HEEL ANGLES IN TURN AND PASSENGER SAFETY

V Ferrari, H v d Boom, A S Kisjes, F H H A Quadvlieg, MARIN, the Netherlands

SUMMARY

The present paper addresses the issue of heel angles in turn, focusing on experimental results, existing regulations and passenger safety. Statistical and experimental data show that the maximum heel angles of passenger ships can reach high values, depending on many factors such as rudder angle, approach speed and loading condition. Such values are consistently higher than the ones calculated with the formula for the heeling in turn of passenger vessels present in the current International Code on Intact Stability. This is further confirmed by means of dedicated model tests performed at MARIN and presented in this paper. It is shown that the criterion for maximum angle of heel in turning of the International Code on Intact Stability is inadequate. Furthermore a revision for improving the safety of passenger vessels is proposed after a discussion on safety aspects.

NOMENCLATURE

Δ	Displacement (t)
μ	Static friction coefficient (-)
φ	Heel angle (° or rad)
a_y	Transverse acceleration (m/s^2)
a_z	Vertical acceleration (m/s^2)
C	Empirical constant (s^2/m)
GM	Transverse metacentric height (m)
h	Height of a person's centre of gravity (m)
KG	Vertical position of the centre of gravity from keel line (m)
ℓ	Half of the width of a person's stance (m)
L_{WL}	Length at waterline (m)
M_R	Heeling moment due to turning (kNm)
V_0	Approach speed (m/s)
T	Mean draught (m)
AD	Advance
IMO	International Maritime Organisation
ISC	International Code on Intact Stability
M/V	Motor Vessel
MII	Motion-Induced Interruptions
MSC	IMO Maritime Safety Committee
RINA	Royal Institution of Naval Architects
SDC	IMO Sub-committee on Ship Design and Construction
SLF	IMO Sub-committee on Stability and Load lines and on Fishing Vessels Safety
TD	Tactical diameter

1. INTRODUCTION

Sharp turns of passenger vessels may cause high heel angles, which may lead to dangerous situations on board. Passengers and crew could suffer injuries and any unleashed cargo could start shifting, further compromising the stability of the ship. For this reason the International Code on Intact Stability (ISC), adopted by the International Maritime Organisation (IMO) in December 2008 with resolution MSC.267(85), contains one rule specifically for passenger vessels. It presents a formula with the purpose to estimate the heeling moment due to turning and to verify that this calculated value does not exceed a certain criterion.

The restriction on maximum heel angles is relevant for both passenger safety and to avoid shifting of cargo. It is noted that "weather dependent lashing" has been adopted by many ship owners. However sudden turning of a vessel can occur even in good weather conditions, e.g. for change of course, avoiding collisions, grounding or due to failures in the autopilot or steering gear. In 2018 MARIN investigated the cause of the flooding and sinking of the Korean ferry M/V Sewol, who heeled excessively and capsized while sailing in calm water. The results of the investigation inspired additional research into the heeling during turning for ferries.

This research showed that the present ISC formula underestimates the heel angles when compared to both the maximum and steady heel measured during model tests. Therefore there is a clear need for a revision of the ISC requirement.

This paper presents the results of this research on heeling in turn and discusses their implications with respect to the ISC rule. A revised methodology for evaluating the heel angles in turn is then proposed in order to overcome the limitations of the present ISC formulation. Finally conclusions are drawn in the last section.

2. EXISTING REGULATION

Since 2008, the International Code on Intact Stability is mandatory for ships. This code contains criteria regarding the properties of the righting lever curve. In addition to these rules, a criterion was adopted specifically for passenger vessels. The rule requires that the angle of heel on account of turning shall not exceed 10° when compared to a heeling moment calculated using the formula given in Equation (1). The formula for the heeling moment due to turning is:

$$M_R = 0.200 \frac{V_0^2}{L_{WL}} \Delta \left(KG - \frac{T}{2} \right) \tag{1}$$

where L_{WL} the waterline length [m], Δ the displacement [t], KG the distance between centre of gravity and baseline [m] and T the mean draught [m]. V_0 is the approach speed at the beginning of the turn [m/s], which according to the regulation should be taken equal to the service speed. The resulting moment is expressed in [kNm].

