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Research Project 503
HSC – Heeling Moment Prediction Methods
Final Report

Executive Summary

This report describes Phases I and II of Research Project 503, to study the method of estimating the wind heeling moments of high speed craft, as applied in the 2000 HSC Code.

Phase I comprised a literature search and collation of published wind tunnel test data. Data were available for a small number of catamaran forms, a number of large monohull ships, and a series of rectangular blocks. This preliminary work concluded that insufficient data were available from which to develop a reliable method of predicting the wind heeling moments for multihull HSC. As a result of this finding the continuation of the study into Phase II was agreed.

Phase II comprised wind tunnel tests on models of two types of catamaran HSC, and upright tests on an existing sailing catamaran model (without the rig), which had previously been tested at a range of heel angles but not upright. The models were constructed in modular form to enable tests on a number of configurations, including beam and height variations, and alterations to the superstructure details. A conventional and a wave piercing catamaran were selected as the bases for the two new models, and these incorporated superstructures of contrasting shape.

The test programme concentrated on the upright case, with heeled tests being conducted on only two of the model configurations. It was anticipated that there would be more variation in the upright heeling moment, because of parametric and detailed variations, than in the effects of heel on the moment.

The test results were collated with those derived from published data and this enlarged database enabled the development of a proposed revised formula for the prediction of the upright wind heeling moment. For monohull HSC of relatively narrow form the proposed formula gives similar estimates to that in the 2000 HSC Code. For craft of greater beam to height ratio the proposed formula results in a greater predicted moment.

Whilst it was found that the formula over-predicted the heeling moment in some cases, attempts to refine this prediction were unsuccessful. It is believed that the variations result from detailed differences in superstructure shapes, and it is considered that, even if a method could be developed, to address these would introduce an inappropriate level of complication to the Code.

The variation of heeling moment with heel angle is affected by two separate aspects. Catamaran HSC are not expected to heel to large angles because the wind heeling moment, even in extreme operating conditions, would be insufficient to lift the windward hull from the water. Heel angles therefore will be restricted to a small range, less than 10 degrees in most cases. Over this range of angles the heeling moment defined about the vessel centreline may increase or decrease slightly with increasing heel angle, depending on the vessel shape. Vessels of wider form generally experience greater increases in the heeling moment than narrow vessels.

As a vessel heels, the centre of buoyancy moves transversely and this generates the righting moment defined as displacement x GZ. To assess the moment balance, the heeling moment also should be defined about this point. For monohulls it has been the convention to assume that the heeling force is horizontal, and so the moment about the centre of buoyancy when heeled is the same as that about the vessel centreline. The test results demonstrate that a significant vertical component of heeling force exists, particularly for vessels with a high beam to height ratio. The moment defined about the centre of buoyancy therefore may be substantially greater than that defined about the vessel centre, and the heeling moment at 10 degrees may be greater than the upright moment.

The combination of these two aspects has been considered and a formula for predicting the increase of heeling moment with heel angle is proposed. It is recognised however, that it is based on a relatively small sample of HSC forms.

The increased heeling moment at relatively small heel angles may have a large effect on the ability of some HSC to comply with the 2000 HSC Code criteria, and it is suspected that the assumptions that are inherent in the Code regarding the response to gusts may be invalid.

It is concluded that further study is justified to address two issues:

1. To extend the experimental data with further tests on heeled models to refine the formula for the variation of heeling moment with heel angle.

2. To conduct some experimental work to examine the response of catamaran HSC to wind gusts.

CONTENTS

1 INTRODUCTION

This report describes the work conducted and the findings of Research Project 503, HSC – Heeling Moment Prediction Methods. The research project followed broadly the programme outlined in Wolfson Unit proposal no.2560BD, dated 20th November 2002. The contract for Phase I of the programme, to conduct a literature search and determine the extent of existing wind tunnel data, was issued by the MCA on 15th January 2003.

During the course of Phase I it became clear that insufficient data were available for validation of a revised method in the case of multihull HSC of typical proportions. Only two sets of data were available within the range of parameters typical of such craft. On 21st March 2003 it was agreed to implement Phase II of the project to conduct wind tunnel tests on models of selected HSC.

2 BACKGROUND

The 2000 HSC Code incorporates formulae for the calculation of the wind heeling moment. These take the form:

$$HL = \frac{PAZ}{9800\Delta}$$

Where: HL is the heeling lever (m)
P is the wind pressure (N/m^2)
A is the projected lateral, or profile, area above the waterline (m^2)
Z is the vertical distance from the centre of A to half the draught (m)
Δ is the displacement (tonnes)

For monohull and multihull craft the wind pressure is defined as $P = 500\ (V_w/26)^2$

Where V_w is the wind speed (m/s) corresponding to the worst intended service conditions.
The constants in these formulae imply a heeling moment coefficient of 1.2.

Previous experimental work by the Wolfson Unit has indicated that for some craft, particularly those with a large plan area in relation to their profile area, the heeling moment coefficient might be somewhat greater than 1.2. Wind tunnel tests had been conducted on models of a number of catamaran forms but only one on a passenger ferry representative of HSC.

The scope of this project was to conduct a search for other experimental data and, if necessary, extend the scope of the data with further wind tunnel tests.

3 LITERATURE SEARCH

A search was conducted using the facilities of the University of Southampton library, internet resources, and personal contacts with known researchers in the fields of stability and wind tunnel testing.

A bibliography is presented in Appendix I.

The search suggested a number of sources of information of a general nature in the fields engineering and industrial aerodynamics. While there is a wealth of data on aerodynamic forces on bluff bodies, most references lacked data on overturning moments. A selection of such references is included in the bibliography, but they have not played a significant part in the analysis. The list of which references were used in the analysis, and which were not is detailed in Table 14.1

4 COLLECTED HEELING MOMENT DATA

4.1 Vessel Types

The data gathered as a result of the literature search represents a variety of ship types, and geometric blocks. Table 14.2 presents a summary of their principle dimensions and proportions. Figure 15.1 shows the spread of proportions collated. L and B are the overall length and beam. H is the maximum height of the main superstructure above the waterline.

Only one of the models represented a vessel with direct relevance to this study. This was a catamaran ferry that was selected for testing as part of a previous HSC stability research study conducted for the Department of Transport by Vosper Thorneycroft in 1988. [Refs 3, 4 and 5] The tests were conducted, for two superstructure configurations, by the Wolfson Unit. These are denoted "Passenger Cat" and "Passenger Cat, reduced SS" in Figure 15.1.

Two other catamaran forms were tested by the Wolfson Unit, a sailing catamaran [Ref 2] and a sidewall hovercraft [Ref 6]. The sailing catamaran was tested in a number of configurations without the rig, but the L/B ratio is significantly lower than that typical of catamaran ferries. It should therefore be regarded as an extreme form in that respect.

Heeling moment data were found for a number of conventional ferries and other vessels of similar proportions [Refs 1, 7 and 8]. In terms of the proportions of the above-water part of the hull and the superstructure they do not differ significantly from typical high speed monohull ferries.

Some data were found for floating dry docks [Ref 1]. Although their function and detailed shape are very different from those of ferries, their basic proportions fit within the appropriate range, and their inclusion was considered worthwhile. In addition to data used in this study there was data for other vessels that were deemed to be out with the proportions and shape of high speed ferries and hence not utilised; these ranged from LPG carriers to fishing vessels.

Perhaps the most informative data are those presented by Blendermann [Ref 1] for simple rectangular blocks of varying proportions. Tests were conducted on solid blocks of constant cross section with varying length, and of constant plan with varying height. The first case may be considered as representative of monohulls of varying length/beam or length/height ratio, and the second representative of monohulls and multihulls of varying beam/height ratio.

4.2 Scope of the Data

The data comprise wind tunnel test results. One vessel had also been the subject of full scale measurements, and reasonable correlation with the model test results was found [Ref 7].

While many of the wind tunnel test programmes included a range of wind headings, only those conducted by the Wolfson Unit [Refs. 2, 3 and 6] included tests at heel angles other than upright. The three test programmes conducted by the Wolfson Unit were specifically to investigate stability aspects of wind heeling, whereas in the other test programmes stability was not the primary aim.

One of the Wolfson Unit's test programmes [Ref 2] did not include tests with the model upright. The catamaran configuration did not fit within the turntable recess, and so the leeward hull was fitted into the recess while the windward hull was positioned above the flat turntable surface. This arrangement precluded tests with the model upright.

5 PRESENTATION OF DATA

5.1 Heeling Moment Definition

For most of the published data the heeling moment is defined as the moment about a point on the centreline, at the waterline or at the half draught. The appropriate vertical lever was used when converting the data to non-dimensional form to eliminate this difference.

For the two catamaran vessels the moment was defined about the centreline of the leeward hull rather than the vessel centreline. This definition is appropriate when the windward hull is out of the water; because the aerodynamic force and the opposing hydrodynamic force on the leeward hull generate the heeling couple, and the weight and residual buoyancy generate the righting couple. Whilst it is realistic for a sailing catamaran to heel in this way, it is not appropriate for most HSC. They are more likely to heel as a result of a combination damage, passenger crowding and wind heeling, and both hulls will remain in the water. To generate sufficient wind heeling moment to lift a power catamaran hull typically would require extreme winds in excess of 200 knots. The moment data for the catamarans therefore were transformed to obtain moments about the vessel centreline for comparison with other data.

5.2 Non Dimensionalisation of Data

In most cases the data was presented as a non-dimensional heeling moment coefficient, but where presented as real moments and forces sufficient information was provided to non-dimensionalise the data. The convention followed was to use the formula:

$$C_{hm} = \frac{HM}{qA_{profile}h}$$

where
C_{hm} – Coefficient of heeling moment
HM – Heeling moment
$A_{profile}$ – Projected profile area of the parts of the hull and superstructure
q – Dynamic pressure head ($q = \frac{1}{2}\rho v^2$)
h – Lever arm; height of centroid of profile area

It should be noted that the lever arm used to non-dimensionalise the data (h in Equation 1) varied between references (e.g. Blendermann [Ref 1] used the mean height of the vessel). Where this occurred the data were adjusted accordingly. The variation of the heeling moment coefficient with yaw angle with the vessel at 0 degrees of heel is presented in

Figure 15.2.

It can be seen from

Figure 15.2 that the general shapes of the heeling moment plots are the same with the exception of the vessel designated TWI0301BN, obtained from Reference 1, which was a SWATH vessel significantly different shape. The reasons for this are unclear, but the profile and plan shape of the vessel are very atypical, with large deck overhangs forward, aft and transversely.

The actual values of heeling moment coefficient vary significantly, with maxima ranging between 2.0 and 0.65. It is worth noting that the majority of the rectangular block data follows a very similar shape and value except for the most extreme shape (H/B = 0.23), which has a significantly higher maximum. Similarly extreme values were obtained for the sailing catamaran data [Ref 2] and these are beyond the scope of the graph, but the data were also obtained at heel, which has a major influence.

In order to obtain a level of parity between the results, various characteristics of the vessel were investigated and incorporated within the heeling moment coefficient. The objective of this was to try and obtain similar maximum values for all the data, and hence determine the key characteristics of the body. Both plan area and H/B ratio were considered, with the most promising influence being the H/B ratio raised to a power. It was found that the values could be brought closer in line with each other, but there was still a degree of scatter.

5.3 Discussion

The range of vessel proportions in the data presented is broad, and generally covers multihull HSC, which are typically of the order L/B = 2 – 4 and H/B = 0.4 – 0.75. While the forms included extend well beyond this range of parameters in all directions, there are few samples with these proportions.

Furthermore, while it may be argued that the data can be considered representative of the proportions of HSC, they are not necessarily representative of their detailed shapes.

It should be noted, with reference to Figure 15.1, that there are only three data samples at low L/B and low H/B ratios. These have been derived from the sailing cat tests, where no upright data were measured, and for the unconventional twin hull ferry, which exhibits an atypical heeling moment trend. It may be argued that the only reliable data for a vessel or shape with the proportions of a multihull HSC are those for the passenger cat used in the previous Department of Transport study.

For the purpose of deriving a generic rule, and to aid the understanding of the flow, the rectangular block data probably are the most informative. With sharp edges, they are not particularly representative of HSC, and they do not include any heeled data.

6 OTHER AERODYNAMIC DATA

The aerodynamics of bluff bodies has been well researched and there are some characteristics of the flow that assist with understanding the data.

The graphs in Figure 15.3, reproduced from Ref. 12, present pressures measured on the faces of a cube resting on the ground. The curves illustrate the variation of pressure around the surface on a vertical plane through the centre of the cube.

With the wind normal to one face, as with a ship at a heading of 90 degrees, the pressure on the windward face is positive, peaking near the top of the face. At the sharp corner there is a change of pressure with a negative pressure, or suction, over the upper face, peaking near the leading edge. Over the leeward face is a, roughly uniform, small negative pressure. It is apparent that the heeling moment is generated by a combination of the pressure difference between the windward and leeward faces, and the lift due to the negative pressure on the upper face. Because the peak suction on the upper face is near the leading edge, the resultant force due to the pressure distribution will be further from the centreline on a wider block.

The lower graph of Figure 15.3 shows equivalent data for the block with wind at 45 degrees to one face, as with a ship at a heading of 45 or 135 degrees. Compared with the 90 degree case, the pressure on the windward face is lower, the peak suction on the upper face is greater, and the suction on the leeward face is reduced.

Both wind tunnel data on models, and full scale data are included and demonstrate good correlation, although the full scale suction on the upper and leeward faces was greater at full scale than in the wind tunnel with wind at 90 degrees.

7 WIND TUNNEL TESTS

7.1 Outline Programme

It was agreed that further wind tunnel tests should be conducted to supplement the published data. The tests were to concentrate on quantifying the upright wind heeling moment for a range of forms, with tests on selected models heeled and trimmed to represent intact and damaged attitudes.

Because power catamarans do not heel to large angles, and the effects of heel on the aerodynamics at small angles were anticipated to be small, the number of heeled cases was minimised so that the maximum number of upright configurations could be tested within the agreed budget.

It was agreed to construct two new models of typical HSC, in a modular form to facilitate tests on different configurations, and to conduct upright tests on the existing sailing catamaran model, without the rig.

7.2 Test Facility and Model Set Up

The tests were conducted at the University of Southampton in the low speed section of the No.1 Wind Tunnel, which has dimensions 4.6 metres wide by 3.7 metres high. The model was mounted on a six component dynamometer located beneath a turntable. Forces from individual load cells were resolved into six components by the data acquisition system. A general view of the working section is presented in Figure 15.4.

The model was suspended from the balance in a tank of water, fitted into the turntable, which provided a seal between the model and the turntable and permitted the measurement of the model forces independent of the turntable. The test system was designed for monohull vessels and the relatively wide beam of the catamarans precluded the possibility of both hulls fitting within the water tank. The starboard hull of the model was connected to the dynamometer using a horizontal rod on the hull centreline at the bow, and a transverse bar near the stern. The full depth of the hull was modelled and immersed to the required waterline in the water tank. The port hull was cut off just above the waterline so that it was held over the solid part of the turntable with a small air gap. A screw adjustment was incorporated into each model to enable fine adjustment of the height of the port hull to minimise the air gap. A thin paper strip was taped to the turntable alongside the port hull to form a seal between the hull and the turntable without inducing any interference with the heeling moment measurement.

For each test configuration measurements were made of the forces and moments at apparent wind angles in the range 30° to 150°.

7.3 Flow Conditions

Tests were carried out at a dynamic head of 6 mm water gauge, which corresponds to a dynamic pressure of 60 Pascals and a wind speed of approximately 10 m/s.

The facility is an aeronautical wind tunnel rather than a boundary layer wind tunnel, and so the wind gradient and large scale turbulence properties of the atmospheric boundary layer were not modelled. A small boundary layer exists in close proximity to the wind tunnel walls and floor. The resulting wind gradient over the turntable is presented in Figure 15.5. The 300mm height range presented is representative of the model heights tested.

Woven screens placed upstream of the working section provide nominally uniform flow across the section, and introduce small scale turbulence which increases the effective Reynolds number. With model Reynolds numbers necessarily less than those at full scale, the increased effective Reynolds number minimises any scaling effects on the flow characteristics. Generally Reynolds scale effects can have a significant effect on flow separation from curved surfaces but are not significant for bodies with sharp corners, although the data presented in Figure 15.3 reveal that differences can occur.

7.4 Models

7.4.1 Model 1 – Sailing Catamaran

The model used for previous work on sailing multihulls was modified to enable tests to be conducted at 0 degrees heel. The previous tests were conducted at a range of heel angles but not upright. While the model was not representative of a typical HSC, and represents an extreme in terms of the range of proportions, it was considered worthwhile to conduct the tests because of the relatively low cost of using the existing model. The superstructure comprised a coachroof with rounded sections and profile typical of contemporary sailing catamarans designed for cruising.

The following model configurations were tested:

1. Hulls only (L/B = 1.86)
2. Hulls only with solid foredeck. This gave a 30% increase in deck area.

3. Hulls only at wide beam (L/B = 1.48)
4. Hulls and superstructure.
5. Hulls, superstructure and solid foredeck.

This model offered a beam variation, and in increase in deck area. It also provided data for a superstructure of rounded form. Photographs of the model are presented in Figure 15.6.

7.4.2 Model 2 – Conventional Catamaran

A model was constructed to represent a conventional small catamaran HSC. The general shape was also representative of many larger vessels. The superstructure shape was of roughly rectangular section with rounded corners and sloping forward faces.

The model was constructed in modular form to enable a range of configurations to represent a wide range of contemporary HSC:

1. Hulls only (L/B = 3.9).
2. Hulls, main saloon and upper wheelhouse
3. Hulls, main saloon and upper wheelhouse, with solid bulwarks
4. Hulls, main saloon and upper wheelhouse, with solid bulwarks decked over
5. Hulls, main saloon, upper wheelhouse and upper aft saloon
6. Hulls, main saloon, upper wheelhouse and upper aft saloon and central bow pod
7. Hulls, main saloon and upper wheelhouse, beam increased (L/B = 2.6)
8. Hulls, main saloon and upper wheelhouse, beam increased (L/B = 2.0)

Configuration 2 was also tested at 10 degrees heel to represent extreme damage to one hull.

This model provided 2 beam variations on the standard, narrow, form, and a number of superstructure configurations. See Figure 15.7 and Figure 15.8. The effects of the deep recesses formed by the bulwarks forward and the side screens aft, were studied by making the bulwarks and screens regular solid panels, and then by decking them over as shown by the centre photograph in Figure 15.8. These closures did not alter the profile or plan areas of the model.

7.4.3 Model 3 – Wave Piercing Catamaran

Models were constructed to represent a large contemporary wave piercing ro-ro HSC in three beam variations. It was not practical to modify the model in the same way as for the conventional catamaran, so three bridge deck and superstructure models were constructed to fit on one pair of hulls. The superstructure was of rectangular section with sharp corners, and with a cambered deck forward.

The model of the mid beam parent form was fitted with an additional layer of superstructure to increase the height without affecting the plan area or upper deck shape.

The tested configurations were:

1. Standard height, mid beam (L/B = 3.3).
2. Standard height, narrow beam (L/B = 3.8).
3. Standard height, wide beam (L/B = 2.7).
4. Increased height, mid beam

Configuration 1 was also tested heeled to 10 degrees at level trim, and then heeled to 10 degrees and trimmed down by the stern to represent extreme damage cases. The latter can be seen in Figure 15.4.

7.5 Test Results

The six component dynamometer measures heeling moments about its centre at the waterline. For these tests this corresponded to the centreline of the starboard hull. The data were transformed to derive moments about the vessel centreline.

Heeling moment coefficients were derived using the conventional parameters, the profile area and the height of its centroid above the waterline, and the dynamic pressure corresponding to the wind tunnel nominal velocity.

The resulting coefficients are presented for each configuration tested in terms of their variation with wind heading. A heading of 0 refers to a head wind and 180 to wind from astern.

To assist in understanding these results, the horizontal and vertical forces that generate the moments are presented for each case. The vertical force is defined as positive downwards. The resultant of the horizontal and vertical forces is the heeling force. It generates a heeling moment about the centre of the vessel that is also dependent on its lever from that point. These levers are also presented in each case.

7.6 Discussion of Results

7.6.1 Model 1 – Sailing Catamaran

See Figure 15.10 and Figure 15.11.
For the sailing catamaran it is clear that the heeling moment coefficients for the model with a flat deck are greater than those with a coachroof. The addition of the solid foredeck resulted in an increase in the coefficient. The increased beam resulted in an increased coefficient.

These results suggest that the profile area and height are insufficient parameters on which to base a coefficient, and that the plan area has an influence.

The maximum moments occur at headings of 80 – 90 degrees. The horizontal forces are similar for all cases, and slightly higher with the coachroof fitted. They remain relatively constant for headings in the range 40 to 130 degrees. The vertical forces are similar for all cases and vary from a lift force with a bow wind to a downward force with wind on the quarter. It is notable that this trend is not affected significantly by the addition of the curved coachroof. The vertical forces are of similar magnitude to the horizontal forces. The heeling levers show a pronounced maximum at about 90 degrees, accounting for the maximum in the heeling moment curves.

7.6.2 Model 2 - Conventional Catamaran

See Figure 15.12 and Figure 15.13.

The width variations investigated with this model show a similar trend to that of the sailing catamaran. The wider beam resulted in increased heeling moment coefficient. The coefficient for the wide model was 2.7 times that of the narrow configuration, although their profiles were the same. For the narrow model the moment remained relatively constant for headings of 50 to 130 degrees, while the wider models showed distinct maxima at around 100 degrees. The horizontal forces are similar for the three widths, and are greatest at headings of 50 and 130 degrees. The vertical forces have different trends, for example the wide model generated a force downwards with the wind on the quarter while the narrower models generated a lift. The vertical forces were significantly less than the horizontal forces in all cases. The levers of the resultant force exhibit the same trends as the heeling moments.

Data for the superstructure variations are presented in Figure 15.14. In comparison with the beam variations they show relatively little variation, with the exception of the coefficients for the model without a superstructure, which are about 3 times greater than the others. It should be noted that the height of the model with the superstructure was 2.35 times greater than that with no superstructure, and the greater coefficient is due largely to dividing the moment by the lower profile area, rather than generation of greater forces. A small increase in the coefficient was also found with the wheelhouse removed. Enclosing the recesses formed by the bulwarks had no effect on the heeling moments. These results imply that the moment is not dependant on the detailed shape of the superstructure.

7.6.3 Model 3 – Wave Piercing Catamaran

See Figure 15.15 and Figure 15.16.

The heeling moment coefficients followed similar trends for all configurations, remaining roughly constant for heading angles of 50 to 120 degrees. The coefficients based on the profile were similar for the standard and increased height configurations, but varied for the beam variations. As with the other models, increasing beam resulted in an increased moment coefficient. The difference between the coefficients for the standard and wide beam models was greater than the difference between those for the narrow and standard models, despite the fact that the difference in beams was greater between the standard and narrow models. This suggests an increasing importance of beam for relatively wide beam configurations.

7.6.4 Summary of Beam Variations

For ease of comparison, the heeling moment coefficients for the beam variations on all three models are presented together in Figure 15.17. The curves show variation in their shape, some remaining constant over a range of headings and others with distinct maxima. The magnitude of the coefficient is clearly dependent on the beam, with maximum values varying from 1.0 for the narrowest model to 5.7 for the widest.

7.6.5 Effects of Damage

The results of tests on heeled and trimmed models are summarised in Figure 15.18, where the moments are defined about the vessel centreline.

With the conventional catamaran model heeled to 10 degrees the maximum heeling moment about the centreline, regardless of heading, increased by about 20%.

With the wave piercing catamaran heeled, the maximum heeling moment about the centreline was less than for the standard configuration upright. With the model heeled and trimmed however, the maximum moment increased by 25%.

Whilst this simple summary implies significant differences, the plot shows that they are generally within the spread of experimental data. This spread is due in part to the variation of forces resulting from the detailed shapes of the models, and undoubtedly includes some experimental scatter.

