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Integrating Structural Reliability Analysis with Advanced Structural Analysis

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Book of Abstracts

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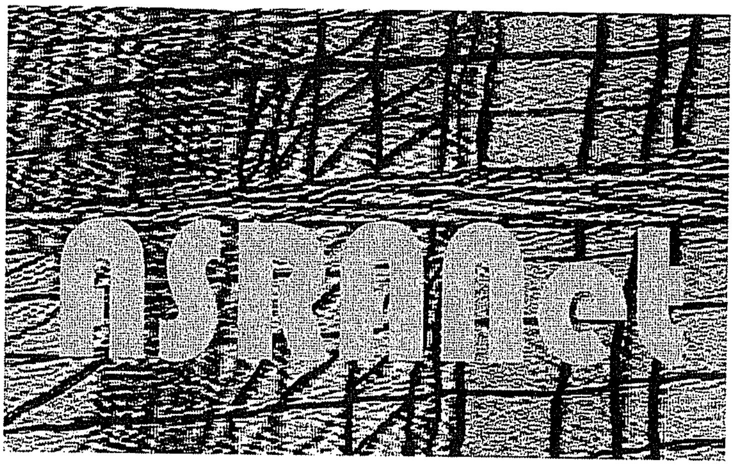

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ASRANet International Colloquium 8-10 July 2002

University of Glasgow, Scotland

Session 8 Effective use of ASA in practical applications [2]

Co-chairs: Dr P.A. Frieze, Mr T. Rhodes

- Toward A More Rational First-Principle-Based Strength Assessment System For Ship Structures, *Professor W Cui, Shanghai Jiaotong University, & W Yousheng, China Ship Scientific Research Centre, China*
- Sensitivity analysis on ultimate hull bending moment and multi-criteria comparative analysis of existing methods, *Ph. Rigo, C, Toderan, University of Liege, Belgium & T. Quesnel, Principia Marine, France*
- Application of response surface algorithms for estimating the reliability of dynamically loaded structures, *Dr Christine Dymiotis Heriot Watt University, UK,& G. Pringuay, Coflexip Stena Offshore, France*
- A note on response surface modelling in practical reliability analysis, *L. Yu , Lloyds Register of Shipping, UK, Professor P.K.Das, & Y. Zheng, Universities of Glasgow & Strathclyde, UK*
- Structural Reliability Assessment Of Computationally Intensive Problems - Non-Linear FEM Analysis, *Drahomír Novák, Radoslav Rusina, Miroslav Voøechovský, Brno University of Technology & Radomír Pukl, Vladimir Cervenka, Cervenka Consulting, Czech Republic*
- Probabilistic approach for the design of thin axisymmetric shells , *Nicolas Gayton & M. Lemaire, Laboratoire de recherche et applications en mecanique avancee, IFMA, France*
- Reliability analysis ship structures fatigue and ultimate strength, *Fabrice Jancart & Francois Benier, Principia Marine, France*
- Reliability Analysis Of The Ultimate Hull Girder Strength Of High Speed Craft, *Jonathan Downes & Dr Yongcheng Pu, University of Newcastle,UK*
- The Application of RSM in the System Resistance of Composite Bridge Based on Non-linear Analysis, *Dr Toula Onoufriou, G. Li, University of Surrey, & Dr Victoria Hogg, Highways Agency, UK*

Session 9 Reliability of deteriorating structures

Co-chairs: Professor J. Kanda, Dr V. Hogg

- A new corrosion model for the deterioration of steel structures in marine environments, *Professor W Cui, & S Qin, Shanghai Jiaotong University, China*
- Reliability of buried pipes, *A. Benmansour, Coheris, France & Z. Mrabet , University of Portsmouth, UK*
- Probabilistic remnant life assessment of corroding pipelines within a risk-based framework, *Dr Amin Muhammed, & JB Speck, TWI, UK*
- Probabilistic error estimation of shape changes during fatigue crack growth, *T. D. Righiniotis, University of Surrey, UK*
- Integration of deterioration modelling with reliability assessment for reinforced concrete structures, *Professor Marios K Chryssanthopoulos, University of Surrey, UK & Dr. G Sterritt, W.S. Atkins, UK*
- Reliability based whole life behaviour assessment of corrosion-affected concrete structures, *W. Lawanwisut, & C Q Li, University of Dundee, UK*

