INTACT STABILITY OF HISTORIC PASSENGER SHIPS IN LIGHT OF THE SECOND GENERATION INTACT STABILITY CRITERIA

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SUMMARY

The paper examines the intact stability of historic passenger ships from the point of view of the contemporary notion of the intact stability, i.e. the Second Generation Intact Stability Criteria (SGISC) framework. An intact stability assessment using the Vulnerability Level 2 calculation procedures of SGISC for the dead ship condition was performed on four ocean liners: RMS Titanic, RMS Queen Mary, SS United States and SS Michelangelo, and two cruise ships: MS Song of America and MS Costa Concordia. In addition, the intact stability of the selected ships was appraised using the present-day mandatory intact stability requirements contained in the 2008 Intact Stability Code. The selected ships are believed to be good representatives of the main trends in passenger ship design over a one-hundred-year span bounded by two well-known maritime catastrophes: the sinking of the Titanic in 1912 and the Costa Concordia disaster in 2012. The paper offers an insight into how major design changes have affected the intact stability properties of passenger ships over this period. It was found that the examined ocean liners would perform well in terms of intact stability in the dead ship condition even from the point of view of the SGISC. The analysis also confirmed the advantages of the approach using the SGISC framework over simplified, (semi)empirical stability assessment methods. By looking into the evolution of the intact stability of ocean liners and cruise ships from the contemporary perspective, the paper draws the conclusions which are considered useful for the design of future passenger ships.

NOMENCLATURE

A	Projected lateral area of the ship above the waterline (m^2)
A_B	Projected lateral area of the ship below the waterline (m^2)
A_k	Total overall area of bilge keels (m^2)
B	Ship beam (m)
C	Long-term probability index of stability failure in the dead ship condition (-)
C_s	Short-term probability index of stability failure in the dead ship condition (-)
C_B	Block coefficient (-)
d	Ship draught (m)
GM	Metacentric height (m)
GZ	Righting lever (m)
KG	Height of the centre of gravity (m)
L	Length of ship (m)
L_{OA}	Length over all (m)
L_{WL}	Length of ship at waterline (m)
P	Wind pressure (Pa)
s	Wave steepness factor (-)
T_r	Natural roll period (s)
V	Ship service speed (kn)
Z	Vertical distance from the centre of projected lateral area of the ship above the waterline to the centre of the underwater lateral area (m)
Δ	Mass of displacement (t)
IMO	International Maritime Organisation
IS	Intact stability
LNG	Liquified natural gas
SGISC	Second Generation Intact Stability Criteria
SOLAS	Safety of Life at Sea

1. INTRODUCTION

The modern history of international maritime regulations began with the Titanic disaster, prompting the development of the first ever SOLAS convention in 1914. Due to the nature of the disaster, subdivision was the focus of the international ship safety regulations from the very beginning, whereas ship stability regulations gained comparably less attention and were developed at a much later stage, see Francescutto & Papanikolaou (2011). It may be argued that intact stability was particularly out of focus, at least from the regulatory perspective, for most of the 20th century. Francescutto (2016) offers possible explanations behind such reasoning: a reliance on "empirical, rather than on scientific methods" (to quote Pierrottet, 1935) initially may have laid in a failure to understand the implications for stability yielded by significant changes in design (i.e. the replacement of sailing ships by steamships). On the other hand, as Pierre Bouguer (who is credited for the notion of metacentre) observed as early as 1746, the inherent complexity of ship stability analysis required the appropriate tools and methods which had yet to be developed. For all practical purposes, such tools were indeed unavailable until fairly recently. This particularly concerns the analysis of the stability-related dynamic phenomena in rough seas. Consequently, the intact stability properties of historic ships are relatively unknown, any data pertaining to intact stability is difficult to retrieve and the related information is largely descriptive and subjective.

The perception of a ship's intact stability has considerably evolved since the seminal works in the field published in the second half of the 18th century and throughout the 19th century (many of which are collected and aptly presented by Sir Edward Reed in Reed, 1885 in addition to his own fundamental work) and the first half of the 20th century (Pierrottet, 1935; Rahola, 1939). In parallel with this process, the evolution of large passenger ships has been taking place as well. The design of ocean liners allowed for fast transatlantic crossings but offered limited opportunities for non-essential activities on-board. As of the end of 1960s, the shifting of focus from transport to entertainment and tourism, considerably affected passenger ship design. Both processes are still ongoing; in addition to “classical” stability problems, the contemporary notion of intact ship stability comprises dynamic phenomena which are closely related to seakeeping and manoeuvring in waves (see Bačkalov *et al*, 2016 and Manderbacka *et al*, 2019), while the contemporary notion of large passenger ships is embodied by cruise vessels, which redefined the very concept of voyage by sea.[1]

The SOLAS convention, marked by the Titanic disaster from its inception, paid little attention to the intact stability until the 1960s or even 1980s. At that time, the stage was already set for the advent of a new type of passenger ship, the so-called cruise ships. Such ships were considered in development of neither the general criteria of ship stability (contained in the present part A/2.2 of the 2008 Intact Stability Code) nor the Weather Criterion (contained in the present part A/2.3 of the 2008 Intact Stability Code) which is concerned with dynamic stability in the dead ship condition, see IMO (2008). Given that these criteria were largely semi-empirical, it was only natural to question their applicability to cruise ships. Indeed, Francescutto & Serra (2001) indicated that the Weather Criterion requirements tend to be too stringent for ships with high *B/d* and *OG/d* ratios and long natural roll periods (which are typical features of modern cruise ships) as several quantities used in the calculation of the rollback angle in the Weather Criterion (the effective wave slope coefficient, the wave steepness) were tuned considering ships whose particulars considerably differed from the cruise ships design. These findings were also confirmed experimentally, see Francescutto & Serra (2002). The inadequacies related to the application of the Weather Criterion to cruise ships were also reported at International Maritime Organisation (IMO) meetings, see IMO (2001) and IMO (2002). To an extent, this issue was addressed by allowing an alternative assessment of the Weather Criterion, by means of model experiments to be performed in line with the IMO guidelines, see IMO (2006).

