Intact Stability Criteria of Ships – Past, Present and Future

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ABSTRACT

This paper contains a brief excursus of the developments of intact stability of ships through the time from stone age, through historical period, modern age, renaissance, completion of the first intact stability code, beginning of development of 2nd generation intact stability criteria, present status and the foreseeable future developments.

Keywords: *Ship stability, 2nd generation stability criteria, ship safety*

1. INTRODUCTION

Sinking due to insufficient buoyancy and capsizing because of insufficient stability are two of the major threats to ship survivability at sea. The safety from sinking and capsizing is thus an important part of the safety of navigation with the entailed safety of life and protection of the environment in waterborne transportation. The two aspects had an extremely different development through history. As we will see, this is substantially due to the different perception of the immediacy of danger and to the very different entailment of physical and mathematical aspects in the two aspects. An important change in the perception was given by the change in propulsion, in particular the passage from sail ships to mechanical propulsion.

Due to the short time available, the paper is just a working scheme for presentation, mostly composed of quotations from relevant literature. The adopted nomenclature for historical periods doesn't conform to the standard use. It has been adapted by the author (Francescutto 1993, Francescutto 2004, Francescutto 2007) to the slow development of ship stability as a science.

2. FROM THE STONE AGE TO THE BEGINNING OF HISTORY

Man has travelled for thousands of years throughout the oceans without knowing how and why this was possible. Although the basic concepts of floatability and stability will have been known before, the basic laws of hydrostatics of floating bodies were introduced by the great Archimedes in 300 BC. It is well established that he was the first to formulate the basic law of buoyancy and eventually floatability. It was, however, only quite recently that it was found that he had also set the foundations of stability of floating bodies, namely by introducing the concept of the balance of couples of forces or moments.

The part of naval architecture known as buoyancy and stability is directly founded on the roots of Archimedes' principle, but it is not clear whether his early findings about the stability of floating paraboloids were generalized by himself to actual ship forms or not. What is certain, is the fact that, after some great scientific achievements in the Hellenistic era, there was a long silence (Russo, 2004). Gained knowledge remained unexploited for centuries (or was simply ignored and not referenced) and it is not known what its impact on later developments in ship stability actually was. The development of ship stability as a science, indeed, occurred very late in the 18th century with two different approaches based on the introduction of the metacentre and the righting moment notions respectively. These approaches were developed respectively by Bouguer and Eulero.

3. THE BEGINNING OF HISTORY

Additional details on the similarities and differences between Bouguer and Eulero are contained in references [Nowacki 2001, Nowacki and Ferreiro 2003 and Francescutto and Papanikolaou 2011]. What is important to remark here is that, after the bright but isolated spot of Archimedes, the decisive progress of ship stability, as we know it now, came from the (mostly) geographer Bouguer while he was strolling up-and-down the Andes in search of a proof that Earth shape was following Descartes theories against Newton's theories. The result was the notion of metacentre, i.e. the upper limitation of the position of centre of gravity that guarantees the stability-in-the-small or initial stability.

It is important to note the observation made by Bouguer in the Preface to his book (Bouguer 1746): "Il n'était guére possible que l'Architecture navale, compliquée comme l'est par la multitude des diverses connoissances qu'elle suppose, fit des progrès aussi rapides quel es autres parties de la Marine qui sont incomparablement plus simples. Il falloit non-seulement que les diverse Théories sur le mouvement dont elle dépend, & dont l'époque est assez recente, fussent portées plus loin, il étoit encore nécessaire que l'Analyse même & les methods géométriques qui devoient servir à réfoudre les grandes difficultés qui lui sont propres, parvinnent elles-mêmes à un degré de perfection qu'il ni a pas longtemps qu'elles ont acquis."

This witnesses the intrinsic physical and mathematical difficulties connected with the development of the subject. It is not casual that previous development was due to the best mechanician-mathematician of the ancient Greece (although he flourished in Magna-Grecia, present Italy…).

