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Guidance Note Maneuvering of Fast ships in waves: Broaching-to

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Guidance Note Maneuvering of Fast ships in waves: Broaching-to

- *What it is*
- *When it can occur*
- *What can happen if it happens*
- *What is known about it*
- *How it can be investigated further*
- *Practical ways to prevent it in design and in operation*

Jointly developed as a part of the MANIFAST project



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1. The phenomenon of Broaching-to

1.1. What is this broaching-to?

Broaching-to is a dynamic instability event that makes the vessel lose control of its heading when sailing in following seas. This phenomenon is also referred in literature as broaching or broach. There are many ways to define broaching. In this document, a broach is defined as a condition in which:

- the heading of the vessel has deviated 20 degrees or more off course, and
- the course deviation is increasing, despite the maximum counter-action of the steering devices.

In this definition, the 20 degrees threshold deviation is an arbitrary but practical choice.

The definition makes clear that the phenomenon is not only related to the sea conditions, but also to the capabilities of the steering system to correct the course.

The broaching instability is characterized by high turning velocity and acceleration, that threaten the safety on board.

1.2. How can a broach occur?

Broaching-to can occur to sailing yachts when sailing downwind in smooth water, due to wind/sail interactions that cannot be compensated by the rudder. In the case of motor vessels broaching is mostly associated to sailing in significant following and stern-quartering seas, due to the destabilizing action of the waves on the hull. This document covers only broaching in waves occurring to motor vessels.

A broaching event is usually preceded by *surf-riding*. When surf-riding, a wave pushes the ship forward on its downslope and accelerates it to the velocity of propagation of the wave crest. This velocity is usually referred to as the *wave celerity*. In a sea wave, the orbital velocity of the water in a wave crest is in the direction of the wave, and in the wave trough the water moves in the opposite direction. Depending on the wave characteristics (length and steepness), during a surf-riding the stern sits near the incoming wave crest or on the wave front (downslope), whereas the bow sits near the trough or on the back of the subsequent wave: consequently, the bow will see an increased water flow in a direction opposite to the course direction while at the same time the stern is pushed forward in the wave direction. When the ship is at an angle to the wave, this will result in a yawing moment causing the ship to turn away from its course. Figure 1 shows these concepts more clearly.

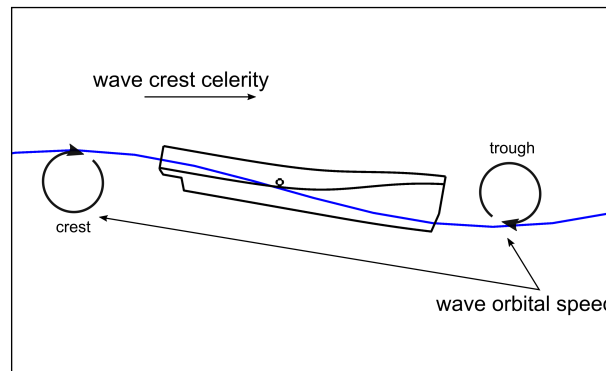


Figure 1 Most probable position of the vessel in the wave during the inception of surf-riding/broaching-to and relative wave orbital speeds.

The magnitude of the moment pushing the vessel off-course depends on several factors related to the steepness and the length of the wave, the ship speed and the position of the ship in the wave.

The steeper the wave, the larger the difference in velocity of the water between the wave crest and the wave trough, so the stronger the effect. Also, the center of gravity of the vessel is somewhere halfway between bow and stern, so on the slope of the wave, and therefore, by simple hydrostatic action, gravity pulls the hull forward, down the slope. The bow of the vessel, in the back slope of the previous wave, will see a hydrostatic effect in the opposite direction.

As stated, *surf-riding* is the most common prelude to broaching. It shall therefore also be obvious that the initial speed of the vessel in the direction of the waves must be close enough to the wave celerity to start *surf-riding*. If the difference in speed is too large, the incoming wave cannot bring enough energy into to speed the vessel up to wave crest celerity and will simply overtake the vessel.

In a broaching situation the ship is overpowered by an excessive wave yaw moment which cannot be counterbalanced by the maximum moment produced by the rudder. It has been suggested that also the reduced effectiveness of the rudder on the wave's down-slope might be an important factor while others considered this to be a secondary effect.