It would be misleading though to think that naval architects had no guidance when assessing the intact stability of passenger ships before stability regulations were enacted on an international level. It would be also incorrect to conclude that dynamic stability under the influence of beam wind was not considered prior to introduction of the Weather Criterion to the international regulatory framework. Reed (1885) presents an extensive analysis of influence of freeboard on dynamic stability in beam wind, noticing, however, the limitations of applied methodology and thus confirming Bouguer’s remark on the inherent complexity of the analysis of ship stability in rough weather. However, based on the available literature, it may be concluded that the recommendations at the disposal of the designers of ocean liners were mostly descriptive and based on the principle which prevailed between the First and the Second World War that the metacentric height alone was an adequate measure of stability (see Kobylinsky & Kastner, 2003). The 1939 edition of Principles of Naval Architecture (Rossell & Chapman, 1939) provides a list of recommendations for the “suitable metacentric height” for passenger ships. The metacentric height should be large enough to prevent listing to “unpleasant and dangerous angles” as a consequence of the crowding of passengers on one side, and to diminish “the possibility of a serious list” due to beam wind. Conversely, it should be small enough to prevent violent rolling in waves as “the traveling public is inclined to avoid vessels known to roll badly”. In addition, Kobylinsky & Kastner (2003) cite some recommendations for minimal metacentric heights of large passenger ships, published in the 1920s and 1930s, which will be discussed in Section 4 of the paper. The Principles of Naval Architecture seem to capture well the notion of ship stability at the time: the quantitative recommendations for adequate *GM* were sparse; the focus was on stability in damaged condition; intact stability was regarded from the point of view of static stability; rolling in waves was associated with comfort rather than safety.

Previously described shortcomings of semi-empirical intact stability regulations could be overcome by a regulatory framework based on more accurate mathematical modelling of ship dynamics and environmental conditions. Such a framework would include stability assessment methods independent of specific ship design features and applicable to unconventional ships. This was the principal motivation behind the development of the Second Generation Intact Stability Criteria (SGISC) framework, along with the possibility to analyse other stability-related ship dynamics phenomena such as parametric resonance or broaching-to. It may be stated that the methods and tools adequate for ship stability analysis, anticipated by Bouguer in the 18th century, became finally available with the advent of SGISC. The work on SGISC formally started in 2002 (although until 2005 it mainly focused on the revision of the IS Code) and was finalized in 2020. Over the years, the SGISC were tested on various ship types, including cruise ships.

This paper follows in the footsteps of Francescutto & Papanikolaou (2011) who acknowledged the idea put

[1] Consequently, the RoPax ships were not analyzed in the paper.

forward by Brown (1992) that a proper analysis of available historical data "can be of great value to the designers of future ships". The paper aims to bring together two processes which have been simultaneously taking place over the last one hundred years: the evolution of passenger ship design and the evolution of intact stability concepts. Therefore, the intact stability (as one of the essential ship safety properties) of prominent historic passenger ships was analysed using the SGISC thus bringing the examined ships to "a level playing field" with respect to the stability assessment.

2. EXAMINED SHIPS

In order to get an insight into the evolution of passenger ships over the last 120 years, a database consisting of 50 ocean liners and 50 cruise ships was formed. The oldest ship in the database is Prinzessin Victoria Luise (built in 1900), while the most recent one is the LNG-powered Mardi Gras (launched in 2020). The main features of the database are presented in the form of histogram plots in Appendix 1. Despite the considerable number of ships included, the database is certainly not exhaustive. Moreover, some data were unavailable, while on the other hand it was not possible to verify the accuracy of some of the available data. Notwithstanding said deficiencies, the database allows us to detect major trends in the design of passenger ships throughout the 20th century and to this day.

Within this time span, two distinct periods may be recognized: the era of ocean liners (primarily related to transatlantic voyages) which lasted (roughly) until the end of the 1960s, and the era of cruise ships. Analysis of intact stability is carried out on ships which were selected so as to reflect well the main trends in the passenger ship design over a period of one hundred years, starting with the sinking of the Titanic in 1912 and ending with the loss of the Costa Concordia in 2012. Furthermore, the selected ships are famous either because of their specific design features or because of their importance in the history of ship safety (or both). Four ocean liners (RMS Titanic, RMS Queen Mary, SS United States, and SS Michelangelo) and two cruise ships (MS Song of America and MS Costa Concordia) were selected for this study. The most important information on the selected ships is provided in Table 1. To the best of authors' knowledge none of the selected ships has suffered any major intact stability failure.

Even though the beginning of the transatlantic liners' era dates back to the 1830s, the modern passenger ships (that is, the ships without sails as main or auxiliary means of propulsion) entered service towards the end of the 19th century. One of the most famous ocean liners of that period was the RMS Mauretania (built in 1906) which held the record for the fastest transatlantic crossing (the so called Blue Riband) for 20 years. However, beyond any doubt, the most (in)famous ocean liner was the RMS Titanic, the largest passenger ship in the world at the time, whose epic tragedy profoundly influenced a range of cultural aspects in the 20th century. The sinking of the Titanic due to extreme flooding, which occurred on her maiden voyage in 1912, has left an indelible trace on perception of both ship safety and the safety of human life and assets in general, as it also shaped the modern apprehension of tragedy in popular culture. The large number of fatalities was in stark contrast with the public image of the ship which had been advertised as "practically unsinkable" (see Hackett & Bedford, 1997). In fact, the demise of Titanic and the image of her sinking outlasted the passenger ocean liners and remained strongly associated with the notion of a large-scale catastrophe decades after the era of ocean liners came to an end. On the other hand, it did not only trigger the formal process towards developing an international regulatory framework, but it decisively contributed to the very concept of safety of life at sea, as noticed by Hackett & Bedford (1997).

The rivalry over the Blue Riband intensified in the early 1930s. The RMS Queen Mary is arguably the most famous British ocean liner, equally renowned for her stylish interiors as for her speed. The RMS Queen Mary held the Blue Riband record between 1938 and 1952; in addition, during the Second World War, she successfully served as a troopship. In 1952, the Blue Riband was taken over by the SS United States and remained in her possession until 1969, that is, until the ship was no longer in service. In addition to being the ultimate holder of the Blue Riband, the SS United States was the largest ship ever built in the United States of America. Interestingly, the SS United States was also designed to serve as a troopship in times of war.