8 DEVELOPMENT OF HEELING MOMENT PREDICTION METHOD

8.1 Variations in the Data

It should be borne in mind that the data included in this study have been sourced from experimental studies by a number of different organisations over a considerable period of time. There will be variations in methods of testing and analysis that lead to variations in the data.

In particular, there are differences between the methods of mounting the models for testing. All of the test results in the published data were derived using models suspended just above the floor of the wind tunnel. No attempt was made to seal the air gap between the floor and the model, but the experimenters assumed that the flow through it, and the resulting forces, were negligible. For the catamarans tested for this study the air gap was closed. Any flow beneath the model will tend to reduce the heeling moment, but the magnitude of this effect is not known. This difference may be responsible for some or all of the difference between the published data and those derived for this study.

The heeling moments derived for the various ships are taken about the waterline or the half draught. Those for the rectangular blocks are about their base, equivalent to the waterline. The appropriate values for the height of the centroid have been used in the derivation of the coefficients so that this difference should not affect the analysis or comparison of the data. In general in this study moments have been defined about the waterline because it is the aerodynamic aspects that are of interest, and the draught of a particular vessel is not of relevance to them. Provided the same lever is used to define the moment and non-dimensionalise it, the difference has no effect.

The ship models incorporate varying levels of detail. Masts, antennae, lights, railings, ship's boats and other fittings will affect the heeling moments to some extent, and introduce some scatter in the data. None were included on the models tested by the Wolfson Unit. Similarly, details of the shapes of hulls and superstructures will result in variations of the heeling moment that a simplified calculation method cannot be expected to predict.

8.2 Parametric Dependency

To assess the dependency of the heeling moment on various parameters, the coefficients obtained from published literature were combined with those from the wind tunnel tests, and plotted against various parameters and ratios. Figure 15.19 presents the variation of the coefficient, based on the profile area and height of the centroid above the waterline, against ratios of length, height and beam, where:

Length is defined as the length overall
Height is defined as the profile area divided by the length overall
Beam is defined as the beam overall

There is a clear dependency on the beam/height ratio, but the other ratios appear to have less importance, there being no obvious trends.

The sailing catamaran tests, where the plan area was increased by infilling with a solid foredeck, indicated that the heeling moment is influenced by the plan area. Since the heeling moment is dependent on an area, to generate a force, and its lever, to generate the moment, one might expect the plan area moment to be of importance for a wide vessel, as the profile area moment is for a narrow form. To investigate these parameters the variation of heeling moment with the ratios of plan area to profile area, and plan area moment to profile area moment, are presented in Figure 15.20. The variation with B/H ratio is presented again for ease of comparison.

Plan area moment = Plan area x B/2
Profile area moment = Profile area x height of centroid

The data obtained from Ref.1 on rectangular blocks are highlighted on the graphs. In each case, they suggest that the relationship is not linear but that the coefficient is in the range 1 to 1.2 at low values of each ratio, and increases with increasing ratio above a certain value.

The coefficient of 1.2 assumed in the 2000 HSC Code is indicated on the graphs and it is clear that, for the narrower craft, with low values of the ratios, this estimate of the heeling moment coefficient generally compares well with the measured value. In some cases the Code overestimates by 30%, but it does not underestimate the measured moment for any of the monohull forms, apart from the rectangular block with the highest beam to height ratio. The origin of the value 1.2 is not known to the authors but, for ships of normal form, it appears to offer a good estimate for regulatory purposes, where one would not wish to underestimate the moment. It is possible that the value 1.2 was chosen on theoretical grounds as an estimate of the coefficient of a bluff body, and that this is reasonable is borne out by the rectangular block data. It is also possible that it was based on a coefficient value of 1.0, which appears to correspond to the mean of the measured data, with a 20% safety factor.

It should be borne in mind that the heeling moments of full size vessels generally will be greater than those derived from the models because of the addition of masts, aerials, railings and other details. These additions will be small in most cases but are another consideration in favour of adopting an estimate approximating to the upper limit of the data, rather than a mean value.

For catamarans of narrow form the measured data show rather more scatter than for the monohulls, and the value 1.2 represents the mean of the measured data. For wider vessels, with high values of these ratios, the 2000 HSC Code underestimates the coefficient. The plot of coefficient against B/H ratio shows good collapse of the data at high B/H ratios. The plots against area ratio and area moment ratio show that the data do not collapse as effectively. This suggests that the heeling moment is more dependent on the B/H ratio than the other ratios, despite the fact that they include more information that one might expect to be relevant.

In an attempt to reduce some scatter in the data the height used in the ratio B/H was replaced by the height of the centroid of the profile area, as used in the coefficient derivation. Unfortunately the use of this parameter increased the scatter slightly.

To investigate further the trend with B/H, the heeling moments were normalised with respect to the plan area and half the overall beam, rather than the profile and height of centroid. These coefficients based on the plan rather than the profile of each vessel are presented in the lower graph of Figure 15.21, with the coefficients based on the profile presented again in the upper graph for ease of comparison. It is interesting to note that the coefficients for the very wide vessels are roughly constant, albeit with the data derived for this project giving rather higher coefficients than the published data and blocks.

These two graphs show that, for vessels of low B/H ratio the heeling moment is dependent principally on the profile, and for those with high B/H ratios it is dependent on the planform. In both cases a constant may be selected for the coefficient to enable a reasonable estimate of the heeling moment. Unfortunately most HSC fall in the intermediate region with B/H ratios of 1.5 to 3.5, where the scatter in the coefficient data is greatest.

Both graphs show a clear non-linearity of the coefficients with respect to the B/H ratio, and Figure 15.22 shows the same two coefficients plotted against the square of the B/H ratio, or its inverse in the case of the lower graph. This reveals a roughly linear relationship in both cases, for the full range of proportions. The coefficients based on the profile are less scattered in terms of the percentage variation at a given B/H ratio than those based on the plan. The profile therefore appears to offer more suitability for use in estimating the heeling moments.

8.3 Options Considered

A number of possibilities were considered for methods of estimating the heeling moments. Various combinations of the following options were considered.

1. Use the existing formula.
2. Option 1 + a linear function of the B/H ratio for vessels with high B/H ratio.
3. Option 1 + a higher power function of the B/H ratio for vessels with high B/H ratio.
4. Option 1 + a constant value of the coefficient based on the plan area for vessels with high B/H ratio.
5. Options 1 & 4 + a linear function of the B/H ratio for vessels of intermediate B/H ratio.
6. Use a linear function of the $(B/H)^2$ ratio for all vessels.

Option 1 has the obvious advantage of not requiring any changes to the Code, but gives an underestimate of the moments for the wider vessels. It therefore does not err on the side of safety.

Options 2 and 3 have the advantage that they use the existing method of determining the moment for narrow vessels, and a simple adjustment to it for wider vessels.

Option 4 has the advantage that constant values are used throughout, albeit they are different values for narrow and wide vessels.

Options 4 and 5 require calculation of the plan area, which is a trivial calculation but represents a significant departure from the traditional method.

Options 2 to 5 require switching between methods depending upon the value of the B/H ratio.

Option 6 offers the possibility of using a single formula for all vessels, regardless of their proportions. It can be used equally for monohulls and multihulls and in that respect may be the simplest option to incorporate into a code of practice.

In addition to these options, it would be possible to use the height of the centroid of the profile area rather than the mean height in defining the B/H ratio. This would eliminate the need to calculate the mean height from the function Profile Area/Length. This calculation is relatively trivial however, and the use of this value for H appears to result in less scatter in the data. For this reason, and perhaps surprisingly, this value results in slightly better estimates of the heeling moment.

8.4 Proposed Revision to the Existing Formula

Option 6 was selected as the most suitable, giving the best compromise in terms of accuracy and simplicity.

A proposal is indicated on the graph in Figure 15.22 for a possible formula with which to estimate the heeling moments of all vessels.

$$C_{hm} = 1.08 + 0.12(B/H)^2$$

This may be translated into the form used in the 2000 HSC Code, where the existing formula for wind pressure, that incorporates a coefficient of 1.2, could be altered.

The existing formula is:

$$P = 500\,(V_w/26)^2$$

And could be changed to:

$$P = \left(450 + 50(B/H)^2\right)(V_w/26)^2 \qquad \textit{Formula 1}$$

Figure 15.22 shows this formula to follow the trend of the measured values. It bounds the upper limit of the data for values of $(B/H)^2$ up to 19. That is equivalent to beam/height ratios greater than 4, which exceeds the range of typical HSC. The experimental values furthest from the line are those for the sailing catamaran, and some of those taken from published data. For a B/H ratio of 1 the formula gives the same estimate for heeling moment as the existing value, 1.2, and therefore is considered appropriate for monohull vessels. The amount by which it overestimates the heeling moment is generally within 25% for the conventional catamaran and wave piercing catamaran, but is up to 50% for the narrowest cases.

If it is considered that this formula gives too high an estimate, it could be adjusted by reducing the constant 450 and, or, the constant 50. The former would have the effect of lowering the line on Figure 15.22, while the latter would reduce its gradient. It could, for example, be adjusted to the mean of the experimental data, but it is suggested that the conservative formula proposed is more appropriate for regulatory purposes.

9 EFFECTS OF HEEL ON THE HEELING MOMENT

9.1 Moment Definition

The effects of heel on the definition of heeling moment were described briefly in section 5.1 with regard to the fact that, when upright the moment should be taken about the centreline of the vessel but if heeled this may no longer be the preferred reference.

The righting couple is defined as displacement x GZ, and is generated by the weight and opposing buoyancy. Whilst the buoyancy is normally taken to be equal to the displacement, if there is a significant vertical aerodynamic force the buoyancy will be reduced, and with it the righting couple. Since the vertical force is not normally considered it is preferred to consider it as part of the heeling couple rather than an adjustment to the righting couple. For this reason it may be more intuitive to consider the balance of moments about the centre of buoyancy, so that the righting couple remains displacement x GZ. On a catamaran this moves progressively to leeward until it is within the leeward hull.

The heeling couple is normally taken as the horizontal aerodynamic force opposed by an equal hydrodynamic force acting at the half draught. On a catamaran the point at which the hydrodynamic force acts moves towards the leeward hull, as does the centre of buoyancy. Whilst this does not affect the lever of the horizontal component significantly, it does affect the lever of the vertical component, and hence the resultant aerodynamic moment.

As the heel angle increases, the heeling moment increases because of this increasing lever and its effect should be borne in mind when considering the implications of wind heeling on catamarans.

This subject is illustrated and described in more detail in Appendix 2 – Heeling Moment Definition.

9.2 Test Results

9.2.1 Sailing Catamaran

The heeling moments generated the sailing catamaran model upright are substantially lower than those measured in the previous study on multihull sailing vessels, with the model heeled. Data for the upright model are presented together with heeled data from the previous study in Figure 15.23. Data for two headings are presented. The heading of 50 degrees corresponds to the maximum heeling moments measured with the model heeled. The heading of 90 degrees was selected as representative of the maximum heeling moments for the upright model. The data show good correlation with the previous test results in the consistency of the relative magnitudes for the various configurations. The heeling moments increase rapidly with heel angle as the windward hull rises above the water surface and the effective area increases considerably. The coefficients become particularly high as they are based on the profile area, while at high heel angles the much larger deck area dominates.

The heeled data are presented for moments taken about the vessel centreline and about the leeward hull. To transfer the moment the measured horizontal and vertical forces were analysed and transformed to the revised axis. The effect of transferring the moment to the leeward hull is an increase of around 50%.

All heeled data were obtained with the windward hull out of the water.

9.2.2 Conventional Catamaran

Moments were measured with the model heeled 10 degrees to represent damage to the leeward hull, and the maximum moment was increased by 12% relative to the upright value. This does not include any transfer of the lever towards the leeward hull because, when heeled as a result of damage, the centre of buoyancy will remain near the centreline.

9.2.3 Wave Piercing Catamaran

Moments were measured with the model heeled 10 degrees to represent damage to the leeward hull, and the maximum moment was reduced by 7% relative to the upright value. As for the conventional catamaran, this does not include any transfer of the lever towards the leeward hull.

9.2.4 Passenger Catamaran of Refs.4 & 5

Figure 15.24 presents data derived from the Wolfson Unit files of the results of tests conducted for Vosper Thorneycroft.

As for the sailing catamaran, they are presented for moments both about the vessel centreline and the leeward hull. A third, solid, line presents the coefficients of the moments defined about the centre of buoyancy. The windward hull would be above the water at angles in excess of 18.5 degrees, and the movement of the centre of buoyancy is linear until this point [Ref 4]. This causes a near linear transfer between the curves for the moment about the vessel centreline and the hull centreline.

The increase in heeling moment that occurs around 20 degrees illustrates the aerodynamic effect of the windward hull rising above the water surface.

Figure 15.25 presents the heeling moment arm against the righting lever for this vessel in 50 knots and 100 knots of wind.

9.2.5 Collated data

Figure 15.26 presents results from all models that were tested at a heel angle. For the wave piercing and the conventional catamarans, the moment has been taken about the point where the centre of buoyancy would have been if the vessel were intact and at the specified heel angle.

The upper graph presents the measured heeling moment coefficients at 10 degrees heel, based on the profile areas, against the B/H ratio. The angle 10 degrees was selected because it is well below the angle of hull emergence, and should therefore be within the linear range of the increasing heeling moment, for all cases studied. There is a clear non-linear trend to the data. It is suspected that the heeled moment may be proportional to the cube of the beam, because the plan area and horizontal lever become increasingly important as the vessel heels, giving a dependency on the beam squared, and the beam governs the transverse shift of the centre of buoyancy. Unfortunately the limited amount of data, combined with the substantial difference between the two data points at B/H = 4.9, preclude any definite conclusion.

In the lower graph the ratio of the heeling moment about the centre of buoyancy at 10 degrees of heel to the upright moment is presented with respect to the B/H ratio. In each case the maximum value of the heeling moment in the heeled attitude has been used, so that the data are not constrained to a particular heading. The plot illustrates that the current assumption used in the HSC Code, that the heeling moment does not vary with heel angle, is invalid. There is some scatter of the data because of other parametric variations, but a strong relationship with the B/H ratio is indicated.

The value of the moment when heeled is influenced by the angle at which the windward hull emerges from the water, and the centre of buoyancy transfers to the leeward hull. This is dependent on the distance between the hull centres, the beam, and the draught of the hulls. Attempts were made to identify a relationship between the ratio of moments to the draught, or beam/draught ratio and these are illustrated in Figure 15.27. In these Figures the draught is referred to as T. While each of these plots shows a similar trend to the lower graph in Figure 15.26, the data do not collapse further.

9.3 Discussion

The sailing catamaran data indicate that the coefficient can increase by an order of magnitude from the upright value to the maximum value at an extreme heel angle. This model has a very high beam to height ratio however, and its proportions are extreme in HSC terms.

The passenger catamaran data indicate a more modest increase of moment with heel angle. The moment about the centreline remains roughly constant with heel angle, but if the transfer towards the leeward hull is taken into account, it increases by a factor of 3 up to a maximum at an angle of 20 or 30 degrees, depending on the heading. Although the upright heeling moment coefficient is lower than the value of 1.2 assumed by the 2000 HSC Code, it rises to that value at a heel angle of about 4 degrees with moments taken about the centre of buoyancy. The wind speed required to lift the windward hull from the water is in excess of 120 knots, and so there is no potential for capsize purely as a result of wind heeling.

It is considered impossible for a catamaran to roll such that one hull emerges from the water as a result of wave action alone, except if struck by a very large breaking wave. Model tests conducted in the towing tank for the study described in Ref.2 revealed that a catamaran could be rolled to extreme angles by impact with a breaking wave, where the height of the breaking crest is approximately the same as the beam of the vessel. Given the operational limits of HSC, this is not considered to be a relevant scenario.

The relationship between the B/H ratio of a vessel and the increase in the heeling moment incurred at an angle of heel appears to be strong. Other factors have an effect but do not appear to be preferable for prediction purposes.

9.4 Prediction of the Heeling Moment Variation with Heel Angle for Intact Vessels

On the basis of the trend identified, relating the heeling moment coefficient at a heel angle of 10 degrees to that upright, a simple method may be proposed to predict the heeling moment at a heel angle for intact vessels.

It must be borne in mind that the graphs presented in Figure 15.26 and Figure 15.27 represent the ratios of heeling moments measured in the wind tunnel. When assessing the heeling moment for regulatory purposes the upright heeling moment coefficient normally will be estimated. Plotting the ratio of the heeling moment at 10 degrees of heel to the estimated upright moment, rather than the measured upright moment, reduces the scatter of the data. The plot of this ratio against the square of the B/H ratio is presented in Figure 15.28. Formula 1 of section 8.4 was used to obtain the estimate of the upright heeling moment coefficient. The models are identified by the numerals alongside the data points. (For the conventional and wave piercing catamarans the ratios differ considerably from those suggested by the relative magnitudes of the curves in Figure 15.18, because there the moments were defined about the centreline rather than the centre of buoyancy). The data for the lower B/H ratios, which are representative of most HSC, show a linear trend on this plot. The trend results from the fact that the estimated upright data have been derived from a function of the $(B/H)^2$ parameter, while the measured heeled data follow the power function of B/H indicated by the upper graph of Figure 15.26. The reduced scatter reflects that in the upper graph in Figure 15.26.

Two lines are shown on Figure 15.28. The assumption inherent in the 2000 HSC Code is illustrated as a horizontal line with the ordinate 1.0. The other line is one that might be used to provide an estimate of the increase in heeling moment at 10 degrees compared to the predicted upright value.

It is defined by the formula:

Heeling moment at 10 degrees = $[0.75 + 0.1(B/H)^2]$ Predicted heeling moment upright

There is a range of angles for which the beam wind heeling moment increase with heel angle remains approximately linear. The range extends to the angle at which the windward hull emerges from the water and is considered to be the limit of interest for HSC Code vessels. It corresponds to the linear portion of the GZ curve. This linear relationship enables the formula to be rewritten to estimate the heeling moment at any angle within this range:

Heeling moment at θ degrees = Predicted heeling moment upright $[7.5 + (B/H)^2]\ \theta/100$

Or for the purposes of estimating the heeling lever in the Code:

$$HL_\theta = HL_0\left[7.5 + (B/H)^2\right]\frac{\theta}{100} \qquad \textit{Formula 2}$$

The accuracy of the prediction given by this proposed line appears to be better than that offered by formula 1 for the upright moment. The worst case for the examples shown in Figure 15.28 is an overestimate of 39% for the moment at 10 degrees, for the conventional catamaran.

If it is considered that this formula gives too high an estimate, it could be adjusted by reducing the constant 7.5 and, or, the constant 1 applied to the $(B/H)^2$ ratio. The former would have the effect of lowering the line on Figure 15.28, while the latter would reduce its gradient. It is suggested that the formula proposed is appropriate for regulatory purposes for a number of reasons. It agrees well with the two monohull data points at the lowest B/H ratios, it is central to the data points at extremely high B/H ratios, it comprises simple constants, and it incorporates the same parametric ratio as formula 1.

Whilst the accuracy of the predictions offered by formula 1 are somewhat disappointing, the estimates at 10 degrees given by formula 2 appear to be better. It should be appreciated that, in comparing a heeling arm curve with a GZ curve for the purposes of stability assessment, the magnitude of the heel angle at 10 degrees has greater significance than that upright.

It is recognised that the number of data points from which this formula has been derived is limited, with only 4 relating to HSC forms. Further experimental work may be warranted in confirming or adjusting this prediction method.

MCA Research Project 509 is to address the stability criteria, and a revised prediction of the wind heeling moment will need to be considered in conjunction with the criteria to which it applies in that study.

9.5 Prediction of the Heeling Moment Variation with Heel Angle for Damaged Vessels

This method should not be applied to the angle of loll of damaged vessels because the centre of buoyancy does not move off the centreline to the same extent, and so the heeling moments are substantially lower. Based on the evidence of the tests on the wave piercing and conventional catamarans at 10 degrees heel, it can be assumed that the moment at the equilibrium angle following damage is the same as that upright. Subsequent heel will result in movement of the centre of buoyancy in the same way as when intact, and so the method described above may be used to obtain the heeling moment at an angle 10 degrees greater than the equilibrium angle, if required.

10 VELOCITY GRADIENT

Among stability standards worldwide some assume a uniform velocity and others incorporate a velocity gradient.

Because the atmospheric boundary layer results in a velocity gradient over the earth surface, there is a strong argument in favour of using a gradient for stability assessment. Large, tall vessels experience greater wind speeds over upper decks and masts than small vessels. Small vessels therefore may be penalised by assuming a uniform wind speed.

The velocity gradient is variable and may be eliminated in gusts, and particularly in squalls which frequently have a strong downward component. Small vessels therefore may be subjected to the same wind speeds as larger vessels.

It is standard practice to quote wind speeds at a reference height of 10 metres. In the presence of a velocity gradient the speed will be slightly greater above this height, and lower below it. For example, at a height of 20 metres the speed would be about 10% greater, and at a height of 6 metres about 10% lower. For most high speed craft 10 metres is representative of the superstructure height.

The use of a gradient complicates the calculation of the wind heeling lever with no guarantee that the result will be any more accurate or representative. Its use is not considered worthwhile.

11 GUST RESPONSE

11.1 Gusts

Gusts may be defined as variations in wind speed resulting from turbulence in the atmospheric boundary layer.

The 2000 HSC Code applies a gust factor of 1.5 on the wind heeling moment.

Meteorological data have been studied by others to determine gust factors over the sea, and their findings are summarised in Ref 22.

The magnitude of the maximum probable gust factor is dependent on the duration of the gust. Because turbulence in the atmospheric boundary layer exists at a range of scales and frequencies, gusts of very short duration can exhibit higher gust factors than those of longer duration. The gust factor appropriate for gusts of 1 second duration is 1.4 on velocity, that is a factor of 2 on wind pressure and heeling moment. The gust factor appropriate for gusts of 10 seconds is 1.23 on velocity, that is 1.5 on pressure and heeling moment. For 100 second gusts the factor is 1.12 on velocity, or 1.25 on moment. These values are based on the hourly mean wind velocity.

It is implicit in the value used in the 2000 HSC Code therefore, that a 10 second gust is assumed.

When developing UK stability requirements for commercial sailing vessels [Refs 23 & 24] the maximum probable gust factor of 1.4 was used on the basis that gusts of shorter duration might have a significant impact on a small yacht. This factor was used in combination with an assumed static response to the gust, rather than a dynamic response predicted by matching areas under the wind heeling and righting arm curves as in the conventional weather criterion.

The gust response of sailing vessels was determined through a programme of model tests and full scale measurements. It was found that, in response to a gust, the vessel heeled to the angle corresponding to the steady heel angle under the gust wind speed with very little heel angle overshoot. Principally this is believed to be because, provided the vessel heels from upright to the response angle in a time equal to, or greater than, one quarter of the natural roll period, there is no dynamic element to the response. Using the maximum probable gust factor 1.4 therefore also provided a safety margin for gusts of long duration that are more likely to hold a vessel at the gust response angle for a prolonged period.

The gust responses of monohull and multihull HSC is not known, and so it is unclear whether the existing weather criterion provides an accurate representation of their behaviour, or whether a static approach, as used for sailing vessels, would be more appropriate.

It is the view of the Wolfson Unit that a static approach would be simpler, and more representative for HSC, and should be used in conjunction with the maximum probable gust factor, but no experimental or full data are available to support it.

This is an important aspect of the stability assessment that appears to have little technical basis, and one that warrants further study. The level of safety offered by the existing stability criteria is the subject of MCA Research Project 509, although the response to gusts was not identified as a particular area to be addressed.

11.2 Squalls

Squalls may be defined as an increase in wind speed resulting from an encounter with a small scale weather system. Gust factors for squalls, based on the hourly mean wind speed, may be much greater than those for gusts. Factors on velocity of more than 10 have been recorded, resulting factors on pressure and heeling moment of more than 100.