A broach can be caused by poor directional stability of the vessel, affecting the ability of the vessel to limit its turning motion. It is not clear to which extent the course keeping ability plays a role in the inception of broaching-to; nonetheless, the characteristics of a ship which make her to be dynamic unstable in the following sea are still not fully understood.

1.3. Which are the conditions under which broaching-to can occur?

As indicated the broaching phenomenon is related to ship speed, the relative position of the ship in the waves and the steepness and length of the waves.

It can be assumed that the vessel is not susceptible to broaching as long as (see also Figure 3):

- the waves are either shorter than the ship length, or more than 3 times the length of the ship;
- the steepness of the waves is less than 0.03. An upper limit steepness of 0.15 can be assumed because such very steep waves will break before they can accelerate the vessel.
- the speed is not more than $1.84 \cdot S(L)$ knots, (with L being the length of the ship in meters).

Depending on the above factors, the instantaneous position of the vessel in the wave determines the build-up of surf-riding and the wave upsetting yawing moment.

Based on the conditions outlined above, the most vulnerable vessels in the broaching problem are small-medium size vessels operating above $Fr > 0.3$ in a semi-displacement regime. Those are typically vessels like fishing trawlers, tugs, patrol vessels, rescue boats and small frigates. Figure 2 illustrates the typical length/speed combination of the vessels, and the fraction of time the length of the sea waves is within the range where broaching may occur. The above limitations exclude the larger displacement vessels sailing below $Fr < 0.3$ from the broaching problem, this includes many merchant vessels, ferries and cruise ships, for example.

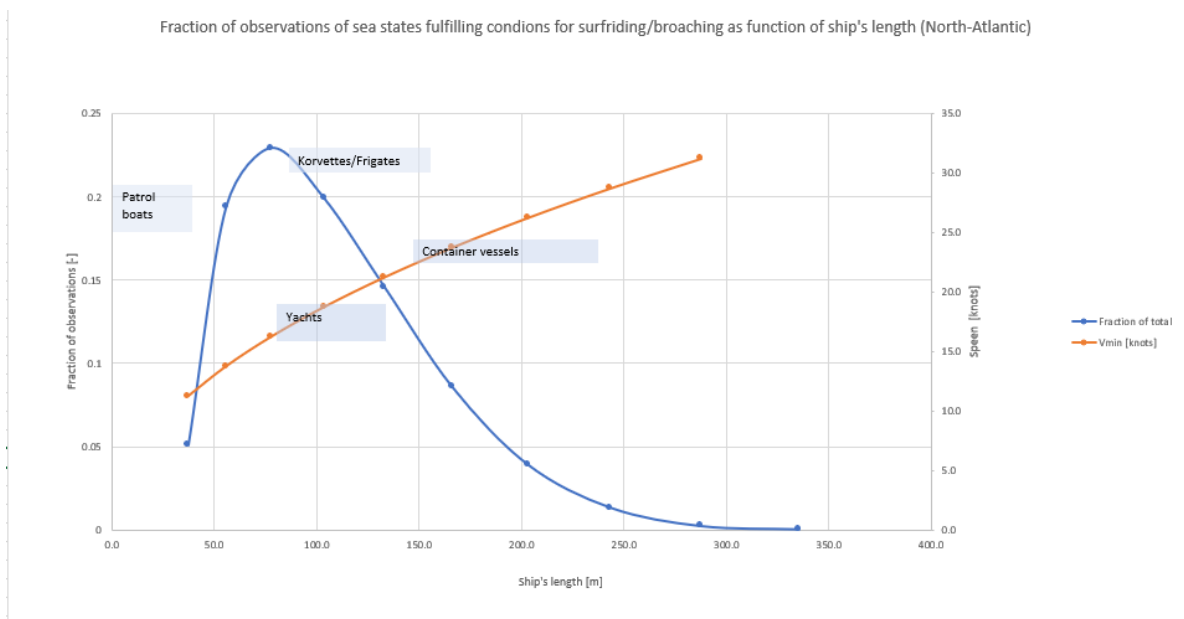


Figure 2: typical areas of vulnerability

If the vessel has sufficient power to accelerate fast enough to a speed well above the wave celerity the helmsman can increase power to break free of any beginning surf. The time duration between the start of surf-riding and an actual broach makes this option practically available only for small powerboats.

