Stability of sail training vessels

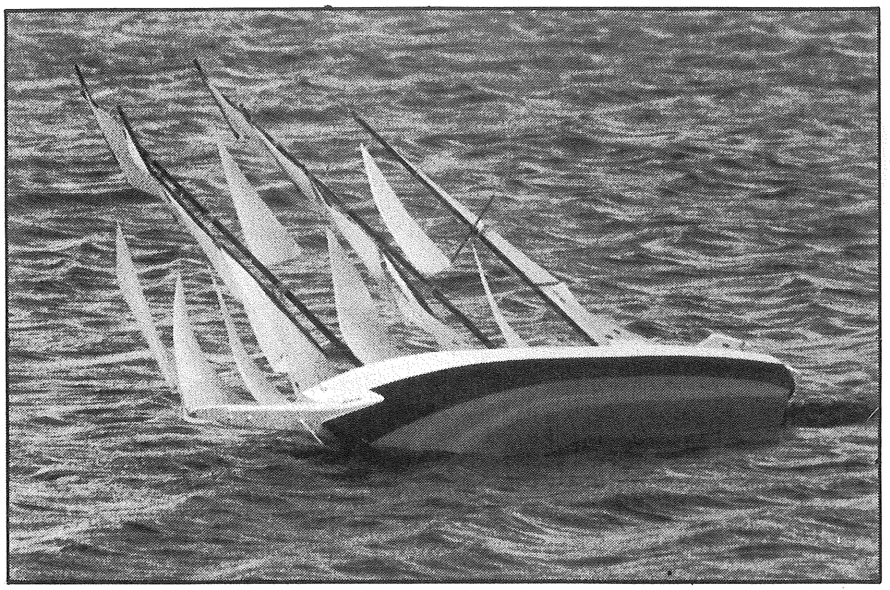
In his article 'Safety and Sail Training Vessels (*S&B,* May 1989), Brian Rice discussed the need for technically sound and practical regulations. Barry Deakin of the Wolfson Unit MTIA now describes some aspects of the development and the implications of the Department of Transport's new standards which are contained in the Code of Practice published recently.

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 regulations 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 regulations in force in other countries are frequently criticised because they result in restrictions on the sail plan which may be carried. On the east coast of the USA for example, some schooners must operate without topmasts, and suffer a significant loss of performance in light airs, in order to comply with the Coast Guard regulations. There are, however, in equal danger when under reduced sail in a gale, whether the topmasts are there or not. One of the aims in developing these standards was therefore to enable the master to judge what sail plan should be set in the prevailing conditions, but to provide him with the best possible information to aid his decision.

The stability requirements are apparently very simplistic, taking no account of such aspects as the area under the GZ curve or even the sail plan of the vessel. Their format is therefore a departure from conventional regulations for motor vessels and from those applied to sailing vessels in other countries. They have, however, been compiled with the benefit of improved understanding of the dynamics of sailing vessels which is the product of the Wolfson Unit's extensive programme of model tests and full scale data logging. Further details of this work are contained in a paper presented at the recent RINA Spring Meetings (Ref. 2).

The conventional methods of sailing vessel stability assessment attempt to predict the heeling moment of the rig in some nominal wind speed, and equate that to the righting moment of



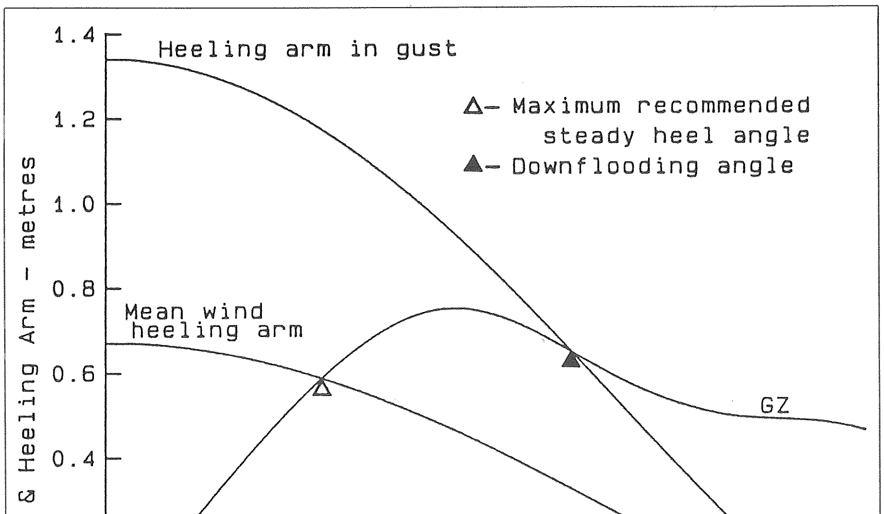
Radio-controlled 1:25 scale model of Lord Nelson *sailing overcanvassed.*

