DSM DESIGN OF LIPPED CHANNEL COLUMNS UNDERGOING LOCAL/DISTORTIONAL/GLOBAL MODE INTERACTION

Nuno Silvestre*, Pedro B. Dinis*, Dinar Camotim* and Eduardo M. Batista**

* Civil Engineering Department, IST-ICIST, Technical University of Lisbon, Portugal
{nuno.silvestre;dinis;dcamotim}@civil.ist.utl.pt

** Civil Engineering Program, COPPE, Federal University of Rio de Janeiro, Brazil
batista@coc.ufrj.br

Keywords: Cold-formed steel columns, Lipped channels, Local/distortional/global mode interaction, Ultimate strength, Direct Strength Method (DSM).

Abstract. *This work aims at contributing towards extending the domain of application of the available DSM, by making it capable of estimating the ultimate strength of cold-formed steel lipped channel columns affected by local/distortional/global interaction. The current DSM expressions, as well as those applicable to interactive buckling design, are first introduced and an extensive numerical (shell finite element) study involving fixed columns is reported – the column geometries are selected in order to have nearly coincident local, distortional and global buckling loads. The numerical ultimate strength values obtained are then used to assess the accuracy of the DSM expressions. As a preliminary recommendation, the current DSM expressions are adequate to estimate the collapse load of lipped channel columns affected by local/distortional/global interaction.*

1 INTRODUCTION

The Direct Strength Method (DSM) has already been included in the most recent versions of the North American and Australian/New Zealander cold-formed steel design specifications. DSM provides an efficient approach to estimate the ultimate strength of cold-formed steel members experiencing global (flexural, flexural-torsional), local (L) or distortional (D) collapses, or failing in mechanisms that involve L/G interaction. The column nominal global (f_{ne}), local (f_{nl}) and distortional (f_{nd}) strengths are given by

$$f_{ne}=\begin{cases} f_y\left(0.658^{\lambda_g^2}\right) & \text{if} \quad \lambda_e\le 1.5 \\ f_y\left(\dfrac{0.877}{\lambda_g^2}\right) & \text{if} \quad \lambda_e>1.5 \end{cases} \qquad \text{where} \qquad \lambda_e=\sqrt{\frac{f_y}{f_{cre}}} \tag{1}$$

$$f_{nl}=\begin{cases} f_y & \text{if} \quad \lambda_l\le 0.776 \\ f_y\left(\dfrac{f_{crl}}{f_y}\right)^{0.4}\left[1-0.15\left(\dfrac{f_{crl}}{f_y}\right)^{0.4}\right] & \text{if} \quad \lambda_l>0.776 \end{cases} \qquad \text{where} \qquad \lambda_l=\sqrt{\frac{f_y}{f_{crl}}} \tag{2}$$

$$f_{nd}=\begin{cases} f_y & \text{if} \quad \lambda_d\le 0.561 \\ f_y\left(\dfrac{f_{crd}}{f_y}\right)^{0.6}\left[1-0.25\left(\dfrac{f_{crd}}{f_y}\right)^{0.6}\right] & \text{if} \quad \lambda_d>0.561 \end{cases} \qquad \text{where} \qquad \lambda_d=\sqrt{\frac{f_y}{f_{crd}}} \quad , \tag{3}$$

where (i) f_y is the yield stress and (ii) f_{cre}, f_{crl} and f_{crd} are the global (flexural or flexural-torsional), local and distortional critical buckling stresses. The current DSM version stipulates the need to perform two separate safety checks, regardless of the member critical buckling mode nature: (i) one against a distortional failure, involving Eq. (3), and (ii) another against a local/global (interactive) failure, given by

$$f_{nle} = \begin{cases} f_{ne} & \text{if} \quad \lambda_{le} \leq 0.776 \\ f_{ne}\left(\dfrac{f_{crl}}{f_{ne}}\right)^{0.4}\left[1-0.15\left(\dfrac{f_{crl}}{f_{ne}}\right)^{0.4}\right] & \text{if} \quad \lambda_{le} > 0.776 \end{cases} \qquad \text{where} \qquad \lambda_{le} = \sqrt{\frac{f_{ne}}{f_{crl}}} \quad , \quad (4)$$