The above rule is an empirical formulation of the heel angle during a steady turn. However, it is known from experience that the maximum heel angle actually occurs during the transient phase at the beginning of the turn and can be much higher than the steady-state heel angle. For this reason some concerns were raised in the past regarding the adequacy of this formula. It was argued that it underestimates the maximum heel angles of a passenger ship in turn and therefore it is not a safe requirement. In 2011 the United Kingdom proposed to the IMO to investigate the issue with support of the Royal Institution of Naval Architects (RINA). The IMO SLF-SDC sub-committee was tasked to further study this point. During the following discussions, contributions were submitted by RINA ([1] and [2]), Japan [3], Poland [4] and the International Association of Classification Societies ([5] and [6]). Nonetheless, the sub-committee decided at that time, that additional studies were required and no further action should be taken at the moment to amend the International Code on Intact Stability [7].

3. EVALUATION OF THE HEEL ANGLES IN TURN

3.1 BACKGROUND

In 2018 MARIN performed a study specifically to assess the issue of heel angles in turn. This investigation was triggered by two factors. The first was the sinking of the Korean ferry M/V Sewol and its subsequent investigation by extensive turning tests at model scale [8]. The second was the observation that during model tests and sea trials many passenger vessels whilst turning reach heel angles exceeding 10, 15 and even 20 degrees. Figure 1 shows the number of occurrences in the MARIN database of maximum heel angles, for different passenger vessels above 100 m. It is based on more than 200 turning circles obtained from model tests of different prototypes, new designs and full scale trials. It can be seen that there is a relatively large amount of occurrences above 10 and 15° of maximum heel angles.

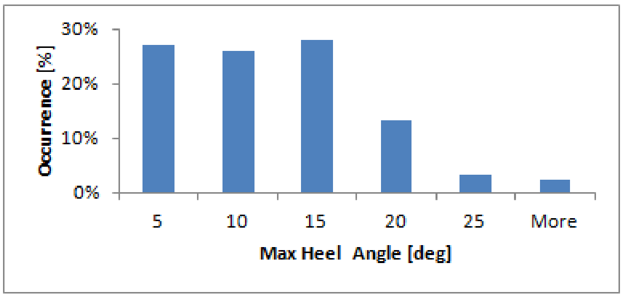

Figure 1: Number of occurrences in MARIN database of maximum heel angle, for different passenger vessels above 100 m

3.2 EXPERIMENTAL EVALUATION

3.2 (a) The test-case

In order to further evaluate the adequacy of the ISC chapter 3.1.2 rule, a dedicated model test campaign was performed by MARIN in 2018, with the explicit purpose of investigating the relationship between the heel angles calculated with the ISC formula and the ones measured during model test. The test-case ship used is a 190 m ferry called MARIN Ferry. It has a twin-screw twin-spade rudder configuration and its hull lines are representative of contemporary ferry designs. The model is shown in Figure 2 and the main particulars are given in Table 1.

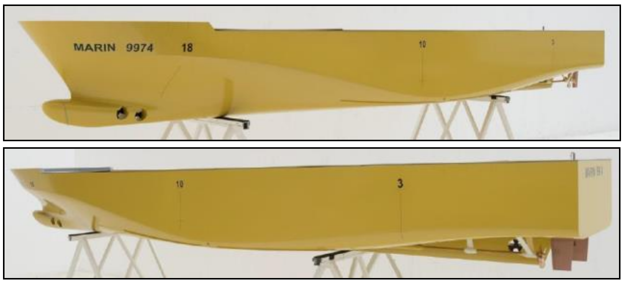

Figure 2: Fore and aft views of the test-case ferry.

Table 1: Main particulars of the test-case ferry.

Designation	Value	Unit
Length between perpendiculars	190.0	m
Breadth	30.0	m
Draught at midship	7.0	m
Trim	0.0	°
Displacement in salt water	25118.3	t
Longitudinal centre of gravity w.r.t. station 10	-4.02	m

Model tests for this ferry were performed at MARIN's Seakeeping and Manoeuvring Basin, which measures 170m*40m*5m, in length, width and depth respectively. The free running model was self-propelled and connected to the carriage by power cables and wires for the steering and measurement signals. This connection was set-up in such a way that the cables did not influence the behaviour of the model. The motions in 6 degrees of freedom were recorded together with the thrust and torque of both propellers. The standard zigzag and turning circle manoeuvres were performed with two skeg lengths, three stability levels (GM), three approach speeds and three rudder angles. All these parameters were varied in order to demonstrate their influence on the heeling angles during a turn. The rudder steering rate was 2.32°/s, which is the minimum requirement for the steering equipment. An uncertainty analysis of the tests is presented in [9], where it is shown that the uncertainty of the maximum heel angles are within 1° with a confidence level of 95% for the tested GM of 2.0 m with a long skeg. The complete test procedures and results are reported in [10].

