WOLFSON UNIT
FOR MARINE TECHNOLOGY & INDUSTRIAL AERODYNAMICS

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MARITIME & COASTGUARD AGENCY

Research Project 534
Stability Criteria for Large Sailing Yachts

Final Report

EXECUTIVE SUMMARY

This report describes a review of the sailing vessel stability requirements of the Large Yacht Code, and considers the validity of their application to modern, very large yachts.

The size of the largest yachts appears to be increasing, and is far beyond the scope of the database used in developing the method of assessment and criteria. Some designers of these vessels have experienced difficulties in complying with the stability criteria, and have put forward arguments in favour of a relaxation of the requirements.

A study of the fleet was made, with stability data on a substantial sample of yachts provided by designers. The various parameters that affect stability under sail were examined, to determine any trends associated with size. This exercise concluded with the finding that, in general, the relationship between heeling moment and righting moment does not tend to vary with size, so that there is no justification for relaxing the requirements for larger yachts on the basis of size alone.

The Wolfson Unit has conducted wind tunnel tests on many large yachts, and a database of test results was compiled to search for variations of heeling moment coefficient with size or rig type. Differences in the performance of different rig types could be identified, but no trends of heeling moment variation with size were found. Additional wind tunnel tests were conducted to confirm the assumptions regarding the maximum heeling moments that can be generated.

In depth discussions with designers and rig suppliers enabled a review of design methods, design loadings and failure modes of rigs. It was concluded that rigs may be assumed to be sufficiently strong to transmit sufficient heeling moment to the yacht to result in a knockdown. Similarly, discussions provided information on the sail handling systems, their capabilities and their limitations. Anecdotal reports of specific incidents by designers and captains supported the majority view that automated sail handling systems should not be relied upon as a fail safe means of limiting the angle of heel in an emergency, when stuck unexpectedly by a severe gust or squall.

In most cases there appears to be no justification for relaxing the existing criteria. It is recognised, however, that some vessels may have very high initial stability and/or small rigs, such that it would require unreasonably high wind speeds to cause a capsize. For such cases a criterion is proposed such that, if the anticipated wind speed to cause knockdown is greater than 40 knots, the range of stability may be less than 90 degrees. This is similar to the Code requirement for multihulls.

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1 INTRODUCTION

Over the last ten years, the physical size of the largest sailing yachts has grown significantly, taking them well beyond the size of vessels considered during development of the stability requirements incorporated in the Large Commercial Yacht Code. For some current projects designers are experiencing difficulty in attaining the requirements. It is unclear whether this is a function of individual design or is inherent in the size of the vessels, and thus whether the Code needs to address stability and safety of very large sailing yachts in a different manner.

A preliminary study was conducted in 2004 to advise the MCA on the scale of the problem, and the scope of the research that might be conducted to develop revisions to the Code, if appropriate. That study was designated TA10/03 and was described in Wolfson Unit report 1740/02 dated June 2004.

This report describes the subsequent phase of the work, which addressed the issues in more detail. The work was commissioned by a letter from Susan Nash of MCA, ref. MSA 10/9/199, dated September 2005.

2 BACKGROUND

The stability requirements of the Code were developed by the Wolfson Unit in 1989. A full description of the work was described in the report to the Department of Transport, Ref 1, and a more concise description was presented as a paper, Ref 2. Originally the requirements were developed for the Code of Practice for sail training ships between 7 and 24 metres load line length. For this purpose the Wolfson Unit considered stability information on a range of sailing yachts and sailing ships. The database included yachts principally in the range 7 to 24 metres, with a few examples up to 34 metres, and ships of up to 40 metres in length.

The same stability requirements were included in the original large yacht Code, which applies to yachts in excess of 24 metres. Some yachts up to 90 metres are now being built in accordance with the Code, and so the validity of its application is in doubt.

The Code was revised and reissued in 2005, and this later version frequently is referred to as LY2. The same stability requirements for sailing monohulls were incorporated, and additional requirements were introduced for sailing multihulls.

3 WORK PROGRAMME

A list of objectives was defined, and an outline programme of work suggested, by the MCA. These are summarised briefly in the following list:

1. Confirm and expand the database assembled during the scoping study.
2. Investigate the variation of stability and heeling moment parameters with size and rig type, using wind tunnel data for a variety of large sailing yacht rigs.
3. Conduct a limited study of the failure modes of modern materials and structures and their effects on stability and safety.
4. Investigate whether modern safety mechanisms and systems affect the requirement for survival of a knockdown.
5. Engage in discussions with other regulators for the purpose of peer review of the proposals.

4 COMPILATION OF A DATABASE

A database of sailing yachts in excess of 35 metres, built over the last 35 years, was compiled for the scoping study. This was expanded to include yachts delivered since that work was conducted, and some examples of yachts under construction. Because of the short time interval between these two studies, the additions to the database did not influence the general findings of the scoping study. For completeness, some Figures from that study are reproduced in this report with the additional data included.

Figure 1 presents the length of yachts in relation to the year they were delivered, and it is clear that the maximum size of yachts has increased significantly since 1999, until which time the maximum length was under 60 metres. Figure 2 shows the distribution of the fleet in terms of length overall and demonstrates that, although yachts are approaching 100 metres, the number of yachts over 50 metres remains small.

5 CONSULTATION WITH INDUSTRY

During this study, and the previous scoping study, designers, builders and captains were circulated with requests for information and opinions relevant to the subject. Publicity for the project was obtained by publication of an article in the periodical The Yacht Report, which is a highly respected publication with an extensive circulation among industry professionals. Appeals for information were sent directly to designers and builders, and discussions took place with designers, builders and equipment manufacturers, through meetings, telephone calls, and correspondence.

The first appeal resulted in considerable assistance with the collection of stability data, while the later discussions concentrated on gathering opinions on the subject. These varied considerably, and this report attempts to represent the range of opinions, and incorporate them where appropriate.

6 VARIATION OF STABILITY WITH SIZE

The size at which the stability requirements of the Code start to influence the design to a significant extent is variable, and depends upon a number of parameters. Some designers do not regard this as a problem because they consider the rationale behind the criteria to be valid, while others find that it conflicts with other requirements of the project, and compromises the result.

Some designers who have experienced difficulty with the criteria have identified particular characteristics that have an influence on the compliance:

- Performance orientated design. Owners seek performance and are attracted to forms that resemble those of modern racing yachts.
- Low displacement/length ratio. Light displacement is good for performance but may result in low ballast ratio and a relatively high KG. Weight growth during the design or building phases may result in reduction of ballast to maintain the design draft, accentuating the problem.
- High beam/draft ratio. Wide beam provides good initial stability and sailing performance, and a spacious interior.
- Low freeboard/beam ratio. The popular style for sailing yachts is for a single deck of accommodation below the main deck. The depth of this accommodation remains roughly constant regardless of the size of the yacht, because it is dependent on headroom requirements.
- Low superstructure height and volume. For reasons of styling and performance, superstructures tend to comprise a single deck, and large areas of open main deck facilitate sail handling.
- High performance, high aspect ratio rig, with mast height greater than yacht length.
- Lifting ballasted keel or unballasted centreboard. Shallow hull draft enables access to a wide range of ports with the keel raised.

Most of these characteristics are recognisable as being desirable in terms of performance, and contribute to good stability at low angles of heel. Unfortunately they are detrimental to stability at large heel angles. Some of these performance related features, one might expect to be size dependent. For example, light displacement is desirable for small yachts because they need to operate in the semi-planing or planing regime to achieve high speeds. Very large yachts can operate in the displacement mode at speeds in excess of 20 knots, and so the need to strive for light displacement should be less critical. The variation of displacement with length is presented in Figure 3. The graph is plotted on the basis of length cubed and it is clear that most yachts fit a linear relationship. There are two notable exceptions, one of which was designed and built as a racing yacht.

Figure 4 shows that the relationship between beam and length is particularly dependent on the keel configuration for the very large yachts. For yachts below 50 metres there appears to be little difference between the beams of fixed and lifting keel yachts. Above 50 metres the yachts with lifting keels have significantly higher beams for a given length. The wide beam provides stability at normal sailing heel angles and reduces the need for a high ballast ratio, but such a combination provides less stability at large angles than narrow beam with a high ballast ratio.

The beam/length ratios are presented in Figure 5. There is a distinct trend of decreasing beam/length with increasing length for the fixed keel yachts, but a constant value is maintained among the largest yachts with lifting keels. The initial stability is proportional to the product of the length and the cube of the beam, divided by the displacement. It is therefore proportional to the square of the beam. Figure 6 presents the ratio of the square of the beam to the waterline length, and shows that, despite the decreasing beam/length ratio, there is considerable scatter but no trend with length for the fixed keel yachts. For the lifting keel yachts the ratio increases with length, demonstrating an increasing reliance on beam rather than ballast for the larger lifting keel yachts.

Figure 7 presents four stability parameters, and their variation with length. It appears from these data that there may be a trend for increasing GM and maximum GZ with size, but this does not extend to the largest yachts in the database. In fact, study of a selection of yachts of about 10 metres overall length showed that their maximum GZ values lie in the range 0.5 to 1.0 metres, which is similar to the values for the yachts featured here. The apparent variation with size for the smaller yachts in this database is thought to be the result of greater scatter in the smaller vessel data. GM and GZ are dimensional parameters and the fact that they do not increase with size is likely to be the result of the reduction in the beam/length ratio.

The righting moment therefore does not increase with size as a result of increasing GZ, but it does increase as a result in increasing displacement. The righting moment, therefore, tends to increase in proportion with the length cubed.

The range of stability is highly variable, between 80 and 180 degrees, and many of the large yachts have a range just above 90 degrees, perhaps as a result of the Code requirements. Some of the very large yachts have substantial superstructures and, if they are of adequate strength and watertight integrity, their inclusion in the stability calculations is acceptable. Such additional buoyancy, which becomes immersed at large angles, provides considerable righting moment and is likely to result in positive stability at 90 degrees heel.

In the event of being pinned down by a squall for a prolonged period, the effective range is limited to the critical downflooding angle. This tends to be around 60 degrees for the large yachts and, again, this may be the result of the Code requirements.

7 VARIATION OF HEELING MOMENT WITH SIZE AND RIG TYPE

7.1 Performance tests data

Wind tunnel tests have been conducted by the Wolfson Unit in support of the design of sailing rigs for a wide range of yachts and sailing ships. Data from such tests were used to create a database of lift, drag and centre of effort values. While some data were unsuitable for consideration, 75 data points have been collated, encompassing maximum lift, maximum heeling force and maximum drag values. In some cases, more than one data point was derived from one model, because different rig options or sail combinations had been tested.

The data represent yachts ranging in length from 8m to 91m on the waterline, with one, two or three masts. The rig configurations varied, including –

- Bermudan sloops
- Gaff cutters
- Ketches
- Staysail schooners
- Square rigger
- Innovative and non-traditional

Figure 8 to Figure 10 present the variations in the number of masts, main mast height and sail area with vessel length. Data from the general database have been included with the wind tunnel test samples on these plots to maximise the definition of the trends. It appears that twin mast rigs become practical at lengths above 25 metres, and 3 mast rigs above 40 metres, but there is considerable overlap in each case. Mast heights tend to be roughly proportional to the length of the yacht, although there appear to be some practical limits as might be expected. For larger yachts, structural considerations and operational requirements, such as bridge heights, restrict the mast height in many cases. A common height limit appears to be about 63 metres, which corresponds to Panama canal restrictions but, where this is exceeded, the linear relationship with length may be maintained.

Figure 10 demonstrates that sail areas tend to increase roughly in proportion with the square of the length, and shows that the transition from a single to a multi-mast rig enables greater sail area to be carried. These data do not include the areas of downwind sails such as spinnakers, which might increase the total area by over 50%.

