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ISSN 0007-215X
eISSN 1845-5859

IACS INCREMENTAL - ITERATIVE METHOD IN PROGRESSIVE COLLAPSE ANALYSIS OF VARIOUS HULL GIRDER STRUCTURES

UDC 629.5.021
Review paper

Summary

Intended purpose of the paper is to compare results obtained by a different existing ultimate bending capacity assessment methods for different hull girder structures, with particular emphasis on the results obtained by the subgroup of methods comprised of the various incremental-iterative progressive collapse analysis methods based on the Smith's approach. Within this subgroup of methods, additional consideration is given to the results obtained by different implementations of the same method prescribed by the International Association of Classification Societies (IACS) Common Structural Rules (CSR), since this method is incorporated into the OCTOPUS computer program, developed at the Faculty of Mechanical Engineering and Naval Architecture (University of Zagreb). Various characteristics and capabilities of the implemented IACS CSR incremental-iterative progressive collapse analysis method are considered on the example of the hull girder structure of the chemical tanker, along with the comparison of the results obtained by the nonlinear finite element method.

Key words: *Hull girder ultimate strength, longitudinal ultimate load-capacity, progressive collapse analysis, Smith's method.*

1. Introduction

Contemporary methods for determination of the ultimate load-capacity of the ship structures are based on explicit evaluation of their ultimate limit state. Flexural load resistance capability is of predominant importance in ultimate limit state design and analysis of many types of ship structures. Consequently, ultimate limit state could be considered as synonymous to structural collapse induced by the progressive decrease in the load-capacity of the structural members when imposed with the effects of the extreme global bending loads.

The most accurate results in this respect can be obtained by utilization of the nonlinear finite element analysis (NLFEA), yet at the same time, significant amount of time, knowledge and experience is still required for the successful completion of all phases of the NLFEA. Furthermore, NLFEA results depend significantly on propriety of the employed structural description and idealization techniques (geometrical and material properties) and boundary conditions (loads and displacement constraints). Although consideration of the complete structural model is always recommendable, available computing and pre/post-processing timeframe often necessitates resortion to the partial structural models, where sensitivity of results to idealization of the realistic boundary conditions is even more pronounced. Finally, the effect of all relevant initial structural imperfections should also be accounted for appropriately, since they can have considerable influence on the calculated ultimate load-capacity. Hence, demand for sufficiently accurate and fast alternative analysis methods arises.

Among the number of contemporary alternative methods, various incremental-iterative progressive collapse analysis method based on Smith's approach [1] are arguably the most commonly used, since rules of many classification societies prescribe utilization of the incremental-iterative procedures based on Smith's approach for evaluation of the longitudinal ultimate load-capacity of ship structures.

Intention of the present study is to compare the results obtained by the different existing ultimate bending capacity assessment methods for various hull girder structures, with particular emphasis on the results obtained by the subgroup of methods comprised of various incremental-iterative progressive collapse analysis methods based on the Smith's approach. Within this subgroup of methods, additional consideration is given to results obtained by different implementations of the same method prescribed by the IACS Common Structural Rules (CSR) [2-3], since this method is incorporated into the LUSA module of the OCTOPUS [4] computer program, employed by the coauthors. Overview of the different existing methods for the hull girder ultimate load-capacity calculation can be found in [5-8].

2. Models of considered hull girder structures

Various hull girder structures considered by benchmarking study presented within Section 3 of the present paper are:

- Container ship (marked as model M1).
- Bulk carrier (marked as model M2).
- Suezmax class double hull oil tanker (marked as model M3).
- Double hull VLCC oil tanker (marked as model M4).
- Single hull VLCC oil tanker (marked as model M5).

Examined structures belong to the standard set of the ISSC benchmark examples and all relevant data regarding their material and geometric properties is given in [7, 8]. Figures 1 to 5 illustrate one-bay structural models of all considered structures. Structural model definition, essential for all ultimate bending capacity calculations performed by the coauthors for the purposes of the present paper is done using the MAESTRO [11] computer program. Inherent capabilities and accuracy of the IACS CSR incremental-iterative progressive collapse analysis method discussed within the Section 4 of the present paper are demonstrated using the example of the hull girder structure of the 40 000 DWT ocean going chemical tanker, which represents one of three specific products considered within the scope of the FP6 STREP project IMPROVE [9]. The main particulars of the vessel are as follows:

Length overall:	182.88 m;
Length between perpendiculars:	175.25 m;
Beam molded:	32.20 m;
Depth to main deck:	15.00 m;
Scantling Draught:	11.10 m;
Cargo tanks capacity (total):	44 000 m^3.

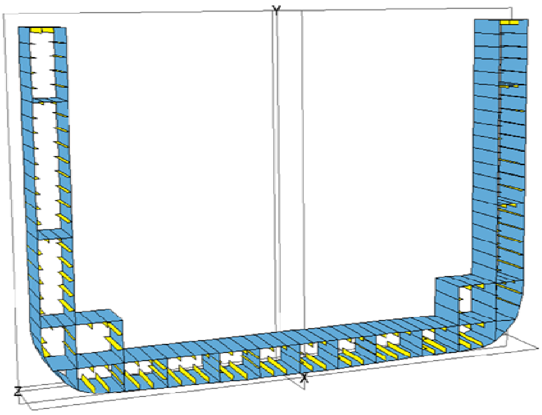

Fig. 1 One-bay model of the container ship midship section structure (model M1)

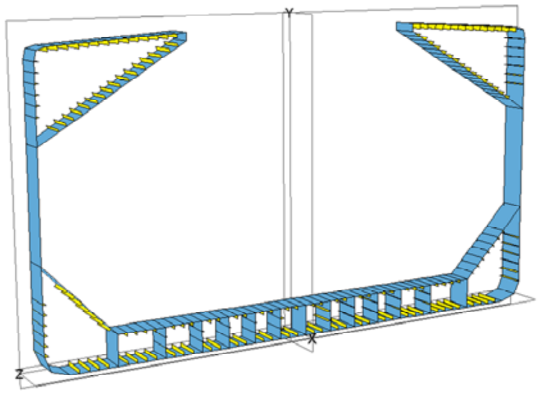

Fig. 2 One-bay model of the bulk carrier midship section structure (model M2)

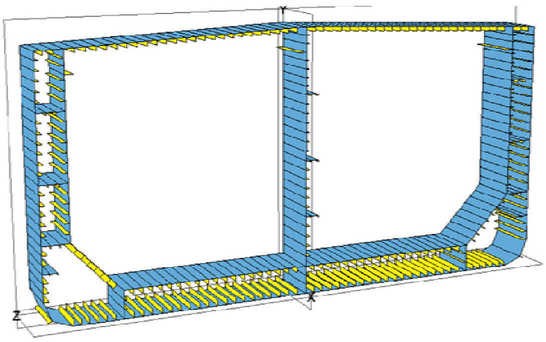

Fig. 3 One-bay model of the Suezmax class double hull oil tanker midship section structure (model M3)