3.2 (b) Test results

The results and conclusions of this new test campaign add further support to the concerns regarding the formula in the International Code on Intact Stability 2008 chapter 3.1.2 on heel in turning. The most important conclusion of this research is that indeed the present ISC formula consistently underestimates the heel angles, when compared to both the maximum and steady values measured during model tests.

The maximum and steady outward heel angles are taken as reference since they are important parameters to characterise the heeling dynamics of a turning ship. An example of a time trace of the heel angle during a turning circle is shown in Figure 3. In the beginning there is a very small negative heel angle, which represents in this case an inward heel. During the rest of the turn the ship heels outwardly, as normal for all displacement ships. The maximum heel angle happens during the initial transient phase, after which the heel angle stabilises to the steady value. The heel angle then returns to 0° during the pull-out manoeuvre, when the rudders are set back to the neutral position.

The maximum and steady heel angles measured during the model tests are presented in Table 2 and compared to the results of the ISC chapter 3.1.2 formula. It is shown that the ship does fulfil the ISC requirement for all cases, whereas in reality the heel angles reach values high above 10°. The configuration short skeg with a GM of 1.6 m is further analysed in Figure 4, showing that both maximum and steady heel angles can reach values above 20°, even at moderate approach speeds and rudder angles.

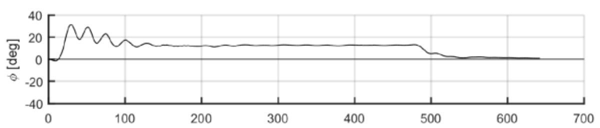

Figure 3: Time trace of the measured heel angle, 35° rudder angle, 25 kn approach speed, at GM 1.6 m and with short skeg

Table 2: Comparison between the calculated heel angles from ISC and as measured from the experiments, with rudder angle 35° and approach speed 25 kn.

Skeg configuration	GM [m]	ϕ_{ISC} [deg]	ϕ_{ISC} < 10°	ϕ_{max} [deg]	ϕ_{max} < 10°	ϕ_{steady} [deg]	ϕ_{steady} < 10°
Short	1.6	7.5	Yes	30.6	**No**	13.9	**No**
	2.0	6.1	Yes	25.7	**No**	11.5	**No**
	3.0	3.3	Yes	16.2	**No**	8.3	Yes
Long	1.6	7.5	Yes	25.9	**No**	13.9	**No**
	2.0	5.7	Yes	19.5	**No**	11.1	**No**
	3.0	3.3	Yes	12.0	**No**	7.7	Yes

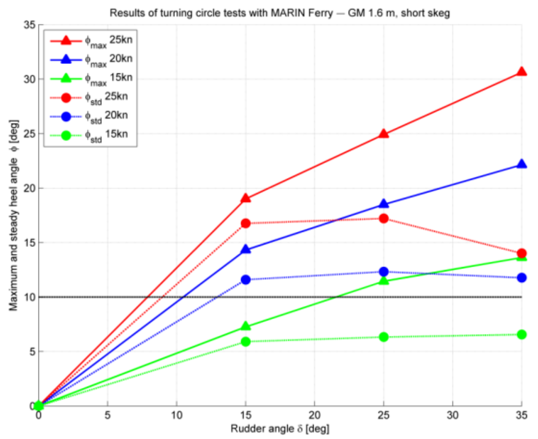

Figure 4: Maximum and steady heel angles as function of speed and rudder angle, at GM 1.6 m and with short skeg

4. EVALUATION OF THE IMPACT OF DYNAMIC HEEL ANGLES

4.1 GENERAL CONSIDERATIONS

Given the discrepancy between heel angle predicted by the ISC formula and the measured ones, which could result in potentially unsafe ship designs, it is deemed necessary to resume the discussion on an improved regulation and to revise the existing code.

First of all it is considered that the most relevant parameter to be checked when analysing the heel angles in turn is the maximum outward heel angle. This value is typically higher than the steady angle, as already seen in Figure 3, and Figure 5 further shows that the maximum heel can reach up to 5 times the steady value. Therefore the maximum heel angle can lead to more dangerous situations for passengers and cargo than a steady heel, especially considering the fact it happens during the dynamic part of a turn.