Squalls are of great importance to sailing vessels because, if they are unexpected, sails set may be suitable only for the light winds preceding the encounter with the squall. For most engineering design studies they are of little importance because the wind speed in a squall is unlikely to exceed the maximum wind speed in storm conditions.

High speed craft are a slightly different case because they may be certificated for operation up to a maximum anticipated wind speed, and it is possible that an unexpected squall might result in an encounter with conditions beyond the normal operational limit.

To incorporate such a scenario into the wind heeling assessment is not considered appropriate, but the possibility of encountering severe squalls should be borne in mind in the operational procedures for vessels certificated only for moderate conditions.

12 IMPLICATIONS OF THE PROPOSALS

To illustrate the implications of the formulae described in sections 8.4and 9.4 on sample HSC, the three beam variations of the conventional catamaran ferry were considered. The narrow beam version is the example with the greatest deviation from the line in Figure 15.28, and so it represents the greatest overestimate for the examples considered.

The vessel parameters of displacement, draught, profile area and centroid above the waterline were held constant for all three cases. A wind velocity of 50 knots was used.

Vessel	Righting lever at 10 degrees heel (m)	2000 HSC Code heeling lever, HL_1 (m)	Upright heeling lever by formula 1 (m)	Heeling lever at 10 degrees by formula 2 (m)	Upright heeling lever measured in wind tunnel (m)
Narrow	1.297	0.235	0.298	0.333	0.110
Mid-width	4.195	0.235	0.405	0.637	0.184
Wide	6.396	0.235	0.544	1.177	0.306

Vessel	Heel angle due to 2000 HSC Code heeling lever HL_1 (degrees)	Heel angle due to formulae 1 & 2 (degrees)
Narrow	1.8	2.5
Mid-width	0.5	1.0
Wide	0.3	0.6

Under 2000 HSC Code, HL_2 ($=1.5HL_1$) must not cause the vessel to exceed 10 degrees of static heel. The righting arms are substantially greater than the heeling arms and so there exists a very large margin over the minimum requirements in all cases.

The proposed formulae increase the estimates of the heeled moment such that the estimated angle of heel increases for all of these vessels. For the wide vessel the increase in the heeling lever is 500%, but the resulting heel angle remains very small at 0.6 degrees. The large increase in the heeling arm would affect any criterion related to the area under the heeling arm curve.

Perhaps the most significant increase is in the case of the narrow vessel, where the estimated heel angle increases by 42%, which represents 0.7 degree increase.

These examples are illustrated graphically in Figure 15.29.

13 CONCLUSIONS

The literature search revealed valuable published data on wind heeling moments, but generally these were restricted to vessels outside the range of parameters of typical HSC.

The wind tunnel tests extended the published data to cover a wider range of parameters, and included tests on two typical HSC forms.

Heeling moments tend to be dependent on the profile area and height of the vessel, for vessels of low beam to height ratios.

Heeling moments tend to be dependent on the plan area and beam of the vessel, for vessels of high beam to height ratios.

The formula used in the 2000 HSC Code to estimate the heeling moment provides an overestimate for monohulls and other vessels of low beam to height ratios. It underestimates the heeling moment for vessels of high beam to height ratios.

A formula is proposed with which to estimate more accurately the upright wind heeling moment for vessels of high beam to height ratio. It may be applied to monohulls with low beam to height ratios and, for them, gives similar predictions to the method used in the 2000 HSC Code.

The heeling moment remains largely unaffected by trim of the vessel.

The heeling moment is affected by heel angle in two ways. The moment about the vessel centreline is affected in a minor way and may increase or decrease slightly provided the windward hull remains immersed. There is a significant vertical component that results in an increase in the moment about the centre of buoyancy as this point moves to leeward with increasing heel angle. A formula is proposed with which to estimate increase in the heeling moment with heel angle. Whilst it appears to give reliable estimates, it is recognised that it is based on a relatively small data sample. It is recommended that additional tests be conducted to increase the sample and refine this formula if necessary.

The effects of wind gradient may result in generally lower heeling moments for smaller vessels, and greater moments for larger vessels, but gusts and squalls can eliminate the velocity gradient. The inclusion of wind gradient would increase the complexity of the Code without necessarily improving the accuracy of the assessment.

Gust factors of up to 1.4 on wind speed may be experienced over the sea for gusts of short duration, and the Code assumes a factor of only 1.22. The responses of HSC to such gusts are not known and so refinement of the Code with regard to gusts may not be appropriate at this time. It is recommended that tests be conducted in a gust facility to establish the heel response of sample HSC to wind gusts.

Incorporating the proposed formulae into the HSC Code in conjunction with the existing criteria may be inappropriate. The proposed methods should be incorporated together with any revised criteria that result from Research Project 509.

14 TABLES

Table 14.1 Data presented in references

Source	Presented	Heel	Yaw	Absent
-------- Data used in analysis ----------				
Blendermann, 1999	Chm & Cfy, principle dims	0	0-180	
Blyth 1991	moment lever arm	0-60	90	Method of non dimensionalising lever; assumed to be displacement
Roberts 1991	rule limit	0-60	0-180	Experimental data
WUMTIA report 841	Moment and force	0-60	0-180	
WUMTIA report 1441/1	Moment & force	10-90	20-140	
Aage, 1998	Chm & Cfy, principle dims	0	0-180	
Serra, 2002	Moment, force & centroid	-20 - 50	90	Accurate listing of dimensions
---------- Data not used in analysis ----------				
Isherwood, 1973	No moments or centroids presented			
Molland 2003	No moments or centroids presented			
Bosch, 2001	No moments or centroids presented			
Richards, 2001	Cp plots, but no specific moment data		0, +/- 45	
Tieleman, 1998	No moments or centroids presented			
Holmes, 2001	No moments or centroids presented			
Uematsu, 1999	No moments or centroids presented			
Barlow, 2001	No moments or centroids presented			
ESDU, various	Non dimensional forces and centroids	various	various	Raw experimental data

Table 14.2 Principle dimensions and proportions of vessels in review

Vessel Name	**Vessel Description**	**Source**	**Loa**	**L/B**	**H/B**	**Profile Area**	**Centroid Height**	**Plan Area**
CAR 0102BN	Car carrier	Blendermann, 1996	190.7	8.31	1.00	4378	11.96	-
CAR 0201BN	Car carrier	Blendermann, 1996	195.0	6.50	0.78	4586	12.56	-
CAR 0202BN	Car carrier	Blendermann, 1996	195.0	6.50	0.80	4694	12.65	-
DRY0101BN	Empty dry dock	Blendermann, 1996	97.5	4.55	0.42	745	4.48	2091
DRY0102BN	Dry dock & boat	Blendermann, 1996	97.5	4.55	0.72	1266	8.20	2091
DRY0201BN	Empty dry dock	Blendermann, 1996	206.5	5.10	0.36	2795	7.19	8363
DRY0202BN	Dry dock & boat	Blendermann, 1996	206.5	5.10	0.52	4023	10.50	8363
DRY0203BN	Dry dock & boat	Blendermann, 1996	206.5	5.10	0.58	4501	12.41	8363
Fincantieri	Cruise Liner	Serra, 2002	290.0	8.99	1.25	10600	27.50	-
M/F Povl Anker	Ferry	Aage, 1998	121.0	5.63	0.80	2079	10.10	-
FER0301BN	Ferry	Blendermann, 1996	161.0	5.55	0.90	4223	14.85	-
TWI0103BN	Twin hull ferry	Blendermann, 1996	51.5	1.62	0.26	422	8.20	-
Sailing Cat, no rig	Charter Sailing Catamaran	WUMTIA report 1441/1	13.6	1.85	0.37	26	1.08	76
Sailing Cat, no rig or deckhouse	Charter Sailing Catamaran	WUMTIA report 1441/1	13.6	1.85	0.16	20	0.79	76
Passenger Cat	Foot Passenger Catamaran	WUMTIA report 841	26.8	2.39	0.80	154	3.24	325
Pass. Cat, reduced superstructure	Foot Passenger Catamaran	WUMTIA report 841	26.8	2.39	0.63	113	2.53	325
Block, H/B = 1.00	Block, varying height	Blendermann, 1996	-	6.67	1.00	-	-	-
Block, H/B = 0.6	Block, varying height	Blendermann, 1996	-	6.67	0.60	-	-	-
Block, H/B = 0.43	Block, varying height	Blendermann, 1996	-	6.67	0.43	-	-	-
Block, H/B = 0.3	Block, varying height	Blendermann, 1996	-	6.67	0.30	-	-	-
Block, H/B = 0.23	Block, varying height	Blendermann, 1996	-	6.67	0.23	-	-	-
Block, L/B = 6.67	Block, varying length	Blendermann, 1996	-	6.67	1.00	-	-	-
Block, L/B = 4.00	Block, varying length	Blendermann, 1996	-	4.00	1.00	-	-	-
Block, L/B = 2.00	Block, varying length	Blendermann, 1996	-	2.00	1.00	-	-	-
Block, L/B = 1.00	Block, varying length	Blendermann, 1996	-	1.00	1.00	-	-	-

15 FIGURES

Figure 15.1 Extent of the available data in terms of vessel proportions

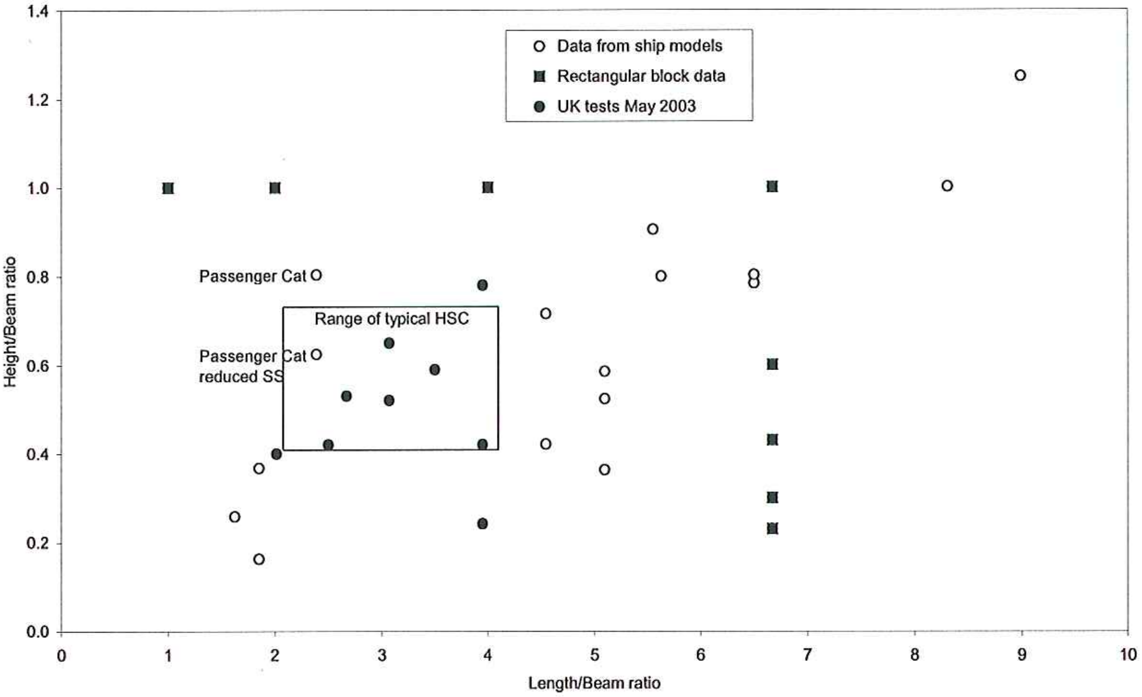


Figure 15.2 Non dimensional heeling moment coefficients from published data

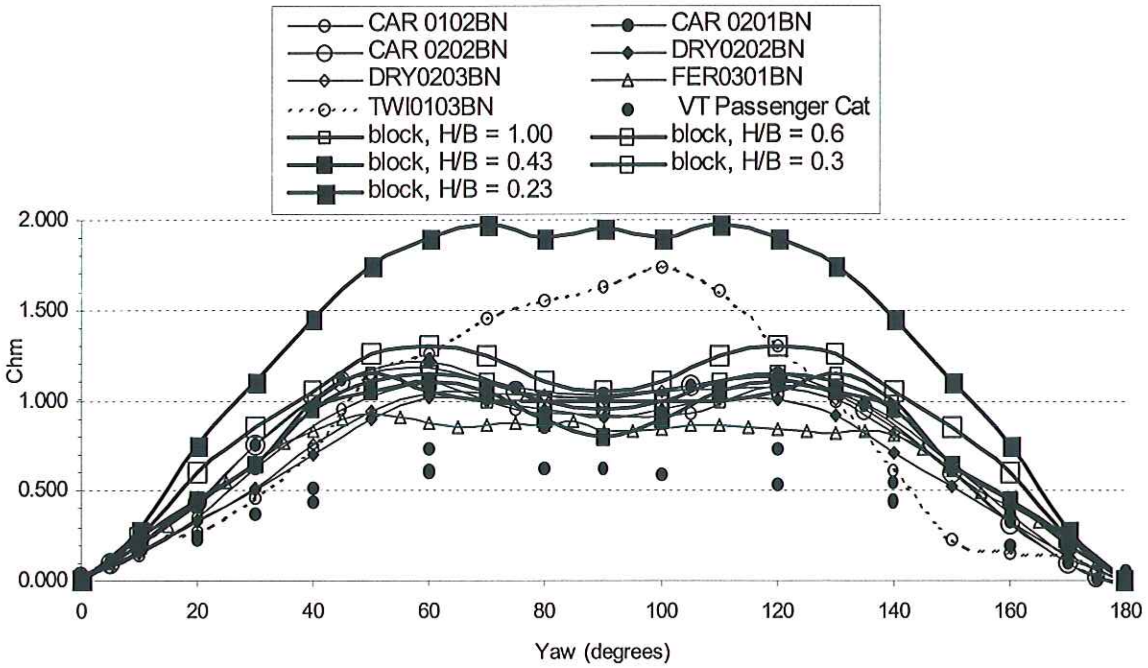
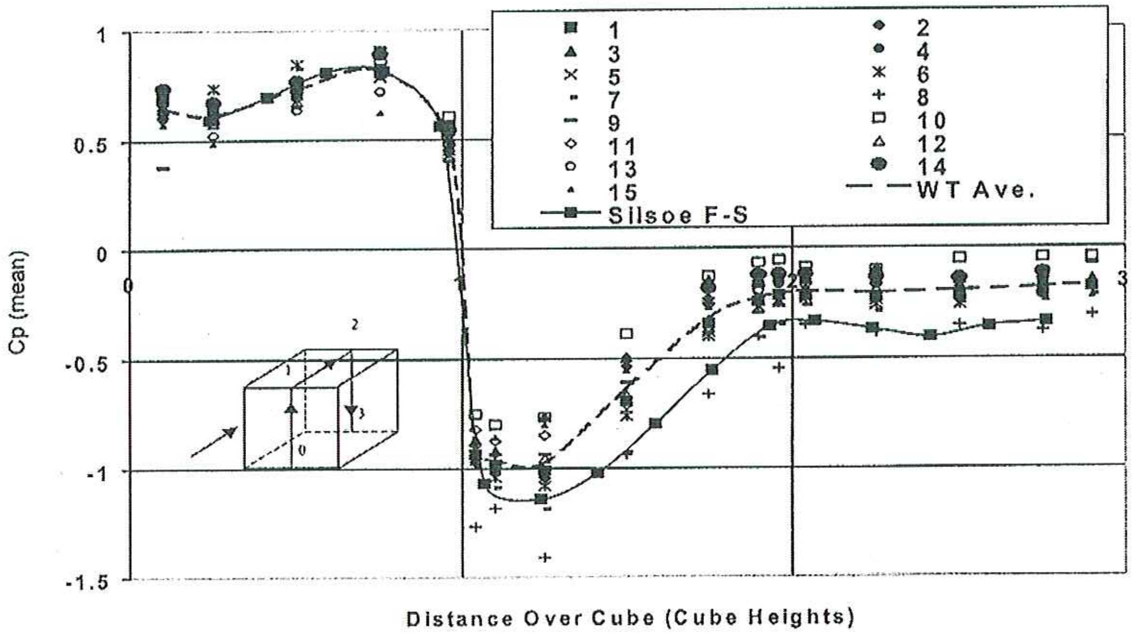


Figure 15.3 Pressure coefficients measured at model and full scale on a 6 metre cube on the ground

Wind normal to one face



Wind at 45 degrees to one face

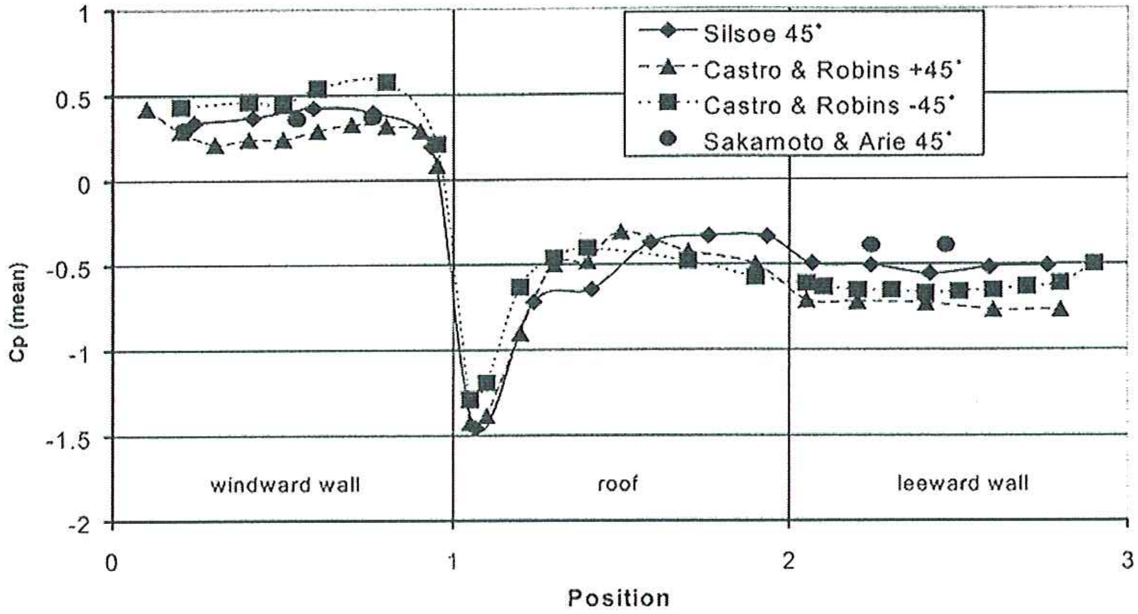


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Figure 15.4 Wind tunnel low speed section, looking upstream

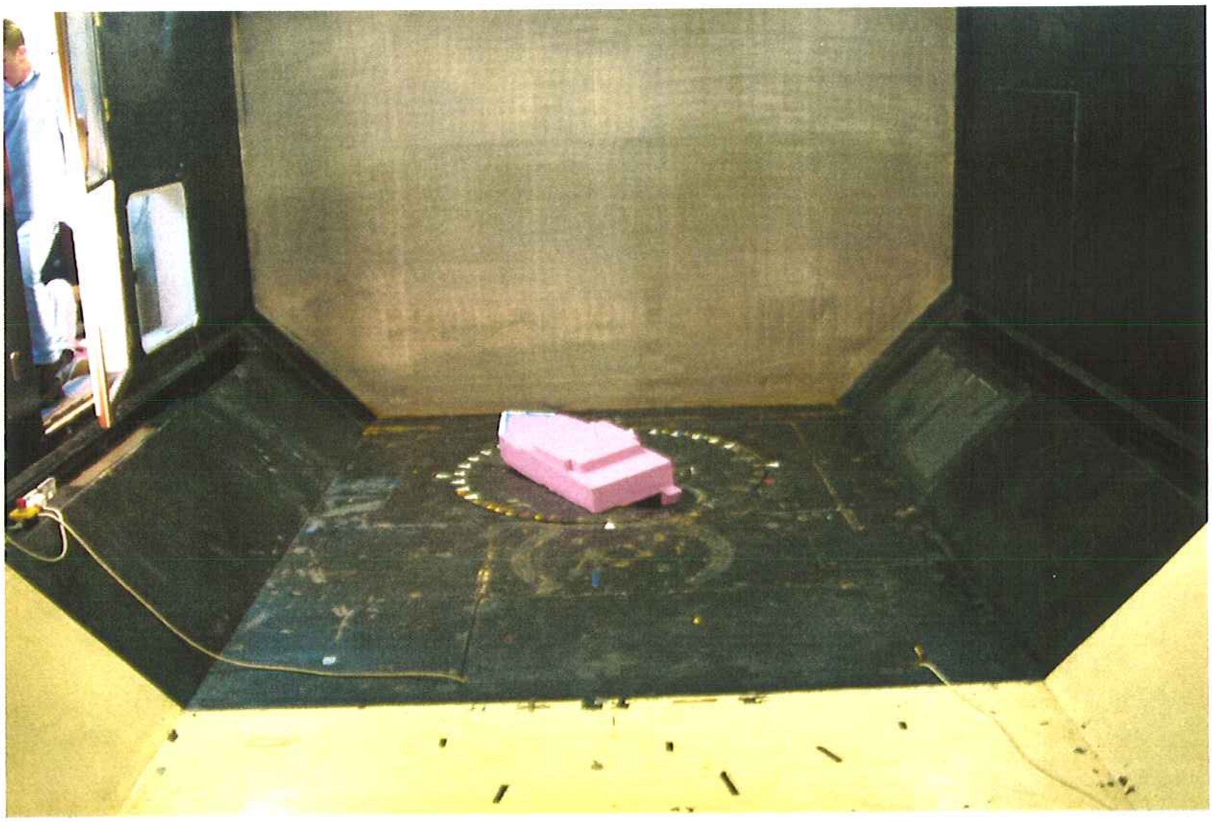


Figure 15.5 Velocity gradient measured over the centre of the wind tunnel turntable.

