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Causes of Yacht Capsizing in Heavy Seas

Jan O. de Kat

Maritime Research Institute Netherlands, Wageningen

ABSTRACT

This paper presents an overview of capsize modes that are relevant to intact ships and sailing yachts subjected to waves and wind. For larger size ships following and stern quartering seas tend to be most critical from a stability perspective. Sailing yachts in extreme weather conditions will be vulnerable particularly to wind-induced knowckdown and breaking impact.

The probablity of capsize of sailing yachts depends on the probability of occurrence of (possibly breaking) waves with critical height and period. For long-crested seas it is possible to derive relevant statistics based on the joint distribution of wave height and period, as is illustrated for measured storm waves. A discussion is given of design factors that influence the resistance against capsizing. Safety against complete foundering is dicussed briefly.

INTRODUCTION

Knowledge of the dynamics and physics involved in vessel capsizing should enable us to assess and improve the performance of a design in extreme weather conditions. The safety against capsizing of intact ships and yachts alike depends on the intact stability properties and on the occurrence of critical wave and wind conditions.

To illustrate the differences and similarities as regards dynamic stability between large ships and sailing yachts, this paper describes the capsize physics for both vessel types. Yachts are vulnerable to steep, breaking waves of critical height, the occurrence of which is discussed for storm wave conditions. To reduce the risk of capsizing for a yacht, a number of design parameters play an important role: displacement, righting arm curve (angle of vanishing stability and area), and moment of inertia. Adequate reserve buoyancy is a critical parameter to avoid foundering in the case of flooding of non-draining spaces through openings.

CAPSIZE MODES FOR SHIPS

The following modes are relevant to ships:

- Static loss of stability
- Dynamic loss of stability
- Broaching
- Other factors: cargo shift, water on deck, wind

Combinations of modes are possible. The above capsize modes are discussed below in some detail.

Static Loss of Stability

Loss of static stability refers to the quasi-static loss of transverse stability (associated with an excessive righting arm reduction) in the wave crest. This mode occurs typically at forward speed in regular or irregular following to stern quartering waves with low encounter frequencies. The ship can capsize when it experiences temporarily a critically reduced (possibly negative) righting arm for a sufficient amount of time, while the wave crest overtakes the ship slowly and the ship is surging or surf-riding periodically. For this mode of capsize to occur in irregular waves, one encountered wave of critical length and steepness is sufficient to cause the sudden catastrophic event. Experimental evidence can be found in Oakley et al. (1974) and Kan et al. (1990).

Dynamic Loss of Stability

A ship can lose stability dynamically in conjunction with extreme rolling motions and lack of righting energy under a variety of conditions. This major capsize mode may be associated with the following phenomena.

- *Dynamic Rolling:* This mode of motion occurs at forward speed in stern quartering seas, which can be of regular or irregular nature. Here all six degrees of freedom are coupled, where in addition to roll, surge, sway and yaw can exhibit large amplitude fluctuations. The motion is characterised by asymmetric rolling: the ship rolls heavily to the leeward side in phase with the wave crest (approximately) amidships and rolls back to the windward side in the wave trough, albeit with a shorter half-period and smaller amplitude. Due to the associated surging behaviour, the ship spends more time in the wave crest than in the trough, resulting in a periodic and longer duration reduction of the righting arm in the crest and restoring in the trough (shorter duration) of the righting arm. The roll period may exceed the natural roll period significantly. In the case of a capsize, the roll motion typically builds up over a number of wave encounters to a critical level, and the ship will usually capsize to leeward in the wave crest.

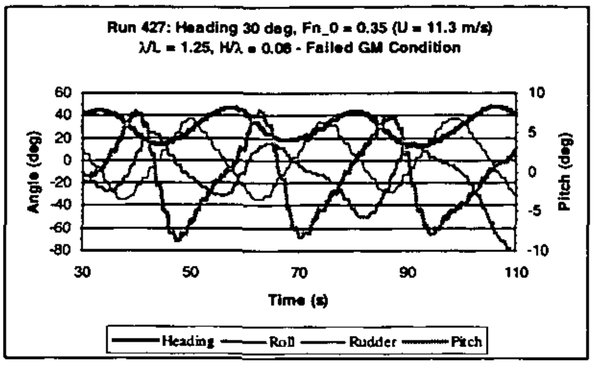

Figure 1. *Capsize: dynamic loss of stability for frigate wth low GM in stern quartering waves. Model tests with measured heading, roll, pitch and rudder angles*

Figure 1 illustrates this capsize mode in steep stern quartering waves for a frigate model with low initial stability (De Kat and Thomas, 1998); in this case the GM was such that the vessel would fail to satisfy the relevant stability criteria.

