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MARINE SAFETY AGENCY

CAPSIZE AND STABILITY OF SAILING MULTIHULLS

CONTENTS

1. INTRODUCTION

The following report describes a programme of work to study the stability characteristics and capsize behaviour of sailing multihulls, with the aim of improving on the simple method of assessment which is incorporated in the current Code of Practice.

The work was conducted broadly in accordance with Wolfson Unit Proposal No. 1635 dated 11th November, 1994, and was commissioned by the Marine Safety Agency on 10th January, 1995.

2. OBJECTIVES

A number of objectives were stated by the Marine Safety Agency in a project specification:

a. To examine a range of sailing multihulls, suitable for coastal or offshore voyages including catamarans and trimarans, and identify the occurrence, circumstance and mechanism of any stability casualty, together with the significance of the incident.

b. To determine the critical design features which influence each mechanism of capsize for each characteristic vessel type.

c. To recommend an appropriate measure of intact survivability and capsize safety and, if possible, suggest minimum acceptable levels.

d. To develop simplified instructions, for on board use, to increase the crew's knowledge of their level of safety while under sail and indicate measures to be taken by the skipper as particular circumstances are forecast or encountered.

3. BACKGROUND

Following the loss of the Marques in 1984 the Wolfson Unit was commissioned by the Department of Transport to investigate the stability of monohull sailing vessels. That programme of work provided a new level of understanding of sailing vessel stability and culminated in recommendations by the Wolfson Unit for the format of new stability standards, which were later adopted by the Department of Transport in their Code of Practice for Sail Training Vessels. A revised Code of Practice, applied to all small commercial sailing vessels, was published in 1993 and included a method of assessment for multihulls. The method was based upon a conventional approach to multihull stability, and the Marine Safety Agency became concerned that it might incorporate invalid assumptions or oversimplify the problem. It was considered necessary to ensure that both the methods of assessment and the applied standards were adequate for the purposes of the Code.

The monohull stability research had provided a simple means by which sailors could assess their level of safety from capsizing or downflooding whilst sailing, and it was hoped that this philosophy might be applied to multihulls.

In comparison with monohulls, multihulls have very high initial stability, as measured by the conventional righting arm, or GZ curve, but the curve reaches a peak at a lower angle and reduces to zero at around 90 degrees. If capsized the multihull is, for practical purposes, impossible to right and this fact has concerned multihull designers and sailors for many years. Considerable discussion has taken place between individuals with boundless enthusiasm for multihulls, and those who consider them unseaworthy, and the subject of multihull capsize was dealt with comprehensively in 1980, Ref. 1.

4. COMPILATION OF THE CASUALTY DATABASE

4.1 Data Gathering

It was considered fundamental to this study that a representative database be compiled, to identify the scale of the problem, and enable some statistical analysis of the causes of capsize. Several methods of gathering data were attempted, with varying degrees of success.

a. Books, Papers and Periodicals

Various items have been published on the subject of multihull capsizing. Some of these provided detailed incident reports while others gave brief mentions of casualties.

b. Organisations Contacted

Appeals for data were made to a number of organisations known to have been involved in the design, operation or regulation of sailing multihulls, or which might have their own casualty databases.

The Multihull Offshore Cruising and Racing Association (MOCRA) sent copies of two published accident reports, but were not willing to release any further information on the grounds of confidentiality.

No multihull casualty data are held by the Royal Yachting Association (RYA), or the Marine Accident Investigation Branch (MAIB). No detailed casualty records of vessel type are kept by the Royal National Lifeboat Institution (RNLI) or the Coastguard. The RNLI do however maintain a database of lifeboat launches which includes a category for sailing multihulls with engines. These have been incorporated.

No replies were received from the Polynesian Catamaran Association, the Multihull Association, the Royal Western Yacht Club, the International Yacht Racing Union (IYRU), the US Coastguard, the National Transportation Safety Board of Canada or the French organisations Ministry of Transport and Equipment, and I.C.N.N.

The Amateur Yacht Research Society (AYRS) sent copies of a number of their publications containing accounts of incidents.

The Convenor of ISO/TC188/WG22, an international committee currently considering the stability of small craft including multihulls, provided a list of those members who had expressed some interest in the subject. In addition to the U.K. members they included representatives from Japan, U.S.A., France, Sweden and the Netherlands, and an appeal for data was sent to them. One reply only was received, from the Dutch representative, who could offer no data. The Convenor also supplied copies of relevant papers which had been submitted to the group for discussion.

c. Designers Contacted

A letter appealing for data was sent to some 24 multihull designers, sailmakers and importers, in the U.K., the U.S.A., New Zealand, Denmark, Germany the Netherlands and France. Whilst replies were received from about half of these, and some reported incidents to one or more of their designs, requests for detailed information on yacht parameters and circumstances brought no further information. Some of the designers did provide their thoughts on the subject however, through correspondence or interviews.

d. Press Releases

Press releases appealing for data were sent to fifteen prominent journals which feature articles on multihull design, cruising or racing. Many of these were published, and they prompted a small number of enthusiastic contributions, some of them incorporating incident reports.

e. Appeals to Journals

Whilst the Wolfson Unit subscribes to a number of yachting journals, storage of back issues is limited, and it was hoped that the publishers of those and other journals might be able to offer relevant articles sourced from their indices. None were able to offer any information however, and one which had previously published a multihull capsize database did not refer to it in its reply.

Many of the people who were contacted referred to representatives of MOCRA and the IYRU, who were understood to have collected casualty data. No data were obtained directly from these representatives however. 40% of the casualties identified were listed in a previously published database, The Capsize Bugaboo, Reference 1. The remainder were collected from a variety of sources, and often a combination of sources. In some cases the same incident was reported in different ways in two or more journals or reports, and care had to be taken to ensure that an incident does not appear more than once in the database. For this reason the names of the yacht, its designer, class and skipper were all included in the database if possible, although they do not appear in the version presented herein.

4.2 Data Fields

It had been the intention that the database would include principal dimensions of the yachts and the type of accident, to enable any correlation between them to be identified. The number of yachts for which design data were available was too small to enable a meaningful study however, so only the length overall is included in the database.

The date of construction was included, if known, to enable an assessment of whether historical design trends have affected safety, but this information was available for only 13% of the entries. The date of the incident was included, and this was known in most cases.

The casualties were categorised according to the basic reason for, or the mode of capsize. The categories used are as follows:

Breaking Wave. Where the yacht was overcome by a large breaking wave, which alone was responsible for the capsize.

Wave. Where the yacht was reported to have been capsized by wave action, but no mention was made of the waves breaking.

Wave and Wind. Where the report indicated that some combination of wind and wave action caused the capsize.

Wind. Where the yacht was apparently carrying too much sail and the mean wind speed increased until the heeling moment exceeded the yacht's righting moment.

Wind Gust. Where a sudden increase in wind speed resulted in the heeling moment exceeding the righting moment.

Pitchpoled. Where the yacht capsized over its bow, normally as a result of sailing downwind and burying the bow of one or more hulls in a wave.

Reverse Pitchpoled. Where the yacht capsized over its stern, normally by a large wave when beating to windward.

Broached. Where broaching was reported as being a fundamental reason for the capsize.