the hull to predict a steady heel angle. In addition they attempt to predict the angle to which a vessel will heel if struck by an instantaneous gust. These calculations are based on a number of simple assumptions.

1) The wind speed is uniform over the full height of the rig.
2) The heeling moment coefficient of the sails is unity.
3) The heeling moment varies with heel angle according to the function: $\cos^2$ (heel angle). [the square of the cosine of the heel angle].
4) When struck by a gust the vessel will heel until the area under the righting moment curve is equal to the area under the heeling moment curve.

All four assumptions are shown to be invalid by the recent work, and any attempt to predict the heel angle in a particular set of conditions is not consider-

Fig. 1: Derivation of maximum recommended steady heel angle.



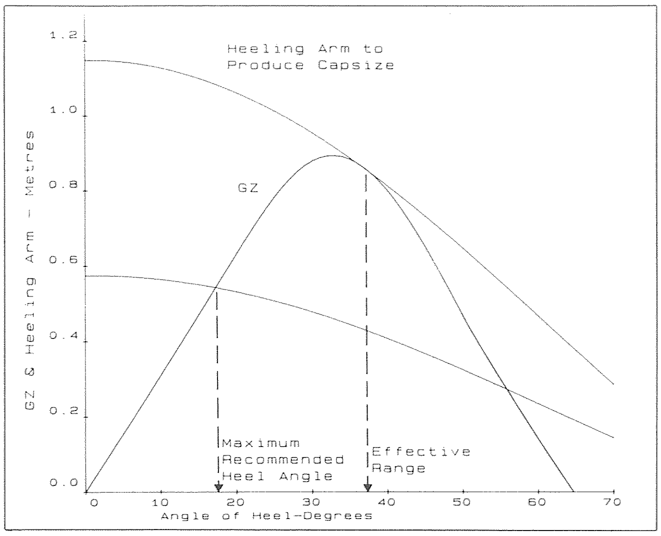


Fig. 2: Stability curve for a vessel with good initial stability but a range of only 65°.

ed worthwhile since actual conditions vary so much in terms of sails set, sheeting angles, apparent wind direction and wind speed. Furthermore, the master needs no estimates of the heeling moment to predict heel angles because he can see and feel the actual heel angle resulting from the combination of conditions present.

The master, however inexperienced, will always shorten sail before his vessel is any danger from a steady wind. It is therefore to other dangers over which the crew have less control that regulations should be addressed.

The capsizing forces which are most likely to affect sailing vessels are large breaking waves and increases in wind pressure, due to fluctuations in the turbulent atmospheric boundary layer or to small scale weather systems such as frontal squalls.

The research has revealed that the combination of the finite rise of gusts and the powerful aerodynamic damping of the rig ensures that vessels under sail rarely heel significantly beyond the steady heel angle resulting from the gust wind speed. The traditional view of gust impact response being likened to that of a spring hit by a hammer cannot be justified.

Wind pressure is unlikely to force a vessel to heel beyond 90 degrees, since at that angle the heeling moment is negligible. An exception would be the case of a gust with a significant downward component which might cause the vessel to heel until the rig became submerged. In the case of a wide vessel of light displacement such as a racing yacht, this might be as much as 100 degrees. None of the recent sailing ship casualties, the *Albatros*, *Marques*, *Pride of Baltimore* and *Isaac H Evans*, heeled beyond 90 degrees, despite having ranges of stability of less than 90°.

Fore and aft rigged vessels rarely suffer knock downs due to the wind since the wind heeling moment is maximised when beating to windward, and if struck by a gust most vessels are readily luffed or indeed head upwind automatically as a result of the increased weather helm.

