THE SIXTH INTERNATIONAL
SYMPOSIUM ON
PRACTICAL DESIGN OF SHIPS AND
MOBILE UNITS
PRADS SEPTEMBER 17-22, 1995
SEOUL KOREA

BENCHMARKING OF ULTIMATE STRENGTH PREDICTIONS FOR LONGITUDINALLY STIFFENED PANELS.

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ABSTRACT

This study is concerned with a comparison of the ultimate strength of stiffened steel panels as predicted by different codes/methods. Ten multi-span stiffened panels subjected to axial compression and combined compression and lateral pressure are considered. The focus is on failure modes, the effective width of flange plating and the ultimate strength of (multi-span) stiffened panels between transverse frames. The model uncertainty related to each code/method is estimated and the influence of imperfections on the accuracy of the methods is discussed. The influence of effective width on ultimate strength is tabulated. This benchmark study highlights two types of uncertainty: the model uncertainty associated with the model for strength prediction and the "human factor" uncertainty associated with computer codes for ultimate strength and especially their use.

INTRODUCTION

A number of classification societies and other organizations that have been engaged in the development of strength formulations for stiffened panels were asked to participate in a benchmark exercise by the ISSC Committee V.1 (Applied Design) for 1991-94 [1]. The aim was to determine the ultimate capacity of 10 multi-span stiffened panels subjected to axial compression and combined compression and lateral pressure. The study concentrated on failure modes, the effective width of flange plating and the ultimate strength of (multi-span) stiffened panels between transverse frames. Of the ten panels, eight were longitudinally compressed panels and two were subjected to combined loading. Six of the panel geometries were based on similar panels tested by Smith [2] (same nominal geometry and material properties and comparable imperfections) and four were typical panels from the "Energy Concentration"[3], a VLCC that broke its back during the discharge of oil in 1980.

Comparisons refer to the ultimate strengths (excluding safety factors on strength, corrosion factors or allowances, etc.) that are predicted by the different codes/methods. The model uncertainty defined as the test strength versus the predicted strength is estimated for each code/method,.

The names of the contributors (A to F) and codes/methods used (M1 to M9) are the following: A: University of Liege, B: Imperial College, C: DnV, D: Hitachi Zosen Corporation, E: Lloyd's Register, F: Bureau Veritas, M1: ECCS (column approach) [8], M2: ECCS (orthotropic approach) [8], M3: BS5400 [4], M4: Imperial College [9-12], M5: DnV - CNB, Notes 30.1 [6], M6: DnV, Ship Rules [7], M7: Dr. Ueda's method [14-15], M8: Lloyd's Register [13] and M9: Bureau Veritas [5].

All contributors were given the same information regarding input parameters (Figs 1, 2 and Tables 1, 2) and were asked to report on strength predictions as well as on important interim results (e.g. plate effective width). After collecting all the results, it became clear that certain clarifications were necessary. Thus, the opportunity to re-calculate, if felt necessary, was given. The results presented in this paper are those from the second round and as such represent the "best shot" that an analyst can have within, of course, practical constraints.

PRESENTATION OF THE SELECTED PANELS

Tables 1, 2 and Figs 1, 2 give all the relevant information used by the contributors to analyse the 10 selected panels. These are the following :

- geometric characteristics (Table 1): panel size, plate thickness, frame and girder spacing, web and flange dimensions, these can be summarized (Table 2) by appropriate non-dimensional parameters such as the aspect and stiffening ratio and the plate and column slenderness,
- mechanical characteristics: Young's modulus, yield stress of plate and stiffener,
- residual compressive stress in the plating: compressive stress level and distribution of the tensile block (η),

- initial imperfections for plate and stiffener,
- lateral pressure considered.

The panels had to be considered as multi-span stiffened panels between transverse frames. Contributors were free to chose the "right" boundary conditions to use in the codes/methods that they used according to the code specifications and their own experience.

In calculating the ultimate strength, contributors were requested not to apply safety factors on the strength, or any corrosion factor, e.g. reduced plate thickness.

