THE DEVELOPMENT OF STABILITY STANDARDS FOR UK SAILING VESSELS

by B. Deakin,* B.Sc., C.Eng (Member)

Read in London at a meeting of the Royal Institution of Naval Architects on April 23, 1990, Mr J.A.H. Paffett, R.C.N.C. (Honorary Vice-President) in the Chair.

SUMMARY: This paper describes the work undertaken by the Wolfson Unit and sponsored by the UK Department of Transport to develop stability criteria appropriate for the safe operation of sailing vessels. An extensive series of model tests and full scale trials have shown many of the conventional assumptions used in sailing vessel stability calculations to be invalid. New methods of assessment have been established which incorporate the results of the research. Whilst the stability criteria themselves appear very simple, the regulations also require presentation of information to aid the master in assessing his safety when under sail. The presentation to be used has been developed as an integral part of the work and is a significant advance in enabling the master to measure his vulnerability to gusts.

The experimental work which led to such an improvement in the understanding of sailing vessel dynamics is summarised, and the implications of the findings on traditional calculation methods, particularly in the determination of wind heeling moments, is discussed. The results include new information on wind heeling moment and its variation, the response of a vessel to gusts of various kinds, the effect of inertia, damping and rolling, and the characteristics of gusts themselves.

The paper concentrates on the philosophy behind the new requirements and the information for the master, rather than the experimental techniques, and concludes with the implications for the U.K. sail training fleet.

1. INTRODUCTION

The nature of the oceans and the earth's weather systems is such that vessels will occasionally be exposed to severe capsizing forces. The structure of a successful set of standards will identify those vessels which are most vulnerable to such forces, and it is then a matter of discretion on the part of the appropriate authority to determine the level at which a vessel is deemed too vulnerable. This level, of course, depends in turn upon the acceptability of risk. When sailing ships were trading in large numbers, workers were exposed to higher levels of risk, both at sea and ashore, and these risks were considered acceptable. Current expectations are for reduced levels of risk, particularly by those paying a fee for their transport or leisure activities, and it is because of this general raising of standards that some vessels which were once considered sufficiently seaworthy are no longer considered so.

The general lack of appropriate stability requirements for sailing vessels came to light during the investigations into the loss of the sailing vessel 'Marques'. Stability criteria are set by some countries, notably those where sailing vessels have remained a prominent part of a naval or merchant seaman's training, although they vary considerably in complexity and severity. The UK introduced mandatory stability requirements for all merchant ships in 1968. They were based upon the IMO Resolution A167, but in reality were appropriate only for mechanically propelled ships. Since the decline of sail power, requirements applicable to sailing vessels have been largely ignored.

During the Marques investigation the Wolfson Unit carried out, for the UK Department of Transport, a study of UK sailing vessels and also the stability requirements used in other countries and their suitability, Ref. 1. This study revealed that more than 70% of UK ships engaged in sail training carried no stability information and that there was a lack of understanding of the mechanism of wind heeling and the dynamics of capsizing. The report of the court of enquiry, Ref. 2, recommended that further work be conducted to research the subject and develop a set of requirements with a more technical basis than those currently in existence.

The Wolfson Unit was asked to conduct the necessary work and make suggestions on future standards. The work was carried out during 1988 and the resulting recommendations have now been adopted by the Department of Transport in their 'Code of Practice for the Construction, Machinery, Equipment, Stability and Survey of Sail Training Ships Between 7 metres and 24 metres in Length'.

2. BACKGROUND WORK

The stability of vessels under sail has traditionally been assessed in terms of the power to carry sail. This is merely a measure of the initial stability or stiffness of the vessel and gives no indication of its ability to withstand heeling to large angles. In the late nineteenth century analytical studies by Reed, Ref. 3, and White, Ref. 4, resulted in an appreciation of the importance of looking beyond initial stability, and a method of calculating the dynamic response of a vessel to a gust was adopted which remains pivotal to the most advanced standards currently applied by the authorities.

More recently, with the ability to determine stability characteristics by computer, the attention of the U.S. Coast Guard was turned to the problem of assessing the stability of the large number of sailing vessels offering short voyages along their Atlantic Coast. The work of Beebe-Center and Brooks, Ref. 5, and later Long and Marean, Refs. 6 and 7, produced the only significant advance in assessment methods and formed the basis of the Coast Guard's regulations, which are the most thoroughly researched of those in use by other authorities. Their rules set minimum levels for the wind pressures required to heel a vessel to the angles of deck edge immersion under steady conditions, and downflooding and capsize under dynamic conditions. The heeling moments and dynamic responses are determined in the normal way, and the minimum requirements were derived from a statistical study of known vessels and casualties. The rules and their limitations are discussed in Ref. 1.

A major criticism of existing regulations is that, in evaluating the stability of a vessel by assessing its ability to withstand certain conditions, with either full sail or a fixed proportion of that sail area set, a vessel with poor stability characteristics can gain approval by removing part of the

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*Wolfson Unit, M.T.I.A., University of Southampton

rig. Thus there are sailing vessels approved by various authorities which sail without, say, their topmasts. These vessels are severely handicapped when the winds are light, being unable to set sufficient sail to make good progress, but are still able to set the same sails in more dangerous storm conditions as they could prior to regulation.

In response to the tragic Fastnet race of 1979 when a large proportion of the fleet of racing yachts capsized, a flurry of research activity on both sides of the Atlantic resulted in a scientific appreciation of the mechanism of capsizing in breaking waves. References 8 and 9 discuss the results of the research, which demonstrated the importance of this mode of capsize, and highlighted the fact that many modern designs, being influenced mainly by yacht rating methods, are less seaworthy in this respect than traditional yachts. Yacht rating authorities responded with amendments to their rules to address the stability aspect, and these continue to be developed, although as yet with limited success in reducing the vulnerability of racing fleets to breaking wave capsize.

3. ASSUMPTIONS MADE IN CONVENTIONAL METHODS

Calculations of statical stability can be carried out to a high degree of accuracy, but their application to the case of a vessel in a seaway involves many assumptions, in particular that the influence of waves is negligible. Similarly the conventional calculation of wind heeling and its effects on stability incorporate a number of assumptions which should be questioned. Ref. 10 includes a discussion of these assumptions and attempts to quantify their effects where possible. Those of most interest here are as follows:

i) The wind is of uniform velocity at all elevations.
ii) All sails are aligned along the ship's centreline.
iii) All sails have a heeling force coefficient of unity.
iv) Overlapped sail areas produce no heeling moment.
v) The heeling moment is maximised with the wind on the beam.
vi) Heeling moments vary with $\cos^2$ (heel angle).
vii) When considering response to a gust, the increase in wind speed is instantaneous.
viii) When struck by a gust the vessel is upright.
ix) The vessel's inertia and damping have no effect on its gust response.

There is no experimental or theoretical justification for any of these and only the first has been studied in detail. Much work has been done by meteorologists and engineers in the civil and aeronautical fields to define the wind gradient generated in the atmospheric boundary layer. A good account of the state of the art is given in Ref. 11. Considerable discussion in recent years has revolved around the remaining assumptions and, prior to the compilation of new U.K. stability standards, it was felt that they should be investigated by full scale measurement or physical modelling. In addition to this work the effect of following seas on sailing vessels' stability properties was investigated by computer modelling.

4. SUMMARY OF EXPERIMENTAL TECHNIQUES

4.1 General

Having identified the shortcomings of other regulations in terms of the assumptions inherent in them, a programme of work was devised to resolve the unknown aspects. It comprised wind tunnel tests to measure the forces and moments on a variety of rigs, tests in a specially developed facility to investigate the response of vessels to gusts, and measurements onboard sailing vessels during their normal course of operation. A detailed description of these tests is beyond the scope of this paper but the following outlines, it is hoped, will enable a general appreciation of the processes involved.

4.2 Force and Moment Measurements

Tests were conducted on a six component balance, built specifically for this work, which minimised interference with the wind tunnel floor and the model mounting system. The model was suspended via the dynamometer, in a tank of water within a turntable. The model could be restrained upright or at the desired heel angle and yawed to any heading. The system was mounted in the floor of a large boundary layer wind tunnel. Two models were used: a 1:25 scale model of the Jubilee Sailing Trust's barque 'Lord Nelson' and a 1:30 scale model of a proposed 56 metre 3 masted staysail schooner. The models enabled a variety of both fore and aft, and square rigs to be tested. Figure 1 shows the barque model undergoing tests.

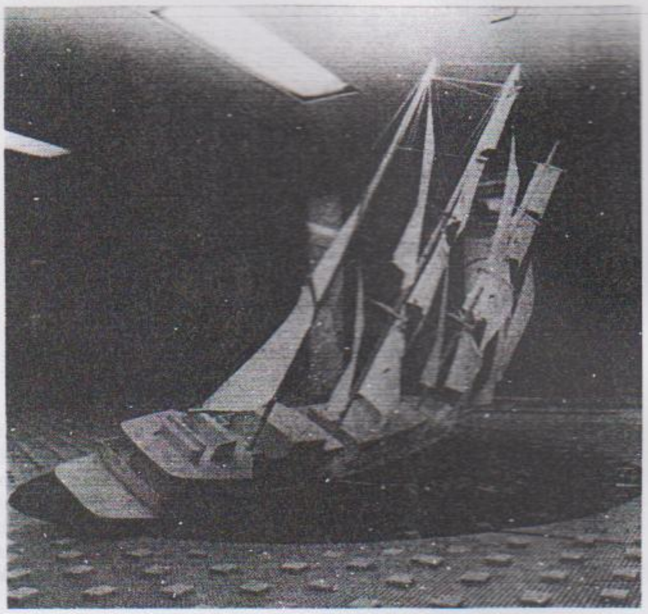

Fig. 1. A model on the six component balance in the wind tunnel.

4.3 Gust Response Tests

In the same wind tunnel, a pond was constructed in which Froude scaled models could be floated and subjected to gusts of wind. Gusts of various characteristics were generated by opening an array of shutters downstream of the pond. The model was prevented from sailing forwards but was otherwise unrestrained. Its response was measured by a roll gyro and compared with the wind pressure time history which was monitored simultaneously. A 1:25 scale model of the 'Lord Nelson' was again used, together with a 1:9 scale model of a Nicholson 55 cutter. By movement of ballast the stability and inertia of the models could be varied. Figure 2 shows the cutter model prepared for testing.

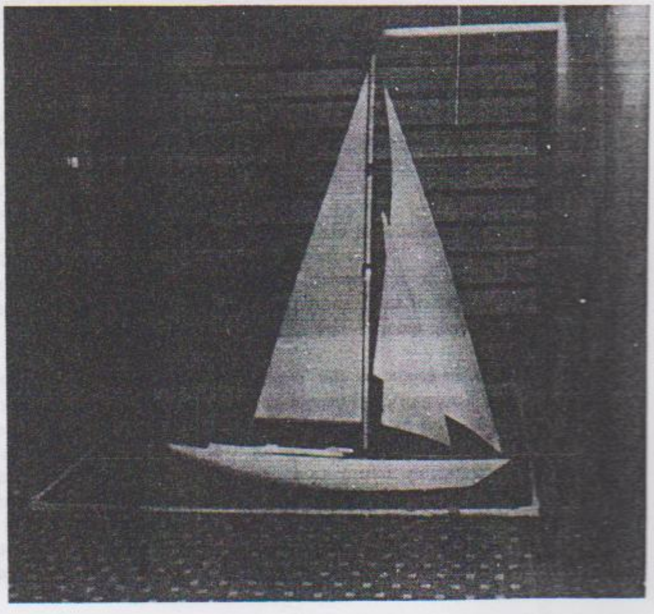

Fig. 2. A model prepared for testing in the gust facility.

4.4 Full Scale Measurements

To enable validation of the tests, and obtain firm evidence of how sailing vessels behave at sea, recording instrumentation was installed on both the 'Lord Nelson', and the Nicholson 55 'Kukri' operated by the Joint Services Adventurous Sail Training Centre.

An anemometer, wind direction indicator, and clinometer were linked to a portable computer which acquired data every second and stored it in blocks of two minutes. By programming the system to store only those data of most interest, it could be left unmanned for voyages of up to two weeks duration, the collected records being retrieved for analysis on the vessel's return to port. These records were supplemented by regular entries by the crew in a log book to provide a record of the sails set. In this way a large volume of interesting data was gathered throughout the 1988 sailing season with no interference to the vessels' operations and with the minimum use of the Wolfson Unit's staff.