Flooded. Where capsize occurred after one hull became partially flooded as a result of damage below the waterline or leakage through a hatch.

Obviously these categories are subjective and rely to a large extent on the eye witness accounts giving adequate details. In many cases (39%) there was insufficient information to enable categorisation, and some of the categories are bound to overlap, for example Wave and Wind with Broached.

If the yacht was known to be racing this was noted. If the yacht was known to be sailing this was noted, and in some cases the sailing speed was reported. If a drogue of some kind was being towed this too was noted in a separate field. These fields contain simply Y or N to indicate where the yacht was (yes) or was not (no) known to be racing, sailing or using a drogue as appropriate. A similar code was used to indicate when design parameters were known, with a P used to indicate that principal dimensions only were available.

To grade the environmental conditions, the wind strength was included in terms of the Beaufort Force, and in a few cases the wave height was also reported.

The source of the information was included as a data field, and a brief description of the circumstances of the incident was entered in the comments field. This includes any information which may be relevant, such as where the incident occurred, whether the yacht was racing, what sails were set, and any action taken by the crew.

The database does not contain any information on the outcome of the incident in terms of the survival of the yacht or its crew, as this was not considered relevant to the question of why the incident occurred.

Informative accounts of incidents can be found in References 2 - 8.

4.3 Data Gathered

The database is presented in Table 1. It contains information on 124 incidents, comprising 33 catamarans, 2 proas, 67 trimarans and 22 multihulls of unknown type.

4.4 Historical Distribution of Data

The earliest capsizes on the database were in 1964. The incidence of capsizes since that time is presented graphically in Figure 1. It is clear that the average number of casualties per year appears to have remained constant over the 30 year period, being about 1 catamaran and 3 trimarans per year.

The large number of casualties in 1979, a year in which many monohulls capsized in the Fastnet Race, appears to be coincidental, the incidents having occurred at various locations around the world. Two of those casualties occurred during the storm which caused problems for the Fastnet Race, one of them being in the same location. The same number of casualties occurred in 1994.

The lack of data between 1983 and 1986 inclusive may be due to the data gathering circumstances rather than a true lack of capsizes. The source which provided many early data was published in 1980, and the appeals for data have largely brought responses from people who have been involved in incidents during the last 5 years. The magazine 'Multihull International' was the source for some of the recent data, but only the back issues held at the Wolfson Unit were searched, and these extent back to 1987.

4.5 Length of Casualties

Yachts of less than 7 metres length overall were not included in the database. Such craft are normally sailed inshore or raced with safety cover, and the incidence of capsize is relatively high because the consequences are less serious. They were therefore considered to be outside the scope of this study.

The distribution of casualties in relation to their length is presented graphically in Figure 2. It shows the highest concentration between 7 and 11 metres. This may be due to the greater popularity of yachts of that size rather than their increased vulnerability, and it is thought to be likely that this distribution reflects that of the numbers of multihulls in use. Attempts to quantify the relative numbers of type and length of multihulls in use were unsuccessful. Neither the RYA or MOCRA could supply such data.

The discrete secondary peak at 18 - 19 metres comprises ten yachts of 18.3 metres (60 feet), a size which corresponds to the maximum allowable length for many ocean races. Seven of these were known to be racing when they capsized.

The distributions are virtually the same for catamarans and trimarans, and are not illustrated separately.

4.6 Types of Casualty

Where a yacht was known to be lying ahull or not sailing for some other reason, this is noted in the 'sailing' column of the database. Although this information is not known in all cases, it is notable that 14 of the trimarans were known not to be sailing when capsized, while there are no such records for catamarans. Six of the trimarans were known to have been capsized by breaking waves, and it is likely that some of the others were also. These data therefore suggest that catamarans are less vulnerable to capsize by breaking waves. In all, 9 trimarans were known to have been capsized by breaking waves compared with one catamaran.

To gain a broader picture of the proportion of yachts capsized by various means, the data are presented as pie charts in Figure 3.

The diagrams are substantially different, with a greater variety of casualty types for the trimarans. If it is assumed that the casualty types: wave and wind; wind; wind gust and pitchpoled, are all attributable to the wind, together they constitute 84% of the catamaran capsizes, but only 47% of the trimarans. This does not indicate that trimarans are less vulnerable to capsize by the wind because there are 47 trimaran capsizes in this sample compared to 25 catamarans. Rather, it implies that trimarans are vulnerable in more ways than catamarans.

4.7 Wind Strengths

The distributions of the catamaran and trimaran casualties with respect to the wind strength measured on the Beaufort scale are presented in Figure 4. The distributions are markedly different, with the catamaran capsizes occurring in winds up to Force 9, while many of the trimaran capsizes occur in higher winds. These data appear to support the indication that catamarans are most likely to capsize as a result of wind action when sailing, whereas trimarans are also vulnerable to large breaking waves, which are more likely to occur at the higher wind strengths.

The various sources which gave wind conditions did so in different ways. Many of the reports described the conditions as 'gale' or 'storm'. These have been categorised as Force 8 and 10 respectively, in accordance with the Beaufort scale, and these account for the particularly large numbers in these categories.

5. TRANSVERSE STATICAL STABILITY CHARACTERISTICS

5.1 Conventional Calculations

Traditionally the stability of the sailing catamaran has been determined by calculating the maximum righting moment. This occurs as the windward hull emerges from the water and is approximately equal to ½ B x Displacement, where B is the distance between the hull centrelines. This is readily calculated and acceptably accurate for most design purposes, although some refinements have been made and are discussed in Reference 9.

A similar calculation may be used for trimarans, where it is assumed that the leeward float supports the yacht, and the maximum righting moment occurs when the centre hull emerges.

Used without care, this simple calculation may be misleading since it provides only the maximum point on the stability curve, is likely to overestimate the value, and provides no information on the variation of stability with heel angle. The calculation utilises the assumption that the vertical centre of gravity, the trim of the yacht, and the shape of the hulls, have no relevance.

To investigate the magnitude of the effects of varying some basic parameters, stability curves were computed accurately, for the full range of positive stability, for a sample catamaran and trimaran. These yachts were already held as digitised computer files, having been used for a brief study of the subject, Reference 10. At 10.65 and 8.25 m in length respectively, they represent the smaller end of the scale to be addressed by the Code of Practice, but the trends indicated remain valid for all sizes of craft.

5.2 The Effects of Displacement

Figures 5 and 6 present stability data for the catamaran at three displacements. Whilst the GZ curve remains virtually unaffected by the displacement variations of ± 30%, the righting moment is changed in direct proportion to the displacement. A heavier displacement therefore increases a catamaran's ability to resist wind heeling moments, but does not affect its range of stability. It has a small effect on the angle of maximum GZ or righting moment because, at a heavier displacement and increased draught, the heel angle required for hull emergence is greater.

Figures 7 and 8 present equivalent data for the trimaran. The GZ curve is adversely affected by the increase in displacement. This yacht has relatively low buoyancy floats by current standards, and at the design displacement each float has a total buoyancy 13% greater than the displacement. With a 30% increase in

displacement therefore, the floats can each support only 87% and the centre hull will not emerge. The range remains unaffected. The initial stability is low for the light displacement case because the floats are not immersed.