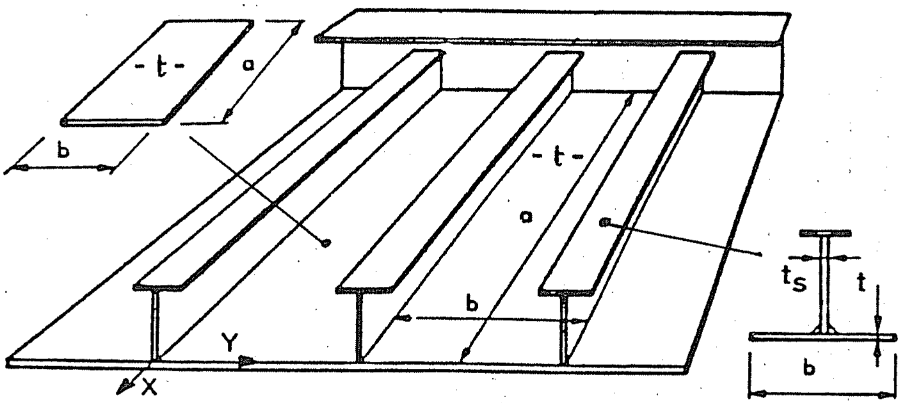

Figure 1 : Dimensional parameters for longitudinally stiffened plate

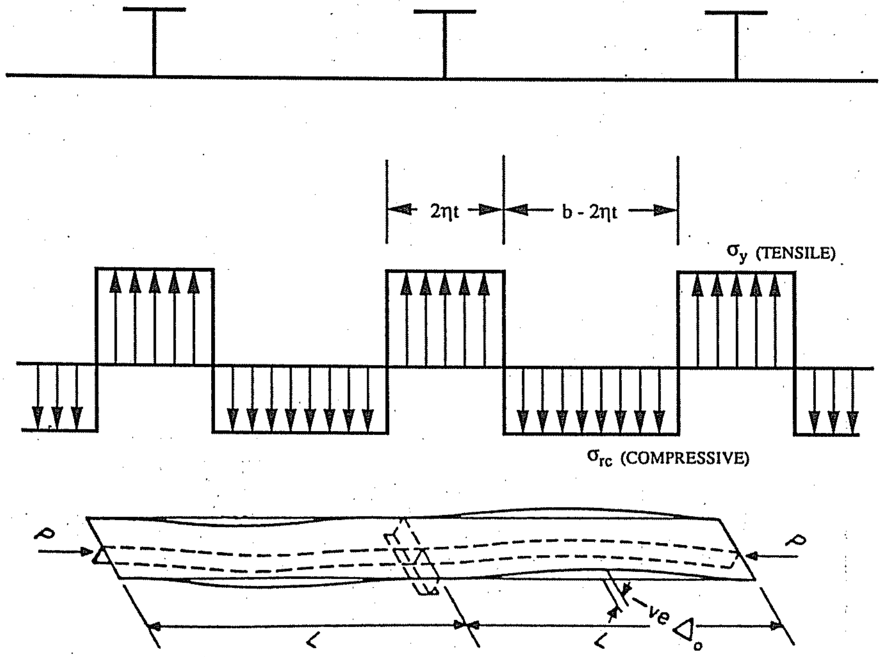

Figure 2 : Idealised residual stress distribution and initial deformation of stiffener.

Table 1 : Geometric and mechanical characteristics of the selected continuous panels.

SELECTED CONTINUOUS STIFFENED PANELS											
Panel Reference N°	Panel Size		Plate thickness t (mm)	Unstiffened plate size		Girders (longitudinal)		Young Modulus E N/mm2	Yield Stress		Lateral pressure P (kN/m2)
	L= N * a (mm)	B= M * b (mm)		Transverse frames spacing a (mm)	Girders (longitud.) spacing b (mm)	Web (mm * mm)	Flange (mm * mm)		Plate N/mm2	Stiff. N/mm2	
UNIFORM AXIAL LOADING											
Model of ship bottom configuration											
1 Smith 1-a	6000	3000	8.0	1200	600	154 * 7.2	79 * 14.2	208 E03	253.2	257.8	0
2 Smith 2-b	6000	3000	7.4	1500	300	115 * 5.4	45 * 9.5	208 E03	264.0	279.5	0
3 Smith 3-b	6000	3000	6.4	1500	300	77 * 4.6	28 * 6.4	208 E03	256.3	227.0	0
4 Smith 4-a	6000	3000	6.4	1200	250	77 * 4.8	28 * 6.4	208 E03	264.0	237.8	0
Model of frigate strength deck											
5 Smith 5-a	6000	3000	6.4	1500	600	116 * 5.3	46 * 9.5	208 E03	251.7	234.7	0
6 Energ. Conc. (bottom shell)	20400	6000	25.0	5100	1000	830 * 15 (stiffener : tee bar)	200 * 33	208 E03	315.0	315.0	0
7 Energ. Conc. (upper deck)	20400	6000	25.0	5100	1000	480 * 32 (flat plate stiffener)	no flange	208 E03	315.0	315.0	0
8 Energ. Conc. (side shell)	20400	5550	23.5	5100	925	772 * 12.7 (L - shape stiffener)	180 * 25	208 E03	315.0	315.0	0
COMBINED LOADING : AXIAL LOAD + LATERAL PRESSURE											
9 Smith 1-b	6000	3000	7.9	1200	600	152 * 7.1	76 * 14.2	208 E03	256.3	254.8	103.4
10 Energ. Conc. (bottom shell)	20400	6000	25.0	5100	1000	830 * 15 (stiffener : tee bar)	200 * 33	208 E03	315.0	315.0	200.0

Table 2 : Residual stress and initial imperfection of the selected panels.

