Practical Design of Ships and Other Floating Structures
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ULTIMATE STRENGTH OF LONGITUDINALLY STIFFENED PANELS: MULTI-CRITERIA COMPARATIVE ANALYSIS

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ABSTRACT

Based on a recommendation of the ISSC 2000 Committee VI.2 (Yao et al. 2000) which has shown that the main factor to assess the ultimate bending moment of a hull girder is the quality of the "σ-ε" curves, we achieved an extensive comparison on the available methods providing the ultimate compressive strength and the average "σ-ε" relationship of longitudinally stiffened panels. This assessment mainly focuses on passenger ships (cruise ships, fast ferries) and naval vessels having the plate and column slenderness of standard steel stiffened panels produced in France. At the first stage, we compared 18 different methods to assess the ultimate strength of a hull girder. These methods may be classed into 3 types: empirical, intermediate (analytical or semi-analytical) and generic (e.g. ISUM and FEM). Only the methods able to rapidly provide "σ-ε" relationships are relevant for our purpose but others were also considered as valuable references. From this comparison, a set of "σ-ε" models were selected using a multi-criteria comparative analysis for advanced numerical tests. Then, the selected "σ-ε" models were compared on different stiffened panels. In addition, comparative tests on simple box girders were carried out to assess the effect of the "σ-ε" model capabilities (initial deflections, residual stress, lateral loads, ...) on the ultimate bending moment of a hull girder.

KEYWORDS

Ultimate strength, Axial compression, Longitudinally stiffened panel, Collapse analysis, Hull girder, Buckling, Ultimate bending moment, Multi-criteria analysis.

1 INTRODUCTION

One of the main IRCN's concerns deals with the development of a new shipyard-oriented tool which has at the design stage the capability to assess the ultimate bending moment of a hull girder. Our purpose is not to implement a high sophisticated approach asking for long and time-consuming numerical analysis but a method which gives a good compromise between accuracy and simplicity. In order to meet this requirement, a multi-criteria analysis was performed. To compare the "average stress

– average strain" curve ("σ-ε" curve) provided by different approaches, it was decided to review a series of models able to evaluate the ultimate bending moment of a hull-girder. All these models provide the panel's ultimate strength but only some of them give a "σ-ε" curve (these ones being the most relevant for our purpose). In fact, the quality of component behaviour is the predominant factor to assess the ultimate bending moment. However, in a first stage, all models have been considered to qualify all the different types of approach and to have more references.

The 18 methods listed in our study are briefly presented in Table 1. A method can be either an original method or a regrouping of very closed formulations proposed by different authors.

TABLE 1

INVENTORY OF METHODS TO ASSESS THE ULTIMATE STRENGTH OF A HULL GIRDER

N°	Name of Methods	References
1	Caldwell (Direct approach)	(Caldwell 1965)
2	Paik (Direct approach)	(Paik et al. 1995)
3	Smith (FEM for "σ-ε")	(Smith 1977, Dow et al. 1981)
4	Adamchak	(Adamchak 1984)
5	Hughes (SSD) without post collapse strength	(Hughes 1988 - Ch. 17)
6	Lloyd Register (Rutherford)	(Rutherford et al. 1990)
7	Bureau Veritas & Gordo-Soares	(Beghin et al. 1995, Gordo et al. 1996)
8	Yao (HULLST)	(Yao et al. 1991, 1992)
9	Rahman + Hughes	(Rhaman et al. 1996, Hughes 1988 – Ch. 14)
10	FEM (full non-linear analysis)	
11	ISUM	(Ueda et al. 1991, Paik et al. 1996)
12	I.A.C. (*) + FEM for "σ-ε"	
13	I.A.C. (*) + SPINE (Paik) for "σ-ε"	(Paik 1999)
14	I.A.C. (*) + Hughes for "σ-ε"	(Hughes 1988 – Ch. 14)
15	I.A.C. (*) + Imperial College for "σ-ε"	(Dowling et al. 1991)
16	I.A.C. (*) + Paik (empirical) for "σ-ε"	(Paik 1997)
17	I.A.C. (*) + ULSAP (Paik) for "σ-ε"	(ULSAP 2000)
18	I.A.C. (*) + Faulkner (ABS) for "σ-ε"	(Guedes Soares 1997)

(*) I.A.C.: Incremental Algorithm of Curvature for progressive collapse analysis of a hull girder (Smith method)

To perform this comparative review, criteria with associated weighting are used (see Table 2).