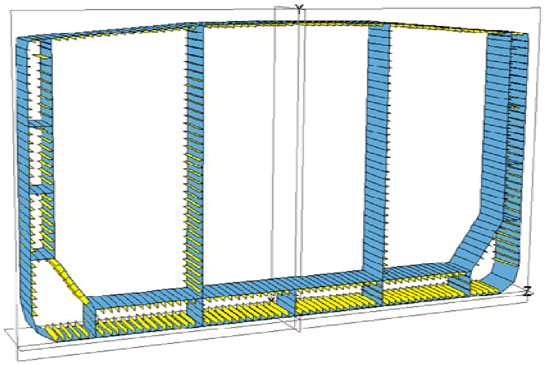

Fig. 4 One-bay model of the double hull VLCC midship section structure (model M4)

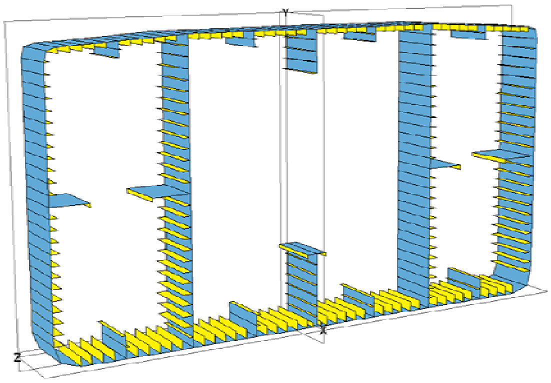

Fig. 5 One-bay model of the single hull VLCC oil tanker midship section structure (model M5)

Structural dimensions and stiffener scantlings used for modeling are given by Figure 6, while relevant properties of the used materials are specified by Table 1. Material distribution and used one-bay model (marked as model M6) of the ship's midship section is depicted by the Figure 7.

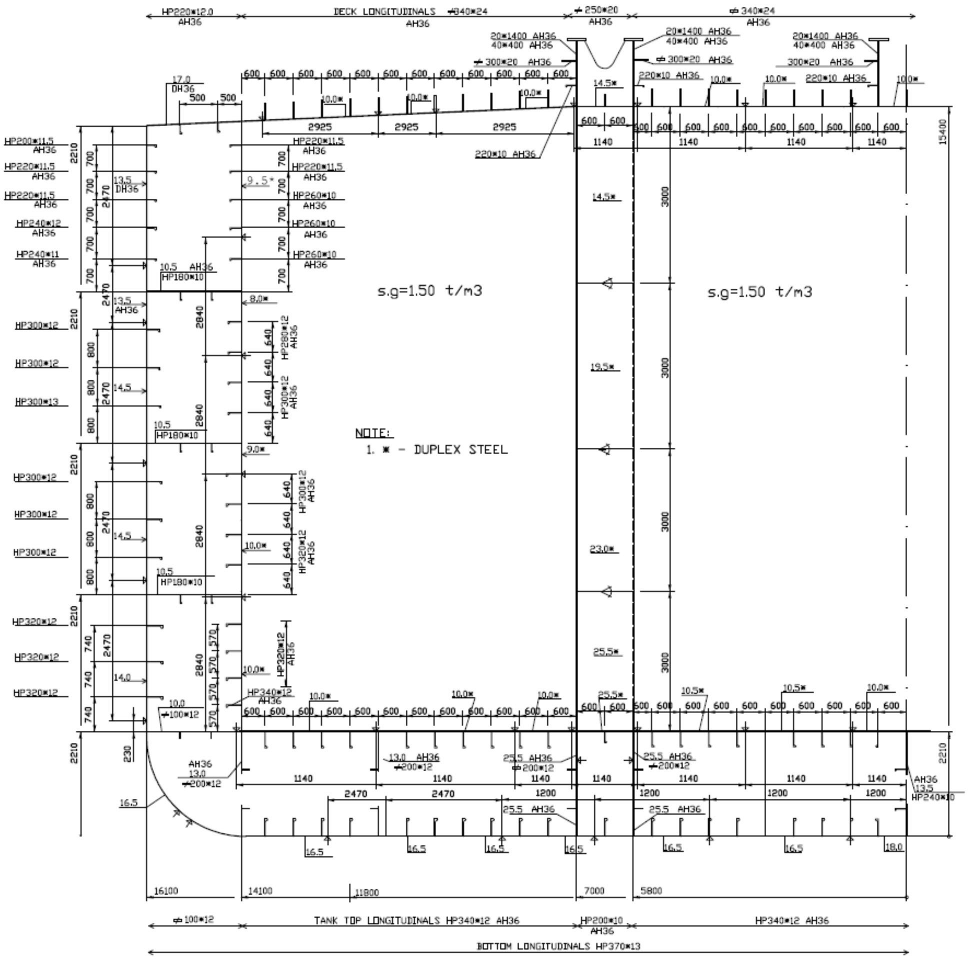

Fig. 6 Drawing of the chemical tanker midship section [10]

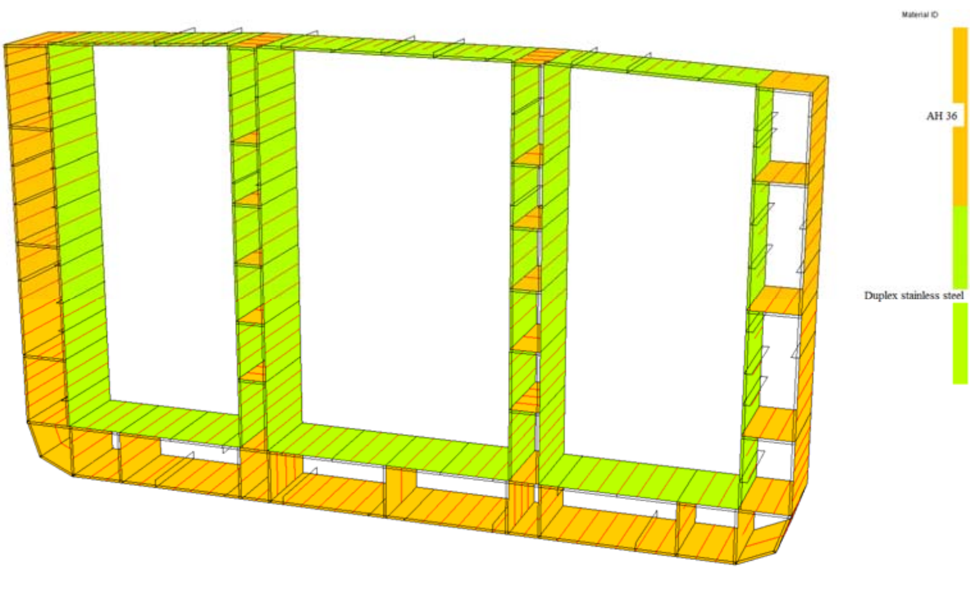

Fig. 7 One-bay model and material distribution of the chemical tanker midship section structure (model M6)