SELECTED CONTINUOUS STIFFENED PANELS (continued)								
Panel Reference N°	Aspect ratio a/b	Stiffening ratio α As/Ap	Slenderness		Residual compressive stress in plating (1)		Initial deflection d (2)	
			Plate β	Column λ	Stress (MPa)	η (distrib.)	Plate δ/b	Stiffener δ/a
UNIFORM AXIAL LOADING								
Model of ship bottom configuration								
1 Smith 1-a	2.0	0.44	2.63	0.23	-	-	0.0060	0.00150
2 Smith 2-b	5.0	0.45	1.45	0.40	126	5.1	0.0060	0.00190
3 Smith 3-b	5.0	0.26	1.64	0.70	153	7.2	0.0150	0.00410
4 Smith 4-a	4.8	0.32	1.39	0.53	146	5.5	0.0081	0.00340
Model of frigate strength deck								
5 Smith 5-a	2.5	0.26	3.26	0.45	60	9.4	0.00100	0.00100
6 Energ. Conc. (bottom shell)	5.1	0.74	1.56	0.19	0	0	0.0057	0.0010 or 0.00083 (3)
7 Energ. Conc. (upper deck)	5.1	0.61	1.56	0.42	0	0	0.0057	0.0010 or 0.00083 (3)
8 Energ. Conc. (side shell)	5.5	0.64	1.32	0.18	0	0	0.0049	0.0010 or 0.00083 (3)
COMBINED LOADING : AXIAL LOAD + LATERAL PRESSURE								
9 Smith 1-b	2.0	0.43	2.67	0.23	-	-	0.0077	0.00150
10 Energ. Conc. (bottom shell)	5.1	0.74	1.56	0.19	0	0	0.0057	0.0010 or 0.00083 (3)

(1) The residual stress is assumed to be distributed as compressive and tensile blocks (Fig. 2)

(2) The initial deflection is based on an average value for the plate and the maximum value for the stiffener given by Smith [2]

(3) The values of (δ/a) should be 0.0010 or 0.00083 when the relevant failure mode is plate - or stiffener - induced, respectively

As = cross section of stiffener Ap = Plate flange cross section

i = Radius of gyration (plate and stiffener)

PRESENTATION OF THE RESULTS

Table 3 shows the main results of the benchmark test in terms of Pu/Po (model ultimate load divided by squash load). To assess model uncertainties, results are also expressed, when available, by a second ratio: experimental ultimate strength versus code/model ultimate strength (Table 4).

The contributors are referred to by one capital letter (A, B, C, etc.) and the codes by the symbols (M1, M2, etc.). Note that some codes have been used by several contributors, for instance the M5 code/method was used by the B and C contributors.

Table 5 presents the plate effective width considered by the different codes/methods and Table 6 shows the induced failure modes obtained by each contributor. The failure modes presented in the table are those obtained by the contributors themselves. For comparison, the experimental induced failure modes observed by Smith [2] are also mentioned. To clarify this comparison, only "plate induced failure" and "stiffener induced failure" modes are mentioned.

Table 3 : Computed ultimate strength versus squash load (Pu/Po).