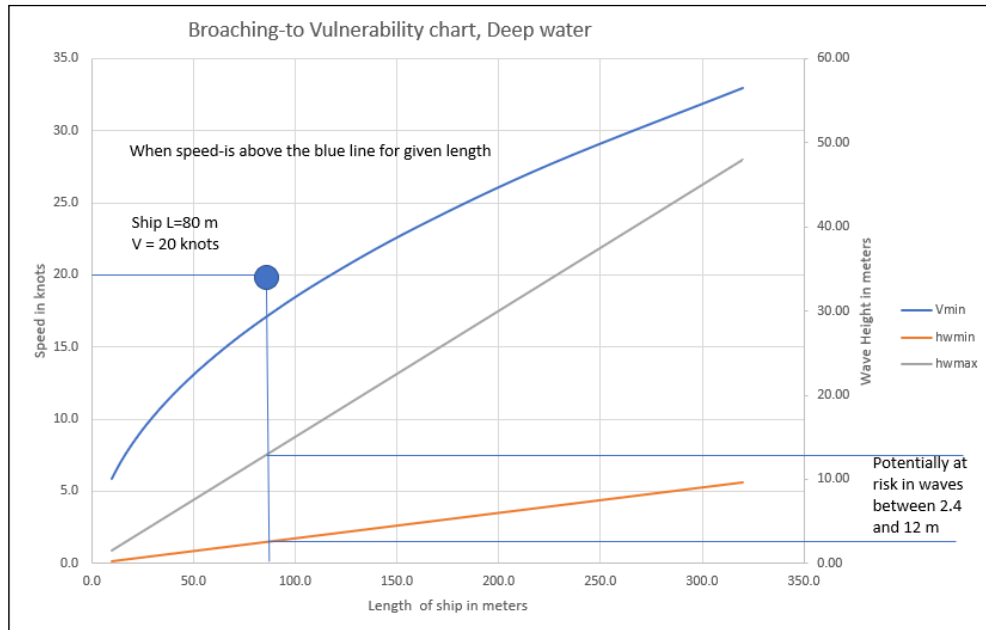


Figure 3 Limitations for broaching-to vulnerability.

Broaching can typically occur when returning-to-port, close to the shore. In this situation masters are forced to sail in the same direction of the sea, due to the sea in many cases directing its crests parallel to the coast. In coastal shallow water the waves start breaking, as shown in Figure 4, becoming relatively more powerful and more aggressive on the ship. Even relatively small waves that break can increase the likelihood of having a broach.

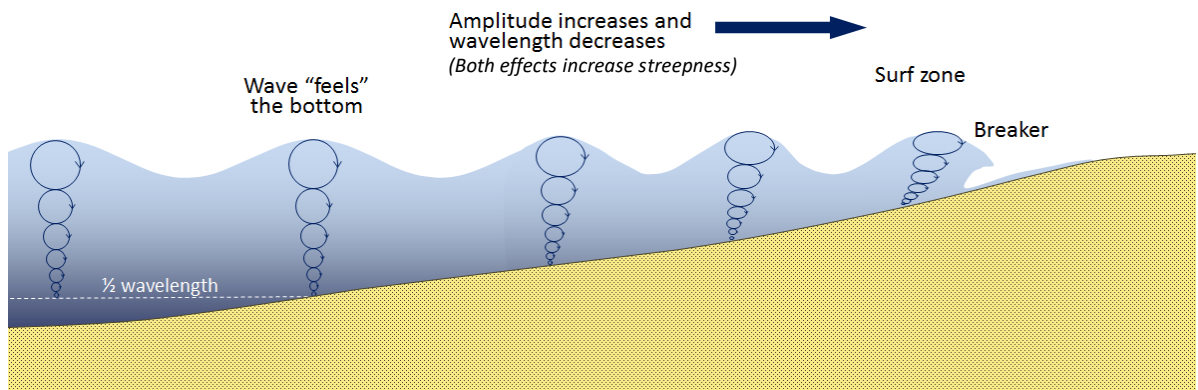


Figure 4: Wave development toward and close to coastal areas¹.

