MODEL TESTS TO STUDY CAPSIZE AND STABILITY OF SAILING MULTIHULLS

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ABSTRACT

Sailing multihull cruising yachts cannot be righted from a capsize without external assistance, and so they present a difficult problem for regulatory authorities concerned with commercial operation of such craft. A standard is required which enables their stability to be assessed at a similar level to that of monohull yachts. Unfortunately their stability characteristics and behaviour are very different to those of monohulls, and the normal methods of assessment are not appropriate. Some aspects of multihull capsizing are addressed, with a discussion of the results of an innovative programme of wind tunnel and towing tank tests. It is hoped that the paper will be of assistance in directing others in their assessment of multihull safety, and will provide a technical basis for further discussion of the subject.

1. INTRODUCTION

This paper summarises the work and principal findings of a research project conducted for the Maritime and Coastguard Agency. As the regulatory authority in the UK, the MCA had introduced a Code of Practice for the safety of small commercial sailing vessels in 1993, and this incorporated a section on multihulls. It was considered that certain aspects of that part of the Code might be improved and the Wolfson Unit were contracted to conduct some limited research. Phase 1 of the work, conducted in 1995, comprised a study of multihull stability incidents to identify the mechanisms of capsize. This highlighted a number of areas where reliable data were lacking. The work in Phase 2 comprised wind tunnel tests to study wind heeling moments, and towing tank tests to study roll responses to waves and vulnerability to pitchpoling. A full report on Phase 2 of the work is available from the MCA, Ref.1.

2. CASUALTY DATABASE

A database of 124 stability incidents was compiled using data from various sources. The incidents were to 33 catamarans, 67 trimarans, 2 proas, and 22 multihulls of unknown type, which capsized during a 30 year period to 1995. Craft of less than 7 metres were not included.

The casualty rate remained relatively constant over the period, perhaps indicating that multihulls are becoming safer, if their numbers are increasing. The distribution of the number of casualties with respect to their length reflected what was assumed to be the distribution of the number of multihulls in use. Most casualties were to yachts of up to 11 metres, with a secondary peak at 18 metres, a common length for ocean racing yachts.

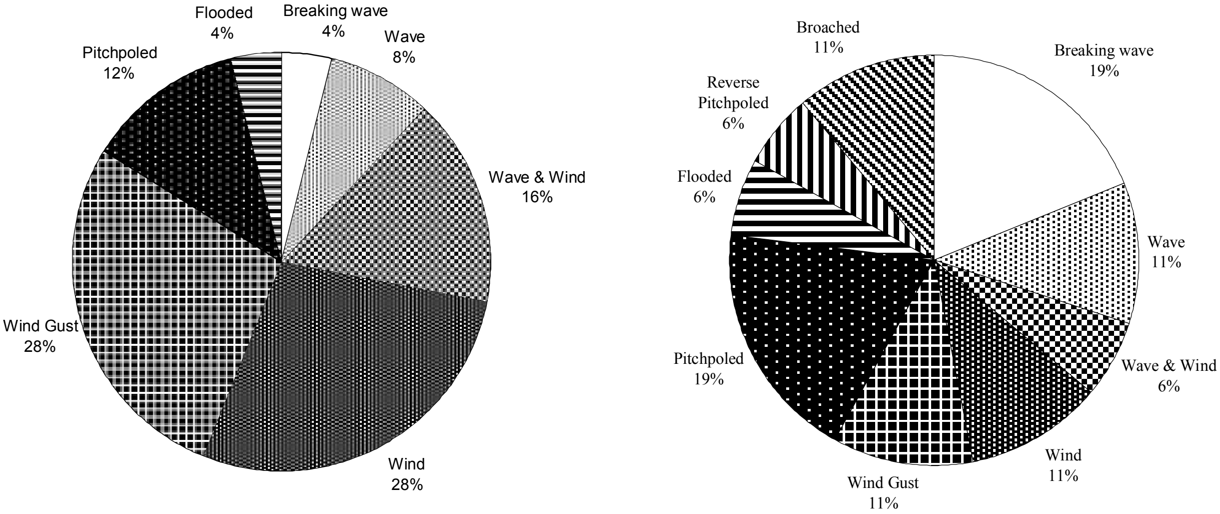

Figure 1. Types of casualty categorised in the database for catamarans (left) and trimarans.

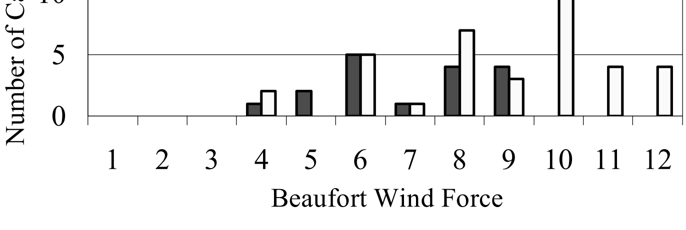

Figure 2. Incidence of casualties with respect to wind conditions.

Interesting results were obtained from a crude assessment of the type of casualty, illustrated in Figure 1. 84% of the catamaran casualties were the result of wind induced capsize or pitchpoling, whereas only 47% of the trimaran casualties were directly attributable to the wind. This does not indicate that trimarans are less vulnerable to capsize by the wind, because there are twice as many trimarans as catamarans in this sample. Rather, it implies that trimarans are vulnerable in more ways than catamarans. Another indicator of this difference was the distribution of casualties with respect to wind strength, Figure 2. Most of the catamaran casualties occurred in winds of force 6 to 9, with none documented in more severe conditions. The trimaran casualties occurred over a wider range of conditions, with a large proportion in force 8 to 12 conditions. It was assumed that in severe conditions the catamarans would have little or no sail set and their vulnerability would be low. Trimarans on the other hand, appear to be more vulnerable to breaking wave capsize in severe conditions.

Many accounts of incidents included references to the effects of waves, and frequently the capsize was attributed in part to wave action lifting one hull. It appeared that there might be some dynamic effect resulting from an encounter with a non-breaking wave on the beam, but the mechanism was not clear.

3. CHOICE OF MODEL TEST PROGRAMME

Phase 1 of the work concluded with recommendations for further study of the variation of wind heeling moments, the dynamic effects of waves, vulnerability to breaking waves and to pitchpoling. The small number of commercial sailing multihulls in the UK could not justify a major research investment, but it was proposed to conduct four basic test programmes using relatively simple models.

4. WIND TUNNEL TESTS

These tests followed a similar format to those conducted on monohull sailing yachts in 1989 as part of a programme of work on sailing vessel stability which was conducted for the Department of Transport. Details of those tests are described in full in Ref.2.

4.1. Model

A 1:12 scale model was constructed of a 13.6 metre catamaran, which had been designed for the charter industry by Alexander Simonis Naval Architects. The design of this yacht is described fully in Ref.3. As the model was intended to be representative of cruising catamarans, rather than an accurate model of a specific design, small details were neglected. The rig was constructed in accordance with the design drawings, and sails were manufactured to represent the mainsail, the full headsail, and the headsail furled to 70% of its area.