TABLE 2

MAIN CRITERIA FOR THE MULTI-CRITERIA COMPARATIVE ANALYSIS

Criteria	Weighting A	Weighting B
1. Considered approach Direct Approach, Progressive Collapse Analysis, Global analysis	10% [15 - 10 %(*)]	7% [9 - 5% (*)]
2. Quality of the geometrical modelling of the structure From simplified (box-girder) to detailed (fine FEM mesh)	15% [15 - 10 %(*)]	10.5% [13.5 - 7.5%(*)]
3. Quality of the "σ-ε" model Model capabilities: - considered failure modes (plate, web and column buckling, tripping, yielding) - interaction between basic components - initial imperfections (initial deflections, residual stress) - lateral pressure	50% [40 - 60 %(*)]	35% [45 - 25% (*)]
4. Facility of use (from the end-user point of view)	25% [30 - 20 %(*)]	17.5% [22.5 - 12.5%(*)]
5. Availability of the model (from the developer point of view)	Not used	30% [10 - 50 %(*)]

(*): Variants for sensitivity analysis of classification to the weighting selection

All the methods have been ranked twice. The first selection was performed with weighting A, "σ-ε" **model quality** and **facility of use** being the main criteria (Fig. 1). This group was then compared to the leading methods with weighting B. For each case, in order to assess influence of weighting selection, a range of variation for the five criteria was considered (variants in Table 2). For instance, Figure 1 shows results for weighting A.

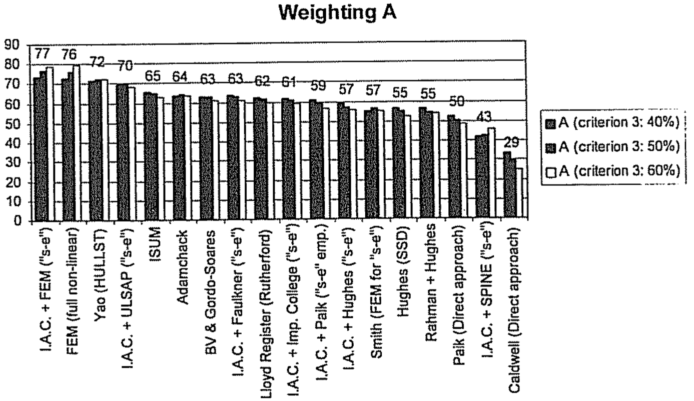

Figure 1: Classification of methods with weighting A

Based on these classifications, we have eliminated the direct approaches (1 and 2), the too "simple" progressive methods (5: no post-collapse strength, 9: too approximate geometrical modelling) and also method 13 (SPINE is only recommended for unstiffened plate). Moreover, the full FEM non-linear analysis does not suit for our purpose (too long analysis in design stage). We noticed that *BV-Gordo Soares* and *I.A.C. + Faulkner* methods have very similar formulations for the stiffened panel behaviour ("σ-ε" curves) and get close results. So, these two methods were grouped in method 7 (Table 1). Due to the availability criterion, methods 3 and 6, which have got average results, and also method 11 were not kept. At the end, it remains 5 methods of level 1 (good availability and well suited to our purpose): the *Yao (HULLST)* method which offers a good potential with a "σ-ε" numerical-analytical formulation, the *Adamchak, I.A.C. + Imp. College* and *I.A.C. + Hughes* methods with "σ-ε" analytical formulations and the *I.A.C. + Paik (empirical)* method with "σ-ε" empirical formulation. Three other methods (level 2), were also kept: the *BV-Gordo Soares* method which is consistent with our purpose but with restrained availability, the *I.A.C. + ULSAP* method which capacities must be verified and the *I.A.C. + FEM ("σ-ε")* method with "σ-ε" curves for references. Afterwards, more tests were completed for methods of level 1 than for methods of level 2.

2 DIRECT COMPARISON OF "σ-ε" ELEMENT MODELS

We have defined 10 test panels to compare the 8 remaining methods. Geometry of test panels corresponds to various stiffened panels either from ships manufactured in French shipyards (passenger ships, fast ferries, naval vessels) either from cargo ships. Dimensions, plate and columns slenderness for S235 are shown in table 3. We have considered 8 standard stiffened panels (with all identical stiffeners) and 2 mixed stiffened panels (with primary and secondary stiffeners). Each test panel was considered in two steel grade (S235 and S355 or other grade with yield stress higher than 235 MPa), with and without welding residual stress ($\sigma_r = 0\%$, 7.5% and 15 % of σ_y), with and without initial plate and stiffener deflections (maximum plate imperfection from 4 to 15 mm. in accordance with quality standards of fabrication, maximum stiffener defection at 0.1% of the span length), and with or without lateral pressure panels (from 5.10^{-3} MPa for deck (classical rule pressure) to 0.13 MPa for bottom panels). For each panel, 10 tests were carried out.

