STABILITY REGULATION OF VERY LARGE SAILING YACHTS

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ABSTRACT

The effects of size on the stability and safety of very large sailing yachts is considered, with particular regard to the requirements of the MCA Large Commercial Yacht Code. Recent trends in hull design influence the stability and different rig types affect the wind heeling moments. These factors are considered, along with rig structures, sail handling systems and other operational aspects, to evaluate the current MCA Code and its application to the largest yachts now being designed.

Keywords: *Sail, yacht, stability, stability regulation, wind heeling,*

1. INTRODUCTION

Over the last fifteen 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 recent projects, designers experienced difficulty in attaining the requirements. It was unclear to the Maritime & Coastguard Agency (MCA) whether this was a function of individual design or was inherent in the size of the vessels, and thus whether the Code needed to address stability and safety of very large sailing yachts in a different manner. In 2005 the MCA commissioned a study to address the issue.

2. BACKGROUND

The stability requirements of the Code were developed by the Wolfson Unit in 1989. A full report was presented to the Department of Transport (Wolfson Unit 1989), and a more concise description was presented as a paper by Deakin (1991). Originally the requirements were developed for the Code of Practice for sail training ships between 7 and 24 metres. For this purpose the Wolfson Unit considered stability information on a range of sailing yachts from 7 to 34 metres, and sailing ships 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 was 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. INFORMATION GATHERING

A database was compiled of sailing yachts in excess of 35 metres, built since 1980. Yachts built since the study have been added for the purpose of this paper. 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. Although yachts are approaching 100 metres, the number of yachts over 50 metres remains small.

The subject was discussed with designers, builders, captains, mast manufacturers, riggers and rigging system manufacturers, sail makers, winch manufacturers, classification societies, and other regulatory authorities. The designers provided considerable assistance with the collection of stability data, and most individuals offered opinions on the subject. These varied considerably, and every effort was made to incorporate them in the study.

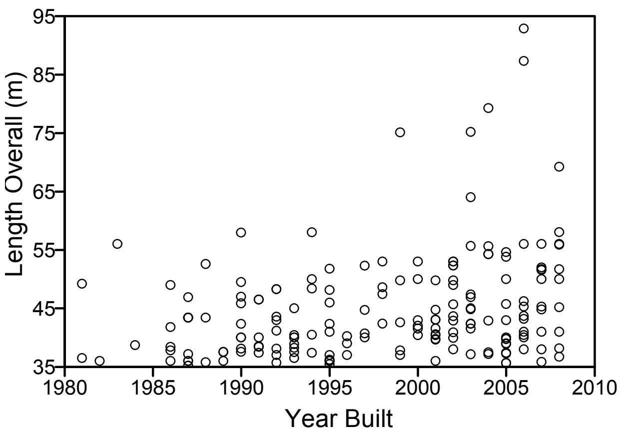

Figure 1. Recent growth in size of the largest yachts.

All designers are aware of the constraints imposed by the Code, but most do not regard them as a problem because they consider the rationale behind the criteria to be valid. Two designers and one builder had experienced severe difficulties with compliance in the case of specific designs, and these experiences led to strong views that the requirements of the Code are unduly conservative. Subsequent design experience led to a softening of this view in one case.

4. STABILITY VARIATION WITH SIZE

For safety from being knocked down or capsized, and to comply with the Code requirements, a yacht needs good stability at large angles of heel. Some design characteristics affect this quality adversely, and trends in large yacht design have led to conflicts in this respect. In particular, owners seek performance and are attracted to forms that resemble those of modern racing yachts. The following characteristics were identified as problematic.

Light displacement is good for performance but may result in a 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.

Wide beam provides good initial stability and sailing performance, and a spacious interior, but may lead to poor large angle stability.

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, and so large yachts have relatively low freeboard.

For reasons of styling and performance, superstructures tend to comprise a single deck, and large areas of open main deck facilitate sail handling. Superstructure volume therefore is relatively low.