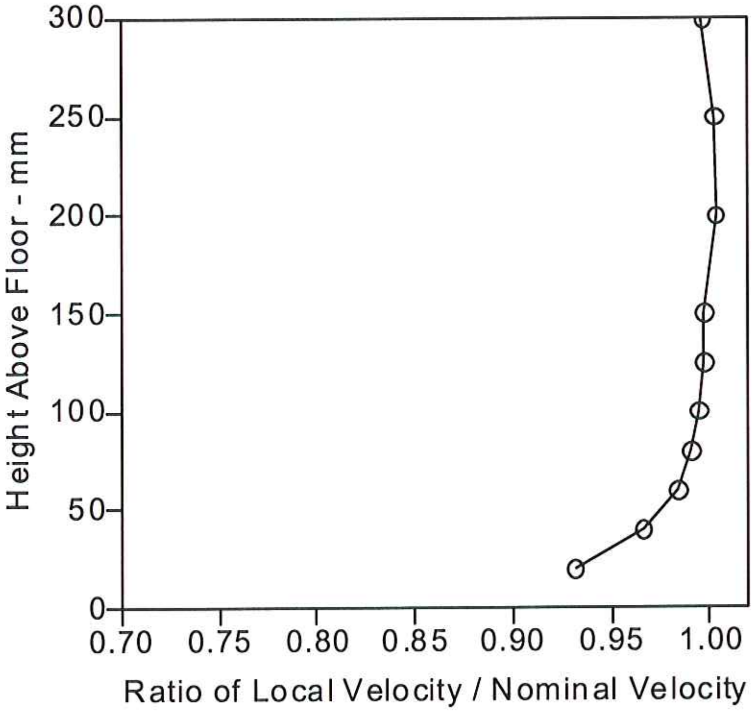
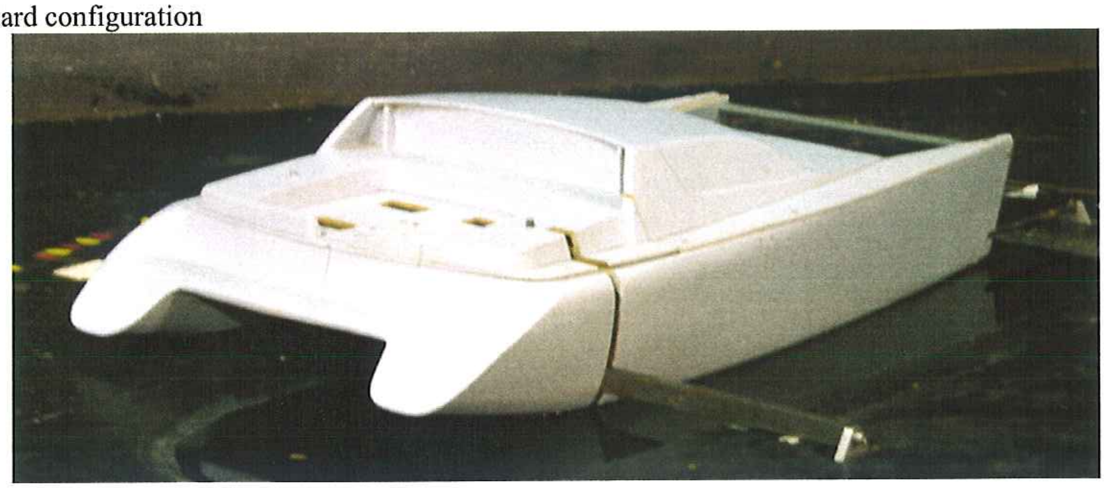


Figure 15.6 Sailing catamaran model

Standard configuration



Solid foredeck

Wide beam, no superstructure

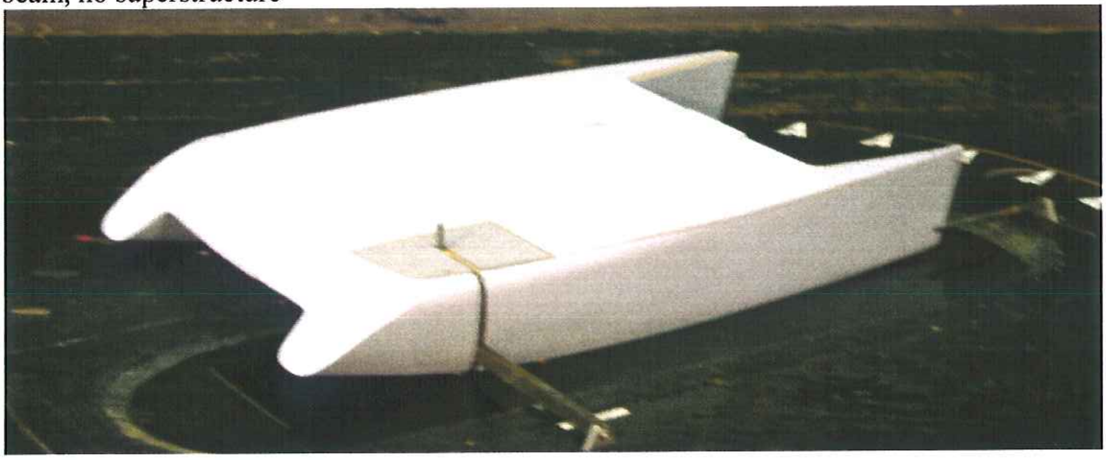
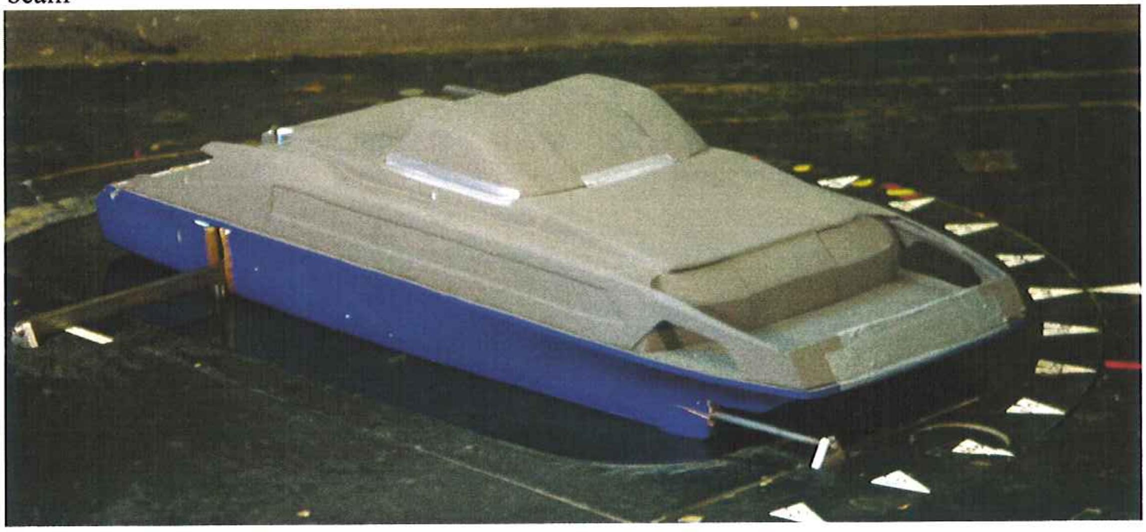


Figure 15.7 Conventional catamaran model

Narrow beam, with wheelhouse and upper saloon

Mid beam

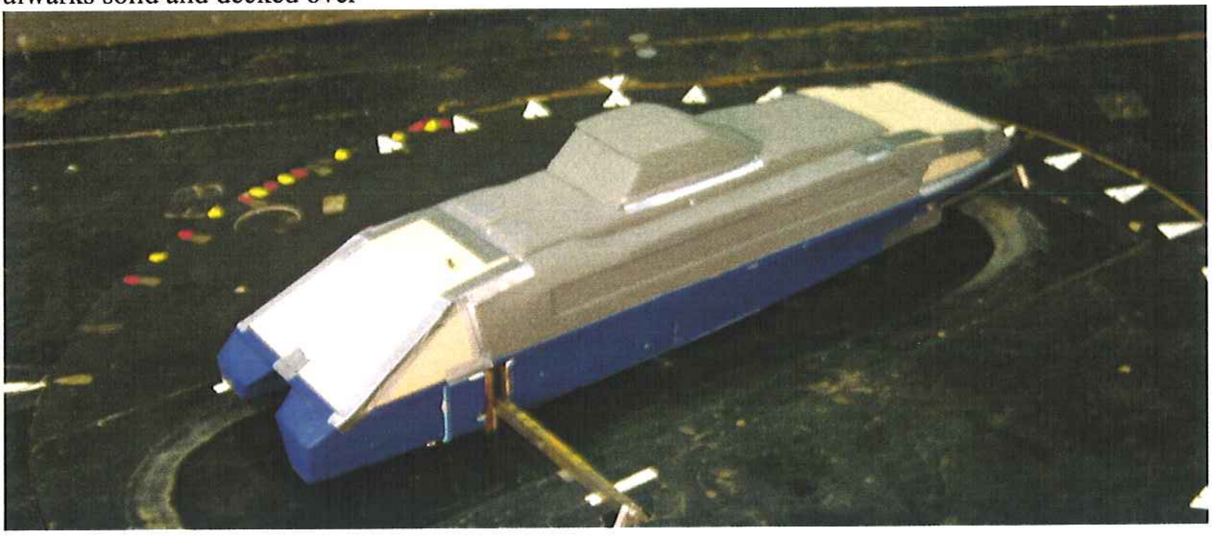


Wide beam

Figure 15.8 Conventional catamaran model

Wheelhouse removed

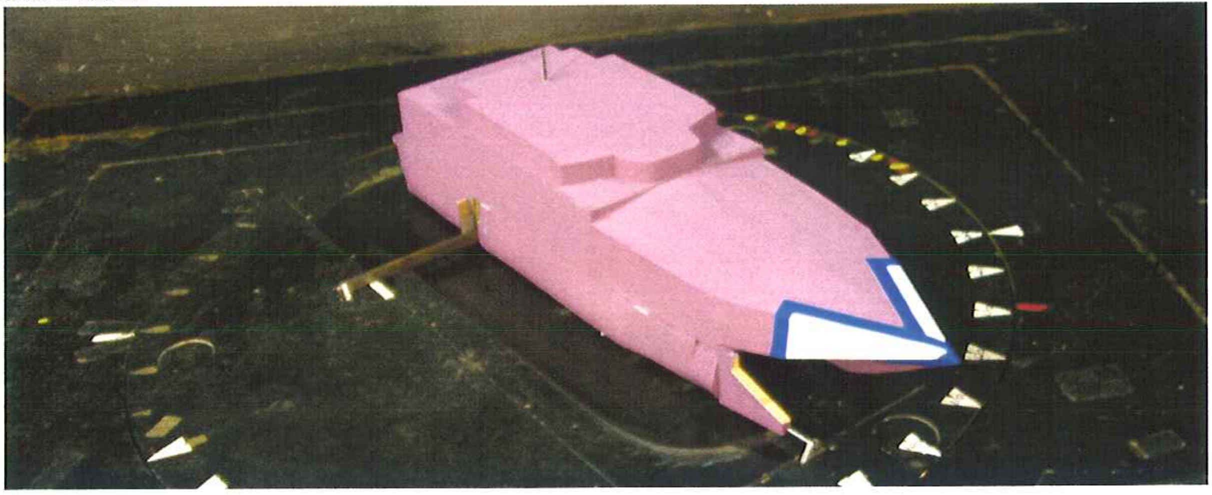
Bulwarks solid and decked over



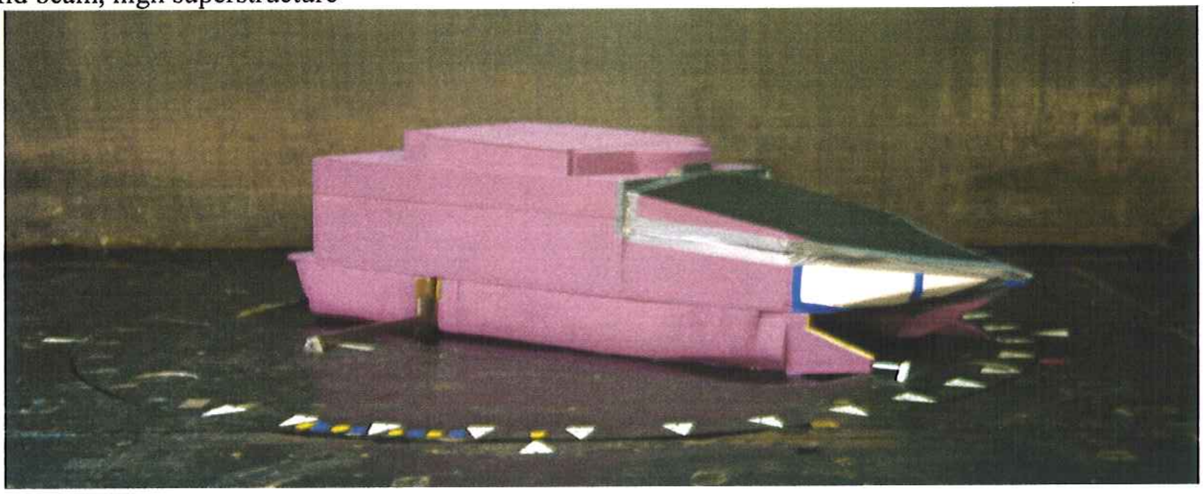
Heeled 10 degrees to represent damage to port hull

Figure 15.9 Wave piercing catamaran model

Narrow beam



Mid beam, high superstructure



Wide beam

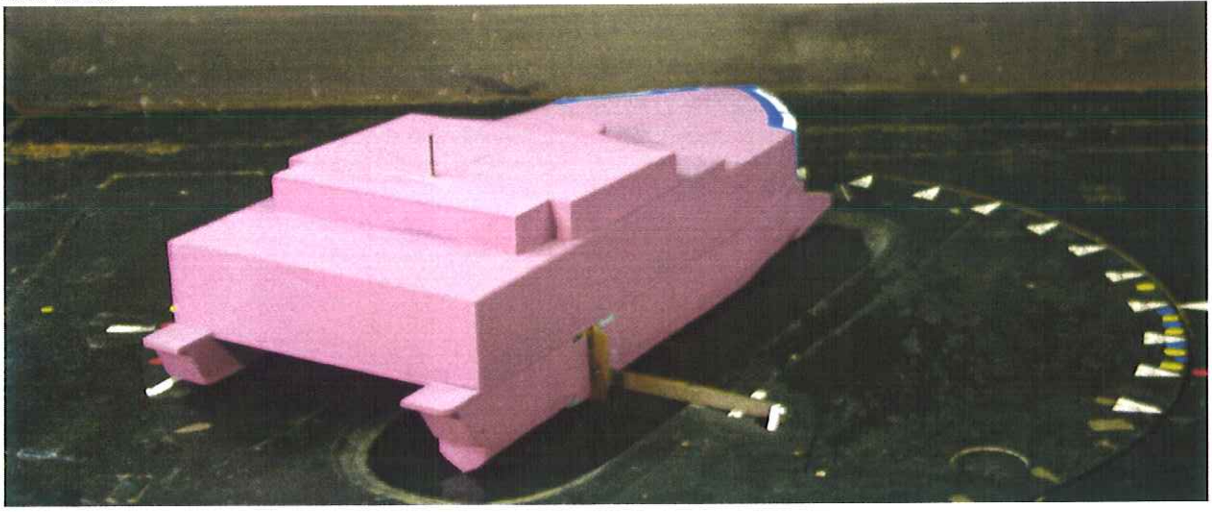
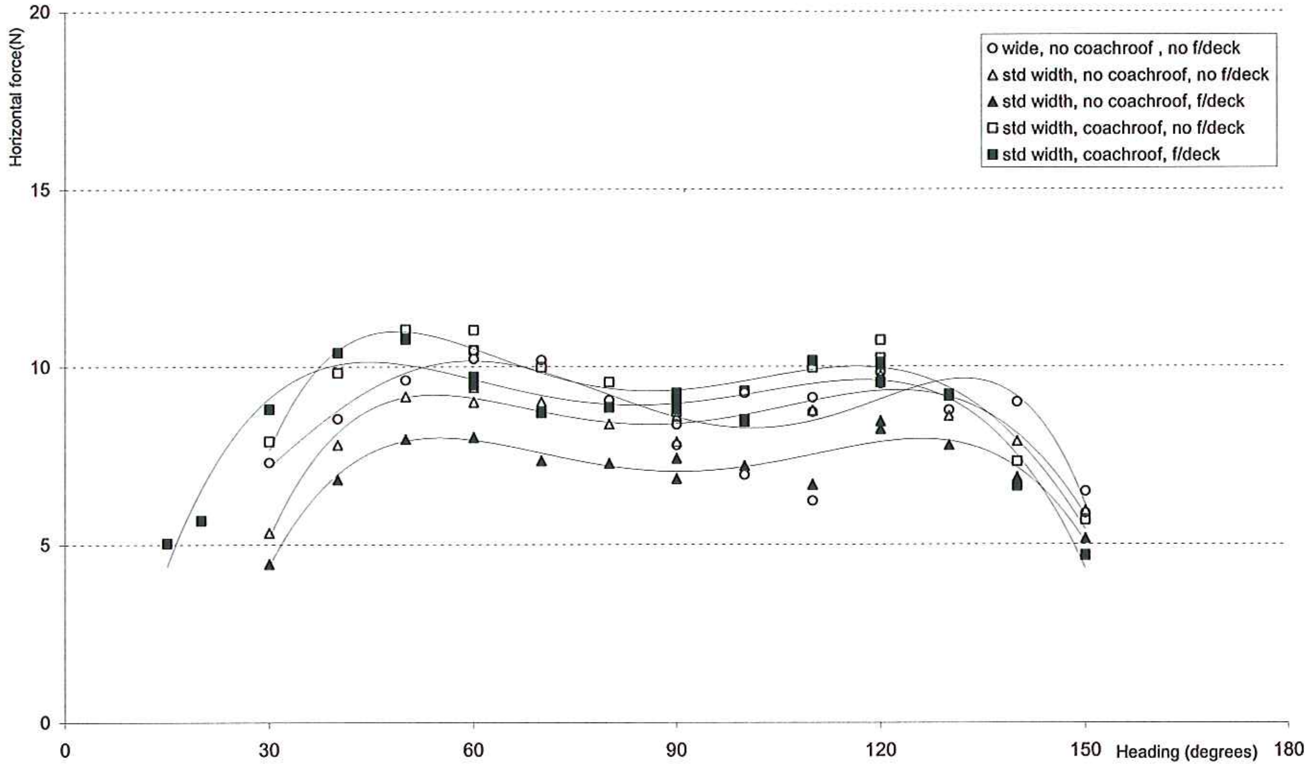


Figure 15.10 Sailing catamaran – horizontal and vertical forces



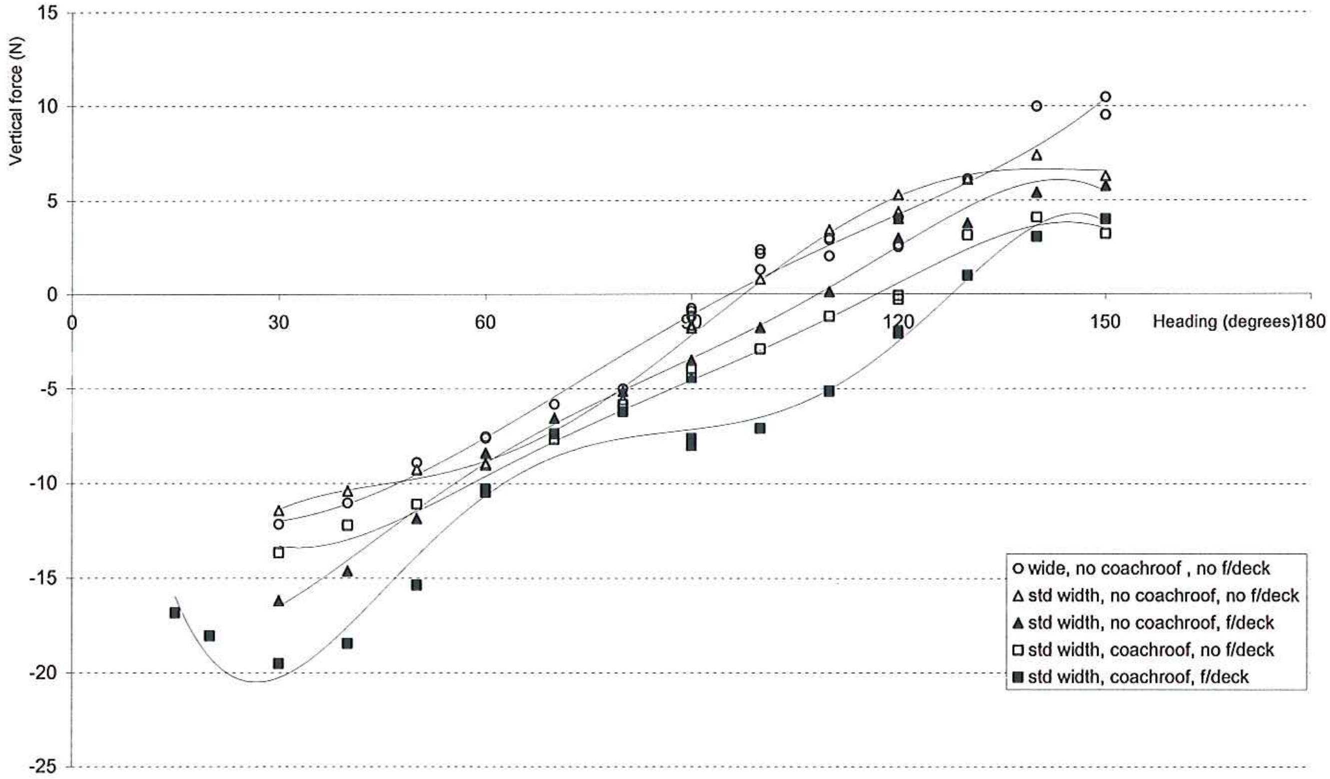
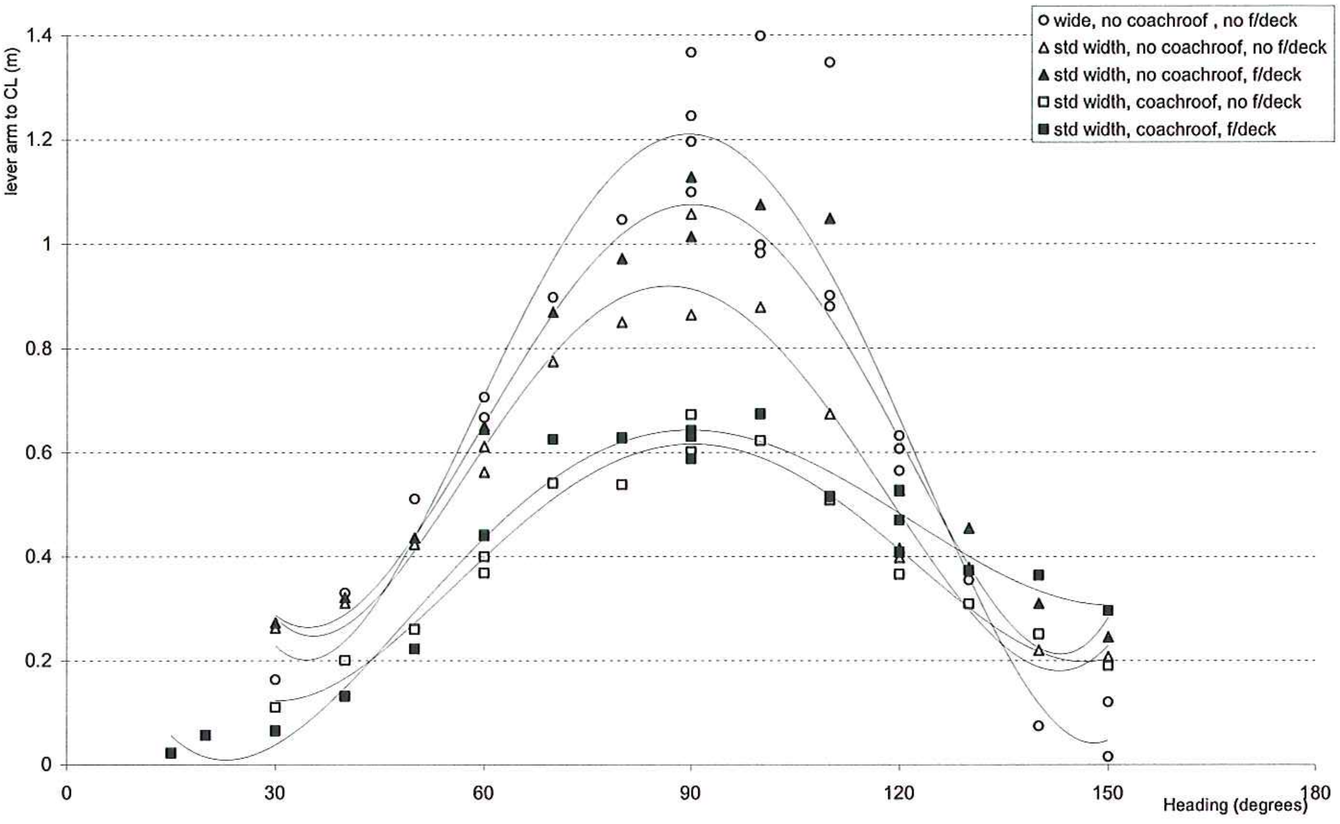


Figure 15.11 Sailing catamaran - lever of the resultant force, and heeling moment