5. WIND HEELING MOMENTS

5.1 Effect of Wind Gradient

Wind speeds are quoted by meteorologists at a standard height of 10 metres. Above this the speed will be greater and, at ground level, will reduce to zero. Up to about 100 metres the wind speed varies generally according to a log law but is dependant on the terrain and various atmospheric conditions. The gradient in an offshore wind is thus likely to be very different from that in an onshore wind.

The wind gradient causes the upper part of the rig to contribute a relatively large proportion of the heeling moment while the hull, being in a region of very low velocity, has a small contribution. The gradient contributes to a reduction in heeling moments at large angles of heel, and results in large sailing ships with tall rigs being exposed to velocities considerably greater than those quoted at the standard height.

5.2 Heeling Moment Coefficients

Wind heeling moment coefficients are normally defined with the vessel upright, as

$$C = \frac{M}{PAH}$$

Coefficients were determined from the wind tunnel tests using the formula

$$C = \frac{M}{\Sigma(pah)}$$

By summing the (pah) contributions over the full height of the rig, the total pressure x area x lever of the rig in the measured wind gradient was obtained.

Prior to the wind tunnel tests it was anticipated that different coefficients might be derived for sails of various planforms, and that these, in conjunction with the area of each sail, its height, and an approximation of the wind gradient, would enable a good prediction of the heeling moment of a particular rig. In practice however the coefficients were found to vary significantly as a result of sail sheeting and camber, and these effects were as important as those due to planform.

The crew of a sailing vessel sheets the sails to suit the apparent wind angle, and the heeling moment varies with this angle, generally reaching a maximum value at some close hauled condition. If, when sailing upwind the vessel alters course to increase the apparent wind angle without easing the sheets, the heeling moment may increase still further. The same effect will occur when a gust or wind shift causes a change in the apparent wind direction. The maximum possible heeling moment does not therefore correspond to a normal sailing condition.

Square rigged vessels, because of limitations on the angle to which the yards can be braced and the high windage of the rig, cannot typically sail at apparent wind angles of less than 50 degrees. Their heeling moment is maximised with the sails set for this angle but with the apparent wind at about 90 degrees. The heeling moment coefficient is then about 1.2 if sail overlaps are neglected in the usual way. Thus the worst possible case is when struck by a gust on the beam while the sails are sheeted for sailing close hauled.

For a fore and aft rigged vessel, which will typically be able to sail at smaller apparent wind angles, the heeling moment is maximised with the sails again sheeted in tight, but with the apparent wind angle between 40 and 60 degrees. Coefficients will then be about 1.5 but may exceed 2 in some circumstances.

Coefficients are thus very variable and difficult to predict from a sail plan, and are further complicated by the aerodynamic efficiency of the rig. An illustration of their variability even for a particular boat is provided by Figure 3 showing data obtained on the Nicholson 55 with mainsail and no. 1 genoa set. The different symbols indicate data aquired at different times during a single passage. The vertical axis is the heel angle divided by the nominal wind pressure, that is the dynamic pressure at a height of 10 metres. As the GZ curve is virtually linear over the range of typical sailing angles, this expression is proportional to the heeling moment coefficient. In this illustration therefore, the heeling moment coefficients vary by ± 40% from the mean at the same apparent wind angle. It is interesting to note that the lower bands of data were gathered at night when the crew were presumably not driving the yacht as hard.

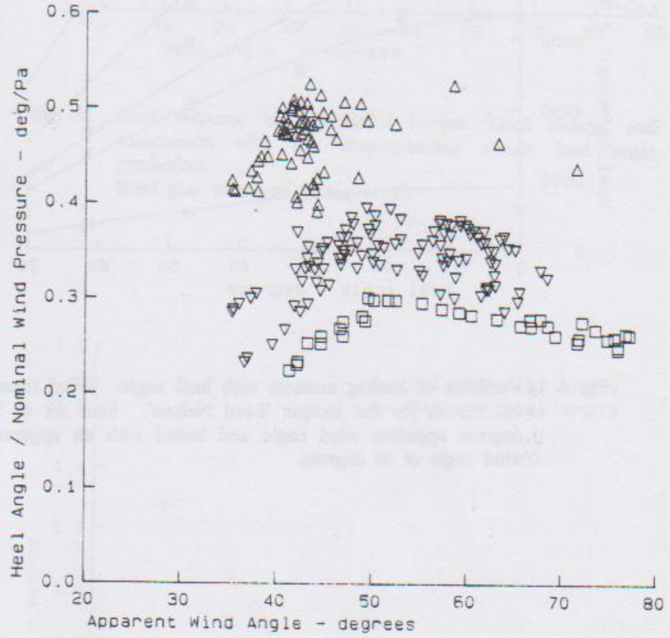

Fig. 3. Full scale data showing the variation of heeling moment coefficient, to which the vertical scale is proportional, for a single combination of sails.

5.3 Variation of Heeling Moment with Heel Angle

Naval Architects concerned with yacht performance assume that the heeling moment varies with cosθ. This assumption was validated in the wind tunnel tests for close hauled sailing conditions up to heel angles of about 30 degrees. Regulatory authorities concerned with stability at large angles assume that the heeling moment varies with $\cos^2\theta$, which would be the case for a flat plate retaining a coefficient of unity at all angles. With the upright heeling moment maximised however, the moment was found to vary with $\cos^{1.3}\theta$. This function gave the best fit to the data in general, and indeed gave a good fit whether considering square rig, fore and aft rig, or even bare poles. Figures 4 & 5 show wind tunnel test results for a number of configurations to support this conclusion, and that suggested in 5.1 above, that the heeling moment at 90 degrees of heel is negligible compared with the upright value. For the barque under bare poles the upright value is lower than that at 17 degrees because when upright the yards are aligned to the wind. Further evidence was obtained from the gust test facility where the function again fitted the data well but, fortunately for the crews, the full scale data included few samples at heel angles beyond 30 degrees and so a comparison could not be made.

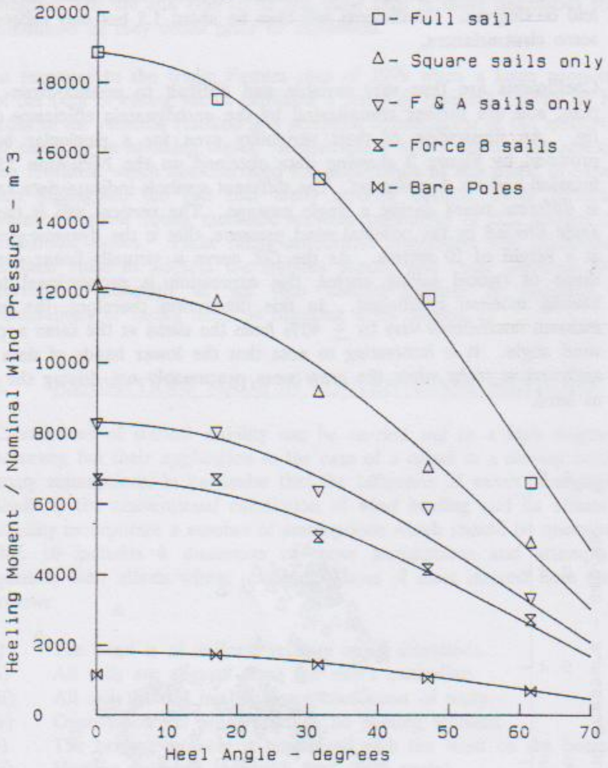

Fig. 4. Variation of heeling moment with heel angle. Wind tunnel test results for the barque 'Lord Nelson'. Sails set at 50 degrees apparent wind angle and tested with an apparent wind angle of 90 degrees.

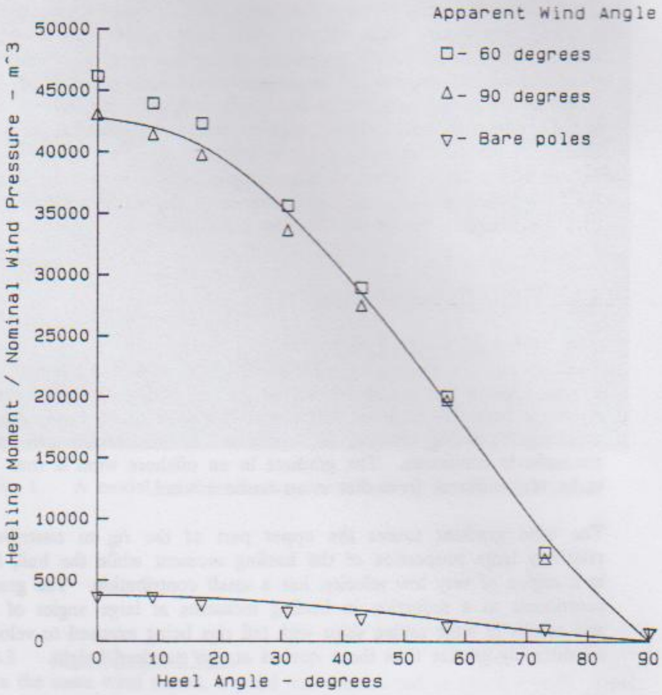

Fig. 5. Variation of heeling moment with heel angle for the schooner with wishbone rig. Sails set at 35 degrees apparent wind angle.

6. RESPONSE TO GUSTS

6.1 Conventional Assessment

Assumptions vii to ix in Section 3 are inherent in the normal method of prediction of gust response, that is the energy balance method. It is assumed that when a gust strikes, the vessel will heel until the area under the wind heeling moment curve (work done by the wind) is equal to the area under the righting moment curve (energy absorbed by the hull). By predicting the heeling moment and equating these areas the resulting heel angle is determined. Refinements to this method incorporate the effects of the initial steady heel angle and perhaps the effects of being initially rolled to windward as in the beam wind and rolling criteria used for other types of vessel.

6.2 Gust Characteristics

Gusts may be broadly divided into two types. The atmospheric boundary layer contains turbulence at a range of frequencies and amplitudes. Turbulence levels are dependant on terrain roughness but over the sea the strongest gusts are unlikely to exceed a velocity 1.4 times the hourly mean, Ref. 11. Significant gusts of this type typically have a rise time of 10 to 20 seconds and a short duration, normally less than a minute.

The second type are produced by small scale weather systems and are normally known as squalls. Little is known of their characteristics since they are of no interest to most engineers, their maximum speeds being less than those encountered in periods of very high mean wind speeds such as hurricanes. They are however one of the greatest fears of sailing vessel masters, and indeed the cause of most disasters, since they may strike the vessel with little warning during a period of generally light winds. Squalls have been recorded with wind speeds up to 10 times the mean for the previous hour, that is 100 times the wind pressure. Often generated by the descent of cold air from a storm cell, they may have associated with them a downward component, may completely destroy the wind gradient, and may strike from any direction as the descending air radiates near sea level. Their rise time is variable and they may last for several minutes.

Because the rise time of a significant gust is normally greater than the natural roll period of a sailing vessel, the vessel does not respond as if to a sledgehammer blow to the mast, but is able to adjust its heel angle as the heeling moment increases.

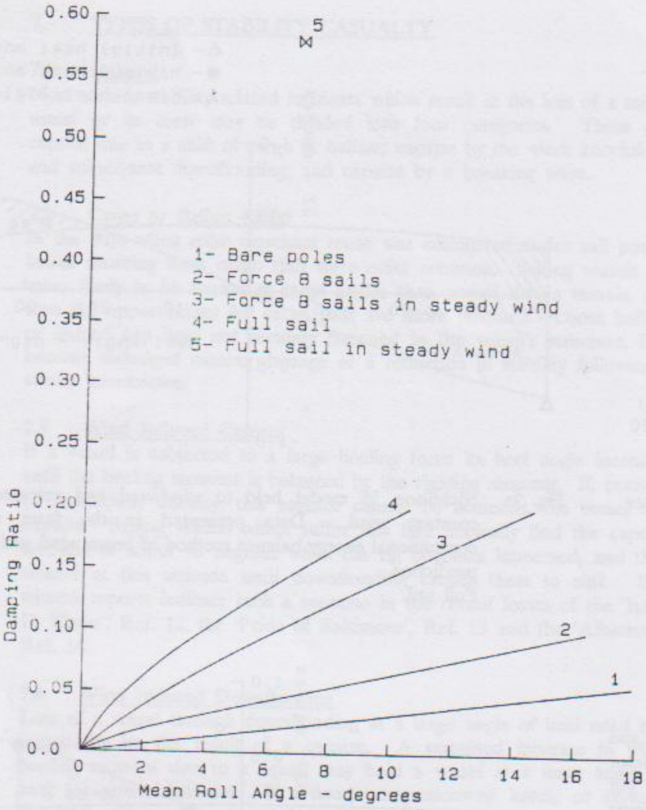

Fig. 6. The effect of sails on damping. Data from the gust test model barque 'Lord Nelson'.