However, during the 1960s the ships ceased to be the primary means for long-distance travel; this function was taken over by airborne transport. Consequently, the importance of speed in transatlantic crossing began to fade which reflected on the design speed of the passenger ships (see Figure 1). More importantly, the very role of large passenger ships had to be reinvented as well. One of the last ocean liners to be built was the SS Michelangelo, which entered service in 1965 as the largest Italian ship at that time, and the fifth fastest ocean liner of the era. The SS Michelangelo was recognizable for her novel reticulate funnels structure topped with a smoke deflector, an innovation well ahead of its time. In 1966, while crossing the Atlantic, the SS Michelangelo encountered an unusually high and steep wave in an accident which claimed three lives and caused considerable damage to the hull structure. The photos taken on that occasion are often used as a rare testimony of the rogue wave phenomenon.

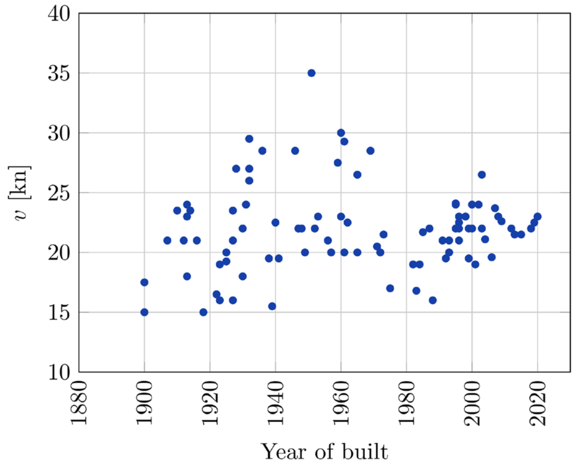

Figure 1. Evolution of the service speed of passenger ships

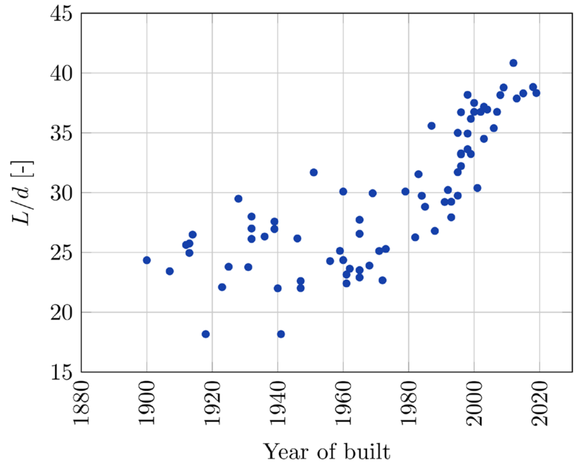

Figure 2. Evolution of the length-to-draught ratio of passenger ships

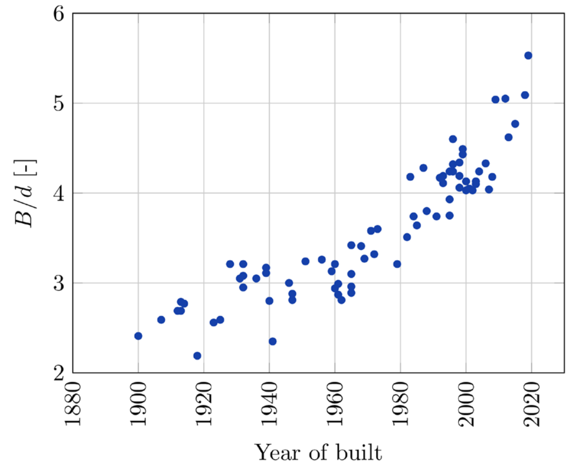

Figure 3. Evolution of the beam-to-draught ratio of passenger ships

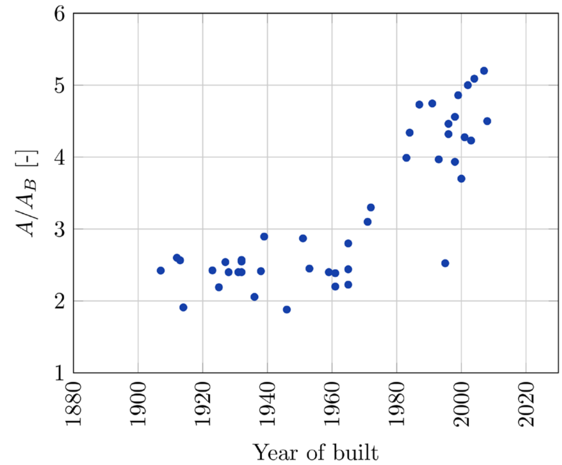

Figure 4. Evolution of the ratio of projected lateral areas of the ship above and below the waterline of passenger ships

Table 1: Main particulars of the examined ships.

	RMS Titanic	RMS Queen Mary	SS United States	SS Michelangelo	MS Song of America	MS Costa Concordia
1)	1912	1936	1952	1965	1982	2006
2)	1912	1967	1969	1975	3)	2012
L	269.1	294.1	287	276.2	214.5	247.4
B	28.2	36	30.9	30.1	28.41	35.5
d	10.5	11.8	9.53	10.4	6.8	8.2
V	21	28.5	35	26.5	21	19.6
4)	2435	2139	1928	1775	1664	3780
5)	900	1101	900	720	540	1100

1) year when ship entered service
2) year when ship went out of service
3) ship still in service
4) number of passengers
5) number of crew

The concept of cruising (albeit not in its present form) existed already in the 19th century. However, it was not until the 1970s that passenger ships were built as cruisers exclusively. As the operational profile and purpose of passenger ships considerably changed, so have their main features. The draughts have become shallower, the windage areas greater, and the importance of speed diminished. The relative increase of *L/d* and *B/d* ratios, derived from the database presented in Appendix 1, is given in Figure 2 and Figure 3, respectively. The increase of above water lateral area relative to underwater lateral area is given in Figure 4.

The analysis presented in this paper includes two cruise ships, the smaller MS Song of America, which entered into service in 1982, and the larger MS Costa Concordia, which entered into service in 2006. When the MS Song of America was launched, she was regarded as a true model of modern cruisers and she was showcased in a range of professional publications. The MS Song of America featured a specific space organisation (which resulted in large open deck areas) and some of the most advanced machinery and systems. The MS Costa Concordia was one of the largest ships built in Italy at the time of her launching. She was considered to be a typical representative of large passenger ships at the beginning of the 21st century. Unfortunately, she gained worldwide fame after suffering a tragic accident which claimed 32 lives in 2012. The accident was widely covered in the media, and it drew a range of comparisons with the Titanic, as it occurred in the year which marked the centenary of the infamous disaster.