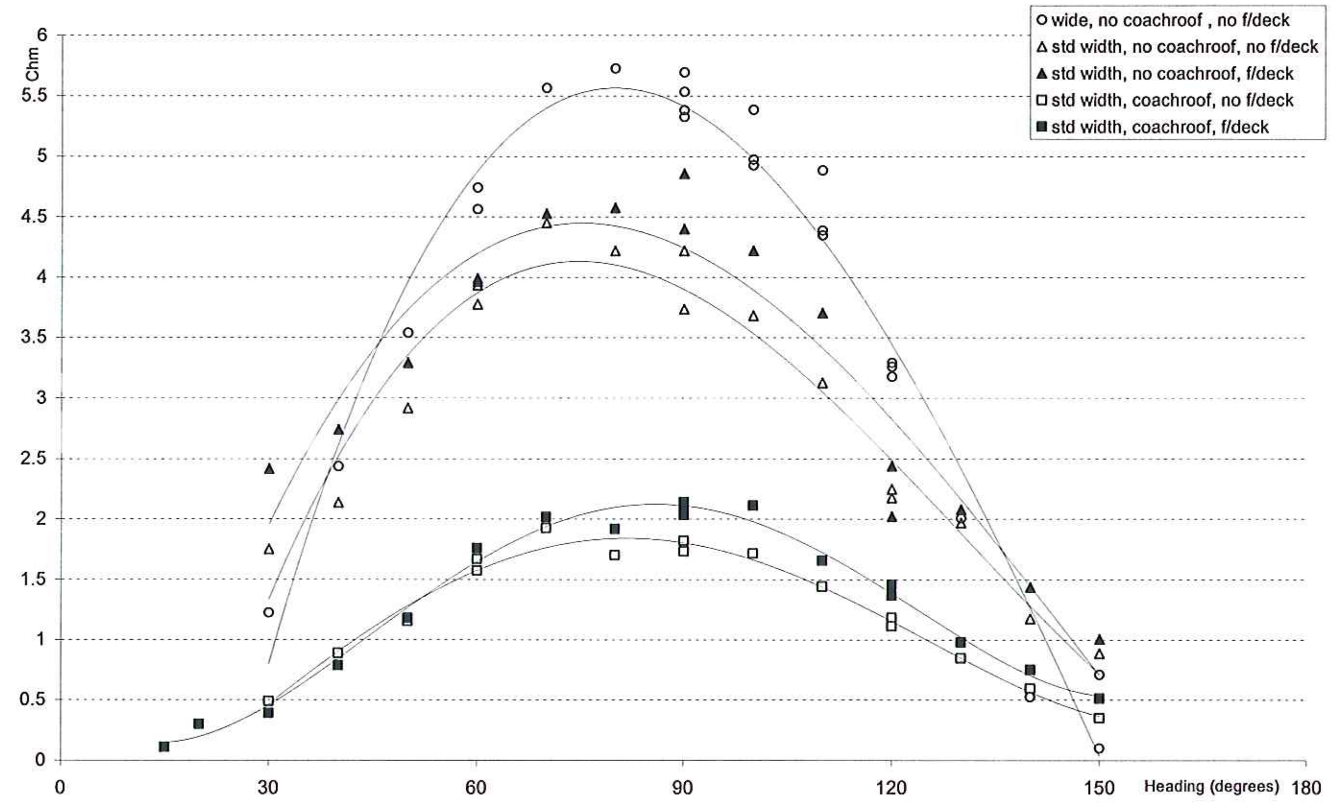
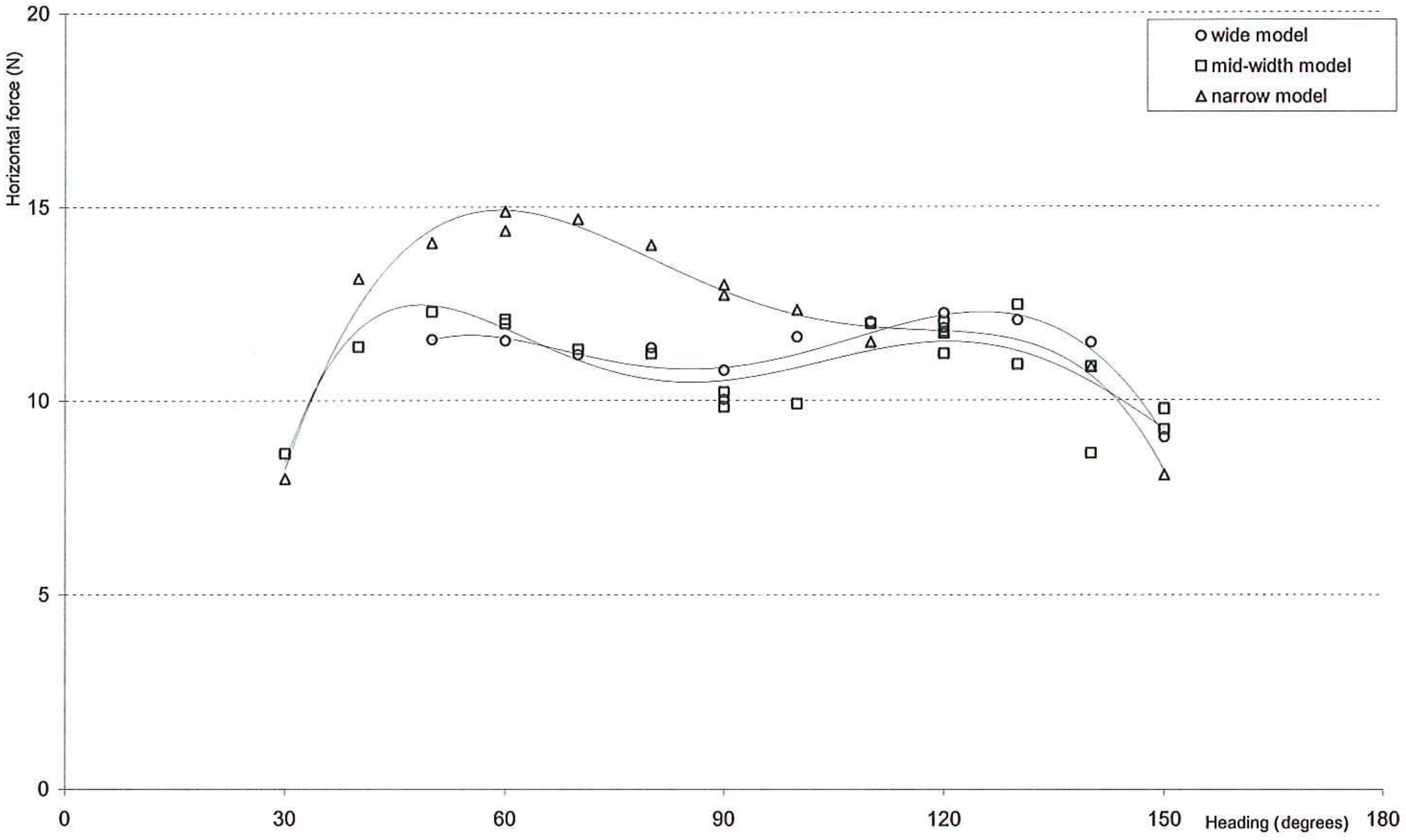


Figure 15.12 Conventional catamaran - horizontal and vertical forces



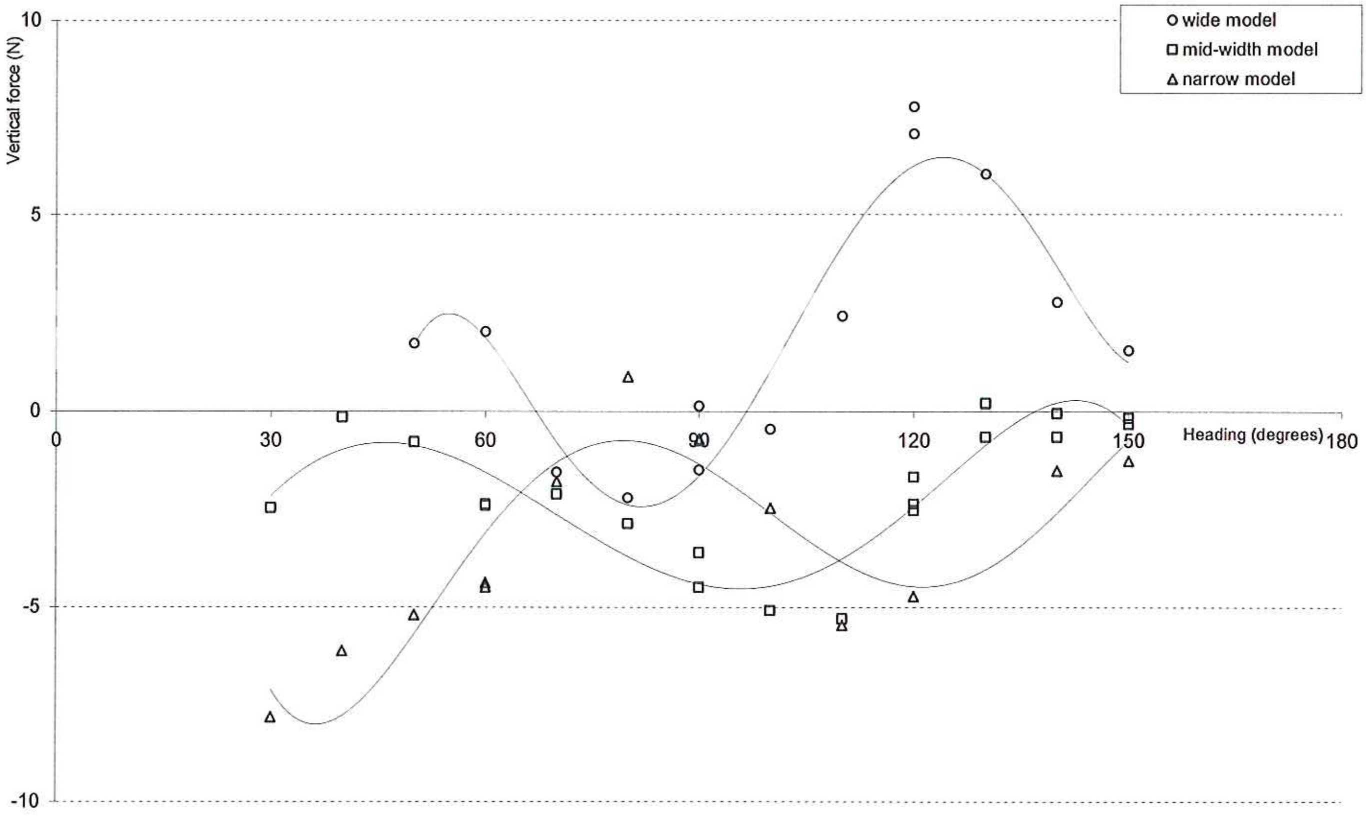
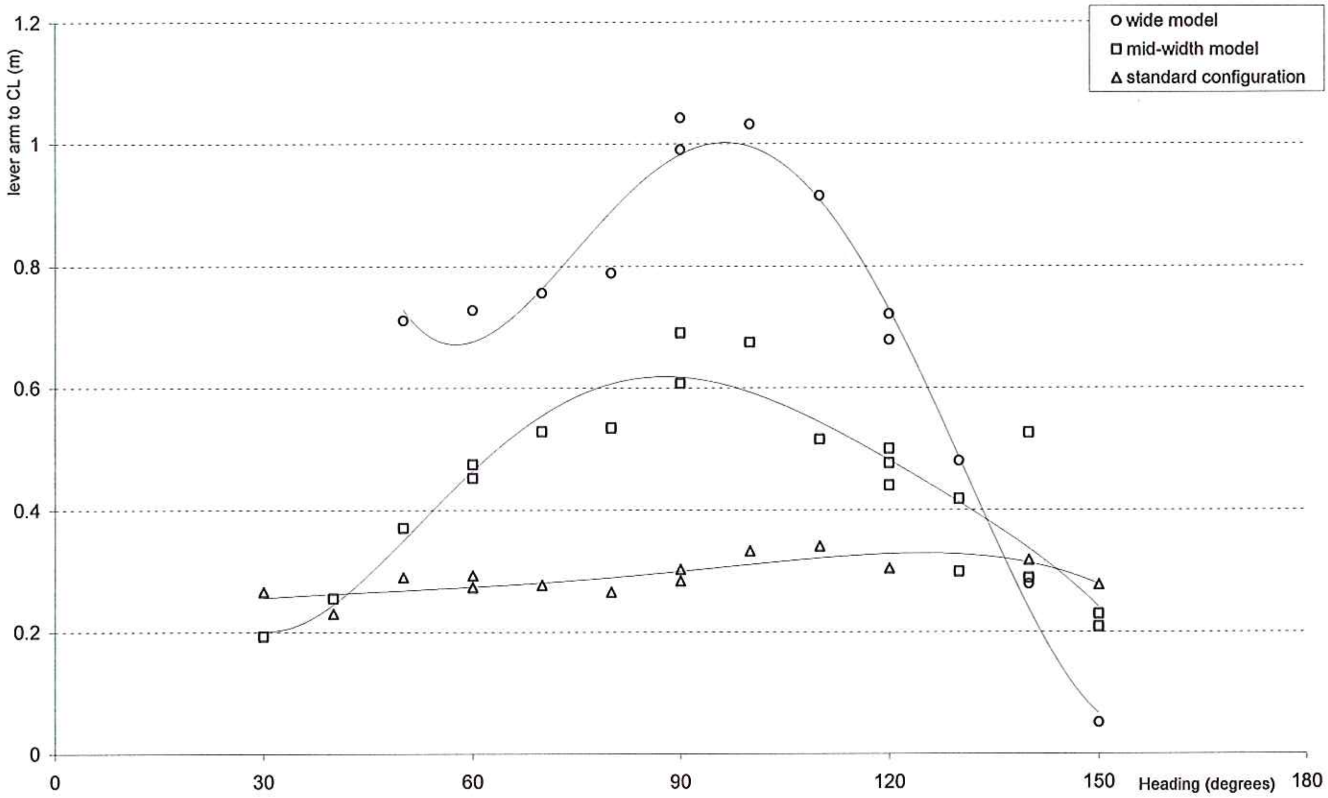


Figure 15.13 Conventional catamaran - lever of the resultant force and heeling moment



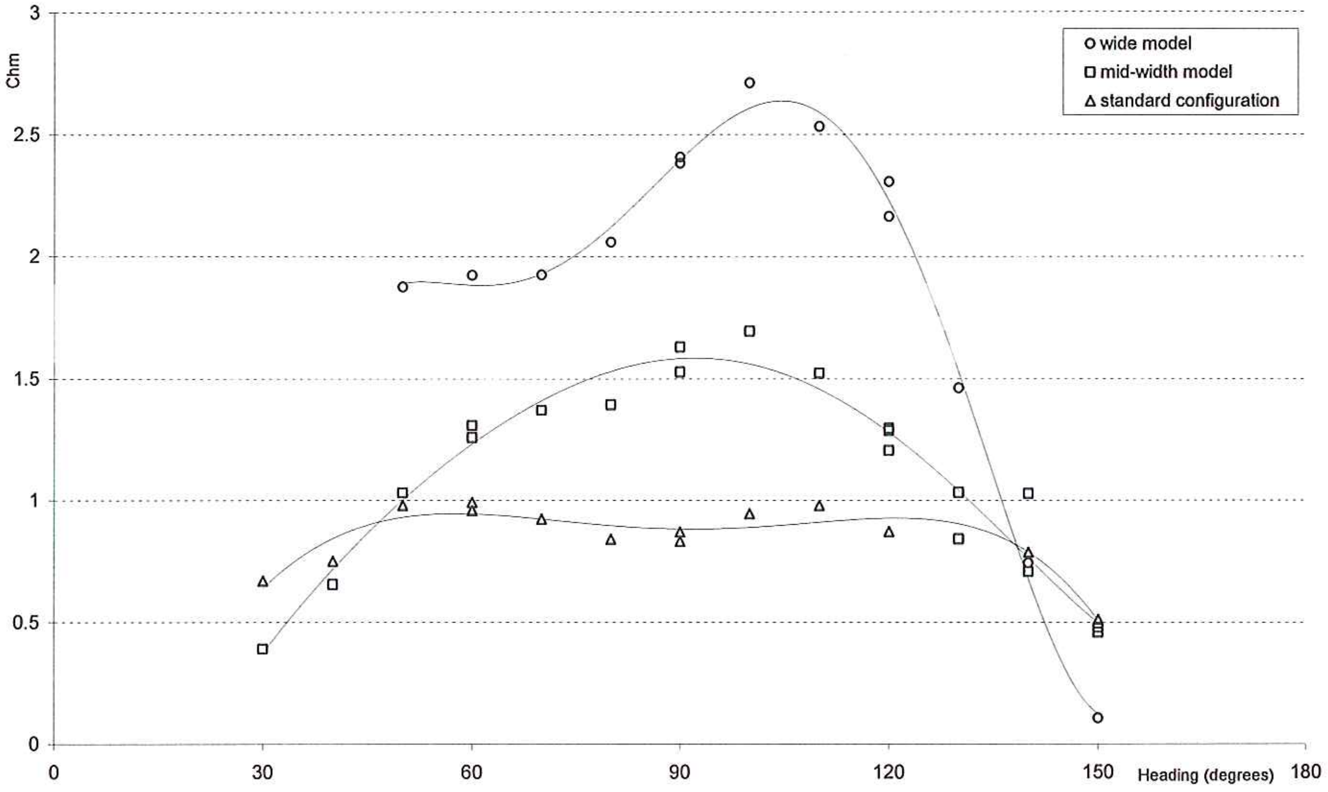


Figure 15.14 Conventional catamaran with superstructure variations- heeling moment

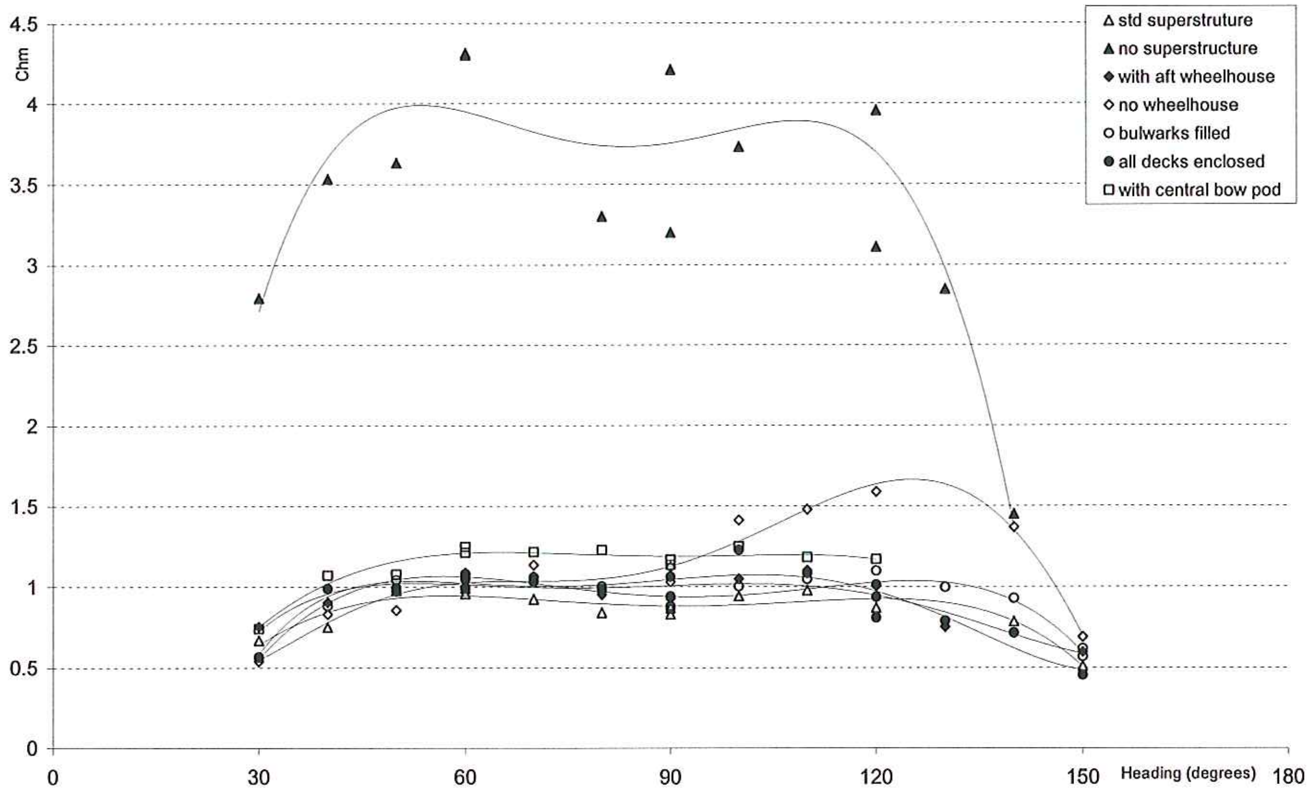
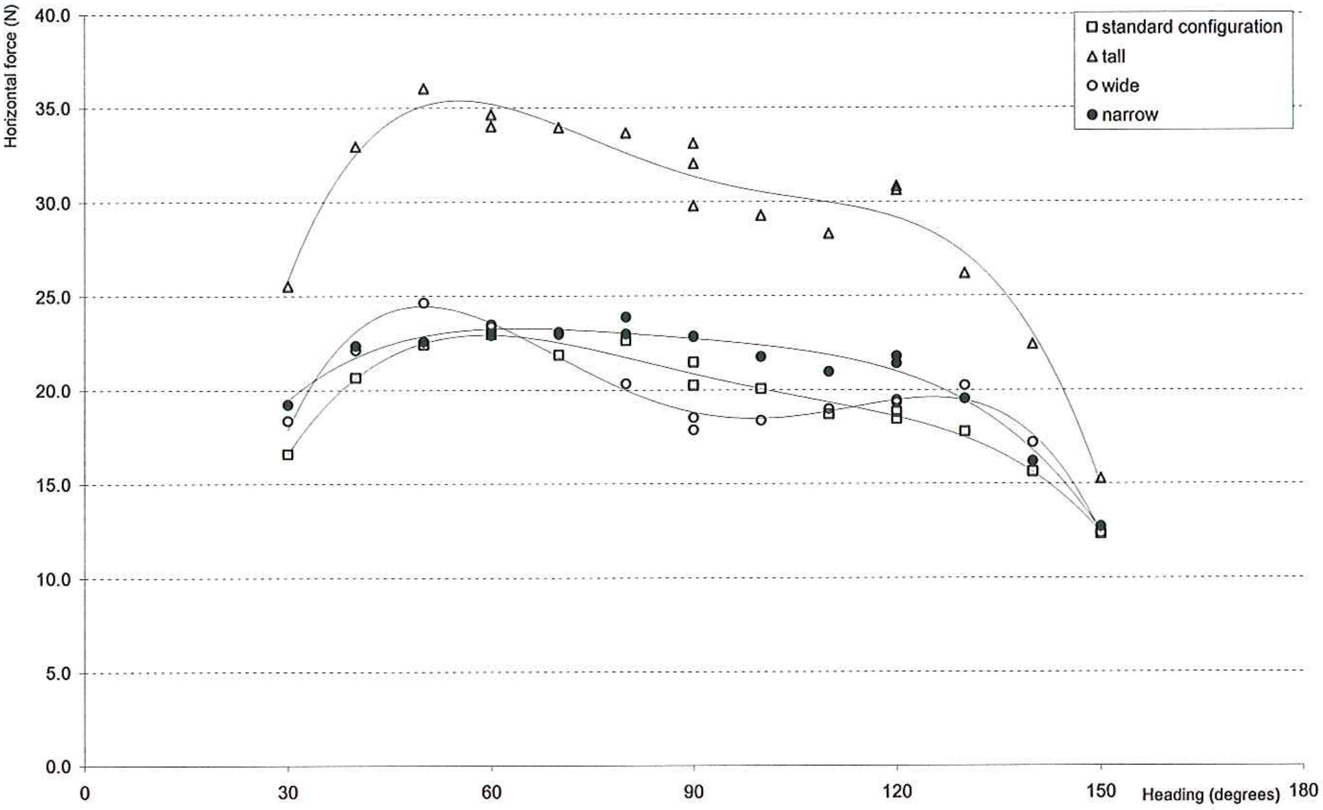