Equations 1 to 4 below define the non-dimensional coefficients and the relationship between the aerodynamic lift and drag forces and the boat heeling and driving forces. The aerodynamic forces are referred to the wind frame of reference, while the driving and heeling forces are defined with respect to the vessel frame of reference.

Heeling force coefficient,

$$C_{HF} = \frac{H_F}{\frac{1}{2}\rho V^2 A}$$

Equation 1

Non-dimensional centre of effort height,

$$C_{EH} = \frac{H_M}{H_F} \cdot \frac{1}{Height_{MAST}}$$

Equation 2

Heeling moment coefficient,

$$C_{HM} = C_{HF} \cdot C_{EH}$$

Equation 3

Heeling and driving force coefficients

$$\begin{aligned} C_{HF} &= C_L \cos(\beta) + C_D \sin(\beta) \\ C_{DF} &= C_L \sin(\beta) - C_D \cos(\beta) \end{aligned}$$

Equation 4

Where β is the apparent wind angle.

Figure 11 to Figure 13 present the variations of non dimensional heeling force, centre of effort height and heeling moment against the vessel length. For some projects, the plots include data for a number of rig configurations or sail combinations, so that several data points have a common length. They show that there is no discernable trend in the variation of heeling force or heeling moment coefficient with length, and the maximum values remain constant in all cases. One data point exceeds the general maximum in each case, and this is for an unconventional square rig. In general the centre of effort was within 3% of the mast height of the geometric centre of area.

Figure 14 presents typical lift and drag data to illustrate their variation with apparent wind angle. At low wind angles the lift force component dominates, and at large angles this reduces towards zero and it is the drag of the sails that is the major component. With the appropriate sin or cosine factor, these combine to produce the driving and heeling forces and, for the latter, give the characteristic curve shown in Figure 15. This shows the variation in wind heeling force with apparent wind angle, and the range of values found within the database. The spread of maximum heeling force measured for a given sail and mast configuration depends upon the efficiency of the rig, and this includes factors such as the aspect ratio of the rig, relative positioning and overlaps of the sails, and the windage of the mast and rigging. The database includes the results of tests analysed at different times using slightly different techniques, and the sail area may be either developed surface area or projected area. Such area calculation differences could account for 5% difference in the results.

The effects of different number of masts is shown in Figure 16. A single mast rig will produce a larger heeling force coefficient, compared to multi-mast rigs, with the maximum occurring at approximately 35°. As the number of masts increases, the maximum force coefficient decreases, and the angle at which it occurs increases up to 50° apparent wind angle for a three mast rig. The effects of different rig types are illustrated in Figure 17, which presents data for a square rigger and a staysail schooner, both of which have three masts. These curves have been derived from a large number of rigs, but it is possible that novel and atypical sail plans or rigging styles may produce data beyond the bounds shown in Figure 15. The overall maximum heeling force coefficient generated, as presented in Figure 15, ranges from 1.4 to 2.2, but the majority of results were close to the mean, or "best fit", line. The limits were only reached for extreme and atypical configurations.

7.2 Comparison with Conventional Assumptions

A value for the heeling force coefficient of 1.2 frequently is assumed in sailing vessel stability and rig design calculations, and it is interesting to note that these data reveal many cases where this is exceeded by a significant margin. There are a number of factors that contribute to this difference.

These coefficients are based on the forces generated by the sails alone, because the hull and superstructure forces are deducted in the wind tunnel measurement and analysis process. This contrasts with conventional stability assessments, where the profile areas of the hull and superstructures frequently are included. This will account for part of the difference between the coefficients because the force coefficients for the hull and superstructure will be about 1. The overall effect of using a lower coefficient with the total area will depend on the relative magnitudes of the hull and sail areas.

In some cases these wind tunnel data may provide an optimistic value of the lift that can be generated by the sails, because the model sails can be sheeted harder than on the full size yacht, but they show that there is the potential for heeling force coefficients much greater than 1.2 to be generated.

In the wind tunnel, the heeling moment is defined about the waterline, whereas for stability assessment it is normal to take moments about half the draft, or the centroid of the underwater profile, because the heeling couple is due to the aerodynamic force on the sails reacted by the hydrodynamic force on the hull and keel. The wind tunnel instrumentation measures the moment and the force directly, deriving the lever from those two measurements, and so the heeling force values presented here remain valid when considering the longer lever for stability purposes.

7.3 Maximum Heeling Moments

To extend the existing performance test database, tests to produce as large a wind heeling moment as possible were conducted on a sloop rigged model. This model was provided by Hoek Design, and is shown in Figure 18. The tests were conducted in March 2006 in the low speed section of No1 wind tunnel at the University of Southampton.

The model was rigged as for performance tests, but rather than optimising the drive force for each wind heading, sail settings were maintained over a range of wind angles. In general, upwind sheeting angles were used, where the sails were pulled in tight. The turntable on which the model was mounted was then rotated through a range of apparent wind angles, and the forces and moments recorded at each angle. All data were scaled in the same manner as the performance data, accounting for wake blockage and downwash angles.

The maximum heeling force produced with sails set for apparent wind angles of 25° and 45°, which are representative of upwind sailing angles, are presented in Figure 19 These are overlaid on the optimum curve derived from the usual performance testing, with the sails adjusted for each heading. For both of these fixed sheeting cases, a small increase in the wind angle from the optimum produced a small drop in heeling force, and then, as the wind angle increased further, the heeling force remained relatively constant up to a beam reach with 90° apparent wind angle. The centre of effort for optimum and non-optimum sail sets is also presented, on the lower graph in Figure 19 The centre of effort does not vary significantly with the sail setting or the apparent wind angle, so the heeling moment will behave in a very similar way to the heeling force.

This result is representative of a high performance single mast rig, designed to perform well at very low apparent wind angles. This is where the dominant component is the lift force, which the sails are designed to maximise. If the wind heading is increased without adjusting the sails, the lift decreases and the drag increases rapidly, because the sail is stalled and the flow is separated. The results for this rig show that the maximum heeling force produced by a non optimum sail setting, even when stalled, is less than the maximum possible with an optimum setting. These measurements with sails sheeted hard but the wind on the beam represent the case of a vessel sailing to windward, then struck by a gust from abeam, which is recognised as a particularly hazardous scenario, but does not necessarily represent the maximum heeling moment.

When the current method of assessment was developed, heeling moment data were obtained from wind tunnel tests on two models, a 3 masted barque and the 3 masted staysail schooner shown in Figure 20. Tests were conducted to obtain the maximum heeling moment and determine its variation with heel angle. This was achieved by sheeting the sails to suit an upwind heading, of 35 degrees apparent wind angle in this case. The model was then rotated through a range of wind angles, as for the recent tests. The model was also progressively heeled to measure the moment at a range of angles. The schooner model was also tested for performance purposes. Samples of the performance data are presented on Figure 21, together with the data obtained for the purposes of developing the method of stability assessment. In these performance tests, the sails were sheeted to the optimum configuration for each apparent wind angle, and then the model was rotated upwind until the sails were luffed and downwind until they were beginning to stall.

Figure 21 provides a good illustration of the effects of sheeting and wind angle on a multi-mast cruising yacht. The heeling force associated with the optimum sail settings is shown by a line passing through the optimum data points. A second line shows the maximum heeling force that might be generated by over sheeting the sails, which might occur with careless or inexperienced sail trimming. This line has been drawn through the data points obtained at the heading where the sails were clearly beginning to stall, so no sail trimmer would over sheet to a greater extent than this. Although greater heeling moments are unlikely to be generated by over sheeting, they might result from an unexpected gust from a greater wind angle than the mean wind. The third line represents this scenario, with relatively high heeling forces generated with winds on the beam. At low wind angles the optimum sail settings do not generate the highest heeling force, as was the case for the sloop rig. The multi-mast rig has a lower aspect ratio, and a cascade of 8 sails compared with the sloop's 2. The large number of slots in this complex configuration may enable the rig to develop relatively high lift forces at angles where the sloop rig sails would stall, as is the case with an aeroplane wing utilising slots to delay stall during take off and landing. The maximum force coefficient is greater than for the single mast rig, perhaps for the same reason, but the measurement of sail area, and degree of overlap, may be a factor.

The force coefficient for the sails fully eased, to the point where they are flogging, is also presented on Figure 19. The potential range of forces that may be generated therefore lies between the uppermost curve and the line labelled "sails flogging". When sailing at small apparent wind angles, the heeling force may be reduced by about 50% by fully easing the sheets. When sailing at greater apparent wind angles the sails are eased in order to obtain optimum performance, and so the reduction possible by fully easing the sheets is reduced. At an apparent wind angle of 50 degrees, fully eased sheets reduce the heeling force by 25%.

7.4 Summary and Implications

These data provide no evidence that the maximum heeling moment coefficients vary with size. The maximum heeling force coefficient typically has a value of about 2, and the centre of effort height is close to the centroid of sail area. This is considerably greater than the value of 1.2, which is often assumed in traditional methods of stability assessment, although different methods of analysis account for a small proportion of the difference.

Different rigs behave differently in terms of the effects of sail sheeting and heading. While high performance rigs have the potential to develop high heeling forces at their optimum sail settings when beating to windward, multi-mast cruising rigs may be more vulnerable to over sheeting and the effects of encountering an unexpected gust on the beam.

The heeling moment is the product of the coefficient, the square of the wind speed, the centre of effort height and the sail area. The wind speed is independent of vessel size, while the product of centre of effort height and sail area is proportional to the cube of the length. These data indicate, therefore, that the wind heeling moment can be assumed to increase in proportion to the length cubed.

It may be argued that, because of the wind gradient associated with the atmospheric boundary layer, large yachts experience greater wind speeds because of their higher rigs. This is true under normal sailing conditions but wind gradient is not maintained in gusts and squalls, and is not considered to be of relevance in the scenarios likely to be hazardous to a sailing yacht.

8 WIND SPEEDS REQUIRED TO CAUSE KNOCKDOWN OR CAPSIZE

8.1 Example Yachts

The reasoning behind the minimum requirements is that a yacht with a range of stability of at least 90 degrees is likely to recover from a knockdown, whereas one with a lower range might not. Calculations were conducted to estimate the wind speeds that might be required to capsize example yachts which have ranges of stability less than 90 degrees.

The basis of the existing method of assessment, and provision of information, is that there are an infinite number of combinations of sail area, sheeting, heading and wind speed that can result in a particular wind heeling moment. Prediction of heeling moment is discarded in favour of monitoring of the heeling moment by monitoring the heel angle. Armed with the wind tunnel data described above, however, we can attempt some predictions of the wind speeds that might result in knockdown to a particular angle, or capsize, of a particular yacht.

Stability data and a sail plan were available for only one large yacht that has a range of stability less than 90 degrees. In order to increase the number of examples, two other yachts for which stability data and sail plans were available were considered, with their stability curves adjusted to reduce the range.

The stability curves for the three yachts are presented in Figure 22. Yacht A represents the yacht operating with a range of stability of 80 degrees in its worst operational condition, which is its arrival condition. Yacht B has a range of stability in excess of 90 degrees, and the GZ curve for the actual yacht is shown with a broken line on the plot. It is quite possible that another yacht could be constructed with a similar hull shape, rig and centre of gravity, so that the GZ curve up to 30 or 40 degrees would be the same, giving the same sailing performance, but with a different deck and superstructure arrangement so that the large angle stability would be different. This hypothetical yacht is represented by the solid line. A range of stability of 80 degrees has been assumed. The third example, yacht C, has been derived in a similar way, taking an existing yacht and assuming a reduced freeboard to derive a GZ curve with a range of 80 degrees.