1.4. What can be the consequence of such broaching event?

¹ Image by Steven Earle, Licensed under Creative Commons BY 4.0 International License

- If the broach occurs in confined waters, for example in a downwind port entrance, it can lead to grounding or collision with break waters or other vessels.
- If the broach occurs quickly, so swift rate of turn while the ship is still at speed, additional heeling may occur depending on the vertical distance between the center of gravity of the vessel and the working line of the lateral hydrodynamic forces. (Note this is not related to the 'GM' righting lever, but to 'GM/(BM-GM)').
- The counter-steering corrects the heading during a broaching inception, but also increases the rolling of the vessel. This can lead to very high heeling angle when sailing in following seas;
- A broach can, in extreme cases, cause the capsize of the vessel when turned beam-to-sea.

2. State-of-art of broaching-to research

2.1. Experimental testing

Scientific researches on broaching can be traced back to 1940s, where it was proved that a ship which could keep a straight-line course in calm water might be unable to achieve this if it encountered following waves. In later research it was pointed out the possibility of occurrence of surf-riding if long and steep waves approach a ship from the stern.

A physical model experiment is definitely suitable for realizing dangerous phenomena in ship stability because full scale measurement could be too risky. Through the past years, free-running tests with scaled radio-controlled physical models have taken place in large square ship model basins of the Netherlands, UK, Japan and the USA, in the hope that the pattern of a ship's behavior in waves could be understood by observing the motions of a scaled model and by analyzing their time-series. Perhaps the most complete investigation of broaching-to took place at the Ship Research Institute of Tokyo where many researchers have conducted model experiments in following and quartering waves in seakeeping and maneuvering basins in the early eighties. The procedure recommended by ITTC for an intact stability test consists of holding the vessel on a guide wire near the wave makers while the waves are build up sufficiently and the model's propellers are brought to the desired number of revolutions. Then the guide wire is released at the appropriate moment to make the vessel speed up and settle on a wave. Key parameters to be measured as a function of time would be those that describe the utilization and efficiency of the course control system. The condition where the course control system reaches its limit and the probability of broaching-to becomes significant could be determined at any detail using an iterative method. This probably is more efficient in terms of measurements than running a full condition matrix.

Free running model tests to make a direct assessment of the vulnerability to broaching would of course be the ideal approach. However, broaching-to in following waves is a rarely occurring event. This means that an enormous effort must be spent to encounter a high enough number of waves to ensure a reliable statistical description of the phenomenon.

Less common are the attempts to measure experimentally the forces and moments acting on the vessel in waves. Such tests are in principle useful in the understanding of the ship dynamic stability problem in following waves, they are subjected to a number of technical limitations (complexity of the experimental set-up, limitations in the wave-making process among the others). And most of all, the measure of the loads acting on the hull and appendages are bound to the type of vessel examined. In recent years interest has grown in the experimental measure of the dynamic loads of the ship sailing in a seaway. The main final objective is to validate and improve the mathematical tools and thus the numerical prediction of these complex phenomena.

Bonci [2] describes a method where the model is held from the towing carriage above the (regular) waves on a hexapod until the waves are fully developed, before being lowered into position on a wave and then released. This method obviously will shorten the time to reach the phase where useful results can be obtained from the test and increase the time for data acquisition accordingly, but it needs more complicated equipment.

2.2. Numerical prediction

Well known theoretical studies on broaching were carried out in the UK, Germany, The Netherlands, USA, Japan, Russia, Australia and elsewhere. All these studies concentrated however on the single-degree surge dynamics and, because of this, an explanation on how surf-riding is linked with broaching could not be developed. In recent years, thanks also to the great developments in computational science, numerical investigations are increasingly becoming popular in the study of these problems.

Advanced numerical techniques, like RANSE solvers, are in principle able to model these effects, although an extensive use of those tools in such problems is still impractical. The great complexity of the physical phenomena involved demands too high a computational time that makes the statistical characterization of broaching unrealistic. Simpler mathematical tools seem to be the most suitable means for the problem of the ship in waves.