Interestingly, even though the examined ships are obviously very renowned, the information on their design features (beyond the main particulars) is scarce, not readily available and often ambiguous. Brown (1992) correctly points out that the gathering and analysis of historical facts relevant for ship design is a difficult task although much needed. It should be stressed that much of the information used in this study had not come from an authorized and/or citable source. Most importantly, such is the case with the hull lines of almost all examined ships, apart from the SS Michelangelo and the MS Song of America. The authors have gathered the necessary information from a range of sources: internet forums and websites, archival issues of professional magazines, in communication with naval architects and ship designers and historic ships enthusiasts and admirers from all over the world. The body plans of the selected ships, which were reconstructed based on the available data, are given in Appendix 2 to the paper.

3. INTACT STABILITY ASSESSMENT

3.1 THE PRESENT MANDATORY INTACT STABILITY CRITERIA

The present IS Code requirements applicable to passenger ships include the General criteria (as given in part A/2.2), the Severe wind and rolling criterion, i.e. the Weather Criterion (as given in part A/2.3), and specific criteria which require the verification of static heeling angles due to the crowding of passengers (as given in part A/3.1.1) and due to turning (as given in part A/3.1.2). The minimal metacentric heights of the examined ships in the loading condition at design draught, satisfying each of the mandatory criteria are given in Table 2. The minimal *GM* values that ought to be attained in order to satisfy the most stringent requirement are shaded.

The stability assessment performed following the present-day mandatory intact stability criteria reveals a clear distinction between the ocean liners and the cruise ships. The stability of ocean liners is guided by the requirement to limit the heel due to turn to 10°, while the Weather Criterion is the most stringent stability rule for cruise ships. Such outcome is a consequence of specific design features of the two passenger ship types. Namely, heeling moment due to turn is calculated as:

$$M_R = 0.2 \cdot \frac{V^2}{L_{WL}} \cdot \Delta \cdot \left(KG - \frac{d}{2} \right), \tag{1}$$

where *V* stands for service speed (in m/s). Ocean liners were designed for fast transatlantic voyages and their speeds sometimes considerably exceeded those of cruise ships. Therefore, the heel due to turning is by far the most rigorous stability requirement for the SS United States, the fastest ocean liner ever built.

Table 2: The minimal metacentric heights of the examined ships according to the requirements of the present mandatory intact stability criteria.

2008 IS Code Part A regulation	RMS Titanic	RMS Queen Mary	SS United States	SS Michelangelo	MS Song of America	MS Costa Concordia
	$GM_{\min}$					
2.2	0.150	0.150	0.172	0.150	0.975	0.351
2.3	0.131	0.060	0.378	0.295	1.626	1.048
3.1.1	0.200	0.108	0.248	0.186	0.488	0.485
3.1.2	0.324	0.778	1.135	0.548	0.860	0.856

On the other hand, due to comparably larger lateral areas above the waterline, cruise ships are more sensitive to beam winds than ocean liners. The wind heeling levers used in the stability assessment according to the Weather Criterion:

$$l_{w1} = \frac{P \cdot A \cdot Z}{1000 \cdot g \cdot \Delta}, \tag{2}$$

and

$$l_{w2} = 1.5 \cdot l_{w1} \tag{3}$$

for the MS Song of America and the MS Costa Concordia are respectively 2.54 and 2.61 times greater than the corresponding quantities for the RMS Queen Mary, see Table 3.

The value of the resonant roll amplitude due to irregular beam waves, which is calculated using the following formula:

$$\varphi_1 = 109 \cdot k \cdot X_1 \cdot X_2 \cdot \sqrt{r \cdot s}\ , \tag{4}$$

decreases with the increase of bilge keels and *B/d* ratio, as well as with the decrease of the block coefficient. Even though the higher values of *B/d* ratios contribute to an increase in roll damping, it should be noted that *B/d* values for both examined cruise ships exceed 3.5, which is the upper limit of values considered by the Weather Criterion in the calculation of the resonant roll amplitude.

Therefore, the true impact of high B/d ratios on an increase in roll damping of the examined cruise ships is not properly taken into account in the stability assessment according to the Weather Criterion.

Table 3: Design data necessary for verification of compliance with the Weather Criterion.

	RMS Titanic	RMS Queen Mary	SS United States	SS Michelangelo	MS Song of America	MS Costa Concordia
B/d	2.69	3.05	3.24	2.89	4.18	4.33
C_B	0.660	0.586	0.514	0.570	0.549	0.707
A	5660	7442	6792	6218	5267	10690
A_k	116.1	103.5	148.6	73.9	32.9	230.4
$\frac{A \cdot Z}{\Delta}$	1.91	1.80	2.68	2.43	4.57	4.70

3.2 THE SECOND GENERATION INTACT STABILITY CRITERIA

The intact stability assessment according to the SGISC framework implies a multi-tiered approach whereby the accuracy of the stability assessment increases with the increase of complexity of calculations. The stability assessment levels are designated as:

- Vulnerability Level 1 (L1) which is the simplest, yet the most conservative level,
- Vulnerability Level 2 (L2) which is more complex but (supposedly) less conservative than L1, and
- Direct Stability Assessment (DSA) which is the most sophisticated (and hence the most complex calculation-wise), but the least conservative level.

In general, in case that a ship in a specific loading condition is found to be vulnerable to a stability failure mode at L1, the assessment may be continued at L2. If the outcome of the assessment at L2 confirms the vulnerability, then the assessment may progress to DSA. Alternatively, the design may be modified, or the loading condition could be scrapped. It is also possible to skip L1 and L2 and proceed straight to DSA. The SGISC framework introduces an important novelty: failure to satisfy the stability criteria (even at the highest level of assessment) would not necessarily lead to a ship design modification; instead, it could be possible to develop operational measures aimed at preventing the onset of the dangerous phenomena that might lead to a stability failure.

Within the SGISC framework, five major stability failure modes were identified including stability in the dead ship condition. The complete procedure for stability assessment in the dead ship condition is described in IMO (2019).