The righting moment curves show how the displacement increase counteracts the reduction in GZ giving the heavier case a greater maximum righting moment. The example demonstrates however, that the stability of the trimaran is more complicated than that of the catamaran, and does not necessarily benefit from increased displacement.

5.3 The effects of Vertical Centre of Gravity

The vertical centre of gravity of a multihull is notoriously difficult to measure accurately by a conventional inclining experiment. GM values are typically several tens of metres and the inclining analysis, which relies on the difference between the measured GM and the calculated KM, may result in large percentage errors in KG. The assumption that the VCG has no effect is therefore very convenient for multihull assessment. Figures 9 and 10 present stability curves for the two yachts with VCG variations. The range investigated represents what could conceivably be achieved at the design stage of a cruising yacht, with control over the structure, rig weight and outfit.

The initial stability of the catamaran is so high that the VCG variation has negligible effect. The maximum value of GZ is adjusted slightly however, and the curve from that point to the angle of vanishing stability is altered substantially. The range of stability is reduced by an increase in the VCG. These effects are the same as they would be for a monohull, because the GZ value is reduced by the increase in the VCG height times the sine of the angle of heel. It is because the stability is normally calculated for a very small angle of heel that the VCG appears to have no effect. The same is true for the initial stability of the trimaran as illustrated in Figure 10, but the maximum value of GZ is affected to a greater extent because it occurs at a greater angle.

5.4 The Effects of Trim

Whilst sailing multihulls are normally operated at close to level trim for performance purposes, adverse loading conditions and sail forces can result in substantial trims, and some casualty reports include observations that the yacht was heavily trimmed at the time of capsize. This mode of capsize should not be confused with pitchpoling, where the yacht rotates about an athwartships axis taking trim to the ultimate extreme. A diagonal capsize is also a possibility, but the examples illustrated in Figures 11 and 12 address the transverse stability when trimmed.

Once again the catamaran is affected little by the variation, the only change to the stability being an increase in the angle of maximum GZ. The effects are more significant for the trimaran, and are dependant on the direction of the trim because the floats are located with their centre of buoyancy forward of that of the centre hull in order to resist the bow down trimming moment from the sails. A drastic reduction in stability occurs if the yacht is heavily trimmed by the stern.

5.5 The Effects of Beam

The beam of a multihull is fundamental to its stability when upright or at normal sailing angles. Figure 13 illustrates that it has little effect on the range of stability however. The stability is proportional to the separation of the hulls times the cosine of the heel angle, which of course decreases to zero at 90°. The angle of maximum stability is less for increased hull separation because of the reduced angle of emergence.

The same trends are illustrated for the trimaran in Figure 14.

5.6 The Effects of Volume

The merits of various hull and float forms have been the subject of much discussion in the literature. To determine the sensitivity of the transverse stability to their volume, two examples are illustrated in Figures 15 and 16.

The first presents data for the catamaran with the hull beam increased by 20%, while retaining the same separation. The GZ curve remains unaltered, regardless of whether the increased beam is used to support the same displacement, or the displacement is increased by 20% to retain the same draught. (In the latter case the righting moment will be 20% greater because of the increased displacement). This suggests therefore that differences in form do not have a significant effect on the transverse statical stability.

For the trimaran, Figure 16 shows the powerful effect on the maximum GZ of the larger float volume, although this represents a gross change, with each float's beam increased by 20% and its length by 25%. The total buoyancy of each float was thus 70% greater than the yacht's displacement. The range of stability remains unchanged.

6. LONGITUDINAL STABILITY

The occurrence of pitchpoling incidents prompted an examination of the longitudinal stability. This aspect of yacht stability is rarely considered for monohulls, and a survey of a number of designs indicated that the longitudinal GM is typically in the range 8 - 15 times the transverse GM for cruising monohulls.

The longitudinal stability of the sample catamaran is illustrated in Figure 17. In this case the maximum righting arm in pitch is greater than the maximum in the transverse mode, although the initial longitudinal GM is 25% lower than the transverse GM.

The relationship between the two stability curves is highly dependant upon the overall length/beam ratio of the yacht, which in this case is 1.7/1. Sailing multihulls are designed to a wide range of length/beam ratios from 1 to 3/1, with the lowest ratios generally applying to trimarans and high performance racing catamarans. It is notable that 75% of the pitchpoling incidents in the database are known to have occurred when racing. None are known to have occurred before 1980, when multihulls were generally narrower and slower.

The longitudinal stability will also be affected by variations in displacement and VCG, with similar results to those discussed with regard to transverse stability.

7. LIMITATIONS OF STATICAL STABILITY ASSESSMENT

Traditionally statical stability has been the characteristic used to measure the safety of water borne craft from capsizing, partly because of its ease of calculation and application. In theory it is limited to the provision of steady state forces or moments in calm water. The Wolfson Unit's research into the effects of gusts on monohull sailing vessels, Ref 11, concluded that those vessels do not respond dynamically to gusts of wind. Thus the conventional 'dynamic stability' approach used to assess the effect of beam winds and rolling on, for example, fishing vessels, should not be applied to sailing vessels. It is considered that the monohull yacht responds in a quasi-static way to a gust for two reasons:

a. A yacht rolls through a quarter of a cycle in response to a gust, and the gust rise time is of the same order as, or longer than, the yacht's natural roll period divided by 4.

b. With a particularly fast gust rise time, the aerodynamic damping of the sails prevents a sailing vessel from rolling significantly beyond the steady heel angle for the gust wind speed.

Thus the use of statical stability characteristics was extended to what is often thought of as a dynamic event.

It seems likely that the aerodynamic damping will have a similar effect on a multihull, and the typical multihull's natural roll period is very short in comparison with that of a monohull, so the multihull will also react in a quasi-static way. If this assumption is correct it is valid to compare wind heeling moments directly with righting moments to predict the angles of heel which will result.

The situation becomes somewhat more complex when wave action is involved, and apparently a substantial number of the casualties were affected by waves. In the most extreme cases the yachts were rolled by very large breaking waves. In others, capsizes appear to have resulted when the yacht rolled in response to a large beam sea while sailing, whilst in some cases the yacht broached when running downwind and capsized subsequently with a combination of wind and wave action. The first of these has been demonstrated, in the case of monohull sailing yachts, Ref 13, to be a completely dynamic situation, where the statical stability properties govern the behaviour of the yacht after the passage of the breaking crest but have little or no influence on the capsize resistance. There is no reason to believe that multihulls are different in this respect.

In the second case, where a beam sea causes the yacht to roll, if the wave is of low frequency and smooth crested, the multihull will follow the surface slope in a quasi-static way with no truly dynamic rolling, or heeling beyond the instantaneous static equilibrium. Between the extremes of a long ocean swell and a steep breaking wave there must be some transition zone where dynamics begin to have some effect.

The broaching scenario is perhaps a special case, which may occur on either a broken or an unbroken wave, where the behaviour of the yacht in the period leading up to the capsize will differ from that of a yacht sailing in beam seas, but might not affect the end result.

8. THE EFFECTS OF WAVES ON STABILITY

It has been suggested by many individuals that waves affect multihull stability in some way. An attempt was made in Ref. 12 to quantify the effects of windage and inertia when rolling in beam seas. The paper presents calculations of the angle to which a multihull would roll, assuming an initial roll velocity imparted by a wave, and balancing the inertia against the righting moment to predict the possibility of capsize. Results presented therein suggest that trimarans are vulnerable to capsize as a result of such wave rotation.