The mathematical models used in the field of the ship maneuverability are often parametric, i.e. the forces and moments acting on the ship are approximated by polynomials. The coefficients of the polynomials can be estimated by means of empirical tests, semi-empirical formulations, CFD simulations. This is particularly beneficial since the controllability is governed by a large number of factors. In common maneuverability-in-waves applications, the Froude-Krylov and buoyancy forces are evaluated on the actual wavy submerged geometry. Instead, the damping loads due to the velocity components of the vessel in the horizontal plane are estimated by polynomials, that are estimated in calm water. These methods are often denominated two-scale models since the low-frequency maneuverability motions in the horizontal directions are coupled with the high-frequency motions in the vertical direction. This is a feasible approach for medium-large vessels: the waves are smaller than the vessel size and do not significantly influence the characteristics of the submerged geometry, thus neither the maneuverability loads. This is not applicable for small vessels: the waves are comparable with the vessel size, therefore the submerged geometry and the hydrodynamic loads change with respect to the position in the waves. Moreover, this characterization of the maneuvering dynamics of the ship is bound to empirical data, narrowing the range of application of these methods.

Panel methods represent, for example, an appealing compromise between broadness of applicability and accuracy of results. These models can be applied extensively to the problem of the ship in following waves, and they can even be used to provide statistical data for the probability of occurrence of dynamic instability events. The only drawback of those

mathematical models is that they need validation of the computation of the maneuverability hydrodynamic loads to reproduce the physical reality correctly. This means that they must often be tuned according to the results of experimental investigations.

2.3. Statistical approach

To evaluate danger of broaching in actual seaways, it is essential to evaluate broaching probability or probability of capsizing due to broaching in irregular waves. Umeda et al. (2007) proposed a theoretical calculation method for broaching probability as an extension of Umeda's theory for surf-riding probability (Umeda, 1990). In 2016 Umeda proposed a simplified stochastic method to the direct assessment the probability of broaching-to in realistic sea state conditions by means of numerical simulations in regular waves. The method was validated by means of free-running model tests in irregular waves in a model basin.

Several important issues came out of all these studies:

- From the early stage it was identified that broaching is associated with surf-riding.
- Instability can occur when a ship lies on the down-slope of the wave and the stern is "resting" on a crest; such instability can cause capsizing as a result, even for a ship complying with the current IMO IS code.

2.4. IMO second generation intact stability criteria

To prevent stability failure due to the broaching associated with surf riding, the International Maritime Organization (IMO) decided to develop new physics-based stability criteria to be added to the 2008 Intact Stability Code.

The development of the second-generation intact stability criteria started in 2002 with the re-establishment of the intact-stability working group by IMO's Subcommittee on Stability and Load Lines and on Fishing Vessels Safety. However, due mainly to the priority of revising the IS Code for approval, the actual work on the second-generation intact stability criteria did not commence in earnest until the 48th session of the SLF in September 2005. The Working Group decided that the second-generation intact stability criteria should be performance-based and address three modes of stability failure:

- Restoring arm variation problems, such as parametric excitation and pure loss of stability;
- Stability under dead ship condition, as defined by SOLAS regulation II-1/3-8;
- Maneuvering related problems in waves, such as broaching-to.

Generally, second generation intact stability criteria (SGISC) refers to vulnerability ship stability modes which occurs when the ship sails in rough seas. As waves passes the ship, dynamic phenomenon will affect ship stability that may lead to capsizing.

It is important that a vulnerability criterion can be easily used, can guarantee a conservative safety level and should be based on a non-empirical approach. As a matter of fact, a surf-riding occurrence is taken as limiting criteria also for broaching, because surf-riding is its most common prerequisite without which a broach instability cannot arise. To determine the surf-riding threshold in regular following waves, an analytical solution is obviously most suitable because it is easily evaluated but is still based on a theoretical background.

Because broaching requires the maneuvering elements to be considered on top of the dynamics in waves, its use was judged too complicated to be practicable. The issue of direct stability assessment has not yet been fully resolved by the IMO. It requires the quantification of the probability of broaching under maneuvering in irregular waves, and it is unclear whether current methodologies in ship dynamics can evaluate the probability of broaching sufficiently accurately within a practical calculation time. The major problem is that broaching is a nonlinear phenomenon. A mathematical model of broaching has not yet been fully established, and linear superposition techniques are not adequate to apply.