The Vulnerability Level 1 of the dead ship condition is the Weather Criterion, as given in part A/2.2 of the 2008 IS Code; however, the wave steepness coefficient s, used in calculating the resonant roll amplitude (4), was modified in order to include ships whose roll natural period exceeds 20 seconds, see Figure 5.

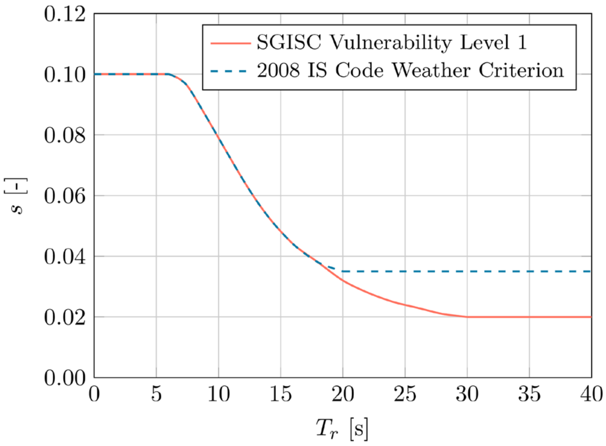

Figure 5. Wave steepness factor s as defined in 2008 IS Code (IMO, 2008) and in the SGISC framework (IMO, 2019).

From the point of view of L1, a ship is not considered to be vulnerable to the dead ship condition stability failure if the dynamic angle of heel in the Weather Criterion scenario φ_2 does not exceed the angle of downflooding φ_f, or 50°, or the angle of second intercept between wind heeling lever l_{w2} (2) and GZ curve φ_c, whichever is less:

$$\varphi_2 \leq \min\left(\varphi_f, 50^\circ, \varphi_c\right). \quad (5)$$

In addition, the static angle of heel due to steady wind, defined by lever l_{w1} (1), should not exceed 16° or 80% of the angle of deck edge immersion, whichever is less:

$$\varphi_0 \leq \min\left(16^\circ, 0.8 \cdot \varphi_{deck}\right). \quad (6)$$

The Vulnerability Level 2 of the dead ship condition is a probabilistic, performance-based procedure which results in long-term probability index C representing the measure of the vulnerability of the stability failure in the dead ship condition. From the point of view of L2, a ship is not considered to be vulnerable to the dead ship condition stability failure if:

$$C \leq 0.06, \quad (7)$$

where C is calculated as weighted average of short-term stability failure indices $C_{s,i}$ which are obtained in N short-term environmental conditions, characterised by weighting factors W_i:

$$C = \sum_{i=1}^{N} W_i \cdot C_{s,i} \,. \tag{8}$$

Weighting factors W_i represent the frequency of the short-term environmental conditions as defined by the wave scatter table for the North Atlantic. It is assumed that the ship in the dead ship condition is subjected to irregular beam waves and gusty beam wind in each of the short-term environmental conditions for an hour. The roll motion is modelled using a one-degree-of-freedom linear differential equation considering the ship roll restoring, roll natural period, and roll damping (for more details, see IMO, 2019).

The consistency of stability analysis across the levels is attained by ensuring that the simpler (simplified) assessment methods return more conservative results. However, the sample calculations for the dead ship stability failure mode showed that cases of inconsistency where L2 calculations return more conservative results than the calculations performed at L1 may exist (IMO, 2019).

In the present study, the minimal metacentric heights satisfying the stability requirements in the dead ship condition were calculated for each of the examined ships using the L1 vulnerability assessment (see Table 4). Furthermore, following the L2 procedure for the dead ship condition, the long-term probability index of examined ships at their respective design draughts (see Table 1) was calculated for a broad range of metacentric heights, accounting for free surface effects, Figure 6. The shaded area in Figure 6 corresponds to the condition (7). The minimal metacentric heights which need to be attained to satisfy the L2 condition (7) are given in Table 4. It should be noted that, in absence of data, the angle of downflooding was not considered in the assessment of critical angles for the purposes of L1/L2 calculations.

Table 4: The minimal metacentric heights of the examined ships according to the requirements of the Second Generation Intact Stability Criteria for the dead ship condition stability failure (IMO, 2019).

Vulnerability level	RMS Titanic	RMS Queen Mary	SS United States	SS Michelangelo	MS Song of America	MS Costa Concordia
	GM_{min}					
L1	0.131	0.060	0.378	0.295	1.626	0.936
L2	0.120	0.169	0.200	0.170	1.130	0.690