The work was completed by the Rev. Moseley (Moseley 1850) introducing the coincept of dynamic stability in 1850: "Whence it follows that the work necessary to incline a floating body through any given angle is equal to that necessary to raise it bodily through a height equal to the difference of the vertical displacements of its centre of gravity and that of its immersed part, so that other things being the same, that ship is the most stable the product of whose weight by this difference is the greatest."

Quoting Barnes (Barnes 1861): "The first general theorem for the determination of the measure of a ship's stability was given by M. Bouguer, in his Traité du Navire, about a century ago. This measure of a ship's stability, although only strictly true when the angle of inclination from the upright is extremely small, yet gives the relative stabilities of ships of the usual form for a tolerably large angle of inclination with sufficient exactness for all practical purposes. Bouguer's measure, in consequence of the simplicity of the calculations for obtaining the height of the metacentre and its close approximation to the correct results, is that which is in general use: but a naval architect should also be familiar with the mechanical principles upon which the stability of a ship depends, and be able to determine the exact stability of a ship of any form whatever, at any given finite angle of inclination."

Unfortunately, the idea of Bouguer didn't have real practical applications. Notwithstanding fierce debates, mostly in the frame of the Institution of Naval Architects, as a consequence of the sudden sinking of the monitor Captain (designed by Cole) having a higher metacentric height but a smaller freeboard giving a smaller range of positive stability with respect to the Monarch (designed by Reed). White and John (White and John 1871) comment: “In 1867 calculations were made at the Admiralty of the stability of two or three low-sided vessels, and the results were embodied in a Paper read by Mr. Reed at the Meetings of this Institution in 1868. With this Paper most of the Members and Associates are doubtless familiar. It showed conclusively that instability would occur in such vessels at a very moderate angle of inclination, and illustrated the contrast, as regards stability and safety, existing between rigged ships with high freeboard and those with low freeboard. … This paper did not succeed, however, in impressing members of the profession with the necessity for more complete calculations of stability, and the subject remained in comparative obscurity until the loss of the Captain forced it into painful prominence.”

The reasons for the absence of transformation of Bouguer intuition in practical (stability) rules are well explained by Rahola in his doctoral thesis: “Even the most recent of the fundamental laws that determine the amount of stability for a vessel are already about 200 years old. Consequently, it would seem natural that the estimating of a vessel's stability and the determining of its minimum amount should have drawn attention very early. However, that is by no means the case. Only about a hundred years after forming the principles for the theory of stability one began to understand, by reason of a certain accident having occurred, the great importance the stability qualities of a vessel have for its seaworthiness and non-sinking qualities. This earlier under-valuation of the stability circumstances appears at first sight difficult to explain, particularly when one compares the fortunes of this question with those of its parallel question, the development of the problem of preventing the overloading of vessels. … The slight interest roused for the amount of a vessel's stability can in a way be explained very simply. So long as the wind was the propelling force for the ships, one was obliged, without studying the matter theoretically, generally to have a comparatively high freeboard for the hull. This brought about at the same time that the range of stability became great. The master of a sailing ship was also aware at every moment of the approximate amount of the stability, because when sailing he constantly happened to perform some kind of inclining experiment with his vessel, even if it was primitive. It was therefore easy for the master to avoid imperiling the stability of his ship, and whenever he was tempted to load an excessive deck-cargo or otherwise reduce the stability, he probably did so well aware of the risk he was causing his vessel. … The construction of a diverging type of vessel led to a flagrant violation of the building rules for well tested sailing vessels.