8.2 Upwind Sailing Scenario

In each case the wind speed required to capsize the yacht, assuming an upwind sailing condition, has been derived as follows:

The heel angle resulting from a steady wind heeling moment corresponds to the intersection of the righting and heeling arm curves, so the heeling arm at the point of capsize is defined where the heeling arm curve is tangential to the GZ curve. The heeling arm curve is defined by the formula:

$$\mathrm{HA}_\theta = \mathrm{HA}_0(\cos\theta)^{1.3}$$

The heeling moment is the product of the heeling arm and the displacement, and

$$\mathrm{HM} = 0.5\rho\,\mathrm{V}^2(A_{sails}h_{sails}C_{sails} + A_{hull}h_{hull}C_{hull})$$

Where: ρ is the density of air
V is the apparent wind speed
A_{sails} is the area of the full upwind sail plan, including sail overlaps
h_{sails} is the height of the centroid of the sail plan above half the draft
C_{sails} is the maximum sail heeling force coefficient, assumed to be 1.75
A_{hull} is the profile area of the hull and superstructures
h_{hull} is the height of the centroid of the hull and superstructure area above half the draft
C_{hull} is the hull heeling force coefficient, assumed to be 1.0

These value of the sail force coefficient was selected on the basis of Figure 11, Figure 12 and Figure 15. It represents common maximum values derived from a wide range of model tests.

For these three example yachts, A, B and C, the wind speeds required to capsize would be 28, 29 and 37 knots respectively. The corresponding heeling arm curves are shown on the plots. Although full sail would not be retained if the wind increased to such speeds, it is possible that a gust or squall could cause a sudden increase. The maximum likely gust factor is 1.4 times the mean wind speed, resulting in twice the wind force. The heeling arm curves corresponding to mean winds, assuming that this gust factor had given rise to the capsizing moments, are included on the plots, and enable potential capsizing scenarios to be envisaged.

In the case of yacht A, a steady wind of 20 knots would result in a heel angle of 15 degrees. A gust factor of 1.4, increasing the wind speed to 28 knots, would result in capsize. This is a quite reasonable scenario, and suggests a relatively low level of safety. Although these values have been derived from specific assumptions regarding sails set and the force coefficients, any sail and wind combination on this yacht that results in a steady heel angle of 15 degrees, renders the yacht vulnerable to capsize in a strong gust. This relationship between steady heel angle and capsize is a function of the GZ curve shape alone. This angle of 15 degrees corresponds to the minimum requirement for the maximum recommended steady heel angle to prevent downflooding in gusts. The yacht does not pass the range of stability criterion and is on the margin with regard to the heel angle criterion.

In the case of yacht B, a steady wind of 21 knots would result in a heel angle of 19 degrees. A gust factor of 1.4, increasing the wind speed to 29 knots, would result in capsize. Although the wind speed required to capsize is similar to that of yacht A, it is somewhat safer because the steady wind heeling angle would be 19 degrees in this case, and the yacht is likely to sail at lower angles most of the time.

By the same reasoning, yacht C is safer again, being able to sail at steady angles up to 25 degrees without risk of capsize in a gust, and requiring 37 knots of wind to capsize.

Easing the sheets in this scenario might enable the heeling moment to be reduced by up to 50%, as indicated by Figure 19. This would enable reduction of the gust heeling moment back to its mean wind level, if the sails were fully eased and flogging, and could be eased to this extent sufficiently quickly.

If the possibility of squalls is considered, the gust factors are not limited to 1.4. Squalls with high wind speeds may occur during periods of light winds. A squall of 40 knots during a period with a mean wind speed of 12.5 knots would give a gust factor of 3.2, and a 10 fold increase in the heeling force. It is quite possible, therefore, that a 30 or 40 knot squall could capsize one of these yachts, if it strikes unexpectedly when a large sail area is set and sheeted for upwind sailing, regardless of the wind speed that prevailed prior to the squall. Easing the sheets might not provide sufficient reduction in the heeling moment in a particularly strong squall. Such squalls can occur in any season in light or moderate winds.

The benefits of a range of stability greater than 90 degrees are demonstrated by Figure 23. Here, the curves for yacht C are shown again, together with wind heeling curves corresponding to much higher wind speeds. In the assumed scenario, the yacht with a range of 80 degrees would be capsized by wind of 37 knots, but the actual yacht, with a range well in excess of 90 degrees, cannot be capsized by wind heeling. The curves show that, if the wind speed increases by fixed increments, the increase in heel angle becomes progressively smaller. A yacht may be knocked down and pinned at a large heel angle but, provided significant downflooding can be prevented, it should retain a positive righting moment that will right the yacht after the gust or squall has passed.

In practice, the relationship between heeling and righting moments is unlikely to fit this theory precisely at 90 degrees. The range of stability will benefit from the buoyancy of rigging, masts and other structures above the deck, but be degraded by any movement of loose items of equipment to the leeward side. The heeling moment curve is based on the assumption that the wind vector is horizontal, but this may not be the case in a squall, and any downward component will increase the heeling moment at large angles of heel. As a yacht recovers from a knockdown to 90 degrees, the stability is likely to be affected by ingress of water to the hull and spars, the latter having potential to degrade the stability dramatically. These factors are too variable to be considered for regulatory purposes, and so the range requirement of 90 degrees was selected in recognition of the theory, and the assumption that other factors will balance out.

8.3 Off Wind Sailing Scenario

If the yacht is sailing on an off wind heading, the sails heeling force coefficient would be considerably lower than the value 1.8 assumed for the upwind scenario. The sail area carried might be considerably greater than the normal upwind configuration. Maximum downwind sail areas may be 50% to 80% greater than the full upwind sail plan, although the largest sails would be of light material and probably would fail in a very strong gust. When sailing off wind, the heeling moment is low and the transverse stability is less important than the longitudinal stability in terms of sailing performance. The yacht speed reduces the apparent wind speed to significantly less than the true wind speed, for example running before the wind at a speed of 12 knots in a wind speed of 25 knots results in an apparent wind speed of only 13 knots. These large sail areas therefore may be maintained in relatively strong winds.

A gust or squall would be unlikely to pose a threat to stability because, as Figure 15 shows, the heeling force coefficient is likely to be less than 0.5.

There may be a danger, however, if the yacht suffers a broach. Consider the scenario of a yacht sailing at a heading with an apparent wind angle of 150 degrees, when a broach reduces this to 90 degrees. Reducing the apparent wind angle will have two effects. The apparent wind speed will increase to equal the true wind speed, and this may be twice the apparent wind speed. This will result in the wind force increasing by a factor of 4. The second effect will be that the heeling moment coefficient will increase. Inspection of Figure 19 shows that, for that yacht, the heeling force coefficient would increase from 0.25 at 150 degrees to about 0.75 at 90 degrees, a three-fold increase. The latter value was derived from an extrapolation of the "sails flogging" line to 90 degrees. The lower graph of that Figure shows that the centre of effort height would remain roughly constant. The heeling moment therefore might increase by the product of these factors, a total factor of up to 12. The consequences of such an increase are likely to have dramatic implications for the stability and safety of the yacht, and for the integrity of the sails and rig. Experienced crews are aware of this potential danger, and exercise prudence when setting sails for sailing downwind in strong conditions.

If the broach is induced following an encounter with a gust or squall, the combined factor will be the product of the gust factor and that described above, further increasing the level of hazard.

9 DEMANDS ON LARGE YACHTS

The types of yacht assessed under the MCA Code range from sedate motor sailers to high performance cruising yachts, and racing yachts converted for charter or fast cruising, and their use is equally variable. Many large yachts are used primarily as platforms for entertainment, and as such may not be sailed in strong winds, rough conditions, or at maximum performance. This is less common for sailing yachts than for motor yachts, however, and many sailing yachts are designed to satisfy an owner's desire for high performance. These may be sailed hard by their owners and crews. There are many prestige regattas for very large yachts, where competition may be at a high level, and interest in these is increasing. At one superyacht regatta in 2006 there were 30 entries between 24 and 55 metres, 19 of them over 35 metres.

It has been argued that a particular yacht may not be sailed in conditions where a stability incident is possible, but this is not a simple criterion to be applied in a regulatory framework. When a yacht changes hands the nature of its use may change, and the level of risk may increase as a result.

10 FAILURE MODES OF MODERN MATERIALS AND STRUCTURES

10.1 Rig Design

Yacht designers, rig designers and rig manufacturers use various approaches to determine the structural requirements. The performance requirements, hull type, rig type, and classification society requirements may have an influence on the design process, but the variations tend to apply to the details of the load cases or the criteria applied, rather than the fundamentals of the process. A standard starting point in rig design is the maximum righting moment of the yacht, supplemented with a safety factor. This represents the maximum transverse loading on the rig, and enables the rig structure to remain intact if subjected to a wind strength and sail combination that combine to result in a heeling moment that is sufficient to cause a knockdown.

For multi-mast rigs, the individual mast structures are designed to transmit a proportion of the heeling moment, and so the load case for each mast will be based on a proportion of the maximum righting moment. Each mast may not be expected to withstand 100% of the maximum moment, but it will be designed to withstand a moment greater than the maximum divided by the number of masts. For example, on a 3 mast rig, the foremast may be designed to take 70% of the maximum moment, while 60% may be used for the mizzen. Overall, therefore, the rig strength will be adequate to transmit heeling moments greater than the maximum righting moment, if the sail area is distributed between the masts.

Other load cases to be considered include running before the wind, when a relatively large sail area may be carried in a given wind speed, because the heeling moment is low. This may be hazardous if there is a sudden shift in wind direction, or if the yacht broaches, because the heeling moment may increase to an unacceptable level and result in a knockdown. The risk may be judged to be acceptable by the captain, however, and the rig therefore must be designed to withstand very high loads with the wind from astern.

Sailing or motoring into rough seas will result in high fore and aft rig loads, particularly if bow slamming occurs. Such shock loading does not appear to be a design criterion, but design strength is well above the fatigue limit. Such loads have been the cause of component failure, perhaps because of faulty components or fittings, or inadequate maintenance.

For a conventional stayed rig, the design case for the mast assumes the most likely failure mode to be Euler buckling of the mast panels in compression. The design buckling load is based on the load due to the selected maximum righting moment, plus the load due to the shrouds and halyards, plus a safety factor.

A recent development in rig design, facilitated by advances in composite materials, is for large unstayed masts. It is possible for the design loads to be met with an unstayed structure that is very flexible, but such a characteristic is undesirable so stiffness criteria then govern the design process. For this reason, unstayed rigs are likely to have a greater margin of safety in relation to the maximum righting moment of the yacht.

Multihulls have special characteristics that influence the design. The very wide shroud base is an asset because it enables the rig to be supported with lower shroud tensions, and the buckling loads therefore are reduced. The very high stability enables very high sail loads to be carried, and requires higher factors of safety because, if struck by a gust, the yacht will not heel significantly to reduce the sail loads. For this reason, multihull rigs are likely to have a greater margin of safety than monohull rigs, but the relationship between rig strength and maximum righting moment is unlikely to be a design criterion.

In cases of very high stability in relation to the rig size, it is possible that the wind speed required to generate a heeling moment equal to the maximum righting moment would be an unrealistic value, perhaps 150 knots. The designer might then use a lower wind speed as the basis of the rig design, probably something well below 100 knots. In such a case it is quite possible that the rig would fail before a knockdown occurred, but it would not be possible for a regulator to determine the wind speed required for failure. There would be uncertainties associated with the failure loading, the failure mechanism, and the residual moment of any part of the rig left standing.

It is often suggested that rigs might be designed to fail at some specified loading below that which might result in a knockdown. Weak links or "fuses" in the rigging have been proposed as a means of dictating the failure mode in extreme circumstances. The variety of load cases described above indicate the difficulties that such an approach would need to address, and all of the designers consulted agreed that it is not possible to design a rig to fail in a particular way. A scenario that might result in the highest operational loading of the rig is if attempting to beat off a lee shore in strong wind conditions, when a yacht might be pressed to relatively large heel angles in rough seas. The combined wind loading and wave induced forces might exceed any predetermined maximum safe steady loading, and loss of the rig in such circumstances is likely to be disastrous.