4.2. Test Arrangements

The tests were conducted at the University of Southampton No.1 Wind Tunnel, which has dimensions 4.6 metres wide by 3.7 metres high. The model was mounted on a six component balance which was attached to a turntable. 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. This arrangement is described in detail in Ref.4. The starboard hull of the model was connected to the dynamometer using a mechanism which enabled the model to be fixed at a range of heel angles from 10° to 90°. The model could not be mounted at 0° of heel because the port hull would foul the turntable.

Figure 3. The model undergoing wind tunnel tests in configuration 5.

4.3. Test Configurations

The model was tested in the following configurations:

1. Hulls and bridge deck only at the design beam.
2. Hulls and bridge deck with the beam increased by 25%.
3. Hulls and bridge deck at the design beam, with a solid forward trampoline. This gave a 30% increase in the bridge deck area.
4. Hulls, bridge deck, and coachroof, as designed.
5. As designed, with the full mainsail and headsail sheeted to obtain the maximum driving force at an apparent wind angle of 30°.
6. As designed, with the full mainsail and headsail eased to reduce the heeling moment by 50%, while maintaining a high driving force/heeling force ratio.
7. As designed, with the mainsail reefed to 80% of its area, and the headsail furled to 70%. The reefed sails were sheeted to obtain the maximum driving force.

4.4. Data Analysis and Presentation

The objective of the tests was to determine the aerodynamic force coefficients, and the effective areas and centres of effort of the structure and sails. The forces and moments therefore are presented independent of wind speed, as force/NWP or moment/NWP, where NWP is the nominal wind pressure. The measured forces were adjusted with boundary corrections and Maskell wake blockage factors.

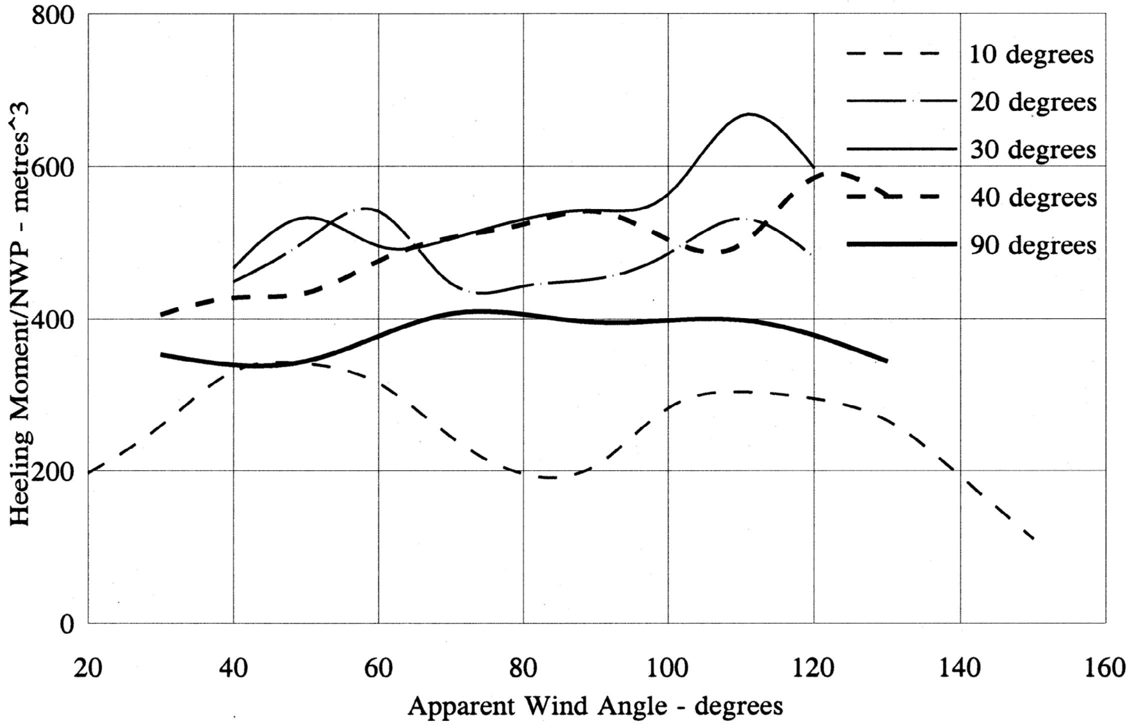

Figure 4. Wind heeling moments in configuration 2 at selected heel angles.

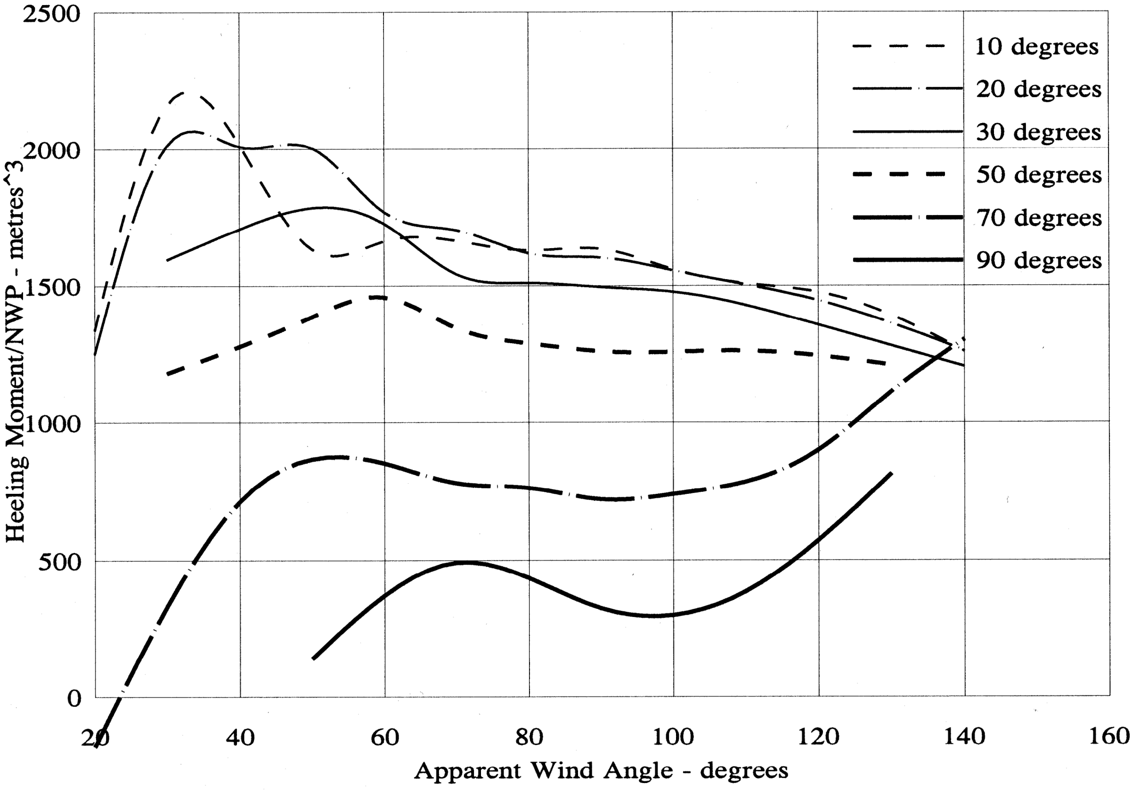

Figure 5. Wind Heeling moments in configuration 5 at selected heel angles.