ULTIMATE STRENGTH																		
CONTRIBUTORS		A	A	A	A	B	B	B	B	B	C	C	D	D	E	F		
METHODS/CODES		M1	M1	M2	M2	M1	M2	M3	M4	M5	M5	M6	M7	M7	M8	M9		
Boundary conditions		With edge stiff.	No edge stiff.	With edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	Single beam column	Single beam column	With edge stiff.	No edge stiff.	Single beam column	Single beam column		
Panel Reference N°	Pu/ Po Experim. C.SMITH	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Pu/ Po	Means	COV
1 Smith 1.a	0,76	0,708	0,672	0,680	0,631	0,672	0,572	0,659	0,686	0,564	0,580	0,520	0,708	0,672	0,751	0,650	0,648	0,094
2 Smith 2.b	0,83	0,805	0,800	0,832	0,812	0,803	0,764	0,811	0,797	0,833	0,810	0,850	0,812	0,803	0,543	0,870	0,796	0,090
3 Smith 3.b (**)	0,61	0,593	0,585	0,588	0,544	0,570	0,559	0,556	0,418	0,683	0,660	0,810	0,634	0,625		0,783	0,615	0,155
															0,118			
4 Smith 4.a	0,82 (*)	0,709	0,703	0,703	0,689	0,693	0,652	0,664	0,560	0,784	0,770	0,860	0,775	0,771	0,508	0,870	0,714	0,133
5 Smith 5.	0,72	0,527	0,495	0,484	0,432	0,493	0,411	0,482	0,542	0,461	0,480	0,340	0,495	0,455	0,378	0,467	0,463	0,112
Energie Concentration																		
6 Bottom Shell	-	0,889	0,871	0,845	0,810	0,880	0,771	0,839	0,858	0,824	0,580	0,690	0,892	0,877	0,731	0,907	0,818	0,107
7 Upper Deck	-	0,798	0,783	0,819	0,794	0,791	0,735	0,752	0,804	0,802	0,750	0,850	0,870	0,858	0,874	0,689	0,798	0,063
8 Side Shell	-	0,928	0,917	0,863	0,843	0,923	0,813	0,887	0,892	0,893	0,840	0,710	0,924	0,915	0,923	0,881	0,877	0,064
9 Smith 1.b																		
. without lateral pressure	-	0,702	0,664	0,662	0,613	0,664	0,556	0,639	0,667	0,559	-	-	0,684	0,645	0,736	-	0,649	0,078
. with lateral pressure P=103.4kN/m2	0,73	-	-	-	-	-	-	-	0,512	0,529	0,540	0,510	-	-	0,670	-	0,552	0,109
10 Energ. Conc., Bottom Shell																		
. without lateral pressure	-	-	-	-	-	-	-	-	0,858	0,824	0,580	0,690	-	-	0,731	-	0,737	0,135
. with lateral pressure P=200 kN/m2	-	-	-	-	-	-	-	-	0,660	0,774	0,580	0,680	-	-	0,820	-	0,703	0,121

(*) C. Smith panel 4.a has longitudinals interspersed with two tee-bars of 40 inches that are not considered by the contributors.

(**) The statistics of panel 3 (Smith 3.b) is calculated without method E

Contributors : A= Univ. of Liege, B = Imperial College, C=DnV, D=Hitachi Zosen, E=Lloyd's Register, F=Bureau Veritas

Codes/methods : M1= ECCS Column, M2= ECCS Orthot., M3= BS5400, M4=Imp. C. , M5= DnV(CN30.1), M6= DnV(ship rules), M7=Ueda, M8=LR, M9=BV

Table 4 : Evaluation of the global uncertainties (exp. strength versus computed strength)

ULTIMATE STRENGTH																	
Contributors	A	A	A	A	B	B	B	B	B	C (***)		D	D	E	F		
Codes/methods	M1	M1	M2	M2	M1	M2	M3	M4	M5	M5	M6	M7	M7	M8	M9		
Boundary conditions	With edge stiff.	No edge stiff.	With edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	No edge stiff.	Single beam column	Single beam column	With edge stiff.	No edge stiff.	Single beam column	Single beam column		
Panel Reference N°	Pu(exp)/ Pu(code)				Pu(exp)/ Pu(code)					Pu(exp)/ Pu(code)						**Means**	**COV**
1 Smith 1.a	1,073	1,131	1,118	1,204	1,131	1,329	1,153	1,108	1,348	1,310	1,462	1,073	1,131	1,012	1,169	1,183	0,101
2 Smith 2.b	1,031	1,038	0,998	1,022	1,034	1,086	1,023	1,041	0,996	1,025	0,976	1,022	1,034	1,529	0,954	1,054	0,124
3 Smith 3.b (**)	1,029	1,043	1,037	1,121	1,070	1,091	1,097	1,459	0,893	0,924	0,753	0,962	0,976	*5,169*	0,779	1,017	0,161
4 Smith 4.a (*)	1,157	1,166	1,166	1,190	1,183	1,258	1,235	1,464	1,046	1,065	0,953	1,058	1,064	1,614	0,943	1,171	0,147
5 Smith 5	1,365	1,455	1,489	1,666	1,460	1,752	1,494	1,328	1,562	1,500	2,118	1,455	1,582	1,905	1,542	1,578	0,128
9 Smith 1.b P=103.4kN/m2	-	-	-	-	-	-	-	1,426	1,380	1,352	1,431			1,090		1,336	0,095
MEANS	1,131	1,166	1,162	1,241	1,176	1,303	1,201	1,305	1,204	1,200	1,207	1,114	1,159	2,053	1,077		
COV(# Smith)	0,111	0,131	0,150	0,179	0,129	0,187	0,135	0,130	0,199	0,167	0,380	0,157	0,188	0,695	0,244		
Min. Value	1,029	1,038	0,998	1,022	1,034	1,086	1,023	1,041	0,893	0,924	0,753	0,962	0,979	1,012	0,779		
Max. Value	1,365	1,455	1,489	1,666	1,460	1,752	1,494	1,464	1,562	1,500	2,118	1,455	1,582	5,169	1,542		

(*) C. Smith panel 4.a has longitudinals interspersed with two tee-bars of 40 inches that are not considered by the contributors.