There appear to be many reasons why rigs are unlikely to fail before a knockdown occurs. There have been many examples of failed rigs, but the majority are on racing yachts, where safety factors are minimised in the desire for low rig weight and maximum stability. Failures on cruising yachts are usually identified as faulty components or fittings, or poor maintenance, rather than inadequacies of the basic design.

10.2 Classification Society Requirements for Rigs

The MCA Code requires that masts and spars should comply with Classification Society requirements. The few Classification Societies that have rules for rig structures adopt different approaches. Lloyds Register, for example, has rules for sailing passenger ships which sometimes are applied to large yachts. It applies rules considering both operational and survival load cases. For the operational cases the designer specifies maximum wind speeds for full sail and reefed configurations, and these are expected to be in excess of 25 and 40 knots respectively. The survival case assesses the bare poles configuration in a wind of 122 knots. Lloyds specify safety factors to be applied in each case to the mast and standing rigging. More details of the process, and the reasoning behind it, are given in Ref 3.

11 SAFETY MECHANISMS AND SYSTEMS

Modern developments in rig systems enable the loads and structures to be monitored to ensure that they maintain their performance and safety during the life of the yacht. Load cells, strain gauged components and fibre optic systems can be incorporated in various ways, and the heel angle remains a very reliable means of determining the overall rig loading. Multihulls do not heel to significant angles, so it is common for the rig loading to be monitored with load cells in the stays. These systems are designed to monitor the rig loadings for the purposes of maintaining structural integrity and performance, and are not designed to provide information on sudden increases in rig loading to which the crew might respond.

Some modern sail handling systems are designed to ease sheets when the sheet load, or the heel angle, exceeds some preset limit. With such systems working efficiently, it is expected that the yacht will not heel to large angles under wind loading.

Most large modern yachts are equipped with captive sheet winches, and these are designed to handle the very high loads associated with large sails. Loads up to 20 tonnes can be handled in some cases, and developments are under way to increase this capability up to 30 tonnes. It would be impractical to configure such winches to release the sheets when the loads exceed a pre-set limit, so they need to pay out the sheets in a controlled way using a powered mechanism.

Some designers have full confidence in these automated systems, and cite them as one of the principle factors in the case for relaxing the stability requirements. Others appreciate the value of modern sail handling systems under normal operating conditions, but do not regard them as providing a fail safe means of avoiding knockdown. There is some concern that the crew may become accustomed to relying on the winch systems to respond to gusts, to the extent that they might pay inadequate attention to the weather conditions. There are a number of scenarios that have been cited as examples of equipment failure, and some where failure might potentially occur.

1. The response rate of a winch may be too slow to ease a sheet sufficiently in an encounter with a sudden gust or unexpected squall.
2. A system may rely on generators that may fail, or will not operate at large heel angles.
3. A sail furling system may not operate when under extreme wind loading.
4. The head of a furling sail may be shackled to the mast, so that it cannot be lowered in the event of failure of the furling system, as one hoisted by a halyard might be.
5. A partially furled sail cannot be lowered in the event of failure of the furling system.

12 INCIDENT REPORTS

No documented reports of serious stability incidents to yachts approved under the MCA Code were found. Some anecdotal evidence was heard, relating to knockdown incidents with very large yachts, but requests for detailed information were not granted.

Large yachts are the pride of their owners, designers and builders, and are valuable assets in the resale and charter markets. It is understandable that there is a general unwillingness to discuss incidents which might damage the reputation of a yacht.

The lack of incident reports is a good indication that disastrous events are extremely rare, or perhaps non-existent, but it does not provide evidence that serious events do not occur. The anecdotal accounts included a wide range of incidents, on yachts up to 75 metres in length. The causes of the incidents included knockdown by a gust or squall, knockdown following a broach, difficulty in lowering sails when heavily loaded, and power failure leading to steering or sail handling problems. Serious downflooding was notably absent from these reports, and this may be the principle distinction between an uncomfortable or alarming incident, and a disastrous one.

13 OPERATIONAL RESTRICTIONS FOR NON-COMPLIANCE

Some large motor or sailing yachts which have encountered difficulties in complying with various MCA Code requirements have been certificated for operation within restricted areas, or distance from a safe haven.

This is appropriate for some Code requirements. For example, if a yacht does not comply with the damage stability requirements, restricting operation to within 60 miles of a safe haven increases the likelihood of successful evacuation of the crew and guests in the event of a damage or flooding incident.

It may be inappropriate in the case of failure to comply with the intact stability requirements. Large yachts are very capable of operating in severe seastates without danger of capsize. Their stability is likely to be greater than that of motor yachts of similar size because of their requirement to carry sail. They are unlikely to be in danger from breaking waves because of their large size. They are, therefore, likely to survive rough conditions in the open ocean with little danger, and this is no justification to limit their cruising range.

If they cannot comply with the sailing yacht stability requirements it is because they are relatively vulnerable to a knockdown from which they may not recover, either because of downflooding or a lack of stability at large angles. Such a knockdown might be the result of an unexpected encounter with a severe squall, and proximity to land does not reduce the probability of such an event.

If a yacht cannot recover from a knockdown the result will be sinking as a result of downflooding, or total inversion, although the latter is considered to be unlikely. Survival rates for such incidents are extremely low because there is little time available to escape from the accommodation, raise the alarm, or gather survival equipment or clothing. Survival is likely to be dependent on successful deployment of liferafts, probably by automatic release mechanisms. These have been shown to be problematic on fishing vessels where liferafts and their painters may become fouled by structures above the deck, masts and rigging. Such problems may be greater on a sailing yacht than on a fishing vessel. Proximity to land will enable a relatively fast response of any rescue effort, but will not ensure that personnel will survive a disastrous knockdown event.

14 CONSULTATION WITH REGULATORS

Approaches were made to a number of regulatory authorities and classification societies. Some authorities have adopted the method of assessment used in the MCA Code, some use a method similar to that used in the UK prior to the development of the Code, and others use a method based on that used by the US Coast Guard.

The different methods of assessment were considered in the 1980s, during the development of the method used in the Code. The older methods were rejected at that time, because they do not necessarily provide a good measure of safety, may limit the sail area that can be carried in light winds, and do not provide any information on the level of safety when sailing. Those authorities who retain their use appear to be satisfied with their application. Few authorities have experience of assessing a significant number of large yachts. Whilst some expressed an interest in the findings of this study, they did not offer new information to assist new developments.

15 SUMMARY OF FINDINGS

1. Some designers experience difficulties in achieving compliance with the existing requirements, particularly a range of stability of 90 degrees. Other designers find that the downflooding angle is the critical parameter.
2. Most designers consider that the Code requirements are necessary to ensure safety from a disastrous knockdown or capsize, because automatic sail handling systems can not provide a fail safe alternative.
3. The different experiences of designers largely are the result of the different styles of yacht being designed. It is clear that yachts of the largest sizes currently being built can be designed to comply with the current requirements. It is unclear whether the style of yachts for which compliance is difficult is necessary to obtain adequate performance, or whether it enables the designer to create a yacht that is desirable in other respects. The fact that yachts of extremely high value are being designed, which have difficulty in complying, is evidence that there is some demand for this style of yacht, whether for performance or other reasons.
4. Stability characteristics are affected by draft restrictions, because of port and navigational constraints. Lifting keels are used in some cases. Shallow draft and lifting keel configurations may constrain ballast to a relatively low weight or high location. This may result in a relatively high centre of gravity. To obtain satisfactory sailing performance, such yachts may have relatively high beam. This combination provides good stability at normal sailing angles but is detrimental to stability at large angles.
5. Other design features, such as relatively low freeboard or small superstructures, are detrimental to the stability at large angles, but may be considered as attractive features of a particular style of yacht.
6. Rig types vary considerably, and differences in their performance can be measured in wind tunnel tests, but there is no evidence that the heeling moment coefficients of particular rigs vary to such a degree that they warrant different approaches for the purposes of safety assessment.
7. Both the maximum righting moment and the maximum heeling moment tend to increase in proportion with the length cubed, so that there is no general trend of reduction in the ratio of heeling moment to righting moment with increasing size.
8. Some very large yachts, with a range of stability less than 90 degrees, may have a combination of sail plan and stability characteristics that make them vulnerable to wind speeds below 30 knots. Such wind speeds may be experienced as gusts in Beaufort force 5 to 6, or in squalls. This is not considered to represent an adequate level of safety for a vessel which is equipped for ocean passages, and is of a size that one would expect to be adequate for such service. One example with such characteristics is known, and it is possible that others may exist, or be built in the future, if regulatory authorities allow.

It is anticipated that owners investing the large sums involved in a large yacht project will expect a high level of safety to be assured by the Code requirements.

9. Rig failures occur in a range of circumstances. They are more frequent on high performance racing yachts, where safety factors are minimised in an effort to reduce rig weight. On cruising yachts they are rare, and tend to be the result of component failures rather than overloading of the mast or rigging.
10. Most yacht designers and rig designers agree that rigs are likely to withstand the forces required to heel a large yacht beyond its angle of maximum righting moment.
11. Powered sail handling systems provide an efficient means of controlling the rig under most circumstances, but cannot be relied upon as a fail safe means of reducing the heeling moment sufficiently, in short the time required, to avoid knockdown in the event of a sudden, unexpected, gust or squall.
12. A knockdown is a real hazard, and there are numerous anecdotal accounts as evidence that very large yachts are heeled to angles sufficient to cause alarm to the captain and crew. Documentary evidence is scarce, and statistics therefore are inadequate to establish whether the probability of a knockdown decreases with size. It is considered likely that such a relationship exists, primarily because large yachts tend to be sailed in a more conservative manner than smaller yachts. It may be argued, therefore, that large yachts are safer because of a lower probability of knockdown, but the possibility of knockdown cannot be neglected.
13. The examples considered indicate that, if a yacht has insufficient stability at large angles to comply with the 90 degree range requirement, it may have insufficient stability to withstand the heeling effects of squalls of about 40 knots.

16 RECOMMENDATIONS

The method of assessment and minimum criteria defined in the existing Code of Practice are considered to remain valid for all sizes of sailing yacht, and no relaxation of the requirements is recommended on the basis of size.

There may be circumstances where the maximum righting moment of a particular vessel is high in relation to the potential maximum heeling moment. Such a relationship may be the result of wide beam, heavy displacement, or a small rig. In such circumstances the wind speed required to capsize the vessel may be sufficiently high that it is unlikely to be encountered, even in a squall, when full sail is set. The requirement for a range of stability of 90 degrees then may be inappropriate, and an alternative approach is recommended.

The wind speed required to capsize should be calculated as follows:

The heel angle resulting from a steady wind heeling moment corresponds to the intersection of the righting and heeling arm curves, so the heeling arm at the point of capsize is defined where the heeling arm curve is tangential to the GZ curve. The heeling arm curve is defined by the formula

$$\mathrm{HA}_\theta = \mathrm{HA}_0(\cos\theta)^{1.3}$$

The heeling moment is the product of the heeling arm and the displacement, and

$$\mathrm{HM} = 0.5\rho\,\mathrm{V}^2(A_{sails}h_{sails}C_{sails} + A_{hull}h_{hull}C_{hull})$$

Where: ρ is the density of air
V is the apparent wind speed
A_{sails} is the area of the full upwind sail plan, including sail overlaps
h_{sails} is the height of the centroid of the sail plan above half the draft
C_{sails} is the maximum sail heeling force coefficient, assumed to be 1.75
A_{hull} is the profile area of the hull and superstructures
h_{hull} is the height of the centroid of the hull and superstructure area above half the draft
C_{hull} is the hull heeling force coefficient, assumed to be 1.0

The yacht should be considered to have adequate stability if the wind speed required to capsize is not less than 40 knots.