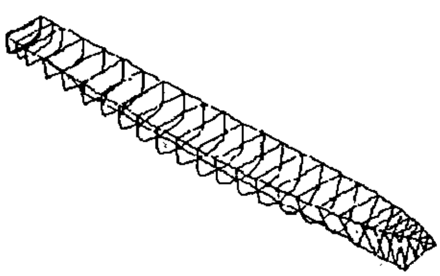

Figure 2. *Isometric sketch of frigate*

The conditions in figure 1 are as follows: mean heading is 30 degrees, calm water Froude number Fn = 0.3, wavelength to ship length ratio λ/L = 1.25, wave steepness H/λ = 0.08, scaled ship length L = 106.7 m (see figure 2 with hull form). The time series for roll, yaw (heading) and rudder angle are plotted on the left vertical axis; the heading varies between 20 and 40 degrees, rudder angle varies between +/- 40 degrees.

- *Parametric Excitation:* Parametric excitation results from the time-varying roll restoring characteristics of a ship typically found in longitudinal waves. The periodic changes in static righting arm during the repeated passage of a wave crest followed by the trough can cause large amplitude roll motions. Roll motions occurring at approximately the natural roll period and simultaneously at twice the encounter period (encounter frequency equals half of natural roll frequency) characterise this mode of motion. The roll motion is of a symmetric nature and the maximum roll angles to port and starboard occur when a wave crest passes the midship area. The wavelength must be of the order of the ship length. In such circumstances, parametric rolling - also referred to as low cycle resonance - can result in capsizing. It can occur in regular and irregular waves. It has been observed in head seas, but parametric excitation in astern seas is typically more critical in terms of capsizing (Oakley et al., 1974). In particular, when a ship travels at the mean group speed in following seas, parametric excitation can occur during the passage (in a regular fashion) of a wave group with a sufficient number of encountered waves of critical height and length.

- *Resonant Excitation:* In principle large amplitude roll motions can result when a ship is excited at or close to its natural roll frequency. Roll resonance (synchronous rolling) conditions are determined by the combination of righting arm curve characteristics, weight distribution, roll damping, heading angle (e.g., beam seas), ship speed, wavelength and height.

- *Impact Excitation:* Steep, breaking waves can cause severe roll motions and may overwhelm a vessel. The impact due to a breaking wave that hits a vessel from the side will affect the ship dynamics and may cause extreme rolling and capsizing (Dahle and Kjaerland, 1979). Possible damage to deck structures and subsequent water ingress may result as a consequence. This capsize mode is relevant especially to smaller vessels in steep seas. Experimental evidence can be found in Ishida and Takaishi (1990).

Broaching

Broaching is related to course keeping in waves. Although there is no uniformly accepted mathematical definition of a broach, it represents the wave-induced undesired, large amplitude change in heading angle. A variety of broaching modes exist in regular and irregular waves:

- Successive overtaking waves (low speed);
- Low frequency, large amplitude yaw motions;
- Broaching caused by a single wave (high speed).

The first mode has been observed to occur in steep following seas at low ship speed, where the ship is gradually forced to a beam sea condition during the passage of several steep waves. The other modes occur at higher speed, typically at a Froude number Fn > 0.3.

The third mode is usually characterised by quasi-steady surf-riding at or above wave phase speed (see e.g. figure 3) and steadily increasing yaw angle. Surfriding is particularly critical when this occurs in conjunction with bow submergence; when the bow is buried in the back slope of the preceding wave while surfriding, a strong destabilizing effect takes place as regards directional stability and a sudden, high speed broach may ensue.

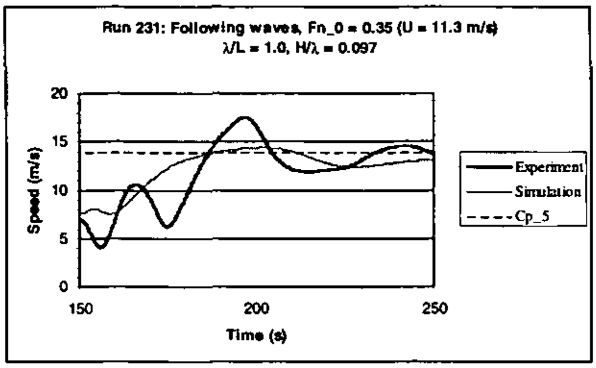

Figure 3. *Measured and predicted ship speed during surfriding events for frigate in steep following seas (De Kat and Thomas, 1998); Cp_5 is the wave phase speed.*

Figures 4a, 4b and 4c depict the occurrence of the second broaching mode for the frigate model tested in the Full Load Condition, illustrating that the ship can experience extreme roll angles in this condition (De Kat and Thomas, 1998). Figure 4b shows that the ship experiences large speed fluctuations in both longitudinal and transverse direction and that it has a significant mean negative drift velocity, i.e. it experiences a rather large drift speed to leeward while yawing. The highest transverse drift velocity occurs when the yaw angle (toward the wave) and forward speed increase while a wave crest is overtaking the ship (from aft to amidships). When the crest is in the midship area and the ship has reached its largest yaw deviation into the wave, the roll angle to leeward (negative sign) is largest; the reduction of the righting arm in the wave crest leads to asymmetric roll motions. In this case the ship experiences large roll angles, but it does not capsize. Figure 4c illustrates the amount of drift a ship can experience in steep stern quartering waves.