High performance, high aspect ratio rigs, with mast heights greater than yacht length, lead to high wind moments and centres of gavity.

With a lifting keel, a shallow hull draft enables access to a wide range of ports, but such keels tend to be of low ballast weight.

Most of these characteristics are recognisable as being desirable in terms of performance, and contribute to good stability at low angles of heel. Some of these 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 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. The beam/length ratio tends to reduce with size, as shown in Figure 2, but this appears not be the case for yachts with lifting keels above 40 metres. 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 3 presents this parameter, and shows that 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.

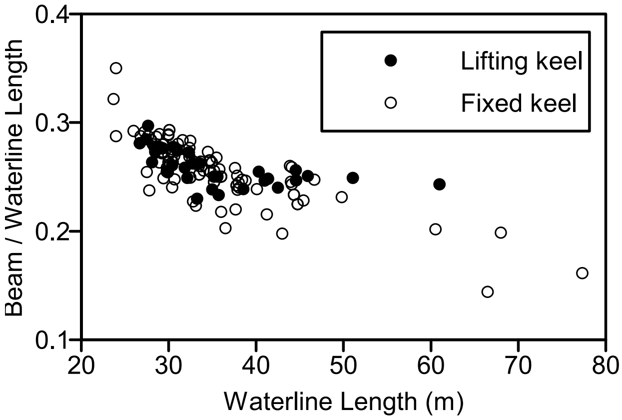

Figure 2. Variation of beam/length ratio.

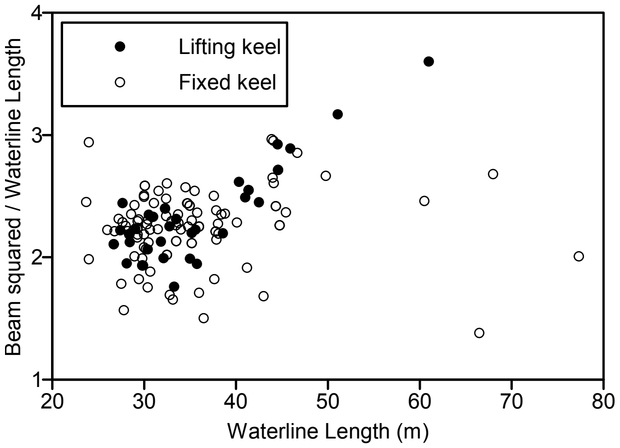

Figure 3. Variation of beam^2/length ratio.

GM and GZ are not non-dimensional parameters but tend not to increase with size, and the largest yachts have values similar to many yachts of only 10 metres. With increasing size, the righting moment increases with displacement, but not because of increasing GZ, and righting moment, therefore, tends to increase in proportion with the length cubed.

The range of stability is highly variable, between 80° and 180°, and many of the large yachts have a range just above 90°, perhaps as a result of the Code requirement. Two examples have very large ranges of stability, one is a modernised and refitted J-Class racing yacht, and the other a recent high performance cruising yacht. To obtain such large ranges of stability, watertight integrity is assumed at all angles of heel. 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.

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° for the large yachts and, again, this may be the result of the Code requirements.

5. HEELING MOMENT VARIATION WITH SIZE AND RIG TYPE

A database of lift, drag and centre of effort values was collated from wind tunnel tests conducted at the Wolfson Unit on a range of sailing vessels, from 8 to 91m on the waterline.

Mast heights tend to be roughly proportional to the length of the yacht, although some designs are influenced by practical limits, such as the Panama Canal height limit of 63 metres. Figure 4 demonstrates that sail areas tend to increase roughly in proportion with the square of the length, regardless of the number of masts. Figure 5 shows that the maximum heeling moment coefficient remains constant regardless of length, although there is one instance of a higher value with an unconventional rig. The heeling moment is the product of these three factors, and so may be assumed to increase in proportion with the length cubed.

