m
Power	twin 70hp o/b
Max. speed	25 kts

Table 2-1: "Educat" Particulars

2.2. INSTRUMENTATION

The "Educat" is instrumented to record loads and motions while operating in a seaway. The vessel motions are obtained from a TSS 335 motion sensor which provides real time heave, roll and pitch, as well as vertical and horizontal accelerations, at a rate of 21.333 Hz.

The sea state is evaluated using CMST wave recorders. These are normally free floating, suspended beneath buoys and the pressure fluctuations, sampled at 4 Hz, are used to calculate the sea surface elevation spectra.
The speed and heading of the vessel are obtained by visual observation of the ship speed display, derived from a water wheel, and a simple compass respectively.

Strain gauges are applied throughout the "Educat" in locations specific to particular load cases. The positions of the strain gauges for measurement of longitudinal bending are shown below in Figure 2-3, with their associated identification. All gauges mounted in the hulls are aligned longitudinally.

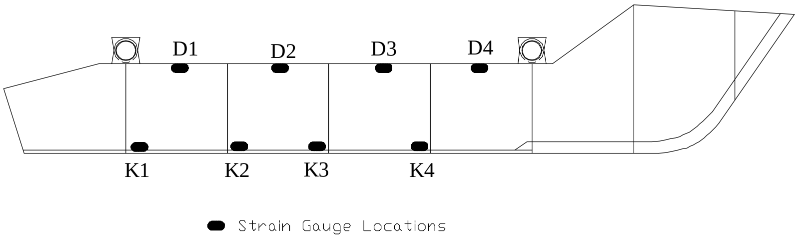

Figure 2-3: Strain gauge positions in starboard hull

Positions of gauges for measurement of cross-structure loads are shown in Figure 2-4.

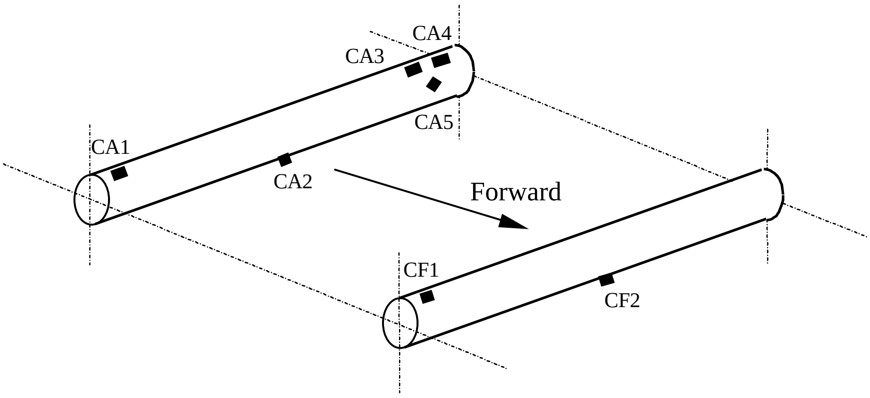

Figure 2-4: Cross-structure strain gauge positions

The strain gauge gives a time varying voltage signal due to a change in resistance of the gauge as it is strained. The change in resistance is quite small and hence the voltage change is also quite small so the signal is amplified up to 5000 times before recording. A half bridge configuration for the strain gauges is also used to increase the output voltage per unit of strain. The analogue signal from the strain gauge is converted to digital using a data acquisition unit (IOTech DAQ book) which also allows filtering of the signal and it is then logged on a PC. Strain gauge data is recorded at a sampling frequency of 100 Hz with a 20 Hz low pass filter.

2.3. CALIBRATION

Due to the small physical size, and relatively simple construction of “Educat”, the strain gauges have been calibrated by applying known loads to the vessel while out of the water. These known load conditions have then been applied to the finite element model to correlate the predicted strains with those measured on the “Educat” during calibration.

Known loads were applied by supporting the vessel in various configurations and changing the loads at the desired location using hydraulic jacks. The loads applied by these jacks were measured with calibrated load cells. The physical deflections were also measured using a theodolite. The deflection results provided independent confirmation of the finite element models validity. The measured deflections showed good agreement with those obtained from finite element analysis.

When converting the strains measured during the calibration procedure to stresses, the value of Young’s modulus was chosen to give the best correlation between the measured and finite element results; “tuning” the model.

An example of this is shown below in Figure 2-6 for the pitch connecting calibration. Figure 2-5 shows the location of the lifting point.