Table 1 Structural material properties of chemical tanker midship section

Material property	High tensile steel	Stainless steel
Youngs modulus (N/mm^2)	210 000	210 000
Poisson ratio (-)	0.3	0.3
Yield stress (N/mm^2)	355	455

Two different materials were used for structural modeling, namely: high tensile steel (AH36) and duplex stainless steel. Duplex stainless steel is used only for the cargo tank plating (inner plating of the double sides and double bottom, cofferdam plating and strength deck plating), while high tensile steel is used for the rest of the structure. Stainless steel, in general, has significant advantages by requiring lesser maintenance and avoiding larger corrosion problems, but it also has a disadvantage in a much higher cost compared to the standard shipbuilding steel. Duplex stainless steel, which is austenitic-ferrite stainless steel, has greater overall corrosion resistance and higher strength then the austenitic grads. The greater strength of the duplex stainless steel as compared to austenitic grades also permits a reduction in scantlings which can result in reduced steel weight and increased cargo capacity.

Span of the considered one-bay model is 3560 mm, while unsupported lengths of the transversely stiffened and cross stiffened panels of the cofferdam are: 890 mm (for panels below the height of 5100 mm) and 1780 mm (for panels above the height of 5100 mm).

For the purpose of NLFEA, a prismatic multi-hold model was produced by MEC, Talin, Estonia [10]. Four node shell elements and two node beam elements are used for discretization. Plating, transverse frames and longitudinal girders are modeled using shell elements only, while longitudinal stiffeners are modeled by combination of the shell elements for stiffener web and beam elements for stiffener flange. Plate between longitudinal stiffeners is meshed with 4 elements in transverse direction and 16 elements in longitudinal direction. Webs of the transverse and longitudinal framing are meshed with 4 elements in the web height direction, while flanges have 2 elements in the flange breadth direction. Longitudinal stiffeners have 1 element in the web height direction. The model is comprised of 1 420 000 elements (1 270 000 shell elements and 150 000 beam elements) and 1 580 000 nodes. The typical element size in a plate field is around 127x220 mm. Since the analyzed structure is symmetric with respect to the center line, a partial (half-breadth) model is used. Therefore, symmetric boundary conditions at all nodes of the symmetry plane are imposed. Vertical and longitudinal nodal displacements are constrained along the bottom support line at one of the structural ends, while only vertical nodal displacements are constrained along the bottom support line at the opposite structural end. The longitudinally distributed hull girder load is applied as a pressure on the ship's bottom with the gradually increasing amplitude of the (constant) load shape, which is determined according to the realistic loading conditions. More detailed data regarding various relevant aspects of finite element modeling and analysis (performed using the LS-DYNA computer program) of the multi-hold hull girder model of the chemical tanker is given in [10].

3. Comparison of results obtained by various analysis methods

Comparison of results for both considered hull girder ultimate bending moments (hogg and sagg) is given in Table 2. Table 2 includes results of analyses performed by the different authors employing various methods, which are consolidated and published in [7, 8]. This data is further extended with results of calculations performed by coauthors of the present study using an IACS CSR incremental-iterative progressive collapse analysis method, marked as method 14-CSR(FSB). For each model (M1 to M5) and type of imposed bending load (hogg or sagg) mean value, standard deviation and coefficient of variation (COV) is calculated for the three groups of the considered methods (see Table 2):

- All methods included (except method 6).
- Methods based on the Smith's approach (methods 7 to 14).
- IACS CSR method, as a subgroup of methods based on the Smith's approach (methods 7, 8 and 14).

Results obtained by method 6, marked as CSR(BV) in Table 2, are excluded from calculations of all statistical measures (mean, standard deviation, coefficient of variation), since significant difference (much lower values) is notable with respect to results of other IACS CSR method implementations. Coauthors speculate that corrosion reduction requested by CSR (0.5 t_{corr}) for the hull girder ultimate strength calculation was considered in performed analyses, which renders obtained results as incomparable with all other results.

Table 2 Summary of hull girder ultimate bending moment results for all methods (1÷14) and models (M1÷M5)

Method	Conteiner ship-M1		Bulk carrier-M2		Tanker Suezmax double hull-M3		Tanker VLCC-double hull-M4		Tanker VLCC-single hull-M5	
	HOGG	SAGG	HOGG	SAGG	HOGG	SAGG	HOGG	SAGG	HOGG	SAGG
	Muh (GNm)	Mus (GNm)	Muh (GNm)	Mus (GNm)	Muh (GNm)	Mus (GNm)	Muh (GNm)	Mus (GNm)	Muh (GNm)	Mus (GNm)
1-ANSYS (PNU)	6.969	6.951	17.5	15.8	14.066	11.151	27.335	22.495	17.355	16.179
2-ANSYS (ISR)	7.49	7.176	18.326	17.726	/	/	30.106	28.175	21.2	20.21
3-ABACUS (CR)	7.664	7.631	18.396	16.855	16.16	14.258	31.006	24.995	21.86	20.625
4-ALPS/HULL (PNU)	6.916	6.635	16.602	15.38	13.308	11.097	25.594	21.967	17.335	17.263
5-Modified P-M(PNU)	6.4	7.077	16.576	14.798	13.965	12.213	25.667	22.39	18.701	17.825
6-CSR(BV)	6.476	6.068	14.822	11.521	/	/	23.431	17.941	17.5	16.029
7-CSR(CR)	7.879	7.589	18.338	14.921	19.045	14.605	29.847	25.014	20.708	18.593
8-CSR(PNU)	7.758	6.851	18.36	14.5	15.714	12.42	28.423	22.13	20.102	18.712
9-RINA Rules (UoG)	6.859	5.898	17.482	13.952	/	/	28.202	21.696	19.836	18.468
10-Rigo(1)-Smith-(ISSC 2000)	7.6	6.513	18.714	14.34	/	/	28.312	19.573	18.46	17.9
11-Cho-Smith-(ISSC 2000)	6.69	5.13	18.99	13.69	/	/	26.66	20.8	20.09	16.75
12-Soares-Smith(ISSC 2000)	7.75	6.68	17.43	13.72	/	/	27.61	19.85	18.79	15.83
13-Yao-Smith-(ISSC 2000)	6.72	6.72	17.36	14.45	/	/	28.88	20.42	19.03	16.84
14-CSR(FSB)	**7.578**	**6.821**	**17.866**	**14.19**	**15.791**	**12.447**	**28.43**	**21.16**	**19.41**	**18.302**
Mean-All methods*	7.252	6.744	17.842	14.948	15.436	12.599	28.159	22.359	19.452	17.961
Stand.dev.-All methods*	0.502	0.661	0.760	1.217	1.929	1.374	1.619	2.418	1.368	1.427
COV-1-All methods*	**0.069**	**0.098**	**0.043**	**0.081**	**0.125**	**0.109**	**0.057**	**0.108**	**0.070**	**0.079**
Mean-Smith based*	7.354	6.525	18.068	14.220			28.296	21.330	19.553	17.674
Stand.dev.-Smith based*	0.506	0.730	0.623	0.421			0.921	1.722	0.763	1.066
COV-2-Smith based*	**0.069**	**0.112**	**0.034**	**0.030**			**0.033**	**0.081**	**0.039**	**0.060**
Mean-CSR based*	7.738	7.087	18.188	14.537	16.850	13.157	28.900	22.768	20.073	18.536
Stand.dev.-CSR based*	0.151	0.435	0.279	0.367	1.901	1.254	0.820	2.005	0.649	0.211
COV-3-CSR based*	**0.020**	**0.061**	**0.015**	**0.025**	**0.113**	**0.095**	**0.028**	**0.088**	**0.032**	**0.011**