When carrying a spinnaker on a reach the vessel cannot luff in a gust because to do so would increase the heeling moment. Most knock down incidents on yachts occur with spinnakers set, or when running downwind and a broach occurs. Broaching may be due to loss of control on a following wave or to oscillatory aerodynamic forces which may increase with roll angle and lead to violent rolls and capsize.

In order to survive a knock down the vessel requires a range of stability in excess of the angle to which is may be heeled and in order to maintain this positive stability in the case of a prolonged gust, downflooding should be avoided. Most yachts with centreline companionways achieve this.

Downflooding points on most merchant vessels are regarded as vents and air pipes which cannot readily be closed, and doors or hatches which cannot be made watertight. It is generally assumed that if a vessel develops a reduction in freeboard by listing or trimming as a result of a cargo shift, accidental flooding of a compartment or damage, the crew will have time to close any doors or hatches which threaten to cause downflooding. In such circumstances even a small vent could cause loss of the vessel since, if primary cause of the reduction in freeboard cannot be corrected, the opening may remain immersed indefinitely. The situation on board a sailing vessel is rather different since the most likely cause of serious downflooding is excessive heel due to a gust of wind.

Most sailing vessels operate with large doors or hatches kept open for ventilation, and in order to avoid the ingress of rain or spray these openings will normally face aft or to the side. If a vessel has doors in the sides of a deckhouse it will typically be the leeward ones which are open. If the vessel is knocked down by an unexpected gust

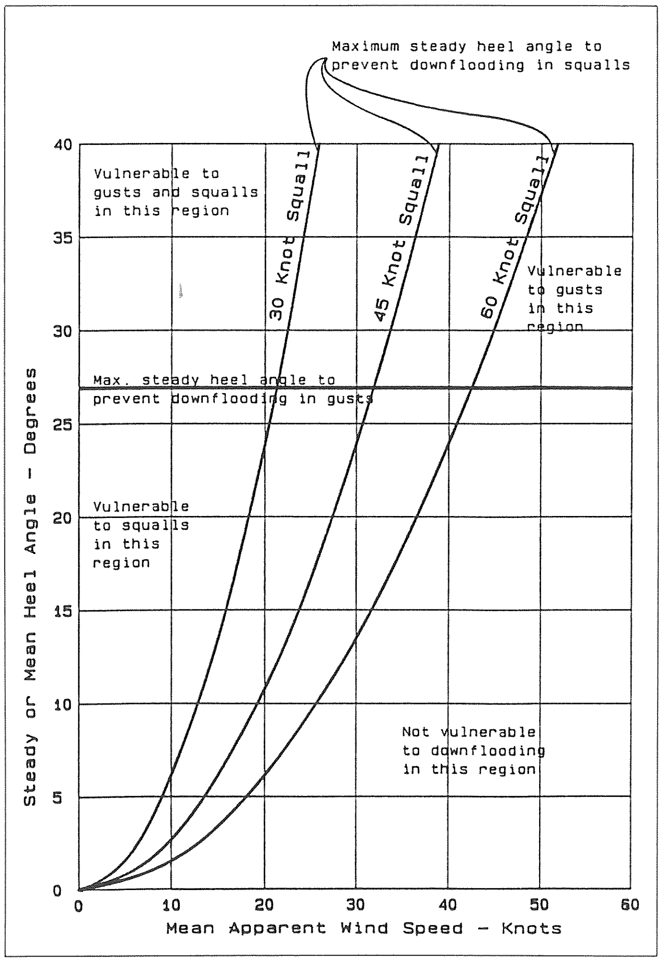
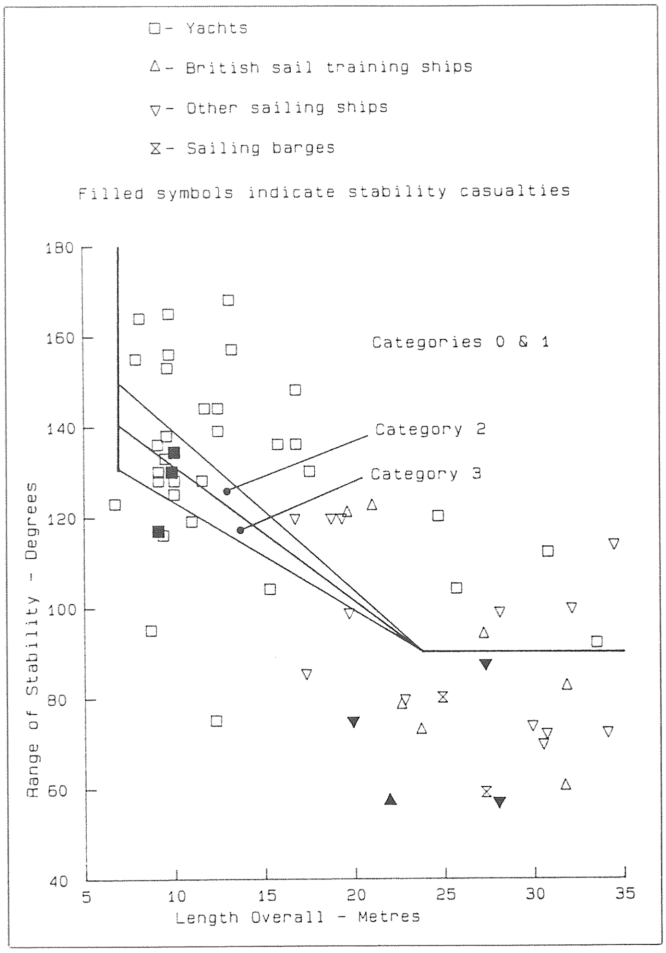