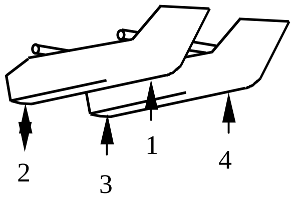

Figure 2-5: Pitch Connecting Lifting Points

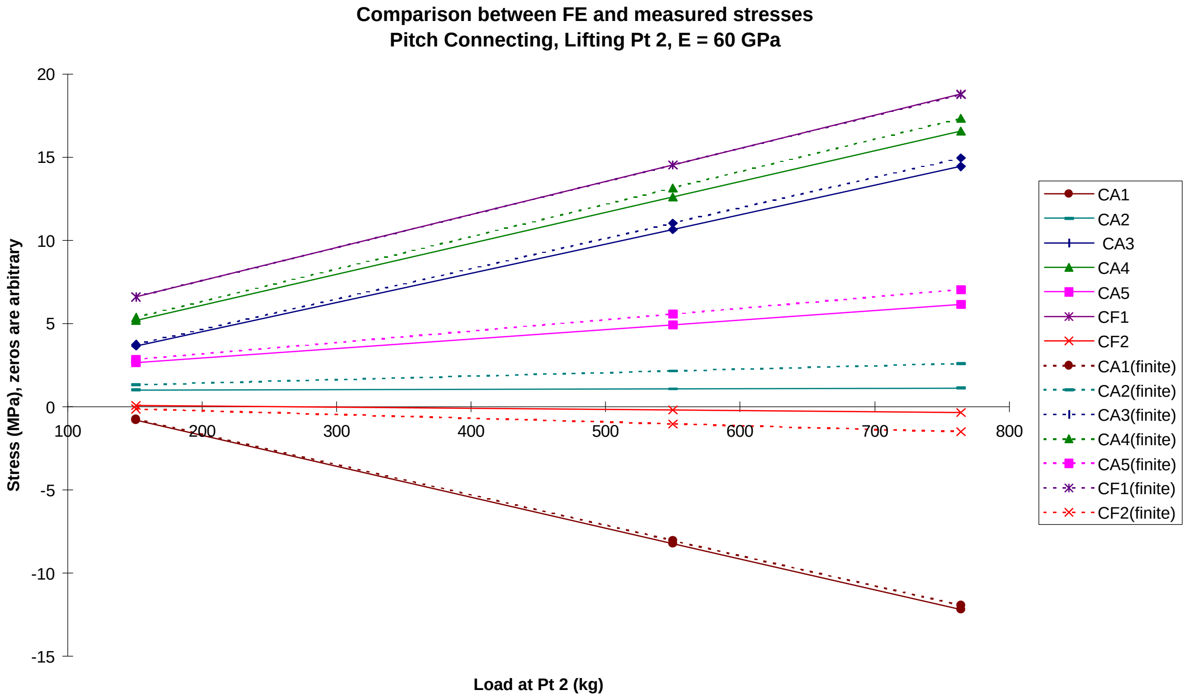

Figure 2-6: Pitch Connecting Calibration Results

Good correlation between experimentally measured strains and those obtained from the finite element model are obtained by applying a young’s modulus of 60 GPa to the experimental strains. The standard value assumed for Young’s Modulus of Aluminium is 70 GPa. This is used throughout the finite element model implying that the strains obtained from the finite element model must be multiplied by a factor of 70/60 to obtain the strains measured during the calibration. Thus the finite element model is "stiffer" than the actual "Educat", as might be expected.

It can be seen that gauges CA2 and CF2 (located at the transverse centre of each cross structure beam) show little response to Pitch Connecting Moment and thus are used to obtain the transverse bending moment directly.

Calibration was conducted for pitch connecting moment, lifting at points 1,2 and 3; transverse vertical bending moment, applying a splitting load between the hulls; and longitudinal bending by applying a point load at the midships of the instrumented hull.

The linearity of the results shown in Figure 2-6 is typical for the other load cases calibrated.

The results from the calibration of the keel and deck gauges used to measure the longitudinal vertical bending moment yielded discrepancies. It was found that significantly different Young's moduli were required to obtain the results predicted by the finite element model. The results from the finite element model show good agreement with simple beam theory, suggesting that the strain gauges may be in error. However Stredulinsky et al (1999) also found discrepancies, of a smaller magnitude, between keel and deck gauges when comparing measured longitudinal bending moments and numerically predicted results. This suggests that further investigation is required.

2.4. TRIALS CONDITIONS

Trials were conducted in Cockburn Sound, off Fremantle, Western Australia, for various headings, speeds and sea conditions. The water depth where the trials were conducted is generally between 15 and 20m.

A list of trials conducted to date is shown below in Table 2-2. Each run was conducted for five minutes duration and a new data set recorded for each different heading and speed. The speeds chosen correspond approximately to those used in model testing.