This recommendation is in line with the requirements for multihulls in the MCA Code for large yachts. They are required to withstand a mean wind speed of 27 knots with the full upwind sail plan set, or to provide adequate buoyancy to maintain floatation if inverted. The wind speed which would result in capsize is determined in a similar way to that described above, and a gust factor of 1.4 is assumed. A mean wind of 27 knots therefore equates to a gust wind speed of 38 knots. The heeling moments of multihulls are determined using a different formula to that for monohulls, because the plan area of the deck has a significant influence, but it is considered appropriate that the limiting wind speeds should be similar.

17 REFERENCES

1. Sail Training Vessel Stability Research, Phase 2. Wolfson Unit Report 908 for the Department of Transport, February 1989.
2. The Development of Stability Standards for UK Sailing Vessels. B. Deakin. Presented at the RINA Spring Meetings, London, 1990.
3. The Verification of Masts and Rigging of Large Sailing Vessels. M.J.Gudmunsen, 16th HISWA Symposium on Yacht Design and Construction, Amsterdam, November 2000.

Figure 1 Illustration of the size of yachts built in recent years

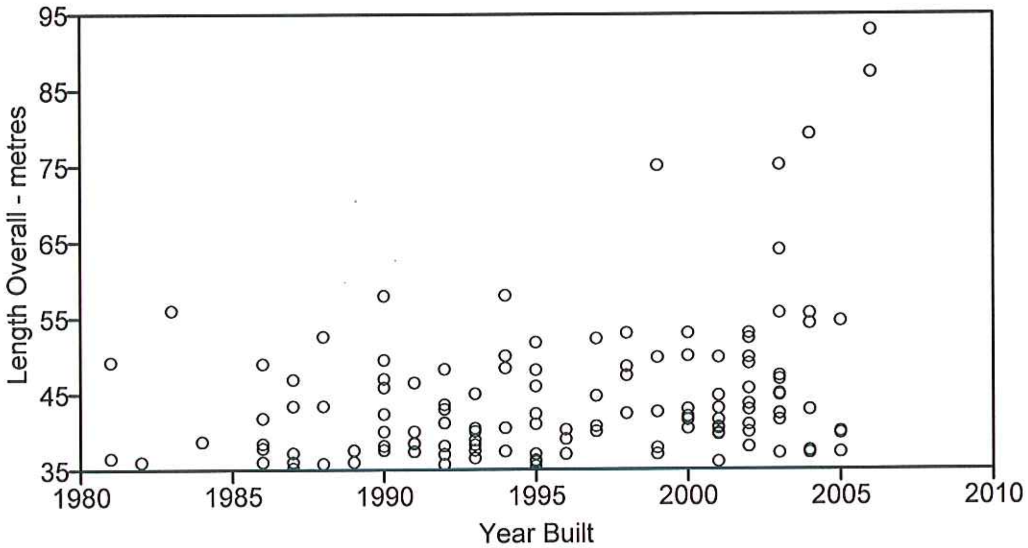

Figure 2 Distribution of size within the fleet

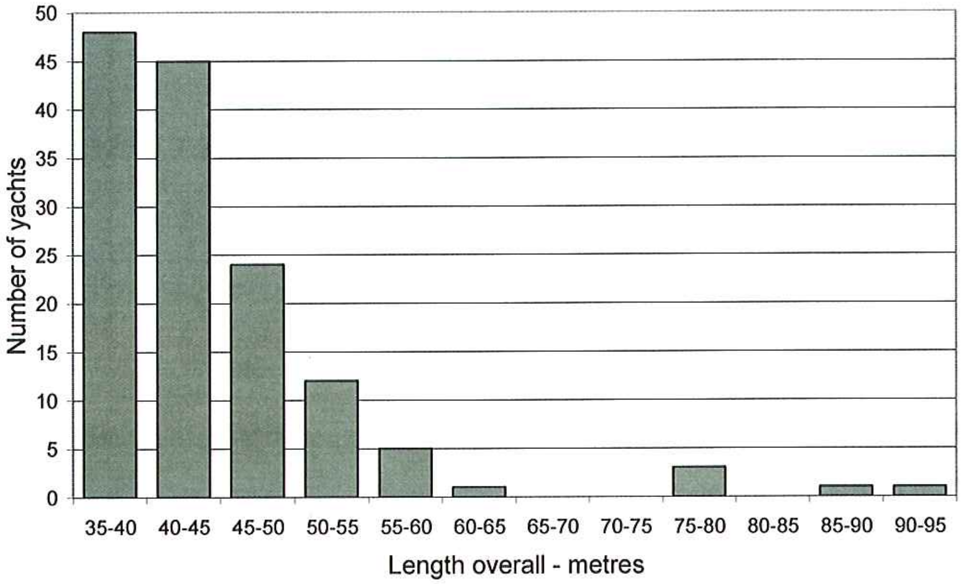

Figure 3 Variation of displacement with length

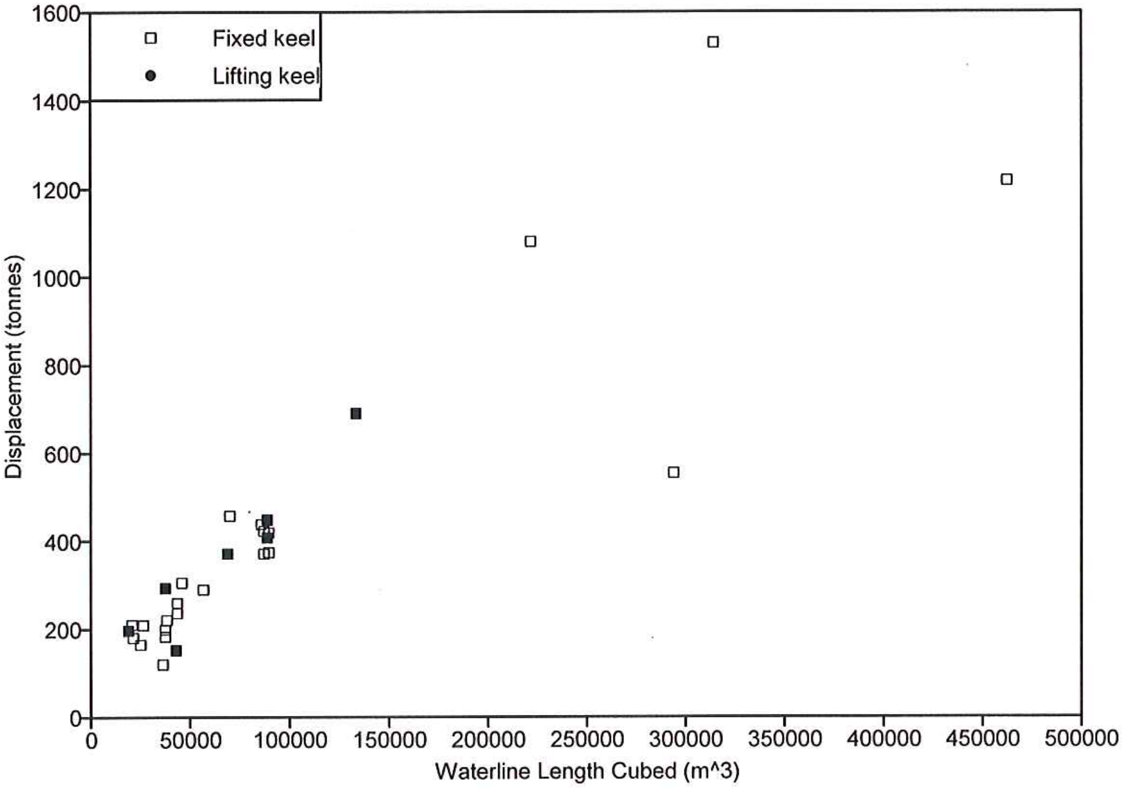

Figure 4 Variation of beam with length, for fixed and lifting keel yachts

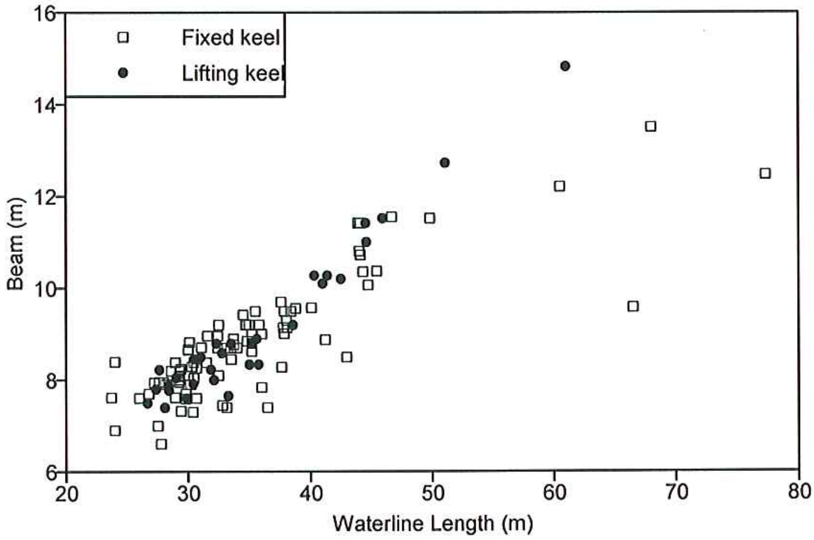

Figure 5 Variation of beam/length ratio

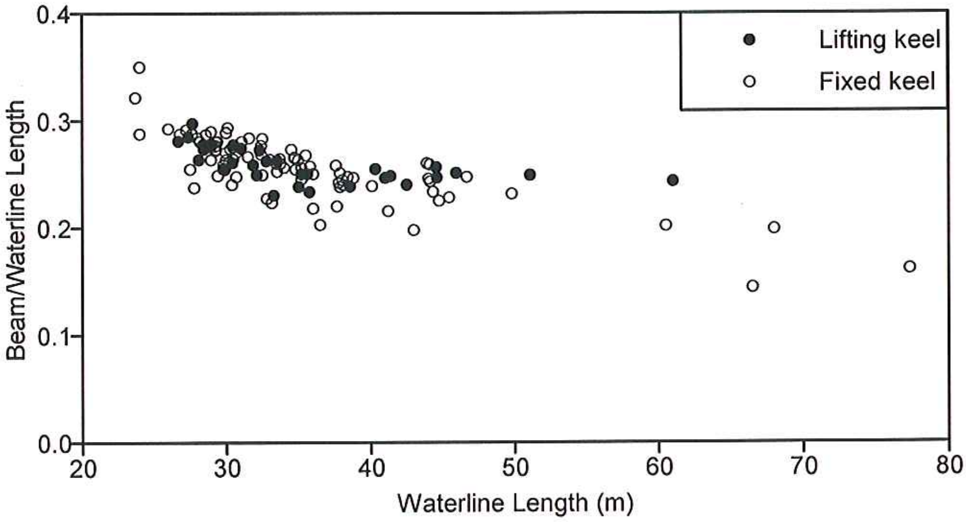

Figure 6 Variation of beam squared/length ratio

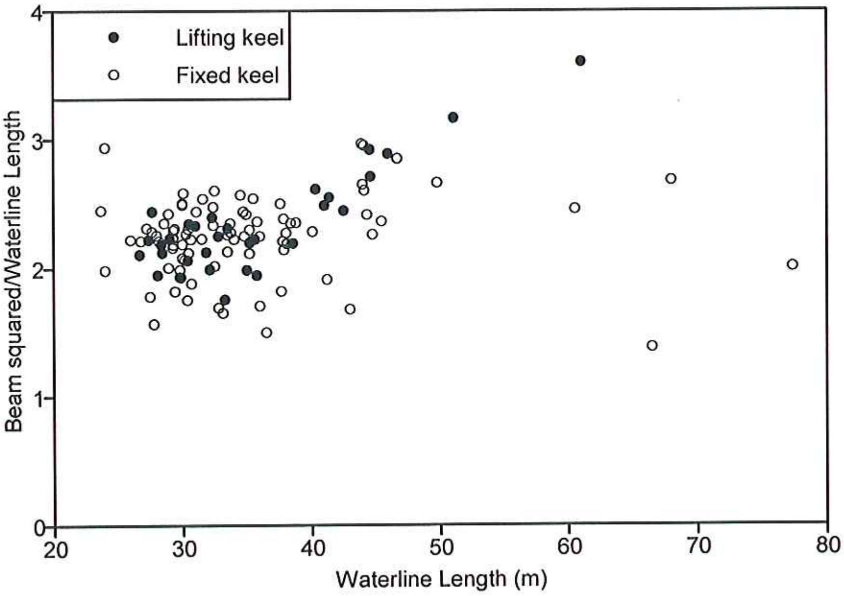

Figure 7 Variation of stability with length

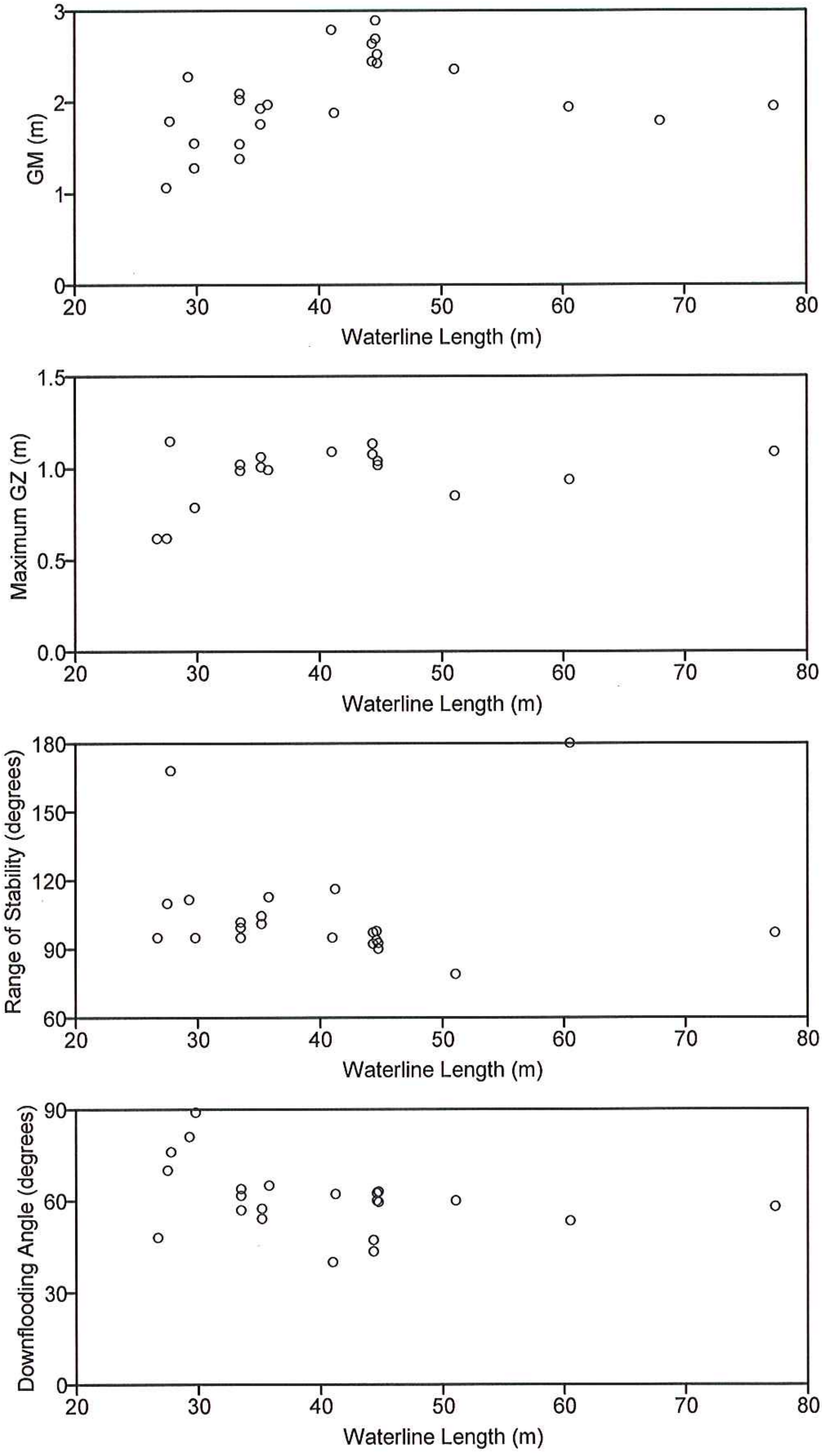

Figure 8 Variation of the number of masts with length