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 a 3 masted staysail schooner. Tests were conducted to obtain the maximum heeling moment and determine its variation with heel angle. For this project, further tests were conducted on the sloop model shown in Figure 6, which is typical of modern high performance yachts.

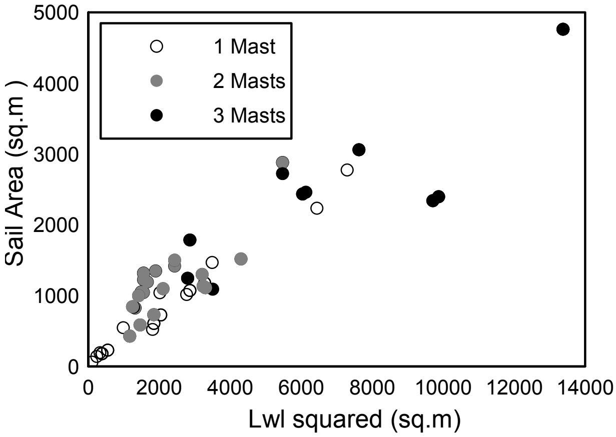

Figure 4. Variation of sail area with length.

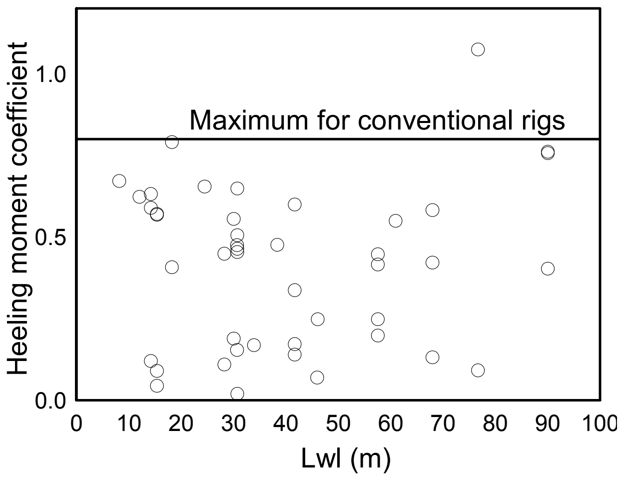

Figure 5. Variation of heeling moment coeff.

In general, upwind sheeting angles were used, with the sails pulled in tight. The turntable was then rotated through a range of wind angles, and the forces recorded at each angle. The maximum heeling force produced with sails set for optimum performance at apparent wind angles of 25° and 45°, which are representative of upwind sailing angles, are presented in Figure 7. These are overlaid on the optimum curve derived from the usual performance testing, with the sails adjusted for each heading. For both of the 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 90° apparent wind angle. The centre of effort height remained constant, so the heeling moment behaves similarly to the heeling force. These results show that the maximum heeling force for such a rig is with an optimum upwind setting.

Figure 6. Model used for maximum heeling moment tests.

Figure 8 provides a good illustration of the effects of sheeting and wind angle on a multi-mast cruising yacht. The optimum settings are shown, and a second line shows the maximum force that might result with careless or inexperienced sail trimming, where the sails begin to stall. The third line represents the scenario with a gust 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. 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. Thus a multi-mast rig may be more vulnerable in the event of a gust or squall.

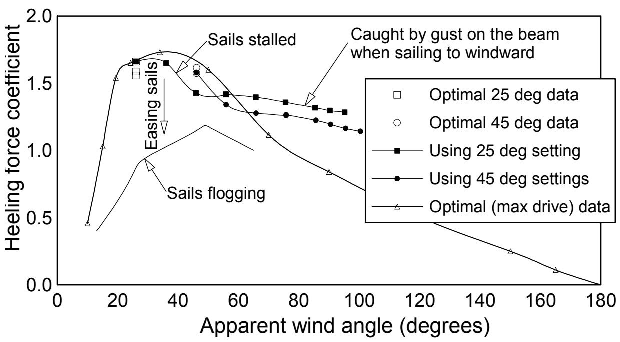

Figure 7. Heeling forces on a single mast rig.