Type	Heading (degrees)	Speed (kts)
Head Seas	180	5
	180	9
	180	12
	180	15
Beam Seas	90	0
	90	8
	90	12
	270	0
	270	15
Quartering Sea	145	8
	145	15

Table 2-2: Trials Conducted

Figure 2-7 show the trials course and positioning of wave buoys. One wave buoy was located at the top and one at the bottom of the trials course to measure the spatial variation in the wave field.

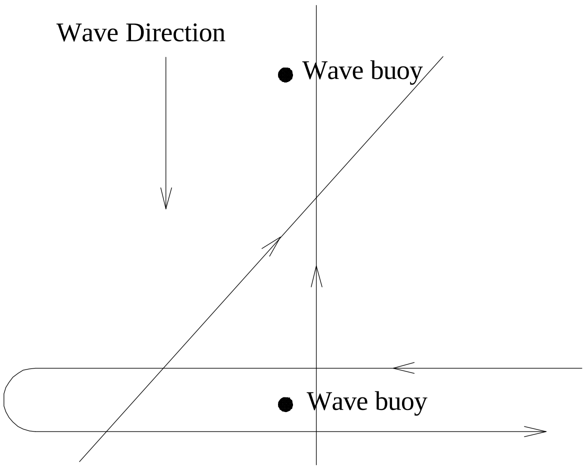

Figure 2-7: Trials Course

The results of these trials are presented in Section 6 and compared with towing tank and finite element results.

3. MODEL TESTS

Captive model tests were conducted at the Australian Maritime College (AMC) in Launceston, Tasmania, in June 1999. The tank is approximately 60 m long, 3.5 m wide, and 1.5 m deep, allowing testing in head seas and zero speed beam seas. The objective of the model test program was to measure the motions of the Educat operating in head and beam seas for regular waves. These results would enable comparisons to be drawn between full scale trials results, theoretical predictions and model measurements, and also an assessment of scale effects.

For head seas five conditions were tested. For one vessel speed three different wave heights were tested to check the linearity of the motion responses. At constant wave height two more speeds were tested.

Beam seas tests were conducted at zero speed for two different wave heights.

The speeds tested and their scaled equivalents are outlined in Table 3-1.

	Model		Educat
LWL (m)	1.7		6.8
Velocity	m/s	Fn	kts
	2.15	0.526	8.4
	2.99	0.732	11.6
	3.27	0.801	12.7

Table 3-1: Summary of Vessel Speeds

The model was a 1/4 scale and the ballast condition tested corresponded to the standard trials operating condition of the “Educat”.

The pitch gyradius was set using a roll frame. Difficulties where encountered with this method and it was later concluded that the desired pitch gyradius was not achieved for the tests. This resulted in poor agreement between tank results, and both “Educat” and Seakeeper pitch response functions.

The results of towing tank tests are presented in Section 6.1.

4. STRIP THEORY PREDICTION

The Seakeeper motions program has been used to evaluate the motions of the “Educat” and investigate the effects of varying displacement etc.

Seakeeper is a two dimensional strip theory method, based on the work of Salvesen et al. (1970). Conformal mapping techniques are used to calculate the section added mass and damping for the vessel. These are then integrated to obtain the global vessel added mass, damping and cross-coupling terms. The coupled heave and pitch equations are solved to obtain the vertical plane RAOs. The motions are calculated for one hull in isolation, previous work (Wellicome et al. 1995) found that little interference between the hulls was found above a Froude number of 0.2. In addition, Seakeeper has been validated against a wide variety of catamaran data (Couser 1999) and found to give acceptable results up to a Froude number of 0.8.

For a user specified wave spectrum, heading and vessel speed, Seakeeper is able to calculate the response of the vessel. Response amplitude operators (RAOs) are computed as well as the added resistance, significant absolute and relative motions, velocities and accelerations of the vessel in the specified sea spectrum. Motion, velocity and acceleration spectra are computed at the centre of gravity and vertical motions may also be computed for other positions on the vessel.

5. FINITE ELEMENT MODEL

A global finite element model has been developed using MSC/NASTRAN. The model is constructed primarily of QUAD4 elements with CBAR elements use to model the stiffeners. Triangular elements are used very sparingly and only in areas where the number of nodes did not allow for a QUAD4 element.
Details are contained in Kastak (1998). Figure 5-1 shows the finite element model of the "Educat".