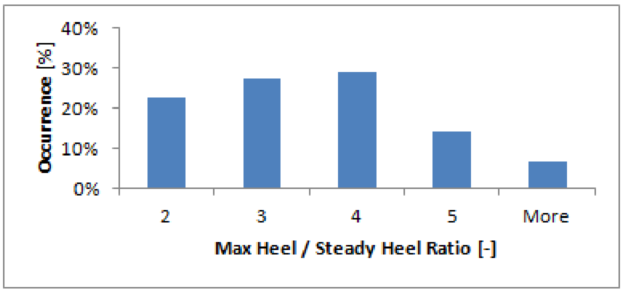

Figure 5: Number of occurrences in the MARIN database of maximum heel / steady heel ratio, for different passenger vessels above 100 m

Having established that the maximum outward heel angle is the parameter to be checked, two aspects need to be further assessed for defining a rule: the limit and the method to verify the limit. The existing rule in chapter 3.1.2 of the Intact Stability Code 2008 and the proposal by Poland [4] consider 10° as limit, whereas the proposal by RINA [2] considers 15° for the maximum outward heel and 10° for the steady heel.

However, choosing the limit angle based on physical consideration gives more relevance and reliability to the revised rule. The following sections present some considerations on possible limits to the heel angles in turn.

4.2 PASSENGER SAFETY

4.2 (a) Motion-induced interruptions

The objective of chapter 3.1.2 of the International Code on Intact Stability 2008 is to ensure the safety of passengers during a turn. There are several studies, for instance [11], relating ship motions to passenger comfort and safety, using factors such as Motion-Induced Illness and Motion-Induced Interruptions (MII). However these criteria mainly refer to periodic movements, defined by a certain frequency and amplitude. Instead, the heeling of a vessel in turn is a single oscillation with a potentially large amplitude and relatively low acceleration compared to seakeeping phenomena. Nonetheless, part of the theory on Motion-Induced Interruptions can also be applied to heel angles in turn.

A good overview of MII theory is presented in [12]. The authors define MII as an incident where ship motions become sufficiently large to cause a person to slide or lose balance, unless they temporarily abandon their allotted task to pay attention to keeping upright. These interruptions can be classified into three categories: lift-off, sliding and tipping/stumbling. The first two occur more rarely and therefore are not considered in this analysis. The tipping represents a momentary loss of postural stability. The occurrence of such phenomenon can be defined by the tipping angle, that is, the angle at which the centre of gravity of one person falls outside his base, resulting in loss of balance unless action is taken by the person.

4.2 (b) Transverse tipping angle

Assuming a heeling motion, the tipping angle depends on whether the person is facing the fore/aft direction (tipping transversally) or the port side/starboard one (tipping longitudinally). A formulation for the transverse tipping angle, taking into account ship motions and disregarding higher order terms, is provided in [13]. According to this formulation, the limit heel angle φ for avoiding tipping is:

$$g\varphi + a_y - \frac{\ell}{h} a_z \le \frac{\ell}{h} g \quad (2)$$

Where a_y, a_z are the transverse and vertical accelerations, respectively, and ℓ/h indicate the position of a person's centre of gravity, as shown in Figure 6.

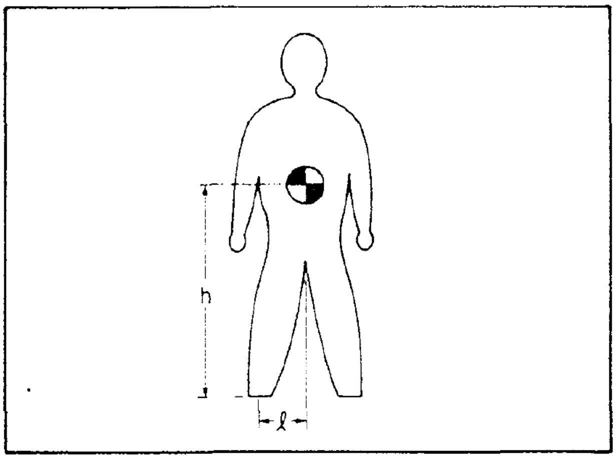

Figure 6: Position of the centre of gravity of a standing person (from [13])

During a manoeuvre in calm water with a displacing vessel the accelerations are relatively small and the effect of heel angle is dominant ([14] and [15]), so a_y and a_z can be disregarded. According to [13], ℓ/h is about 0.25, which results in the following threshold for tipping:

$$\varphi \le 0.25\,[\text{rad}] \quad (3)$$

which corresponds to approximately 14.3°. It is considered that above this angle, passengers and crew will have difficulties in standing and therefore this represents an important safety limit. This threshold is also close to the value of 15° proposed by RINA [2].