* NOTE: Results obtained by method 6 (CSR-BV) were not considered for calculation of mean values, standard deviations and coefficient of variations (COV).

Coefficient of variation (COV) calculated for all methods is given in Figure 8 and varies between 0.043 and 0.125. Average COV calculated for the considered groups of methods is as follows:

- All methods included (except method 6): COV-1 $_{average}$= 0.084.
- Methods based on the Smith's approach: COV-2 $_{average}$= 0.057.
- IACS Common Structural Rules (CSR) method: COV-3 $_{average}$= 0.049.

In accordance with expectations, trend of the decreasing calculated COV value can be noted as similarity of the considered types of methods increases. Additionally, small discrepancies among results obtained by various methods based on the Smith's approach (different formulations of the load – end shortening curves) and within the subgroup of various implementations of the IACS CSR method (same formulations of load – end shortening curves) can also be noted. Although standardization of the modeling principle and identical formulation of the employed load – end shortening curves results with the smaller differences among results, foul influence of the human factor (e.g. software encoding, structural model definition/idealization, etc.) is obviously present, since for the exactly determined and prescribed IACS CSR procedure differences in obtained results might be observed (COV-3 $_{average}$= 0.049). For some models, such as M2 and M5, COVs calculated for various implementations of IACS CSR method are pretty low (about 0.02), while for the model M3 average COV is about 0.1, which is unexpectedly high.

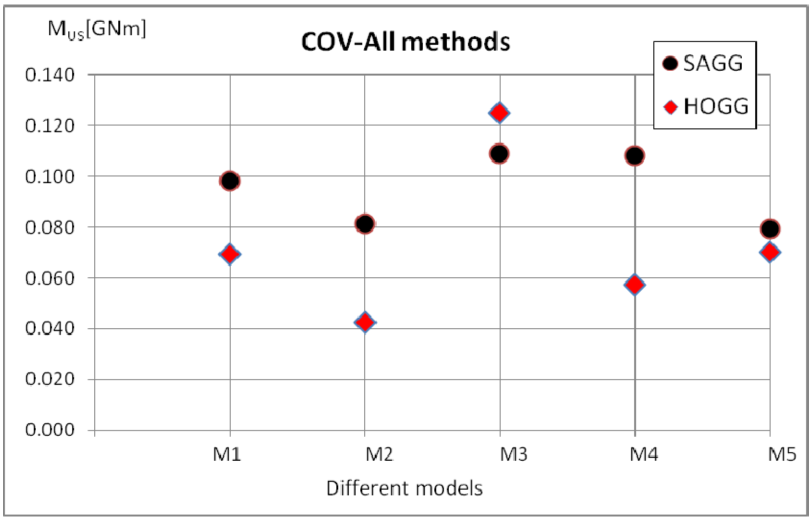

Fig. 8 COVs of all methods for ultimate bending moments calculation in hogging/sagging for different models (M1-M5)

Comparison of ultimate bending moment values obtained by all considered methods (including method 6) for all considered models (M1 to M5) with respect to overall mean values are presented in Figure 9. Differences among calculated ultimate bending moments are much higher for double hull tankers and bulk carrier than for container ship and single hull tanker. It can be observed that implementation of the IACS CSR method used by coauthors very closely follows overall mean value for all examined models (differences less than 5%).

For all examined models detailed analysis of the collapse sequence for both hogging and sagging cases was performed [12], as exemplified by Figures 11 and 12. In accordance with expectations, obtained ultimate bending moment values are higher for hogging than sagging for all models (see Figure 9) and deck always represents (critical) portion of the hull girder structure which collapses first, even for hogging.

4. Inherent capabilities and accuracy of IACS CSR incremental-iterative progressive collapse analysis method

Since structural bending load-capacity has predominant significance in ultimate limit state design and analysis of many ship structures, ultimate bending load-capacity (ultimate bending moment) can be considered as one of the most important global safety measures in concept design of various ship structures. Hence, various inherent capabilities of the IACS CSR incremental-iterative progressive collapse method, relevant within context of the concept ship structural design, are discussed within this section. Furthermore, accuracy of the method is demonstrated by the direct comparison of the results obtained by the IACS method employing one-bay model of the considered hull girder main frame (model M6) with results of the NLFEA of the discretized multi-hold model of the ship's hull girder [10].