Other factors that influence capsizing

Water on deck can occur in conjunction with (and hence influence) the capsize modes discussed above. Large amplitude relative motions and breaking waves can result in the temporary flooding of the deck, which from a stability viewpoint is relevant especially to vessels with bulwarks, such as fishing vessels. Furthermore, deck edge submergence results in loss of waterplane area and righting arm. If a bulwark is present, its submergence will influence the forces acting on the vessel. Wind does not necessarily influence wave-induced capsizing in astern seas; in beam waves, however, it may be important. Cargo shift as a consequence of large amplitude rolling and high accelerations is a major cause for ship capsizing.

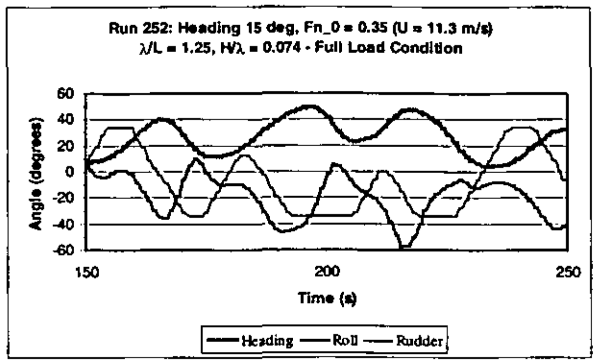

Figure 4a. *Broach mode 2: measured heading, roll and rudder angles for frigate in stern quartering waves*

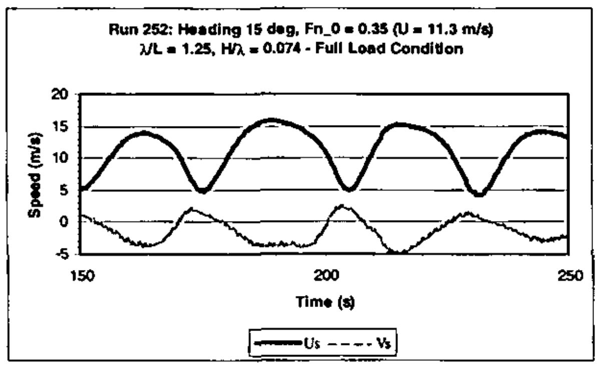

Figure 4b. *Mode 2 broach: Measured longitudinal and transverse ship speeds for run 252*

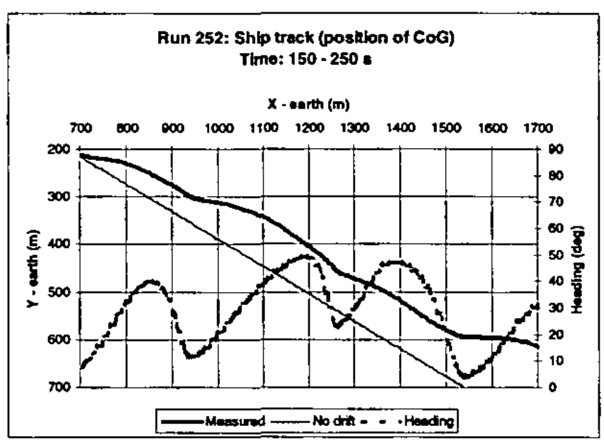

Figure 4c. *Measured ship track and heading associated with run 252 in stern quartering wave (wave direction is along x-axis)*

CAPSIZE MODES FOR SAILING YACHTS

A sailing yacht may capsize in the following modes:

- Breaking wave impact
- Knockdown under sail in heavy wind and waves
- Broaching associated with surfriding and bow submergence (loss of rudder control)
- Combination of above modes

The broaching mode associated with surfriding is similar to the mode 3 broach described for ships above. Whereas ship capsizing can be dominated by loss of stability in the wave crest, this is not the case for yachts. In extreme weather conditions, when a yacht carries as little sail as possible, capsize due to a breaking wave and knockdown in a heavy gust are particularly dangerous. Also, a yacht is vulnerable when after a knockdown it is hit by a steep or breaking wave.

Impact by steep, breaking wave

In severe weather breaking waves are critical to yacht safety, as has been reported by Stephens *et al.* (1981), among others. A wave that is about to break tends to have a steep crest front that travels at a speed that is close to the phase speed of the wave. When this crest front hits a structure or ship, the impact load can be significant (Chan, 1994). For example, the phase speed of a steep wave of height H = 12 m and period T = 9 s is 15 m/s in deep water, which is significantly higher than the crest particle velocities of a similar wave in non-breaking conditions. Figure 5 illustrates the steep face associated with a breaking wave in laboratory conditions.