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SENSITIVITY ANALYSIS ON ULTIMATE HULL BENDING MOMENT AND MULTI-CRITERIA COMPARATIVE ANALYSIS OF EXISTING METHODS

Ph. Rigo [1], C. Toderan [1] and T. Quesnel [2]

[1] Department of Naval Architecture (ANAST), University of Liege,
Chemin des Chevreuils n°1 (B52/3), B-4000 Liege, Belgium
[2] Principia Marine,
1 rue de la Noë, BP 72108, 44321 Nantes Cedex 3, France

ABSTRACT

The authors performed an assessment of the sensitivity of the "average strain-average stress curves (σ–ε)" on the ultimate hull bending moment (Mu) and the moment-curvature relationship (Mu-ϕ). This assessment concerns the ultimate bending moments obtained through standard progressive collapse analysis (Smith Algorithm).
As this analysis has shown that the main factor to assess the ultimate bending moment of a hull girder is the quality of the "σ-ε" curves, the authors performed an extensive comparison on 18 different methods providing the ultimate compressive strength and the average "σ-ε" relationship of longitudinally stiffened panels. Extended and updated results are available in this paper.

KEYWORDS

Ultimate strength, stiffened panels, strain and stress curve, ultimate bending moment, hull girder, progressive collapse analysis, sensitivity analysis, multi-criteria analysis.

INTRODUCTION

Simulation of the collapse behaviour is an essential issue in assessing the safety of marine structures. An accurate estimate of the maximum load-carrying capacity (ultimate strength) is required to determine the maximum load that the structure can survive. Conventional Finite Element Analysis is too time consuming for elasto-plastic large deflection analysis of such structures (ships, offshore). Many simplified methods for collapse analysis were developed in the recent years, but all of them are limited in their applicability. A comparative analysis of these methods is presented here after that provides useful information to researchers and designers.

1. A GENERIC FRAMEWORK FOR PROGRESSIVE COLLAPSE ANALYSIS

Usually progressive collapse analysis to evaluate the ultimate bending moment of hull girder is achieved in 3 steps and each step is characterised by a numerical model associated to theoretical assumptions. For each model, it is necessary to specify the assumptions and to assess their influence (sensitivity) on the result (ultimate bending moment of hull girder). This is particularly relevant as the paper's aim is to assess the sensitivity of the "σ–ε" curves on the ultimate bending moment (Mu).

At the beginning of a "Progressive Collapse Analysis" (PCA) the "*raw data*" are the same for each model/user and they concern:

- the scantling (plates, stiffeners, ..) of the mid-ship section and the frame spacing,
- the initial imperfections (plate deflection, stiffener deflection and residual stress).,
- the lateral loadings (if considered by the "σ–ε" element model)

The 3 main steps of a complete "Progressive Collapse Analysis" (PCA) are the following:

STEP 1: Modelling (to decompose the structure in elements and to build the mesh model),

STEP 2: Evaluate the "$\sigma-\varepsilon$" element curve. This requires a stress-strain model called "STR" model.

- STEP 2.1: Assessment of the "σ_u" compressive ultimate strength of each element. This requires to survey all the failure modes (plate and stiffener induced buckling, tripping, yielding and local instabilities) and to model of the initial imperfections and boundary conditions.
- STEP 2.2: Definition of the "shape" of the "$\sigma-\varepsilon$" curves, particularly in the "post-critical behaviour" region.

NB: Steps 2.1 and 2.2 can be performed together in the same routine (e.g.: HULLST, Yao and Nikolov, 1991) or independently (e.g.: Rahman and Chowdhury, 1996).

STEP 3: Perform the Progressive Collapse Analysis (using a "PCA" model that includes an incremental procedure of the curvature).

In order to choose a method to evaluate the ultimate strength of a hull girder, a designer have in fact to select 2 models, one for STEP 2 (the "STR" element model) and one for STEP 3 (the "PCA" model). Sensitivity of both has to be evaluated.