The effects may be divided into two distinct types, quasi-static and dynamic.

a. Quasi-Static Effects

With a multihull positioned beam on to a long ocean swell, the high GM and short roll period enable the yacht to follow the surface of the wave. Results of Froude's experiments, published in 1861, demonstrated that in such circumstances, the weight and buoyancy forces always act in a plane normal to the local wave surface. This phenomenon results from the orbital motion of the water particles during the passage of a wave, and the corresponding motion and accelerations of the floating body. The implications for stability are that the multihull will be in a momentary state of stable equilibrium, with no righting moment, when it is at the angle of the wave surface. Its GZ curve will maintain the same magnitude and range but with the heel angles adjusted by the wave slope. Figure 18 illustrates the effect for a catamaran on a wave with a maximum slope of 10°. These effects will be transient with the passage of beam seas, and are unlikely to influence the way in which the yacht is sailed. The same effects will apply in pitch, when a yacht is in head or, more appropriately, following seas.

b. Linear Dynamic Effects

With progressively reducing wavelength, true dynamic effects may become increasingly relevant. It is normal to represent the responses of a vessel in waves in terms of their response amplitude operators (RAO's). These are the responses rendered non-dimensional with respect to the waves. The roll, heave and pitch RAO's for multihulls will be of the form illustrated in Figure 19. At low encounter frequencies the responses will be matched to the wave, that is the yacht's heave will be equal to the wave height and its roll angle will be equal to the wave slope in beam seas, or its pitch equal to the maximum wave slope in head or following seas. These are the quasi-static effects described above. A long ocean swell is a low frequency wave.

With an increase in the encountered wave frequency, as a result of shorter wavelengths or a change of speed, the responses may increase to some extent until the resonant frequency is encountered. With RAO values in excess of 1 the yacht will roll or pitch to greater angles than the wave slope, and may heave by more than the wave height. Computer predictions of such responses for powered catamarans have indicated maximum RAO values of 1.5 for the roll response in beam seas, and in excess of 3 for the heave and pitch responses in head seas. These values are highly dependant on the vessel's inertia, and on its hull form and speed, both of which influence the hydrodynamic damping.

If the encounter frequency increases further the responses decrease, the vessel being unable to respond quickly enough, until they become negligible as in the case of capillary waves or ripples. The vulnerability of a vessel to being rolled over by an unbroken wave, or a series of similar waves, will depend upon the magnitude of the RAO. Uncomfortable or hazardous synchronous rolling has been reported for a number of vessel types, but is not known to be a problem for multihulls. It is possible however, that the roll response to a particular wave may be sufficient to increase the heel angle, with the aid of wind heeling, beyond the angle of maximum GZ, and hence into a region of uncertain stability.

No data have been calculated or measured to determine the responses of sailing multihulls, and the magnitudes of the RAO's cannot be estimated reliably. It is worth noting the common claims of designers that the 'hobbyhorsing' behaviour, which was characteristic of many early multihull designs, has been eliminated. This uncomfortable pitching motion was the result of a large RAO value at a common encounter frequency. In order to have reduced the tendency, the recent designs must have lower RAO values or a resonant frequency not often encountered. The former is more likely, and with considerable debate and progress being made in the design of multihull bow and stern shapes, it is assumed that pitch damping characteristics have been improved.

c. Non-Linear Dynamic Effects

The responses remain linear, that is proportional to wave height or maximum slope, for a range of wave conditions. In severe conditions or at high speeds however, the responses will become non-linear. This will occur for example, when discontinuities in the hull become submerged, a hull emerges, or substantial spray is produced. Slamming of a hull or bridge deck is a typical non-linear response.

Short steep waves, associated with wind against tide conditions or overfalls, are likely to result in non-linear responses, as are waves with breaking crests which are common in winds above force 5. Large breaking waves will give extreme examples of non-linear responses.

The magnitudes of these non-linear effects are notoriously difficult to predict, but it is feasible that the assumptions used in Ref. 12 to predict propensity for capsize by wave rotation, which include a very fast initial roll rate, could be valid in such circumstances.

9. WIND FORCES AND MOMENTS

9.1 Conventional Calculations

For stability purposes the wind heeling moment when upright is calculated using the formula:

$$HM = \frac{1}{2} \rho V^2 CAh$$

where $\frac{1}{2} \rho V^2$ is the wind dynamic pressure, C is the heeling force coefficient, A is the sail area and h is the height of the centre of effort.

Variations in the definitions of A and h are common, for example depending on whether the sail area includes the mast and topsides, the full headsail area or the foretriangle area neglecting any overlap with the mainsail, and whether h is referred to the waterline, half the draught or the centroid of the underwater lateral area. Further variations are common in the choice of C, and the values 1, 1.2 and 1.5 have all been used, in Refs. 12, 14 and 15 respectively.

Various wind tunnel test programmes conducted by the Wolfson Unit on modern rigs have demonstrated that coefficients of around 1.8 are likely, and that they may be as high as 2 in some cases.

9.2 Upright Sail Forces

With the aid of wind tunnel test data on sailing rigs, and a VPP (sailing yacht performance prediction) program developed by the Wolfson Unit, two examples of hypothetical multihulls were studied. The aim of these calculations was to illustrate and quantify the variations in sail forces which might be experienced on a multihull, and highlight the differences between a high performance yacht and a more sedate cruising yacht. The yachts were assumed to have the same rig so that common sail coefficients were used, and all calculations were for a wind speed of 15 metres/second (Beaufort force 7).

Figure 20 shows the assumed variation of speed with true wind angle. Multihulls sail fastest in beam winds, and this is reflected in the examples.

Figure 21 reveals the variation of apparent wind speed, compared to the true wind speed, at a range of true wind angles. It is clear that when sailing downwind, the apparent wind speed is substantially lower than the true wind speed.

In the cases assumed, at 160° to 180°, the apparent wind speed is 25% and 37% lower than the true wind speed. The true wind speed can therefore be underestimated by a substantial amount, particularly in performance multihulls. If we take as a basis the apparent wind speed which is that measured directly on board, the true wind speeds in the examples are 34% and 60% greater. The true wind pressures which would be experienced by a stationary yacht, being proportional to the square of the wind speed, are correspondingly higher by the factors 1.8 and 2.5. The variation of true wind pressure/apparent wind pressure with wind angle is presented in Figure 22. This result is fundamental to the problem of pitchpoling, where a yacht sailing downwind is stopped by a sudden increase in resistance after the bows become immersed in a wave, and the apparent wind speed quickly increases to the true wind speed.

When sailing upwind the boat speed combines with the true wind speed to increase the apparent wind speed. The true wind pressure is therefore less than the apparent wind pressure, and again the faster yacht shows a greater variation. When sailing upwind therefore, being stopped by a wave is not such a dangerous scenario since the sail forces will decrease. When sailing with the true wind just aft of the beam the boat speed has only a small effect on the apparent wind speed.

Figure 23 illustrates the relationship between the true and apparent wind angles. When sailing close hauled or dead downwind the apparent and true wind angles are similar, because the yacht speeds are relatively low and the angle between the vectors is small. When sailing in beam winds the relationship is very dependant on boat speed. The higher the speed, the lower the apparent wind angle.