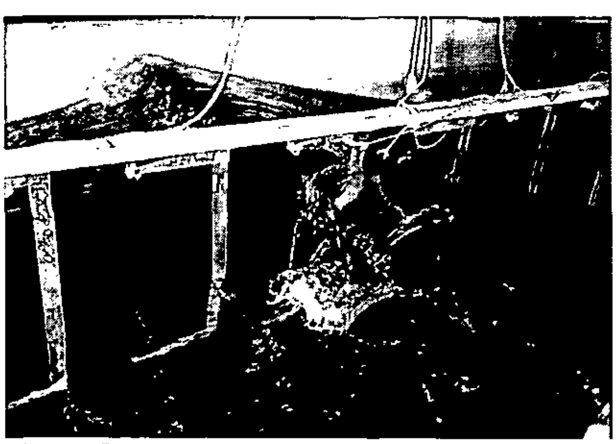

Figure 5. *Breaking wave measurements in model basin (MARIN).*

At the moment of impact, an upright yacht would be subjected to the following roll moment balance:

$$(I_{44} + a_{44})\ddot{\phi} \approx \tfrac{1}{2}\rho V^2 S.r$$

where I_{44} is the roll moment of inertia in air, a_{44} is the added mass roll moment, V is the velocity of the crest front (jet), S is the projected area of impact, and r is the arm at which the impact force acts with respect to the centre of gravity of the vessel. In other words, the initial roll acceleration experienced by the yacht because of the impact is approximately proportional to the following:

$$\ddot{\phi} \approx \frac{\tfrac{1}{2}\rho V^2 S.r}{m\rho_{xx}^2 + a_{44}}$$

where m is the mass of the yacht and ρ_{xx} is the radius of gyration for roll.

The above equation is a very rudimentary one, but it does indicate some of the critical components. Obviously, to predict the roll response accurately, a more complete description of the equations of motion is necessary; Blume (1987) and Dahle and Kjaerland (1979) have attempted to describe the equations of motion for the case of impulsive impact due to breaking waves. Figure 6 shows the sequence of measured yacht capsize subjected to a transient breaking wave from abeam (Nimura *et al.*, 1996). This figure illustrates the occurrence of a semi-stationary knockdown stage - nos. 5, 6 and 7 - before capsize.

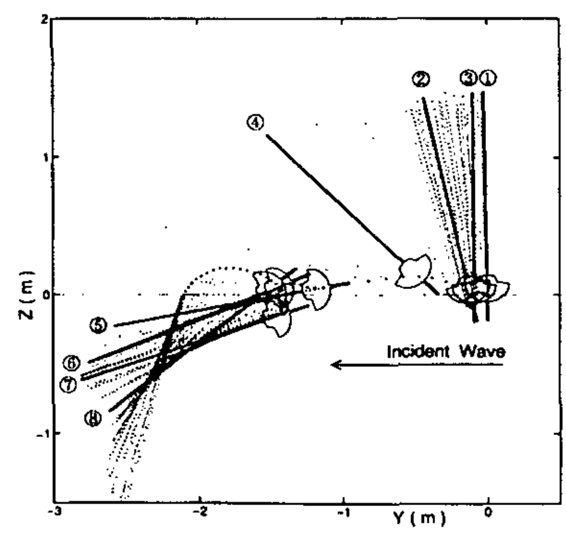

Figure 6. *Motions of capsizing yacht subjected to a transient breaking wave (model tests by Nimura et al., 1996).*

CRITICAL WAVE CONDITIONS

It is common to refer to wave conditions in terms of a reference wave height or "sea state number" (the latter especially in navy context). The reference wave height tends to be the significant wave height, which is the statistical average of one-third of the highest waves (and which corresponds approximately to the estimated wave height observed at sea). The most probable maximum wave height that can be expected in 1000 wave encounters is related to the significant height as follows:

$H_{max} = 1.86H_S$

where for a narrow-banded process the significant wave height is related to the area m_0 under the energy spectrum:

$H_S = 4\sqrt{m_0}$

Associated with the energy spectrum is a peak period:

$T_p = 2\pi/\omega_p$

where the peak frequency is the frequency associated with the maximum energy in the spectrum. The characteristic steepness of the sea state, s_{char}, determines the probability of occurrence of critical, steep waves:

$$s_{char} = \frac{H_s}{gT_p^2/(2\pi)}$$

The maximum steepness observed for ocean waves lies typically around $s_{char} = 0.05$; the average characteristic steepness for worst North Atlantic storm waves is approximately $s_{char} = 0.035$ (De Kat *et al.*, 1994). In terms of risk of yacht capsize, critical waves are those individual waves that are very steep: capsize risk is directly related to the probability of occurrence of almost or completely breaking waves. The same has been found to apply to the capsize risk of liferafts (Paterson *et al.*, 1996). For larger size ships, critical waves can be expressed in terms of wavelength in relation to ship length and steepness.

Although it is difficult to predict the probability of wave breaking in a sea state in deep water conditions, it is possible to make an assessment of the probability structure of individual waves based on the joint distribution of individual wave heights and periods. By applying a zero-crossing analysis of wave elevation time series, it is possible to obtain information on the characteristics of individual waves.

Let us consider as an example the properties of a steep storm sea state based on measurements in the North Atlantic, taken in deep water off the East coast of Canada. The significant wave height is 10.7 m with a peak period of 12.4 s ($s_{char} = 0.044$); to obtain statistically reliable distributions, the 20 minute time series with measured wave data were concatenated into a stationary time series of about two hours duration. Figure 7 shows the joint distribution (probability density function, or *pdf*) of the zero-crossing wave periods, T_z, and associated (crest-to-trough) wave heights, H.