6.3 Effect of Damping

Figure 6 presents curves of damping ratio obtained from roll decrement measurements with the barque model in three different configurations. Damping Ratio = $\ln(\theta_n/\theta_{n+1})/\pi$ where θ_n and θ_{n+1} are consecutive roll amplitudes to port and starboard.

With bare poles the damping is purely the hydrodynamic contribution from the hull. The addition of sails causes a significant increase in the damping, and a further increase is provided with wind applied to the sails. In this case the damping ratio with full sail in a steady wind is 0.58 at a mean roll angle of 6.8 degrees compared with 0.15 in still air, and 0.02 under bare poles. These results are for a model with no forward speed, and for a vessel under way the hydrodynamic damping will be increased. The tests with a model restrained from sailing forwards, therefore represented the worst case, but by no means an unrealistic one. The vessel 'Isaac H Evans', Ref. 12, capsized and sank after failing to complete a tack and being struck by a gust from abeam whilst stationary, fortunately without loss of life as it was close inshore at the time.

When the rise time of the gust is short, the high damping provided by the rig prevents the vessel from responding in the dynamic way normally considered by naval architects. Figure 7 presents model test data for the barque when struck by gusts of both brief and prolonged duration. In order to develop these plots, the initial heel angle measured in a steady wind was first marked on the GZ curve. A heeling arm curve was then drawn through this point using the $\text{Cos}^{1.3}\theta$ function. The measured gust factor was then applied to the upright heeling arm and a second heeling arm curve drawn. The intersection of this curve with the GZ curve indicates the heel angle that would be expected with a steady wind at the gust velocity. The measured values of the maximum heel angles show good correlation with these steady heel angles due to the gusts. There was obviously some scatter in the experimental data but the measured maximum heel angle never exceeded the predicted steady heel angle due to the gust by more than 10%, except when the maximum heel angle was less than 20 degrees and the experimental errors were thus magnified.

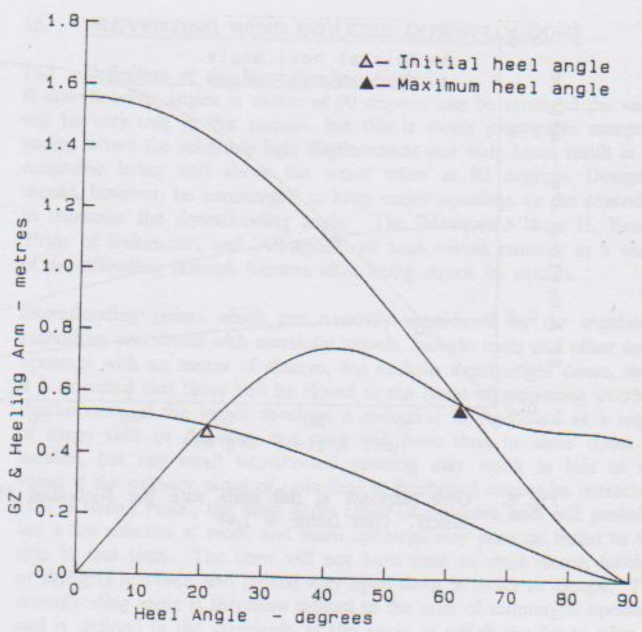

Fig. 7a. Gust response of the model barque 'Lord Nelson' and comparison with the corresponding steady heel angle prediction.
Brief gust with gust factor = 1.7

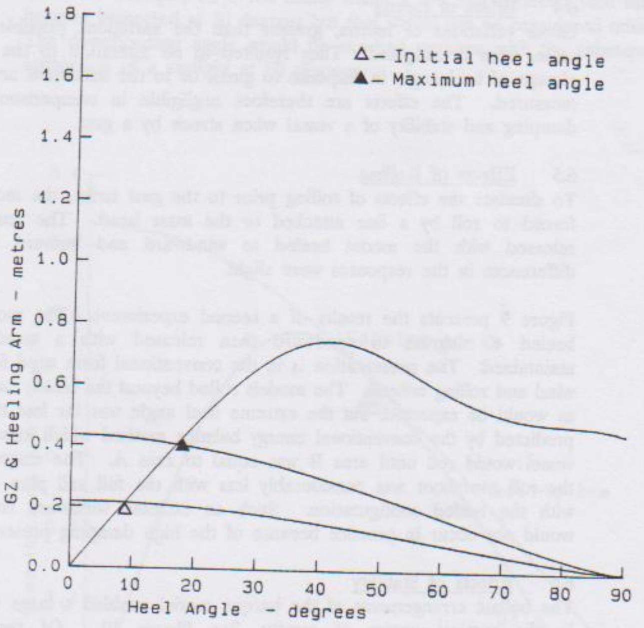

Fig. 7b. Prolonged gust with gust factor = 1.4

The greatest heel angle overshoots were obtained with heavily reefed sail plans, when the aerodynamic damping was reduced, but these remained within the range described.

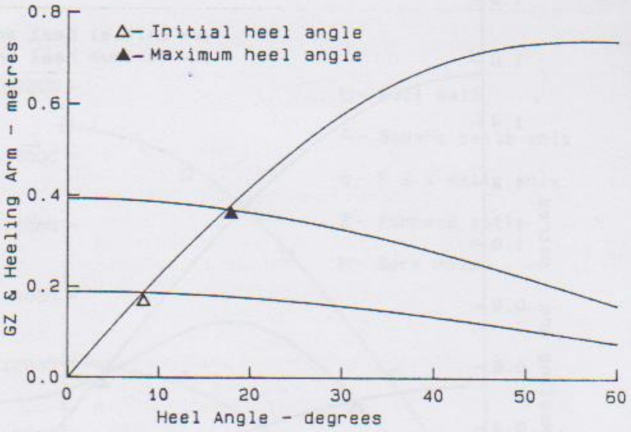

Fig. 8. Gust response at full scale with the Nicholson 55 cutter 'Kukri'. Gust factor = 1.44

Full scale measurements confirmed this finding for both vessels, and Figure 8 shows a sample result for the Nicholson 55. The gust factor exceeds 1.4 here not because the vessel was struck by a squall but because the wind speed immediately prior to the gust strike was lower than the hourly mean to which the gust factor normally refers.

6.4 Effect of Inertia

Gross variations of inertia, greater than the variations possible at full scale, were investigated. They resulted in no alteration to the rate of change of heel angle in response to gusts, or to the maximum heel angle measured. The effects are therefore negligible in comparison to the damping and stability of a vessel when struck by a gust.

6.5 Effects of Rolling

To simulate the effects of rolling prior to the gust strike, the model was forced to roll by a line attached to the mast head. The gusts were released with the model heeled to windward and leeward but the differences in the responses were slight.

Figure 9 presents the results of a second experiment. The model was heeled 40 degrees to windward then released with a steady wind maintained. The presentation is in the conventional form used for beam wind and rolling criteria. The models rolled beyond the steady heel angle as would be expected, but the extreme heel angle was far less than that predicted by the conventional energy balance method which assumes the vessel would roll until area B was equal to area A. The magnitude of the roll overshoot was considerably less with the full sail plan set than with the reefed configuration. Such an extreme windward roll angle would not occur in practice because of the high damping present.

6.6 Effects of Stability

The ballast arrangements of the barque model enabled a large variation in the vertical centre of gravity, See Figure 10. Of these four configurations the only one which could be knocked down in the gust test facility, as might be expected, was the high KG case with a range of only 67 degrees.

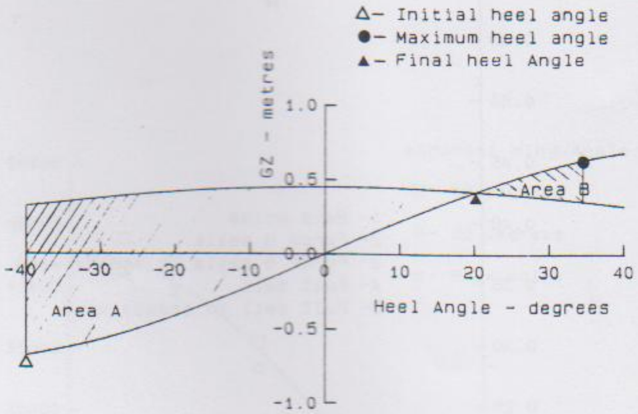

Fig. 9a. Nicholson 55 model held to windward and released in a constant wind. Data presented in the form of the conventional energy balance method of beam wind and rolling prediction.
Full sail.

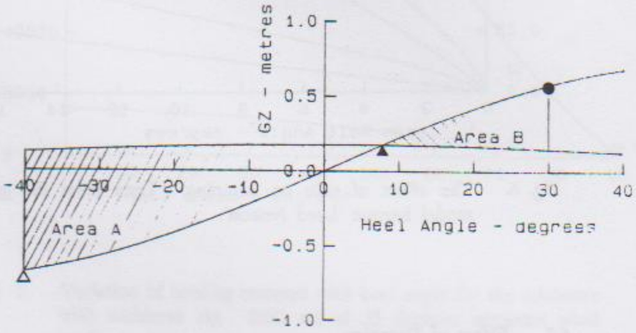

Fig. 9b. Reduced sail.

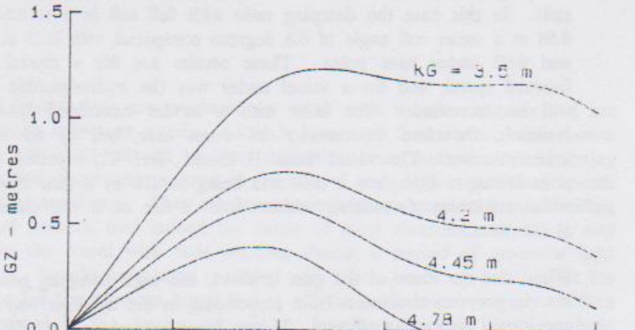

Fig. 10. Stability curves for the barque corresponding to the conditions at which the gust model was tested. The ship has a KG of 4.2m.

7. TYPES OF STABILITY CASUALTY

7.1 General

Most serious stability related incidents which result in the loss of a sailing vessel or its crew may be divided into four categories. These are: capsize due to a shift of cargo or ballast; capsize by the wind; knockdown and subsequent downflooding; and capsize by a breaking wave.

7.2 Cargo or Ballast Shift

In the days when most merchant trade was conducted under sail power, losses resulting from cargo shift were quite common. Sailing vessels are more likely to be heeled to large angles than power driven vessels, and thus the opportunities for cargo shift are more frequent. Loose ballast, or indeed any item not securely fastened to the vessel's structure, may become dislodged causing damage or a reduction in stability following a severe knockdown.

7.3 Wind Induced Capsize

If a vessel is subjected to a large heeling force its heel angle increases until the heeling moment is balanced by the righting moment. If, because of insufficient stability, this balance cannot be achieved, the vessel will capsize. Sailing vessels which suffer this fate normally find the capsize arrested at about 90 degrees when the rig becomes immersed, and they remain at this attitude until downflooding causes them to sink. Eye witness reports indicate such a scenario in the recent losses of the 'Isaac H. Evans', Ref. 12, the 'Pride of Baltimore', Ref. 13 and the 'Albatross', Ref. 14.

7.4 Wind Induced Downflooding

Loss of a vessel through downflooding at a large angle of heel need not necessarily be the result of a capsize. A sustained increase in wind heeling moment due to a squall may hold a vessel at a large angle of heel for several minutes. If a door, companionway, hatch, or skylight becomes submerged under such circumstances, total loss may result.

7.5 Breaking Wave Induced Capsize

The horizontal and rotational energy imparted to a vessel when struck by a large breaking wave on the beam, may be sufficient to knock it down beyond 90 degrees. Indeed there have been numerous incidents, notably during the 1979 Fastnet race, when small vessels have been rolled through 360 degrees.

8. PREVENTING LOSS OF STABILITY BY CARGO OR BALLAST SHIFT

The Department of Transport's new standards do not address the problem of cargo stowage since they are aimed primarily at sail training vessels. Many of the sail training ships now in operation carry stones or metal pigs in the bilge. These and all other heavy items are required to be secured to prevent movement in the event of a knockdown to 90 degrees. The attachment of external ballast keels is not specifically addressed but all structural aspects of the hull are required to be approved by a classification society or the approval authority.