4.2 (c) Other considerations

As mentioned previously there is also a longitudinal tipping angle, when a person is standing in port side/starboard direction during a heeling motion. This is further investigated in [16], where the foot base divided by height of the body's centre of gravity ratio is estimated to be 0.17. This would be lower than the 0.25

rad threshold proposed in the previous section. However, it is also mentioned in [16] that a person can resist more easily a force from the back than from the front by a factor about 1.58, resulting in a threshold of 0.27 rad. Thus the value 0.25 rad remains a good indication of passenger safety except for the very specific case of passenger facing the elevation. Moreover it can also be questioned whether it is still realistic to assume an immobile person when calculating the longitudinal tipping angles, considering how natural it is to put one foot forward or back for balance. For these reason the value of 0.25 rad is still suggested as limit for heeling in turn.

An additional aspect is the difficulty for people to move along inclined planes. In ship design this is usually studied during evacuation simulations of passenger ships. An example of such analysis is presented in [17]. It is mentioned that beyond 15° of listing, the evacuation time increases rapidly, due to the effort of movement. The heel angle in this scenario is static and therefore does not take into account dynamic phenomena. Nonetheless, it further corroborates the potential dangerousness of reaching heel angles above 15° during a turn.

4.3 CARGO SAFETY

Movement of the cargo during a sharp turn can have a large impact on the heeling dynamics of the ship. It could induce unstable behaviour which would compromise the restoring capability of the hull, and that could be critical for RoPax type of ships. This phenomenon was noted for instance during the accident of the Korean ferry M/V Sewol [8]. Dashcams recovered from the vehicles on board show that during that accident some trucks start to slide at an angle of about 18° and most of the cargo at 33°.

The heel angle is dominant during a turn in calm water for the movement of cargo or balance of passengers. As a result, the threshold below which a weight does not start sliding along an inclined plane can be expressed as:

$$\varphi \leq \arctan \mu \tag{4}$$

where μ is the static friction coefficient. Values from 0.4 to 0.8 are found for rubber on steel contact, representing vehicles on a deck. These coefficients correspond to a range of 22 to 39°. More study would be needed to evaluate precisely the coefficient for a wheel of a vehicle on a car deck. However, it is estimated that the threshold heel angle for cargo sliding will be higher than 14.3°. Therefore, considering the tipping angle as limit should be conservative as it would prevent the sliding of vehicles as well.

4.4 RUDDER LIMITS

A possible solution to prevent the occurrence of large heeling angles could be to limit the maximum rudder angle below 35° in such a way that the limit heel angle is not exceeded. This is already done as regular nautical practice by ship captains during normal operations and in safe situations, in order to reduce passenger discomfort caused by the vessel's heeling. Instructing the crew not to use a dangerous combination of approach speed, steering angle and loading condition is certainly beneficial to passenger safety. This could be done for instance by preparing simple diagrams showing the maximum and steady heel angles as function of the three previously mentioned parameters. Despite this, it is considered that this would not entirely prevent accidental human or mechanical errors. Instead, a technical solution at the design level would represent an inherent improvement of ship safety and is therefore considered safer than a human-driven solution.

In the proposal by RINA [2] it is recommended to physically limit the steering gear if the ship does not fulfil the proposed requirement on heeling angles in turn, except for emergency situations. Using a smaller rudder helm, however, affects the manoeuvring characteristics as well, such as the turning ability. The advance (AD) and tactical diameter (TD) will increase, whereas these two characteristics are limited by IMO Regulation MSC.137(76) on ship manoeuvrability due to their importance for nautical safety.

This can be seen for instance on Figure 7. The plot presents an overview of the compliance to both heel angle and turning circle requirements, as function of approach speed and rudder angle, for the configuration long skeg with GM 1.6 m. It can be seen that reducing the rudder angle to 15° decreases the maximum heel to below the proposed limit of 14.3°. However, at the same time this leads to an increase in advance and tactical diameter, resulting in these values not fulfilling any more the IMO manoeuvring criteria. The only possibility would be to limit the ship speed, which however would have other inconveniences such as less controllability, engines possibly not working at optimal design conditions and difficulty in keeping route schedules.