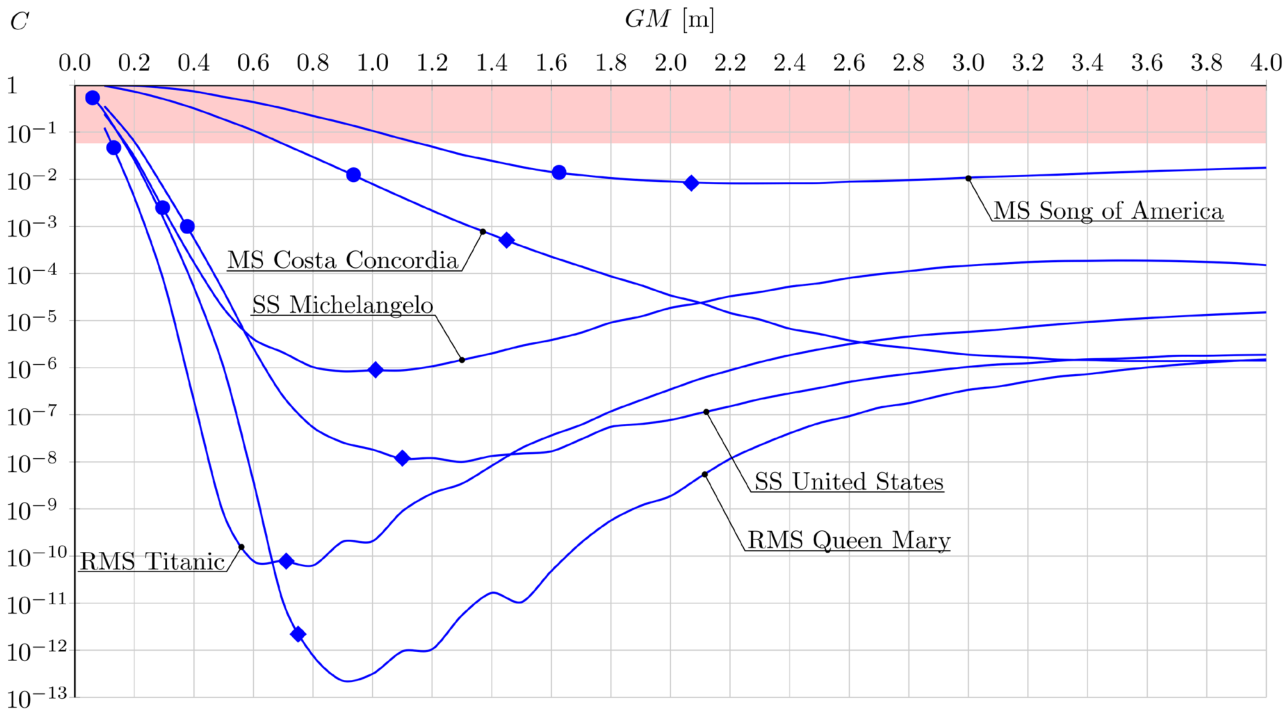

Figure 6. Long-term indices of stability failure in the dead ship condition (C) of examined passenger ships as a function of metacentric height (GM). Circles represent C values corresponding to minimal metacentric heights according to Vulnerability Level 1 (IMO, 2019), see Table 4. Diamonds represent C values corresponding to metacentric heights recommended by Anderson (Kobilinsky & Kastner, 2003), see Table 5.

4. DISCUSSION

Based on the obtained results, the following may be observed:

- The minimal metacentric heights of most of the examined ships, derived using the Weather Criterion (as given in part A/2.3 of the 2008 IS Code) and the Vulnerability Level 1 of the SGISC are the same, see Tables 2 and 4. The only exception is the MS Costa Concordia, for which the minimal metacentric height calculated according to L1 is lower than $GM_{\min}$ resulting from the IS Code Weather Criterion. This is a consequence of a modification in the wave steepness factor s presented in Figure 5. The decrease of factor s for ships with $T_r > 20$ s (which is a typical feature of modern passenger cruisers such as MS Costa Concordia) results in lower values of the angle of roll (4) in comparison to calculations performed according to the IS Code Weather Criterion, which in turn leads to lower required GM values. Interestingly, for each of the examined ocean liners, the limiting metacentric height resulted from the static stability condition (6), not the dynamic stability condition (5).
- There is a clear difference between the curves calculated for the ocean liners and the ones corresponding to cruise ships. The minimal values of long-term indices of the ocean liners are obtained in a range of metacentric heights $GM \approx 0.7\text{-}1.2$ m. Regarding cruise ships, the minimal values of long-term indices are attained at much greater metacentric heights: at $GM \approx 2.3$ m in the case of the MS Song of America and at $GM \approx 3.7$ m in the case of the MS Costa Concordia. There are also considerable differences between the minimal values of C for two ship types: the order of magnitude of the minimal long-term indices for ocean liners is between 10^{-13} (as for the RMS Queen Mary) and 10^{-7} (as for the SS Michelangelo), whereas the minimal long-term index of stability failure of the MS Costa Concordia and the MS Song of America is $C \approx 1.38\cdot10^{-6}$ and $C \approx 8.2\cdot10^{-3}$, respectively. Furthermore, it may be noticed that the curves corresponding to ocean liners are generally lower than the curves corresponding to cruise ships.
- The stability assessment of the examined ships performed using the SGISC framework for the dead ship condition is generally consistent as the L1 is more conservative than L2 (see Table 4). However, a case of inconsistency may be observed: L2 is more stringent than L1 for the RMS Queen Mary.
- The long-term indices of stability failure in the dead ship condition of the examined passenger ships differ up to three orders of magnitude in cases when the ships satisfy the minimal stability requirements of Vulnerability Level 1 (see circles in Figure 6). This result confirms the inherent inconsistency of (semi)empirical stability assessment methods (such as Weather Criterion) which reflects in their inability to properly rank ships with respect to safety against stability failure in the intact condition.
- As it was already pointed out, it is difficult to obtain credible information on design properties of historic passenger ships. This is particularly valid for the data pertinent to ship stability, even the fundamental ones, such as the metacentric height at design draught. Kobylinsky & Kastner (2003), however, present the recommendation of Johow-Foerster (published in 1928), according to which the metacentric height of large passenger ships on departure should be at least 0.7-0.8 m. Kobylinsky & Kastner (2003) also cite the recommendation of Anderson (published in 1923) which is especially interesting as it presents an effort to account for the effect of wind on stability:

$$GM_{\min} = \frac{0.213 \cdot A}{C_B \cdot A_B}. \tag{9}$$

The minimal metacentric heights of the examined ocean liners calculated according to recommendation (9) are given in Table 5. According to Hackett & Bedford (1997) the metacentric height of the RMS Titanic at her design draught was $GM = 0.802$ m, which fits well into the presented recommendations.

Interestingly, $GM_{\min}$ values of ocean liners given in Table 5, calculated according to the recommendation (9) are considerably higher than the minimal metacentric heights corresponding to the Weather Criterion requirements (Table 2) which are guided, as previously pointed out, by the static stability condition (6). This would have provided for a substantial static stability margin of the examined ocean liners, in line with the previously discussed recommendations given in the Rossell & Chapman (1939) edition of the Principles of Naval Architecture.

On the other hand, it may be noticed that the minimal long-term indices of ship stability failure in the dead ship condition of ocean liners, given in Figure 6, correspond to metacentric heights which are remarkably close to those recommended by Anderson. This is particularly striking for the RMS Titanic and the SS Michelangelo for which the $C_{\min}$ is obtained for $GM \approx 0.7$ m and $GM \approx 1$ m, respectively. When deliberately applied to the examined cruise ships, the same recommendation returns a metacentric height which is (curiously) still relatively close to the minimum of the long-term stability failure index curve corresponding to the MS Song of America. However (as it might have been expected) the GM recommended by Anderson is far from the metacentric height which corresponds to the minimal long-term stability failure index of the MS Costa Concordia.

Table 5: The minimal metacentric heights of examined ocean liners and cruise ships according to recommendation of Anderson (published in 1923) for large passenger ships, see Kobylinsky & Kastner (2003).

