THE SHIP HULL STRENGTH DEVIATIONS DUE TO TOLERANCES OF ROLLED STEEL PRODUCTS

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ABSTRACT

The paper considers the assessment of uncertainties of the ship hull strength with respect to uncertainties of built-in steel products such as plates and sections. The general procedure for worst-case approach based on tolerances is applied. A review of tolerances on rolled plates and sections provided for shipbuilding, according to the classification societies, international standards as well as the tolerances defined by the steelworks, is given herein. Using tolerances of plates and sections, the deviations of strength of the hull, structural parts and substructures from the nominal strength are assessed by application of the worst-case approach. Global longitudinal strength and local strength of the ship hull built from mild shipbuilding steel, under various lateral and in-plane compression loads with respect to yielding and buckling, are considered. Rates of changes of strength with respect to basic scantlings are introduced. Additionally, the influence of the geometrical tolerance in production, like cutting, welding and other workmanship, on the strength of the ship hull has been found insignificant. Five typical plane stiffened panel types, most frequently used in the ship construction and a typical double bottom of a general cargo ship are subject to strength deviation analysis. A typical bulk carrier midship section has been investigated with respect to longitudinal strength deviation.

1. INTRODUCTION

Complex technical problems are always faced with objective and/or subjective uncertainties of their components as well as with inaccuracies of the modelling, calculation, numerical, operational and production procedures. The consequences of the uncertainties are that the technical products differ from planned, designed or simply desired features, sometimes denoted as the nominal characteristics. A widely used method for prediction of the uncertainties is based on statistical data on the component level and usage of statistical inference to predict the uncertainties of the complex system. Statistical methods requires a large amount of data, the collection of which can be time consuming and costly. The application of statistical methods requires significant experience in application and interpretation of results.

There are some complex technical problems with essential lack of statistical data. For those reasons the paper will not deal with statistics but with tolerance. In many technical problems the use of tolerances is much more suitable and simpler, due to the fact that tolerances of components are either known, or given, or can be assumed by using common engineering reasoning, and, last but not least, the tolerances of components can in general be easily controlled in the design and production process. The characteristics of components are in general represented by their nominal values. The tolerance represents the bounds of acceptable uncertainties and usually represents the deviations from nominal values. The amount of tolerance can also be expressed as fractions of the considered component characteristic. Tolerance can in some problems be expressed in terms of standard deviations, e.g. threefold the standard deviation. A reasonable assessment of component tolerance can contribute to predict the deviation of complex system characteristics or to define an acceptable tolerance level using a minimal and maximal tolerance procedure, e.g. for linearised non-linear functions, the worst-case approach [Creveling 1966] or exact non-linear procedure [Žiha 1997].

The idea underlined in the paper is to investigate the effects of tolerances of steel products on the deviation of the ship's hull longitudinal, local, yielding and buckling strength. Rates of changes in hull strength with respect to scantlings can be useful. The procedure can in general case lead to a non-linear analysis. Presented approach is illustrated by examples.

2. TOLERANCES ON STEEL PRODUCTS

The underdimensions of ship hull parts jeopardise the structural integrity of the ship construction and therefore the reduction on ship scantlings is a serious problem in shipbuilding and a subject of rules of classification societies.

In contrary to the underdimensions, the overdimensions of scantlings in general improve the structural capabilities, or strength and no special considerations of classification societies are provided. On the other hand overdimensioning increases the weight of built in steel products being in this sense a serious problem for shipbuilders and shipowners, which should be held under control.

Earlier, classification societies defined their own tolerances. Nowadays, in the case of plates steelworks should manage the constant underthickness tolerance of about -0.3 mm, related to the full range of thickness.

The underthickness tolerance provided recently by classification societies should be in accordance to EN10029 standards using four classes according [BSI Standards 1991] as shown in Table I. In case of overdimensions the relevant data are declared by standards and by the steelworks.