4. THE BEGINNING OF THE MODERN AGE

This is situated in the ‘30s of last century and is substantially based on two papers. First of all, Pierrottet (Pierrottet 1935) laid the foundations of what later will be the weather criterion. During his presentation in front of the Royal Institution, the following debate, illuminating about the general conception of stability at that time, was recorded: “The CHAIRMAN: I do not wish in the least to detract from the good work that Professor Pierrottet has done. I think the Paper will be very useful to us, but I do hope it will be a long time before it is made the basis for new Board of Trade regulations by the Classification Societies. The number of losses from capsizing is so exceedingly small, even more tiny than he says, that it would be a very stiff to impose these regulations. After all, when you had imposed them, the skipper might upset them all by his loading of the ship. There is the difficulty. I hope Professor Pierrottet will not assume that I am pouring too much cold water on his scheme, for I think you will agree with me that he has devoted his energy, brains and ability to producing an interesting and, I believe, a useful Paper, and that we ought to accord him a very hearty vote of thanks"

PIERROTTET: "To Sir Archibal Denny I would say that I think the problem of stability is rather neglected by ship designers. I can see danger in his recommendations of empirical, rather than scientific methods. If the proportions of bridges across rivers were decided empirically, I am sure that sooner or later there would be many a disaster. The limits of the field over which empirical methods can safely be applied are very vague. It is my opinion, therefore, that no effort should be spared to study scientifically the stability of ships, and to ensure that designers do not neglect its consideration. I am rather doubtful, moreover, if this object can be attained without the application of binding regulations. I quite agree that at 50° inclination nothing would remain still on deck, but that is not the problem : when a ship is unfortunate enough to acquire a list of 50°, the problem is not so much of how to keep all the passengers safely on board, but rather to prevent her from capsizing. I should not be adverse, though, to reducing the proposed 50° to some smaller figure."

Second came the PhD Thesis of Rahola (Rahola 1939). It is a too important contribution to be summarized here, but it is important to consider at least the following couple of sentences from the introduction: "The object of the present investigation is to find a procedure by means of which it may be possible to judge with adequate certainty the amount of the stability of a certain vessel which may come to navigate under the conditions prevailing on the lakes and the waters adjacent to our country, and to decide whether it is sufficient or not." … "With regard to stability circumstances we must clearly make a distinction between the determining and the judging of stability."

Almost contemporarily, the first issue of the Principles of Naval Architecture (Vincent 1939), in line with the thinking of the time, considering that still paid more attention to comfort that to safety from capsizing: "Suitable Metacentric Height. Metacentric height is one of the fundamental features of a design and should have such a value that it will meet the following requirements:

(a) Large enough in passenger ships to prevent capsizing or an excessive list in case of flooding a portion of the ship during an accident.

(b) Large enough to prevent listing to unpleasant or dangerous angles in case all passengers crowd to one side. This may require considerable GM in light displacement vessels, such as excursion steamers, carrying large numbers of passengers.

(c) Large enough to minimize the possibility of a serious list under pressure from strong beam winds.

(d) Small enough to prevent violent rolling in waves. As explained in Chapter I, Volume 2, an excessive GM results in unpleasant rolling that may even be dangerous should the period of roll approximately synchronize with that of the waves. The traveling public is inclined to avoid vessels known to roll badly. Several large ships that were unpopular because they rolled badly have undergone costly major alterations to improve the condition."

And following: "Damaged stability considerations may occasionally require excessive metacentric heights. Recognizing this, several formulas have been devised to establish the maximum GM that need be provided in the interest of safety. In the light condition modern passenger vessels ordinarily have very little positive GM, often not over 1 per cent of the beam, and many of the older liners have negative GM when light. For all classes of vessels there is an advantage in having at least positive GM in this condition, as such a vessel does not require as careful handling as one that has a negative GM. A few authorities insist upon at least positive GM in the light condition. The above views on the maximum GM acceptable for passenger vessels are those of the author (S. A. Vincent) but not those of all naval architects and others interested in shipping. Some believe that a higher load GM should be used, if necessary to give adequate stability in the flooded condition."

It is worth Noting that at the time, no substantial progress was still made by SOLAS, still involved in the development of subdivision rules after Titanic's sinking, in addressing the issue of stability. Finally, concerning dynamic stability, in spite of the tremendous work done, mostly published in the Proceedings of the Institution of Naval Architects (PNA 1988) following Moseley: "The dynamical stability of a ship at a given inclination is defined as the work done in heeling the vessel to that inclination. Dynamical stability is rarely calculated in practical merchant ship design work, but is used in investigations of the motion of a vessel among waves, the list due to firing guns and similar problems."