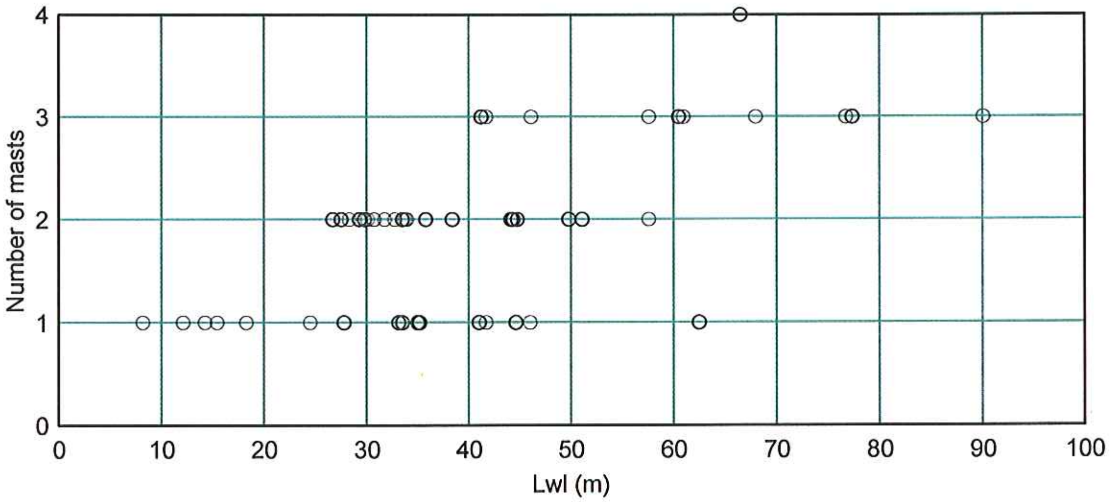

Figure 9 Variation of reference mast height with length

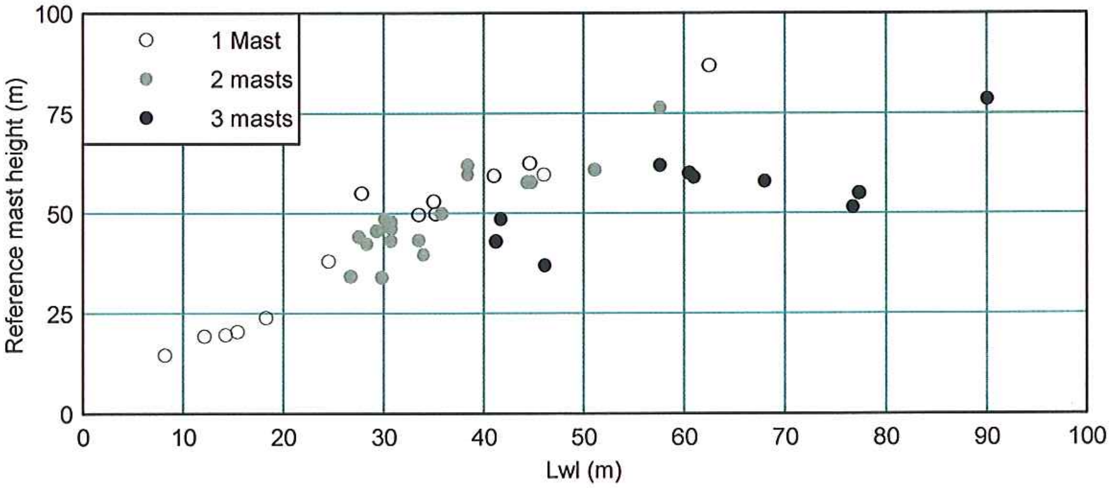

Figure 10 Variation of sail area with length

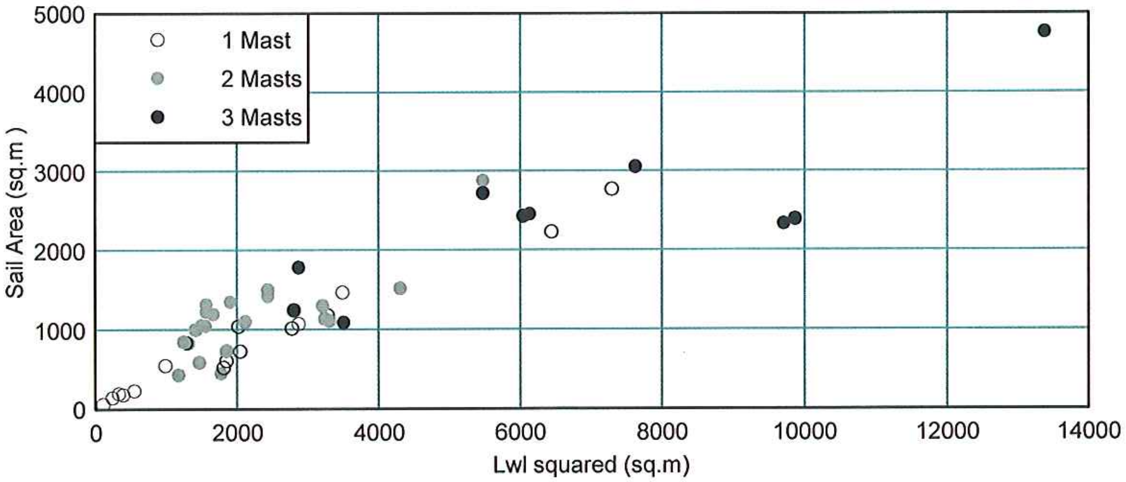

Figure 11 Heeling force coefficient variation with length

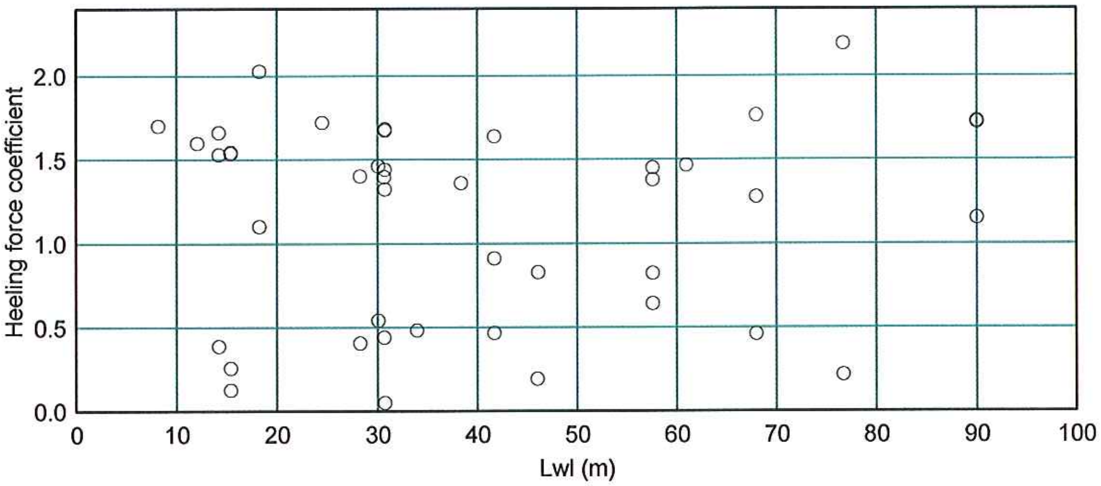

Figure 12 Centre of effort height variation with length

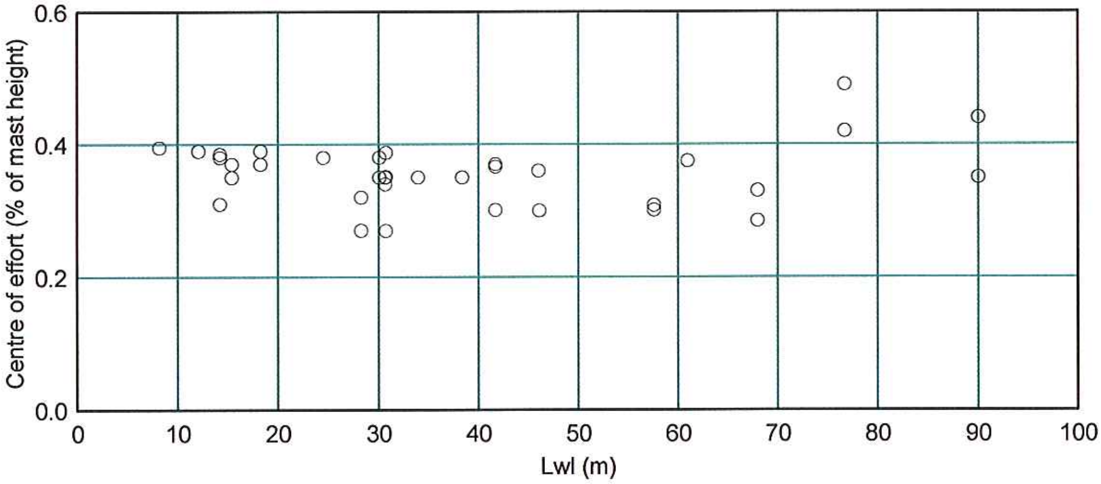

Figure 13 Heeling moment coefficient variation with length

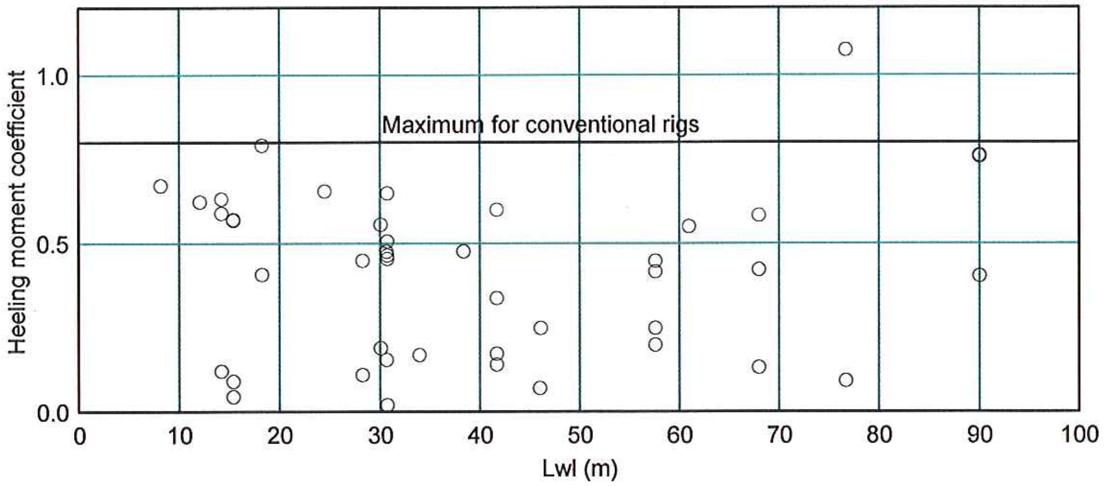

Figure 14 Typical lift and drag coefficients and their variation with apparent wind angle

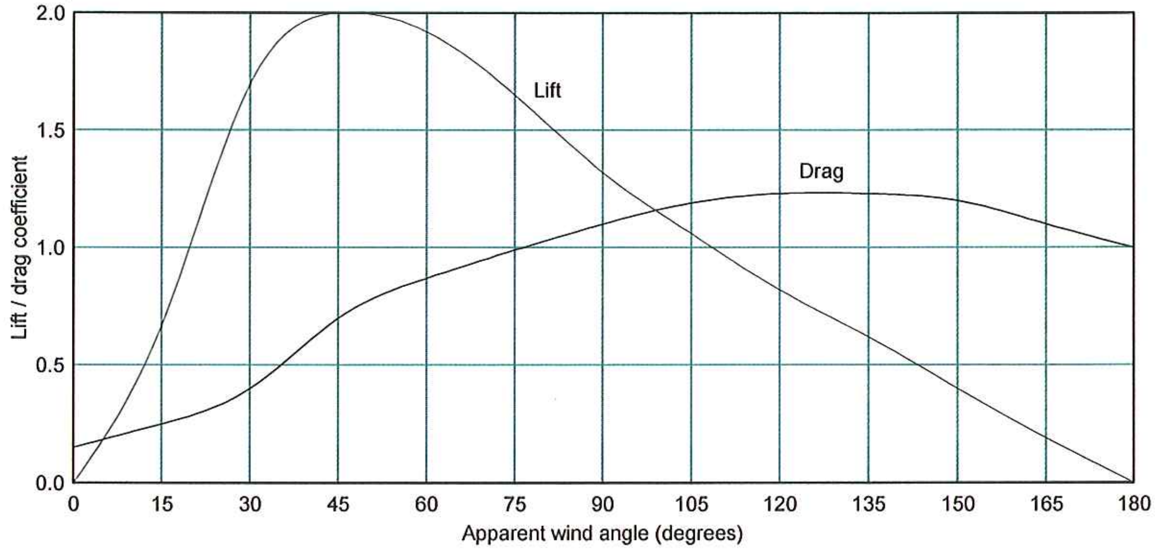

Figure 15 Variation of heeling force coefficient with apparent wind angle

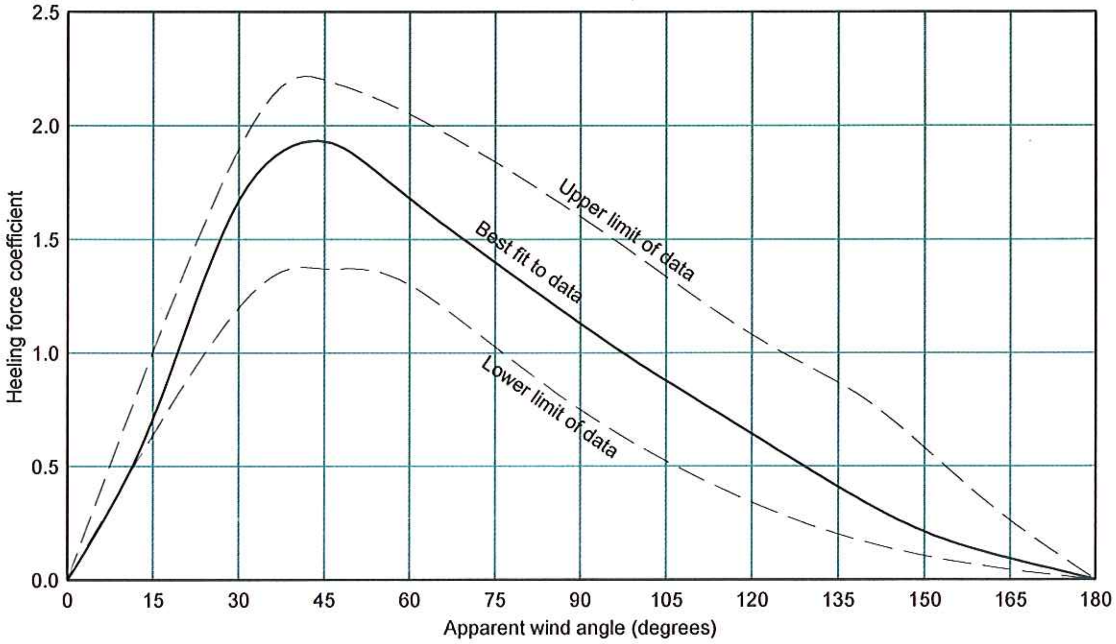

Figure 16 Heeling force variation with number of masts

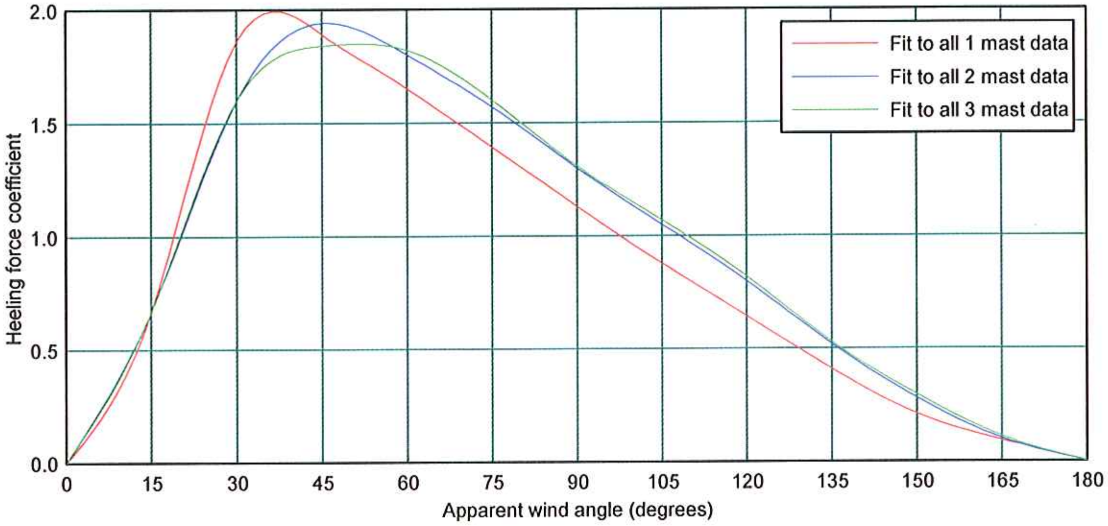

Figure 17 Heeling force variation for 3 masted vessels with different rig configurations