Figures 4 and 5 present the heeling moments for two of the test configurations. The data are presented as curves of heeling moment variation with apparent wind angle for each heel angle. Note that, in Figure 4, the heeling moment is greater at apparent wind angles of 50 and 110 degrees, than at 90 degrees where the area of the model presented to the wind is greatest.

In configuration 6, where the sails were eased to reduce the heeling moment by 50% at 30 degrees apparent, the heeling moments at other headings showed much smaller reductions from the values of configuration 5. Easing the sails resulted in only a 25% reduction in heeling moment at 50 degrees, and only 13% at 90 degrees apparent. With the sails set for high efficiency, as they were at 30 degrees, small changes in the sheeting bring substantial changes in the forces, however, with sail settings off optimum, changes in their settings or heading result in smaller changes in the forces. Figure 5 illustrates the sensitivity of the heeling moment to sheeting angle around the optimum sail setting, in this case at 30 degrees apparent and 10 degrees of heel. This characteristic mitigates against accurate estimation of sail heeling moments.

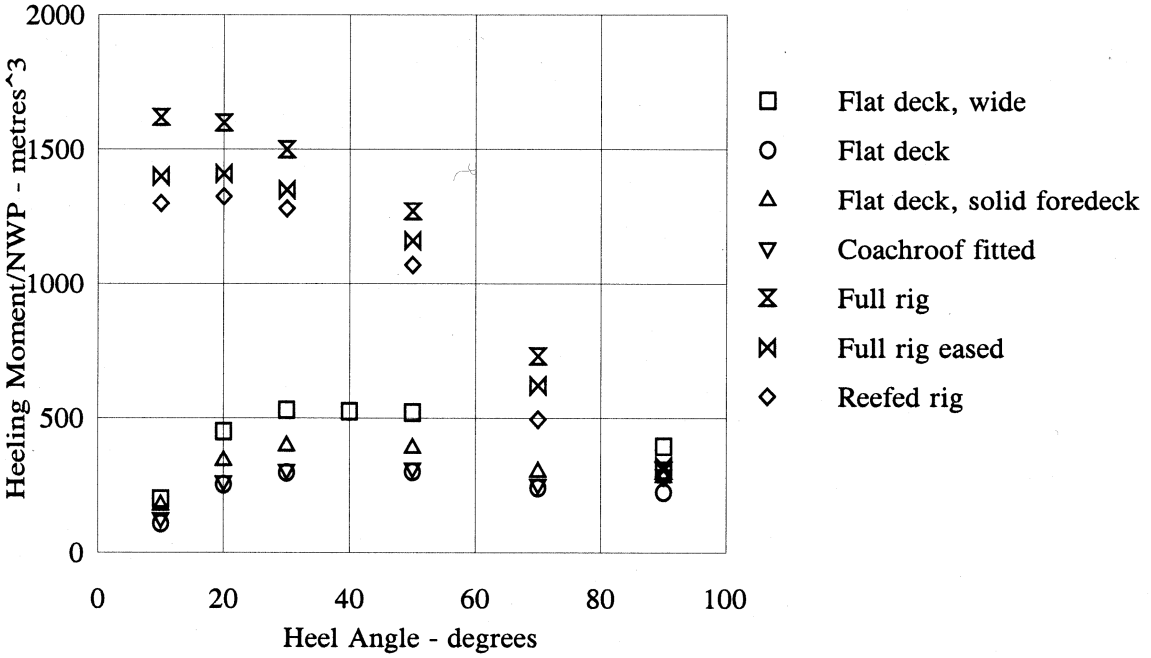

Figure 6. Variation of heeling moments with heel angle.

Figure 6 shows the variation of heeling moment with heel angle for the various test configurations, at an apparent wind angle of 90 degrees. The data for the model without sails indicate that the heeling moment is dependent on the deck area, since the wide model gave the highest moments, and with the solid foredeck the moments were higher than for the open foredeck. The addition of the coachroof had little effect. In all cases without sails the heeling moment tended to increase with increasing heel angle, reaching a maximum at around 30 degrees, and then remained roughly constant up to 90 degrees. With the sails fitted the moments reached a maximum at 10 or 20 degrees of heel, then reduced with increasing heel angle.

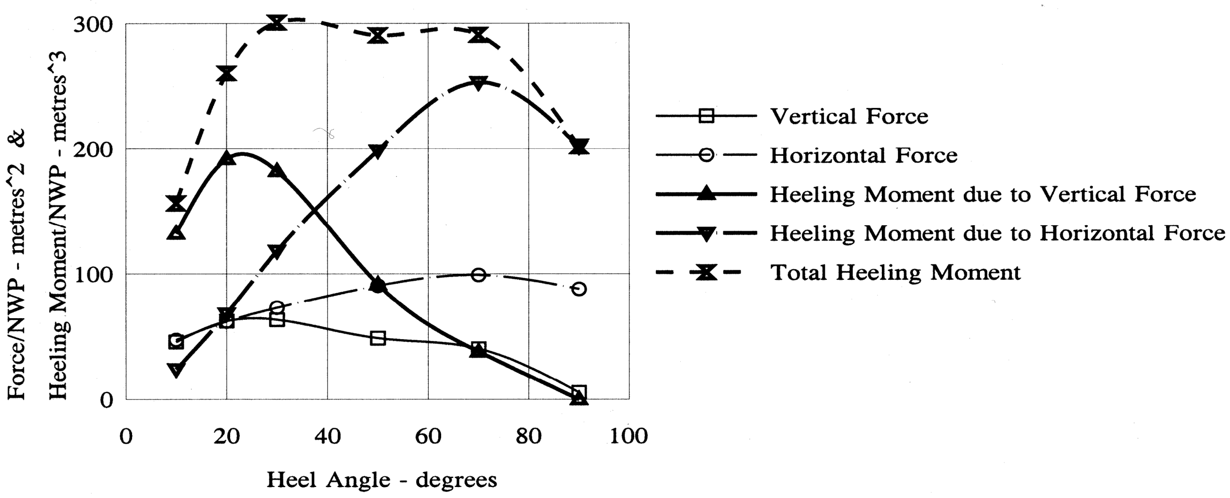

Figure 7. Contributions to heeling moment due to vertical and horizontal forces on the structure.

Past experience has shown that the resultant sail force tends to be approximately normal to the mast. A detailed analysis of the forces on the hull and deck structure was undertaken to investigate the nature of its resultant aerodynamic force. Figure 7 presents data for test configuration 4, the hulls deck and coachroof, and shows the vertical and horizontal components of force. At low angles of heel the vertical and horizontal forces are equal, while at high angles of heel the horizontal force is greater. The vertical force is generated by acceleration of the flow over the structure, which results in low pressure on its upper surface. At low angles of heel the vertical force dominates the heeling moment because it acts nearly normal to the deck and has a large lever, whereas the horizontal force acts parallel to the deck with a small lever. At a heel angle of 90 degrees the horizontal force has a large lever, whereas the lever associated with the vertical force reduces to zero.