9. PREVENTING WIND INDUCED CAPSIZE

Figure 11 shows the GZ curve of the Isaac H. Evans in a fully laden condition. Whilst it has a range of stability of 75 degrees, if it were to be capsized by a steadily increasing wind, it would have no reserve of righting moment, and would thus capsize, if the wind caused the steady heel angle to exceed 40 degrees. The effective range of stability of the 'Isaac H. Evans' under wind heeling was therefore just 40 degrees. The effective range of stability under wind heeling can be found for other sailing vessels simply by drawing a series of heeling arm curves using the formula: Heeling Arm = $x \cos^{1.3}\theta$ for various values of x. By trial and error a curve will quickly be found which is tangential to the GZ curve at some angle. Such a condition will only be found however if the range of stability is less than 90 degrees. By this principal a vessel whose range is less than 90 degrees is particularly vulnerable whilst a vessel with a range in excess of 90 degrees cannot be capsized by the wind unless it has a downward component. The standards therefore require a minimum range of 90 degrees.

10. PREVENTING WIND INDUCED DOWNFLOODING

10.1 Definition of the Downflooding Angle

If downflooding angles in excess of 90 degrees can be arranged the vessel will be very safe in this respect, but this is rarely practicable except in yachts, where the relatively light displacement and wide beam result in the centreline being well above the water when at 90 degrees. Designers should, however, be encouraged to keep major openings on the centreline to maximise the downflooding angle. The 'Marques', 'Isaac H. Evans', 'Pride of Baltimore', and 'Albatross', all sank within minutes as a result of downflooding through hatches after being struck by squalls.

Downflooding points which are normally considered by the regulatory authorities concerned with merchant vessels, include vents and other small openings with no means of closure, but exclude weathertight doors, since it is expected that these will be closed at the onset of worsening weather. Furthermore, if the vessel develops a reduction in freeboard as a result of cargo shift or flooding, the crew will have time to close doors or hatches, but any small unprotected opening may result in loss of the vessel if the primary cause of reduction in freeboard cannot be corrected. For a sailing vessel, the most likely cause of excessive heel will probably last a few minutes at most, and small openings may pose no threat to the ship in that time. The crew will not have time to close doors, hatches or skylights however, and indeed may open them in order to escape. The downflooding angle is therefore related to the area of submerged openings and is defined in the standards as the angle at which the lower edge of the critical opening becomes submerged. That is the opening which, if submerged, would result in a certain total area of openings being immersed. The area is determined by the formula:

$$\text{Area (metres}^2\text{)} = \frac{\text{Displacement (tonnes)}}{1500}$$

With a smaller area immersed the vessel could probably survive without serious loss of stability for up to 5 minutes.

Thus, for example, on a 100 tonne vessel a 200 mm diameter vent might become immersed at 50 degrees but that would not be considered critical. The downflooding angle would be reached perhaps with the subsequent immersion of a skylight at 60 degrees.

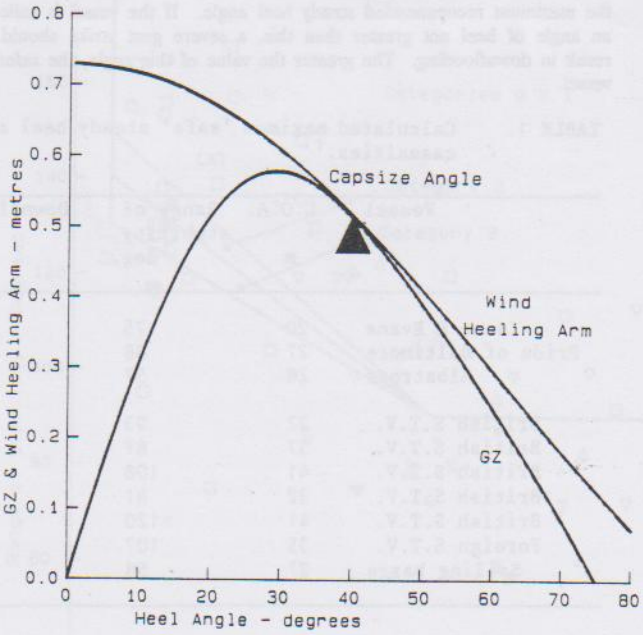

Fig. 11. The stability curve of the 'Isaac H. Evans' with a heeling arm curve leading to capsize.

10.2 Preventing Downflooding in Gusts

10.2.1 Identifying the Problem

There is an enormous variation of vessel types to be considered by these standards and some typically sail at 30 degrees of heel whilst others rarely heel beyond 10 degrees. To suggest a single angle, such as say 60°, as a minimum criterion for downflooding may therefore be rather lenient on a yacht, but extremely onerous on a low freeboard ship with very little sail area. A vessel is vulnerable to downflooding if it sails at an angle which is close to its downflooding angle, and is thus susceptible to immersion of an opening when struck by a gust. In the past, the approach of the authorities has been to attempt to calculate the heel angle at which a vessel will be sailed in certain conditions, and compare this with the angle of deck edge immersion. This research has shown that such predictions of heel angle are worthless and, as most yachtsmen know, a sailing vessel is operated for much of the time up to a limiting heel angle at which sail area is reduced. The angle is governed by the master's feel for the safety of the vessel and a compromise between speed and comfort. What the master cannot include in his assessment is what the effect would be of a severe gust strike when sailing at that angle.

10.2.2 Development of a Maximum Recommended Steady Heel Angle

The logic used in the analysis of the gust tests and sea trials data, described in section 6.3, may be used in a slightly different way to determine at what steady heel angle a vessel becomes vulnerable to downflooding in the event of a severe gust. The derivation of this angle is illustrated in Figure 12.

The method requires no knowledge of the sail plan since the incident may occur in, say a force 5 under full sail, or a force 10 under storm canvas. If the strongest possible gust were to be encountered the heeling moment would be doubled regardless of the sail plan set, and so the response of the vessel would be virtually the same.

Armed with merely the GZ curve and downflooding angle, the upright heeling arm which would result in downflooding can be derived using the equation:

$$HA_o = \frac{GZ_f}{\cos^{1.3}\theta_f}$$

If the gust producing this incident results in twice the pressure of the mean wind i.e. a gust factor of 1.4, the preceding mean heeling arm would have been half this value. Thus the mean wind heeling arm curve can be drawn and its intersection with the GZ curve found to determine the maximum recommended steady heel angle. If the vessel is sailed at an angle of heel not greater than this, a severe gust strike should not result in downflooding. The greater the value of this angle, the safer the vessel.

The information should be of considerable interest to the sailing vessel master who can use it to judge his safety in terms of stability at all times except if running before the wind. Then the steady heel angle may be low but if broached or struck by a gust on the beam, a large heel response could result. The information is therefore required to be included in the stability information booklet. The likelihood of encountering a gust of sufficient duration to cause serious downflooding, with a speed 40% higher than the hourly mean, is highly unlikely. The master watching his clinometer will not however be mentally averaging the last hour's readings, but will perhaps be aware of the readings over the last 5 or 10 minutes, and a gust factor of 1.4 based on the 5 or 10 minute mean is a real threat.

The standards thus put the onus of responsibility on the master to maintain a safe angle of heel. In order to guard against the operation of a vessel with a particularly low downflooding angle, which would result in an unrealistically low maximum steady heel angle, the standards stipulate for that angle a lower limit of 15 degrees. This limit was selected after consideration of the values derived for known vessels including casualties. Samples of these data are presented in Table 1.

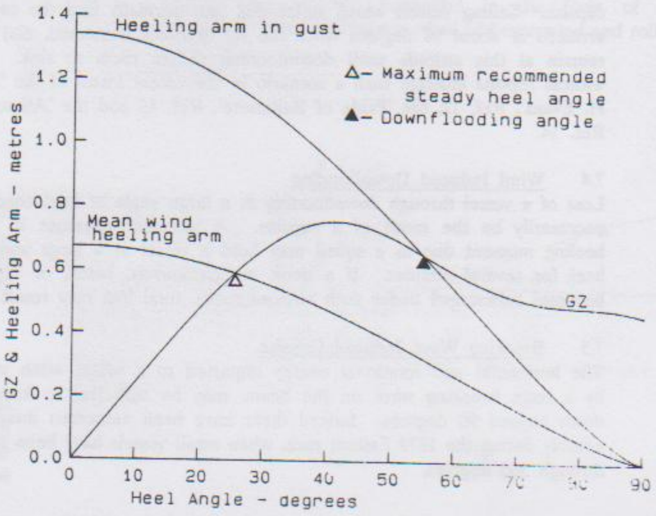

Fig. 12. Method of derivation of the maximum steady heel angle to prevent downflooding in gusts.

TABLE 1. Calculated maximum 'safe' steady heel angles for a number of vessels. The first three are stability casualties.[1]

Vessel	L.O.A. m	Range of stability deg.	Downflooding angle deg.	Effective range under wind heeling	Steady heel angle prior to gust (factor=1.4) which will result in: Downflooding	Capsize
Isaac H Evans	20	75	40	40	12	12
Pride of Baltimore	27	88	55	54	15	15
Albatross	28	57	57	31	*	12
British S.T.V.	27	93	37	>90	16	**
British S.T.V.	37	87	46	80	21	30
British S.T.V.	41	108	55	>90	23	**
British S.T.V.	32	81	44	45	15	15
British S.T.V.	41	>120	87	>90	>80	**
Foreign S.T.V.	35	107	72	>90	50	**
Sailing barge	27	58	64	30	*	11

* - indicates that the vessel will become unstable and capsize before the downflooding angle is reached.
** - indicates that this angle cannot be defined for a vessel having positive stability beyond 90 degrees.

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[1] The 'Marques' has been excluded from these data.

10.3 Preventing Downflooding in Squalls

Maintaining a mean heel angle below the maximum recommended will not necessarily provide protection against downflooding in a squall, since the wind pressure produced by a squall may be many times that of the preceding wind. A further requirement of the stability booklet is a graphical presentation of the maximum heel angle at which the vessel may be sailed in a given wind speed, in order to withstand a squall of a certain strength. Curves of maximum steady heel angle for the prevention of downflooding in squalls are derived using the same logic as was developed for deriving the corresponding angle for gusts.

If it is assumed that a 45 knot squall will heel the vessel to the downflooding angle, the corresponding heel angle can be found for the vessel with the same sails set in a lesser wind speed which might preceed the squall. By the use of a range of preceding wind speeds a curve can be defined.

Figure 13 shows an example of this graph. If the master considers squalls are an imminent threat, and that they may be of, say, about 45 knots, he should reduce sail until the heel angle at the prevailing wind speed is below the 45 knot line. A reliable anemometer and clinometer are thus a further requirement of the standards.

This information cannot be used as a definitive prediction of heel angle in a squall since squall speeds cannot be reliably predicted. It is hoped however that familiarity with this graph will enable the master to judge his level of safety in terms of stability. Furthermore, when making his decision on whether or not to shorten sail, he will have at his disposal one more piece of information than has previously been available.

10.4 Preventing Downflooding through Minor Openings

The standards also state that no opening, regardless of size, should be immersed at an angle less than 40 degrees. This is to ensure protection of machinery and equipment under normal sailing conditions, when rolling in beam seas, or during the passage of waves which may cause occasional ingress of water.

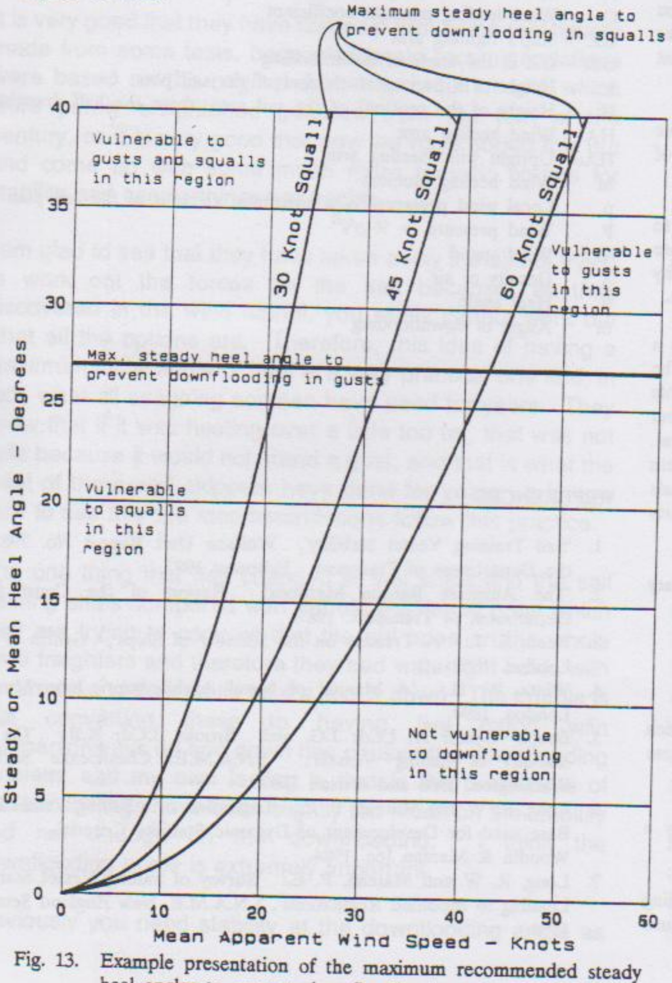

Fig. 13. Example presentation of the maximum recommended steady heel angles to prevent downflooding in gusts and squalls.