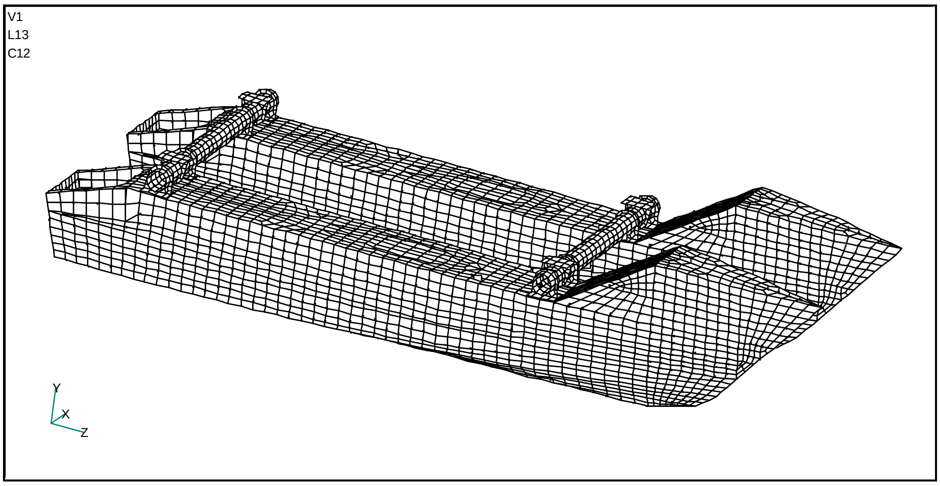

Figure 5-1: "Educat" Finite Element Model

6. RESULTS COMPARISON AND DISCUSSION

The following section presents a small sample of the data which has been obtained for the "Educat" from the various tools mentioned in the preceding sections. At present, analysis of this data is at an early stage and the full implications of this research have yet to be assessed.

6.1. MOTIONS

A typically encountered wave spectrum during "Educat" trials is shown below in Figure 6-1.

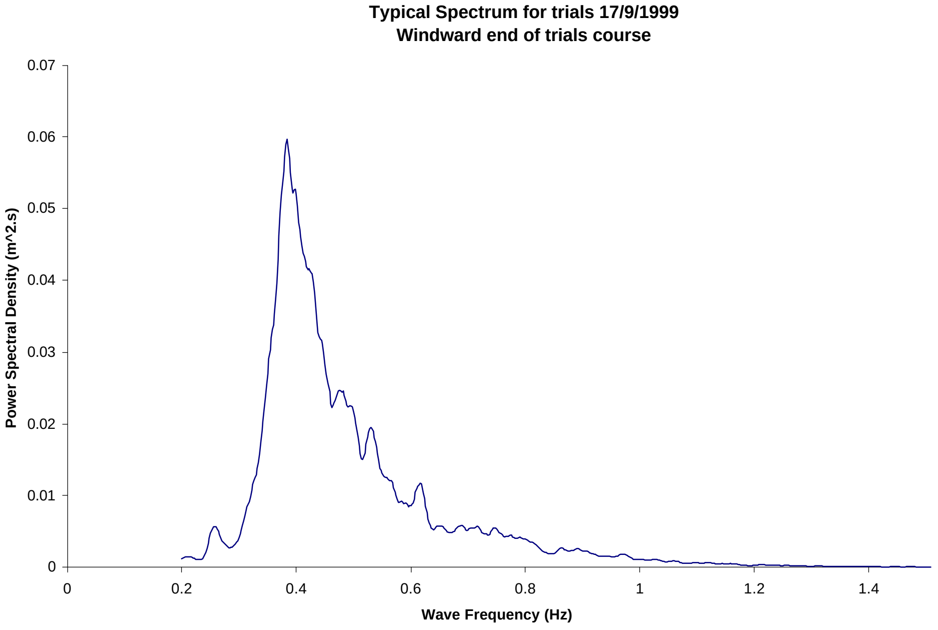

Figure 6-1: Typical Wave Spectrum

Analysis of the TSS motion sensor output gives the spectral densities for the roll, pitch and heave motions. Dividing the spectral densities and taking the square root gives the response amplitude operator (RAO) for the given motion. Throughout the duration of the trials the variation in the wave field is accounted for by calculating the wave spectrum in 40 minute windows and for each run the corresponding wave spectrum in time is used to calculate the RAO. The spatial variation is generally small and the spectrum from the closest buoy is used in the RAO calculations. The measured RAOs are compared to the RAOs predicted from the Seakeeper motions code and towing tank results in Figures 6-2, 6-3, 6-4, and 6-5. A cut-off frequency of 0.25 Hz has been applied to the trials results. Below this frequency there is very little energy in the wave spectrum, as can be seen in Figure 6-1.