The data in Figures 20, 21 and 23 are intimately linked, and given three of the variables the remaining two can be calculated. Thus, on a yacht equipped to measure boat speed, apparent wind speed and apparent wind angle, the true wind speed can be determined. Because the relationships depend on the performance of the yacht however, they are difficult to estimate or predict.

Figure 24 presents the variations of the sail force, resolved into the components of driving and heeling force, for the range of true wind angles. The driving force is consistently lower for the faster yacht because, at large wind angles the apparent wind speed is lower, and at low wind angles the apparent wind angle is lower. The yacht is faster because of its lower hydrodynamic resistance. The driving force is considerably higher when reaching than when beating or running downwind.

The heeling force peaks at about 60° and reduces dramatically with increasing wind angle. Multihull sailors may make use of this feature by bearing away in gusts to reduce the heeling moment. During tests in the wind tunnel the heeling moment has been measured while the sheets are progressively eased. When the sails are fully eased the heeling moment typically is half the value obtained with the sails driving effectively.

If a yacht sailing downwind is broached therefore, the heeling force will not increase in accordance with the curves shown in Figure 24 but to about half the value. Thus if a yacht is broached and turns 90° to the wind, the heeling force is likely to increase approximately to twice the level of the driving force prior to the broach. Since the transverse and longitudinal righting moments may be similar, if the yacht was being driven close to the limit of its longitudinal stability, the broach could have serious consequences.

The ability to ease sheets quickly is important for a multihull when a gust strikes. The heeling moment can normally be reduced by half, but a feature of many multihull rigs is the aft location of the shrouds, which often prevents the mainsail from being eased, by restraining the boom and the sail battens.

9.3 Variations with Heel Angle

The effect of heel angle on the heeling moment is often neglected because only small angles of heel are considered. It may be adjusted by a cosine or cosine^2 factor to take account of the heeled rig, and may include an estimate of the bridge deck windage when heeled. The variation of heeling moment with heel angle which was derived for monohull sailing vessels, discussed in Ref. 11, will not be valid for multihulls, as there are two significant effects particular to the multihull configuration.

Because the axis of rotation is in the leeward hull, the height of the rig initially increases with heel angle, and the centre of effort may increase in height until it is vertically above the point of rotation, typically at an angle of about 30 degrees.

The broad streamlined shape of a cruising multihull may provide an efficient lifting surface, and the aerodynamic forces on it are more variable with heel angle than on a monohull, which more closely resembles a cylinder. The lift generated by flow over the large coachroof and deck area may result in a significant contribution to the heeling moment, since the centre of pressure is likely to be near the windward side well away from the centre of rotation. Wind tunnel data described in Ref. 16 revealed that the maximum heeling moment for a passenger catamaran with a large superstructure occurred at around 40 degrees, and was about twice the upright value. The authors suggested that the heeling moment at a heel angle, θ could be approximated by the formula:

$$HM_\theta = HM_{upright} (1 + \text{Sin } 2\theta)$$

This formula may not be applicable to sailing multihull structures, particularly those without complete bridge decks, but it is likely that the maximum heeling moment of the structure will occur at an angle greater than that at which the maximum righting moment occurs, and that it is more dependant on the shape and plan area of the deck than the profile area.

Consider a fully decked cruising catamaran of length 10 metres and beam 4.5 metres, in a wind of 10 metres/second (Beaufort force 5). If a lift coefficient of 0.5 is assumed the vertical lift on the yacht would be 0.15 tonnes, around 5% of the displacement. This would increase to 12% in force 7 and 25% in force 9. These figures should come as no surprise when one considers that the plan area of a fully decked multihull is normally greater than the sail area. Such forces, being centred near the windward side, will significantly affect the stability.

When at 90 degrees of heel, a beam wind on the underside of the bridge deck will result in a heeling force coefficient of about 1 and the heeling force could therefore be similar to that of the sails when upright.

The effects of heel angle therefore depend on many variables, and predictions are unlikely to be accurate. It may be adequate to assume that the heeling moment remains constant with heel angle, but even this may be an under-estimate.

In an attempt to quantify some of the above effects the following assumptions have been made:
The heeling force coefficient of the sails is 1.8.
The sail area reduces with heel angle as a cosine function.
The centre of effort height of the sails varies with heel angle in accordance with the function:

$$h_\theta = h_o \cos\theta + \frac{B}{2} \sin\theta$$

The bridge deck and hull structure generates a heeling force with a coefficient of 1 centred at the yacht centreline.

These assumptions lead to the following equation, which gives estimates of the heeling moments due to the sails and the deck.

$$HM = \tfrac{1}{2}\rho V^2 \left[1.8\ S\ \cos\theta \left(h \cos\theta + \frac{B}{2} \sin\theta \right) + D \frac{B}{2} \sin^2\theta \right]$$

where, HM = heeling moment at any heel angle, θ
S = sail area
h = centre of effort height
B = beam of yacht between hull centres
D = plan area of the hulls and bridge deck

Figure 25 presents an example of this function, with the sail and deck components identified, for a hypothetical fully decked catamaran with the following properties.

S	=	50 square metres	h	=	4.5 metres
B	=	6 metres	D	=	60 square metres

The heeling moment curve used for sailing monohull assessment is shown for comparison. The important features of the total moment curve are that it reaches a maximum at some angle other than upright, and that the moment at 90 degrees is substantial.

As stated in the previous section, wind tunnel test results have shown that the heeling moment is highly dependant on sail sheeting but, even with the luffs of sails backwinded, the heeling moment cannot be reduced to less than half the maximum value. Nothing can be done by the crew to reduce the heeling moment of the bridge deck. The ability to reduce heeling moment, for example in response to a gust, is therefore limited. Figure 26 illustrates the range of the total heeling moment which is available with sheet control. Note that the upright heeling moment can be reduced by a factor of 2, but at 90 degrees of heel no reduction is possible.

For clarity the total moment curves are reproduced with a righting moment curve in Figure 27. The yacht will sail at a heel angle corresponding to the first intersection of the heeling and righting moment curves. At this point the yacht is in a state of stable equilibrium. If a gust is anticipated the sheets may be eased, the heeling moment will decrease, and the heel angle will reduce accordingly.

Figure 28 illustrates the danger of underestimating the strength of a gust, or carrying too much sail. With a heeling moment greater than the maximum righting moment there is no intersection of the curves and no angle of equilibrium. If a yacht is heeled beyond its angle of maximum stability, that is with the windward hull emerged, the sails must be eased quickly to reduce the heeling moment to a value lower than the righting moment at that angle. In the example illustrated, the wind has increased such that there is no angle of equilibrium. The yacht cannot sail at angle B. The yacht would capsize with the sails sheeted in, but if the crew ease the sheets fully when they have heeled to 20 degrees the yacht will have a margin of righting moment over heeling moment and will recover to point A, in stable equilibrium.

Racing multihull crews use this ability to their benefit by sailing with the windward hull emerged when possible. They are operating between points B and C on the example, and are in a state of unstable equilibrium. They are able to maintain this attitude by sheeting and steering to control the heeling moment, and aim to sail with the windward hull just clear of the water for maximum efficiency. If they allow the heel angle to exceed point C they can do nothing to reduce the heeling moment and will capsize.