Table I

The tolerances of plate thickness (mm) according to EN10029 (also DIN1543)				
Nominal thickness	Permissible nominal thickness deviation			
	Class A	Class B	Class C	Class D
≥ 6 < 8	-0.4/+1.1	-0.3/+1.2	0/+1.5	-0.75/+0.75
≥ 8 <15	-0.5/+1.2	-0.3/+1.4	0/+1.7	-0.85/+0.85
≥15 <25	-0.6/+1.3	-0.3/+1.6	0/+1.9	-0.95/+0.95
≥25 <40	-0.8/+1.4	-0.3/+1.9	0/+2.2	-1.10/+1.10
≥40 <70	-1.0/+1.8	-0.3/+2.5	0/+2.8	-1.40/+1.40

In case of sections, none of present international (and as suppose also national) standards accept constant underthickness tolerances. The underthickness tolerances of sections as set forth by standards are related to their width and depth but not to their thickness, e.g. DIN Standards 1985. Sections of the same thickness and various dimensions have different underthickness tolerances, e.g. [INEXA-PROFIL Product range 1997].

Tables II and III, show cross-section tolerances of bulb flats, Jumbo bulb flats and T-sections defined by INEXA-PROFIL. Closer tolerances can be delivered by agreement.

Table II

Cross-section tolerances of bulb /Jumbo bulb (mm) according to INEXA-PROFIL		
Width	Width tolerance	Thickness tolerance
60 – 80	+ 2.0 / - 1.0	+ 0.8 / - 0.2
100 – 120	+ 1.5 / - 1.5	+ 0.7 / - 0.3
140 – 180	+ 2.0 / - 2.0	+ 1.0 / - 0.3
200 – 300*	+ 2.0 / - 2.0	+ 1.0 / - 0.3
320 – 430*	+ 2.0 / - 2.0	+ 1.2 / - 0.3

Note: Closer tolerance than DIN standards.

Table III

Cross-section tolerances of T-sections (mm) according to INEXA-PROFIL			
Flange width	Tolerance	Web flange thickness	Tolerance
100–300	+2.5/-2.5	12 – 20	+0.5 /- 0.3
(300)–600	+3.0/-3.0	(20) – 40	+1.0 /- 0.3

3. PANELS STRENGTH DEVIATION

Orthogonally stiffened plates constitute about 50% of steel hull structural weight and dominate the total cost and production time. Consequently, their structural integrity and total weight and cost must be carefully analysed [Hatzidakis and Bernitsas 1994]. Shipyard practice has established several widely used types of plane stiffened panels. Five typical configurations of orthogonally stiffened plates were identified by surveying shipyards [Winkle and Bird 1985], Fig. 1. The five plane orthogonally stiffened panel's principal scantlings on Fig. 1. are given in Table IV.

The panel's weight deviation was investigated earlier [Žiha, Mavrić and Maksimović 1998].

Table IV

The five orthogonally stiffened panels principal scantlings (mm)						
ITEM	x	A nom	B nom	C nom	D nom	E nom
Length of panel	lp	10700	10700	10700	10700	10700
Width of panel	bp	9500	9500	9500	9500	9500
Thickness of plating	tp	11.0	21.0	8.0	11.0	11.0
No.of main long.. girders	n1l	1	1	5	0	1
Web height	h1l	1200	900	600		1200
Web thickness	t1l	12.0	10.0	6.0		12.0
Flange width (keel)	b1l	400	400.	200		400
Flange thickness (keel)	f1l	30.0	30.0	8.0		30.0
No.of longitudinal girders	n2l	4	4	flat30	0	10
Web height	h2l	870	700.	114		550
Web thickness	t2l	12.0	10.0	12.0		10.0
Flange width	b2l	360	250			250
Flange thickness	f2l	30.0	30.0			20.0
No.of main trans. Girders	n1t	bulb14	bulb6	6	1	0
Web height	h1t	150	200	600	250	
Web thickness	t1t	11.0	8.0	8.0	8.0	
Flange width (keel)	b1t			150	150	
Flange thickness (keel)	f1t			8.0	15.0	
Number of trans girders	n2t	0	0	0	13	0
Web height	h2t				600	
Web thickness	t2t				10.0	
Flange width	b2t				250	
Flange thickness	f2t				20	

Orthotropic plate theory is a useful analytical alternative to computer-based discrete beam approach, such as Distributed Reaction method, and FEM. Modelling of stiffened panels using orthotropic plate theory provide a satisfactory degree of accuracy for single plated laterally loaded cross-stiffened panels with closely spaced stiffeners [Hughes 1982].