(**) The statistics of panel 3 (Smith 3.b) is calculated without method E but statistics of method E is done with the panel 3 included.

(***) Contributor C does not distinguished the plating yield stress from the stiffener yield stress (plating yield stress is considered).

Contributors : A= Univ. of Liege, B = Imperial College, C=DnV, D=Hitachi Zosen, E=Lloyd's Register, F=Bureau Veritas

Codes/methods : M1=ECCS Column, M2=ECCS Orthot., M3=BS5400, M4=I. C., M5=DnV(CN30.1), M6=DnV(ship rules), M7=Ueda, M8=LR, M9=BV

Table 5 : Effective width used by the different codes/methods.

EFFECTIVE WIDTH (b/beff)											
Contributors	**A**	**A**	**B**	**B**	**B**	**B**	**B**	**C**	**D**	**E**		
Panel Reference N°	M1	M2	M1	M2	M3	M4	M5	M5	M7	M8	**Means**	**COV**
1 Smith 1.a	0,563	0,563	0,560	0,560	0,568	0,606	0,568	0,568	0,500	0,682	0,574	0,076
2 Smith 2.b	0,840	0,840	0,839	0,839	0,827	0,831	0,861	0,855	0,500	0,884	0,812	0,129
3 Smith 3.b	0,781	0,781	0,782	0,782	0,777	0,779	0,936	0,933	0,500	0,475	0,753	0,193
4 Smith 4.a	0,858	0,858	0,857	0,857	0,844	0,849	0,961	0,961	0,480	0,851	0,838	0,151
5 Smith 5	0,475	0,475	0,475	0,475	0,484	0,543	0,477	0,477	0,430	0,518	0,483	0,058
Energie Concentration												
6 Bottom Shell	0,807	0,807	0,806	0,806	0,798	0,801	0,826	0,944	0,510	1,000	0,811	0,148
7 Upper Deck	0,807	0,807	0,806	0,806	0,798	0,801	0,826	0,944	0,510	1,000	0,811	0,148
8 Side Shell	0,881	0,881	0,881	0,881	0,866	0,871	0,903	0,968	0,460	1,000	0,859	0,163
9.a Smith 1.b . with lateral pressure P=103.4kN/m2	-	-	-	-	-	0,524	0,563	0,563	-	0,605	0,564	0,051
10 Energ. Conc. . without lateral pressure	-	-	-	-	-	0,801	0,826	0,944		1,000	0,893	0,092
. with lateral pressure P=200 kN/m2	-	-	-	-	-	0,721	0,826	0,944	-	1,000	0,873	0,124

Contributors : A= Univ. of Liege, B = Imperial College, C=DnV, D=Hitachi Zosen, E=Lloyd's Register, F=Bureau Veritas

Codes/methods : M1= ECCS Column, M2= ECCS Orthot., M3= BS5400, M4=Imp. College , M5= DnV(CN30.1), M6= DnV(ship rules), M7=Ueda, M8=LR, M9=BV

Table 6 : Induced failure mode obtained by the different contributors.

FAILURE MODE																
Contributors	**C. Smith**	**A**	**A**	**A**	**A**	**B**	**B**	**B**	**B**	**B**	**C**	**C**	**D**	**D**	**E**	**F**
Panel Reference N°	**Experim. tests.**	M1	M1	M2	M2	M1	M2	M3	M4	M5	M5	M6	M7	M7	M8	M9
1 Smith 1.a	PL	ST	ST	ST	ST	PL	ST	ST	ST	PL	PL	PL	ST	ST	PL	ST
2 Smith 2.b	ST	ST	ST	ST	ST	PL	ST	ST	ST	PL	ST	PL	ST	ST	PL	ST
3 Smith 3.b	ST	ST	ST	ST	ST	ST	ST	ST	ST	ST	ST	PL	ST	ST	PL	ST
4 Smith 4.a	ST	ST	ST	ST	ST	ST	ST	ST	ST	ST	ST	PL	ST	ST	PL	ST
5 Smith 5	PL	ST	ST	ST	ST	ST	ST	ST	ST	PL	PL	ST	ST	ST	PL	ST
6 Energ. Conc	-	ST	ST	ST	ST	ST-PL	ST	ST	ST	PL	ST	ST	ST	ST	ST	ST
7 Energ. Conc	-	ST	ST	ST	ST	ST	ST	ST	ST	PL	ST	ST	ST	ST	ST	ST
8 Energ. Conc	-	ST	ST	ST	ST	ST-PL	ST	ST	ST	PL	ST	ST	ST	ST	ST	ST
9.a Smith 1.b . with lateral pressure	PL	-	-	-	-	-	-	-	ST	PL	PL	PL	-	-	PL	-
10 Energ. Conc. . with lateral pressure	-	-	-	-	-	-	-	-	ST	PL	ST	ST	-	-	ST	-