Through this analysis it can be shown that the resultant force on the structure remains approximately normal to the deck at all angles. The total heeling moments acting on the vessel in the sailing configuration therefore were considered to be comprised of two orthogonal components. One due to the lift on the deck structure aligned roughly perpendicular to the deck, and the other due to the lift on the sails perpendicular to the mast.

Table 1 presents the total profile and plan areas, and moments of area, for each of the model configurations tested. The levers associated with sail areas are vertical distances, and those associated with the hull and deck areas are horizontal distances measured transversely across the deck, to the centreline of the leeward hull at the waterline. The total plan area of the hull and deck structure of the yacht as designed is more than 50% of the sail area. Its lever about the leeward hull is considerably smaller however, and so the moment of the deck area is only 15% of that of the sail area moment.

Test Configuration	**Total Profile Area**	**Moment of Area**	**Total Plan Area**	**Moment of Area**
	metres^2	**metres^3**	**metres^2**	**metres^3**
1. Flat Deck	0.00	0.00	75.9	208.7
2. Wide, Flat Deck	0.00	0.00	94.6	347.7
3. Flat Deck + Foredeck	0.00	0.00	88.6	243.7
4. Coachroof Fitted	0.00	0.00	75.9	208.7
5. Full Rig	143.2	1377.9	75.9	208.7
6. Full Rig, Eased	143.2	1377.9	75.9	208.7
7. Reefed Rig	111.6	989.3	75.9	208.7

Table 1. Full scale areas and levers represented by the model.

4.5. Derivation of a Formula to Estimate Heeling Moments

In order to enable prediction of the maximum likely wind heeling moments for other multihulls, attempts were made to fit curves to the measured data. The data for an apparent wind angle of 50 degrees were used for this exercise since, in general, they represent the maximum heeling moments. The proposed formula, presented in Figure 8, was derived bearing in mind dual requirements for a reasonable fit to the data, and ease of application.

The formula used was: Heeling Moment/NWP = 1.3 [Sh Cos(heel angle) + Db]

where: S is the total sail area
h is the height of the centroid of the sails above the waterline
D is the plan area of the hulls and deck
b is the distance from the centroid of the deck area to the centreline of the leeward hull.

The contribution of the hulls, deck and coachroof is assumed to remain constant at all angles of heel. This may appear to be an over-simplification but, as can be seen in Figure 8, the errors involved represent a small percentage of the total moment with sails set. The profile areas of the hull and coachroof have not been used in this analysis since they have little influence on the heeling moment.

This formula represents a refinement of contemporary methods of calculation. The formula currently used in the UK Code of Practice, for example, takes no account of the deck area but includes the profile area of the hull structure, and assumes a force coefficient of 1.2 rather than 1.3 as suggested here. For the yacht modelled, the proposed formula gives a heeling moment estimate 15% greater than that given by the formula in the Code of Practice.

The wind heeling moment reduces with heel angle at a lower rate than the righting moment of a typical multihull. Their range of stability normally is about 60 to 80 degrees, and the wind heeling moment remains significant at 90 degrees. The wind heeling moment is therefore greater than the righting moment at large angles of heel, even at low wind speeds, and this fact may have implications for multihulls heeled to large angles by wave action. In this respect multihulls differ from ballasted monohulls which, when at 90 degrees, have positive righting moments but negligible wind heeling moments.

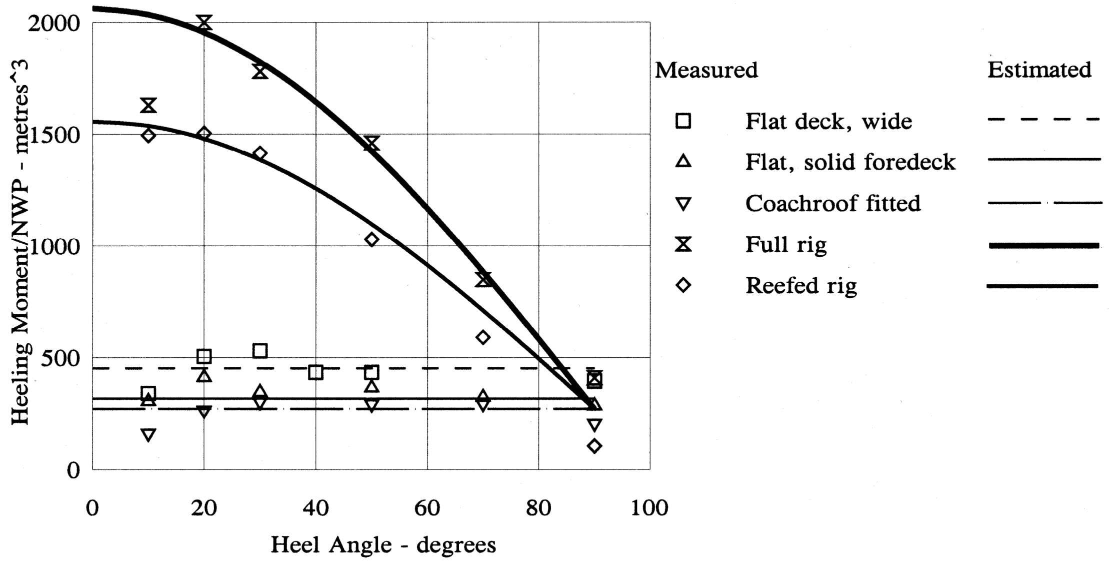

Figure 8. Estimates of heeling moment using the proposed formula compared with test data.

5. ROLLING AND CAPSIZING TESTS

Tests were conducted in a towing tank to study the response of multihulls to beam seas, and four types of test were employed:

1. Roll decrement tests were used to determine the natural roll period, by allowing the model to roll freely in calm water.
2. Linear roll response tests were used to determine the roll response amplitude operators, or RAOs, by measuring the roll angles over a range of wave frequencies in small regular waves.
3. Non linear roll response tests were conducted in large regular waves to identify any tendency for the waves to induce extreme roll angles.
4. Tests in breaking waves were conducted to study the vulnerability to capsize.

5.1. Models

A simple catamaran model, comprising hulls, bridge deck and mast, was based on the same design as used for the wind tunnel tests, modelled at a scale of 1:15. The model length overall was 0.9 metres. The overall beam was made adjustable by a joint in the bridge deck, and various ballast locations were used to enable variation of the vertical centre of gravity and roll inertia.

A simple trimaran model comprised a main hull the same as those of the catamaran, with floats connected by two alloy cross beams and the same mast as used for the catamaran. Two pairs of floats were constructed, one pair each had a volume equal to 100%, of the standard displacement, so that one float fully submerged would just support the model. The other pair each had a volume equal to 200% of the model displacement. As with the catamaran, the model component weights were adjusted to be representative of a sample trimaran. For the tests in breaking waves, two additional trimaran conditions were tested with the displacement increased, so that the float volumes no longer represented 100% and 200% of the test displacement.