2.5. Summary from latest Sub-Committee on Ship Design and Construction (SDC 6), 4-8 February 2019

The Sub-Committee has been working to develop second generation intact stability criteria since 2002. Significant progress has now been made, including the specification of direct stability assessment; the preparation and approval of operational limitations and operational guidance; and vulnerability criteria for all five stability failure modes: pure loss of stability; parametric roll; surf-riding/broaching; dead ship condition; and excessive accelerations.

The correspondence group on intact stability was re-established to consolidate the draft guidelines so as to complete the work on the second-generation intact stability criteria at SDC 7 in 2020, for submission to the MSC.

3. Review of the assessment tools

3.1. Experimental techniques

3.1.1. Free running model tests

Radio-controlled and auto-propelled ships model are employed to assess directly the probability of broaching in a certain sea state. The revolution rate of the propellers/waterjets in equipment to the model is typically set constantly at the value correspondent to the equilibrium throttle in calm water. Steering devices as rudders or waterjets shall move according to pre-defined autopilot settings.



Figure 5 Free sailing model tests on an auto-propelled vessel.

3.1.2. Captive model tests

Captive model tests are aimed to the measurement of the total forces and moments acting on the ship model. The model must be stiffly attached to the towing tank carriage, that moves at the desired speed. In maneuvering-in-waves studies, the model can be orientated in the desired positions, for example by means of an oscillator, or let it to be free to move in some directions. It is of paramount importance that the model, when tested in following and stern-quartering seas, can assume its vertical running attitude in the waves.



Figure 6 Model test. On the left, the set-up lets the model free in heave and pitch; on the right, the model is fully captive.

The rotations are set around the center of gravity of the model; the motions and rotations must be measured by a 6DOF system capable to record move in six degrees of freedom.

The vessel is, in general, symmetric so, by definition, in a captive test all measured data representing non-symmetrical effects, like roll-sway force coupling, roll-yaw moment coupling, roll-roll moment should taper to zero when the heeling angle is zero. If this not the case, the cause may be in misalignment of the model potentially combined with insufficient stiffness of the capture system. Verification and correction depend on the situation and the use of the data. Alignment can be by verifying for example if the results obtained for 4 degrees heel to portside gives the same but opposite value of the results for 4 degrees starboard for a symmetrical test case.

3.2. Numerical tools

The motions of the ship in following and stern-quartering waves is non-oscillatory and highly non-linear. Therefore, ship motion numerical simulations must be conducted in the time domain, implying the direct computation of the loads acting on the hull at each time-step. This can be a significant computational burden especially for more sophisticated mathematical models.

3.2.1. Parametric models

The hydrodynamic forces and moments acting on the ship are approximated by parametric formulations, typically polynomials function of the motions of the vessel. The coefficients of the polynomials can be estimated by means of empirical tests, semi-empirical formulations, CFD simulations.

3.2.2. CFD

CFD tools are widely used in ship hydrodynamics. However, the complexity of the following seas dynamics excludes advanced numerical tools, such as RANSE solvers, from a wide utilization in the problem. It would be very unpractical to statistically describe the vulnerability of a vessel to dynamic instability in a seaway by means of CFD simulations.

3.2.3. Two-scale models

These methods sum linearly the high-frequency dynamics in the vertical plane governed by the wave induced motions, and the low-frequency maneuverability dynamics in the horizontal plane. The maneuvering model often derives from the calm water condition: for this reason, these models are not fully suitable for the highly non-linear motions of small vessels sailing in following waves.

3.2.4. Strip theory

These tools are widely used to calculate the ship motions in waves. The practical and reliable use of these methods is unfortunately limited by the necessity of empirical formulations to express viscous phenomena and the sectional added mass characteristics.

3.2.5. Boundary element methods (BEM)

Potential flow BEMs account also for the memory effects and the surface dynamics around the ship body, making them more accurate than strip theory. Potential blended flow methods represent a good compromise between accuracy and versatility of application. However, work must be still carried out for a reliable validation of these tools, especially for the maneuvering loads.

4. Practical application in design and operation

4.1. Risk

Risk, by definition, is the probability of occurrence of the events multiplied by the severity of the consequences.