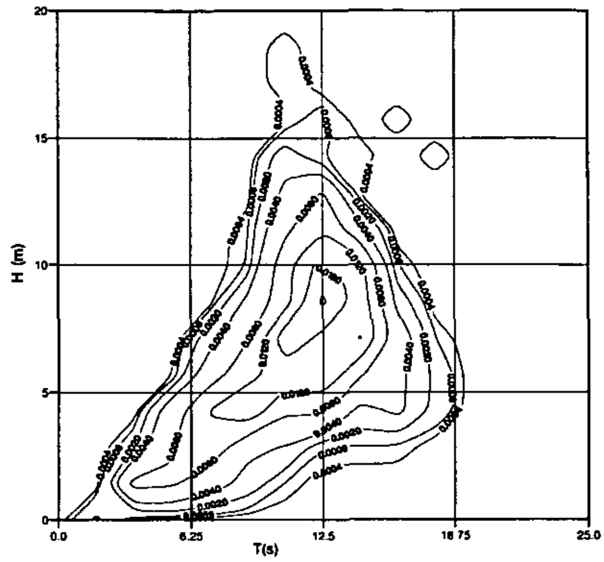

Figure 7. *Joint probability distribution function of wave period and height (full scale measurements, H_s = 10.7 m, T_p = 12.4 s).*

The outer contours represent the waves with smallest probability of occurrence; figure 7 shows that the highest observed wave has a height of about 19 m and a period of 10.7 s. The same information can be represented in terms of zero-crossing wave lengths, where the wavelength is taken to be:

$$\lambda = \frac{gT_z^2}{2\pi}$$

Figure 8 shows the resulting joint distribution of wavelength and height. It can be seen, for instance, that waves with a height of more than 15 m have lengths ranging between 170 m and 300 m.

As a last example of how such data can be presented, figure 9 shows the joint distribution of wave steepness as a function of wavelength, where the individual wave steepness is taken to be:

$$s = \frac{H}{\lambda}$$

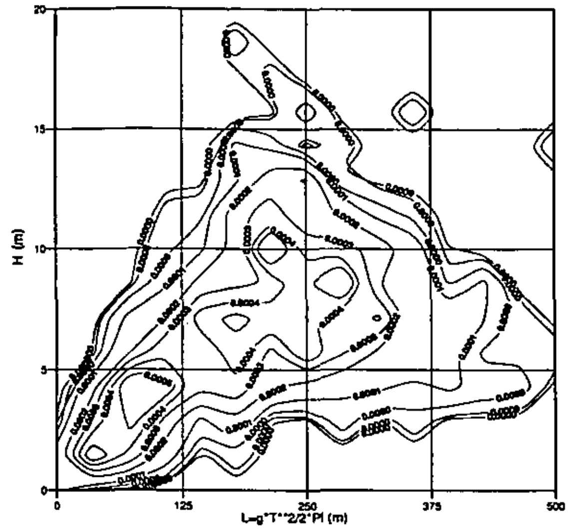

Figure 8. *Joint pdf of wavelength and height (full scale measurements, H_s = 10.7 m, T_p = 12.4 s).*

Figure 9 shows that the steepest waves have a length ranging from about 50m to 180 m; their maximum steepness is around s = 0.10, for which wave breaking could be likely (and dangerous, considering the size). Myrhaug and Kjeldsen (1987) suggest that the probability of wave breaking is linked to a crest steepness parameter, which should apply to long-crested waves. In short-crested waves, however, wave breaking is not linked strongly to wave steepness: 3D waves can break at low and high steepness with similar probability.

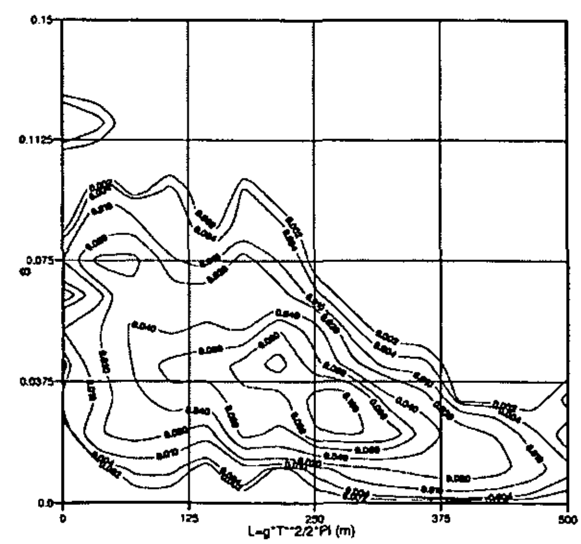

Figure 9. *Joint pdf of wavelength and steepness (full scale measurements, H_s = 10.7 m, T_p = 12.4 s).*

Nevertheless, the probabilistic description of the wave surface as discussed above provides a clear indication of the severity of a given sea state. A sea state with a realistic occurrence of high, steep waves can be considered potentially dangerous. It is possible to estimate the capsize risk due to steep waves, if one knows the critical wave height and associated steepness values in which a given vessel would capsize in e.g. beam sea conditions. The probability of capsize in a given sea state can then be obtained by integrating the joint probability density function over the critical range of wave heights and steepness values.