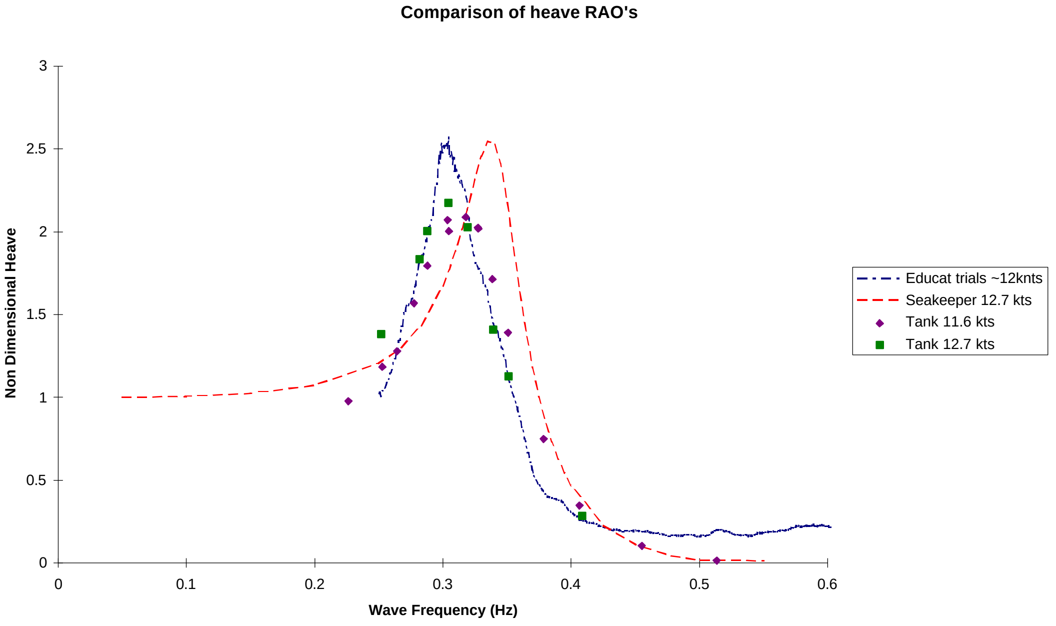

Figure 6-2: Comparison of Heave RAOs in Head Seas

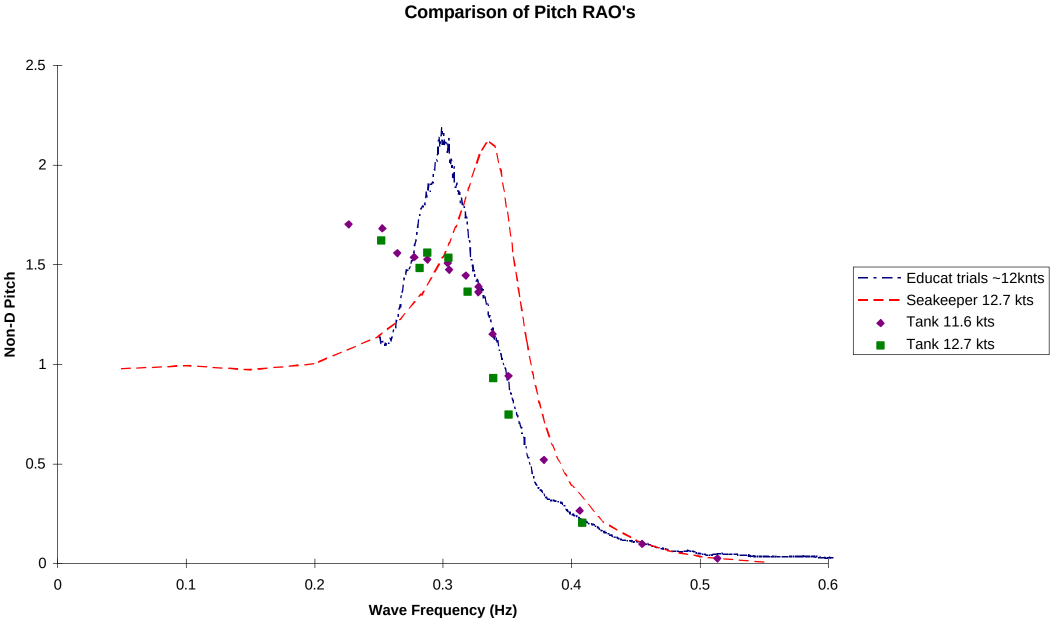

Figure 6-3: Comparison of Pitch RAOs in Head Seas

As previously mentioned difficulty was encountered in setting the pitch gyradius for the model. Using the Seakeeper motions package it was found that increasing the pitch gyradius to 34% LOA, from 25% LOA (desired pitch gyradius), does produce similar results to the model tests.

It is interesting to note that the magnitudes of the motion peaks from full scale trials and those predicted by Seakeeper are in good agreement, though Seakeeper tends to overpredict the resonant frequency. Both these sets of data show a resonant peak significantly greater than that measured in the model tests; though the effective scaled wave height used in the model tests and that present during the sea trials were very similar. In addition the motions measured during the model tests showed good linearity with wave amplitude. Similar results were found by Maggi et al (1998), where the peak amplitude of tank tests at higher speeds were somewhat smaller than those measured at full scale.