The far-looking intuitions of Rahola and Pierrottet, not to speak of Bouguer and Moseley, had to wait long time, respectively 30 and 50 years, and the birth of IMCO (later IMO), before becoming international regulations. Only starting with the 1988 edition the Principles of Naval Architecture dedicates due attention to minimum standards of intact stability: "In Chapter II more attention is given to stability curves and to criteria for acceptable stability based on them."

5. THE FIRST GENERATION INTACT STABILITY CRITERIA

Provisions concerning intact ship stability have been introduced at a late stage in international regulations of ship safety. The need of intact stability rules was indeed uncertain until SOLAS 1948, where it was stated, in the Recommendations contained in Annex D:

"The Conference examined the need and the practical possibility of adopting rules relative to the intact ship stability. Considering that the rules adopted relatively to the damage stability have an influence on the intact stability of the ship, the Conference believes that, before establishing additional rules concerning intact stability, further experience to establish the extent to which such rules are necessary is needed. The Conference recommends therefore to the Administrations to examine in more detail the intact ship stability and to exchange information on such subject.".

We have not to forget that the adopted rules for damage stability practically consisted in: "In the case of symmetrical flooding the residual metacentric height shall be positive, except that, in special cases, the Administration may accept a negative metacentric height (upright) provided the resulting heel is not more than seven degrees."

The first international intact ship stability rule was originated by a recommendation contained in the conclusions of SOLAS'60: "The Conference, having considered proposals made by certain governments to adopt as part of the present Convention regulations for intact stability, concluded that further study should be given to these proposals and to any other relevant material which may be submitted by international Governments.

The Conference therefore recommends that the Organization should, at a convenient opportunity, initiate studies on the basis of the information referred to above, of:

a) intact stability of passenger ships;

b) intact stability of cargo ships;

c) intact stability of fishing vessels, and

d) standards of stability information…"

As a result, the General Stability Criteria based on righting arm characteristics was adopted by IMCO in 1968 as Res. A.167. Following Kobyliński (Kobyliński 1975): "In 1962 IMCO started its work towards the development of stability criteria for fishing vessels for small passenger and cargo vessels of less than 100 metres in length. The work was completed in 1968 the criteria were introduced by IMCO as recommendations"

The Weather Criterion was adopted in 1985 as Res. A.562. Again, this rule originated as an answer to a recommendation given in the conclusions of SOLAS'74: "(IMO) Recommends that steps be taken to formulate improved international standards on intact stability of ships taking into account, inter alia, external forces affecting ships in a seaway which may lead to capsizing or to unacceptable angles of heel".

Weather Criteria were already enforced in several countries including Japan (Yamagata 1959) and Australia. We just mention here that present weather criterion was obtained merging the Japanese standard, which still constitutes the backbone, with the Russian standard especially for the evaluation of roll-back angle and the effect of appendages on roll damping.

Both criteria were based on ideas, concepts and ship typologies/dimensions, existing long before their adoption.

6. THE "RENAISSANCE"

The renaissance of Ship Stability in general and Intact Ship Stability in particular can be identified with the mid '70s of past century due to the intuition of Prof. Kuo from Strathclyde University that there was a diffuse greater sensitivity to the subject. In 1975 he organized *The* International Conference on Stability of Ships and Ocean Vehicles which was an unprecedented event with many consequences. In addition to gathering the experts on the subject, he organized a Questionnaire which is of great interest to understand the feeling of that time. Almost all contributions to the Conference and to the Questionnaire should be mentioned in this paper, which is out of possibility. It is however important to remind the answers to selected questions:

Existing criteria (IMO Res. A.167): only 29% of respondents felt that the existing stability criteria based on the use of the righting arm curve met practical needs. Almost 50% felt that the criteria were unsatisfactory;

Main priorities: the two main priorities for research were seen as: (a) the effects of waves, and (b) the development of fresh methods for relating motion characteristics to stability criteria;

Metacentric height: a large majority of respondents considered such knowledge to be very important whereas the remainder thought that it was not important as long as it had a positive value. Of the respondents to the question on minimum metacentric height 55% of all respondents opted for 300 mm or more.