Fig. 3: Curves to be used by the Master to assist in determining his level of safety from squalls.

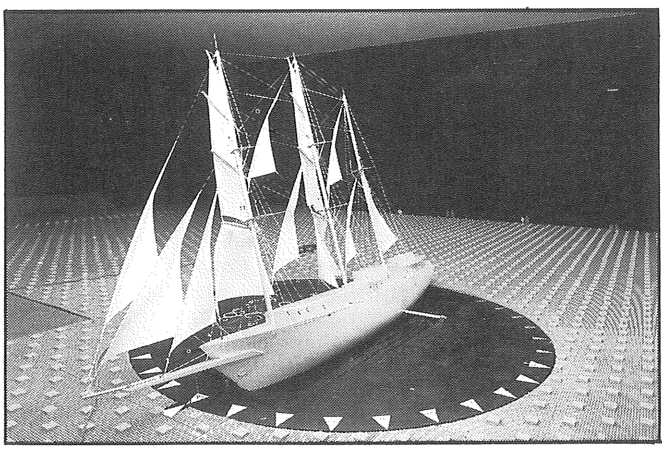
or squall the crew will not have time to close such openings and indeed may want them open as a means of escape. Squalls may be of several minutes duration and in such a period a door or hatch will permit sufficient water through to sink a vessel without compartmentation. This is exactly the scenario in which the four vessels mentioned earlier were lost. In such circumstances, however, a small vent or air pipe would probably not pose a serious threat to the vessel, which will return to a reasonable sailing angle after the passage of the gust. The definition of a downflooding point for a sailing vessel should therefore be one which could cause serious loss of stability after immersion for, say, 5 minutes and should include all openings used for regular crew access or for ventilation. Obviously the smaller the vessel, the more serious would be the consequences of immersion of a specific size of opening. A 400 tonne ship could withstand immersion of a 250mm porthole for 5 minutes and still retail stability characteristics, whereas a 10 tonne yacht would probably sink with the resulting weight of floodwater aboard. The downflooding angle is therefore defined as the angle at which the immersed openings have an aggregate area (in square metres) greater than the displacement (in tonnes)/1500, and will normally correspond to the immersion of a skylight, hatch or door.

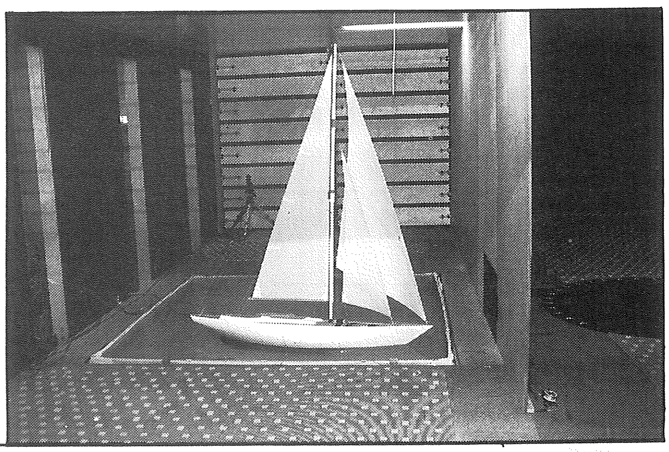
Fig. 4: Range of stability of sailing vessels used in the Wolfson Unit's study. The diagram also shows the minimum range required by the code.