1.1 Sensitivity of the PCA model (STEP 1 & STEP 3) on the ultimate bending moment

The accuracy and reliability of a progressive collapse analysis are strongly influenced by the mesh model "*quality*" (STEP 1). In fact, the mesh model of the considered structure (STEP 1) depends on the considered PCA model and the available elements: plates, stiffeners, stiffened plates, stiffened panels, curved elements, hard corners, etc. In short, we can say that a PCA model is "better" than another if the mesh model of the structure requires less simplifications/assumptions. For instance, the simplified Rahman progressive collapse model (*Rahman et al. 1996*) has the same background as the sophisticated HULLST model (*Yao, 1999*) but is less accurate as it requires a simplified modelling. Most of the available PCA models are based on the model of C. Smith (1977). Only the quality of the numerical procedure can generate some differences between the different PCA models.

1.2 Assessment of the sensitivity of the shape of the "$\sigma-\varepsilon$" curve (same "σ_u")

To provide reliable information to select a relevant "STR" model (STEP 2), it is necessary to assess separately the sensitivity of STEP 2 on the ultimate bending moment. This job was initiated by P. Rigo and the ISSC'2000 Committee VI.2 through a series of analysis that quantify the sensitivity of the "$\sigma-\varepsilon$" curves on the ultimate bending moment (*Rigo et al. 2001*). To achieve this goal, the ultimate bending moment of 3 ships studied by the ISSC Committee were re-evaluated with different STR models (STEP 2) but with the same PCA model (STEP 1 and STEP 3) using the PROCOL software. PROCOL links the Yao's Progressive Collapse Analysis Model (PCA) with several STR models developed by different authors (*Paik et al. 1997; Rahman et al. 1996; Dowling 1991; Yao and Nikolov 1991*). For each ship an identical mesh model is used, including 105 elements for the VLCC, 90 elements for Energy Concentration and 99 for the Container. Only the stress-strain curves differ. All the relevant data are available in Yao et al. (2000).

In addition to these rationally based "$\sigma-\varepsilon$" curves (HULLST, Rahman-Hughes, etc.), five simplified "$\sigma-\varepsilon$" curves are considered (see Figure 1, Shape 1 to Shape 5). These simplified curves are built by PROCOL and are composed of a perfect elastic deflection, a plastic deflection (*ultimate strength's plateau)* and a linear post-collapse deflection. All consider a buckling effect and have the same "σ_u" compressive ultimate strength. They only differ by the shape of their post-collapse residual strength:

Shape 1: no residual strength after ultimate strength,
Shape 2: a sharp reduction of the residual strength and no ultimate strength's plateau,
Shape 3: a smooth reduction of the residual strength and no ultimate strength's plateau,
Shape 4: a smooth reduction of the residual strength and a long ultimate strength's plateau,
Shape 5: no reduction of the strength after the ultimate strength.

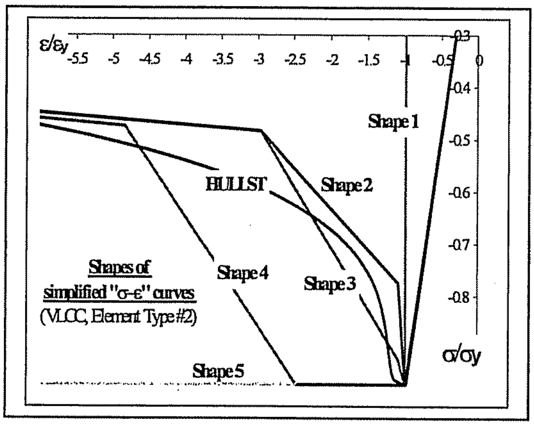

Figure 1: Shapes of the simplified "σ–ε" element curves (with same σ_u) for the sensitivity analysis of the shape of "σ–ε" curve (STEP 2.2).

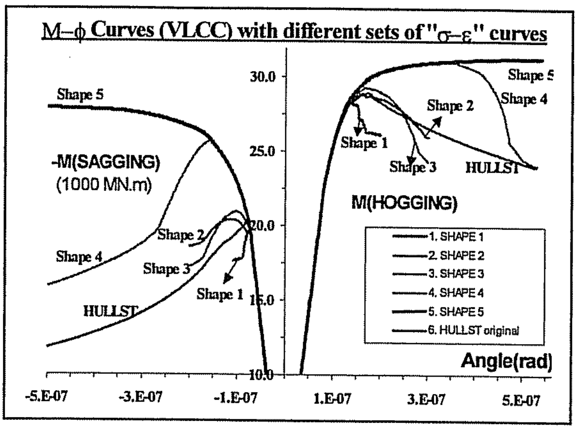

Figure 2: Moment-curvature relationships (VLCC) with different "σ–ε" curves
(same mesh model, same "σ_u" element ultimate strength and same PCA model).
Sensitivity analysis of the shape of "σ–ε" curve