TABLE 3

TEST PANEL DIMENSIONS AND SLENDERNESS FOR S235 STEEL

		Plate characteristics		Stiffener characteristics					S235 slenderness	
Designation	a	b	t	Type	h_w	t_w	b_f	t_f	Plate β	Column λ
P1 (deck of cargo ship)	4000	800	15	flat-bar	250	19			1.784	0.599
P2 (side of cargo ship)	3750	785	19	angle	500	12	150	23	1.382	0.197
P3 (side of cargo ship)	4000	800	15	angle	235	10	90	15	1.784	0.516
P4 (bottom of cargo ship)	4000	800	20	angle	383	12	100	17	1.338	0.317
P5 (bottom of cruise ship)	2750	700	25	angle (equivalent bulb-bar)	263.5	11	82.52	16.5	0.937	0.343
P6 (bottom of fast ferry)	1500	315	5	angle (equivalent bulb-bar)	111	6	29.33	9	2.107	0.370
P7 (deck of naval vessel)	2000	500.4	9.67	tee-bar	119.07	6.22	103.9	8.06	1.731	0.457
P8 (deck of naval vessel)	1500	700	6	tee-bar	200	6	100	10	3.903	0.195
P9 (deck of cruise ship)	2700	750	5	1 tee-bar (primary stiffener)	420	10	200	10	5.018	0.163
				8 angle-bars (eq. bulb) (secondary stiffener)	91	6	25.33	9	5.018	1.062
P10 (deck of fast ferry)	1500	300	4	1 tee-bar (primary stiffener)	300	5	80	8	2.509	0.128
				14 angle-bars (eq. bulb) (secondary stiffener)	54	4	23.67	6	2.509	0.819

a: span length (mm)
b: stiffener spacing (mm)
t: plate thickness (mm)
h_w: web height (mm)
t_w: web thickness (mm)
b_f: flange width (mm)
t_f: flange thickness (mm)

We can notice that common plate slenderness of passenger ship and fast ferry deck are greater than the standard values met in panels of cargo ship. On the contrary, stiffeners of P8 panel and primary stiffeners of P9 and P10 panels are very stocky. Their column slenderness are much smaller than the standard values for which most of the available formulations have been established and validated.

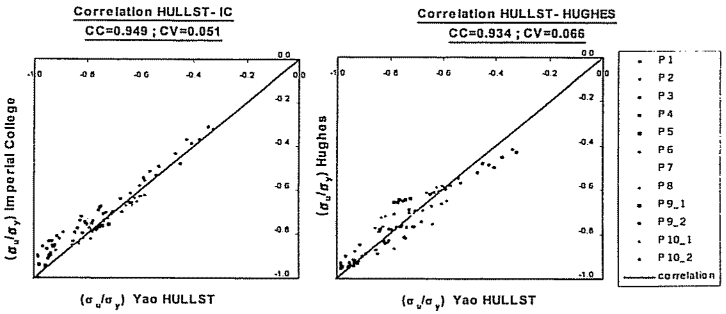

Figure 2: Correlation of ultimate stress for all test panels

The first decisive factor in quality of "σ-ε" model is the value of the ultimate stress associated to the critical collapse mode. We have considered *FEM*'s results as valuable reference unless panel geometry is perfect. Moreover, *Yao (HULLST)* based on a rational formulation also provides reliable results. So, we have used results from these two methods as references to compare the ultimate stress between all the models (Fig. 2). A synthesis of the comparison of the various "σ-ε" models is presented in Fig. 3.

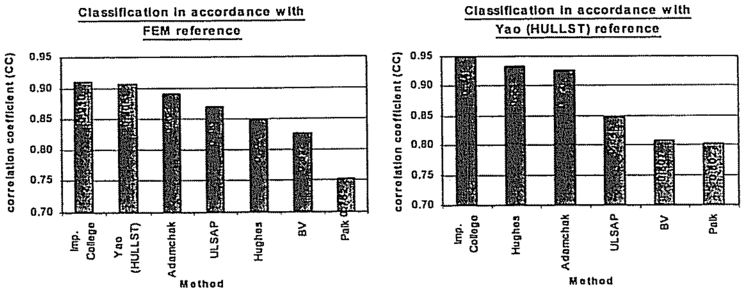

Figure 3: Synthesis of ultimate stress comparison

In fact, we can see that *BV* and *Paik (empirical)* models get the least accurate results. These models are yet valuable at design stage because they generally provide conservative values of ultimate stress. Moreover, they implicitly considered a basic imperfection, so they give an unique value for each panel (geometry and material combination). In fact, they are suited for rule design. The *Imperial College, Adamchak and Hughes* models get good correlation coefficients. These three models use analytical formulations, so they quickly provide "σ-ε" curves on the contrary to the two reference models. Furthermore, their formulations explicitly consider the level of some imperfections (residual stress, column deflection and lateral load).