Figure 15.15 Wave piercing catamaran - horizontal and vertical forces



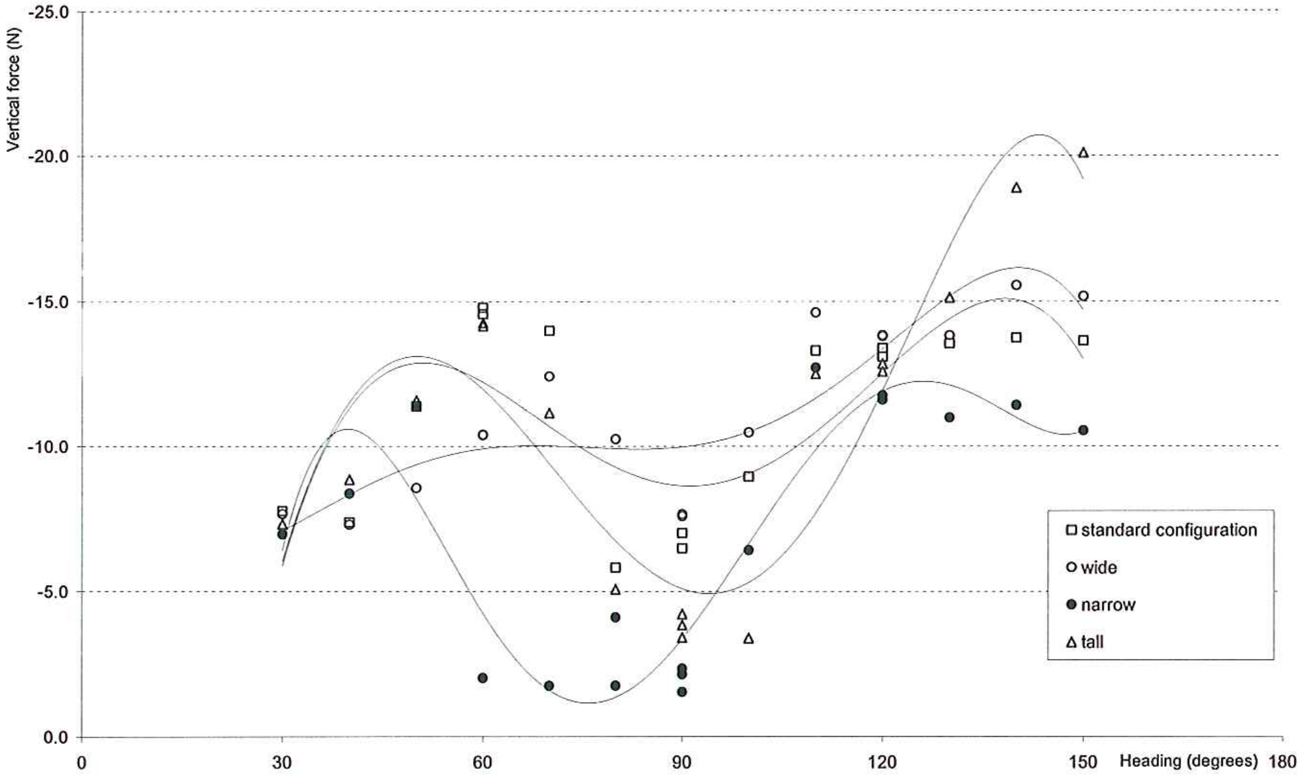
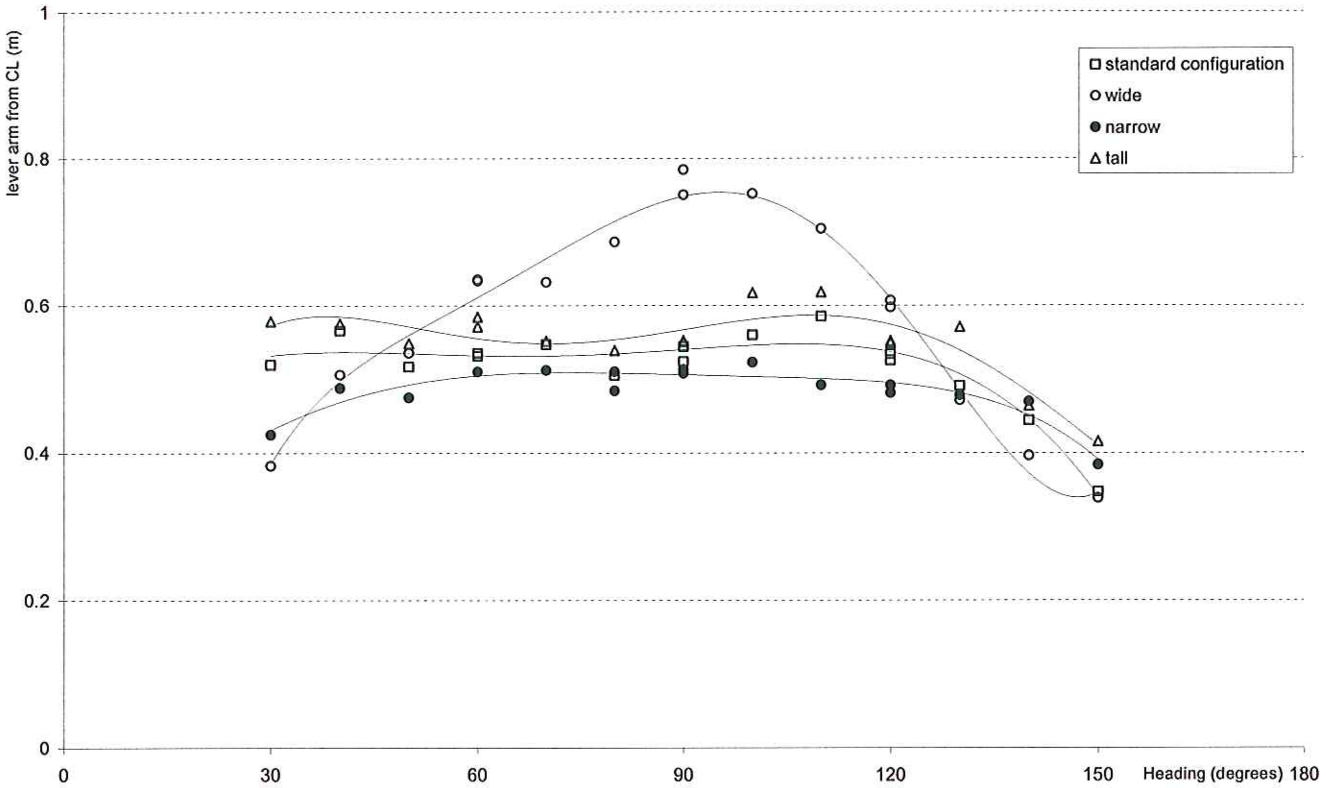


Figure 15.16 Wave piercing catamaran - lever of resultant force and heeling moment



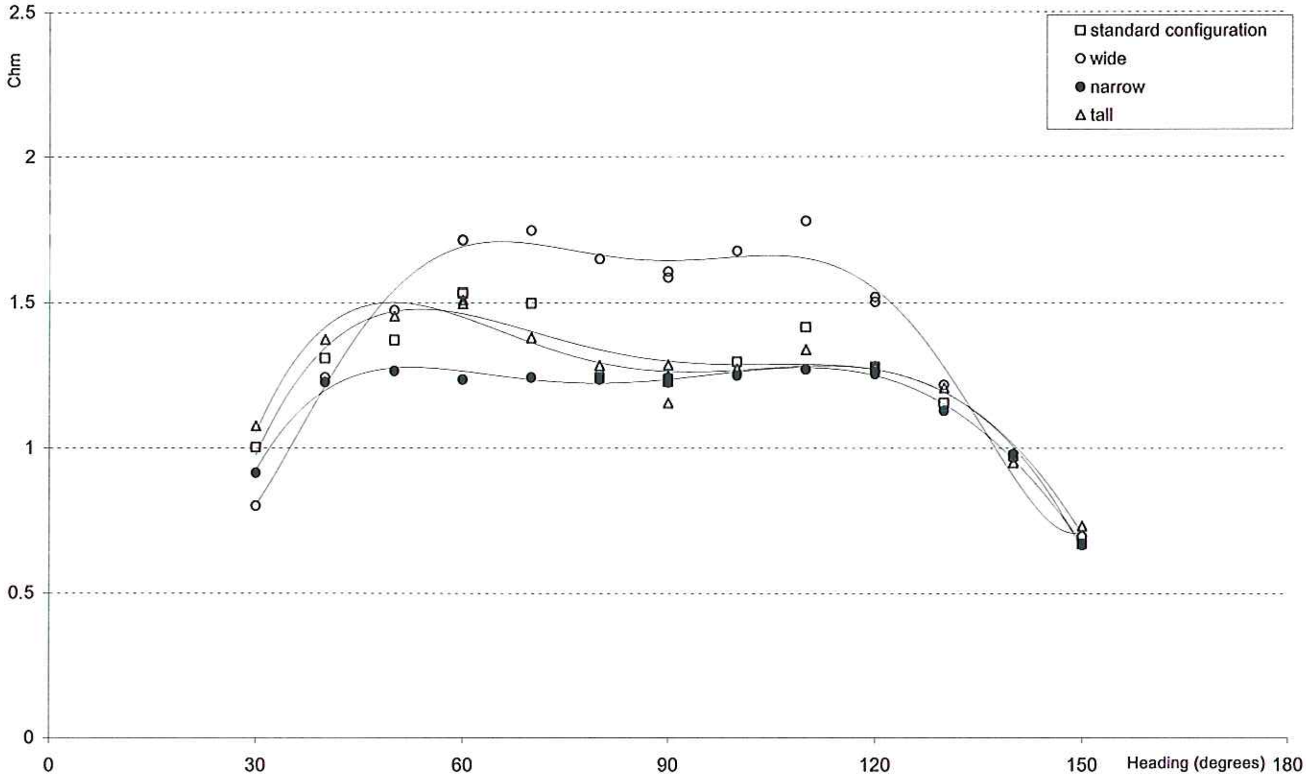


Figure 15.17 Summary of heeling moment data for beam variations on 3 models

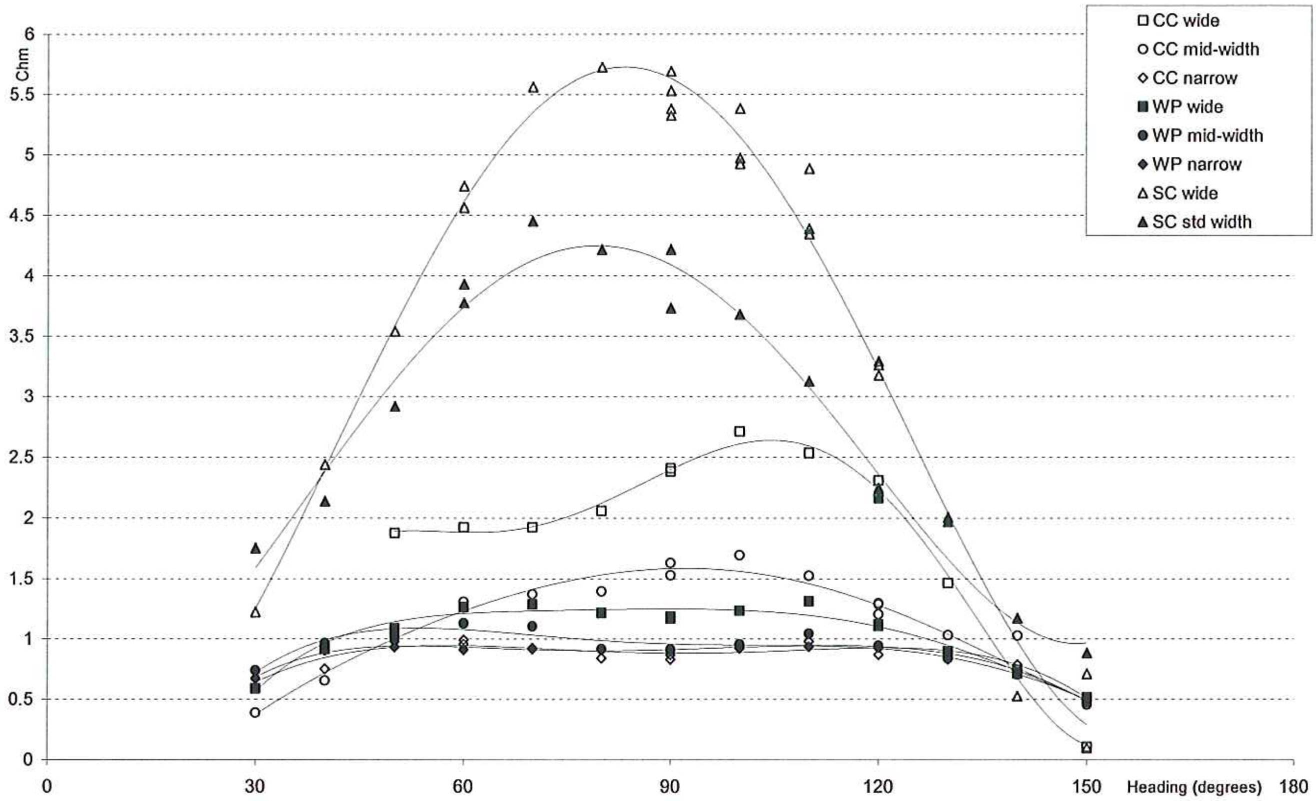


Figure 15.18 The effects of heel and aft damage trim on heeling moment

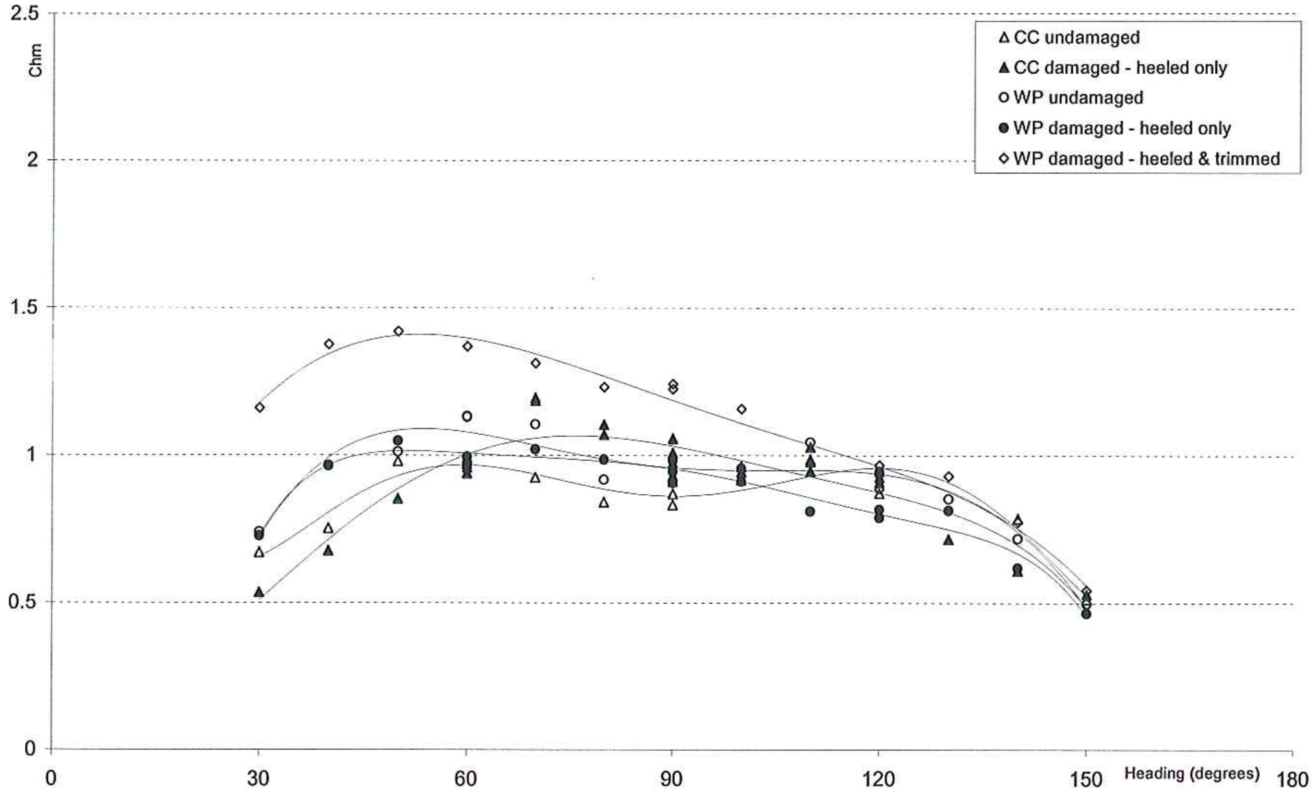


Figure 15.19 Variation of heeling moment coefficient with length, beam and height ratios

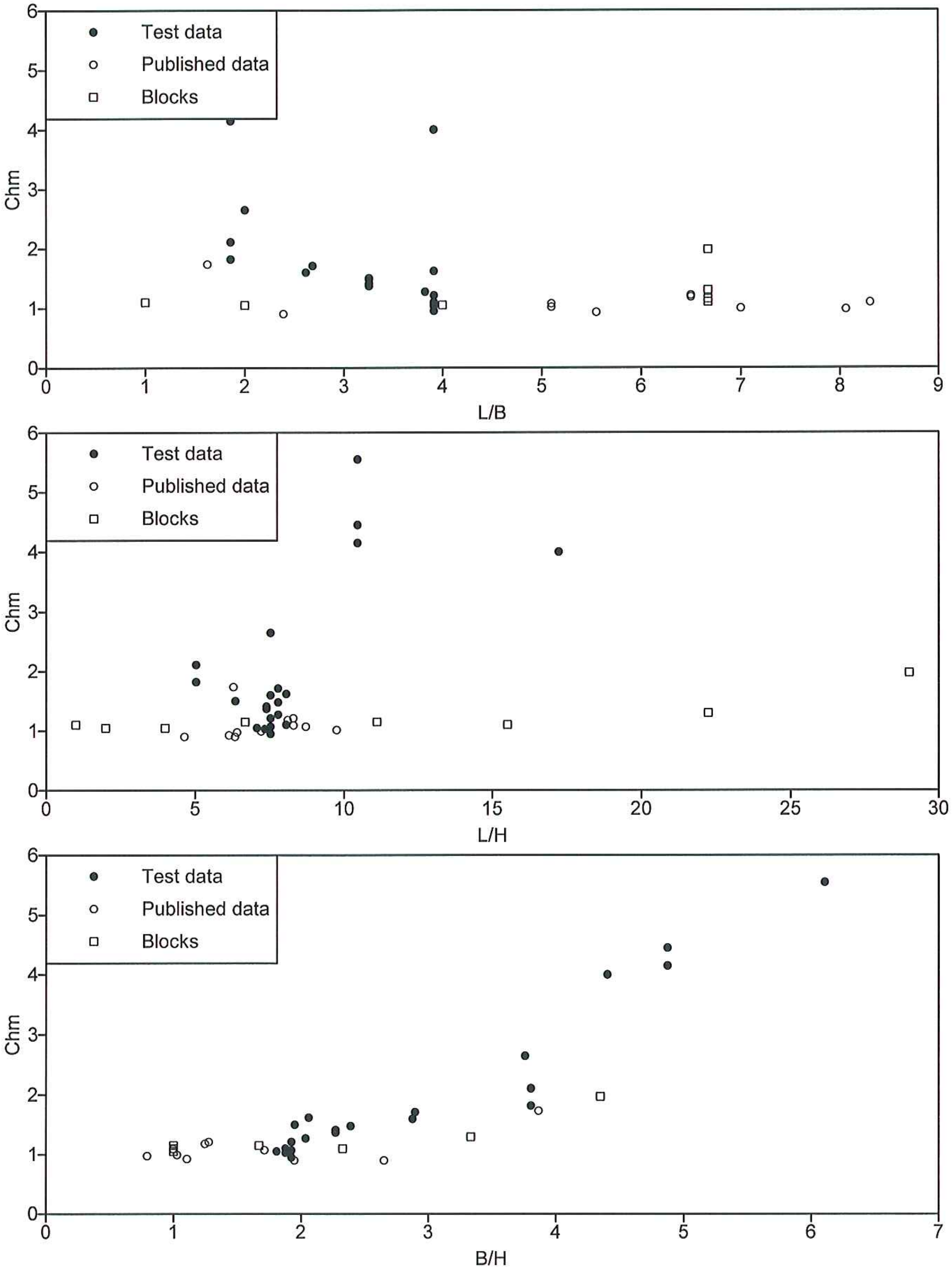


Figure 15.20 Variation of heeling moment coefficient with plan and profile ratios