These findings suggest that there may be significant scale effects for vessels of this type, and this is an area worthy of further investigation.

Figures 6-4 and 6-5 show the response of the Educat in beam seas. During the trials the “Educat” was free to drift with the prevailing wind and waves. Surge and sway motions were constrained in the towing tank. The trials results have been adjusted for an estimated drift speed of 0.75 kts.

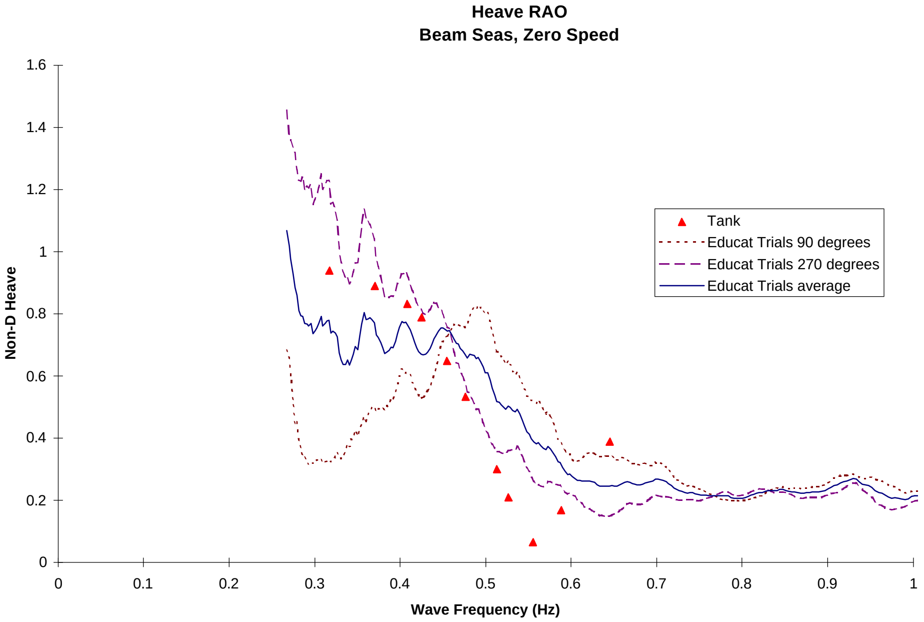

Figure 6-4: Comparison of Heave RAOs for Beam Seas

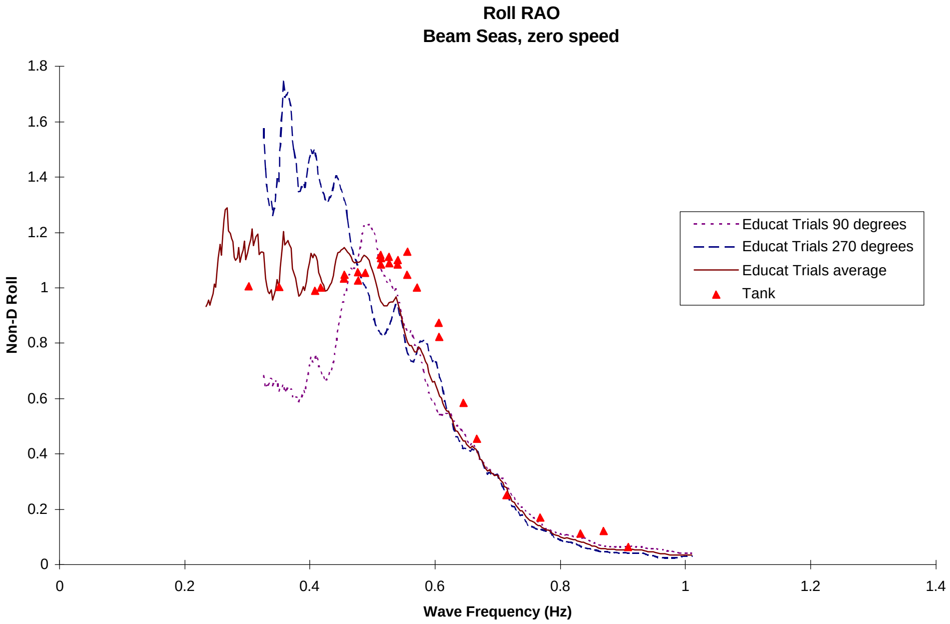

Figure 6-5: Comparison of Roll RAOs for Beam Seas

These results highlight some of the problems which may be experienced during full scale trials. During trials, it is not always possible to obtain uni-directional spectra, in addition it may also be difficult to precisely ascertain the principal wave direction. The results above suggest that there was some wave spreading, particularly at low wave frequency. This is possible since the swell often comes from a different direction to the wind-generated waves. However, averaging the data for 90° and 270° gives a reasonable result.