Moreover, since this article is mostly oriented to investigation of relative effects of tolerances rather then to accurate calculation of deflections and stresses, a linear small-deflection orthotropic plate theory is applied to laterally loaded cross-stiffened panels. Solutions are available in form of diagrams. Marguerra and Woernle have presented a comprehensive range of solutions for various boundary conditions [Hughes 1982]. Shade have presented simplified solutions commonly used for ship panels [Hughes 1982].

The rates of changes, i.e., the sensitivity factors given in Table V express the change in maximal panel deflections under bending loads in *mm* with respect to the unit change of the thickness of plating in *mm*, obtained by finite difference method.

Table V

The five orthogonally stiffened panels Rates of changes (sensitivity factors) for deflection in *mm* with respect to plate thickness *mm*					
ITEM	A	B	C	D	E
Simply supported	0.00170	0.00104	0.04680	0.09040	0.00288
Short clamped	0.00036	0.00020	0.01096	0.00068	0.00058
Long clamped	0.00162	0.00100	0.04550		

A practical computer program was prepared in Fortran90 by digitalisation of Marguerra-Woernle's and Shade's diagrams and quick interpolation of input parameters of considered panels. The program has been applied to five stiffened panels of mild steel, as described earlier. EN standard tolerance class B are applied to strength deviation calculation.

The summarised results of calculations of bending strength deviations due to tolerances of scantlings under lateral loading of 3 *m* water column are presented in Table VI.