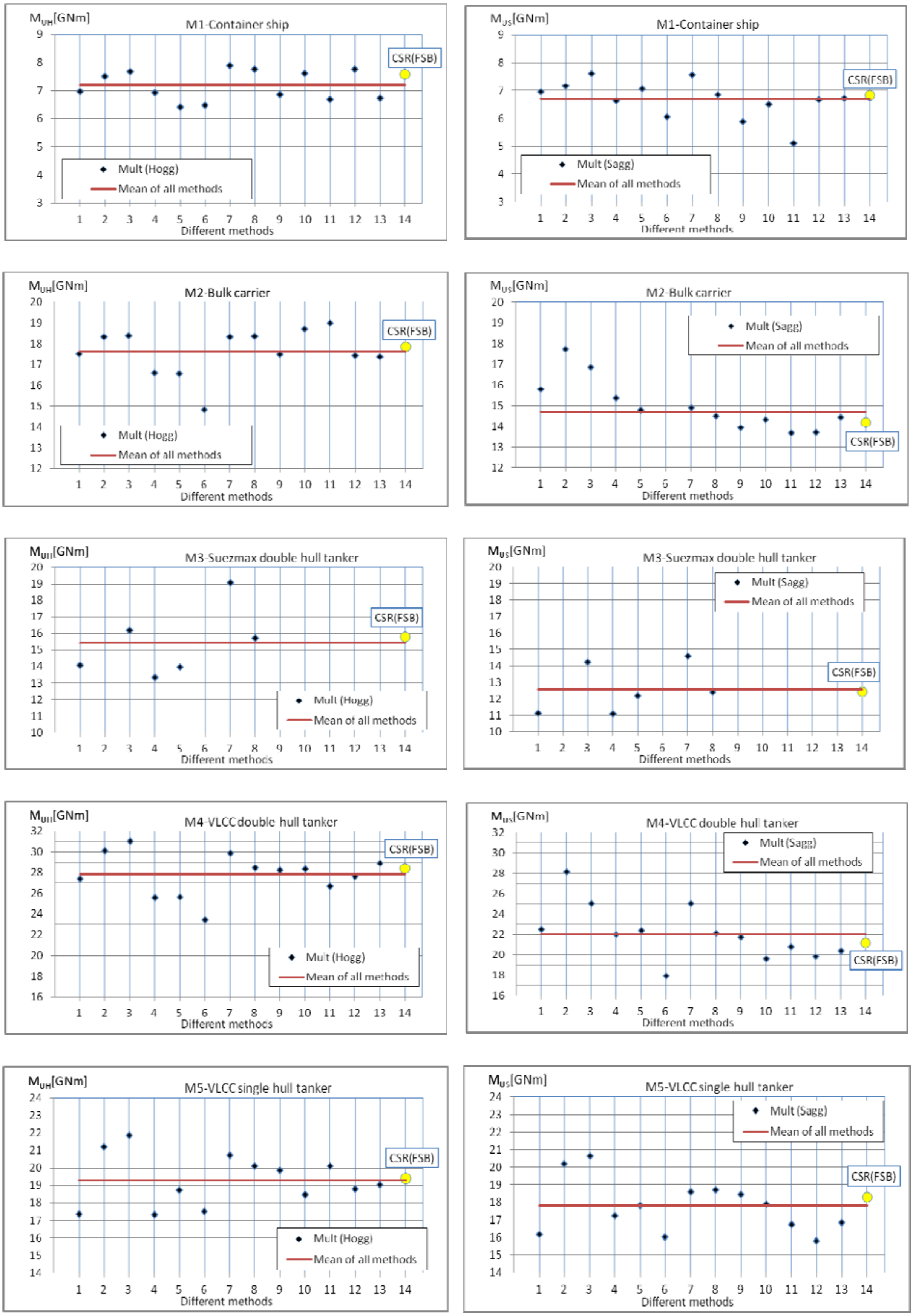

Fig. 9 Hull girder ultimate bending moments and mean values of all methods for different models (M1-M5)

Since the overall collapse of the ship structures is mainly induced and governed by buckling and/or plastic collapse (yielding) of its stiffened panels and/or primary support members, accurate and efficient ultimate load capacity calculation of structural members should be employed within the utilized progressive collapse analysis methods, which should account for the number of various feasible collapse modes (and their interactions). Although IACS CSR method uses load – end shortening curves (prescribed by [2, 3]) for description of the structural member's longitudinal (ultimate) load-capacity according to the supported collapse modes (beam-column buckling, torsional buckling, web local buckling, plate buckling, elasto-plastic collapse – yielding), various contemporary stiffened panel collapse mode formulations can be found in [13, 14]. IACS CSR method enables quantification of the instant longitudinal load-capacity on the global (considered transverse cross section) and local (individual longitudinally effective structural member) level, as well as the tracking of changes in the cross sectional distributions of the average longitudinal stress for each state of the structural equilibrium considered by the progressive collapse analysis.

Figure 10 illustrates average longitudinal stress (longitudinal load-capacity of the individual structural members) distributions calculated by the IACS CSR method for both vertical bending cases (sagg/hogg) at three different bending load intensities ($0.4M_{ult}$, $0.8M_{ult}$ and M_{ult}) imposed on the model M6. Scattered character of the indicated longitudinal stress distributions is due to the different structural materials of the double side and cofferdam discrete structural elements located at the same vertical position (see Figure 7). Pronouncement of this effect is proportional to the increase in the vertical distance between the centroid of the respective elements and the cross sectional neutral axis, as well as to the increase in the magnitude of the imposed flexural load (curvature).

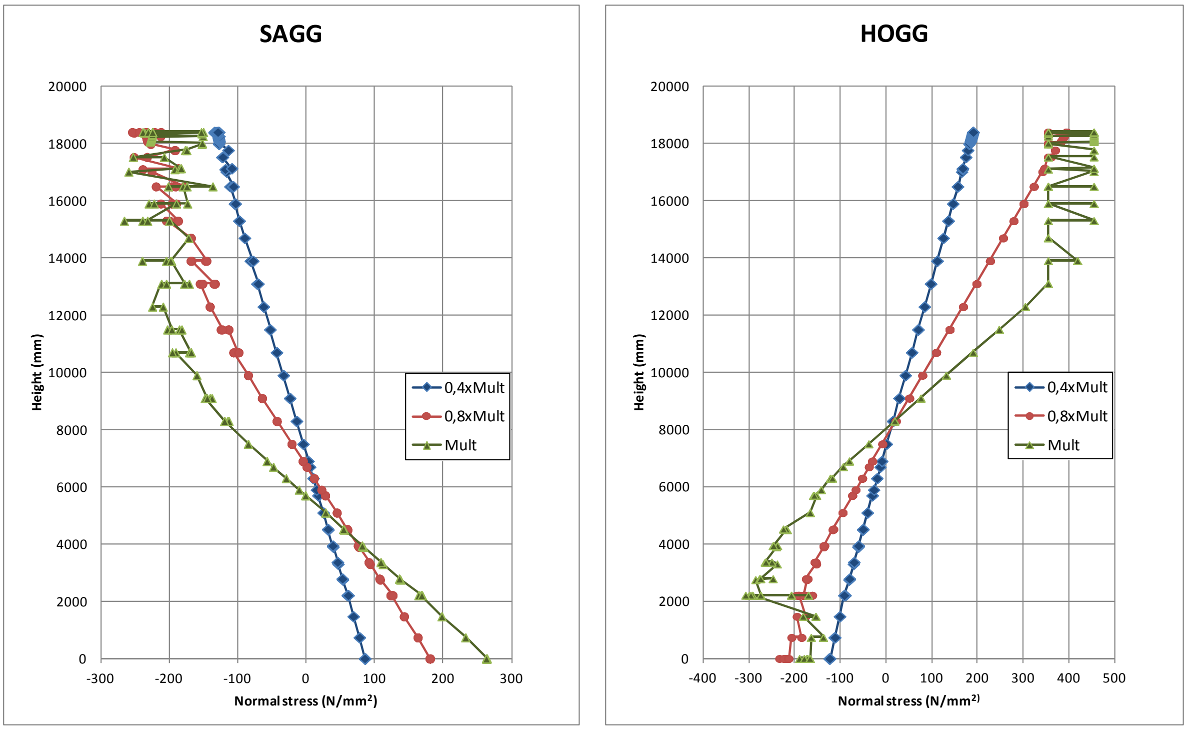

Fig. 10 Cross sectional distributions of structural members average longitudinal stress for different cases (sagg and hogg) and intensities ($0.4M_{ult}$, $0.8M_{ult}$ and M_{ult}) of bending load imposed on model M6