PL. : Plate induced failure ST. : Stiffeners induced failure

Short Description of the Codes/Methods

For axial compression loading, all the methods used are based on the so-called single (or isolated) beam-column model. However, ECCS [8] offers in addition an alternative method based on orthotropic plate thoery. A common feature of code formulations is that there is no direct dependence between predicted strength and imperfection/residual stress level. This has been the normal practice for many years both in marine and bridge codes and the rationale is that the predicted strength for any particular geometry accounts for a level of manufacturing tolerances specified in the relevant workmanship part of the code. In this repect, it is important to note that some of the imperfection values chosen are beyond the tolerances specified in codes. Tables 7 and 8 give an idea of the level of imperfection tolerances specified in some of the codes used and of the compliance of the imperfections in the benchmark panels with these tolerances. As can be seen, some panels fail to meet these tolerances and, in this respect, the predicted strengths may be considered too optimistic. However, there is no guidance on how to modify strength predictions when tolerance are exceeded.

Residual stress levels are not explicitly treated but it is normally assumed that the strength formulae account implicitly for a certain level of residual stresses associated with typical manufacturing methods. The implied level of residual stresses and the specified imperfection tolerance values vary from one code to another (e.g. marine vs. brige codes), probably due to differences in manufacturing methods used.

The method developed by Imperial College [9-12] was conceived as being relevant to both initial design and assessment of existing panels. It was thus decided to retain the stiffener imperfection as a variable in the formulation, so as to enable strength evaluation for any desired imperfection level. However, an explicit dependence on the level of plate imperfections and residual stresses was removed since stiffened panel strength is less sensitive to these parameters, within practical limits.

The Lloyd's Register method [13] retains explicit dependence on both plate and stiffener imperfections and residual stresses. It has been extensively calibrated against geometries typical of merchant ships but is possibly out-of-range for very slender panels such as case 5, more typical of naval ships.

Insofar as combined axial and pressure loading is concerned, it is clear from the results shown in Table 3 that fewer codes deal with this loading case, partly due to the fact that it is not explicitly considered in bridge design codes (e.g. BS5400, ECCS). The methods are based on an interaction approach but with some differences with regard to, for example, the effect of pressure on plate effective width and the degree of end restraint afforded to the stiffened panel between transverse frames.

DISCUSSION

Reliability of the Codes/Methods

Six contributors used 9 different codes/methods (Table 4) providing altogether 15 different analyses for each panel. Six analyses based on 4 methods provide overestimated ultimate strength (2 to 25 %). The ultimate strength is underestimated by 25 to 50% (or more) in the case of panel 5 (with a very slender plate).

Table 7 : Code Tolerances for Initial Imperfections.

Design Code	Plate Imperfection	Stiffener Imperfection (Column Mode)	Stiffener Imperfection (Tripping Mode)
BS5400: 1980	No limit for $b/t \leq 25\ [\sigma_o/355]^{1/2}$ For $b/t > 25\ [\sigma_o/355]^{1/2}$ $[G/165]\ [\sigma_o/355]^{1/2}$ or 3mm whichever is the greater G = a for a < 2b G = 2b for a > 2b	G/750 or 2mm whichever is the greater G = a	$[G/375]\ [\sigma_o/355]^{1/2}$ or 2mm whichever is the greater G = Min[a, 2b]
DnV (MOS): 1987	b/100	a/667	a/667
ECCS: 1990	b/500 but ≤ 4mm	a/500 but ≤ 8mm	a/500 but ≤ 8mm
API RP 2V: 1987	b/100	a/667	a/667

Table 8 : Assessment of benchmark study panels w.r.t; code tolerances.

Case	Column Imperf.			Plate Imperf.		
	BS5400	DnV	ECCS	BS5400	DnV	ECCS
1	P	P	P	P	P	F
2	P	F	P	P	P	F
3	F	F	F	F	F	F
4	F	F	F	P	P	F
5	P	P	P	P	P	F
6	P	P	P	P	P	F
7	P	P	P	P	P	F
8	P	P	P	P	P	F
9	P	P	P	P	P	F
10	P	P	P	P	P	F

F : Fails to meet tolerances; P: passes tolerances

Ultimate Strength of Axially Loaded Stiffened Panels

Several reasonably accurate formulations for axially loaded stiffened panels are identified, typically, with a bias and COV of 1.15 and 15% respectively. This result is confirmed by a more extensive comparison of some methods with 23 test results in [12]. From the results of panel 5 (Table 4), it seems that most of the codes/methods are better suited to ship bottom configuration than for the frigate strength deck having a high slender plate coefficient (β=3.26) and a low stiffening ratio (α=0.26). For panel 5, the bias reaches 1.578 even though the COV is low (0.128). It is noted that the result (5.169 of Table 4) provided by the E-M8 contributor/code being "out of range" has been excluded of the statistics of panel 3.