10. BEHAVIOUR IN BREAKING WAVES

The database lists a number of trimaran capsizes resulting from encounters with breaking waves, but only one such catamaran casualty. Experience gained by watching models capsizing in breaking waves has led to a good understanding of the capsize mechanism.

The waves required to cause such capsizes are typically greater than 5 metres high and can impart a very large amount of energy to the yacht. The breaking crest of the wave is a body of water moving at a speed equal to or greater than the speed of the wave, unlike the water in an unbroken wave crest, which has little forward motion. If the breaking crest is big enough its impact will accelerate the yacht and, depending on its presentation to the wave, it may surf or slide sideways on the wave face. If the resistance to motion down the wave face is high, the continued force of the moving crest will rotate the yacht. The keel of a monohull sailing yacht prevents sideways motion and the yacht is rolled to a large angle on the wave face. Narrow, deep hull forms may slide sideways in this attitude whereas wide shallow forms tend to immerse the deck edge. This increases the resistance again and causes them to rotate further.

Multihulls tend to be light compared to monohulls of the same length and will therefore accelerate readily. Their low resistance enables them to surf on the wave face if they are heading downwind. The behaviour of a multihull struck on the beam will depend on its hydrodynamic resistance. Most multihulls do not have fixed keels to restrict sideways motion, but the one catamaran casualty in the database had been fitted with fixed keels by the owner. Lifting keels are often fitted, but are not likely to be lowered in severe conditions.

Catamarans have considerable reserve buoyancy in the hulls and because they remain level with respect to the wave surface, the deck edge is unlikely to become submerged. Model tests on a large catamaran motor yacht, which were commissioned by the designer, demonstrated in that instance the resistance to capsize by a breaking wave. The breaking crest struck the windward hull and the catamaran heeled to the steep wave slope. Having a high displacement compared to a sailing multihull, the model did not accelerate to the speed of the wave and the crest passed beneath the windward hull. It then struck the leeward hull, causing a second acceleration, and a rotation of the model to windward, thus arresting or reversing the roll induced by the first impact. Whilst this behaviour might not be representative of a sailing catamaran, it demonstrated significant differences in behaviour between catamarans and monohulls.

Trimarans have relatively little reserve buoyancy in their floats, even those with relatively large floats have a reserve buoyancy only of the order of the yacht displacement in each float. This compares with cruising catamarans which have reserve buoyancy in each hull of the order of 10 times the yacht displacement. When a trimaran is struck on the beam by a breaking crest it is accelerated sideways and the windward float is lifted by the crest. The leeward float becomes depressed and its deck edge may be submerged. The increased resistance to sideways motion reacting against the impact generates a large couple because of the high maximum beam of the trimaran. Further rotation causes greater immersion of the leeward float, and after the wave crest passes beneath the windward float it will impact on the main hull, and a heeling moment will be retained. The higher incidence of trimaran capsizes in breaking waves is considered therefore to be a valid reflection of their vulnerability.

It must be stressed that the waves which have sufficient height to cause yacht capsize, generally similar to or greater than the beam of the vessel, unleash enormous amounts of energy when they break. Differences in design, be they hull form, centre of gravity, weight or inertia, become insignificant in their ability to reduce capsize vulnerability once the situation has arisen. The monohull designer can provide a good chance of recovery from capsize by ensuring the yacht has a large range of stability, but this is not possible with a multihull. The important conclusion therefore, particularly for trimaran sailors, is not to allow the yacht to be presented beam on to a large breaking wave. The light weight and low resistance enables multihulls to travel relatively fast, even under bare poles in severe conditions. The high speed can become hazardous with potential for pitchpoling or broaching, and the motions and accelerations can become a problem. The technique of running before a gale can be successful if the helmsman has sufficient competence, stamina, and sea room.

In severe or prolonged bad conditions it may be preferable to slow the yacht by towing a drogue or warps, or to present the bows to the waves by rigging a sea anchor. Reference 8 lists seventy reports of vessels using such devices in hazardous conditions, including 8 trimarans and 4 catamarans towing drogues, and 13 trimarans and 12 catamarans using sea anchors from the bows. These personal accounts of severe weather tactics provide a convincing basis for the recommendation that all multihulls venturing offshore should be equipped with an effective sea anchor, the means to bridle it from the bows of the floats, and sufficient nylon warp to enable it to be streamed well upwind.

11. CATAMARAN CHARTERING - A CHARTERER'S EXPERIENCE

A Fountaine Pajot 37' Antigua cruising catamaran was chartered from a specialist multihull company by a group including Ian Campbell, a Wolfson Unit engineer. The charter was during a week in June 1995 from Portsmouth. The cruising limits were from Brest to the Elbe, as are standard in insurance policies. The catamaran was privately owned and the charter company acted as an agent. The inventory included all navigation and safety equipment and was checked by the charter company and the charterer before departure. No tuition was given in the operation of the boat but it was understood that instruction was normally given in handling the boat under power.

The Antigua 37 was a modern performance cruising boat equipped for 10 people, but more suited for 6 to 8 people. It had a high freeboard under the bridge deck, a streamlined bridge deck saloon midships with a netting trampoline forward to the bows and standing headroom in the hulls. The rig consisted of a fixed mast stayed with single aft swept shrouds, a fully battened mainsail and a roller furling mast head jib. A spinnaker could be set from the masthead and the halliard and reefing winches were attached to the mast. There were two main sheet winches in the cockpit with all sheets led through rope jammers. The main sheet was led to a traveller track which extended across the full width of the boat, at the back of the cockpit.

The navigation equipment included a GPS navigation set, a boat speed log and full wind instruments that could display both true and apparent wind speed and direction. The ship's manual gave instructions for reefing, with the required number of reefs in the main and furls in the jib based on the apparent wind speed. There was also a direction not to carry the spinnaker in more than 15 knots of true wind and a monograph was provided to enable the true wind speed to be calculated from the apparent wind speed and direction and the boat speed, although the true wind facility on the wind instruments rendered this unnecessary.

The charterers were a group of experienced sailors, two of whom had RYA Offshore Yachtmaster's Certificates, but with very limited multihull experience. The charter company accepted the charter without raising any queries. The planned and completed cruise was from Portsmouth to the Isles of Scilly and back via Alderney. This comes within the constraints of Category 2 as defined by the Code of Practice. Approximately 550 miles were logged under sail and power, including two night passages. According to the ship's log, this was the most extensive cruise undertaken in the boat over the previous two years, and many previous charterers had not ventured beyond the Hampshire coast. The wind conditions were generally light to moderate from the north giving slight seastates but the Channel crossing to Alderney was made in a southwesterly wind of force 6 to 7 in poor visibility and a rough sea.

The boat did not sail particularly fast in the conditions experienced, averaging 6 to 8 knots on the passages, and it was felt that it only started to sail well when the apparent wind speed exceeded 15 knots. The boat speed could be increased to 10 knots and higher with the spinnaker set in winds close to the maximum limit of 15 knots true. On the passage to Alderney bursts of speed of up to 15 knots were achieved by surfing down wave fronts, even though the rig was reefed as required. Both the log and the wind instruments worked well and were used to aid the sailing and to judge when to reef or take down the spinnaker.