Table 1: Sensitivity of the shape of the "σ–ε" curves [step 2.2] on the ultimate bending moment of hull girders (VLCC; Energy Concentration and Container Ship)
(Same mesh model [step 1]; same element ultimate strength [σ; step 2.1] and same PCA model [step 3])

SAGGING	VLCC (see Figure 4) 105 elements		ENERGY CONCENTRATION 90 elements		CONTAINER 99 elements	
"σ–ε" Curve Shape (same σ_U, ε_U)	Mu 1000 MN.m	Mu/M(ref)	Mu 1000	Mu/M(ref)	Mu 1000	Mu/M(ref)
M(ref) (HULLST)	20.42		16.84		6.72	
Shape 1	19.64	0.962	16.27	0.966	5.77	0.859
Shape 2	20.38	0.998	16.28	0.967	5.89	0.876
Shape 3	20.94	1.025	16.43	0.976	6.08	0.905
Shape 4	25.65	1.256	18.91	1.123	7.15	1.064
Shape 5	27.91	1.367	19.39	1.151	7.35	1.094
Mean Variation =		13.77%		7.32%		10.35%

M(ref) = Ultimate bending moment obtained with the HULLST software

HOGGING	VLCC (see Figure 4) 105 elements		ENERGY CONCENTRATION 90 elements		CONTAINER 99 elements	
"σ–ε" Curve Shape (same σ_U, ε_U)	Mu 1000 MN.m	Mu/M(ref)	Mu 1000 MN.m	Mu/M(av)	Mu 1000 MN.m	Mu/M(av)
M(ref) (HULLST)	28.88		19.03		6.72	
Shape 1	28.25	0.978	18.49	0.972	5.95	0885
Shape 2	28.89	1.000	18.49	0.972	6.27	0.932
Shape 3	29.29	1.014	18.69	0.982	6.50	0.967
Shape 4	31.03	1.074	19.87	1.044	7.06	1.050
Shape 5	31.26	1.082	20.41	1.072	7.11	1.058
Mean Variation =		3.86%		3.82%		6.46%

As 5 different standard shapes are considered (see Figure 1), 5 sets of "σ–ε" curves are defined. Then, the sensitivity of the "shape" of the "σ–ε" curves on the (Mu) ultimate bending moment (see Table 1) are evaluated by using the 5 sets of "σ–ε" curves in the PROCOL model. Table 1 shows that the shape sensitivity on (Mu) is higher for sagging than hogging (twice). Between *shape 1* (no post collapse strength) and *shape 5* (perfect elasto-plastic strength) the average variation is about 25% in sagging and 12% in hogging. Comparison between *shape 3* and *shape 4* shows that the length of the "*ultimate strength's plateau*" is the more sensitive parameter.

An overestimation of the length of the *plateau* (shape 4) increases the ultimate bending moment of 10 to 20 %. On the other hand, shape 2, which has no plateau, provides more conventional results (i.e. close to the reference value). With shape 2, Mu seems accurate for the VLCC, is underestimated by 3% for Energy Concentration and about 7% for the container. However, it should be noticed that the actual length of the *plateau* depends on the scantlings of the panel and the stiffeners.

Figure 2 shows the (M-ϕ) moment-curvature relationships obtained for the VLCC with 5 different sets of "σ–ε" curves (simplified shapes) and the HULLST's set of curves (same mesh model, same "σ_u" element ultimate strength and same PCA algorithm). Sensitivity analysis on the ultimate bending moment with respect to various factors (plate and stiffener thickness', yield stress, residual stress, initial deflections and frame spacing) is included in *Yao et al.* (2000).

2. MULTI-CRITERIA ANALYSIS ON DIFFERENT EXISTING METHODS

The sensitivity analysis has shown that the main factor to assess the ultimate bending moment of a hull girder is the quality of component behaviour ("σ-ε" curve). Conventional Finite Element Analysis could provide an accurate simulation of "σ-ε" curve for a beam-column element. Unfortunately, such elasto-plastic large deflection analysis including initial imperfections and lateral loads is impossible to implement in the current activity of shipyards. Our goal is not to implement a high sophisticated approach asking for long and time-consuming numerical analysis but a method that 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 are able to evaluate the behaviour before and after collapse ("σ-ε" curve). These ones are the most relevant for our purpose.