Risk management therefore can be done in two ways, or a combination of the two:

- Reduce the probability a broach occurs, so avoid the conditions.
- Reduce the consequences if a broach occurs.

4.2. Practical reduction of probability of occurrence of a broach.

Because, as described above, broaching is most commonly preceded by surfriding, the probability of broaching is strongly related to the probability of surfriding.

4.2.1. Practical reduction of risk of occurrence of surfriding.

For conventional vessels with lightest operational displacement more than $0.04 \cdot (L \cdot B)^{3/2}$, and of a size covered by the international conventions, the risk in given sea conditions for surf-riding in worldwide unrestricted service can be considered very small if in the governing wave conditions the speed is kept below the values indicated in table 1 below.

When significant wave height ² more than:	And length between		Be careful at speed above
[m]	L_min [m]	L_max [m]	[kts]
0.18	10.0	30.0	5.8
0.25	14.0	42.0	6.9
0.36	20.0	60.0	8.2
0.51	28.0	85.0	9.8
0.72	40.0	120.0	11.7
1.00	57.0	170	13.9
2.44	80.0	240.0	16.5
2.03	113.0	339.0	19.6
2.87	160.0	480.0	23.3

Table 1: typical critical areas of length/speed/wave height

² Significant Wave height scaled to allow for maximum waves 1.67 times the significant value.

This table is *very* generic and does not give influence of the hull form. It can be assumed the figure relates to relatively fine lines ships with a transom stern as customary for the speed-length ratio mentioned.

Where it is not feasible to reduce the speed in such conditions, or the ratio between mass and waterplane area is so low that the vessel will be easily accelerated by the waves, a certain probability of wave riding to occur must be accepted. The course of action would be to reduce the probability surf riding leads to a broach.

4.2.2. Practical reduction of probability that surf-riding results into a broach.

For a given loading condition of the ship, there is not much the crew can do in operation to reduce the probability of surf-riding developing into a broach. The time between the start of the surf-riding and the broach in most cases is simply too short to allow effective measures. Any mitigation measures are to be made in the design phase, and they can include, but need not necessarily be limited to:

Provide extra power so the vessel can 'run out' of the overtaking wave and take back control of the movement of the vessel. Operators of fast commonly use this solution, but of course this action can be done safely only by an experienced helmsman who knows the vessel and the sea well.

4.3. Design reduction of the risks connected to broaching

- Avoid bow shapes that are highly-effective in generating changes in transverse force in water under small changes of angle of attack.
- Ensure the vessel 'climbs' the wave and does not try to 'pierce' it, which gives lead to additional exposed surface to transverse flow.
- Enhance the steering ability or the directional stability of the vessel:
 - Enlarge the rudders,
 - Add stern fins or skegs,
 - Increase the rudder rate of turn (if that is a limiting factor).
- Consider integration of fin stabilizers in the steering system.
- As with any optimization process, improvement of performance in one aspect will go at the expense of performance in other aspects: boost power for example gives extra cost and weight. It is the task of the designer to balance the relative importance of all aspects.

4.4. Practical reduction of consequences associated with the occurrence of a broach.

In the best case the consequences of a broach are limited to the vessel making a short yaw off-course and some rolling, leading to inconvenience but no real harm or risk of life.

In a given loading condition, operational measures would consist of the usual measures of seamanship: ensure cargo and outfit/equipment is properly stowed, keeping doors and hatches closed to prevent down-flooding and keeping people inside and, where they constitute a significant mass, ensure they stay on the lower decks.

Design measures to mitigate the consequences would include (but not be limited to):

- Ensure sufficient range of intact stability also when the transom area is not fully effective.
- Bring down the center of gravity to reduce the overturning moment.
- Allow ample 'cheek' in the bow area to add buoyancy forward, reduce width of transom.
- Avoid sharp bilges.
- Reduce area of bilge keels to reduce the overturning moment they give when the vessel is subject to transverse water flow.

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[1] *Code on Intact Stability (IS)*. International Maritime Organization (IMO), 2008.

[2] Bonci, M., De Jong, P., Van Walree, F. et al. The heel-induced sway force and yaw moment of a high-speed craft in following regular waves. *J Mar Sci Technol* (2019) doi:10.1007/s00773-019-00637-0.