11. PREVENTING BREAKING WAVE CAPSIZE

The research described in Refs 8 and 9 indicate that the most important characteristic for survival of a breaking wave capsize is a large range of stability, since vessels with low ranges are prone to remaining inverted following such an incident. Furthermore, the vessels most vulnerable to such a capsize are wide, shallow, light hulls, and these characteristics normally go hand in hand with a relatively low range of stability. It is likely therefore, that a vessel with a low range will be more likely to capsize and less likely to self-right than one with a large range of stability. A high roll inertia is of benefit in reducing capsize vulnerability but is difficult to calculate or measure and so has not been incorporated in the standards.

The larger the wave encountered, the more likely is the capsize, so smaller vessels have a higher probability of capsize. To maintain a more even probability of capsize the standards require a greater range of stability for smaller yachts. Figure 14 presents the requirements graphically with a number of actual vessels superimposed. The Wolfson Unit's proposal was for a single category using the most stringent requirement shown. Discussions with representatives of the sail training industry resulted in a modification of this proposal. As a consequence various regional categories were developed for those vessels operating closer to land; the coastal (3) and near continental (2) categories requiring a lesser range than the offshore categories (0 and 1) Vessels of less than 7 metres are not subjected to these standards so the range requirements are terminated at that length, and 90 degrees is the minimum requirement for vessels greater than 24 metres in length.

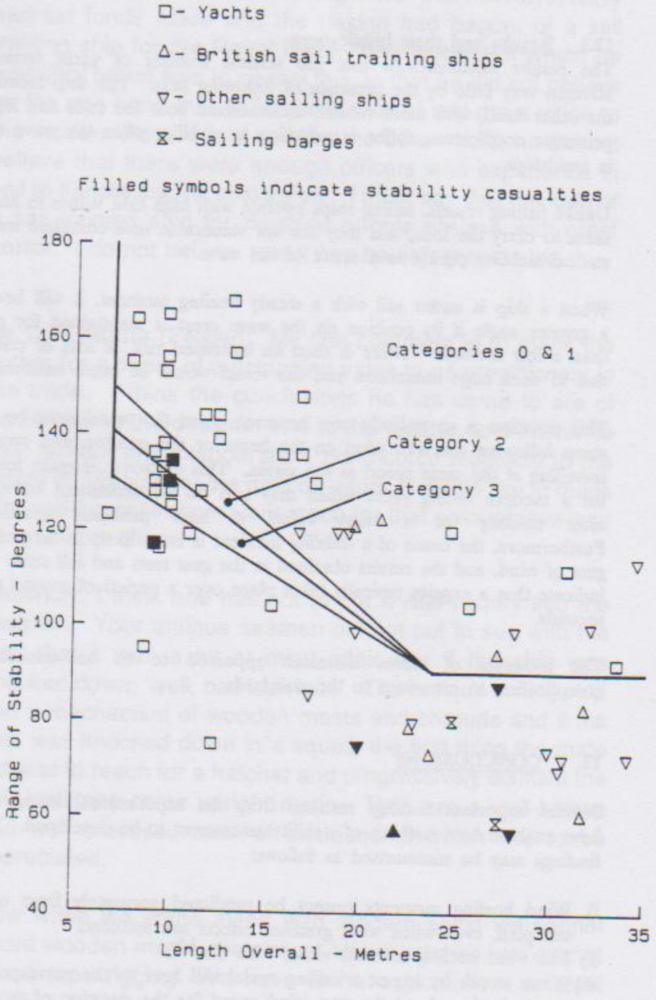

Fig. 14. Range of stability of the vessels studied and the minimum range requirements for operation in the various regional categories.

Traditional cruising yachts all lie well above the upper line whilst racing yachts designed to the current rating rules generally lie below it. Many modern cruising yachts are based on successful racing forms and therefore lie close to the line or in the lower categories. Despite changes in the rating rules aimed at encouraging good large angle stability, the average range of stability of racing yachts appears to be decreasing.

12. THE EFFECTS OF WAVES ON STABILITY

12.1 General

It has been established that the stability of some vessels, such as fishing vessels, is significantly reduced when operating in following seas at such a speed that the wave encounter frequency is low. The vessel may then remain in the same position relative to the wave for sufficient time for a capsize to occur if the stability is severely reduced.

12.2 Method of Assessment

The Wolfson Unit's own statical stability program was modified to enable a wave of specified shape, length, height, and longitudinal location to be input. The water surface elevation was calculated at each hull section and the vessel was balanced at the equilibrium draught and trim for each heel angle at which stability data were required. The program therefore modelled the static case of a vessel held stationary on a following wave with freedom to trim and heave to maintain equilibrium. Trochoidal waves were used throughout the calculations.

Vessels were selected to cover a range of hull types from a modern racing yacht to a traditional sailing ship. All these examples had been subjected to an inclining experiment so their displacements and centres of gravity were known accurately.

12.3 Results and their Implications

The results demonstrated that the statical stability of yacht forms is affected very little by the presence of following seas. The ship forms on the other hand, with more volume concentrated near the ends and higher prismatic coefficients, suffer a reduction in stability when the wave crest is amidships.

Unlike fishing vessels, sailing ships operate with high GM values to enable them to carry the sails, and they are not vulnerable to a complete loss of statical stability purely as a result of the wave.

When a ship is under sail with a steady heeling moment, it will heel to a greater angle if its position on the wave crest is maintained for more than a few seconds. There is then an increased risk of loss of stability due to deck edge immersion and the vessel would be more vulnerable.

This situation is an unlikely one, however, since the vessel must be in a steep following sea with wind on the beam or the quarter, and must be travelling at the same speed as the waves. This of course is quite feasible for a modern racing yacht which may surf on an occasional wave, but most unlikely for a heavy vessel of high prismatic coefficient. Furthermore, the cause of a stability incident is most likely to be a severe gust of wind, and the results obtained in the gust tests and full scale trials indicate that a capsize typically takes place over a period of around thirty seconds.

The inclusion of waves therefore appeared to be an unnecessary complication to introduce to the standards.

13. CONCLUSIONS

Several important findings resulted from the experimental work, which have enabled new methods of stability assessment to be developed. These findings may be summarised as follows:

i) Wind heeling moments cannot be predicted accurately from only a sail plan, even when wind gradient effects are included.
ii) The wind heeling moment varies with $\mathrm{Cos}^{1.3}\theta$.
iii) When struck by a gust a sailing vessel will heel to the corresponding steady heel angle at the gust wind speed for the duration of the gust.

The work has resulted in new standards which enable those vessels most vulnerable to stability incidents to be identified without recourse to wind heeling calculations, and has provided a method for informing masters of their level of safety when sailing. The standards place no restriction on sail area carried, enabling the master to use his judgement to set the sails appropriate to the prevailing conditions. They will however prevent the use of some existing vessels for sail training, since, with low freeboard, a vessel not meeting the range criterion may be unable to increase its stability sufficiently by ballasting.

Whilst there is no direct requirement to achieve a specific large downflooding angle, it is hoped that the standards will result in an increased awareness of the importance of the downflooding angle and that designers will be encouraged to maximise its value.

Some small vessels will be restricted to operating in a coastal or near-continental category where they will be better able to run for shelter, thus avoiding the extreme conditions which might result in capsize. The combination of racing success and market forces has resulted in a steady reduction in the stability of cruising yachts and with it has come a reduction in the ease of handling. Much has been written on this subject, but at present the trend continues and it is hoped that the introduction of these requirements will highlight the virtues of a large range of stability, and encourage designers of sailing school yachts to work towards a good range, giving their clients the option of cruising far afield if they so desire.

NOMENCLATURE

a	Area of a horizontal element of the sail plan
A	Sail area, excluding overlapped areas
C	Wind heeling moment coefficient
GZ	Ship's righting arm
GZ_f	GZ at the angle of downflooding
h	Height of a horizontal element of the sail plan
H	Height of the centroid of the sail area above the half draught
HA	Wind heeling arm
HA_o	Upright wind heeling arm
M	Wind heeling moment
p	Local wind pressure on a horizontal element of the sail plan
P	Wind pressure = $\frac{1}{2}\rho V^2$
V	Wind speed
ρ	Density of air
θ	Heel angle
θ_f	Angle of downflooding

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ACKNOWLEDGEMENTS

This paper is based on work commissioned by the Department of Transport and conducted by the Wolfson Unit for Marine Technology. The assistance of members of both organisations in conducting the experimental work and developing the standards is gratefully acknowledged by the author.

DISCUSSION

Mr I. Hannay: I would like to thank Barry for a very interesting paper because sail training stability has been quite a problem. Like everyone else, I was brought up on the old notion of heeling arm using cos squared.

It is very good that they have come up with some real figures made from some tests, because the old recommendations were based on the original Admiralty requirements which were purely enlightened guesses from the turn of the century, so it is very good that now we have sorted this out and come up with some much more realistic figures for stability and seaworthiness of yachts.

I am glad to see that they have taken away the aim of trying to work out the forces on the sail because, as they discovered in the wind tunnel, you really cannot work out what all the options are. Therefore, this idea of having a maximum initial angle of heel is a very practical one and, in fact, what all seagoing seamen have used for years. They knew that if it was heeling over a little too far, that was not safe because it would not stand a gust, and that is what the 'seat of the pants' skippers have done for years. It is now nice to see that the recommendations follow this practice.

The one thing that has changed in sail ships and the sail training ships compared with the old traditional ones which they are trying to copy, is that the old ones on the whole were freighters and therefore they had watertight holds with covers on and they could take a knock down. The trouble is that converting these to having live cargo with companionways up and down has caused the downflooding problem, and my own feeling is that in the past some of these followings have been slightly too much on the stability and not enough on the downflooding. I think the downflooding angle is extremely important.

Obviously you need stability at the downflooding angle as well, but from my point of view, as you can see from the list of casualties, if a boat exceeds the downflooding angle then in many cases it is gone. So whether you have stability of 100° or 120°, if you have exceeded the downflooding angle you have got a problem. Therefore, my own feeling is that the downflooding angle should be treated with a greater degree of seriousness than it is at the moment, rather than purely the stability and the vanishing angle of stability.

Mr D.K. Brown, M.Eng., R.C.N.C. (Fellow): Ref. 4 of this interesting paper is, in fact, William White's Manual of Naval Architecture in which he gives GZ curves for quite a number of sailing frigates of the 19th century which form a very nice sample. There are quite a lot of them and very few of them actually suffered stability failures, in other words capsized. In general, these ships in their seagoing condition would have had a range of stability of between 70° and 80° and a maximum GZ of just over 2ft at around 40°. So that just slightly falls short of the author's criterion of 90°, but they did in general have highly trained officers even though the crews were not necessarily so well trained, which leads on to the second point.

Admiral of the Fleet, Lord Chatfield, (a former President of this Institution) when he became First Sea Lord in the mid 1930s, discovered to his absolute horror that the Royal Navy had set funds aside and the design had begun, of a sail training ship for the Royal Navy. The first act of which he was very proud was to cancel this, in that he did not believe on the one hand that sail training was of any great value to the modern Royal Navy and, on the other hand, he did not believe that there were enough officers with experience in sail to handle such a ship safely. I must say that the idea of a sail training ship for disabled people fills me with great horror. I do not believe that it can be safely operated.

Mr C.C. Mudie (Fellow): My first comment is to thank the author for a paper of outstanding value to us practitioners in the trade. I think the conclusions he has come to are of value both to the designer and to the master, and I think he has, without any exaggeration, contributed markedly to the safety of sailing over the next 50 years. I would like to thank him and his colleagues very much for that point of view and congratulate them.

Secondly, I think one has got to put a little history into the situation. Your antique seamen did not put to sea with the idea that it was a hit or miss affair and if the ship was knocked down, 'well, bad luck lads'. The antique sailing ship had a mechanism of wooden masts and shrouds and if the ship was knocked down in a squall, the first thing the mate did was to reach for a hatchet and progressively dismast the ship until she came upright again. That was a well known and well practised form of seamanship which has to be appreciated.