In a first stage, all models have been considered in order 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 2. A method can be either an original method or a regrouping of very closed formulations proposed by different authors. To perform this comparative review, criteria with associated weighting are used (see Table 3). All the methods have been ranked twice.

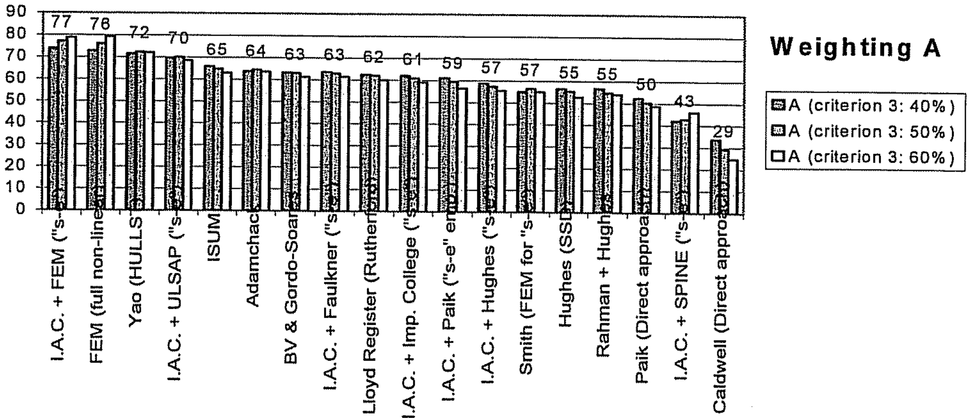

Figure 3 : Classification of Methods with weighting A

The first selection was performed with weighting A, "σ-ε" model quality and facility of use being the main criteria. 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 3). For instance, Figure 3 shows results for weighting A.

TABLE 2: 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	(Rahman 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)

TABLE 3: 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

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 (as SPINE is only recommended for unstiffened plate). Moreover, the full FEM non-linear analysis does not suit for our purpose (too time-consuming 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.

<u>2.1 Direct comparison of "σ-ε" elements models</u>

Ten test panels were defined to compare the 8 remaining methods. Geometry of these 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 (σ_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 analyses were carried out. We can notice that standard 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. Theirs column slenderness' are much smaller than the standard values for which most of the available formulations have been established and validated.

The first decisive factor in quality of "σ-ε" model is **the value of the ultimate stress (σ_u)** associated to the critical collapse mode. We have considered *FEM*'s results as valuable reference unless when 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. 4). A synthesis of the comparison of the various "σ-ε" models is presented in Fig.5. As we can see, *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. 6.

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 smooth strength decay in post-collapse. Formulations of *Hughes-Rahman (as extended by Rahman for post-collapse)* and *Adamchak* 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.

TABLE 4 : 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)

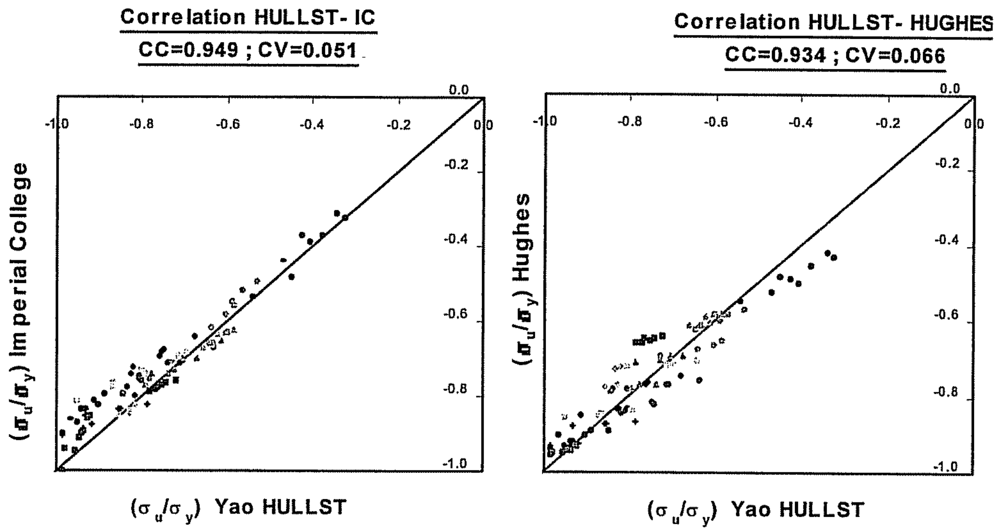

FIGURE 4: Correlation of ultimate stress for all test panels

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 that only depends 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.