Passenger ship	GM_{min}
RMS Titanic	0.71
RMS Queen Mary	0.75
SS United States	1.10
SS Michelangelo	1.01
MS Song of America	2.07
MS Costa Concordia	1.45

5. CONCLUSIONS

The historic ships examined in the paper were designed before international regulations on intact stability were enforced. In fact, the ocean liners analysed in the paper were designed even before the first recommendations on the intact stability assessment were enacted on an international level. This does not mean that due attention was not given to the intact stability calculations at the time. Nevertheless, as the first intact stability criteria were not agreed on international level until the late 1960s (and even then, just as recommendations for passenger and cargo ships under 100 m in length), it is difficult to establish the exact scope and extent of intact stability analysis performed in the course of the design process for particular ocean liners. It is, however, possible to get a grasp of the principles on which judgement of the intact stability was based. Furthermore, it is reasonable to assume that the intact stability requirements (and, hence, corresponding calculations) varied across the globe, as they were a matter of national regulations. Considering that the first IMO Code on intact stability (still in form of recommendations) was issued in 1993, similar conclusions may apply to at least one of the examined cruise ships.

Over the last two decades, the approach to intact stability significantly changed, resulting in the finalisation of the Second Generation Intact Stability Criteria. Even though the "first generation" stability criteria remain in place, it seems that the very notion of the intact stability irreversibly changed. More importantly, the stability assessment methods available at more sophisticated levels of the SGISC framework (L2 and DSA) are considerably less reliant on either specific ship design features or operational experience and, as such, more comprehensive and capable of properly taking into account even unconventional and novel ships.

The analysis given in the paper confirms the advantage of the SGISC Vulnerability Level 2 approach over simplified, (semi)empirical stability assessment methods, based on judging individual stability-related features (such as metacentric height). While lower metacentric heights proved to be beneficial for ocean liners, the examined passenger cruisers performed better at much higher values of *GM*. The same conclusion applies to methods based on a mathematical model which incorporates a range of assumptions and/or which is tuned to design features of a particular population of ships (such as Weather Criterion/Vulnerability Level 1 of the dead ship condition). Vulnerability Level 2 calculations exposed the inconsistency of such methods, as the long-term indices of stability failures of examined ships, satisfying the minimal requirements of the Weather Criterion, differed by three orders of magnitude.

Even though precise information on the intact stability of historic passenger ships is missing, it is possible to conclude what was the typical range of metacentric heights of ocean liners at their design draughts. Assuming that this conclusion is reasonably accurate, the analysis performed in the paper shows that these famous ocean liners would exhibit an excellent intact stability performance in the dead ship condition, even from the point of view of the contemporary stability standards, i.e. the Second Generation Intact Stability Criteria, which were conceived long after the final voyage of many of the ships examined in this study was completed.

The role of passenger ships dramatically changed by the end of the 1960s as both the socio-economic and the technological developments (which affected social and economic climate) enabled airborne transport to take over the long-distance passenger voyages sector. It is not beyond belief to imagine that the role of passenger ships, and hence their design, could change once again. Therefore, an insight into intact stability, as an essential aspect of ship safety, in relation to major design changes, could prove to be useful. Such an insight, however, could not have been possible without the comprehensive methods developed within the framework of the Second Generation Intact Stability Criteria.

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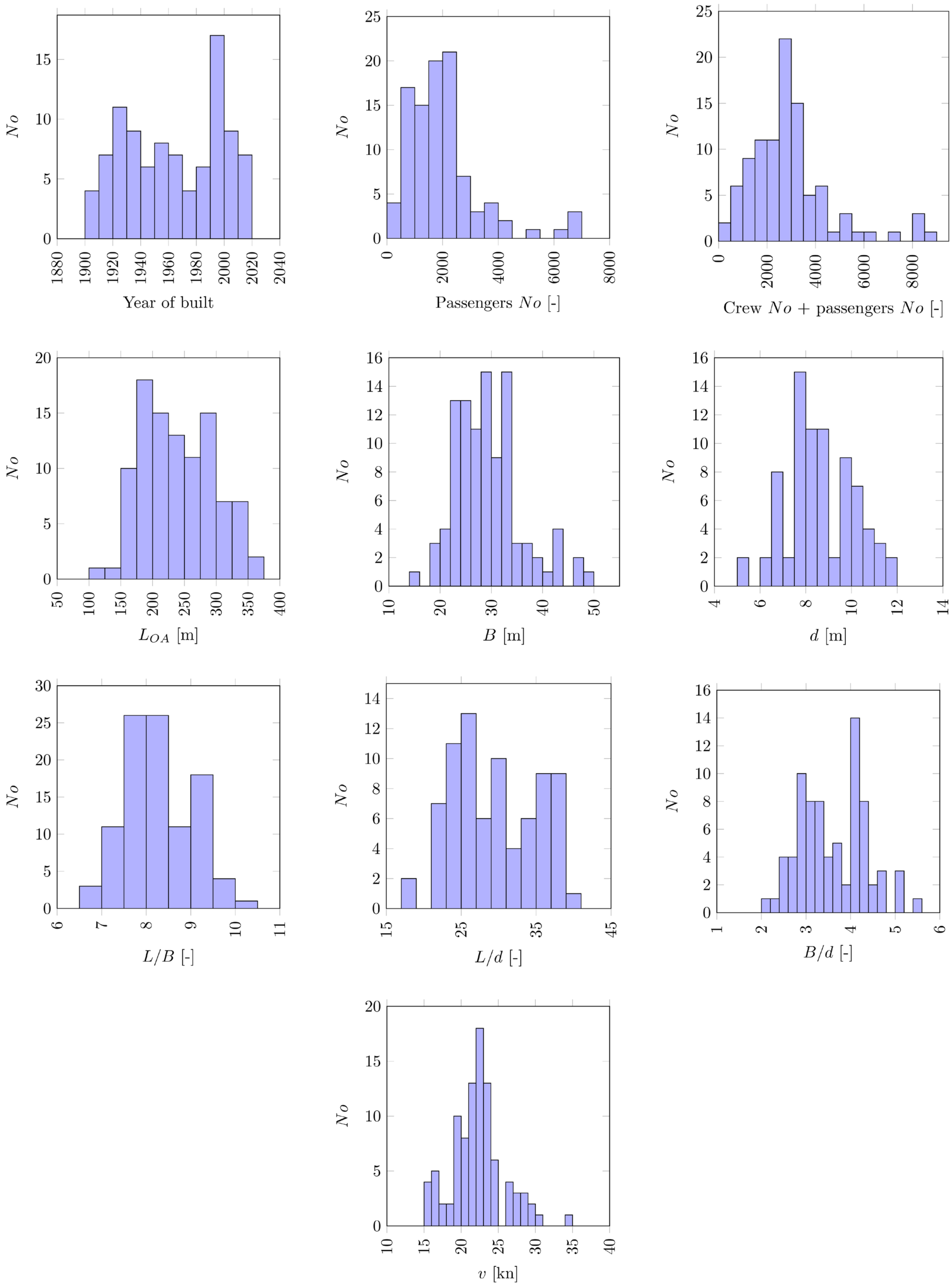
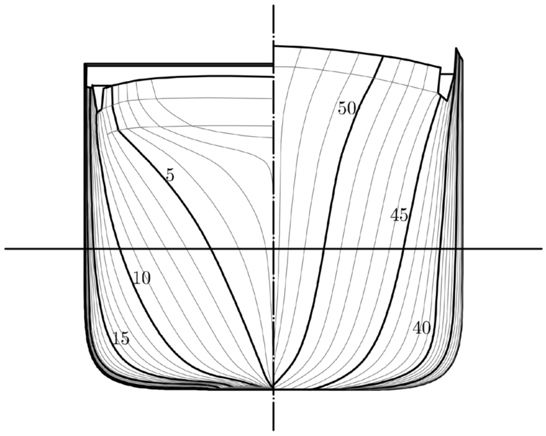
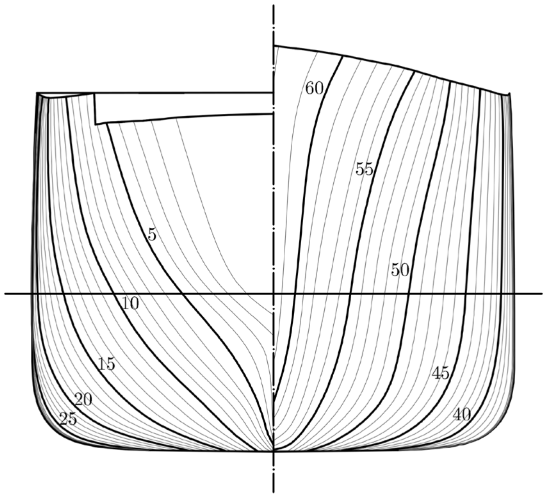
APPENDIX 1. The main features of the passenger ship database used in the study.