The two types of gust which cause dangerous heel angles have rather different characteristics. The normal gusts which arise from general boundary layer turbulence have a maximum gust factor of 1.4 based on the hourly mean wind speed and in such gusts the wind gradient at low elevations may retain its shape approximately. It can be assumed therefore that, when sailing in turbulent wind, the maximum possible gust will have a speed of 1.4 times the mean, a pressure twice that of the mean and will result in an upright heeling moment twice that of the mean. All vessels must therefore be able to withstand an upright heeling moment equal to twice the mean value, at any time. Wind turbulence increases with terrain roughness so sailing close inshore increases the probability of encountering a severe gust. As already discussed, the calculation of heeling moment cannot be relied upon for an accurate prediction. The master will use his experience to decide when the heeling moment has reached a safe maximum limit and his decision will depend upon his judgement of the heel angle, rig strength, structural integrity of the vessel, crew ability and comfort. He cannot deduce from the heel angle and motion of the vessel what would happen if the wind pressure were to double, unless he was unfortunate enough to have experienced such an incident in the past. He should therefore be made aware of the result of such an increase in stability information carried on board. The format chosen for that information is a maximum recommended steady heel angle which, if exceeded, would result in downflooding in the event of a gust striking the vessel with a pressure twice that of the preceding mean wind. This value applies whether heavily reefed in a gale or under full sail in lighter winds.

It is a simple matter to calculate the heeling moment required to cause downflooding or capsize. It requires no knowledge of the rig, merely details of the GZ curve and the downflooding angle. Wind tunnel tests indicated that heeling moment reduces with heel angle





Below left: 1:25 scale model of the Jubilee Sailing Trust barque Lord Nelson, *one of the models used to determine the characteristics of wind heeling moment. It is seen on a 6-component balance in a large boundary layer wind tunnel.*
Below right: a one-ninth scale model of a Nicholson 55 being tested in the wind tunnel. Shutters downstream of the model open to release a gust, the model's response being monitored with a gyroscope.

according to the function $\cos^{1.3}\theta$. So to determine the upright value of the heeling arm which would cause downflooding, one divides the value of GZ at the downflooding angle, θ by $\cos^{1.3}\theta$. By halving this value and plotting a new heeling moment curve, the intercept with the GZ curve will define the maximum steady heel angle. See Figure 1.

A vessel can only be capsized by a horizontal gust of wind if its range of stability is less than 90 degrees. If such is the case the $\cos^{1.3}$ curve will be tangential to the GZ course at some angle below 90 degrees. It is in fact this angle which is the effective range of positive stability under the wind heeling, and the quoted range of statical stability will only be realised by the vessel when the gust has passed. Because of this fact the effective range of stability under wind heeling is dramatically reduced when the quoted range falls below 90 degrees. Figure 2 shows the stability curve for a vessel with good initial stability but a range of only 65 degrees. A wind heeling arm curve is shown which is tangential to the GZ curve at 37 degrees and if heeled by the wind beyond this angle the vessel would capsize. In this instance the maximum recommended heel angle to prevent capsize would be 18 degrees.

The regulations therefore set a minimum value for this steady heel angle at 15 degrees and require a range of statical stability of at least 90 degrees.

The logic is taken further to provide the master with an indication of the ship's vulnerability to squalls.

The characteristics of squalls are less predictable than those of gusts resulting from boundary layer turbulence. Squalls typically result from the descent of cold air from a storm cell. The air radiates as it nears the ground or sea surface so the local gusts may have a downward component, may come from any direction regardless of the prevailing wind and are likely to eliminate the wind gradient. Their gust factors may be as high as 10 or more (100 times the wind pressure!). They may be anticipated if visibility if good but on occasions they are not foreseen, as was the case in the sinking of the *Albatross*, the *Marques* and the *Isaac H Evans*. Storm cells can become particularly well developed over a warm land mass so being in coastal waters increases the probability of encountering a severe squall. Furthermore, the strength of such storms is maximised during the summer months in periods of light winds. In the same way as the maximum steady heel angle was derived, one can calculate a corresponding angle for the prevention of downflooding in squalls if one assumes a squall speed. The angle will be different for all mean apparent winds and squall speeds but curves of maximum steady heel angle plotted against mean wind speed for a number of discrete squall speeds give the master a good indication of his safety in squall conditions. See Figure 3. These curves are required in the stability booklet.