The impact of a limit on the steering gear might also be difficult to assess and its implementation complex to realise. It is considered more practical and reliable to verify compliance to the proposed heel angle requirement already in design stage, focusing on ensuring a safe design rather than enforcing safe operations. Alternative measures involving automatic limitations to the steering gear or ship speed could still be applied but should be left to special circumstances and discussed on a case-by-case basis.

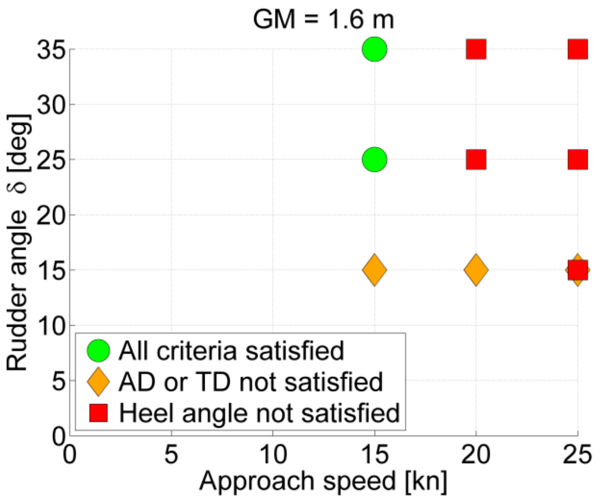

Figure 7: Compliance to proposed heel angle and IMO turning circle requirements as function of approach speed and rudder angle for the MARIN Ferry at GM 1.6 m and with long skeg

5. PROPOSAL FOR REVISION

5.1 MULTI-LEVEL ASSESSMENT

The goal of the proposed revision of the ISC is to restrict the maximum heel angle of passenger vessels during turning within 15 degrees. Sea trials are considered to be the most reliable way to verify compliance to the rule. However, as mentioned previously, it is useful for the ship designer to have an indication whether the ship will fulfil the requirement or not in the design stage. A multi-level assessment provides flexibility and prevents that a non-compliance is found too late in the design process. The following procedure is proposed as multi-level assessment for verifying whether a ship fulfils the rule:

- The first step is to verify compliance by means of a simple conservative formula, provided in Section 5.2.
- If the criterion is not met, more advanced methods such as model test should be performed for further investigation. If the rule is still not met, then the design must be changed.
- Sea trials shall always be performed as final verification of compliance to the rule. These trials are specified in Section 5.3.

5.2 SEMI-EMPIRICAL FORMULA

The first level of assessment shall be a simple and conservative formula for estimating the maximum heel angle in early design stage. The formula derived by Poland [4] is used as starting point:

$$\varphi = \arctan\left[C\frac{V_0^2}{L_{WL}GM}\left(KG-\frac{T}{2}\right)\right] \quad (5)$$

where V_0, L_{WL}, GM, KG, T have already been defined previously and C is a coefficient to be determined [s^2/m].

This formula is based on the existing one in chapter 3.1.2 of the ISC shown in Equation (1) and contains some of the most important parameters influencing the heel, that is, the approach speed squared and the stability level. For the coefficient C Poland indicates a value of about 0.07 s^2/m based on model test results. However, this coefficient should not be fitted to exactly match experimental data but it should be purposely conservative, in order to reduce the risk of false negatives. Applying the formula to MARIN's database, it is found that a value of 0.14 s^2/m ensures a conservative and safe approach. This is shown in Figure 8, where it can be seen that in almost all cases the formula overestimates the heel angle while globally keeping the correct trend. It must be noted that there are more parameters that influence the maximum heel angle in turn and that are not taken into account, such as characteristics of the rudder and skeg. Further investigation can be performed in this regard for a more accurate formulation.