Several critical paper were developed to the existing Stability Criteria (mostly to the so-called statistical one represented by Res. A. 167, but also to the Weather Criterion, Res. A. 562, although its being partly a physical approach). Among these, since the beginning, there was Kobiliński (Kobiliński 1975), calling for "rational criteria": "At the time IMCO started its work towards elaborating international stability criteria several countries introduced stability criteria going beyond the requirements of I960 SOLAS Convention, All national requirements and regulations were carefully analysed, but the main source of inspiration for the evaluation of IMCO-Criteria was an analysis of casualty records and a comparison of the various stability parameters for vessels which capsized with those which were found safe in service. From all the stability parameters which could be used as stability criteria, the ones chosen for further analysis were those which lead to the lowest position of KG. This was decided on the basis of statistics. … It should be underlined, however, that the approach was a pure statistical one. Its main drawback was that the available data constituted only a small population of vessels. In consequence, the statistical analysis was not satisfactory. During the discussions at IMCO, the view was expressed several times that in future more rational stability criteria are needed. Rational stability criteria are understood to be those that can take into account the physical phenomena occurring during the ship's service and all external forces exerted on them. The development of such rational criteria is a long-term task and for this reason simpler statistical approaches are first adopted at IMCO."

This objective was futher-on proposed by Francescutto (Francescutto 1993): "As we have seen, too often we assist the attempt to circumvent the actual stability rules, whose inadequacy and arbitrariness, on the other hand, has been declared by different authorities. It is difficult to change mental habits, but it is possible to intervene in the rules, not only to strengthen them, but to change the approach to ship safety. The conclusion is that the only way to overcome the many difficulties lies in the development of a system for the time domain simulation of ship motions in a seaway, including a detailed description of the environment and taking into account the non-linearities present and the dynamic effect of liquids with free surface in tanks, or on board as a result of deck wetness or damage. This will be called the *Physical Approach* to the hydrodynamic aspects of ship safety. Of course, it is a long term program involving the solution of many aspects connected with non-linear dynamics of motions and with the development of the non-linear hydrodynamics necessary to deal with large amplitude, transient asymmetric motions. The reason for the use of such a system as part of the design process from the beginning is to improve ship safety. This allows a further step in a procedure that usually uses optimization taking into account resistance, propulsion and seakeeping only. In this way, the hydrodynamic aspects of ship safety could be treated in a probabilistic way, as pertains to their very nature, overcoming the actual approach based on 'simple, certain, rules'. This could allow the introduction of the concept of 'safety performance' and the development of training tools for safety. It is not clear at this point if this approach leads to much more restrictive rules, but it is clear that the rules will be more realistic and defendable.";

Spyrou (Spyrou 1998): "Whilst one might think of many different methods for assessing the behaviour of a system, there is little doubt that the most reliable are those which are based on sufficient understanding of the system's key properties. For ship stability assessment however the application of this principle has been, so far at least, less than straightforward; because the behaviour of a ship in an extreme wave environment, where stability problems mostly arise, is often determined by very complex, hydrodynamic or ship dynamic, processes."; and by Spyrou and Papanikolaou (Spyrou and Papanikolaou 2000): "Is it possible to use in ship design the latest findings from the modern analyses of capsize based on the theory of nonlinear dynamics? This is the question which we are attempting to address in the present paper. Our goal is the establishment of a rigorous scientific basis for quantitative assessment of dynamic stability which will cover all the known types of ship capsize. Our approach will be comprised of two levels: The first refers to a very early stage of design where it is desirable to have simple analytical predictors of dynamic stability (or, for a certain standard of stability, of the required values of influential parameters such as damping), while our knowledge about the ship is still limited. The detailed account of a ship's form takes place at a second level where the stability analysis is performed with suitable numerical methods. It is remarked that the presented measures of stability could be relevant also for the operational side of the problem which however should be the subject of another publication. We think that a rational approach about ship safety entails the best available scientific knowledge to be "infused" with the current practices of design, operation and rule setting. These notwithstanding, we are urged to note the profound lack of a proper methodological framework of ship stability assessment which would exploit the recent progress in understanding the dynamic origins of capsize and play the role of an interface between practice and research. The development of such a framework is nontrivial because the process of ship capsize is often determined by nonlinear phenomena and is not a simple task to develop scientifically sound and yet simple-to-understand and practical, quantitative measures of dynamic stability covering all possible types of capsize. Recent advances in the study of ship dynamics have allowed us to develop a two-level framework for a rigorous quantitative assessment of ship stability. This framework can be useful to a designer who wants to determine, along with other design considerations, a hull geometry and appendages that maximize safety against capsize."