Table VI

Boundary conditions		w_{max} *mm*	σ long. Plating *N/mm²*	σ short Web *N/mm²*	σ long Plating *N/mm²*	σ short Web *N/mm²*	τ long Web *N/mm²*	τ short Web *N/mm²*	σclamp Plating *N/mm²*	σclamp Web *N/mm²*
Panel A single plated laterally loaded cross-stiffened panel, plate bending, tolerance class B										
Simply supported	nm	4.939	-49.85	58.88	-9.51	50.26	0.110	0.157		
	clas	5.077	-50.96	60.21	-9.63	52.46	0.113	0.161		
	s B	2.79%	2.78%	2.26%	1.26%	4.38%	2.71%	2.54%		
Shorter edges clamped	nm	1.361	-16.63	19.33	-2.83	14.96	0.109	0.119	-20.44	110.
	clas	1.399	-17.17	19.81	-2.88	15.66	0.112	0.122	-20.87	116.
	s B	2.79%	3.25%	2.48%	1.69%	4.71%	2.84%	2.68%	2.10%	5.35%
Longer edges clamped	nm	4.845	-44.72	58.57	-10.85	59.04	0.1120	0.362	-28.80	162.1
	clas	4.998	-46.00	59.98	-10.95	60.20	0.115	0.372	-29.91	171.
	s B	3.16%	2.86%	2.41%	0.92%	1.96%	2.77%	2.67%	0.42%	5.24
Panel B single plated laterally loaded cross-stiffened panel, plate bending										
Simply supported	nm	7.662	-41.89	85.74	-8.91	93.35	0.180	0.178		
	clas	7.894	-42.54	87.66	-9.03	97.54	0.186	0.184		
	s B	3.03%	1.55%	2.24%	1.31%	4.49%	3.05%	3.19%		
Shorter edges clamped	nm	2.162	-13.44	27.02	-2.48	23.09	0.174	0.141	-17.91	190.
	clas	2.231	-13.73	27.75	-2.56	24.30	0.181	0.145	-18.41	202.
	s B	3.19%	2.16%	2.70%	3.14%	5.24%	3.44%	3.05%	2.97%	6.27%
Longer edges clamped	nm	7.365	-36.52	84.34	-10.66	23.78	0.180	0.429	-27.40	281.
	clas	7.613	-37.19	86.52	-10.71	24.06	0.186	0.442	-27.90	298.
	s B	3.37%	1,83%	2.58%	0.47	1.18	3.44%	3.03%	1.83%	6.17%
Panel C single plated laterally loaded cross-stiffened panel, plate bending										
Simply supported	nm	18.12	-52.56	168.50	-73.01	214.60	0.265	0.228		
	clas	19.21	-54.82	178.10	-76.50	226.80	0.280	0.238		
	s B	6.02%	4.30%	5.70%	4.78%	5.68%	5.57%	4.56%		
Shorter edges clamped	nm	8.444	-33.66	123.20	-21.03	85.30	0.451	0.135	-60.20	262.
	clas	8.955	-35.15	130.50	-22.04	90.25	0.476	0.142	-62.90	277.
	s B	6.05%	4.43%	5.93%	4.80%	5.80%	5.75%	4.57%	4.38%	5.84%
Longer edges clamped	nm	17.09	-17.45	44.02	-34.57	119.70	0.183	0.305	-52.36	232.
	clas	17.61	-18.15	46.39	-36.14	126.30	0.193	0.319	-54.570	245.
	s B	3.37%	4,01%	5.38%	4.54%	5.51%	5.69%	4.45%	4.22%	5.73%
Panel D single plated laterally loaded cross-stiffened panel, plate bending										
Simply supported	nm	8.870			-16.58	39.70		0.585		
	clas	9.220			-16.89	40.78		0.602		
	s B	3.95%			1.87%	2.72%		3.01%		
Longer edges clamped	nm	1.774			-5.53	13.24		0.585	-11.05	26.45
	clas	1.844			-5.30	13.60		0.602	-11.26	27.18
	s B	3.95%			-4.16%	2.77%		3.01%	1.90%	2.74%
Panel E single plated laterally loaded cross-stiffened panel, plate bending										
Simply supported	nm	7.454	-96.96	74.93			31.85			
	clas	7.703	-100.2	76.95			32.87			
	s B	3.34%	3.34%	2.70%			3.20%			
Shorter edges clamped	nm	1.491	-32.32	24.99			31.85		-64.64	49.93
	clas	1.541	-33.40	25.67			32.87		-66.80	51.28
	s B	3.35%	3.34%	2.69%			3.20%		3.34%	2.70%

Notes: Nominal (nm) normal (σ) and shear (τ) stresses are given for *plating* and stiffener *web*,
in directions of *long* and *short* edges and at the *clamp*ed edges. w_{max} - maximal deflection

The rates of changes, i.e., the sensitivity factors given in Table VII express the change in maximal panel bending stresses in N/mm^2 with respect to the unit change of the thickness of plating in *mm*, obtained by finite difference method.

Table VII

The five orthogonally stiffened panels Rates of changes (sensitivity factors) for maximal stresses N/mm^2 with respect to plate thickness in *mm*					
ITEM	A	B	C	D	E
Simply supported	0.56	0.22	41.6	0.60	2.42
Short clamped	1.80	1.40	22.80	0.19	
Long clamped	2.80	2.00	17.20		

The orthotropic plate approach can also be used for buckling analysis. Gross cross-stiffened panel buckling under in-plane compression can be assessed by orthotropic plate approach. Moreover, because the elastic gross panel buckling stress for typical ship panels exceeds the yield stress and is therefore not the actual collapse stress, but merely a parameter, which represents the panel characteristics, there is no need for great accuracy in its calculation. Hence it is usually sufficient to use small-deflection theory.

In the following considerations Dx Dy are the bending rigidities and Dxy is the torsional rigidity. The deviations in critical buckling stresses σ_{cr} of the gross panel, plating and stiffening, using tolerance class B are presented in Table VIII.