6.2. LOADS

Shown below in Figure 6-6 are typical strain gauge signals for selected gauges. Their spectral content is shown in Figure 6-7. Slamming events can be seen clearly at an interval of approximately 1 second which corresponds to the encounter frequency. The slamming events are most exaggerated at the end of the cross structure beams (CF1) and result in quite high stresses in the cross-structure in direct head seas. This phenomenon has not been fully investigated but it is thought that because the vessel is not operating in perfect head seas there will be some pitch-connecting moment producing a large bending moment at the beam ends, since the cross beam has to follow the flat deck surface at its' end. This could induce unusual vibration modes - walking mode, longitudinal mode and split mode. The effect of the slamming can also be seen throughout the rest of the structure. The underlying global load can be obtained by spectrally filtering out higher frequencies where the slamming phenomenon occurs. In Figure 6-7 the main peak at approximately 1 Hz corresponds to the underlying global load occurring at encounter frequency. The less defined peak at around 10 Hz is probably a result of the slamming events on the structure.

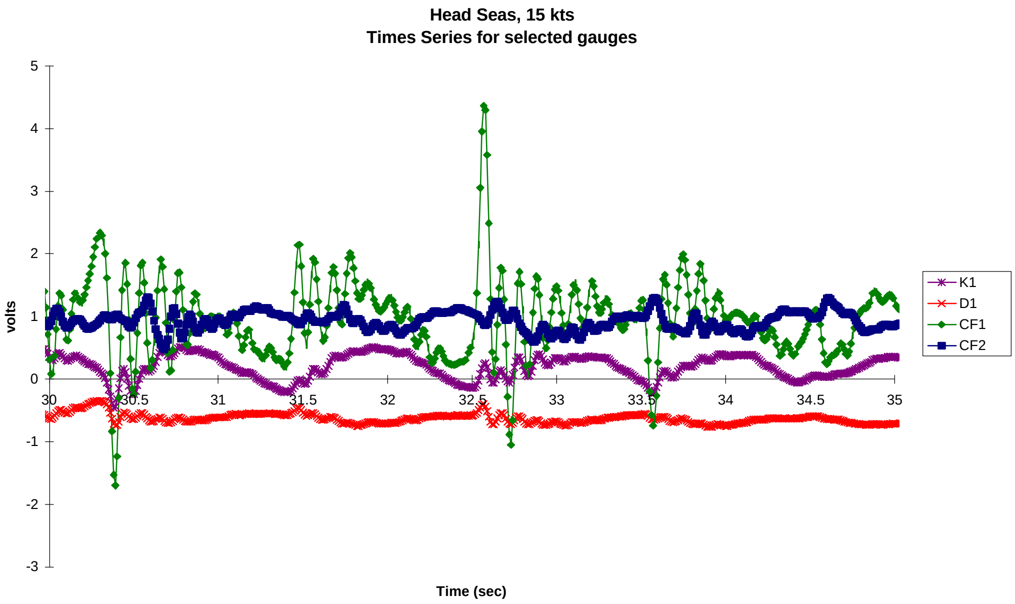

Figure 6-6: Strain Gauge Time Signals

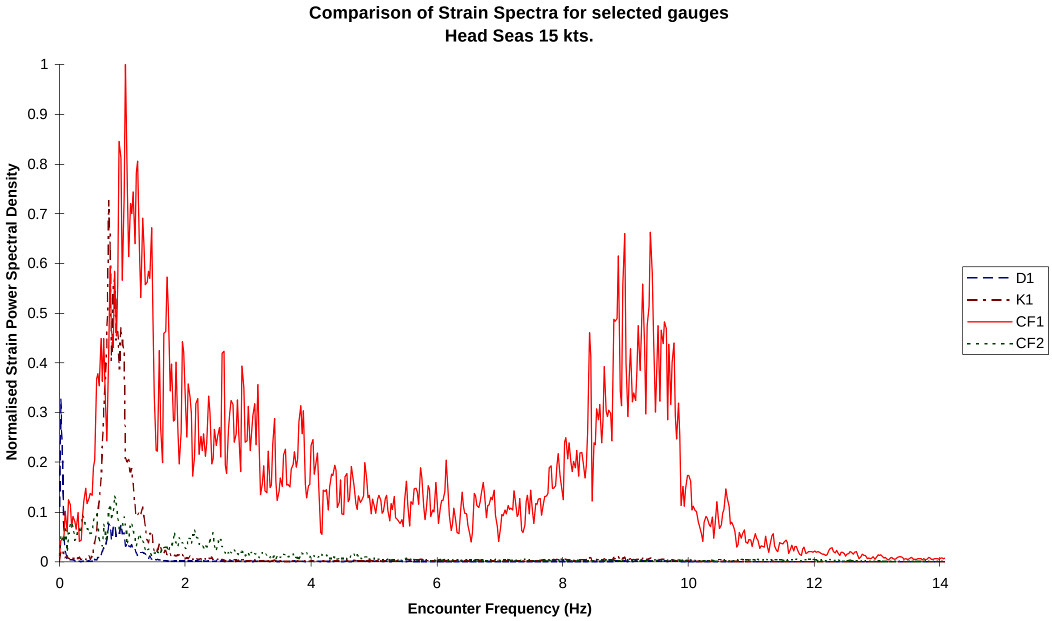

Figure 6-7: Spectral Analysis of Time Signals

Figure 6-8 shows a comparison of maximum strain amplitude (spectral peak) for cross structure gauge CA2 in beam seas for varying speeds. The strain at CA2 is a direct measure of the transverse vertical bending moment in the cross structure. It can be seen that maximum strain amplitude decreases as the speed increases. This agrees qualitatively with findings by Lankford (1967). Interestingly RMS values and energy in the spectrum remain reasonably constant.

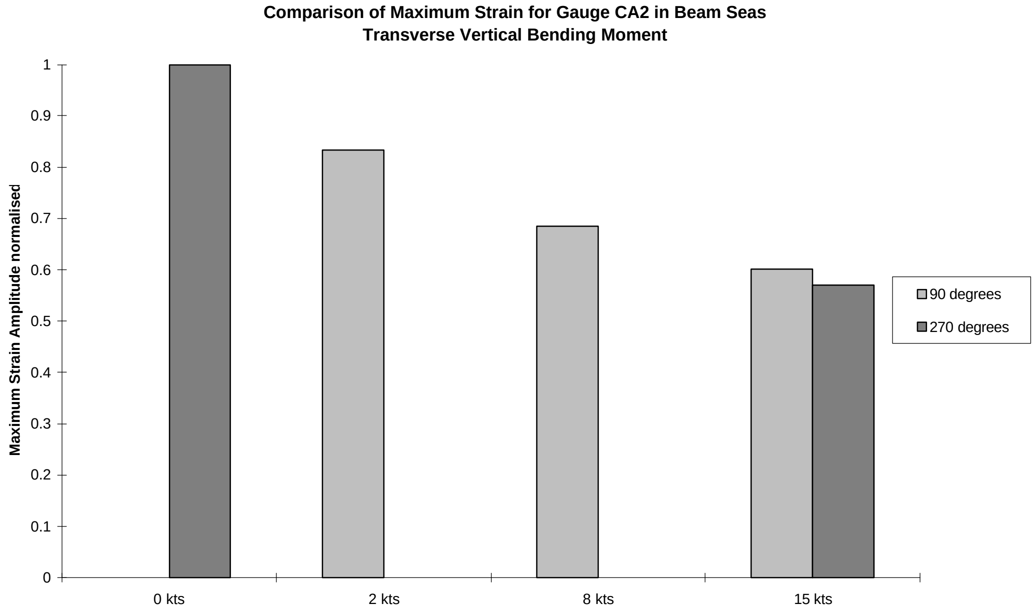

Figure 6-8: Transverse Vertical Bending Moment response to speed.

7. CONCLUSIONS AND FURTHER WORK