Now when we come along with modern ships we cannot afford wooden masts, we cannot afford hatches, we cannot afford rope rigging. We have to have aluminium or steel spars, steel shrouds, and, how do you get rid of that lot if you are knocked down? The answer is, no way, and we have therefore to rely upon a different kind of hull design and a different set up completely, where the stability is intrinsic in the ship and not inherent on the actions of the crew. This is an absolutely basic change that has happened in the last 30 years I suppose, which we have to appreciate and which the Wolfson Unit's work covers exactly.

Just one final word. The LORD NELSON has just completed her hundredth voyage to the great satisfaction of all concerned. She sails well, I think the maximum speed they have recorded is 13 knots, they have taken 5,000 people to sea, and I should just make one small correction: she is not designed specifically for disabled people, she is designed for able and disabled to sail the ship together. I must say I have sailed in her myself and there is no feeling at all anywhere that she is in anyway in the slightest bit unsafe.

Mr D. Stinton M.B.E (Member): I seek enlightenment.

Looking back to sails, wings and aerofoils in Papers 2 and 3 (Refs. 15 and 16), one of the biggest sources of drag and losses of lift are streamwise gaps between different adjacent surfaces, be they slats, flaps, wings or sails. When I look at knock down pictures of sailing ships like the barque, LORD NELSON, I am aware not only of the amount of sail that the ship is carrying, but the amount of gap where there is no sail. Now, if you stick a surface up in the wind like this and you blow air straight at it, and if there is no leakage around the edges, you have a drag coefficient of about 1 (this is the assumption of the Regulatory authorities in your Section 5.3). As soon as there is leakage, you have a drag coefficient of about 1.28 which gives a larger heeling moment at a given angle, θ. It so happens that if we take an angle of heel of 45°:

$$\frac{\text{Cos}^{1.3}\theta}{\text{Cos}^2\theta} = \text{approx } 1.28$$

which is the amount your upright heeling moment maximised exceeds that assumed by the Regulatory authorities. So, I wonder if this is indicating that square sails with gaps, and separate gaffs and topsails, are suffering moment coefficients nearer to 1.28 than to 1.0. If so, gaps could be an area of particular attention for rig designers, and Regulatory authorities.

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Mr D. Vassalos, B.Sc., Ph.D (Member): First of all, let me apologise; I had not read the paper beforehand, so I may have missed a couple of points in my comments. As someone who has worked for quite a number of years on stability I have come to the conclusion that the only way one can tackle stability is the pragmatic way. In view of this I congratulate the author for adopting a very pragmatic view in tackling this project, and for producing some very valuable results. There are, however, one or two points on which I would like to ask his opinion, and to offer comments.

First of all, it is true that waves influence many types of ships other than fishing vessels. I believe that the reason why the effect of waves had little influence in this case was because of the very high GM; that is the main reason. I would suspect that there is still some influence on hydrostatic stability when waves are present.

The other aspect of wave effects relates to the downflooding angle. Again, motions and waves together play a crucial role in defining this angle. You should not consider it on a static basis alone.

Finally, with reference to Fig. 9, I noted the unsuccessful efforts to balance areas A and B, and of course, as you correctly concluded, this failure was due to the fact that the effect of damping was not included. At Strathclyde we have developed software which overcomes this problem in a quasi-dynamic manner. The method used, known as the Energy Balance Method, allows damping to be considered together with all the other factors that are judged to have a crucial influence on vessel stability. In relation to this, I should be glad to give you a free test-run of the software, if you would like to send us the necessary data on the vessel, and the results could possibly be included in the Transactions.

Mr R. Holstead, O.B.E. (Fellow): On behalf of the Marine Directorate of the Department of Transport I would like to express thanks to both Mr Deakin and the Wolfson Unit at Southampton University for the excellent work undertaken in the development of the stability standards for sailing vessels.

It is the opinion of the Directorate that this new approach in assessing the stability characteristics of sailing vessels provides a significant advance over the more traditional methods previously employed. Not only does it provide for a more accurate assessment than the older method, but it is relatively simple to apply and present.

One of the Directorate's primary concerns when considering the development of the new stability standards was to avoid, as far as practicable, dictating to the master how to sail his vessel; in particular, the type of rig to set in the prevailing weather conditions. In this respect, the Wolfson Unit has been most successful with their ingenious introduction of a 'safe heeling angle' concept, this angle being the maximum steady angle to which the vessel can be permitted to heel and thereby still maintain an adequate reserve of stability to withstand the possibilty of knockdown and downflooding from a sudden, severe wind gust. The master's principal task from a stability viewpoint is therefore to keep his eye on the weather and the inclinometer and where appropriate reduce sail or alter heading to ensure the vessel's safe heeling angle is not exceeded.

It is hoped that the work of the Wolfson Unit will lead to safer sailing vessels and simplify some of the duties of their masters. However, I feel sure that the author will be one of the first to agree that the safety of all sailing vessels is highly dependent upon prudent seamanship. In particular it is essential to know the limitations of the vessel and the crew and to ensure that all hatches are kept properly closed at sea, except when in direct use. On this latter point, it should be noted that ensuring sailing vessels have an adequate measure of stability is to no avail if it can be simply negated by seawater gaining easy access to the hull. In fact, the loss of many of the sailing vessels in recent years has been due primarily to the dramatic erosion of stability resulting from the ready ingress of seawater.

As the author has indicated the new stability standards have been incorporated into the Directorate's 'Code of Practice for the Construction, Machinery, Equipment, Stability and Survey of Sail Training Ships'. They are also illustrated in an accompanying Model Stability Booklet and both booklets are obtainable from HMSO.

This Code of Practice is intended to apply only to commercially operated sailing vessels. Even so it is hoped that the remainder of the sailing vessel industry will take note of its requirements and wherever possible adopt them on a voluntary basis. In addition, it is strongly recommended that the stability assessment procedures developed by the Wolfson Unit are studied by all naval architects and yacht designers and applied to all new sailing vessels.

To conclude, I would like to repeat the Directorate's thanks to Mr Deakin and his colleagues for a very detailed and extensive study which it is hoped will do much to simplify the stability assessment of sailing vessels and thereby improve safety standards.

The Chairman then proposed a vote of thanks to the author which was carried with acclamation.

WRITTEN DISCUSSION

Captain E.E. Ewbank: I must thank the author for his invitation to make this contribution to the discussion of his paper. In addition to having designed some sailing ships, my associates and I are consultants to New Zealand's major operator of sail training ships for, among other matters, the stability of its two ships 'Spirit of New Zealand' (designed by us) and 'Spirit of Adventure'.

The author's finding that, due to damping, sailing ships when reacting to a gust do not heel significantly, if at all, past the new steady heel angle, is most important. This information, along with that of the cosine heel index and gust factor findings, will enable us to work with more confidence.

Naturally, the use of a cosine index of 1.3 instead of 2 indicates that a ship will have less reserve positive stability when heeling to a gust than we would have supposed, but this is tempered by the damping effect already mentioned.

I am particularly interested in the proposal to provide masters of sailing ships with a maximum safe angle of heel when sailing, based on the gust factor and downflooding angle. As an ex seafarer, I can see the value in this, and will be pleased to see this information required by class and government authorities as a part of the stability documentation for each sailing ship. However, I think it needs modifying for the case where the heeling arm cosine index 1.3 curve tracks along the down-slope of the righting lever curve, through the downflooding angle. I find this to be the case with both 'Spirit of Adventure' and 'Spirit of New Zealand'.

We regard the wheelhouse side door as being a major potential source of downflooding, even though it may be closed weathertight and substantially watertight, and base our recommendations around this possible threat. In the arrival condition for 'Spirit of New Zealand', the sill of this door immerses at 51° heel. The heeling arm cosine index 1.3 curve through this angle tracks along the GZ curve from about 40° to 60° before the combined effect of the keel leaving the water and the intact deckhouse submerging provides reserve positive stability. This means that, if the gust heels the ship to 40°, she will continue through the possible downflooding to 60°. If the wheelhouse door happened to be open, or if it were a real downflooding point, the situation would be serious. Therefore it is necessary that either the curve crosses the GZ curve at the downflooding angle into significant positive reserve stability, or that it crosses at some lesser angle of heel. Therefore I suggest a simple formulation which will either:

(a) confirm an arbitrary minimum angle of intersection at the downflooding heel angle or, in defualt of that
(b) displace the heeling arm curve so that it crosses the GZ curve at a lesser angle of heel:

$$\theta_s = \frac{(GZ_f - GZ_{f+6°}) \times 180}{\tan C \times Pi} + \theta_f$$

$$HA_s = GZ_{f+6°} / \cos^{1.3} \theta_s$$

where GZ_f = GZ value at the downflooding angle θ_f
$GZ_{f+6°}$ = GZ value at θ_f + 6 degrees
C = A + B
A = $\tan^{-1}((GZ_f - GZ_{f+6°})/0.105)$
B = an arbitrary minimum intercept angle.

If HA_o (as already defined by the author) > HA_s then plot $HA_s \cos^{1.3}\theta$ through θ_s at $GZ_{f+6°}$ or else plot $HA_o \cos^{1.3}\theta$ through θ_f at GZ_f.

I would like to add that the above two ships are quite dissimilar in hull form and overall stability characteristics.

Further, I find this phenomenon of the cosine index 1.3 curve tracking along the GZ curve over a significant range to be the case for two other sail training ships whose stability characteristics are known to us, and in one of these cases, where the range of positive stability does not quite extend to 90°, the cosine index 1.3 curve through 50° (actual downflooding unknown to us) is a capsizing lever.

Ir H. Vreedenburgh (Fellow): The author is to be congratulated on having produced a paper which addresses so many aspects of the safety of sailing vessels as affected by heeling forces, and indeed replacing much guesswork by hard facts and novel methods. The comparison of two heeling moment curves with the stability curve to assess the safety of the ship is most ingenious and of great practical value.

The form of the heeling curve is influenced by the wind gradient which can be expressed as $(h/10)^z$. As an average value z=1/6 is often assumed. However z may vary enormously, at least from 0.05 to 0.74. Variation in wind gradient might well be a major cause for the large variations in heeling shown in the author's Fig. 3. For safety calculations, the lower value of z should of course be used.

The form of the heeling moment curve is also influenced by any variation in the height of the centre of effort a. Increasing wind pressure will increase sail twist and reduce a, especially in fore and aft rigs. In square rigged vessels, the yards are usually trimmed to give a certain twist, but will prevent an increase of twist with wind pressure. Perhaps the author could tell us what the actual wind gradient was during the experiments and whether changes in the centre of effort have been measured.

Above a certain angle of heel the sails will be in the shade of the hull. Quite rightly in Fig. 4 no measurements are shown above 60°. It is not understood how measurements up to 90°, shown in Fig. 5, have been obtained. Their fitting the curves must be pure coincidence. The heeling moment can also be accurately calculated using the expression:

$$MH = a\,\{Cl \cos(\beta-\lambda)\sin x + Cd \cos\theta \sin(\beta-\lambda)\}\, q\, SA \cos\theta^{z}$$

where $\sin x = \sqrt{\cos^2\theta + \sin^2\theta \cos^2(\beta-\lambda)}$ (Ref. 17)

At an apparent angle of incidence (AAI) of 60° to 90° the sails will be stalled. The calculated form of the heeling moment curve, Fig. 15, follows closely the $\cos\theta$ line for z = 0.05. To arrive at the $\cos^{1.3}\theta$ line we must either assume z to be 0.3, not realistic in gusty weather, or a reduction in a, which is quite probable both in the wind tunnel and in reality.

In the close hauled condition, the calculated curves show slightly higher moment values at high angles of heel. The influence of changes in Cl-Cd ratio was found to be rather small for realistic values. The same applies to the AAI, which may increase by 2° to 5° in a gust at constant true wind direction. Of course this applies to the form of the curve, not its magnitude, see Fig. 16.

Given the probable lowering of the centre of effort through sail twist, the use of the $\cos^{1.3}$ would still appear justified for fore and aft rigged ships in all weather conditions. However, for ships carrying square sails only, it might be advisable to use the cos curve instead.

The recommendations of the Wolfson Unit have resulted in a 'Code of Practice for .....Ships Between 7 metres and 24 metres in Length'. It is noted that the ships listed in Table 1 are all near or well above the upper limit. Have any ships nearer to the lower length limit also been investigated? If so, could data be given?