The presence of current may have a major influence on wave steepness. Even in the case of a weak current opposing the wave direction, experiments suggest that the particle velocities in the crest of a breaking wave can increase significantly compared with the zero-current case (Kjeldsen and Myrhaug, 1980).

<u>Bass Strait measurements on 27 Dec. 1998</u>

Through the courtesy of Esso Australia Ltd, data were made available for analysis as regards wind, wave and current obtained at the Kingfish-B Platform in the eastern Bass Strait during 26 through 28 December, 1998. The platform is located in 78 m water depth at 38°35.9' S and 148°11.2' E. The highest wave conditions in that period were measured on 27 December, as shown in figure 10.

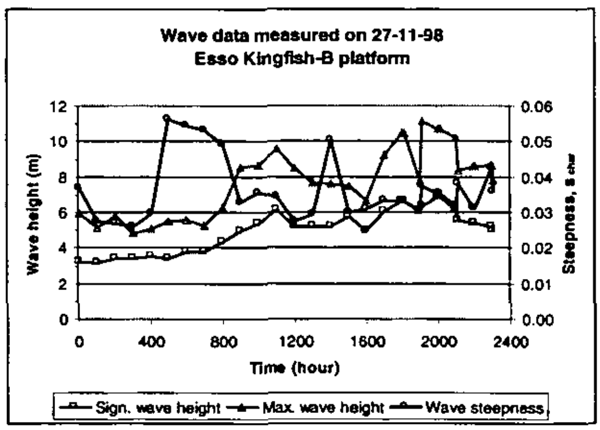

Figure 10. Wave height (significant and maximum) and direction in eastern Bass Strait.

The maximum significant wave height was around 7 m with maximum recorded wave height of around 11 m. The plotted characteristic wave steepness is defined as above. Figure 11 shows the wind data for the same period; the wind speed is an average value at a height of 44.5 m above MWL.

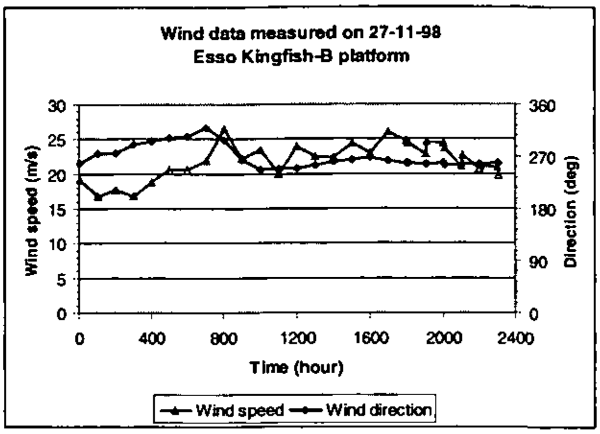

Figure 11. Wind speed and direction in Bass Strait.

Figure 12 shows the current speed and direction.

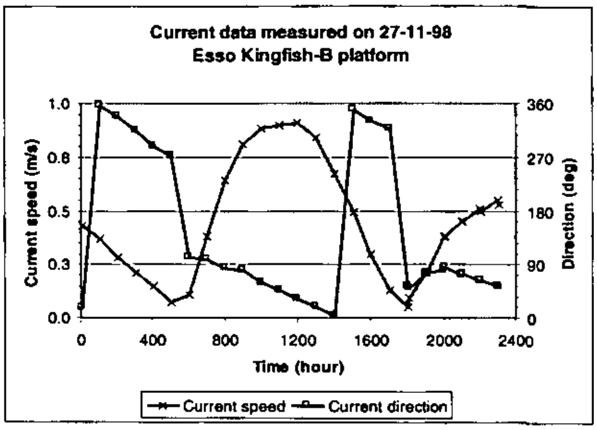

Figure 12. Current speed and direction in Bass Strait.

The figures show that as the wave height builds up between 8 and 12 a.m., the current increases from almost zero to two knots.

DESIGN FACTORS INFLUENCING CAPSIZE RISK OF YACHTS

From a design viewpoint, the following parameters will influence the resistance against capsize:

- Size (displacement)
- Range of positive stability
- Roll moment of inertia

For a yacht in survival conditions, the most relevant capsize modes are breaking wave impact and wind-induced knockdown, assuming that the yacht can be kept under reasonable control in terms of course keeping while avoiding high surfriding speeds.

The analysis in the preceding section suggests that the initial roll acceleration caused by wave impact will be smaller for a yacht with: (1) larger mass, (2) higher moment of inertia. Experience has shown that larger size yachts are at a smaller risk of capsizing. Likewise, a vessel with a higher moment of inertia has been shown less prone to capsize in breaking waves (Rousmaniere, 1987). Rigging will increase the roll moment of inertia compared with the bare hull case; evidently heavy rigging will result in a higher moment of inertia than a lightly constructed system.