Peak values of the average longitudinal stress, determined by the respective load – end shortening curve, represent the ultimate longitudinal load-capacity of the individual structural members and transcendence of those values is interpreted as the structural members longitudinal collapse according to the respective collapse mode. Additionally, particular bending load increment of the progressive collapse analysis within which each structural member reached its ultimate longitudinal load-capacity can be identified, along with the calculated ultimate average longitudinal stress value and the corresponding collapse mode. Hence, in addition to the ultimate bending moment, IACS CSR method enables identification of the characteristic structural collapse sequence accounting for the load-shedding effect during the progressive load incrementation. This capability can enable determination of more rational distributions of the longitudinally effective material within the process of concept design synthesis, i.e. during the consideration of various topologic variants and/or materially-geometrical properties of the feasible structural cross-sections, since it can point to more efficient ways of required structural safety level accomplishment. Furthermore, collapse sequence can also be considered as rational directional indicator during the material reduction process of the initially over-dimensioned cross section (for the case of structural safety criteria over-satisfaction).

Figures 11 and 12 illustrate typical moment vs. curvature curves obtained by the IACS CSR progressive collapse analysis method for hull girder hogging and sagging, respectively. Superimposed on the depicted curves are characteristic structural states which correspond to the collapse of various structural portions of the considered midship section (model M6), as determined by the IACS CSR method generated data.

In addition to the ultimate bending capacity (ultimate vertical bending moment) calculated by the IACS CSR method, values determined by the NLFEA of the multi-hold hull girder model [10] are also given in Figures 11 and 12. A very good agreement of results can be noted for the both cases (sagg and hogg). For the hogging case, difference in the calculated ultimate bending capacities reads -1.04%, while for the sagging case, difference reads 2.22%. In addition to the comparison of results on the level of the ultimate bending capacity value, it is interesting to compare collapse responses of various structural portions of the considered midship section for different bending load increments, as determined by NLFEA and IACS CSR method. For this purpose Figures 13 and 14 illustrate resulting distributions of the equivalent (Von Mises) stress of the relevant part of the considered (deformed) NLFEA model for two different levels of the imposed hogging bending load, namely at 7.90 GNm and 8.63 GNm, respectively. Later value represents the ultimate bending capacity for the hogging case, as determined by the NLFEA.

Figures 15 and 16 represent plots of the uncollapsed discrete structural members of the same midship section for two comparable levels of the imposed hogging bending load, as determined by the IACS CSR method. Figure 13 illustrates collapse of the bottom stiffened plating, as indicated by the NLFEA, while Figure 15 illustrates collapse of the same structural portion, as indicated by the IACS CSR method, at the same level of the imposed hogging load. Previously collapsed deck stiffened plating (see Figure 11) is also deduced from the uncolapsed sectional material shown by Figure 15. At the ultimate bending (hogging) capacity load level considerable similarity of the obtained results can be noted, since both methods indicate collapse of bottom and deck stiffened plating along with the upper portion of the double sides and longitudinal bulkheads.

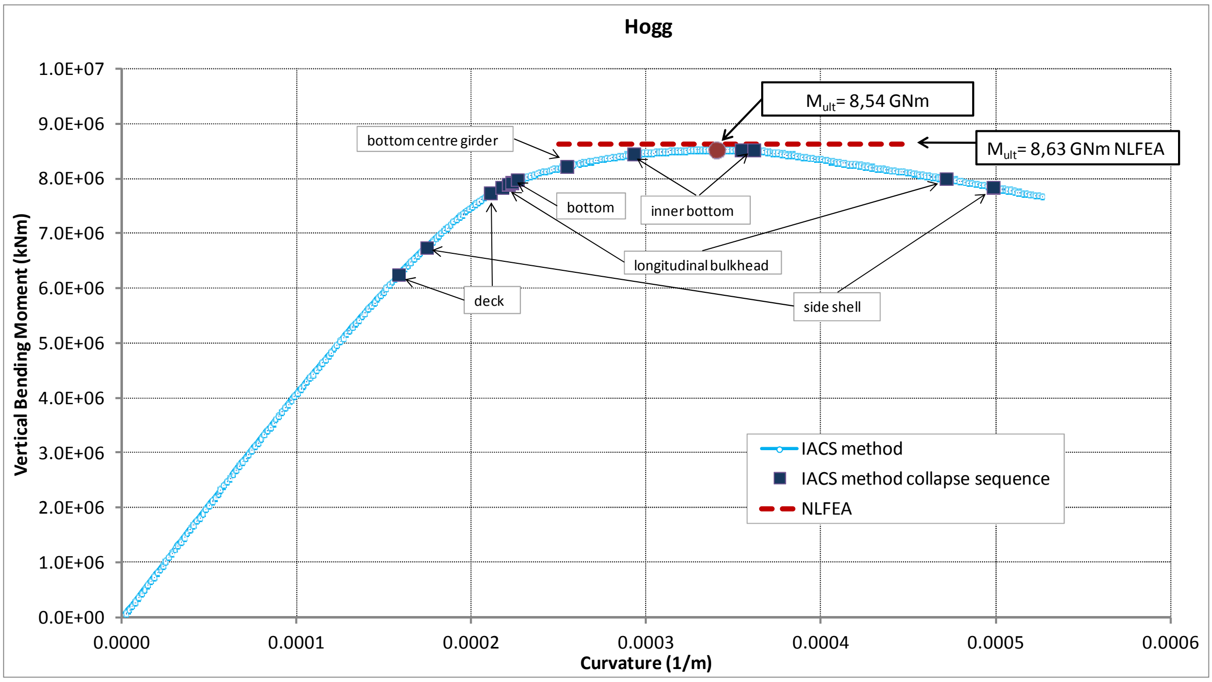

Fig. 11 Moment vs. Curvature curve and collapse sequence determined by IACS CSR method (model M6) with comparison of ultimate vertical bending moments (hogg) determined by IACS CSR method and NLFEA