It is important to ensure protection of equipment and machinery from ingress of water when sailing and for this reason no opening, regardless of size, should become immersed at a heel angle of less than 40 degrees. Such a requirement is roughly in line with those for other vessel types where the area under the GZ curve up to 40 degrees or the downflooding angle if less, is regulated.

When considering the probabilities of capsize, the likelihood of being rolled by a breaking wave increases as the size of the vessel reduces. For this reason the range of statical stability should be greater for a small vessel if it is to have the same probability of survival as a larger vessel. Figure 4 reveals that in general small vessels do have greater ranges and the lines shown represent the required minimum values for sail training vessels. Thus large vessels above 24 metres, which are virtually immune to breaking wave capsize, require a range of at least 90 degrees to survive a wind induced knock down. The minimum size of vessel which is required to meet these regulations is 7 metres and it has been argued that such small vessels should have a range of 150 degrees if making long passages. A linear relationship is used between these points.

Concessions are made to those vessels operating in restricted areas, or categories, by a reduction in the range equipment.

Further concessions are made for small vessels in recognition of the fact that they are unlikely to be lost as a result of wind induced capsize or flooding, and that the cost of a stability booklet would become a more significant part of the operating costs.

Vessels under 15 metres in length need not carry a booklet and need only submit documentary evidence that they meet the range requirement for the proposed category of operation.

Furthermore, such vessels, if fitted with external ballast keels, may be able to meet the range requirement on the basis of an estimated value of the range of stability and thus avoid the expense of an inclining experiment and calculation of a GZ curve. A simple method was developed by the Wolfson Unit by which the range of stability may be approximated using just four parameters to be supplied by the designer or builder of the yacht. This was originally intended to be used to provide a conservative estimate of the range in order that, if a yacht met the requirements on the basis of estimated range it would almost certainly meet them if the range were calculated accurately. Following extensive discussions with representatives of the sail training industry the Department have agreed to a revised formula which results in a less conservative estimate. The Department of Transport will accept this estimate of range if the yacht is operated in a condition close to that intended by the designer, that is without major additions to the outfit.

The formula to be used is:

$$\text{Estimated range} = 110 + 400/(SV - 10)$$

$$\text{where } SV = \frac{B^2}{R\,T\,V^{1/3}}$$

and where B = maximum beam
R = ballast ratio
T = draught at B/8 from the centreline
V = volume of displacement

A third option is open to operators of vessels less than 15 metres, and that is to seek approval through the RYA. The stability will then be assessed using a value to be known as the STOPS Numeral. This value is based on the SSS numeral familiar in yacht racing circles, adjusted by a factor called the Vanishing Angle Factor which in turn is based on the range estimate described above. The SSS numeral itself is made up of eight factors related to hull form and other design aspects and is determined with the aid of a computer program. Minimum values of the STOPS Numeral are required for sailing in the various categories.

Many of the criticism of conventional regulations have therefore been addressed by the research, while the DTp have recognised the needs of the industry in having simple but technically sound regulations, and in keeping the cost of assessment to a minimum for the smallest vessels.

References

1 **The Safety of Sail Training Ships — A Code of Practice.** The Department of Transport, Marine Directorate, 1990. HMSO.
2 **The Development of Stability Standards for UK Sailing Vessels.** B. Deakin. R.I.N.A. Spring Meetings 1990.
3 **The Safety of Sail Training Ships — Stability Information Booklet.** The Department of Transport, Marine Directorate 1990. HMSO.

Degree course

Southampton Institute of High Education is offering a Bachelor of Science degree in Yacht and Small Craft Design, the culmination of many years provision of courses in this field. The degree will be validated by the UK's Council for National Academic Awards and the course will enrol its first students in October of this year.

According to the Institute, the programme is specifically designed to meet the needs of the small craft industry and will include aero and hydrodynamics, aesthetics, CAD design and business management.