Table VIII

The five orthogonally stiffened panels Buckling strength deviations in %					
ITEM	A	B	C	D	E
D_x	3.03	2.79	6.22	3.89	3.98
D_y	9.67	12.60	5.74	6.12	2.94
D_{xy}	8.67	4.41	11.21		
σ_{cr} Panel	3.52	5.35	1.38	3.28	0.49
σ_{cr} Plating	5.36	2.99	7.22	5.38	5.38
σ_{cr} Stiffening	0.52	1.15	1.19	0.82	0.97

4. DOUBLE BOTTOM STRENGTH DEVIATION

For a general cargo ship with following main particulars: $L_{pp}=140m$, $B=21.6m$, $H=13.2m$, $T=7.5m$, $h_{DB}=1.4m$, a double bottom strength deviation analysis using EN standard tolerance class B, has been performed by computing the minimal and nominal stress values, using the orhotropic plate approach.

The following results are obtained:

- The deviation of the maximal deflection amounts to 3.06%.
- The deviation of the stress in the inner bottom plating amounts to *2.90%*.
- The deviation of the stress in the bottom plating amounts to *2.60%*.
- The deviation of the shear stress in the longitudinal girders amounts to *3.33%*.
- The deviation of the shear stress in the transverse girders amounts to *3.05%*.
- The sensitivity factor of the maximal deviation with respect to the double bottom plating thickness amounts to *0.058mm/mm*.
- The sensitivity factor of the stress in the bottom plating with respect to the bottom plating thickness amounts to $5.15(N/mm^2)/mm$.