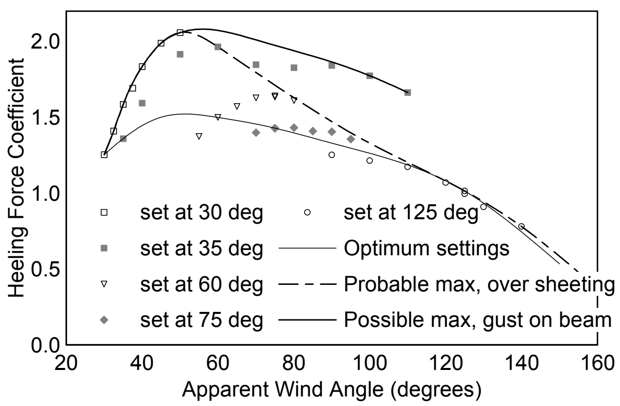

Figure 8. Heeling forces on a multi-mast rig.

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. Figure 7 shows that, when sailing upwind, the force coefficient may be reduced by about 50% by easing the sheets to the point where sails are flogging. At greater apparent wind angles potential reductions are less, reducing to 25% at 50°.

6. ATMOSPHERIC BOUNDARY LAYER

It may be argued that, because of the wind gradient in the atmospheric boundary layer, large yachts, with higher rigs, experience greater wind speeds. Since the selection and sheeting of the sails is in the hands of the crew, not determined by the calculation of predicted heeling moments, the effects of wind gradient on steady sailing conditions are of no relevance to safety. It is the gusts and squalls that pose a threat in terms of stability, and their characteristics are such that the normal wind gradient is likely to be eliminated.

Gusts represent turbulence in the atmospheric boundary layer. There is greater energy at higher altitudes, and the level of turbulence is related to this difference, so that the potential strength of gusts at sea level is dependent on the energy available at higher altitudes. Gust factors near sea level potentially are greater than at higher levels where the mean wind is greater, giving large yachts a slight benefit.

A squall is a small scale weather system that can have a local wind speed many times that of the ambient mean wind. The extent of squalls in terms of the horizontal and vertical dimensions is highly variable, and the direction of the local wind may have a vertical downward component. The normal wind gradient is not likely to be present within a squall.

7. WIND SPEEDS REQUIRED TO CAUSE KNOCKDOWN OR CAPSIZE

Stability data and a sail plan were available for only one large yacht that has a range of stability less than 90°. 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 9. Yacht A represents the yacht operating with a range of stability of 80° in its worst operational condition. Yacht B has a range in excess of 90°, and the GZ curve is shown with a broken line. Another yacht could be constructed with a similar hull, rig and centre of gravity, but with a different deck and superstructure arrangement and hence different large angle stability. This hypothetical yacht is represented by the solid line. A range of stability of 80° 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°.