Once dismasted, a yacht will be easier to capsize; also, Nimura *et al.* (1996) have observed experimentally that the rigging provides additional damping, causing the boat to attain for some time a constant large heel angle before further capsizing to the inverted condition or self-righting would take place.

Once the vessel is heeled over by wave impact or heavy wind gust, or a combination of such factors, the resistance against capsize is governed by the range of positive stability, i.e., the range of heel angles over which the vessel exhibits a positive (counter acting) restoring moment. Furthermore, the area underneath the righting arm curve over the range of positive stability is an important factor, as it determines the required energy to heel a ship. The range of stability and area of the righting arm curve depend on the underwater and above water hull form including cabin and deck camber, freeboard, cockpit, and vertical location of centre of gravity (KG).

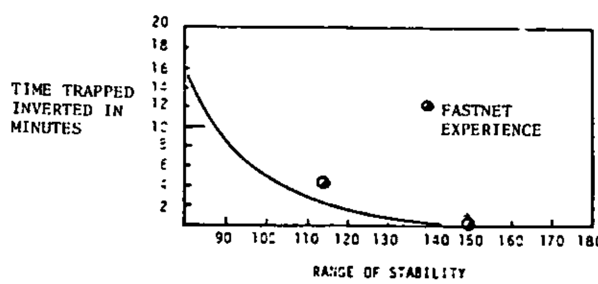

Figure 13. *Relationship between range of positive stability and time inverted after capsize (USYRU, 1985).*

The range of positive stability (RPS) determines the range of which a vessel is self-righting and to what extent a vessel is likely to remain inverted in a stable condition after capsize. Following the Fastnet disaster in 1979, capsize research (Rousmaniere, 1987, and USYRU, 1985) suggests that a yacht with RPS = 140 degrees or more will be safe from ending up inverted or stay in such a position for any significant amount of time, see figure 13. As the RPS becomes smaller (say, less than around 140 degrees), it will take a higher and steeper wave, and therefore more time, to roll a boat back to its upright position; as shown above, the probability of occurrence of waves decreases with increasing height and steepness.

Recent analysis of yacht casualties illustrates the link between safety against capsizing and the range of positive stability (Van Oossanen, 1997). In relation to this study, Figure 14 shows the angle of vanishing stability (i.e., RPS) as a function of boat length for boats that were safe and those that were stability casualties.

The significance of the range of positive stability and total area under the righting arm curve has been proven relevant for other ship types as well. For example, stability research directed at naval ships has shown that a direct relationship exists between the value of RPS and risk of capsize, and that RPS could be used as an additional design parameter in intact stability criteria for frigates (De Kat et al., 1994).

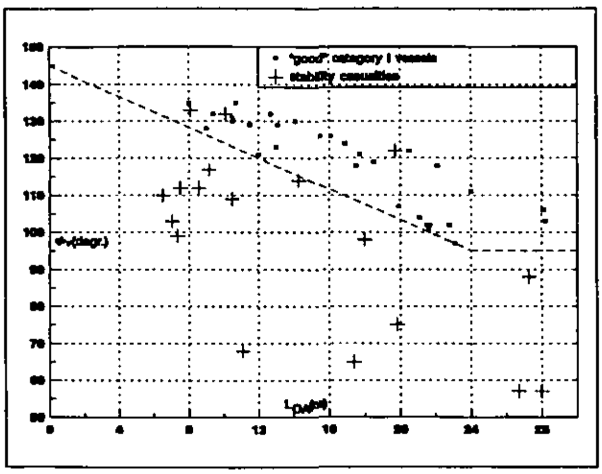

Figure 14. *Angle of vanishing stability as a function of overall boat length for stability-related casualties (+) and safe survival cases (■) obtained from casualty analysis (Van Oossanen, 1997).*

PREVENTION OF FOUNDERING

Besides stability of the intact vessel, there are several important factors that have a bearing on survivability in severe seas:

- Watertight integrity
- Structural integrity
- Reserve buoyancy

Watertight integrity implies the ability of the hull and cabin to safeguard the vessel from water ingress and downflooding into non-selfdraining areas through openings (ventilators, hatches, etc.).

Structural integrity refers to the hull, cabin, rigging and appendages being able to withstand wave and wind induced loads. Hatches with insufficient strength may not be able to withstand the pressure of a wave impact, or rigging may fail under extreme loading when a yacht is overwhelmed by a wave.

When a yacht does lose its watertight or structural integrity in severe weather conditions, it is likely to founder when there is not sufficient reserve buoyancy, as shown schematically in figure 15. While reserve buoyancy determines the floatability in damaged conditions, a damaged vessel may capsize when there is a lack of damage stability (e.g. when the range of stability is too small), but damage stability properties are more relevant to larger vessels.