A strain gauge system has been devised and implemented on the “Educat”. In addition, motion sensors and wave buoys have been used to measure the global vessel motions and local incident wave field respectively. A number of sea trials have taken place and have provided a wealth of full scale motions and strain data.

The strain gauges have been calibrated by applying known load conditions to the vessel. This was carried out on dry land where the loads could be accurately measured with load cells and the displacements of key points on the vessel measured with a theodolite.

A finite element model of the "Educat" has been constructed and the results compared with those from the strain gauge calibration. Initial results look promising but further analysis is required.

Model tests have been completed with a 1/4 scale model. In addition, motions have been predicted with a strip theory code. This data has provided useful validation of the full scale motions measurement systems and provides an insight into scale effects.

Work on this project is ongoing: the strain gauge data collected will be used to statistically predict life time operational loads for the “Educat”. Having established a procedure for calculating the global loads from local strain measurements it will then be possible to compare results with the finite element model for different global load cases. This will give an insight into developing more operational based design loads for catamarans.

Continuing the current research it will be possible to gain an understanding of wave induced loads on catamarans and how these loads can be more accurately modelled. More accurate information on the size of these loads will lead to lighter more efficient vessels without redundancy in their structure, whilst not compromising safety.

8. ACKNOWLEDGMENTS

The authors wish to thank Mr Peter Goss, Incat Designs-Sydney, for his on going support of this project.
Also the staff of AME CRC, particularly those involved with the instrumentation and trials on “Educat”.

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