Another important factor to establish the "σ-ε" relationship is the shape of the "σ-ε" curve. So, "σ-ε" curves of each test (panel, material and set of imperfections) have been plotted in order to compare their shapes. For instance, curves for one test of panel 1 are shown on Fig. 4.
The shapes are various and the differences are bigger in the post-collapse domain. In fact, *FEM* and *Yao (HULLST)* incrementally compute "σ-ε" curves, so they provide a smooth strength decay in post-collapse. Formulations of *Hughes-Rahman (as extended by Rahman for post-collapse)* and *Adamchak*

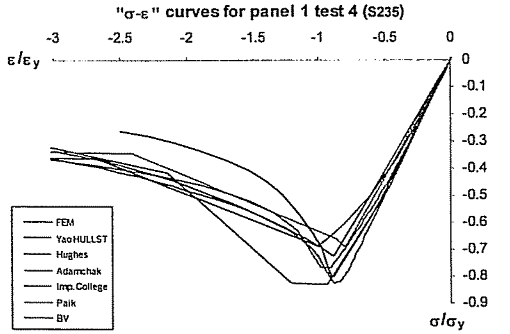

Figure 4: "σ-ε" curves of panel behaviour with 7 different models

present 3 separate domains in their load-shortening curves: a stable part in pre-collapse up to ultimate state, a plateau with practically no unloading and an unloading part. For these analytical formulations, the first part is based on an elastic-plastic buckling analysis and the third part is based on behaviour of a mechanism of collapse with plastic hinge. As *Imperial College* and *Paik (empirical)* models don't provide a shape for post-collapse domain, Rigo implemented an extent in post-collapse. This extent is based on an arbitrary calibrated shape just function of the ultimate state (σ_u, ε_u). For the *BV* model, the shape in post-collapse is also arbitrary but its calibration is based on FEM analysis. For all the tests, the more important difference noticed in shape concerns the plateau's length for the analytical formulations.

3 COMPARISON ON SIMPLE BOX-GIRDER

As our purpose is to assess ultimate hull girder bending moment of ships, it is important to compare bending moment provided with the different "σ-ε" element models. For that, we have used the previous "σ-ε" curves to assess ultimate bending moment of a symmetrical box girder (square of 6 stiffeners with associated plate on each side) with the same incremental algorithm of curvature. Fig. 5 shows moment-curvature curves associated with "σ-ε" element curves.

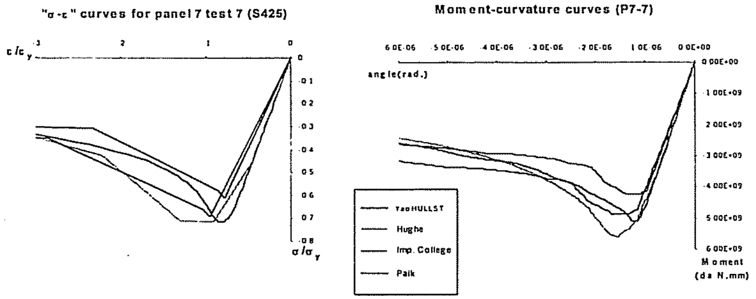

Figure 5: Moment-curvature relationships of a box-girder under longitudinal bending

The influence of "σ-ε" curve on ultimate bending moment is very significant and the shape of the "σ-ε" curve is often the most important factor: ultimate moment associated with *Hughes-Rahman* model is greater than the one from *Yao* model whereas ultimate stresses from each model are close. The excessive length of the plateau at ultimate strength in *Hughes-Rahman* model leads to an optimistic assessment of ultimate moment. The sensitivity analysis performed by ANAST (Rigo et al.) give more details about this remark.