The range of stability required as per Fig. 14 seems rather severe. Without criticising its wisdom, it is noted that Thames barges fell far short of these requirements. Also none of the Dutch traditional fishing boats - botters and the like - comply, being between 10 and 15 metres in length and having a range around 90°. Nevertheless, they have fished the North Sea for ages, even in winter. Nowadays, yachts of the same type sail to the UK, the Channel Islands and the Baltic.

Finally I would draw attention to a type of stability casualty not listed in Section 7, that is the risk of bodily injury at a sudden heavy list not to mention the risk of going overboard.

REFERENCE

17. Vreedenburgh, H.: 'Sails and Simple Aerodynamics', Trans. RINA, Vol. 130, 1988.

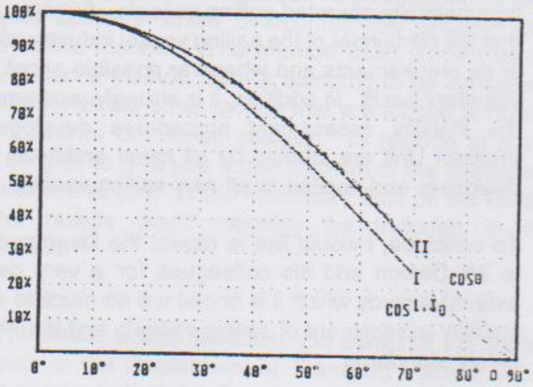

Fig. 15. Heeling moments in stalled condition

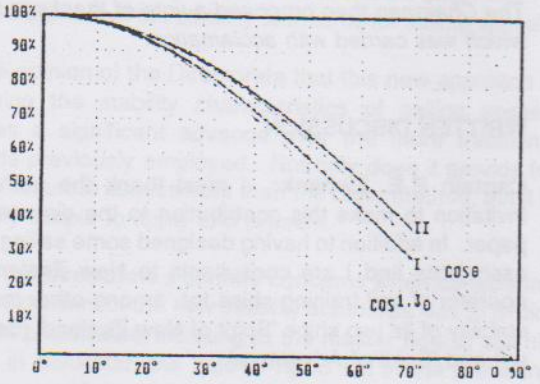

Fig. 16. Heeling moments in close hauled condition

Mr B.N. Baxter, M.Sc., Ph.D. (Fellow): This is a most useful paper and should prove of great benefit to prudent owners and masters of sailing vessels.

In particular, the explanation of the derivation of the curves given in Fig. 11 shows clearly the reason for insisting on a minimum range of stability of 90° and highlights the vulnerability of vessels with a smaller range.

The author states in Section 10.2.1 that the limiting angle of heel is governed by the master's feel for the safety of the vessel. Too often in the past, however, that feeling was based on factors which were only tenuously related to stability. The development of the maximum recommended steady heel angle is sound and this information should not only be included in the stability booklet, it should be referred to constantly.

The stressing of the difference between gusts and squalls is very helpful and it is important that masters should remember and act upon the information contained in Figs. 12 and 13.

The concept of GZ and its link to righting moments is very familiar to naval architects but often proves difficult for some yachtsmen to understand fully. The use, therefore, of information relating to standards being presented in graphical form rather than the solution of formulae or equations is to be recommended. Has the author any thoughts as to how the concept of GZ could be made more familiar to yachtsmen?

The conclusions the author draws from his experimental work are important. It is perhaps unfortunate that a more severe range requirement may prevent the continued use of some vessels for sail training but a number of these have been sailing for years with inadequate reserves of stability. They have, perhaps, been fortunate in not meeting, so far, a combination of circumstances which has resulted in tragedy but such a combination will almost certainly occur at some time.

Mr A.F. Molland, M.Sc., Ph.D. (Fellow): I should like to congratulate the author and his colleagues for obtaining and presenting some excellent experimental data, providing the naval architect with a much better understanding of the physical behaviour of sailing vessels in both steady and gusting winds. The information has provided an excellent basis for developing a much needed code of practice for sailing vessels.

The results in Fig. 9 for the effects of gusting when initially heeled to windward are interesting and informative, particularly since some regulatory bodies have adopted an energy equality approach in their criteria. The influence of sail damping is significant and the results would modify the existing common assumption of making area B = area A, although this assumption is (as we see from Fig. 9) apparently well on the safe side.

The concept of an effective range of stability presented in Section 9 is, I feel, very important, and logically leads to the need for a minimum range of 90°. Does this, however, mean or imply that larger vessels might recover from a knockdown or breaking wave capsize as might be implied in Fig. 14 if read in isolation?

Would the author give some indication as to how the formula (given in Section 10) for maximum area of openings was deduced?

Moving on to one of the major proposals developed in the paper, and discussed in Section 10.2.2. The author is aware, following our discussions on sailing ship stability over a number of years, that I had some misgivings over his proposal to formulate a rule concerning allowable steady heel angle which did not even take account of the sail plan. However, I now take his point when the results of the tests on various rigs are considered and accept that a simple but very effective rule has been evolved. It is to be noted that his approach leads specifically to a safety criterion. Thus the data presented do not help the designer at the preliminary stage in assessing what steady heel the vessel will actually adopt in a particular wind force. Whilst in Section 5.1 the author indicates that heeling moment coefficients for different rig types and settings were not consistent, could he nevertheless publish these 'hard to come by' values so that the designer could at least have some coefficient data for design purposes, albeit approximate?

Finally, I would ask that, for completeness (and ready reference), an appendix be added to the paper which summarises the main features of stability requirements in the proposed code of practice for sailing vessels.

Mr Parker E. Marean III: Mr Deakin, and the groups he represents, are to be congratulated for their contribution to the understanding of sailing vessel stability requirements. Their work provides a much improved basis for relating specific weather events to the response of a vessel.

Going beyond the importance of their experimental data, two worthwhile regulatory concepts were introduced. The first being a rational definition of the 'downflooding' point by relating it to vessel size. The second being the concept of a regulatory 'safe heel' angle for normal operations.

Regarding the latter, while supporting the concept, I remain unconvinced that a safe heel angle can be adequately determined without consideration of the sail plan. In saying this, it must be emphasised that I am not concerned with regard to sails allowed to be carried. Rather, I am concerned by the combination of potential wind heeling moment due to sail, which is controllable, and that due to spars and rigging, which is not under the normal control of the crew.

Further, I am concerned at the extent to which the new standards depend upon the wisdom, experience and predictive skills of the master to judge the probability of future weather events. The events that typically are involved in a sail stability casualty are somewhat extraordinary. It is optimistic, in my view, to expect the master to foresee the extraordinary, especially under conditions of limited visibility.

Mr P.G. Winch, B.Sc. (Member): Having campaigned for better stability standards for yachts for over twenty years I am pleased to see this important matter given proper attention at last, in this paper and others. The news that large angle stability standards in the smaller yachts are getting worse rather than better is worrying, however, and one wonders what tragedy is required to renew awareness of these issues, now that the ill-fated 1979 Fastnet Race is more than a decade in the past. I warned of some of those events in Ref. 18.

The author's approach is commendably pragmatic, and I am aware that he is having to deal with existing vessels as well as suggest rules or guidelines for the design of new ones. I would have taken stronger issue regarding the question of off-centre access doors and hatches. Having insisted on centreline openings (and galley sinks for that matter, and for the same reason) I am appalled to see experienced professional barge skippers going to sea with accommodation openings cut in the sides of their hatch covers very near to the gunwhale. My opinion is that 'when there is a will there is a way', and I am sure that near-centreline accommodation hatches and doors can be arranged in the vast majority of new sailing craft of all sizes, and may be in all of them. Better arrangements could certainly be made in the case of existing craft such as the barges mentioned.

The fact that near-centreline openings can be more safely left open in bad weather is an additional safety advantage, in that the crew may more swiftly abandon ship if they have to, while the arrangement makes such a catastrophe much less likely. Here I emphasise a point the author makes himself.

The ranges of stability shown by the lines in Fig. 14 are difficult to achieve for shoal draught vessels however. I believe that such craft have some inherent advantages, even sometimes for world-wide voyaging. My own criterion has been about 117° statical stability range for extreme type shoal draught estuary and short sea cruising yachts (in fact derived from the barge model and perpetuating many traditional barge features), increasing to about 150° for shoal draught ocean cruising yachts. These figures apply to vessels between 8 and 13 metres.

Provision of these ranges of stability without an external ballast keel requires a main contribution to the inverted buoyancy from intact coachroofs. So flush decks in wide boats with high centres of gravity (whether or not they have deep draught) are out. I appreciate that this is an unpopular view; but I hope we all agree that seaworthiness should come before fashion. I am not here suggesting that the best yachts should be anything less than absolutely beautiful as well as absolutely seaworthy. If anything I think there is room for improvement in the aesthetics department too.

At the other extreme, I am inclined to think that the 180° range of stability required by the RNLI is excessive technically, although it is no doubt sound psychologically. A sea state liable to roll a vessel upside down is equally likely to roll her back up again provided her range of statical stability is large (say in this extreme case, 165° - a large angle in order for the action to be quick). There may be a trade-off for RNLI lifeboats between a less than complete (but sufficient) range of statical stability and some other desirable qualities (such as reduced windage or weight).

I endorse the author's observation that there is nothing better, other things being equal, than a large range of stability for all sizes of craft. Since there are many thoroughly practical and seamanlike ways of arranging this (coachroofs, deckhouses, poops, forecastles, appropriate basic hull proportions, freeboard, structural weights concentrated low down, fixed or water ballast) I feel that a move towards ranges of statical stability in excess of 90° should be encouraged in all sailing craft. The stability ranges for smaller craft shown by the lines in Fig. 14 are good criteria, but as a designer of one type of cruising vessel that falls a little below the line I suggest that such criteria might be associated with other matters to form a balanced judgment. Shoal draught for instance confers some safety advantages (it is arguable that such craft are safer in an 'ultimate storm' for one thing, besides being able to sail over many rocky outcrops, and up the beach); the area of the stability curve below the origin might also be considered, as a measure of 'stability' upside down; and a criterion regarding good design or otherwise might apply, by way of the layout of hatches, vents, engine exhausts and plumbing generally, with regard to keeping water out of the hull at large angles of heel and in storm conditions.

I take it that Figs. 11 and 12 are based on gust factors of 1.4. So the remark that the vessel in Fig., 11 will capsize if her steady sailing angle exceeds 40° has, as I understand the issues, to be qualified to this effect. In fact she could be lucky, and experience no gusts and survive, or she could encounter stronger ones, although I accept that stronger gusts are unlikely. I feel that there is a sense of absolutism implied regarding the figure of 40°, which is in fact a statistical judgment rather than a technical reality.

I hope that designers will welcome Mr Deakin's findings and clear submission, although experience suggests that some of them may still put glamour before common sense, in what I believe to be a mistaken interpretation of their professional role *vis a vis* their clients.

REFERENCE

18. Winch, P.G.: 'Thoughts on Small Craft Stability and Capsize'. The Naval Architect, July 1979.

Mr G.H. Fuller, R.C.N.C. (Fellow): As in many other areas of transportation, the question of inherent safety of a product tends to be 'assumed' especially if the product is traditional, market led and has major inputs of 'fashion'. The pressure for the 'assumption' route to be followed is particularly great for those products which have a long historic backgound, whose accident record has been part of that rich tapestry of life, with a relatively low input of technology and a design and production ethos of craft rather than engineering.

It is wrong to be hypercritical, for those involved are motivated by good intentions not helped by some complacency and ignorance. I would suggest that malice and 'commercial' short cuts only come later and very often when the engineering is understood and can be exploited by the unscrupulous designer. But especially in these traditional products it takes an accident or two to trigger a proper engineering study and create reasonable regulations. It is perhaps unfortunate that the trigger in this case did not occur earlier in the resurgence of sail training and tourism, but we should not be surprised at the situation. Indeed, I am sure there are many other areas as yet undiscovered and it is for this reason that the training (Stage 2) of Chartered Engineers includes the areas of safety and loss prevention. It is also an appropriate area for Continuing Education and Training as this becomes part of the maintenance of engineering qualifications.

How does the author see this aspect being moved forward, especially in industries such as yacht design and production which are small and rarely have resources for training?

AUTHOR'S REPLY

I am grateful to all those who contributed to the discussion of this paper, which I anticipated might cause some controversy among designers and operators of sailing vessels. It has been very encouraging to receive agreement in general terms with the majority of the proposals from many of the contributors.

Special thanks are due to Mr Holstead for his appreciative remarks on behalf of the Department of Transport. He and his colleagues in the Marine Directorate have spent considerable time studying the results of this study and the proposed standards, and it has been a privilege to work alongside them during the latter stages of the project.