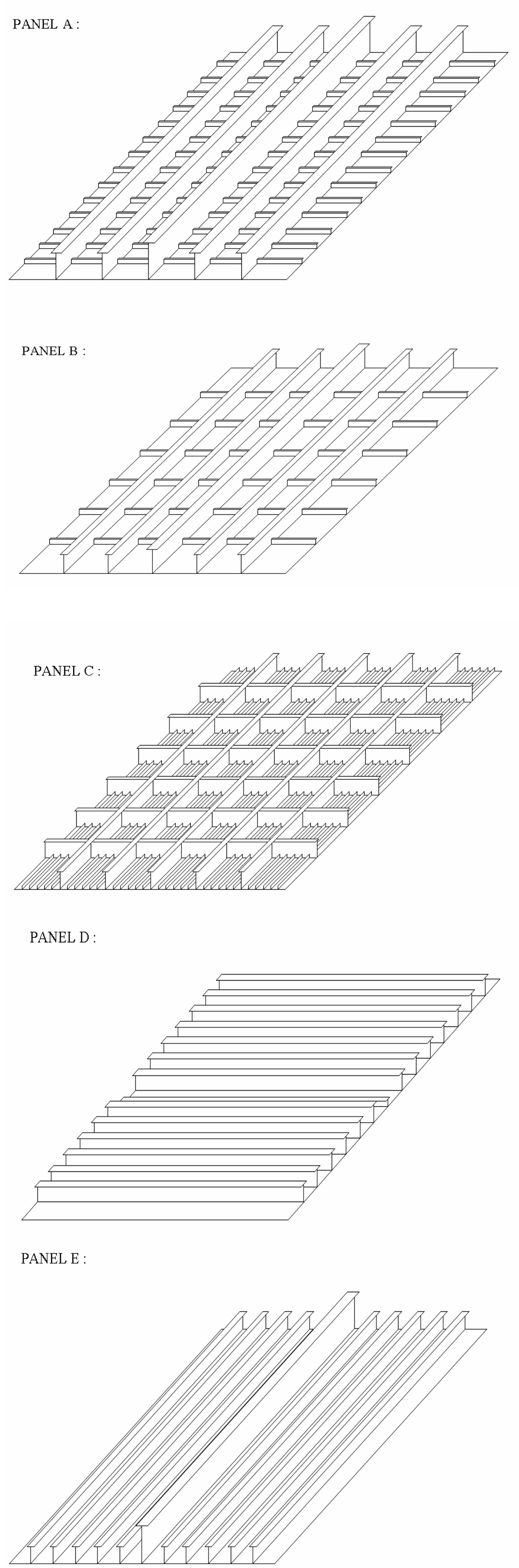

Figure 1 Five typical plane orthogonally stiffened panels

5. LONGITUDINAL STRENGTH DEVIATION

For a bulk-carrier of about 48000 dwt built in a Croatian shipyard Fig. 2., with following main particulars: $L_{oa}=192m$, $L_{pp}=183m$, $B=32m$, $H=16.7m$, $T=10.7$, $Cb=0.836$, a longitudinal strength deviation analysis using EN standard tolerance class B, has been performed by computing the minimal and maximal cross-sectional properties of ship-s longitudinal structural elements [Bureau Veritas 1983], Table IX.

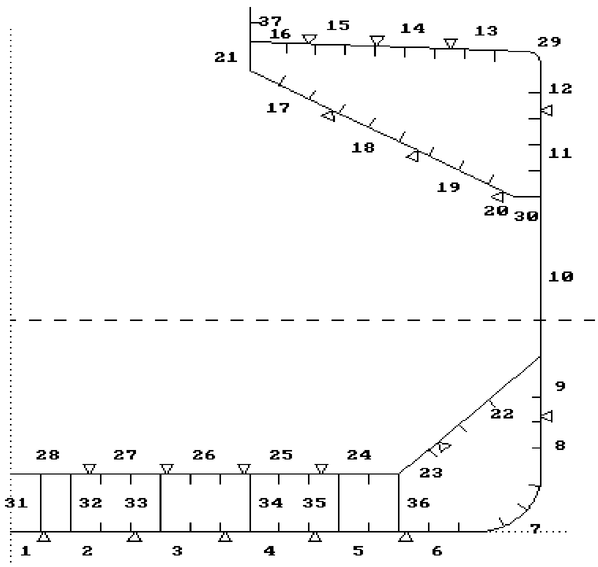

Figure 2. Bulk carrier midship section

Table IX

Characteristics of a bulk-carrier section			
Characteristics	Min	Nom	Max
Cross area of longitud. (m^2)	0.5837 (-2.26%)	0.5972	0.6376 (+6.76%)
Cross area of plating (m^2)	2.8562 (-1.52%)	2.9004	3.1567 (+8.84%)
Cross area total (m^2)	3.4400 (-1.64%)	3.4976	3.7944 (+8.48%)
Neutral axes above BL (m)	11.437 (-1.66%)	11.631	12.566 (+8.04%)
Mom. of iner. about NL (m^4)	163.32 (-1.98%)	166.63	179.30 (+7.60%)
Mom. of iner. about CL (m^4)	440.33 (-1.54%)	447.24	485.12 (+8.747%)
Sec. mod. at deck (m^3)	17.520 (-1.61%)	17.805	19.111 (+7.33%)
Sec. mod. at bottom (m^3)	22.134 (-1.80%)	22.540	24.501 (+8.70%)

6. CONCLUSION

The presented report on deviations of the ship's hull strength is a part of an investigations on effects of tolerances and corrosion to different aspects of ship structural capabilities, like local and global yielding or buckling strength under in-plane and lateral loads as well as weights.

The deviation of deflection and strength of laterally loaded stiffened panels due to tolerances of plates and stiffeners has been investigated on five typical panels and the amount of deflection increase and stress reduction for tolerance class B was about 2% to 6%.

The critical gross panel buckling strength is reduced for tolerance class B in amount 1% to 5%, in plating more significantly (approximately quadraticaly) in amount of 5% to 8% and of the stiffening in amount of only about 1%.

Considering the longitudinal strength by investigating a midship section of a bulk carrier, a reduction of about 2% has been found in case of employing tolerance class B.

The aim of these investigations were in finding out the maximal deviations of strength of ship hull with respect to the tolerances in order to predict more rationally the acceptable limits on the assessment of ship hull strength. The procedure providing rates of changes can render, on one hand, the most influential scantling as well as the tolerances, which can assure tolerable hull strength reduction.

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