4 CONCLUSIONS

In practice, it is very important to use well suited "σ-ε" model in order to assess with accuracy the ultimate bending moment of ships. But, most of the element models don't provide rational formulation for the post-collapse behaviour. For our purpose, it means that we can prefer a model with an explicit formulation for this post-collapse domain. To get a reliable and fast computing "σ-ε" model, an interesting way is to combine a good assessment of the ultimate stress from, for instance, *Imperial College* or *Hughes* models with an analytical post-collapse formulation as proposed by the *Adamchak* and *Rahman* models. Such mixed "σ-ε" relationship model is being developed in the IRCN's ultimate strength tool. However, this mixed model has to be calibrated with experimental results of actual stiffened panels. Particularly, this model must be able to represent the initial imperfections and to integrate the actual production's parameters of a specific shipyard (worker skill, welding type, etc…).

References

- Adamchak J.C. (1984). An Approximate Method for estimating the Collapse of a Ship's Hull in Preliminary Design. *Proc. Ship Structure Symposium' 84*, SNAME (Ed.), Arlington, US, 37-61.
- Beghin D., Jastrzebski T. and Taczala M. Result – a Computer Code for Evaluation of the Ultimate Longitudinal Strength of Hull Girder. *Proc. Int. Symp. PRADS'95*, Seoul, Korea, 832-834.
- Caldwell J.B. (1965). Ultimate Longitudinal Strength. *Trans. RINA* **107**, 411-430.
- Dow R.S., Hugill R.C., Clark J.D. and Smith C.S. (1981). Evaluation of Ultimate Ship Hull Strength. *Proc. Extreme Loads Response Symposium*, SNAME (Ed.), Arlington, US, 133-148.
- Dowling and al. (1991). Design of Flat Stiffened Plating: Phase 1 report. *CESLIC Report* **SP 9**, Dept. of Civil Engineering, Imperial College, London, UK
- Guedes Soares C. and Gordo J.M. (1997). Design Methods for Stiffened Plates Under Predominantly Uniaxial Compression. *Marine Structures* **10:6**, 465-497
- Gordo J.M. and Guedes Soares C. Approximate Method to Evaluate the Hull Girder Collapse Strength. *Marine Structures* **9:3-4**, 449-470.
- Hughes O.F. (1988). *Ship Structural Design*, SNAME, New Jersey, US
- Paik J.K. and Mansour A.E. (1995). A Simple Formulation for Predicting the Ultimate Strength of Ships, *Journal of Marine Science and Technology* **1**, 52-62.
- Paik J.K., Thayamballi A.K. and Che J.S. (1996). Ultimate Strength of Ship Hulls under Combined Vertical Bending, Horizontal Bending, and Shearing Forces. *Trans. SNAME* **104**, 31-59.
- Paik J.K. and Thayamballi A.K. (1997). An Empirical Formulation for Predicting the Ultimate Compressive Strength of Stiffened Panels. *Proc. 7th Int. Offshore and Polar Engineering Conf.*, Honolulu, USA, **4**, 328-338.
- Paik J.K. (1999). *SPINE, A Computer Program for Analysis of Elastic-plastic Large Deflection Behavior of Stiffened Panels by the Incremental Energy Method. User's Manual*, Pusan National University, Korea
- Rahman R.K. and Chowdhury M. (1996). Estimation of Ultimate Longitudinal Bending Moment of Ships and Box Girders. *Journal of Ship Research*, **40:3**, 244-257.
- Rigo P., Toderan C. and Yao T. (2001). Sensitivity Analysis on Ultimate Bending Moment. *Proc. 8th Int. Symp. PRADS*, Elsevier Science Ltd., Shanghai, China (to be published).
- Rutherford S.E. and Caldwell J.B. (1990). Ultimate Longitudinal Strength of Ships: A Case Study. *Trans. SNAME* **98**, 441-471.
- Smith C.S. (1977). Influence of Local Compressive Failure on Ultimate Longitudinal Strength of a Ship's Hull. *Proc. Int. Symp. PRADS'77*, Tokyo, Japan, 325-359.
- Ueda Y. and Rashed S.M.H. (1991). ISUM (Idealized Structural Unit Method) Applied to Marine Structures. *Trans. JWRI* **20:1**, 123-136.
- ULSAP (2000). *ALPS/ULSAP User's Manual*, Proteus Engineering, USA, 46p.
- Yao T. and Nikolov P.I. (1991). Progressive Collapse Analysis of a Ship's Hull under Longitudinal Bending. *J. Soc. Naval Arch. of Japan* **170**, 449-461. – (1992). 2nd Report, **172**, 437-446.
- Yao T. et al. (2000). Ultimate Hull Girder Strength: Report of Committee VI.2. *Proc. 14th International Ship and Offshore Structures Congress*, Ohtsubo H. and Sumi Y. (Eds.), Elsevier, **2**, 321-391.

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