Mr Hannay emphasised the desirability of delaying downflooding to a large angle of heel, and indeed this is fundamental to the concept of the maximum recommended heel angle. This angle is derived solely from the downflooding angle and the value of the righting arm at that angle and, in general, the greater the angle the safer will be the vessel.

Mr Brown reflects on the stability characteristics of 19th century frigates, which would not have met the current standards. That these vessels were considered sufficiently safe at that time is appreciated but, as the opening paragraph of the paper suggests, they may not have had sufficient margin of safety to satisfy today's customers of the sail training industry.

I am not qualified to comment on the value of sail training to the Royal Navy, now or in the 1930s, but would refer Mr Brown to the world's largest navies, for whom sail training has been retained to the present day.

Mr Mudie put forward the merits of dismasting in the event of a capsize. Whilst this method of recovery may not be desirable for a sail training vessel, it is by no means a thing of the past., As recently as December 1989 a competitor in the Globe Challenge round the world race brought his yacht upright in this way. Phillippe Poupon's 18 metre long ketch 'Fleury Michon X' was capsized by a breaking wave and remained at an angle of about 110°. Pumping water between the wing ballast tanks failed to right the vessel and it stayed at that angle for about ten hours when, with the aid of another competitor, the mizzen mast was cut away. This example further illustrates the value of preventing flooding of the hull, which would certainly have resulted in loss of the yacht.

Mr Stinton suggests that the $\cos^{1.3}$ function exceeds the conventional $\cos^2$ function at 45° as a result of the increased drag of a slotted sail plan over that of a flat plate. The function was derived from data measured at a range of heel angles and upright, and the heeling moment coefficient of the sail plan is thus incorporated at all angles. The value of the upright heeling moment coefficient is apparently of little significance since the function fits data for a variety of sail plans and even bare poles. The ratio of the cos functions at 45° corresponds to the drag coefficient of 1.28 by coincidence only, and there is nothing special about that particular angle. That gaps in sail plans may result in larger drag coefficients, and hence larger heeling moments, than a single sail of equivalent area, may be of interest to designers. I am certain however that ease of handling will normally sway the design in the conventional direction. If authorities use the method outlined in this paper to assess sailing vessels, they need not concern themselves with estimates of the heeling moment. Authorities who continue to use conventional methods of assessment, with predictions of heel angles under sail, may well wish to refine their regulations in the future by taking account of such variables as slots to improve the accuracy of their estimates.

Dr Vassalos urges that downflooding should not be considered on a static basis but should incorporate the effects of waves. Obviously a wave engulfing a deckhouse or hatch during its passage across the deck will result in a considerable quantity of water being taken below through any large openings. Such an incident is unlikely to be critical to the buoyancy and stability of the ship, however, since it will be of short duration. It is considered that the method of deriving the maximum recommended heel angle, using a gust factor of 1.4, incorporates a sufficient factor of safety to make such incidents unlikely. To have introduced the effects of waves into the standards would have increased their complexity and would have put the assessment of a vessel beyond the current computing capabilities of most design offices.

Referring to Fig. 9, Dr Vassalos apparently saw the beam wind and rolling test as an unsuccessful attempt on our part to validate conventional energy balance methods. We consider any experiment to be a success if it provides reliable data, and I hope that we retain an open mind when conducting tests. These rolling tests gave consistent and reliable data which indicated the effect of damping precisely, with all hydrodynamic and aerodynamic aspects modelled. I would see comparison with a mathematical model as a validation of the model rather than the tests. Indeed research is currently under way at Southampton University to numerically model various aspects of sailing vessel dynamics, and this will use wind tunnel and towing tank data as a basis.

Captain Ewbank's concern for vessels with GZ curves which follow a $\cos^{1.3}$ curve around the downflooding angle, prompts him to propose a modification to the standards. Once again I feel that every effort should be made to maintain simplicity, provided it can be justified. If a vessel with these stability characteristics were to be subjected to a steadily increasing beam wind it would indeed heel rapidly through the range of angles for which GZ follows the heeling arm curve, although damping effects would prevent a sudden lurch. It must be remembered, however, that the $\cos^{1.3}$ function is merely an approximation of the actual function applicable to a particular sail plan, as the data in Figs. 4 and 5 illustrate. Without knowledge of whether the chosen function has too steep or too shallow a gradient at the downflooding angle, it is pointless to make fine adjustments. Furthermore, if the function proves to be precise for the vessel under consideration with the sail plan set, the wind heeling arm curve drawn through the downflooding angle will be that which results in flooding. Minor alterations to the derivation of the maximum recommended heel angle result in small variations in that angle, which has to be compared with a fluctuating value derived on a rolling ship. It must be stressed that this method is not intended to be precise but to give the master an additional factor by which to judge his level of safety.

Mr Vreedenburgh suggests that wind gradient variation may have been responsible for some of the heeling moment variations measured at full scale, and I agree that this is quite possible. The wind gradient used in the wind tunnel corresponds closely to the function $(h/10)^z$ where $z = 1/9$. Centre of effort positions were indeed measured during the tests and, as the models were heeled, the centre of effort position remained virtually unchanged when measured along the mast. Its height therefore varies approximately in proportion with cos (heel angle).

The wind tunnel balance is able to measure forces and moments with the model at 90° if the rigging does not interfere with the turntable. For the two models tested in this work, this would have required removal of the rig and was not possible in the time available. The 90° value given in Fig. 5 is a calculated value based on the measured wind gradient and an estimate of the drag coefficient of the hull. The values at 73° were measured.

In proposing the use of the cos function for the heeling arm of square rigged ships, Mr Vreedenburgh would introduce an additional factor of safety but would complicate the standards in so doing. Some vessels would fall into a category which carry a small number of square sails but frequently sail to windward under fore and aft sails alone. If an authority chose to use the cos function for added safety, I would advise them to apply it to all vessels.

Vessels throughout the size range have been studied, as shown in Fig. 7. The value of the maximum recommended heel angle is dependent only on the shape of the GZ curve and the downflooding angle, and small vessels generally have larger ranges of stability and centreline openings. The derived angles are often greater than the angles at which these vessels could be sailed and in such cases the value is meaningless to the master. It does however indicate that the vessel is very safe in terms of capsize or downflooding as a result of wind forces alone.

Dr Baxter voices a familiar plea for an explanation of the GZ curve which is easily visualised by the layman. I cannot offer such a service but recommend that use is made of the term righting moment, rather than GZ, when introducing the subject. It is hoped that seamen who understand the reasons behind these standards, and in particular the maximum recommended heel angle, will not require a detailed knowledge of stability in order to sail with safety.

Dr Molland raises the question of whether large vessels are expected to self-right in the event of a capsize. The greater the range of stability, the better will be the chances of recovering from a capsize by a breaking wave. The low chance of recovery offered by a range of only 90° is offset by the unlikelihood of encountering a wave large enough to capsize a vessel of 24 metres.

The formula proposed for definition of the downflooding angle was derived in the following way. It was assumed that openings have a discharge coefficient of unity, and an immersion of 1 metre below the surface. It is unlikely that a vessel would remain a suitable survival capsule after the ingress of a quantity of water equal to its own displacement. When subjected to squalls, periods of knockdown up to several minutes may be experienced, and a duration of 5 minutes was taken as the maximum which a vessel could reasonably be expected to survive. The area defined by the proposed formula will result in doubling of the displacement due to flooding in about five minutes.

For the information of Dr Molland and others, a selection of heeling moment coefficient data are presented in Table 2, on the following page. These were derived from wind tunnel measurements combined with the conventional method of sail area measurement, with and without overlaps included, in the measured boundary layer of the wind tunnel.

I am grateful to Mr Marean for pointing out that the master should not be expected to predict the strength of approaching wind with any accuracy. There will always be casualties at sea as a result of extreme, unforeseen circumstances. We can only work to minimise them, and more information for the master will hopefully assist in that aim.

Mr Winch may have misunderstood Fig. 11. The vessel would capsize if wind caused it to heel beyond 40°. If we consider that wind to be the result of a gust of factor 1.4, the preceding mean wind would have given a steady sailing heel angle of just 12°, as stated in Table 1. Thus the vessel would be considered at risk of capsize when sailing in gusty weather at more than 12°.

Mr Fuller puts forward a case for continued training of professional engineers with which I am in agreement. The cost of formal re-training is, as he says, beyond the scope of many smaller businesses, but I am of the opinion that much can be offered through the pages of trade journals in the form of papers, articles and case studies. The journals of this Institution, and the yachting press, frequently publish safety related articles which help to keep the industry up to date.

I hope that this work and the resulting code of practice will inspire others to look at this subject with a fresh view, and that we may look forward to further discussion in the near future.

TABLE 2

Measured Upright Wind Heeling Moment Coefficients

RIG	HEELING MOMENT COEFFICIENTS INCLUDING OVERLAPS	 EXCLUDING OVERLAPS
BARQUE	Sails set at 50°, tested at 90° apparent wind	
Full Sail	0.98	1.17
F & A only	1.03	1.07
Square only	0.98	1.00
Force 8 sails	0.86	0.94
SCHOONER	Sails set at 35°, tested at 90° apparent wind	
Staysail rig	1.32	1.38
Trisails removed	1.22	1.31
Wishbone rig	1.23	1.28
	Sails set at 60°, tested at 90° apparent wind	
Staysail rig	1.19	1.24
Wishbone rig	0.93	0.97
	Sails set at 35°, heeling moment maximised	
Staysail rig	1.42	1.48
Trisails removed	1.27	1.36
Wishbone rig	1.33	1.38

NEW MEMBERS

The following new members were elected as from 4 October, 1990:

FELLOWS (eligible for C.Eng) (3)

* HADJIPATERAS, Dimitris Constantine, BSc, Marine Managers Ltd, London.

* KWON, Young-Joong, BSc, MSc, Ulsan Institute of Technology, Ulsan, Korea.

* MATTEN, Richard Brian, PhD, Noble Denton Consultancy Services Ltd, London.

MEMBERS (eligible for C.Eng) (8)

BARRIE, David Alexander, BSc, PhD, YARD Ltd, Charing Cross Tower, Glasgow.

† GALE, Christopher Adrian, BSc(Hons), MSc, Vickers Shipbuilding & Engineering Ltd., Bath, Avon.

† GUNTER, Christopher Howell, BSc, F.B.M. Marine Ltd, Cowes, Isle of Wight.

LEE, Tak-Ming, Norman, Dodwell Ship Management Ltd, Hong Kong.

† NISBET, Charles Paterson Craig, BSc(Hons), MSc, Vosper Thornycroft (UK) Ltd, Portsmouth.

† OWEN, William Jones, BSc, Consultant Naval Architect, Chester.

‡ PEARSON, Andrew Maxwell, BSc, Brooke Yachts International Ltd, Suffolk.

SELVAPATT, Chelliah, BSc(Hons), Brown & Root Vickers Ltd, London.

MEMBER (non C.Eng) (1)

MITCHELL, John F., BSc, Noble Denton & Associates, London.

OVERSEAS MEMBERS (not eligible for C.Eng) (2)

GLOWACKI, Edmund, BSc, Bold Craft Engineering Corp., Florida, USA.

SHARP, Douglas Hill, BA, BSc, The Sharp/De Fever Group Inc., San Diego,USA.

GRADUATES (8)

‡ BRICKWOOD, John, BSc, The Wolfson Unit, University of Southampton.

‡ CH'NG, Poh Weng, B.Eng(Hons), Australian Maritime College, Tasmania, Australia.

‡ DUNN, Alan, B.Eng(Hons), Kvaerner Govan Ltd, Glasgow.

HARARI, Youval, M.Eng, M.Eng graduate in Ship Science, University of Southampton.

LAVEROCK, Ian Crawford, BSc, graduate in Naval Architecture & Ocean Eng., University of Glasgow.

‡ LISTER, Graeme Peter, B.Eng, Highland Fabricators Ltd, Tain, Scotland.

‡ MAFFIN, David James Bentley, B.Eng(Hons), Cochrane Shipbuilders Ltd, Selby, Yorkshire.

‡ WILSON, James David Kirkby, BSc(Hons), MacAlister Elliott & Partners, Lymington, Hants.

ASSOCIATE-MEMBER (1)

TEALE, Bernard, Salters Maritime Consultants, Greece.

JUNIOR MEMBERS (4)

FOSTER. Lee Thomas

FOGG, R.J. (Reinstatement)

GILBERT, Peter David

STARBUCK, Dennis James

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* Transferred from Member

† Transferred from Graduate

‡ Transferred from Junior Member