It is worth noting that both call, in some way, for layered approach to stability regulations, an approach later-on adopted in the development of Second Generation Intact Stability Criteria.

7. THE SECOND GENERATION INTACT STABILITY CRITERIA

The revision process started in 2001 (Francescutto 2004, Francescutto 2007) with a critical analysis submitted by Italian delegation to IMO (IMO 2001, Francescutto et al. 2001) concerning the need of updating and tuning some coefficients of the Weather Criterion in view of its excessive weight in determining the limiting KG for ships with large values of B/d. This was considered a good opportunity to "shake" the ISC foundations putting them on a more physical basis through the development of new *performance based criteria* (PBC) originally intended to replace the old ones. These last were indeed identified as a source of difficulties due to their partly or totally empirical character which originated a non-uniform distribution of safety among different ship typologies. At the same time, their structure rendered these criteria quite difficult to modify without a possible significant loss of safety level of covering of present world fleet. The first part of the long work undertaken in the revision of the IMO Intact Stability Code in 2001 with the establishment of an ad-hoc Working Group (WGIS) operating during the Sessions of the Sub-Committee on Stability and Load Lines and on Fishing Vessel Safety (SLF) and intersessionally between them, was completed in 2008.

This part of the WGIS activity was mostly devoted to restructuring the previous Intact Stability Code (IMO 1993) in several parts and making Part A of the new International Code on Intact Stability, 2008 (IS Code 2008) mandatory under the provisions of both SOLAS and ILLC Conventions. This action was partly a consequence of the development of an FSA study, made by the German Delegation at IMO (IMO 2003), proving the potential cost-effectiveness implied in this change of legal status. The Code was also subject to some polishing and clarification, elimination of some ambiguities. In addition explanatory notes to the 2008 IS Code have been issued mostly consisting in a review of history of intact stability leading to present regulatory situation. It is however noteworthy that explanatory notes also contain guidance for an alternative application of "criteria regarding righting lever curve properties", in particular the rule requiring the position of the maximum of GZ to be above 25 deg. The new Part A contains mandatory instruments for passenger and cargo ships, while Part B contains recommendations for other ship typologies. An originally planned "Part C" containing nomenclature, an historical part describing the origins and the developments of intact stability criteria and explanatory notes to the new International Intact Stability Code 2008, has been finalized as an MSC Circular

(MSC.1/Circ.1281). Although what is now Part A was previously made de-facto mandatory under umbrellas different from IMO (European Directives, Classification Societies rules, etc.), the fact that after its adoption by SOLAS/ILLC the Code will become mandatory erga-omnes, constitutes a big change, because no attenuation to its standards is acceptable unless the "equivalent level of safety" with existing regulations is proved to the satisfaction of Administrations. This in turn is made difficult by the lack of knowledge of the actual safety level of present regulations. There is in fact the strong feeling that they provide an unequal distribution of safety among different typologies and, even within the same typologies, to different ship size. As a result, the revision made necessary the request and subsequent implementation of some important changes in the two basic design criteria.

As to the Weather Criterion, an alternative way of assessment, completely or partially based on experiments on scale models in towing tank/wind tunnel, was approved, based on both the obsolescence of the existing Weather Criterion due to the variations in ship forms and loading, and to correct some inconsistencies in the original formulation.