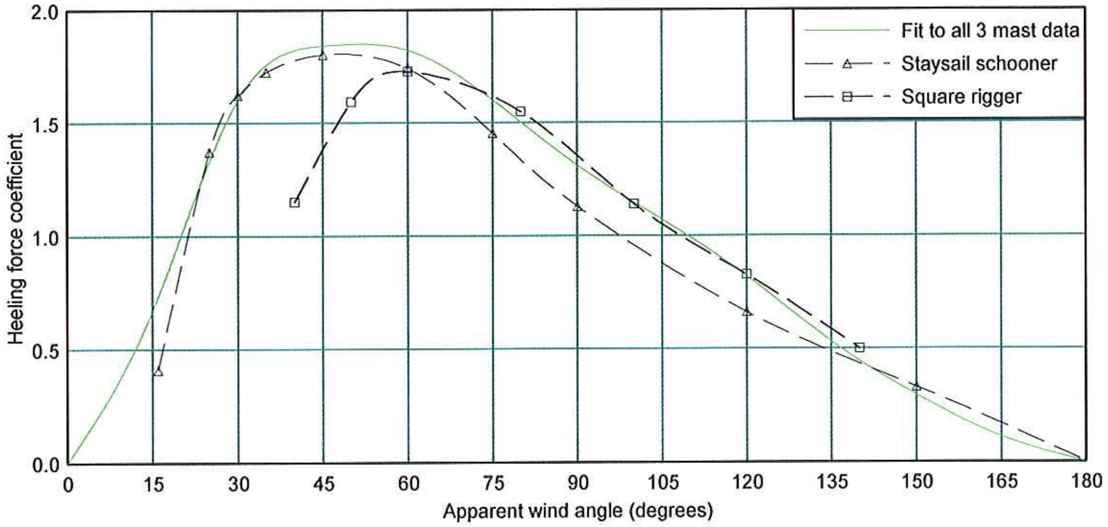

Figure 18 Sloop model used for maximum heeling moment tests

Figure 19 Heeling force magnitude and centre for non-optimum sail settings

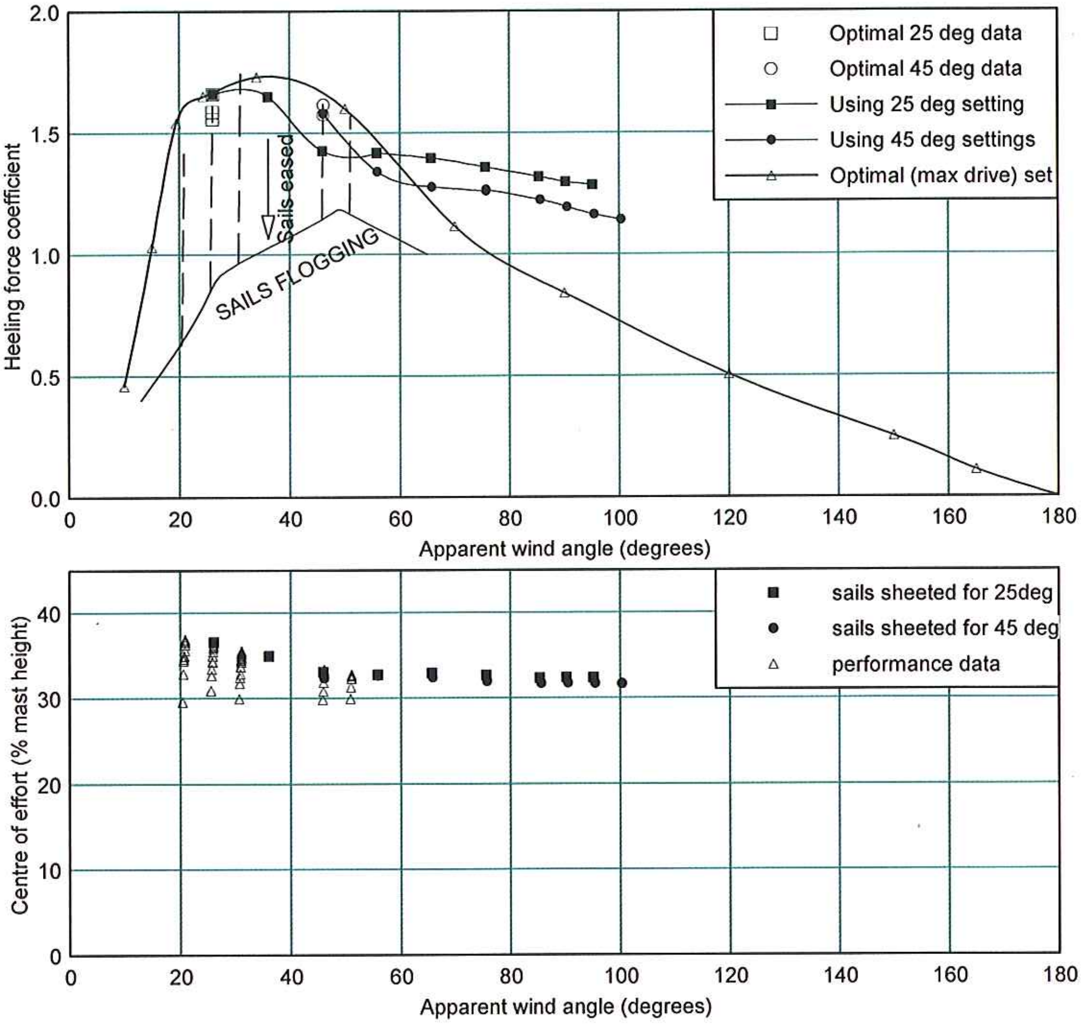

Figure 20 Schooner model used for development of the Code requirements in 1989

Figure 21 Comparison of performance test data with that originally used to develop the Code

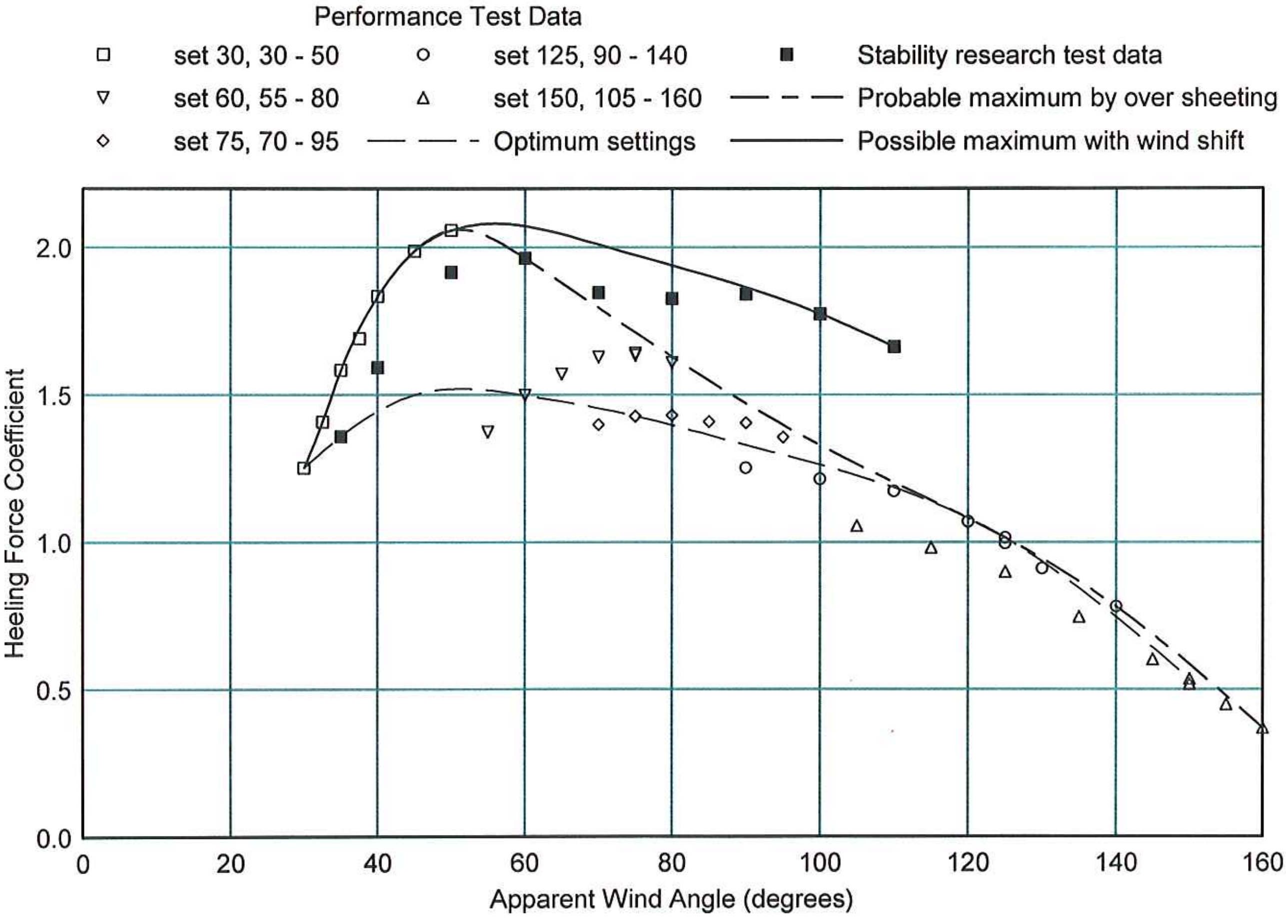

Figure 22 Wind speeds required to capsize yachts with a range of stability of 80 degrees

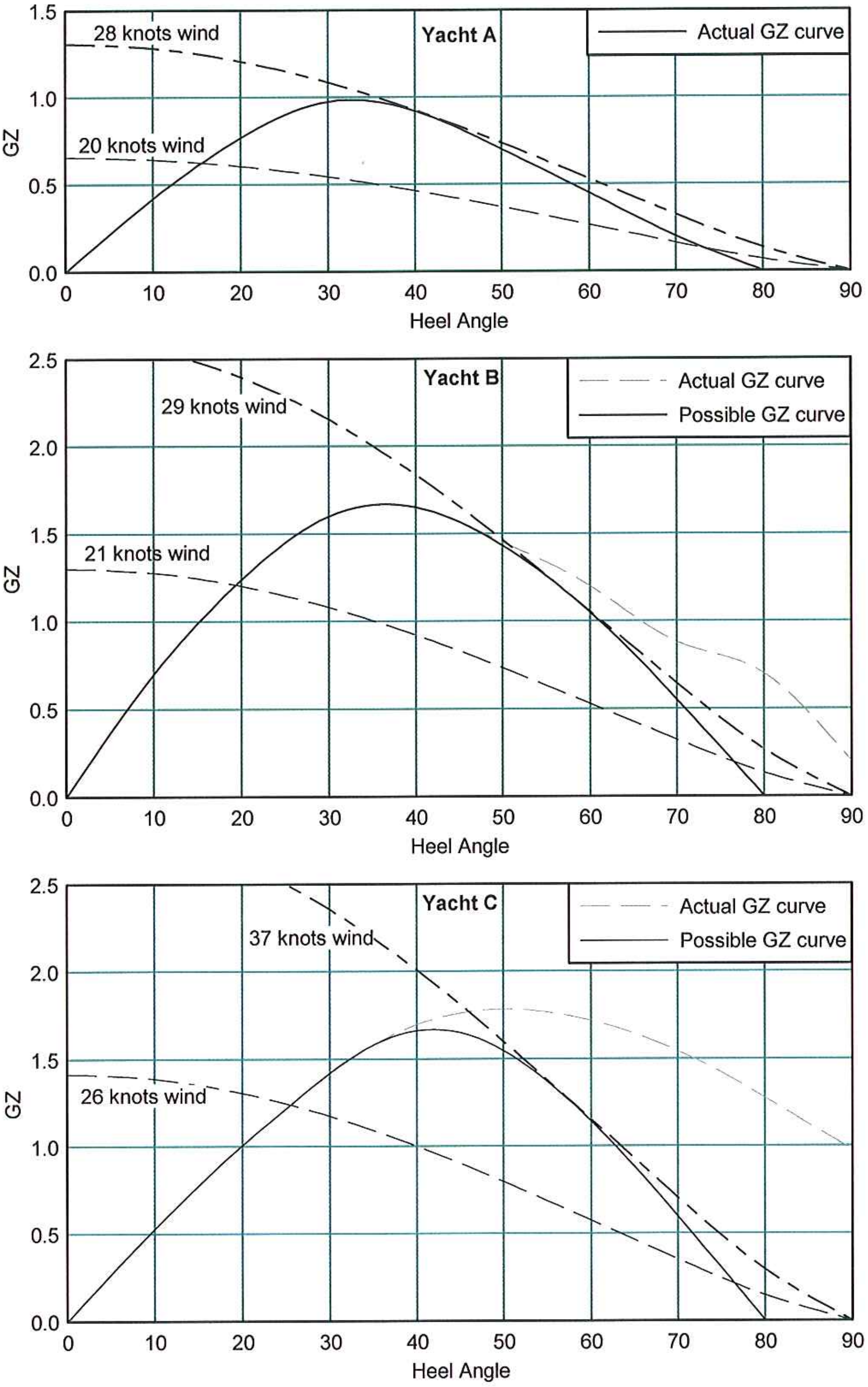

Figure 23 The effects of increasing wind speed on the actual yacht C