It is also worth noting that most code predicted strengths appear conservative compared to the experimental results for panel 3 and 4 even though the actual imperfections exceed the tolerances specified. This can be attributed to the built-in conservatism of code type formulations. However, in this case, one might expect a method which accounts explicitly for imperfections to give a better prediction with regard to these results. In fact, the Imperial College method was even more conservative than the codes for panels 3 and 4. This can be explained by the fact that the maximum experimentally recorded imperfection was used in predicting the strength, clearly a conservative choice. However, this also poses a more interesting question: given a strength formulation that allows some freedom in specifying a random quantity, such as the imperfection, which criterion should the designer use in selecting a suitable value? It is obvious that the actual imperfection in the test panel will contain a number of harmonic modes and will also vary substantially from one stiffener to another within the same unit. It is perhaps necessary to carry out more than a single analysis, and to look at the sensitivity of the results obtained, before arriving at a final value which will involve, to some degree, engineering judgement. Whether this is acceptable within codified design or whether it should only be considered in more detailed evaluations is a matter for debate.

Ultimate Strength of Axial and Lateral Loading

Methods for predicting the ultimate strength under combined axial and lateral loading exhibit significantly larger model uncertainty (mean bias of 1.336 for panel 9). Of the nine methods considered only four of them can account for combined loads.

It is therefore recommended to extend the codes to include combined loading (if appropriate) and to improve the reliability of the codes which already consider combined loading.

Plating Effective Width

The effective width of the plate seems to be one of the most relevant parameters in the evaluation of ultimate strength. Effective width deviated typically by between 0 and 15%, but the discrepancy was up to 45% in some cases.

Correlation between the model uncertainty (table 4) and the effective width (table 5) is unclear as the calculation of effective width varies from code to code. For instance it was observed that some reduction factors are included in the computation of effective width or are introduced later in the equation where the effective width is used. Hence the M8 code/method used a different definition than the others. Methods M1 to M4 are based on the same definition. It is observed that these four methods provide similar effective width as well as similar ultimate strength.

Induced Failure Mode.

Table 6 shows that induced failure modes observed during experimental tests differ from those obtained from codes/methods. Moreover, large differences occur between the 15 analyses. Compared to the six Smith tests, only one analysis provided "accurate" induced failure mode (Contributor C with Code M5). This large spread is either due to a different understanding as to what "first failure mode" means or due to different interpretation of the code clauses. For instance, contributor B contained five different failure modes (on 10 panels) compared to contributor C while using the same code/method (M5). Such results would be understandable if the loads associated with the different failure modes were close but this is not the case here.

Uncertainty sources

The major sources of uncertainty appearing from these benchmark tests are the following :

- Boundary conditions :

  Some contributors analysed the panels as simply supported at both ends whilst some others considered multi-spans.

  Most of the codes/methods do not explicitly consider multi-span panels.

- Number of stiffeners to be considered in the analysis:

  Some contributors (Tables 3 and 4) modelled the panels "without edge stiffeners" and some others "with edge stiffeners". For instance, the panel 1 (B=3000 mm and b = 600 mm) was sometimes modelled as a plate of 3000mm width with 6 stiffeners ("with edge stiff.") and also as a plate with 4 stiffeners as the 2 edge stiffeners were considered as having no contribution ("without edge stiff."). This can partly be explained by referring to Smith's test [2] where the boundary conditions were such that no lateral movement of edge stiffeners was allowed.

- Modelling of initial imperfections and residual stresses:

  The influence of imperfections on the accuracy of a method is important as many codes/methods do not account for the actual imperfections and particularly not the residual stresses, but only average values, or upper limits (tolerances).

  Only two codes/methods used by two contributors considers the actual imperfections (i.e. Lloyd's Register and Imperial College). Most of the others consider averages values or upper limits. However, the comments made earlier regarding the difficulty in selecting imperfection values should be remembered.

- Induced failure and collapse modes:
  Definitions of the induced failure and collapse modes are sometimes different from code to code, are perhaps unclear and could therefore be misinterpreted.

- Understanding of code/method rules and specifications:
  Some codes/methods have been used by several contributors. It is seen that the results obtained using the same code by two different contributors are often different. Hence, this benchmark study has highlighted two kinds of uncertainties: the model uncertainty associated with the model for strength prediction (identified above) and the "human factor" uncertainties associated with the user transforming the physical problem into the mathematical model handled by the method (i.e., the modeling of the geometry, boundary conditions, etc.), errors in the respective computer code and the use of the computer. One way of overcoming the latter uncertainty is for those organizations responsible for each code to make available the results of case studies that they no doubt occasionally perform. This would also be in their interest since it would minimize the possibility of user misinterpretation of the relevant code.