Notwithstanding the importance of this work, the most important part of the initial scope of the revision, i.e. the formulation and implementation of a new generation intact stability criteria performance-based was still to a large extent lying on the carpet. The time flown was in any case important for proving the potential cost-effectiveness implied in the new criteria and for the maturation of some important concepts connected with the dangerous phenomena to be covered, the basic structure and dictionary, and the philosophy of application of the new criteria.

It was subsequently decided that the following five possible stability failures should be individually addressed (IMO 2007, IMO 2010, Bassler et al. 2009, Francescutto and Umeda 2010, Peters et al., 2011,):

- dead ship conditions;

- following/stern quartering seas associated with matters related to stability variation in waves, in particular reduced righting levers of a ship situated on a wave crest;

- parametric resonance, including consideration of matters related to large accelerations and loads on cargo and stability variation in waves;

- broaching including consideration of matters related to manoeuvrability and course keeping ability as they affect stability;

- excessive accelerations.

Moreover the new generation intact stability criteria should be structured in three levels:

- Vulnerability 1st level;

- Vulnerability 2nd level;

- Direct assessment.

Specific Operational Guidelines should be added as a sort of "fourth level", in the acknowledgement that not all dangerous situations can be avoided only by design prescriptions.

After an initial good starting, the development of the procedures for the assessment of all the identified failure modes, mostly for the first two levels assessment, slightly diverged in a number for alternatives. During the last meeting of the Working Group, at SDC 2 (IMO 2015) last February, however, several choices were made concerning the application, the resolving of the alternatives for some failure modes, the development of explanatory notes and the development of "ways-out", in the form of operational limitations or operational guidelines (IMO 2013) at the different levels.

Work is in progress at inter-sessional level to arrive at next meeting of SDC 3 in 2016 with a polished text for all the identified failure modes, ready for thorough checks. It is encouraging that both the remaining failure modes for which alternatives were present are presently converging towards an agreed text.

8. REFERENCES

PNA, 1988, "Principles of Naval Architecture - II Revision", Lewis, E. V., Vol. I, Stability and Strength, SNAME.

Barnes, F. K., 1861, "On a New Method of Calculating the Statical and Dynamical Stabilities of a Ship", Trans. INA, Vol. II, pag. 163

Bassler, C., Belenky, V., Bulian, G., Francescutto, A., Spyrou, K., and Umeda, N., 2009, "A review of available methods for application to second level vulnerability criteria", Proceedings of the 10th International Conference on Stability of ships and ocean vehicles - STAB 2009, Saint Petersburg, pp. 111–128.

Bouguer, P., 1746, "Traité du Navire, de sa Construction et de ses Mouvemens (Treatise of the Ship, its Construction and Movements", Jombert, Paris.

Francescutto, A, Umeda, N., 2010, "Current Status of New Generation Intact Stability Criteria Development", Proceedings 11th International Ship Stability Workshop, Wageningen, pp. 1-5.

Francescutto, A., 2004, "Intact Ship Stability - The Way Ahead", Marine Technology, Vol. 41, pp. 31-37.

Francescutto, A., 2007, "Intact Stability of Ships: Recent Developments and Trends", Proc. 10th International Symposium on Practical Design of Ships and Other Floating Structures – PRADS'07, Houston, Vol. 1, pp. 487-496.

Francescutto, A., 1993, "Is it Really Impossible to Design Safe Ships?", Transactions Royal Institution of Naval Architects, Vol. 135, pp. 163-173.

Francescutto, A., Papanikolaou, A. D., 2011, "Buoyancy, Stability and Subdivision: From Archimedes to SOLAS2009 and the Way Ahead", International Journal of Engineering for the Maritime Environment (Proceedings Institution of Mechanical Engineers, Part M), Vol. 225, pp. 17-32.