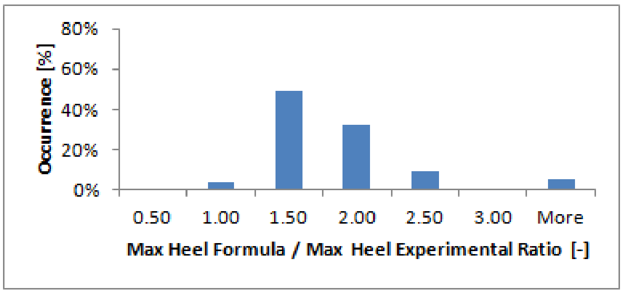

Figure 8: Comparison between experimental and calculated maximum outward heel angle during a turn

5.3 ADDITIONAL VERIFICATION AND SEA TRIALS

If the ship does not fulfil the equation, further investigation with more accurate methods, such as model tests, is required. Final compliance to the rule shall be verified in any case during sea trials.

The sea trials shall be performed in accordance with the turning circle manoeuvring trials presented in IMO Resolution MSC.137(76), with the following exceptions:

- The loading condition at even keel that corresponds to the lowest GM shall be used, instead of summer load draught;
- The turn shall be approached at maximum speed, instead of trial speed;
- The turn shall be conducted with at 35 degrees rudder angle or the maximum rudder angle whichever is the lowest; and
- During the turn the vessel speed, the rudder angle and the heel angle of the vessel shall be measured and recorded with sufficiently high sampling rate to derive the maximum heel angle reliably.

Similarly to the manoeuvring trials, a 5% difference in draught is accepted. If the difference in draught during the trials deviates more than 5% from the draught at the loading condition with the lowest GM, model tests or calculations shall be performed for both loading conditions. These results have to be compared with the results of the sea trials to validate the method of the calculations or model tests.

5. CONCLUSIONS

This paper shows that the existing formulation on heeling angles in turn for passenger ships introduced in the International Code on Intact Stability 2008 is inadequate. Free running model tests with a ferry were performed at MARIN with the purpose of investigating this issue. The results of these tests indicate that both the measured steady heel and maximum heel angles in turn can in some cases reach very high values, while still fulfilling the existing ISC requirement. This shows the need for a revision of the ISC regulation.

To this purpose two aspects need to be considered: the limit and the method to evaluate the limit. The limit itself should be at least partly based on physical considerations, which give more reliability on the regulation. In this paper an overview is given of different possibilities upon which to base the revised limit. The most relevant factor considered is the tipping angle, that is, the angle at which one person would lose balance unless action is taken by the person. Using this approach a value of 0.25 rad is found, equivalent to 14.3°. Other possibilities analysed include the angle at which movement becomes too difficult or the angle at which the cargo starts sliding. However it is estimated that these phenomena happen at angles higher than the tipping angle. Therefore it is recommended to use a value close to 15° as limit of the maximum outward heel angle in order to ensure passengers' safety.

Regarding the methodology, it is considered that it is better to ensure an intrinsic safe design rather than to enforce operational limitations. To this purpose a multi-level assessment is proposed. The first level is a conservative formula, to be used in early design stage so that the ship designer can already have an indication whether the future ship will fulfil the requirement or not. In case the ship does not meet the requirement of the formula, then more accurate methods for assessing the heel angles in turn can be applied, such as model testing. In any case the final verification should be based on measurements during sea trials.

It is expected that this proposed revision of the International Code on Intact Stability will improve the inherent safety of passenger ships during turning thus preventing possible dangerous accidents.

6. ACKNOWLEDGEMENTS

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8. AUTHORS BIOGRAPHY

Victor Ferrari obtained his Master of Science in Naval Architecture And Marine Engineering at the University of Genoa in 2009. He holds the current position of Senior Project Manager at MARIN's Ships department. He is in charge of manoeuvring studies for passenger ships, managing experimental model tests and numerical simulations.

Henk van den Boom is a naval architect (Delft, 1980) with more than 40 years experience in model testing, simulation and ship trials. For 27 years he was Head of MARIN's Trials & Monitoring Department. As a senior project manager he was leading the Sewol investigation at MARIN and participates in the development of new guidelines for the safety of passenger ships.

Anton S. Kisjes holds the position of Project Manager at the MARIN's Ships department. In 2017 he graduated in Marine Technology at the Technical University of Delft. At MARIN his work consist of conducted manoeuvring experiments and simulations to help clients with improving and understanding the manoeuvrability of ships.

Frans H. H. A. Quadvlieg graduated in Marine Technology at the Technical University of Delft in 1992. He holds the current position of Senior Project Manager at MARIN, where he has been working for more than 25 years. He manages both experimental and numerical projects involving complex manoeuvring situations.