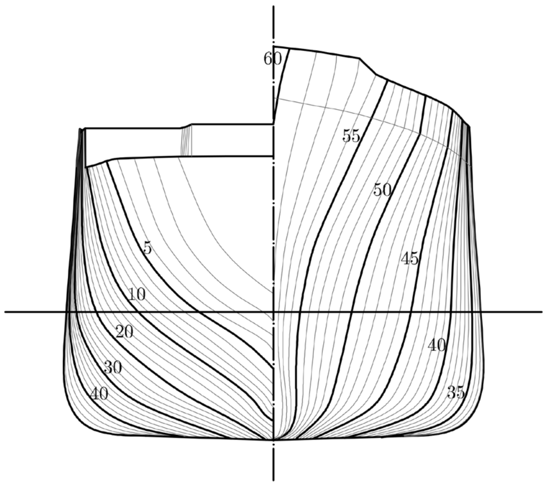
APPENDIX 2. Body plans of the examined passenger ships (given in the same scale). Cross sections are equally spaced at 5 m distance and numbered starting from the aftmost position.



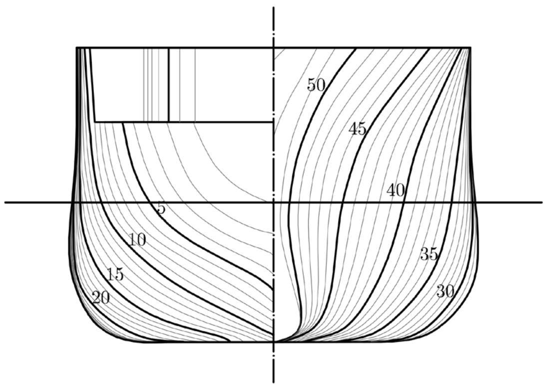
RMS Titanic



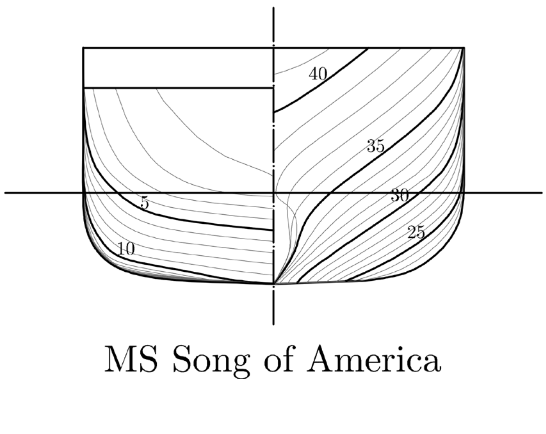
RMS Queen Mary



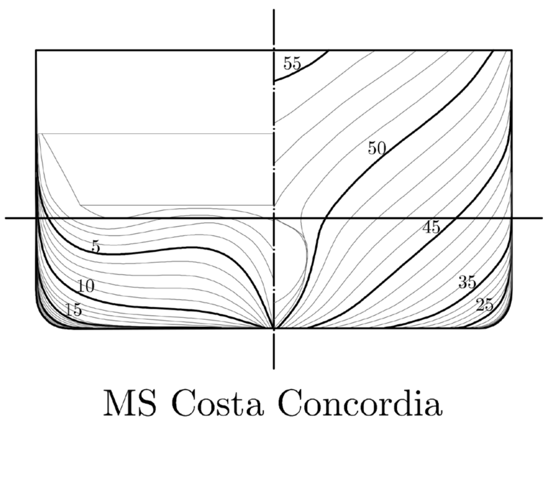
SS United States



SS Michelangelo



MS Song of America



MS Costa Concordia