Francescutto, A., Serra, A., Scarpa, S., 2001, "A Critical Analysis of Weather Criterion for Intact Stability of Large Passenger Vessels", Proceedings 20th International Conference on Offshore Mechanics and Arctic Engineering - OMAE'2001, Rio de Janeiro, Vol. 1, pp. 829-836.

IMO, 1993, "Code of Intact Stability for all Ships Covered by IMO Instruments", Res. A. 749.

IMO, 2001, "Weather criterion for large passenger ships", Submitted by Italy, SLF44/INF.6.

IMO, 2003, "Revision of the Code on Intact Stability", MSC78/24/1, Submitted by Germany,.

IMO, 2007, "Framework for the development of new generation criteria for intact stability, submitted by Japan, the Netherlands and the USA", IMO SLF50/4/4.

IMO, 2010, "Development of new generation intact stability criteria – Report of the Working Group (Part 1)", SLF52/WP.1.

IMO, 2013, "Development of Second Generation Intact Stability Criteria - Comments on present status of development of second generation intact stability criteria", Submitted by Italy, SLF 55/3/7

IMO, 2015, "Development of Second Generation Intact Stability Criteria - Development of Amendments To Part B of The 2008 IS Code on Towing, Lifting and Anchor Handling Operations - Report of the working group (Part 1)", SDC 2/WP.4.

IS Code, 2008, "International Code on Intact Stability, 2008", IMO, London.

Kobyliński, L., 1975, "Rational Stability Criteria and the Probability of Capsizing", Proceedings (1st) International Conference on Stability of Ships and Ocean Vehicles, Kuo, C., Paper 1.4.

Moseley, H., 1850, "On the Dynamical Stability and on the Oscillations of Floating Bodies", Phil. Trans. of the Royal Society of London, Vol. 140, pp. 609-643.

Nowacki, H. and Ferreiro, L. D., 2003, "Historical roots of the theory of hydrostatic stability of ships", Proceedings of the 8th International Conference on Stability of Ships and Ocean Vehicles - STAB 2003, Madrid.

Nowacki, H., 2001, "Archimedes and ship stability", Proceedings of the Euro-Conference on Passenger ship design, operation and safety, Anissaras-Chersonissos, Crete, 2001.

Pierrottet, E., 1935, "Standards of Stability for Ships", Transactions Institution of Naval Architects, Vol. 77, pp. 208-222.

Rahola, J., 1939, "The Judging of the Stability of Ships and the Determination of the Minimum Amount of Stability Especially Considering the Vessels Navigating Finnish Waters", Ph.D. Thesis, Technical University of Finland, Helsinki.

Russo, L., 2004, "The forgotten revolution: how science was born in 300 BC and why it had to be reborn", Springer, Berlin.

Spyrou, K. J., 1998, "Ship Capsize Assessment and Nonlinear Dynamics", Proceedings 4th International Workshop on Theoretical Advances in Ship Stability and Practical Impact, St John's, Newfoundland, Canada.

Spyrou, K. J., Papanikolaou, A. D., 2000, "Ship Design for Dynamic Stability", Proceedings of the 7th International Marine Design Conference - IMDC2000, KS Min & J-J Kim, Kyongju, Korea, pp. 167-178.

Vincent, S. A., 1939, "Transverse Stability", Principles of Naval Architecture – Written by a Group of Authorities, Rossell, H. E. & Chapman, L. B., Vol. I, Chapter III, SNAME, pp. 99-137.

Peters, W., Belenky, V., Bassler, C., Spyrou, K. Umeda, N., Bulian, G.,. Altmayer, B., 2011, "The Second Generation Intact Stability Criteria: An Overview of Development", Transactions - The Society of Naval Architects and Marine Engineers, Vol. 119, pp. 225-264.

White, W. H., John, W., "On the Calculation of the Stability of Ships, and some Matters of Interest Connected Therewith", Transactions Institution of Naval Architects, Vol. XII, 1871, pp. 76-127.

Yamagata, M., 1959, "Standard of stability adopted in Japan", Transactions of Institution of Naval Architects, Vol. 101, pp. 417–443.