Configuration	**Hull or Float Separation**	**Disp.**	**VCG above deck**	**GM**	**Roll Gyradius k**	**Roll Inertia**	**Roll Period**
	mm	**kg**	**mm**	**mm**	**mm**	**kg.mm^2**	**seconds**
Catamarans							
1. Standard*	367	4.35	10	907	204	181365	0.45
2. VCG Increase 1*	367	4.35	53	864	201	175211	
3. VCG Increase 2*	367	4.35	98	819	216	203404	
4. High VCG	367	4.35	131	787	238	247004	0.84
5. Narrow Beam*	293	4.35	10	541	186	150081	0.75
6. Wide Beam	440	4.35	10	1346	224	219201	0.48
7. Light Displacement	367	3.00	-9	1236	244	178178	
8. Low Inertia	367	4.35	10	907	152	100175	0.41
Trimarans							
1. Small Floats	606	2.20	9		247	134663	0.43
2. Small Floats, High Displacement	606	2.90	9		247	134663	
3. Large Floats	606	2.20	9		258	146519	0.55
4. Large Floats, High Displacement	606	2.90	9		258	146519	

* These configurations were also tested with keels fitted.

Table 2. Roll test model configurations and their properties

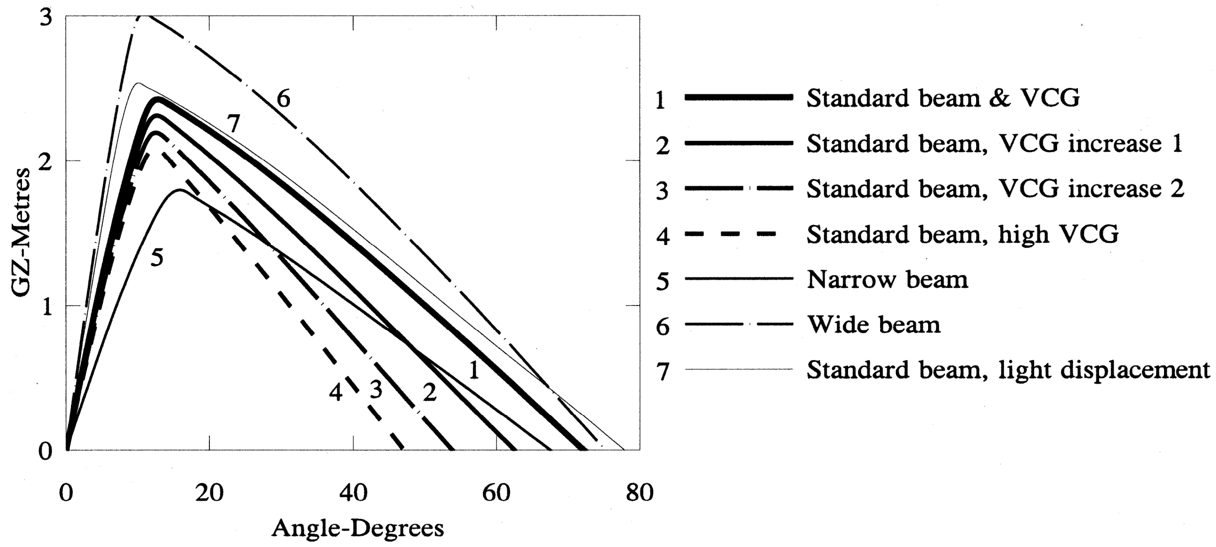

Figure 9. Stability curves for the catamaran models used for the roll tests.

The various model configurations tested are listed in Table 2. The stability curves of the catamaran models are presented in Figure 9 to illustrate the variation in maximum GZ and range of stability. The GZ values presented are for full scale yachts, assuming a model scale of 1:15.

5.2. Test Facility

The tests were conducted in a towing tank which is 60 metres long by 3.7 metres wide by 1.8 metres deep. It is equipped with a manned carriage with a maximum speed of 4.5 metres/second, and computer controlled wavemakers capable of producing regular waves, representative sea spectra, and breaking waves.

5.3. Roll Decrement Tests

The model was released from a heel angle of around 20 degrees in calm water. The resulting motion appeared to be rather irregular, and very heavily damped, particularly with the trimaran models. The roll motion is complicated in comparison with a monohull because the motion of each hull propagates waves to which the other hull responds. Fourier analysis of the roll angle time histories was used to reveal the natural roll period, and a comparison of this with a theoretical prediction, based on the stability and inertia, enabled an estimate of the added inertia.

The natural roll periods for the various model configurations varied from 1.5 to 3.3 seconds at full scale. The added inertia due to water entrained by the heaving hulls was significant, the added mass amounting to more than 50% of the displacement in the case of the model with the longest roll period.

5.4. Determination of Roll Response Amplitude Operators

The roll RAO is a non-dimensional measure of the roll response, defined as the roll angle divided by the maximum slope of the wave surface.

The model was positioned across the tank near to the wavemakers, linked to the carriage only by the transducer cables. Small regular waves were produced and the model response was measured for a period of about 30 seconds. Wave frequencies ranging from 3 to 9.5 radians/second were used, the upper limit being due to the wavemaker frequency response, and the lower limit to the restrictions associated with reflection of the waves from the far end of the tank.

The results of tests on the catamarans are illustrated in Figure 10. For a monohull, the curves of RAO variation with frequency have a characteristic form with an ordinate of unity at very low frequencies, rising to a peak RAO of perhaps 5 to 10 at the natural roll frequency, and then reducing to zero at high frequencies. The multihull models' natural frequencies, as determined from the roll decrement tests, were near or above the maximum frequency of the wavemakers, and so the peak response was not exhibited by all of the models. The exceptions were the catamaran models with high VCG and narrow beam, configurations 4 and 5. Their natural frequencies were 7.5 and 8.4 rad/s. respectively, and their peak RAOs of 2.2 and 1.8 occurred near these frequencies. Below the natural frequency the RAO curves for the catamarans approached unity as expected, albeit with some scatter, but the trimaran models behaved rather differently, with responses increasing at low frequencies, and a smaller local peak at around 7 rad/s.

For the trimaran with 100% floats the two peaks in the RAO curve occur at half and a quarter of the natural frequency, suggesting that the model was responding in a harmonic way, but this was not the case for the model with 200% floats. The motions of the trimaran are particularly complex because the floats alternately submerged and lifted from the water. The motions are not linear because the floats repeatedly slam on the surface, and the RAOs cannot be expected to conform to the usual pattern. Furthermore, when one float is dry, the trimaran behaves like a catamaran with unequal floats.

These results are complex and difficult to interpret in detail, but the principal conclusion of interest here is that the peak responses are significantly less than those for typical monohulls. Response to unbroken waves therefore is not likely to result in heeling to large angles. Where the natural frequencies are above the scope of the test facility, they would correspond to full scale wave frequencies at which there is little energy. For example, the standard catamaran model has a natural frequency of 14 rad/s, which represents 3.6 rad/s for a 13 metre yacht, and this corresponds to a period of 1.75 seconds. A wave of this period has a length of less than 5 metres, and a maximum height without breaking of 0.7 metres. Such a wave would not be of sufficient size to endanger the yacht and, with the wavelength similar to the hull separation, it would excite the yacht in heave rather than roll.