- Range of validity:
  Codes/methods do not make reference to a clear definition of their range of applicability, for instance, the initial geometric imperfection, or plate/column slenderness.
  Even when the range of validity is defined, codes/methods do not provide any guidance, reference, advice or recommendation on how a user can analyse a case which is not included in this range. Some exceptions are beginning to appear, e.g. ECCS rules on shell buckling propose a method to deal with imperfections above tolerances. It was therefore observed that contributors usually use codes/methods without any reference to these ranges of validity. However, contributor E said that panel 3 was out of the range of validity.

CONCLUSIONS AND RECOMMENDATIONS

The benchmark study has demonstrated that various methods used for predicting the ultimate strength of stiffened panels under axial loading provide different results. The few methods available for predicting the ultimate strength of panels subject to combined axial and lateral loading are subject to significant uncertainties. Moreover, the implementation of a method for ultimate prediction in a computer program and its use, may lead to errors (departure from the intended procedure). To reduce such errors, methods and computer codes need to be validated and, in addition, quality assurance of actual calculations needs to be exercised. Despite this, it seems likely that ultimate strength estimates will still be affected by "human factors".

Unfortunately, the limited number of tests available does not allow the authors and the ISSC committee to separately quantify the effect of each uncertainty factor (effective width, initial imperfections, ...). Therefore, to determine the influence of, for instance, the imperfections on the accuracy of the method, it is recommended to carry out more detailed comparisons, e.g. using results obtained by refined non-linear finite element analysis.

It is also demonstrated that strength models recommended in some codes for offshore structures and bridges tend to be more accurate than some of those found in ship rules. However, it is also important to note that land-based codes are less developed than ship rules in treating combined compression and pressure. More optimised designs will result from exploiting the more refined codes. For reassessment, where data on imperfection levels may be available, methods based on numerical methods (e.g. the Imperial College procedure) is to be recommended.

REFERENCES

[1] Moan T., et al., "Report of ISSC Committee V.1 Applied Design - Strength Limit States Formulations", Jeffrey N.E. and Kendrick A.M. (eds), Institute for Marine Dynamics, ISSC, St. John's 1994, Canada, Vol 2, pp1-58, 1994

[2] Smith, C.S, "Compressive Strength of Welded Steel Ship Grillages", Trans. RINA, vol 117, 1975

[3] Rutherford S.E, " Ultimate Longitudinal Strength of Ships : A Case Study", SNAME Transactions, vol 98, 1990, pp441-471

[4] BS5400, "Code of Practice for Design of Steel Bridges, Part III", British Standards Institution, London, 1982.

[5] BV, "Règlement du Bureau Veritas pour la Classification des navires de longueur supérieure à 65 m", Partie II-A Coque, Paris, January 1991

[6] DnV-CNB, "Buckling Strength Analysis", Classification notes 30.1, May 1992

[7] DnV-S, "Rules for Classification of Ships",Oslo, 1992

[8] ECCS, "Recommendations for the Design of Longitudinally Stiffened Webs and of Stiffened Compression Flanges", 1st edition, ECCS - Technical Working Group 8.3 - Structural Stability, Publ. No 60, European Convention for Constructional Steel Work, 1990.

[9] Bonello M A, Chryssanthopoulos M K and Dowling P J, "Ultimate Strength Design of Stiffened Plates under Axial Compression and Bending", Marine Structures, Vol 6, Nos 5&6, 1993, p533-552.

[10] Bonello M.A., "Reliability Assessment and Design of Stiffened Compression Flanges", Ph.D. Thesis, Imperial College, University of London, 1992.

[11] Davidson P.C., "Design of Plate Panels Under Biaxial Compression, Shear and Lateral Pressure", Ph.D. Thesis, Imperial College, University of London, 1989.

[12] Dowling et al., "Design of Flat Stiffened Plating: Phase 1 Report", CESLIC Report SP 9, Dept. of Civil Engineering, Imperial College, London, Dec. 1991.

[13] Rutherford, S.E., "Stiffened Compression Panels. The Analytical Approach", Technical Report HSR No. 82/26/R2, Lloyd's Register of Shipping, London, 1984.

[14] Ueda Y., Yao T., "Fundamental Behavior of Plates and Stiffened Plates with Welding Imperfections", ISMS'91, Shanghai, 1991, p377-388.

[15] Ueda Y., Rashed S.M.H., Paik J.K., "Buckling and Ultimate Strength of plates and Stiffened Plates Under Combined Loads" (to be published in Marine Structures).