Both the steering and sail handling systems on the boat gave problems, which were mainly attributable to poor quality fittings that had worn. The wheel steering had a stiff notchy action at one part, that felt like a broken gear tooth, and the rudders vibrated badly when loaded at the higher speeds, possibly due to the wake from the fixed bladed propellers. This made it difficult to steer the boat precisely. The mainsail traveller would not move down when its control line was eased until the mainsheet was also eased, because of the friction in the blocks, so it was difficult to adjust the main sail sheeting quickly. The jammers for the mainsail reefs were stiff to operate so it took longer to take in a reef than was necessary. These problems may have had more serious consequences had the wind and sea conditions been more onerous than those experienced. The charter company encouraged the reporting of defects and the above were all described to them in detail at the end of the cruise.

Although the boat was relatively easy to sail it was difficult to sail fast. The spinnaker was set on several passages and it took some time to work out the best sheeting arrangements to keep it flying and the boat moving. The reefing requirements were followed and the windward hull never lifted up by more than half its draft when the boat felt pressed.

The rough passage to Alderney was sailed in quartering and beam seas with white capping on the waves and estimated wave heights of 3 metres. No other yachts were seen on passage. Both the pitch and roll motions were quite sharp, causing sickness in two crew members, but it was possible to stand in the cockpit whilst holding on, although more handholds would have been desirable. The cooker did not have fiddles and pans tended to jump off. Objects on the table also jumped off when waves struck the underside of the bridge deck. The jib roller furling worked from the cockpit and it proved relatively easy to adjust the amount of sail furled. The mainsail could not be eased out very much further than the end of the traveller without the battens starting to bend around the shrouds and, if the boat was sailed down wind and wave, the jib became blanketed and the speed dropped. It was generally possible to steer the boat in the desired direction although the worn steering gear inhibited control. There was no tendency to broach but some waves knocked the boat off course.

Although only a single instance, this experience is assumed to illustrate the low level of experience required, and instruction offered, by a charter company. It was stated that the yacht complied with the current code of practice, and in general the yacht was adequately equipped. Realistic sail setting instructions were supplied, and were used by this crew. The charterer company's claims for the yacht's performance were not borne out, but perhaps this does not concern the typical crew, since they apparently undertake relatively modest voyages, in this case confined mainly to the Hampshire coast. Whilst it is understandable that, for commercial reasons, a charter company will want their yacht to be assigned a category offering wide cruising possibilities, their clients might not be inconvenienced by a more restricted category. Few charterers are likely to require a yacht to undertake Category 0 or 1 voyages.

12. DEVELOPMENTS WITH MODEL MULTIHULLS

12.1 Background

In response to our requests for information, Andy McCulloch, a member of the British Model Multihull Association (BMMA), sent several articles and photographs relating to his, and other sailors, experiences sailing model multihulls. In addition to this information Andrew Claughton of the Wolfson Unit attended a BMMA meeting held in Poole Dorset on 17th June, 1995.

12.2 Model Dimensions

The models sailed by the BMMA members are a scale version of a Formula 40. The dimension limits are:
LOA 1.2m.
Maximum Beam 1.2m
Maximum Sail Area 0.9m^2

Within this framework both catamarans and trimarans are designed and the all up sailing weight of the models is 2.5 to 3.5 Kg.

In winds over about 10 knots the sailors use reduced height rigs with less sail area, in fresh conditions of about 15 to 20 knots the sail area is reduced by approximately 50 %.

12.3 Experience with Model Multihulls

Based on the articles supplied by Andy McCulloch and observations made during the meeting at Poole The following are the main points of interest that arose.

The mode of capsize for the trimarans is either a capsize rotating about the main hull centre line or a pitchpole over the leeward bow.

When the boat is hit by a gust when beating to windward, or sailing on a close reach, the helmsman can manoeuvre the boat to try and avoid capsize by easing the sheets slightly and luffing up a few degrees. This technique momentarily reduces the heeling load from the sails, and the turning of the boat reduces the effect of the aft shift of apparent wind angle as the gust strikes. This technique allows the model a fraction of a second to gather speed as the gust strikes. Using this technique it is possible to keep the boat sailing fast in a gust that would have resulted in a capsize if the rudder and sheet controls had been held fixed.

When these types of model were first sailed the sailors had considerable difficulty in racing in any strength of wind due to the frequent capsizes. The ability to sail these models reliably has been improved by two factors:

a) Reducing the all up weight of the model from 3.5 to 2.5 Kg. This has two effects, firstly it allows the boat to accelerate more quickly so that the floats can generate dynamic lift to counter the overturning effect of the sails; and secondly it allows the main hull to fly clear of the water without burying the lee hull. This means that the model can heel as the gust hits, to reduce the power from the sails, without deeply immersing the lee hull which causes an increase in drag that causes the boat to pitchpole.

b) Even with the lighter weights the problem of capsize is still present and the largest factor in making the model multihulls capable of being sailed in strong winds and gusty conditions is the addition of a horizontal foil to the bottom of the rudder. When the model is hit by a gust and the driving force of the rig increases, the model trims down by the bow. This causes the fin to have an angle of incidence to the flow, and the foil produces a downward thrust which counters the bow down trim moment from the rig. Under the influence of these foils the models become much more docile, and their sailing performance in gusty conditions with a skilled helmsman is very impressive, particularly in smooth water: As the gust hits, the model heels slightly and the lee bow dips, but as the model gathers speed it recovers a level trim, seeming almost to be flying on the rudder foil. This profound difference in behaviour was amply demonstrated during observations of the models at Poole where a heavy foil-less trimaran could not be kept upright at all, whilst a similarly canvassed light model with rudder foil could be sailed reliably around a triangular course.

12.4 Application to full size multihulls

The proportions of these model sailing multihulls are such that they do not represent scale models of common full size vessels.

	1	1:10	1:15
LOA (m)	1.2	12	18
Beam (m)	1.2	12	18
Displ (min) (Kg)	2.5	2500	8438
Displ (max) (Kg)	3.5	3500	11813
Sail Area (m^2)	0.9	90	203

The model multihulls have lower displacement/length ratios and higher sail area/displacement ratios than most full size multihulls, with the exception of the open 60' class. Their performance, particularly their acceleration, therefore will not be representative.

At full scale the force required to prevent pitchpoling might pose problems with the mounting of the foil, although these could presumably be overcome. It is understood that an ocean racing trimaran incorporated such a device, but the fact that others did not follow suit suggests that it was not a worthwhile route of development. The foil's effect is to hold the stern down when the model is struck by a gust, enabling it to accelerate forwards without burying the bow. It would be of no benefit to a yacht which is suddenly stopped by plunging its bows into a wave.

13. SUMMARY

The casualty database provided insufficient data for a detailed analysis of specific capsize mechanisms, but the derived statistics support our current understanding of the level of vulnerability to the various modes of capsize.

The particular vulnerability of trimarans with small floats is now recognised by most people in the industry, and requirements for large float volume should be acceptable to them. Whilst particular refinements to hull form or float geometry may influence the performance and seakeeping, they do not alter the basic stability properties and their relationship with heeling moment. Provided the hulls and floats have sufficient reserve buoyancy, it is not considered necessary to regulate their shape, although trimaran floats with their LCB aft of that of the main hull should not be permitted.