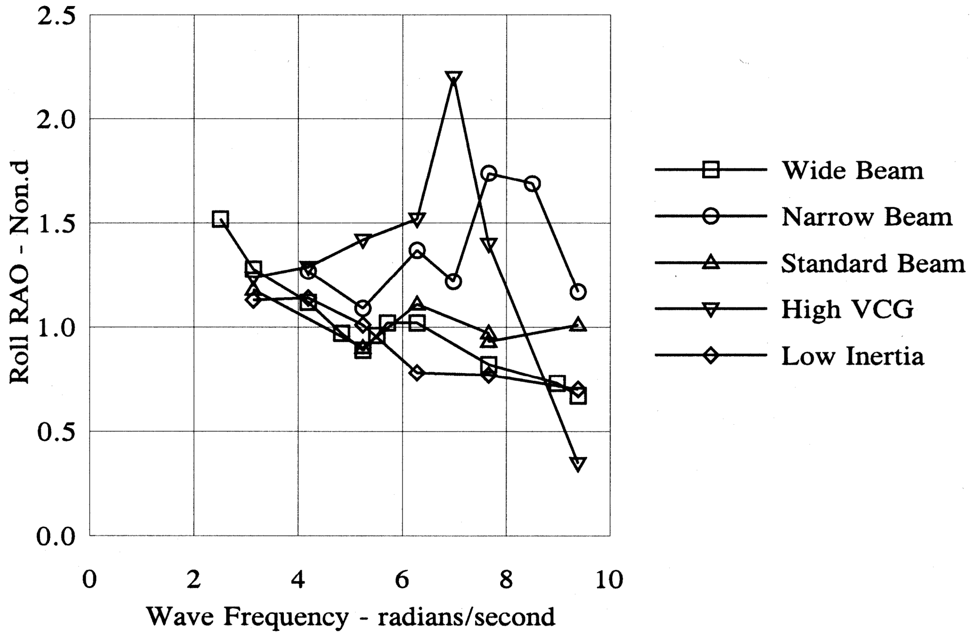

Figure 10. Roll RAOs for the catamaran models.

5.5. Non-Linear Roll Tests in Steep Waves

The five catamaran configurations and two trimaran configurations used for the RAO tests were also placed beam on to larger, steep regular waves to confirm that their roll response did not result in extreme heel angles. For these tests the models were not instrumented, and so were totally free from restraint or interference from cables. The tests were recorded on video to enable careful observation of the roll angles in each case.

The models exhibited no extreme responses, the catamarans generally contouring the waves with no evidence of a hull emerging from the water. The motions of the trimaran models was more complex, as one, or sometimes both, of the floats was out of the water, and the model flopped from port to starboard or vice versa with the passage of each wave. These observations support the results of the RAO tests and suggest that these yachts are not vulnerable to capsize or heeling to large angles under the action of non-breaking waves alone.

5.6. Roll Tests in Breaking Waves

To investigate the vulnerability to capsize in large breaking waves, the models were projected into the wave using a simple catapult mechanism. This enabled the encounter to be carefully controlled in terms of the model orientation and location with respect to the breaking wave. The models were fitted with fixed rudders to improve their directional stability, and were projected forward by a loop of string around the mast. Prior to the test the model was tethered by an aft painter, and this was released by a solenoid operated by a signal from the wavemaker control computer, following some preset delay. The variables of catapult location along the tank and solenoid trigger delay were adjusted to obtain the desired encounter with the breaking wave, and the catapult orientation was rotated to enable the wave encounter on the beam, or the bow or stern quarter. The height of the wave crest was generally 285 mm above the mean water level.

The model configurations tested included those used for the RAO tests, and some additional configurations to enable further investigation of certain aspects of the design. Some catamaran configurations were also tested with shallow keels fitted.

Observations of the tests supported the findings of previous studies of behaviour in breaking waves. A vessel heels in response to the wave slope ahead of the breaking crest and is then struck by the crest. The energy principally is in the broken water which travels along with the wave. There is little rotation in the wave to turn the vessel and it is pushed ahead of the crest by the broken water. Any rotation of the vessel is brought about by its resistance to movement through the water. Typically these models heeled with the wave slope, then heeled further as a result of the wave impact on the windward hull or float which was reacted by the resistance of the leeward hull or float in the unbroken water. On some occasions the breaking crest subsequently struck the leeward hull, rotating the model back to windward.

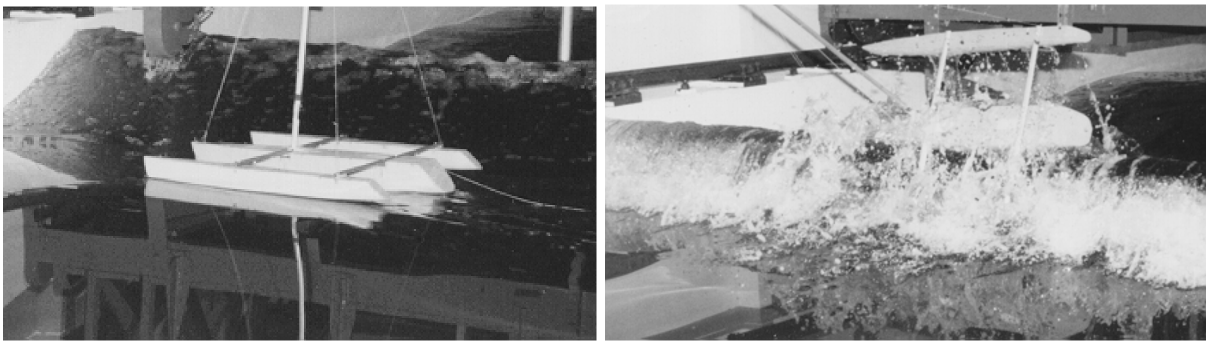

Figure 11. Photographs of a test on the trimaran with large floats in a breaking wave.

It is interesting to note that in several cases the maximum heel angle was greater than the range of positive stability, but the model did not capsize. It appeared that the models were being carried sideways by the breaking crest, sometimes at a steady heel angle, and this force provided an additional righting moment.

Presentation slightly stern to the seas appeared to make little difference to the response, but no capsizes occurred when the model was deployed slightly head to the waves. This may be because the models, particularly the catamarans, tended to yaw beam on to the wave when struck on the quarter.

A summary of the capsize incidence of the various models is presented in Table 4. Of the various catamaran configurations tested, the higher VCG conditions and the narrow beam configuration proved most vulnerable. The standard configuration was based on a real yacht of 13.6 metres, and the VCG increases represent increments of about 0.65 metres on that size of craft.

Configuration	Number of Tests	Number of Capsizes	% Capsize Incidence
Catamarans			
1. Standard	3	0	0
1a. Keels Fitted	3	0	0
2. VCG Increase 1	3	0	0
2a. Keels Fitted	3	0	0
3. VCG Increase 2	6	1	17
3a. Keels Fitted	4	1	25
4. High VCG	2	2	100
5. Narrow Beam	7	1	14
5a. Keels Fitted	5	3	60
6. Wide Beam	4	0	0
7. Light Displacement	3	0	0
8. Low Inertia	3	0	0
Trimarans			
1. Small Floats	18	5	28
2. Small Floats, High Displacement	8	3	38
3. Large Floats	10	1	10
4. Large Floats, High Displacement	5	0	0

Table 4. Summary of the roll tests in breaking waves.