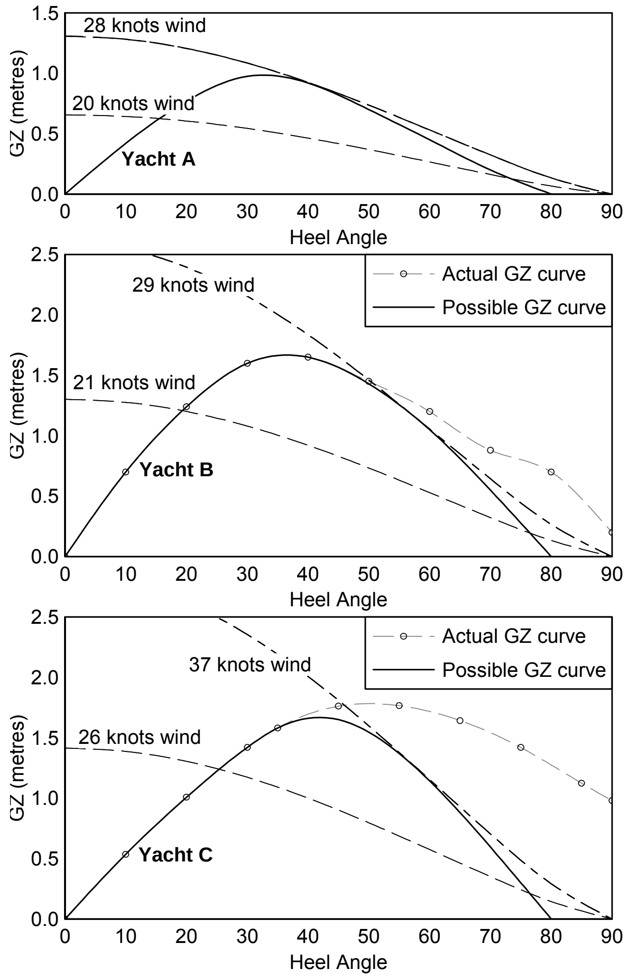

Figure 9. Stability of three sample yachts.

The heeling arm at the point of capsize is defined where the heeling arm curve is tangential to the GZ curve. The heeling arm at an angle, θ, is defined by the formula:

$$HA_{\theta} = HA_0 (\cos\theta)^{1.3}$$

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

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

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, derived from a wide range of model tests and 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 wind speeds required to capsize would be 28, 29 and 37 knots respectively, for yachts A, B and C. See Figure 9. Although full sail would not be carried in steady winds of those 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.

For yacht A, if a steady wind of 20 knots resulted in a heel angle of 15°, a gust factor of 1.4, increasing the wind to 28 knots, would result in capsize. This is a 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° renders the yacht vulnerable to capsize in a strong gust. This relationship between steady heel and capsize is a function of the GZ curve shape alone. This 15° angle corresponds to the Code 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 15° criterion.

For yacht B, a steady wind of 21 knots would give a heel angle of 19° and 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 safer because the steady wind heeling angle would be 19° in this case, and the yacht is likely to sail at lower angles than that for most of the time.

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

Fully easing the sheets in this scenario might enable the heeling moment to be reduced by up to 50%, reducing of the gust heeling moment back to its mean wind level, if the sails could be eased sufficiently quickly. If squalls are considered, gust factors are not limited to 1.4. A squall of 40 knots when the mean wind speed is 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, and easing the sheets might not provide sufficient reduction in the moment.

A range of stability greater than 90° gives theoretical immunity from wind induced capsize. In practice though, the relationship between heeling and righting moments is unlikely to fit the simple model. The range 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°, 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° was selected in recognition of the theory, and the assumption that other factors will balance out.

If the yacht is sailing on an off wind heading, the sails heeling force coefficient would be considerably lower than assumed above, but the sail area might be considerably greater. The yacht speed reduces the apparent wind speed to well below the true wind speed, for example running before a wind of 25 knots at a boat speed of 12 knots results in an apparent wind of only 13 knots. Large sail areas therefore may be maintained in relatively strong winds.

A gust or squall would be unlikely to pose a threat when the heeling force coefficient is less than 0.5, but there is a danger of broaching. The apparent wind speed will then increase to equal the true wind speed, and this may be twice the apparent wind speed, increasing the force by a factor of 4. Additionally, the heeling moment coefficient will increase, perhaps to many times the previous value. A broach may 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.

8. DEMANDS ON LARGE YACHTS

Some yachts are used primarily as platforms for entertainment, but this is less common for sailing yachts than for motor yachts, and many are designed to satisfy an owner's desire for high performance. There are many regattas where competition may be at a high level, and large yachts may be sailed hard by their owners and crews. 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.