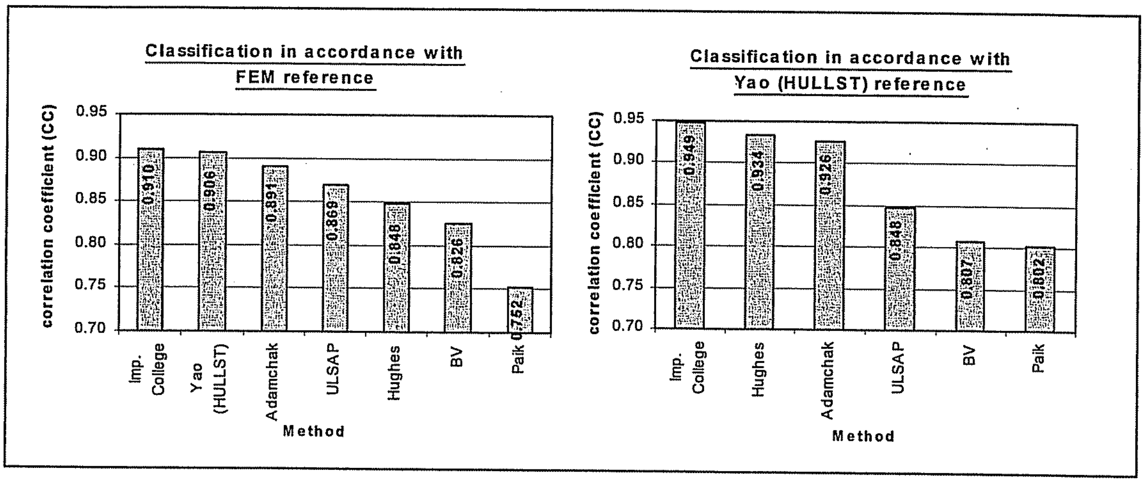

FIGURE 5: Synthesis of ultimate stress comparison

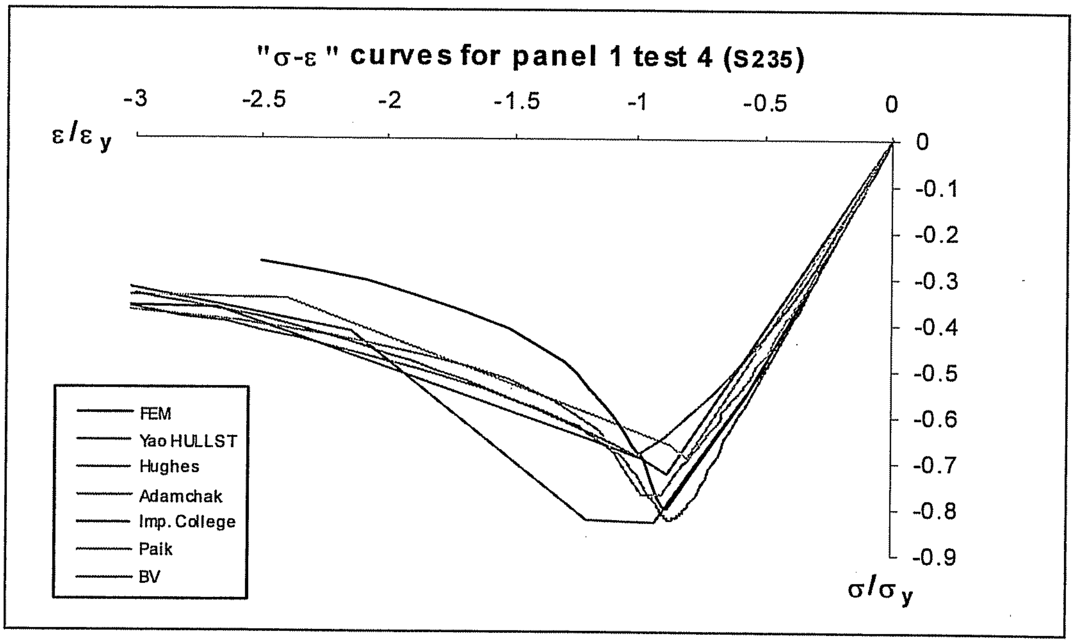

FIGURE 6: "σ-ε" curves of panel behaviour with 7 different models

2.2 Comparison on simple box girders

Model uncertainties related to Progressive Collapse Analysis of hull girder do not only depend on the component behaviour model (STR model) but also the incremental algorithm. 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, the previous component's "σ-ε" curves were re-used to assess ultimate bending moment of a symmetrical box girder (square of 6 stiffeners with associated plate on each side) using the same incremental algorithm of curvature. Fig. 7 shows moment-curvature curves associated with "σ-ε" element curves.

It is observed that 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 the component's ultimate stresses for the different models 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 and al.) give more details about this remark.

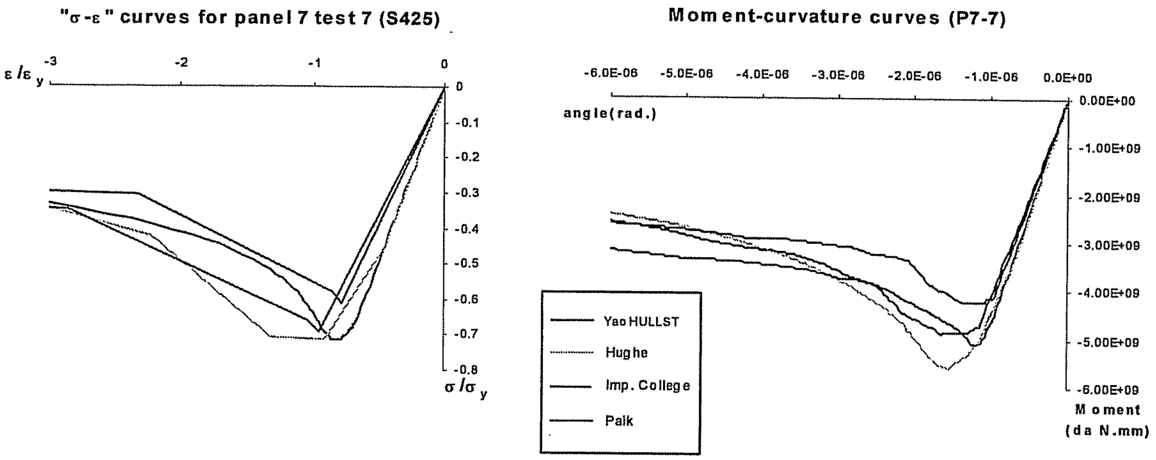

FIGURE 7: Moment-curvature relationships of a box-girder under longitudinal bending

3. CONCLUSIONS

Different "σ–ε" models have been used with the same (PCA) progressive collapse analysis model and using the same structure mesh model. The presented results assess the sensitivity of the "σ–ε" curves on the (Mu) ultimate bending moment. Sensitivity of the shape of the "σ–ε" curves has also been performed. The results show that the main significant factor in the complete procedure of evaluation of the ultimate bending moment is the evaluation of the "σ_u" ultimate compressive strength of the elements/components (σ_u). Moreover the results show that the "shape" is not negligible and particularly the length of the *ultimate strength's plateau.*

A set of simplified published methods was selected and tested in order to choose an alternative model for FEM elasto-plastic large deflection analysis, which is too time-consuming and impossible to implement in practice. 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...). These parameters are easiest to update if an explicit formulation for the post-collapse domain is used. 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-Rahman* models (best correlation with FEM) with an analytical post-collapse formulation as proposed by the *Adamchak* and *Rahman* models. However, this mixed model has to be calibrated with experimental results of actual stiffened panels.

Paik et al (2000) have established a new analytic and rational approach to assess panel ultimate strength. As this method looks very promising it should be worthwhile if the authors could also propose the associated "σ–ε" curve to fit their approach with a rational simplified progressive collapse analysis similar to the Yao's approach (HULLST).

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