With the first VCG increase there were no capsizes, with the second increase there were 2 capsizes in 10 tests, and the model capsized on the only two tests with the high VCG. With the second VCG increase, on two occasions the model was heeled to an angle of around 60° and it remained at that angle for some time before capsizing. The range of stability in that condition was about 54°, and it appeared that the lower range of stability was the controlling factor in the period following wave impact, rather than the capsize being determined during the more dynamic early phase of the incident

. The VCG increments of 0.65 metre are very large, bearing in mind that the depth of the canoe body is about 2.2 metres, and the depth to the top of the coachroof is about 3.3 metres. If the weight of the rig were to be increased by a factor of 2, the VCG would rise by about 0.5 metre. It is conceivable therefore that, for a conventional cruising catamaran, the VCG could be as high as that represented by the second increase, but not the highest VCG.

The range of stability of the narrow model was greater than that of the standard beam model with the first VCG increase, and so the range did not appear to be the sole governing factor.

Although the narrow beam model was 20% narrower than the reference design, it is by no means unrepresentative. The length to hull separation ratio of the narrow model was 3.1 compared with examples of UK registered charter catamarans of 3.05, 3.04, and 2.9. Previous tests with monohull models, Ref.5, indicated that, in general, they could be capsized by a breaking wave of a height equal to or greater than the beam of the yacht. The narrow model had a hull separation of 293 mm which corresponded to the height of the breaking wave at impact.

The addition of the keels appeared to result in a slight increase in the vulnerability to capsize. For the narrow model it increased the capsize incidence from 14% to 60%, and for the standard model with the second VCG increase it increased from 17% to 25%. With the lower VCGs there were no capsizes, but in both cases the maximum angle of heel was greater with keels fitted than without. These results support the theory that it is the resistance to sideways motion that provides the couple to convert the breaking wave energy into rotation.

Only one reliable account has been found of a catamaran capsize due to a beam encounter with a breaking wave. This was a 9 metre yacht which encountered a wave about 9 metres high with a breaking crest. The yacht took the wave on the quarter, broached and capsized. The yacht had a length to hull separation ratio of 3.28 and had been modified by the owner with the addition of keels to improve windward performance. The casualty therefore correlates well with the model test data.

The low incidence of such casualties is perhaps due to the low probability of encountering a wave of sufficient size, on the beam, at the critical time when it breaks. The much greater incidence of monohull capsizes may be because they are of narrower beam and therefore require proportionately smaller waves.

Of the trimaran configurations, those with the smaller floats were most vulnerable, with a 28% capsize rate for the standard displacement and a 38% capsize rate for the higher displacement. In these two configurations the float volumes were 100% and 75% of the displacement respectively. With the larger floats, one capsize was recorded in 10 tests, and that with the standard displacement, that is with 200% floats. With large floats and heavy displacement, that is with 150% floats, no capsizes occurred. At the standard displacement the floats were located such that only one was immersed in calm water but at the higher displacements both floats penetrated the surface. Their behaviour may have been affected by this, and caution must be exercised when interpreting the data with respect to float volume.

The tests confirmed the common opinion that small floats tend to become fully immersed if the yacht is struck by a breaking wave. Their high resistance to sideways motion then encourages rotation. Since the windward float frequently rose above the surface after the initial strike, the model behaved rather like a catamaran with the centre of gravity offset to windward. Its effective beam therefore, was only half the total beam and in these tests was equal to the wave height.

6. PITCHPOLING TESTS

Pitchpoling is a type of incident which affects catamarans and trimarans, and occurs when the yacht is sailing with the wind and waves. The high sailing speeds attained by multihulls may enable them to surf or overtake the waves, and the fine bows may become submerged as the yacht sails into a wave trough or the back of a wave. The speed drops with the increased resistance and this causes an increase in the apparent wind speed which may overturn the yacht. Capsize may be purely longitudinal if the bows submerge symmetrically, but more frequently is about a diagonal axis.

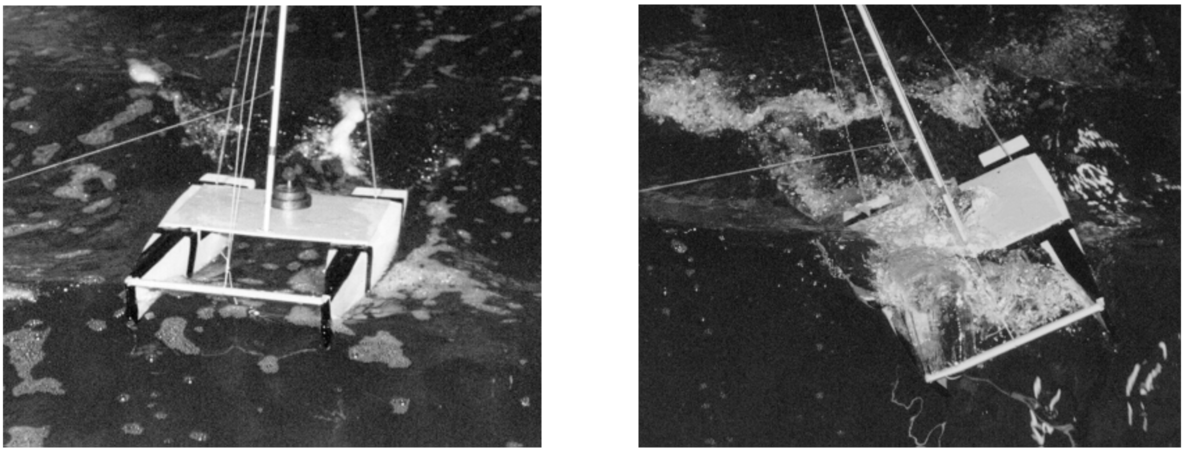

Figure 12. Two photographs from a pitchpoling test on the fine bow catamaran.

6.1. Models

The standard catamaran model was tested at level trim and with bow trim. Two new models were constructed with the LCB moved aft by 5% LWL, resulting in finer forward sections. Above the waterline one model incorporated flared topsides with a deck plan similar to that of the standard form. These were tested with bow and stern trim, and at two displacements. The properties of the pitchpoling models are presented in Table 5.

6.2. Test Technique

Attempts to simulate pitchpoling incidents in the towing tank, using the models constructed for the roll tests, included experimentation with various techniques. The available budget necessitated a simple technique, and that selected was to tow the model in following seas using a towline on a wand. The line was attached to the mast, and the wand held by a person on the moving carriage. The model was rigged with twin forestays with the towline led between them. This enabled a horizontal tow with the tow point located at the required vertical location to represent the aerodynamic force, and gave reasonable directional control. If the model began to pitchpole the force on the towline increased, as the aerodynamic force would, until the wand was released. On some occasions the model broached towards the tank wall, and the towline tension applied in an attempt to pull out of the broach was sufficient to capsize the model. A sample test is illustrated in Figure 12.