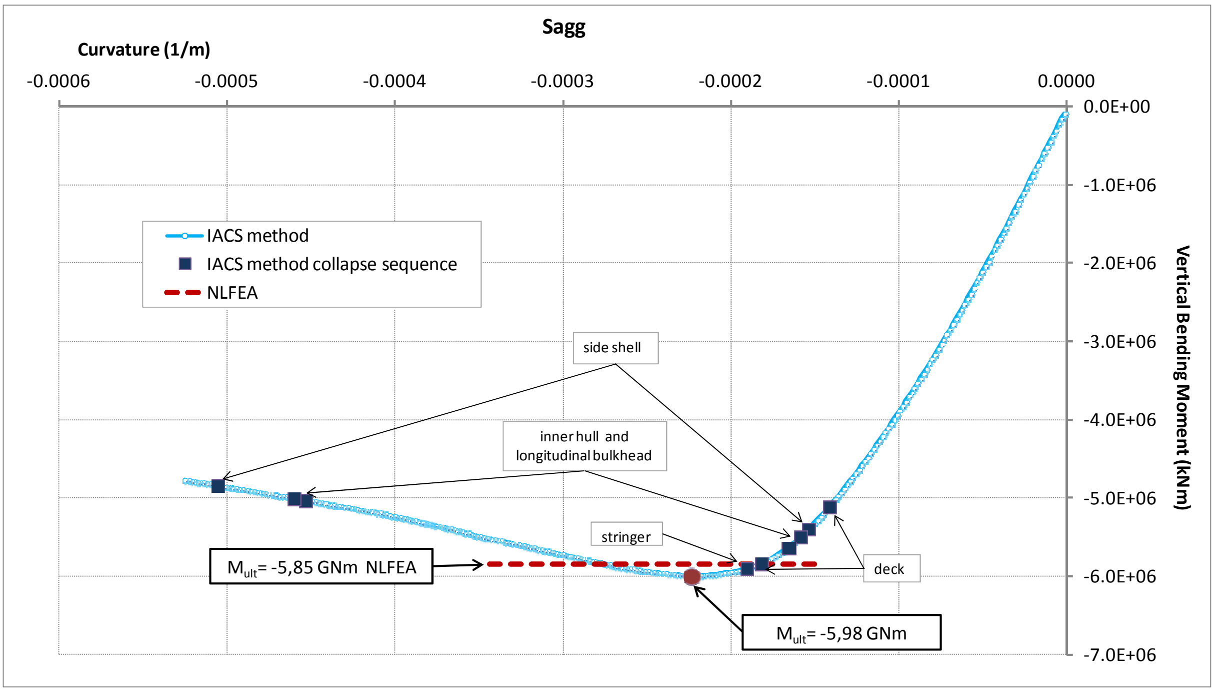

Fig. 12 Moment vs. Curvature curve and collapse sequence determined by IACS CSR method (model M6) with comparison of ultimate vertical bending moments (sagg) determined by IACS CSR method and NLFEA

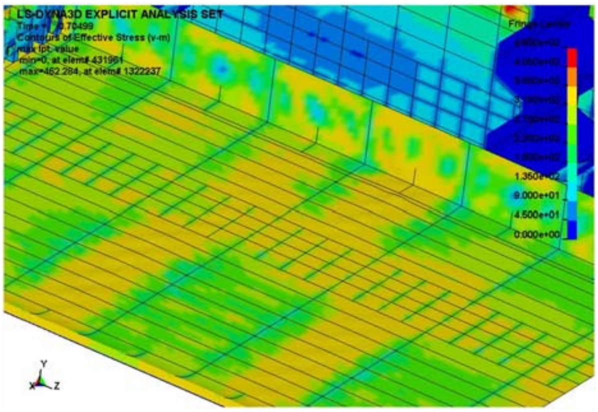

Fig. 13 NLFEA determined failure of midship bottom during hull girder hogging case (M = 7.90 GNm), [10]

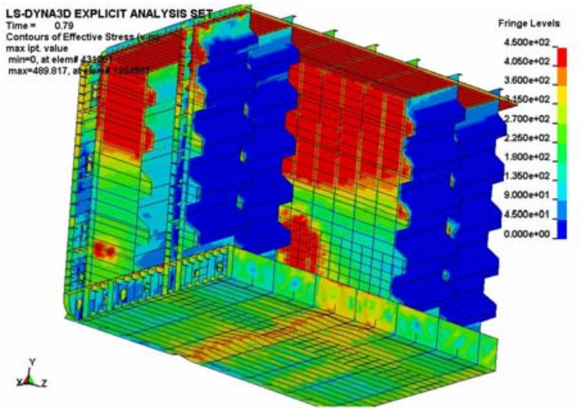

Fig. 14 NLFEA determined collapse of midship section during hull girder hogging case (M_{ult} = 8.63 GNm), [10]

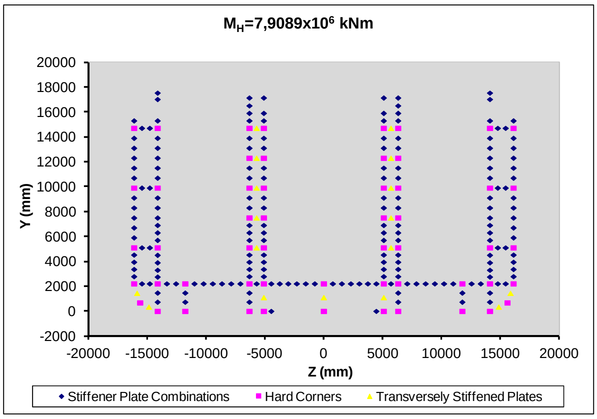

Fig. 15 Uncollapsed longitudinal structural members at hull girder bending (hogg) load of M = 7.91 GNm (IACS CSR method)

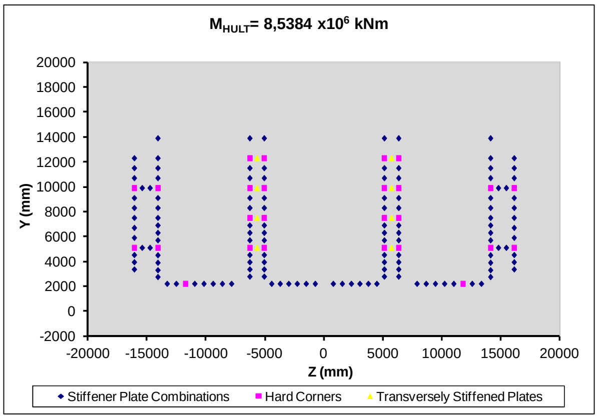

Fig. 16 Uncollapsed longitudinal structural members at hull girder ultimate bending (hogg) load of M_{ult} = 8.54 GNm (IACS CSR method)

Similarly as for the hogging case, Figures 17 and 18 illustrate the resulting distributions of the equivalent (Von Mises) stress of the relevant part of the considered (deformed) NLFEA model for two different levels of the imposed sagging bending load, namely at -3.95 GNm and -5.84 GNm, respectively. Later value represents the ultimate bending capacity for the sagging case, as determined by the NLFEA. Figures 19 and 20 represent plots of the uncollapsed discrete structural members of the same midship section for two comparable levels of the imposed sagging bending load, as determined by the IACS CSR method. It can be noted that for the former level of the imposed sagging load, NLFEA indicates localized buckling of the deck stiffened plating, while IACS CSR method indicates fully effective (intact) sectional material. As for the hogging case, at the ultimate bending (sagging) capacity load level, a considerable similarity of the obtained results can be noted, since both methods indicate collapse of the deck stiffened plating along with the upper portion of the double sides and longitudinal bulkheads.