9. FAILURE MODES OF MODERN MATERIALS AND STRUCTURES

A standard starting point in rig design is the maximum righting moment of the yacht, supplemented with a safety factor, to ensure that the rig structure will remain intact in the event of a knockdown. For multi-mast rigs, each mast may not be expected to withstand 100% of the maximum moment, but will be designed to withstand a moment greater than the maximum divided by the number of masts. For a conventional rig, the most likely failure mode is buckling of the mast panels in compression. The design buckling load is based on the maximum righting moment, plus the load due to the shrouds and halyards, and 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.

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 to prevent a knockdown. Weak links in the rigging have been proposed as a means of dictating the failure mode in extreme circumstances, but 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 loss of the rig in such circumstances is likely to be disastrous.

The MCA Code requires that masts and spars should comply with Classification Society requirements, and the societies involved are taking the problems of rig engineering very seriously in order to provide a professional approval service (Germanischer Lloyd, 2002, and Gudmunsen, 2000). Their involvement further reduces the likelihood of rig failure.

10. SAFETY MECHANISMS AND SYSTEMS

Load cells, strain gauged components and fibre optic systems enable the rig to be monitored to maintain its performance and safety during the life of the yacht. These systems are not designed to provide information on sudden increases in rig loading to which the crew might respond in an emergency.

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. Loads up to 30 tonnes can be handled in some cases and they need to pay out the sheets in a controlled way using a powered mechanism, rather than enable a sudden release of the highly loaded sheet.

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. Their potential is limited though, because their response rate may be too slow, generators may fail at extreme heel angles, furling systems may fail under extreme loading, and furled sails cannot be readily lowered if a furling system fails.

11. INCIDENT REPORTS

No documented reports of serious stability incidents to MCA approved yachts were found. Some anecdotal evidence was heard, relating to knockdown incidents on yachts up to 75 metres in length, but detailed information was not given. 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 principal distinction between an uncomfortable or alarming incident and a disastrous one.

12. SUMMARY OF FINDINGS

Some designers have had difficulty in achieving compliance, but most consider that the requirements are necessary because automatic sail handling systems can not provide a fail safe alternative. The largest yachts can be designed to comply.

Shallow draft configurations may constrain ballast to a relatively low weight or high location. 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.

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.

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. Both the maximum righting and heeling moment tend to increase in proportion with the length cubed, so there is no trend of reduction in the ratio of heeling moment to righting moment with increasing size.

Some very large yachts, with a range of stability less than 90°, 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 be an adequate level of safety for a vessel equipped for ocean passages. 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.

Rig failures occur in a range of circumstances, but on cruising yachts they are rare, and tend to be the result of component failures rather than overloading of the mast or rigging. Most yacht 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.

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 the short time required, to avoid knockdown in the event of a sudden, unexpected, gust or squall.

A knockdown is a real hazard, and there are numerous anecdotal accounts of very large yachts 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.

The examples considered indicate that, if a yacht has insufficient stability at large angles to comply with the 90° range requirement, it may have insufficient stability to withstand the heeling effects of squalls of about 40 knots.

13. 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° then may be inappropriate, and an alternative approach is recommended.

In such cases the wind speed required to capsize should be calculated as described in section 7. 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. 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.

14. REFERENCES

Deakin, B., 1991, "The Development of Stability Standards for UK Sailing Vessels." RINA Journal, The Naval Architect, January 1991, pp 1-20.

Germanischer Lloyd AG, 2002, "Rules for Classification and Construction I – Part 4", Chapter 5: Guidelines for Design and Construction of Large Modern Yacht Rigs, Hamburg

Gudmunsen, M.J., 2000, "The Verification of Masts and Rigging of Large Sailing Vessels." 16th HISWA Symposium on Yacht Design and Construction, Amsterdam.

Maritime & Coastguard Agency, 2007, "The Large Commercial Yacht Code" Merchant Shipping Notice 1792 (M), Edition 2, Southampton.

Wolfson Unit, 1989, "Sail Training Vessel Stability Research, Phase 2." Report 908 for the Department of Transport.