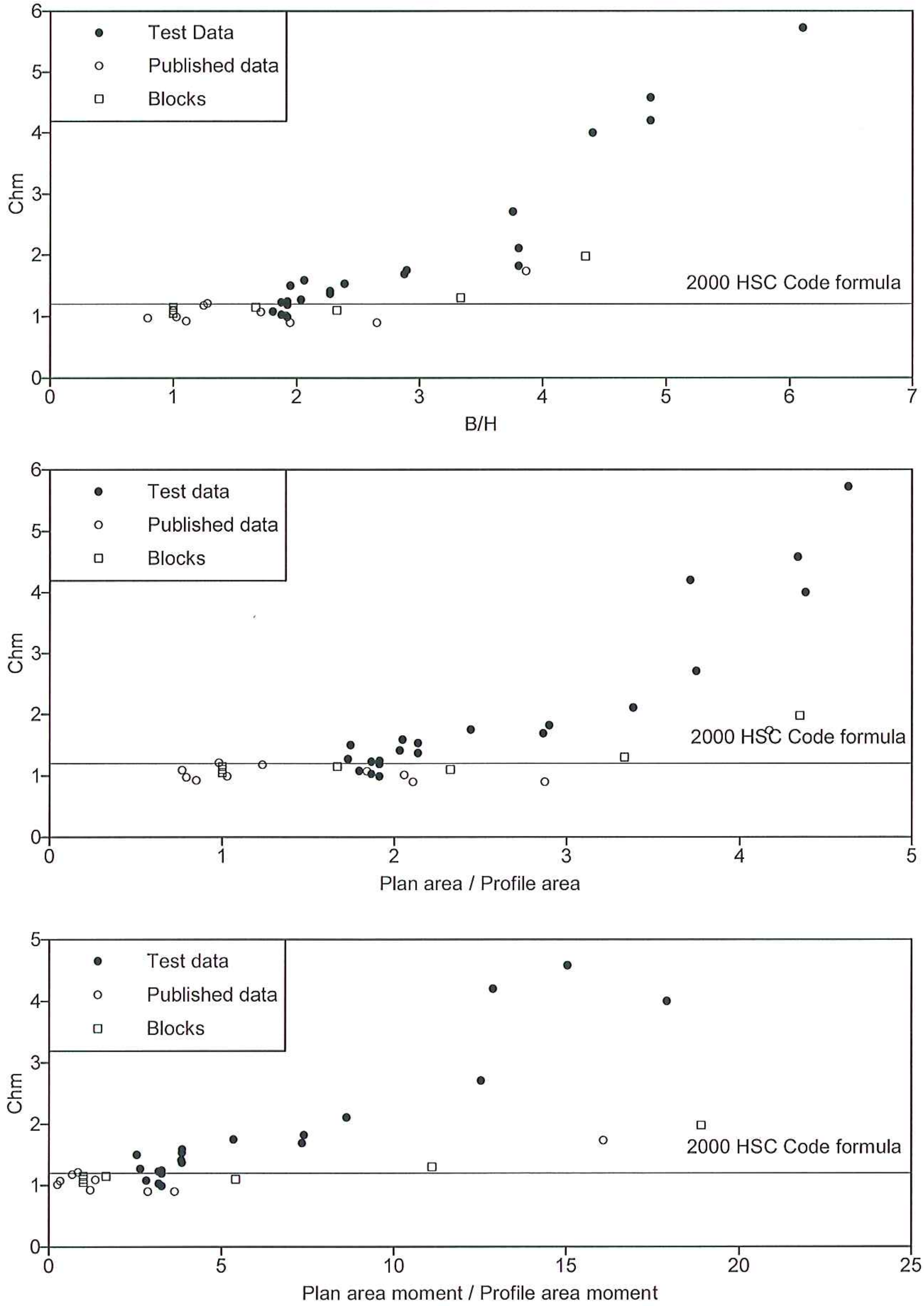
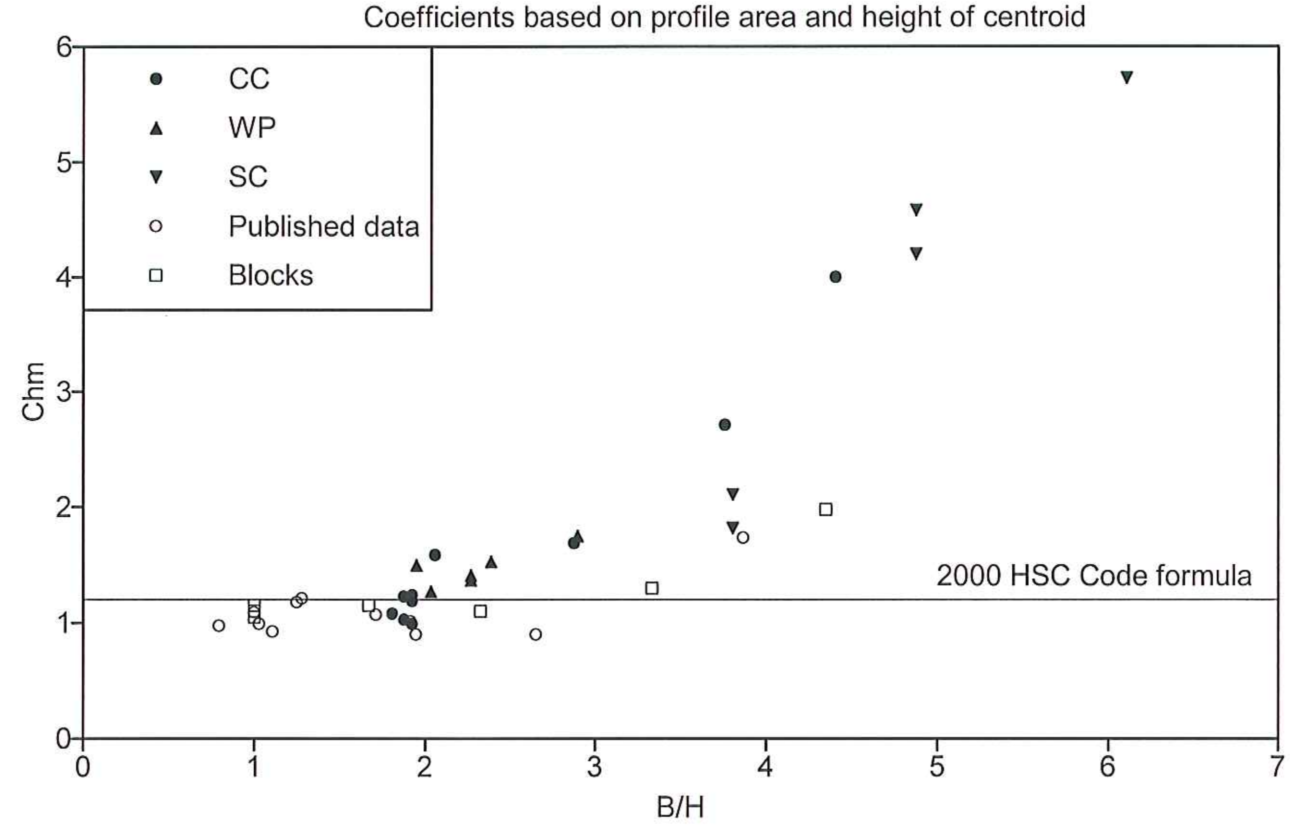


Figure 15.21 Comparison of coefficients based on profile and plan areas and levers, for varying B/H



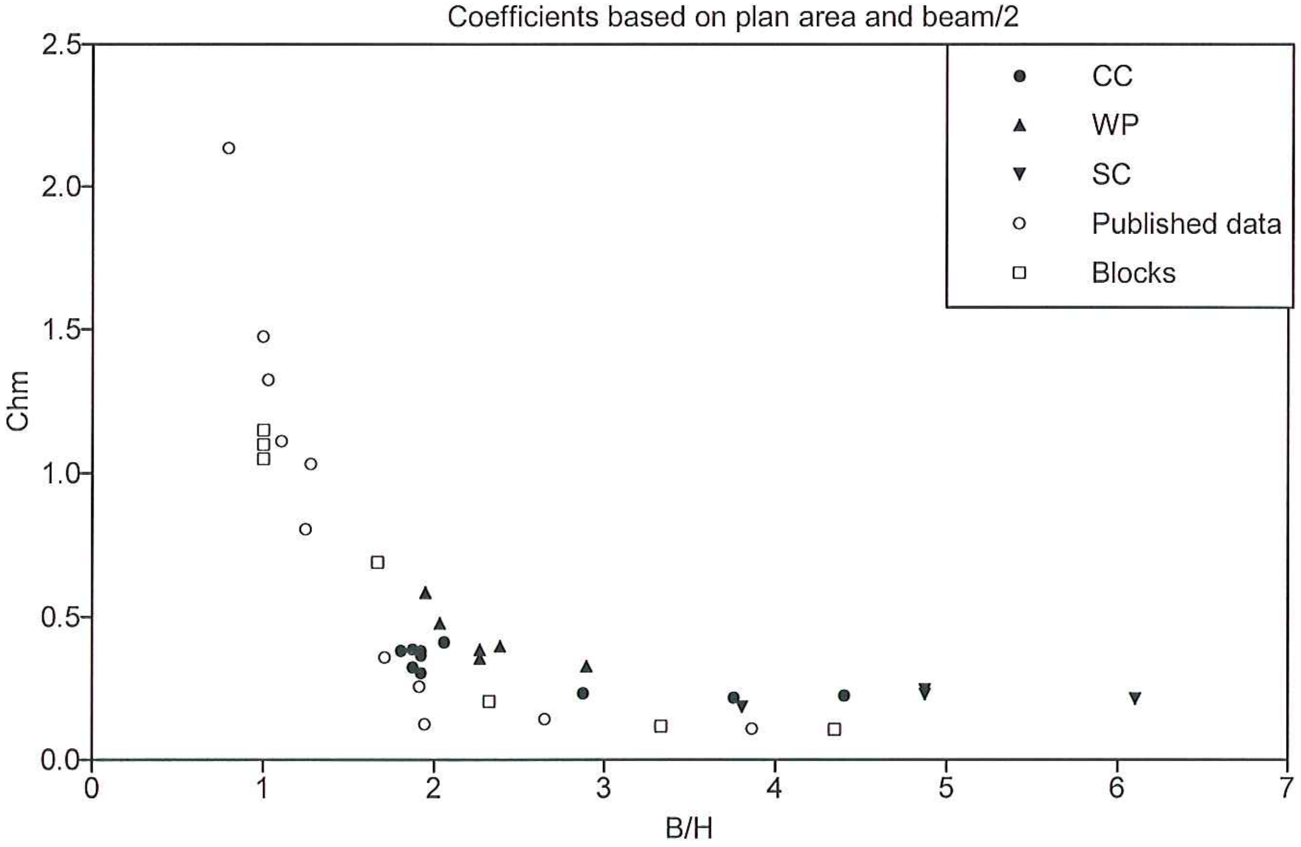


Figure 15.22 Comparison of coefficients based on profile and plan areas and levers, for varying $(B/H)^2$ and $(H/B)^2$

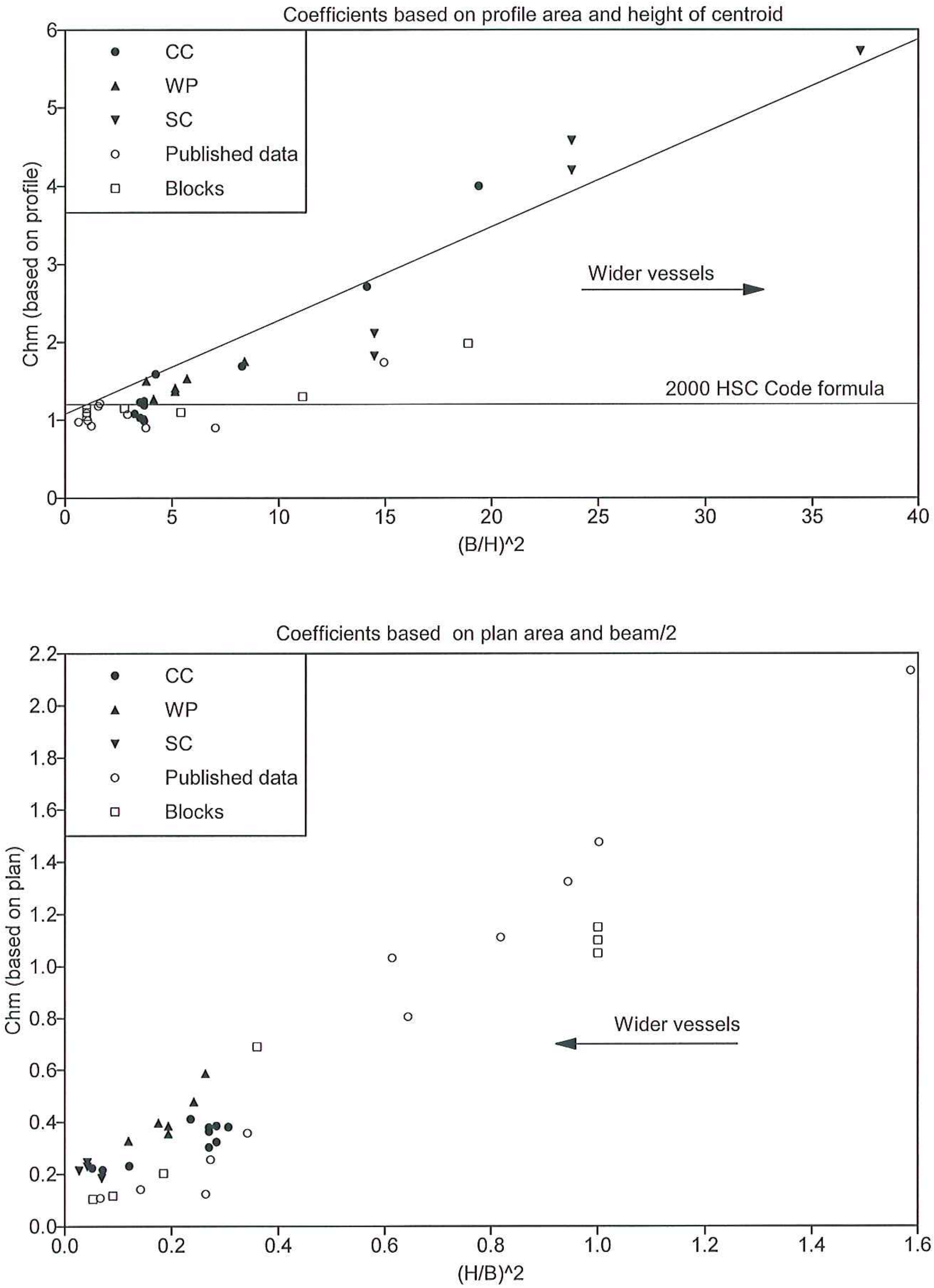


Figure 15.23 Variation of heeling moment with heel angle for the sailing catamaran

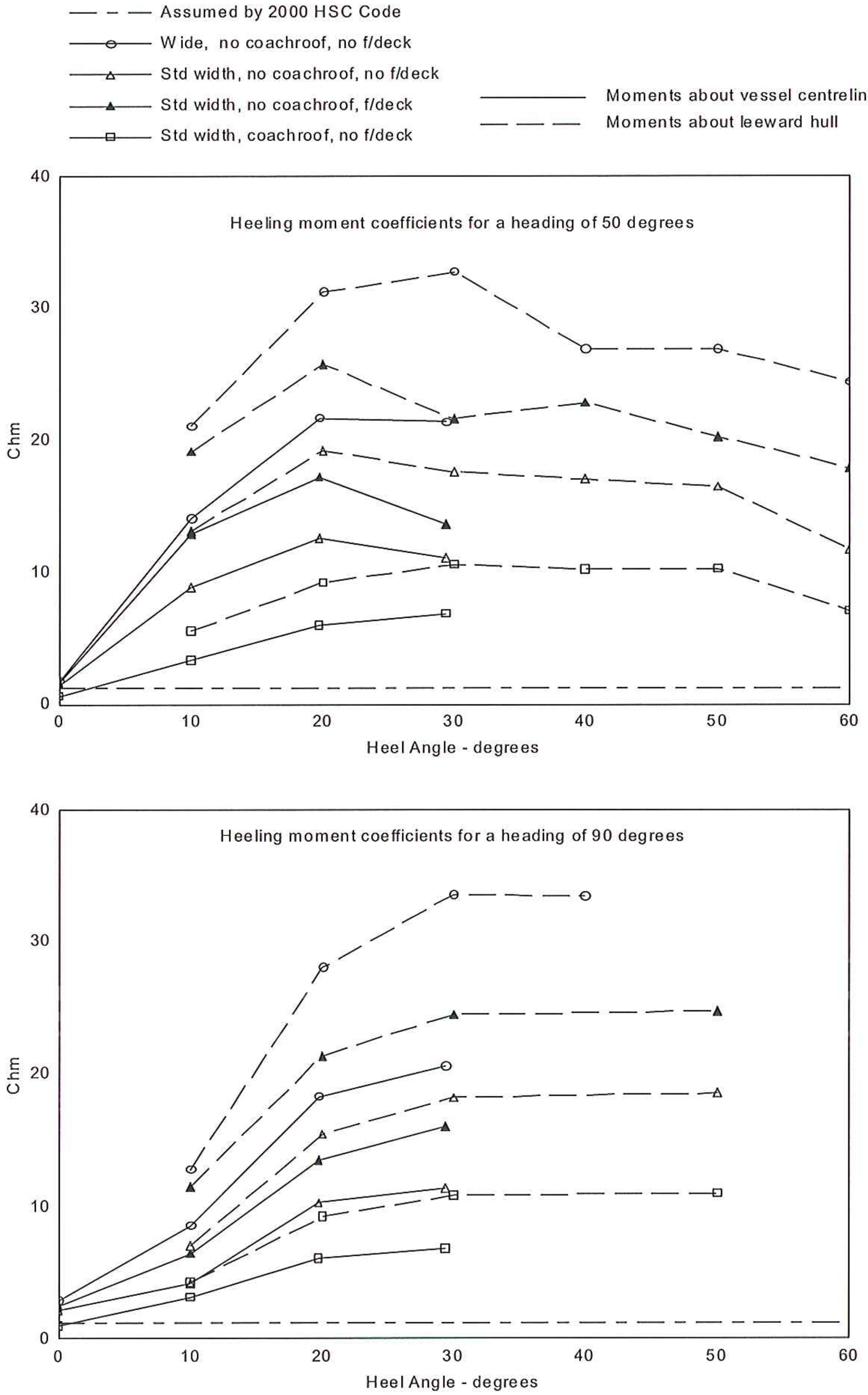


Figure 15.24 Variation of heeling moment with heel angle for the passenger catamaran of Refs 4 & 5

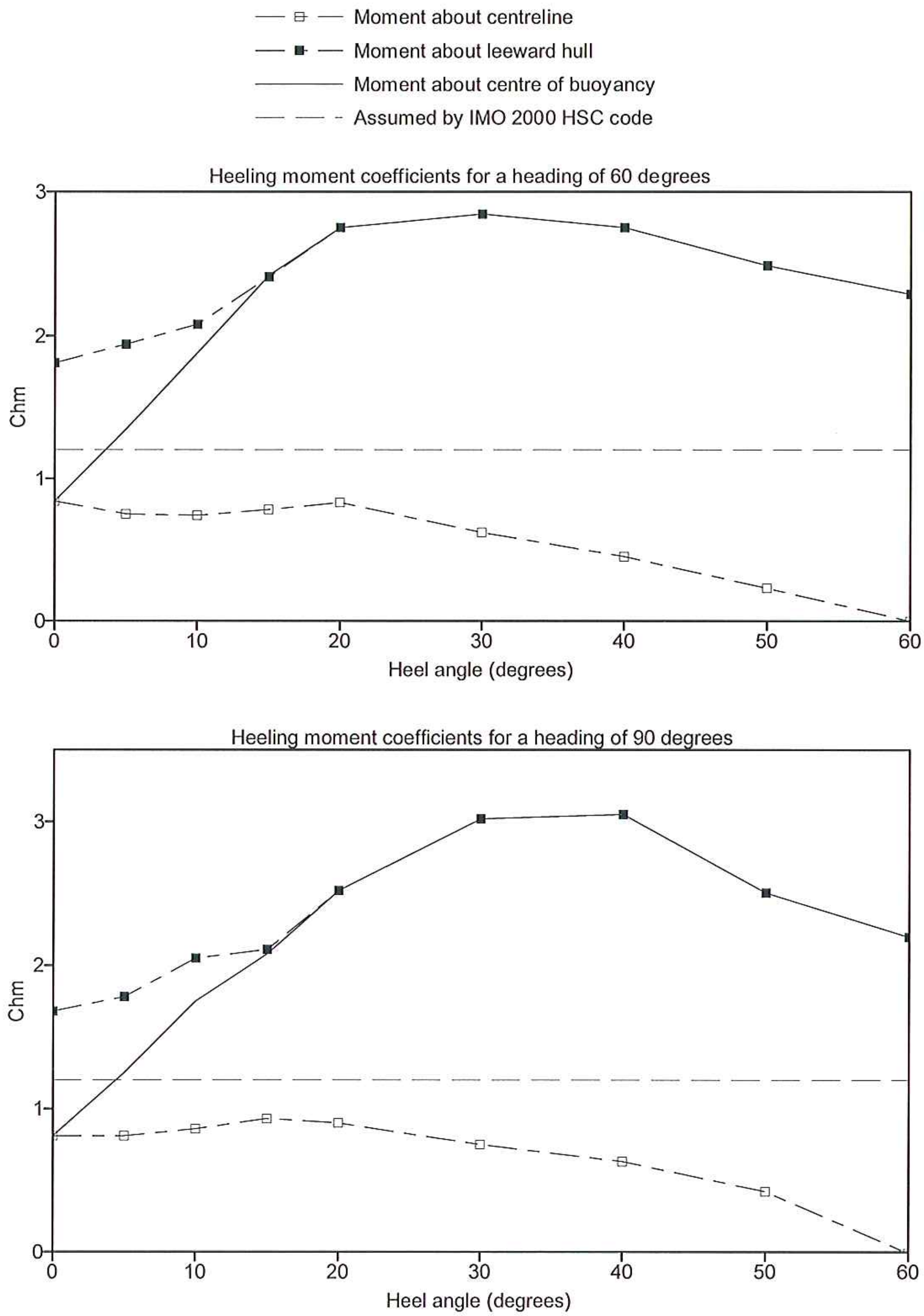


Figure 15.25 Comparison of heeling and righting lever arms for the passenger catamaran of Refs 4 & 5

Heeling lever curves are presented for headings of 60 and 90 degrees, and for the full and reduced superstructure versions

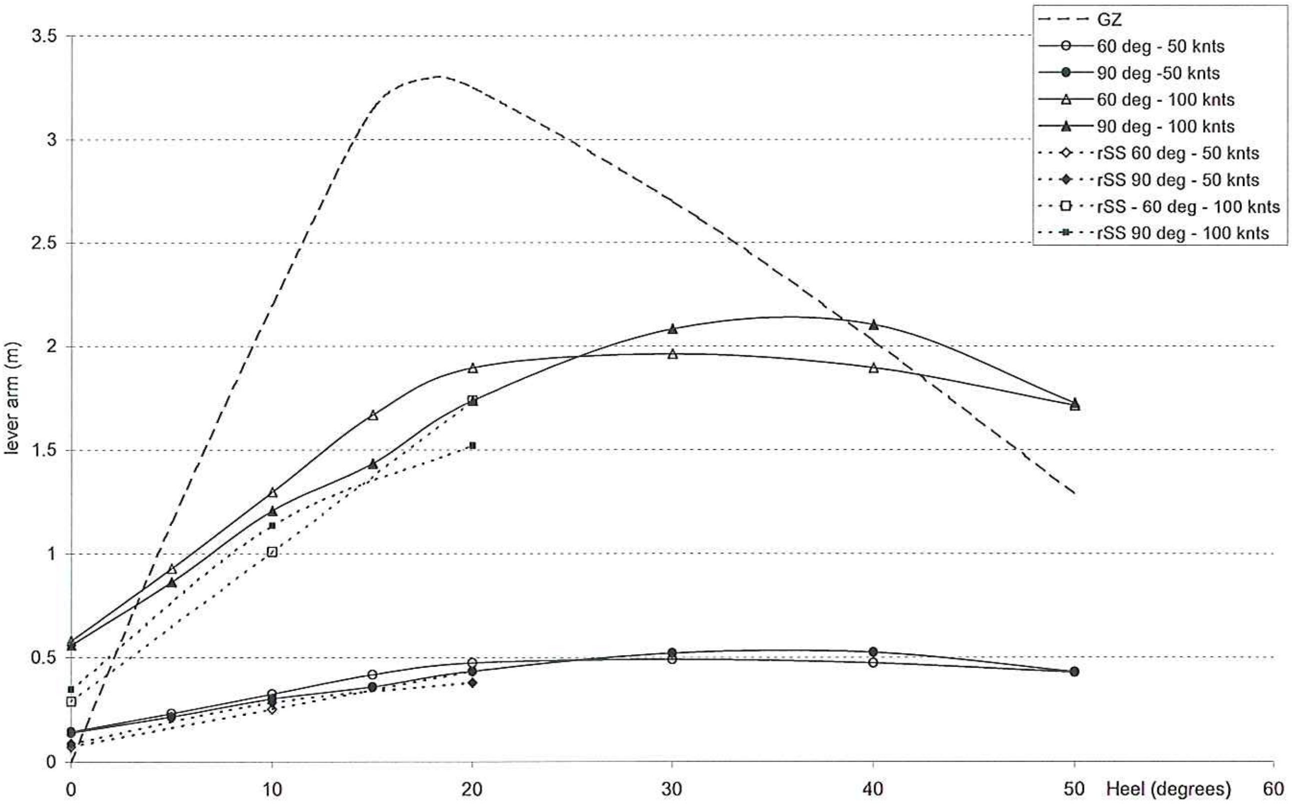
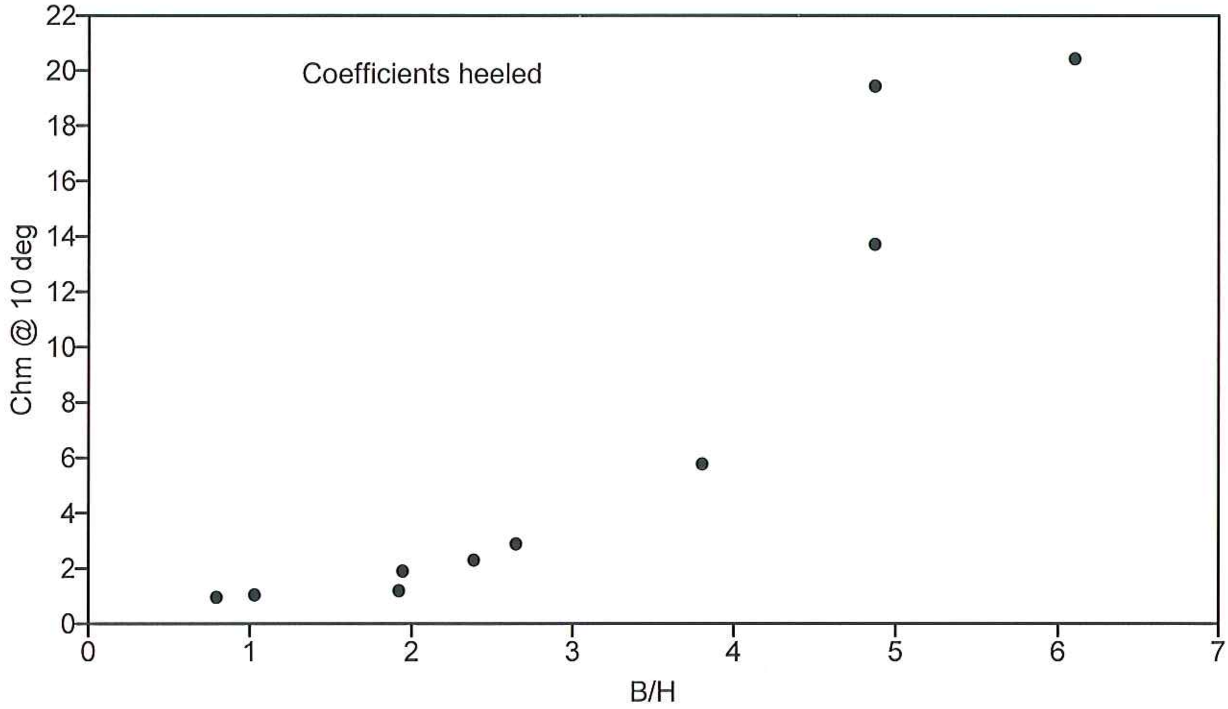