A range of towline heights, wave sizes, and carriage speeds were experimented with until it was decided that, with a constant wave size and towline height, varying the carriage speed enabled the vulnerability of each model to be compared. With the model moving more slowly than the waves, pitchpoling was not a problem. With the speeds equal the yacht tended to surf on the face of a wave and remained in control or broached, depending on its directional stability and control characteristics. With further increases in speed the vulnerability to pitchpoling increased, and so a model which survived tests at relatively high speeds was considered to be less vulnerable.

6.3. Test Results

All of the tests described were conducted in the same regular waves which were 175 mm high with a period of 0.9 seconds and a celerity, or wave speed, of 1.405 metres/second. The speed ratio is the carriage speed divided by the wave celerity, that is the speed of the waves.

Unless indicated otherwise, the towline was attached to the mast at a height of 300 mm above the deck. The other heights used were 370 mm, representing one third of

Configuration	**Disp.**	**LCG**	**LCG**	**Trim**	**GML**
	kg	**mm**	**%LWL**	**mm**	**mm**
Standard Catamaran					
Fwd LCG	4.35	-36	-4.5	-10	1085
Aft LCG	4.35	-70	-8.7	14	1115
Fine Bow Catamarans					
Fwd LCG	4.35	-83	-10.3	-7	990
Aft LCG	4.35	-133	-16.5	32	1005
Light Displacement, Fwd LCG	3.05	-75	-9.3	-7	1115
Light Displacement, Aft LCG	3.05	-104	-12.9	12	1210
Trimarans					
Small Floats	2.20	-50	-6.2	0	550
Large Floats	2.20	-50	-6.2	0	550

Table 5. Pitchpoling test model configurations and their properties.

the mast height above the deck, and 470 mm, representing one third of the mainsail luff length above the deck.

All of the catamaran configurations with the higher displacement could be induced to pitchpole. When the LCG was moved forward it made the model more vulnerable, for example both of the fine bow models pitchpoled at a model speed to wave speed ratio of 1.47 with the aft LCG and at a ratio of 1.15 with the forward LCG. Early tests with the standard model ballasted to a forward LCG did not result in a pitchpole but only three brief tests were conducted and this result should be used with caution.

The models with the fine bows appeared to be more prone to immersing their bows, and sometimes this caused the model to broach and/or capsize. Whilst these incidents were not pitchpoles in the purest sense, in some cases the capsize was caused by increased load on the towline as a result of burying the bow in a broach, and the vulnerability to bow immersion was significant.

The increase in bow flare did not appear to have a large effect on the pitchpoling behaviour, and both of the fine bow models suffered bow immersions even at the light displacement aft LCG condition. The model with increased flare suffered fewer capsizes than the fine bow model.

Tests using the trimaran with small floats, and with a high tow point, confirmed that, although the model surfed on some waves and was prone to broaching, pitchpoling was not a problem at speed ratios of up to 1.

Further tests on the trimaran were conducted with the large floats fitted. The model pitchpoled at a speed ratio of 1.15 with the tow point at 370 mm, and at a speed ratio of 1.47 with the tow point at 300 mm.

Attempts were made to correlate the incidence of pitchpoling with the model type, LCG location and tow height. Figure 13 presents the results of the tests graphically, using the speed ratio and the ratio of towline height to LCG location aft of the mast. The latter ratio is a simple expression relating the pitching moment of the sails and the moment of the yacht's weight about the base of the mast. One might expect a forward LCG or a high centre of effort to increase the vulnerability to pitchpoling, and so a high value of this ratio should increase it.

With a forward LCG the freeboard forward is reduced, and it is clear from the video records that the pitchpoling was induced by immersion of one or more bows. This may be the reason for the increased vulnerability with LCG moved forward, rather than the reduced longitudinal righting moment.

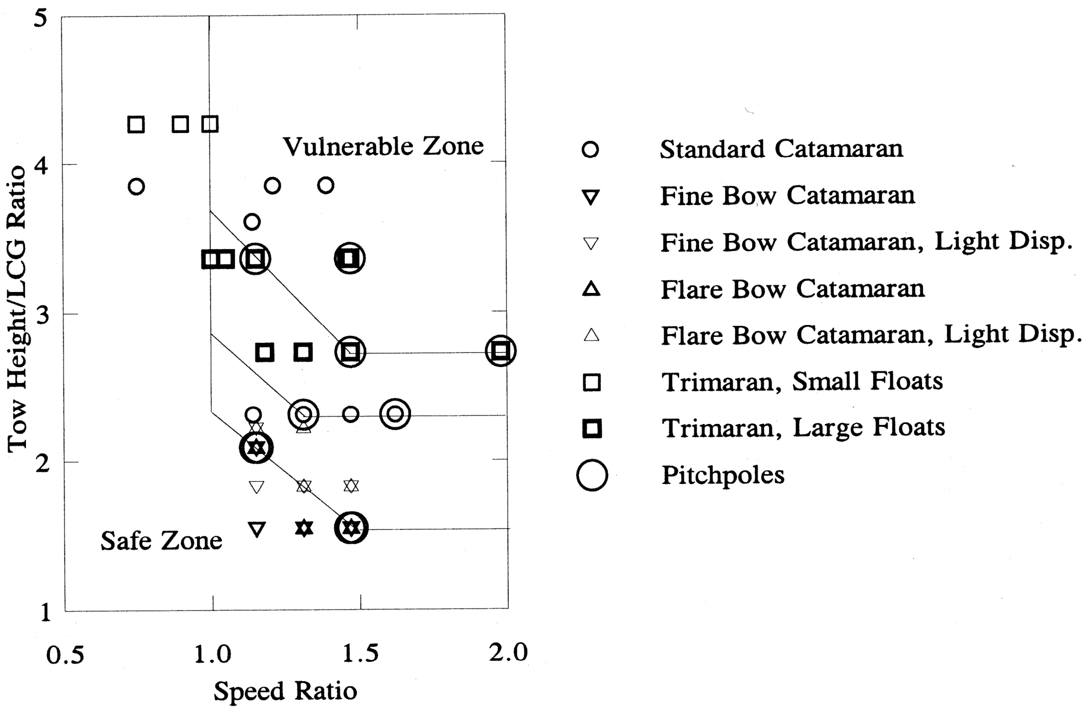

Figure 13. Pitchpoling results with respect to tow height , LCG and speed.

The highly variable behaviour and the large number of design variables which might have an influence make pitchpoling a complex problem. While this limited test programme showed trends, and supported some contemporary theories, it did not provide sufficient data to identify boundaries of design variables which would ensure safety from pitchpoling. It has reinforced some aspects of seamanship however, which knowledge might benefit crews unfamiliar with sailing multihulls. The test method proved capable of identifying differences in designs, albeit through a statistical analysis of a number of tests, and might be used by others to extend the study.

7. CONCLUSIONS

Whilst the tests concluded with certain aspects unresolved, they achieved a number of important gains. Revision of the UK code of practice can now proceed with increased confidence, the wind heeling moments of catamarans are well understood, the level of safety of multihulls in breaking waves has been quantified, and a test method has been developed for investigating pitchpoling behaviour.

It is hoped that, through this attempt to quantify these capsize mechanisms individually, the industry will be prompted into further discussions of the influence of design on vulnerability to capsize.

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