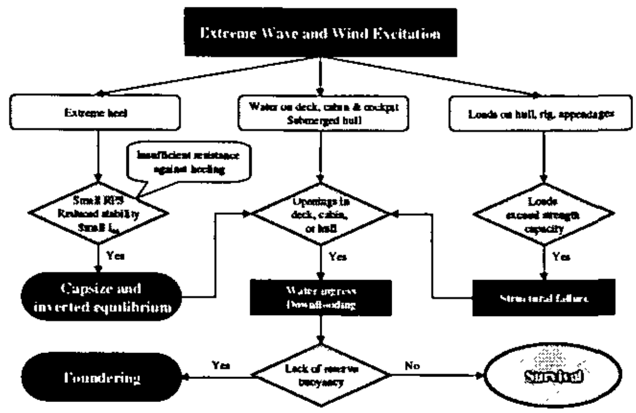

Figure 15. *Hazard identification chart for yacht subjected to extreme excitation in wind and waves*

CONCLUSIONS

This paper provides an overview of capsize modes for ships and sailing yachts. In case of the rare event of capsizing, the capsize mechanism for larger vessels will be mainly related to static or dynamic loss of stability in steep astern seas. For yachts in extreme weather the danger of impact due to steep, breaking waves and knockdown in heavy wind is most critical.

Regardless of ship type, the risk of capsizing depends largely on the probability of occurrence of critical waves. Critical waves are those individual waves that result in capsizing of a vessel with a given set of operating conditions. A methodology is described to represent the probability structure of individual (critical) waves as a function of main sea state parameters. Examples of storm wave data are given.

The paper concludes with a discussion of design factors that influence the resistance against capsizing and foundering of yachts.

REFERENCES

Blume, P. "Uber ein Konzept zur Beurteilung der Sicherheit gegen Kentern", *Schiffstechnik*, Vol. 34, No. 1, May 1987, pp. 21- 27 (in German)

Chan, E.S., "Mechanics of deep water plunging-wave impacts on vertical wave structures", *Coastal Engineering*, Vol. 22, 1994, pp. 115-133

Dahle, E., and Kjaerland, O., "The Capsizing of M/S HELLAND HANSEN", *Proc. RINA, 1979, pp. 51-70*

De Kat, J.O., Brouwer, R., McTaggart, K. and Thomas, W.L., "Intact Ship Survivability in Extreme Waves: New Criteria from a Research and Navy Perspective", *Proc. International Conference on Stability of Ships and Ocean vehicles STAB '94*, Melbourne, FL, Nov. 1994

De Kat, J.O. and Thomas, W.L., "Model Tests for Validation of Numerical Capsize Predictions", *Proc. 4th Stability Workshop*, St. John's, Newfoundland, Oct. 1998

Ishida, S., and Takaishi, Y., "A Capsizing Experiment of a Small Fishing Boat in Breaking Waves", *Proc. STAB'90 Conference*, Vol.1, 1990, Naples

Kan , M., Saruta, T. and Taguchi, H., "Comparative Model Tests on Capsizing of Ships in Quartering Seas", *Proc. International Conference on Stability of Ships and Ocean vehicles STAB '94*, Melbourne, FL, Nov. 1994

Myrhaug, D., and Kjeldsen, "Prediction of Occurrences of Steep and High Waves in Deep Water", *J. Waterway, Port, Coastal, and Ocean Engineering*, Vol. 113, No. 2, March 1987, pp. 122-138

Kjeldsen, S.P. and Myrhaug, D., "Wave-wave interactions, current-wave interactions and resulting extreme waves and breaking waves", *Coastal Engineering, Chapter 137*, 1980, pp. 2217-2303

Nimura, T., Watanabe, I., and Ishida, S., "On the Effect of Hull Forms and Other Factors on the Capsizing of Sailing Yachts", *Journal Soc. Naval Arch. Japan*, Vol. 195, 1994, pp. 57-67

Oakley, O.H., Paulling, J.R. and Wood, P.D., 1974, "Ship Motions and Capsizing in Astern Seas", *Proc. 10th Naval Hydrodynamics Symp.*, MIT, IV-1, pp. 1-51

Paterson, R.B., Hardiman, K.C., McKenna, R.F., Simoes-Re, A., and Radloff, E., "An Investigation of Liferaft Performance and Recovery Systems in Extreme Seas", *Proc. RINA Conference on Escape, Evacuation and Rescue,* Paper no. 9, London, Nov. 1996

Rousmaniere, J., Ed., *Desirable and Undesirable Charactristics of Offshore Yachts*, 1987, W.W. Norton & Company, NewYork

Stephens, O.J., Kirkman, K.L., and Peterson, R.S., "Sailing Yacht Capsizing", *Proc. 5th Chesapeake Sailing Yacht Symposium*, Annapolis, Jan. 1981, pp. 97-119

USYRU (United States Yacht Racing Union) and SNAME Joint Committee on Safety from Capsizing, Final Report of the Directors, June 1985

Van Oossanen, P., "Development of Proposed ISO 12217 Single Stability Index for Mono-Hull Sailing Craft", *Proc. 13th Chesapeake Sailing Yacht Symposium*, Annapolis, Jan. 1997, pp. 97-119