Figure 15.26 Variation of the measured heeling moment heeled, and the heeled/upright ratio, with the beam to height ratio



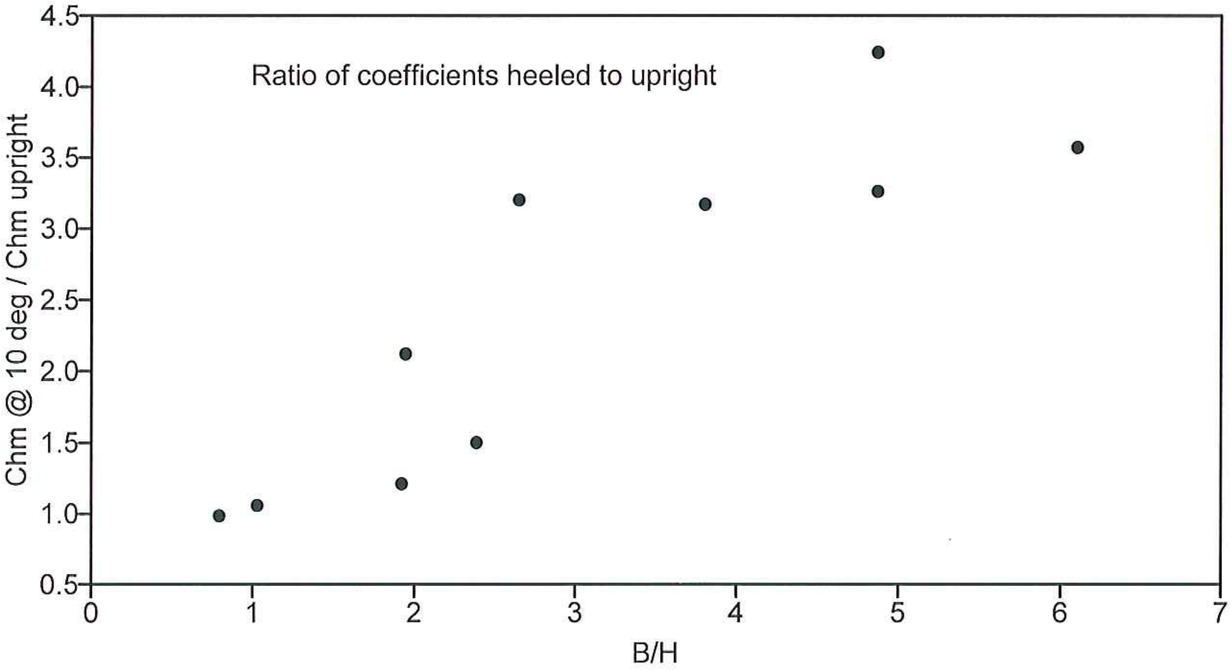


Figure 15.27 Variation of the ratio of measured heeling moment heeled to measured heeling moment upright, with various parametric ratios

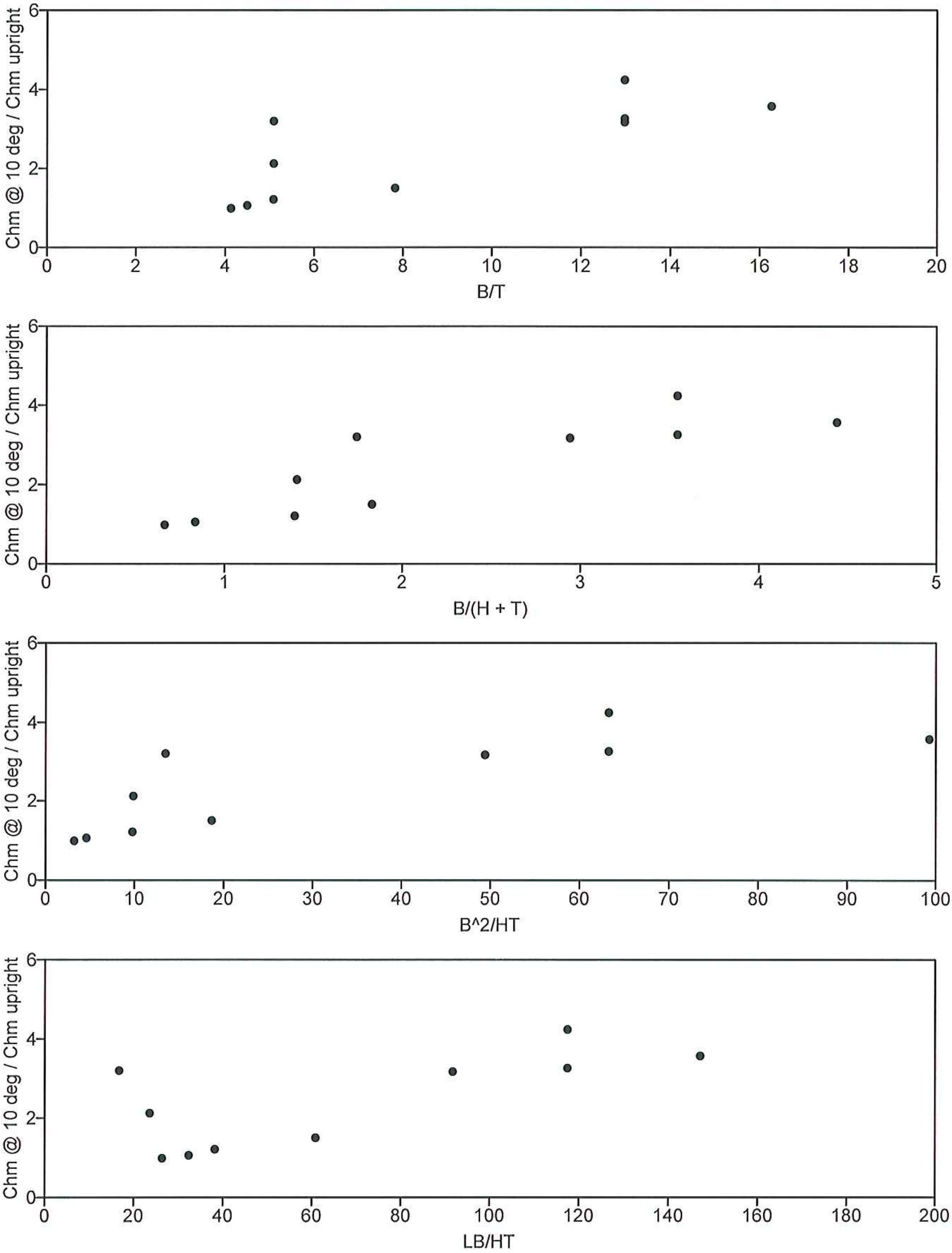


Figure 15.28 Variation of the ratio of measured heeling moment heeled to pre dicted heeling moment upright, with the beam to height ratio

Key

1	Conventional cat, narrow
2	Wave piercing cat
3	Sailing cat, wide, no coachroof , no f/deck
4	Sailing cat, std width, no coachroof, no f/deck
5	Sailing cat, std width, no coachroof, f/deck
6	Sailing cat, std width, coachroof, no f/deck
7	Passenger cat
8	Passenger cat, reduced superstructure
9	Cruise ship, Serra M21412 1
10	Cruise ship, Serra M21412 2

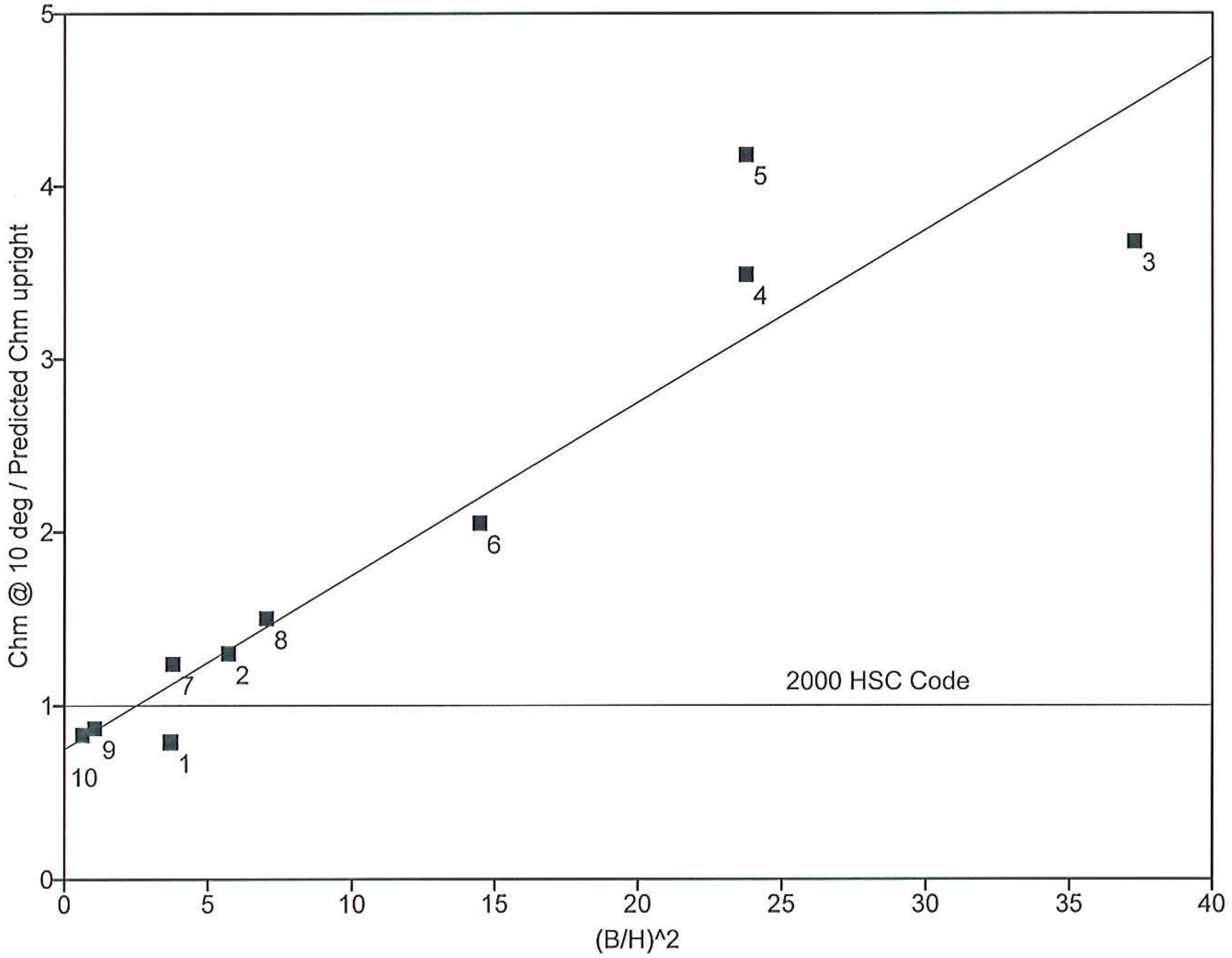
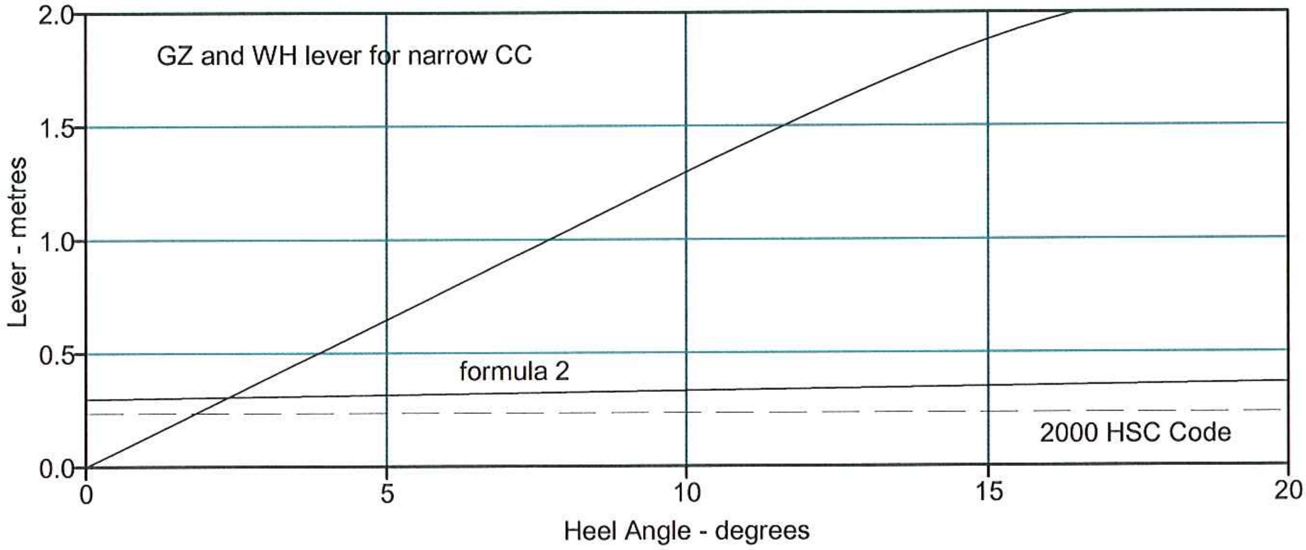
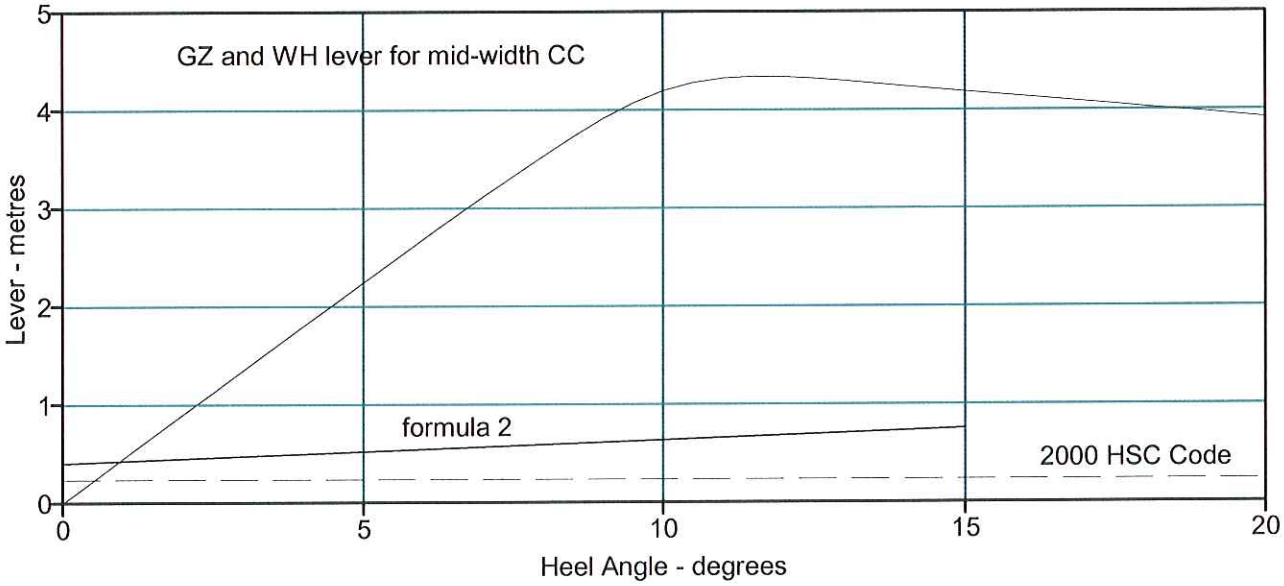
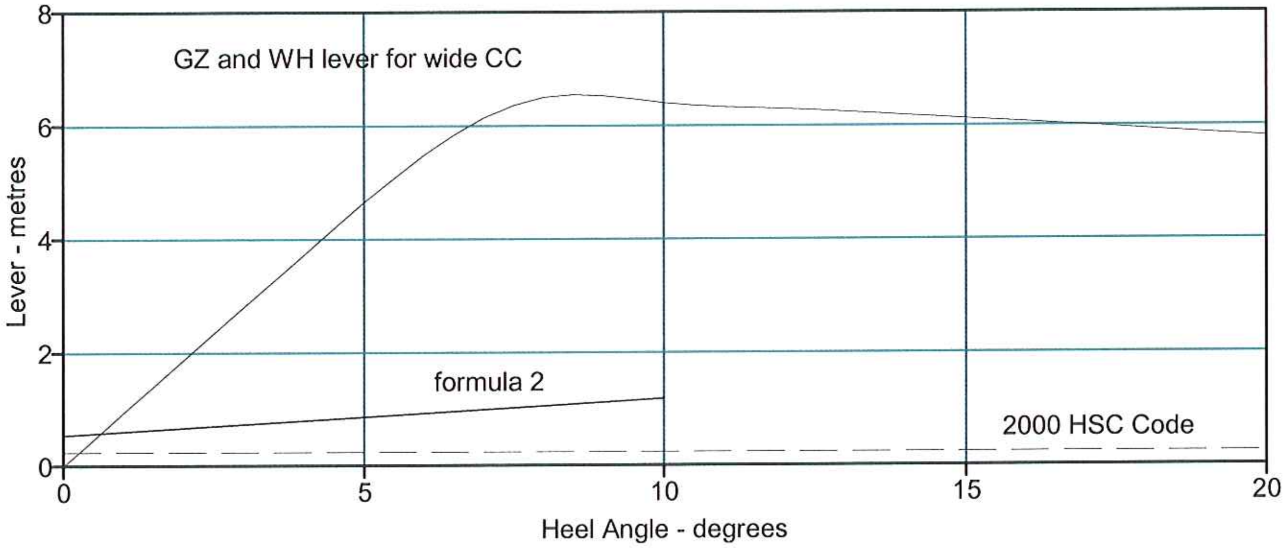


Figure 15.29 Righting and heeling arm curves for three sample catamarans







16 APPENDIX 1 - BIBLIOGRAPHY

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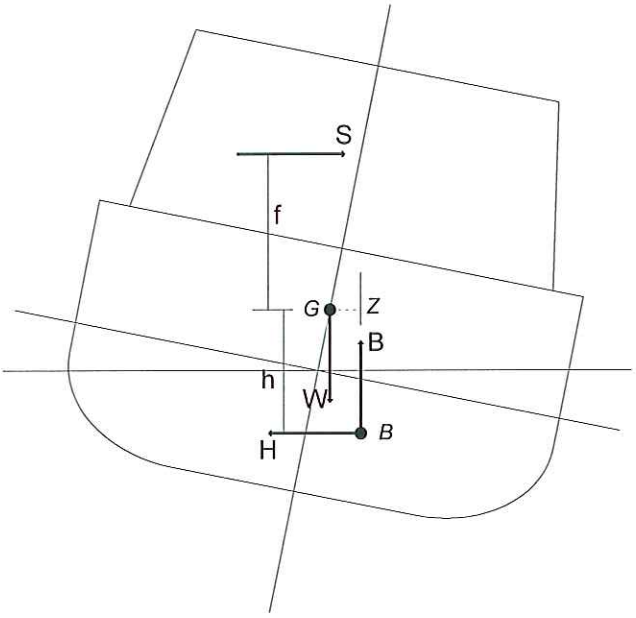
17 APPENDIX 2 – HEELING MOMENT DEFINITION



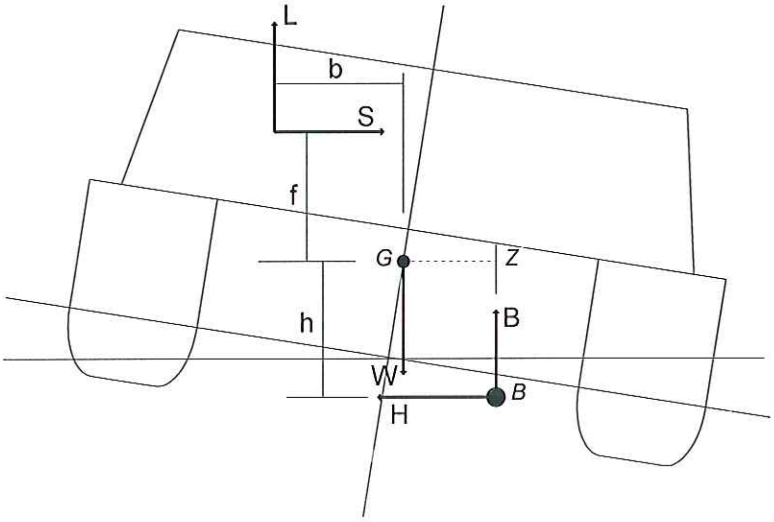
For a monohull it is assumed that the aerodynamic force, S, is horizontal, and opposed by a hydrodynamic force, H, acting at about the half draught or centre of buoyancy.

Taking moments about G:

$$\text{RightingMoment} = B \times \overline{GZ} = W \times \overline{GZ}$$
(since W = B)

$$\text{HeelingMoment} = S \times f + H \times h = S(f + h)$$
(since S = H)

This is the same as taking moments about B, which is the customary method of analysis.



For a catamaran we know that the aerodynamic force has a horizontal component, S, and a significant vertical component, L. The horizontal force is opposed by a hydrodynamic force, H, acting at about the half draught or centre of buoyancy, and the vertical force is balanced by a reduction in the buoyancy force.

Taking moments about G:

$$\text{RightingMoment} = B \times \overline{GZ} = (W - L)\overline{GZ}$$
(since B = W - L)

$$\text{HeelingMoment} = S \times f + H \times h + L \times b = S(f + h) + L \times b$$
(since S = H)

Taking Moments about B:

$$\text{RightingMoment} = W \times \overline{GZ}$$

$$\text{HeelingMoment} = S(f + h) + L(b + \overline{GZ})$$

If we subtract the product of L and GZ from the latter two equations they are identical to those taken about G. If the stability were assessed by taking moments about G, the value B - L would need to be used. It is preferable to take moments about B, as for monohulls. Then the conventional equation for the righting moment is maintained, using the displacement of the vessel which is accurately known, rather than making an adjustment on the basis of an estimated vertical force.