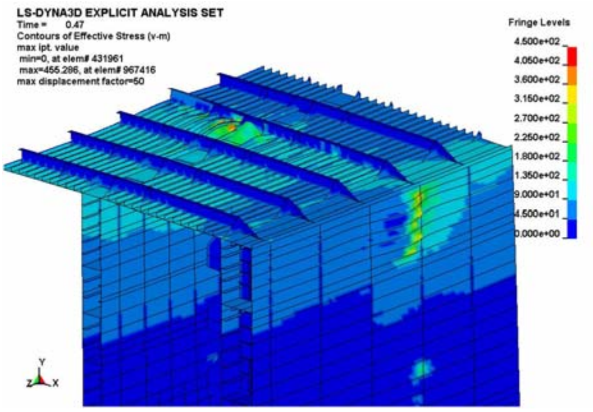

Fig. 17 NLFEA determined local failure of midship deck during hull girder sagging (M = -3.95 kNm), [10]

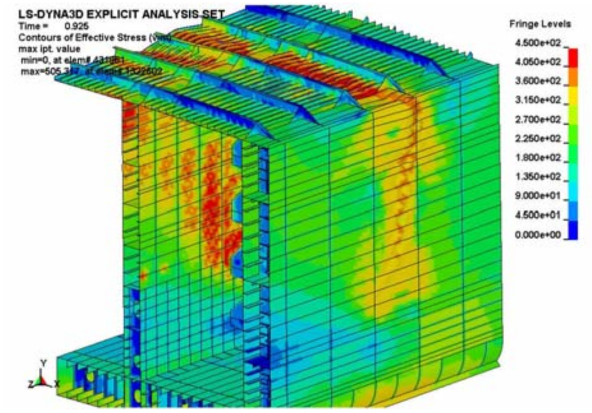

Fig. 18 NLFEA determined collapse of midship section during hull girder sagging (M_{ult} = -5.84 kNm), [10]

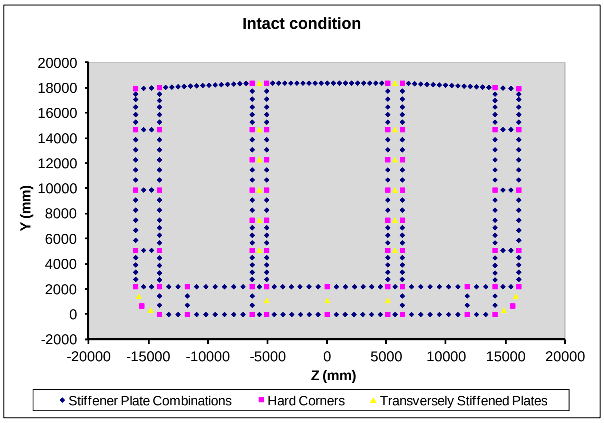

Fig. 19 Uncollapsed longitudinal structural members at hull girder bending (sagg) load of M = -3.95 kNm (IACS CSR method)

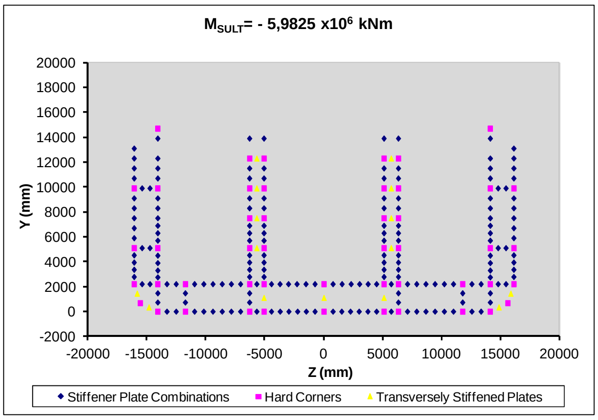

Fig. 20 Uncollapsed longitudinal structural members at hull girder ultimate bending (sagg) load of M_{ult} = -5.98 kNm (IACS CSR method)

5. Conclusions

Results obtained by different existing ultimate bending capacity assessment methods for five different hull girder structures (tankers, bulk carriers, container ship) are presented and discussed. Considered results include published data given in ISSC Reports [7 and 8] and progressive collapse analyses results obtained using IACS CSR method employed by the coauthors. Average COV for ultimate hull girder bending moments read around 0.084 for all examined methods (13 of them), 0.057 for methods based on Smith's approach and 0.049 for various implementations of IACS CSR method. In accordance with expectations, trend of decreasing calculated COV value can be noted as similarity of considered types of methods increases. Standardization of the modeling principle and identical formulation of employed load – end shortening curves given through exactly determined and prescribed IACS CSR method results with the smallest differences among evaluated results. Differences among calculated ultimate bending moments are much higher for double hull tankers and bulk carrier than for container ship and single hull tanker. Furthermore, it can be observed that implementation of IACS CSR method used by the coauthors very closely follows overall mean value for all examined models (differences less than 5%).

Additionally, a very good agreement (difference less than 2.5%) between the ultimate bending capacities determined by NLFEA and IACS CSR method can be noted for both bending cases (sagg/hogg) of the considered example (chemical tanker hull girder structure).

Furthermore, similarity of the collapse sequences identified by two methods can be noted also for both considered bending cases (sagg/hogg).

ACKNOWLEDGEMENTS

Thanks are due to the Croatian Ministry of Science, Education and Sports for the long-term financial support trough the scientific research project 120-1201829-1671. Some of the work presented in this paper was funded by European Commission through FP6 STREP project IMPROVE (Contract No. TST5-CT-2006-031382). Thanks are also due to Prof. Hendrik Naar and the rest of MEC team from Estonia for their work regarding NLFEA modeling and analysis of the multi-hold model of the chemical tanker hull girder.

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Submitted: 22.04.2013.

Accepted: 26.09.2013.

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