Most multihulls are claimed to have far superior sailing performance than equivalent monohulls, but if stability limitations are considered rationally in terms of safety from capsize, the cruising multihull may need to reduce sail to the extent that it becomes only marginally faster than the monohull. All multihulls may be capsized given sufficient wind strength, but it is possible to ensure that this likelihood is minimised by conservative rig sizing, and proper considerations of those parameters which affect the stability. If performance requirements demand a large rig, the onus for safety is passed from the designer to the crew. They will require a good understanding of the transverse and longitudinal stability limitations, and sufficient information to enable them to assess their level of safety under sail. They will need information on the relationship between the righting and heeling moments for a range of working sail plans, and when running downwind they will need to know the true wind speed, their vulnerability to pitchpoling if stopped, and to capsizing if broached.

Since the code of practice is to be applied to a range of commercial vessels including bareboat charter yachts, it should be assumed that the crew may have limited knowledge and experience of multihull sailing. The provision of information for their use should therefore incorporate suitable safety margins and be straightforward in its presentation.

The calculation of transverse stability is straightforward, using either an equation which gives a good approximation, or a suitable computer program. The difficulty with multihulls is in determining the centre of gravity height, a problem which was outside the scope of this study. Without an accurate value for this parameter the maximum righting moment can be found with acceptable accuracy but the range cannot. This appears to have been accepted by the designers as a satisfactory situation, but there is no doubt that most cruising multihulls could be arranged to have lower centres of gravity without too much difficulty, if the

incentive were there. The yacht described in section 11 for example, had large fresh water tanks high in the bridge deck structure. Such features are presumably incorporated in the belief that the stability is so high that their effect is negligible. There is however, considerable benefit in maximising the range of stability, since a larger range may increase the time available for the crew to release sheets, and will enable the yacht to recover from greater angles of heel when such action has been taken, or when a gust has passed.

Since the longitudinal stability may be less than the transverse stability, it should be calculated for a direct comparison, since the danger of pitchpoling is greater for a yacht which cannot resist the same moment in pitch as it can in roll. The limiting wind speed for a particular sail plan should be based upon the lower of the two righting moments. It should be appreciated that the yacht's length may be substantially greater than the beam, yet the GM in pitch less than that in roll because it is dependant upon the second moment of area of the waterplane about the axis of rotation. The transverse GM is particularly high because all of the waterplane area is remote from the axis.

Wind tunnel data give a good indication of the maximum likely heeling moments of the rig, and we know from Ref. 11 that a gust factor of 1.4 (twice the wind pressure) should be allowed to take account of the fluctuations of speed in the atmospheric boundary layer. This may be balanced by the fact that the sheets may be eased by an alert crew, to reduce the heeling moment by up to 50%, but many capsizes have been blamed on the fact that the crew were inexperienced in multihulls, or sheets were cleated. What we do not know is the effect of the hull and bridge deck structure on the heeling moment, particularly at the critical angles when the righting moment is at or beyond its maximum value.

The dynamic effects of gusts are believed to be negligible, but other dynamic effects may be important. The effects of short, steep waves in particular give some cause for concern, and their effects have not been quantified. Several of the sailors interviewed stated that the seastate has considerable influence on the comfort and safety of a multihull, and that drastic sail reductions may be required as seastate increases. The danger of pitchpoling in steep seas is well understood, but their effect on rolling is not certain.

The dangers of capsize in extreme seastates must be addressed for those yachts certificated for operation in the offshore categories. The relatively high windage and low resistance combine to give high speeds in extreme conditions, even under bare poles. To enable the yacht to remain under control, and offer the crew a comfortable refuge, a drogue may be deployed. This may not prevent broaching in very large breaking waves however, and a more reliable device has been found to be an effective sea anchor bridled to the extreme forward ends of the hulls or the trimaran floats.

14. RECOMMENDATIONS

14.1 Stability Assessment

14.1.1 The stability of a catamaran may be computed accurately or estimated using the formula:

$$\text{Righting Moment} = \text{Displacement} \left[\frac{B_{CL}}{2} \text{Cos}\,\theta - (\text{VCG} - \text{VCB})\,\text{Sin}\,\theta \right]$$

where B_{CL} is the beam between hull centres, and the displacement, VCG and VCB are calculated. This is a good approximation to the true curve for angles equal to or greater than that of maximum righting moment or GZ.

14.1.2 The stability of trimarans should be calculated from a computer definition of the lines and a calculated VCG.

14.1.3 The pitch stability should be calculated for comparison of the maximum righting moment with that in heel. The lower of the two should be taken as the limiting stability.

14.1.4 Sail forces and moments should be calculated assuming a force coefficient of 1.8.

14.1.5 Gust forces and moments may be assumed to be balanced by the ability to ease sheets, but for the purposes of the proposed code such action cannot be assumed. The safety factor may also need to take account of the dynamic effects of waves. In the absence of quantitative information on this aspect, a combined safety factor of 2.0 on wind pressure is suggested. Since this incorporates the maximum possible gust factor (with the exception of squalls), and is applied to the maximum likely heeling force coefficient, it will normally allow a margin for dynamic effects.

14.1.6 Sail area limits should be provided based on the true wind speed, and the above coefficients and factors. The displacement used should correspond to the 10% consumables condition.

14.1.7 The floats of trimarans should be of sufficient volume to resist all rolling and pitching moments without submerging any part of their deck. The lack of dimensions available for the casualties in the database has prevented a study of the required float volume, but it is suggested that the floats of yachts operating in categories 0 and 1 should each have a buoyant volume of not less than 2.0 times the fully laden displacement. For trimarans operating in category 2 this could be relaxed to 1.75 times the displacement, and in category 3, 1.5 times the displacement.

14.2 Operational Aspects

14.2.1 Instruments should be installed to provide the value of the true wind speed to the crew.

14.2.2 Instructions on the appropriate sail plan for the environmental conditions should be applied regardless of wind angle.

14.2.3 Instructions on the appropriate sail plan should include a recommendation to remove the mainsail when sailing downwind in strong winds.

14.2.4 Instructions should include a recommendation to raise the leeward dagger board or lifting keel if fitted, in strong winds, squally conditions, or high sea states.

14.2.5 An adequate sea anchor should be carried, together with a nylon warp of length equal to ten times the hull length and of adequate strength, on all multihulls operating in categories 0 and 1. Provision should be made for bridling the sea anchor to the extreme forward ends of the catamaran hulls or the trimaran floats.

14.2.6 Escape hatches should be fitted in a lightly stressed area of the bottom of each hull containing accommodation.

14.3 Further Work

14.3.1 A programme of model tests and sailing trials should be conducted to investigate the dynamic effects of waves.

14.3.2 A programme of wind tunnel tests should be conducted to investigate the magnitude of the heeling moment at a range of heel angles for a number of typical multihull arrangements.

14.3.3 Consideration should be given to developing an acceptable method of deriving the vertical centre of gravity location of multihulls.

14.3.4 A study of existing yachts should be undertaken to assess the validity of recommendation 14.1.7. This should include capsized yachts if sufficient data can be obtained on their shapes and displacements. Alternatively the same subject could be addressed by experimental means.