where f_{ne} is obtained from Eq. (1), using f_{nd} instead of f_y. Since one has $f_{nle} \leq f_{ne}$, the column nominal strength always corresponds to the minimum value of the local/global (f_{nle}) and distortional (f_{nd}) failure stresses (minimum obtained from Eqs. (3) and (4)). The current DSM cannot be applied to members affected by interaction phenomena involving distortional buckling. In a similar way to the L/G interaction (Eq. (4)), Schafer [1] tested expressions to estimate the ultimate strength of columns experiencing L/D interaction, given by

$$f_{nld} = \begin{cases} f_{nd} & \text{if} \quad \lambda_{ld} \leq 0.776 \\ f_{nd}\left(\dfrac{f_{crl}}{f_{nd}}\right)^{0.4}\left[1-0.15\left(\dfrac{f_{crl}}{f_{nd}}\right)^{0.4}\right] & \text{if} \quad \lambda_{ld} > 0.776 \end{cases} \qquad \text{where} \qquad \lambda_{ld} = \sqrt{\frac{f_{nd}}{f_{crl}}} \quad . \quad (5)$$

This approach was then used by Yang and Hancock [2], Silvestre *et al.* [3] and Kwon *et al.* [4]. In a similar way, the nominal strength against distortional/global interactive failure (f_{nde}) may be given by

$$f_{nde} = \begin{cases} f_{ne} & \text{if} \quad \lambda_{de} \leq 0.561 \\ f_{ne}\left(\dfrac{f_{crd}}{f_{ne}}\right)^{0.6}\left[1-0.25\left(\dfrac{f_{crd}}{f_{ne}}\right)^{0.6}\right] & \text{if} \quad \lambda_{de} > 0.561 \end{cases} \qquad \text{where} \qquad \lambda_{de} = \sqrt{\frac{f_{ne}}{f_{crd}}} \quad , \quad (6)$$

where f_{ne} is obtained from Eq. (1), using f_{ne} instead of f_y. Finally, when the three buckling modes (global, local and distortional) occur simultaneously, the column strength is expected to be affected by the three buckling stresses (f_{cre}, f_{crl}, f_{crd}). Very recently, Dinis *et al.* [5, 6] started an investigation on the post-buckling behaviour and ultimate strength of lipped channel columns experiencing L/D/G interaction, comprising both numerical and experimental results – to the authors' best knowledge, there are virtually no other studies available on this subject. Following an approach similar to the previous ones, the ultimate strength of cold-formed steel columns experiencing (triple) interaction between global (FT – flexural-torsional), local (L) and distortional (D) buckling modes can be determined from the expression

$$f_{nlde} = \begin{cases} f_{nde} & \text{if} \quad \lambda_{lde} \leq 0.776 \\ f_{nde}\left(\dfrac{f_{crl}}{f_{nde}}\right)^{0.4}\left[1-0.15\left(\dfrac{f_{crl}}{f_{nde}}\right)^{0.4}\right] & \text{if} \quad \lambda_{lde} > 0.776 \end{cases} \qquad \text{where} \qquad \lambda_{lde} = \sqrt{\frac{f_{nde}}{f_{crl}}} \quad , \quad (7)$$

where f_{nde} is obtained from Eq. (6). The aim of this work is to assess the performance of these approaches in estimating the ultimate strength of fixed lipped channel columns exhibiting nearly coincident global, local and distortional buckling stresses, through the comparison with the numerical results obtained from shell finite element analyses performed in the code ABAQUS [7].

2 COLUMN PROPERTIES, FE RESULTS AND DSM ESTIMATES

Since the existing DSM expressions were calibrated against experimental results concerning mostly fixed columns (rigid plates attached to their end sections), it was decided to analyse also a set of fixed lipped channel columns with geometries (cross-section dimensions and lengths) that are highly prone to L/D/G interaction. In order to estimate the ultimate strength of a given column the DSM requires the evaluation of its local (f_{crl}), distortional (f_{crd}) and global (f_{cre}) critical stresses. In fixed columns, it is well known that semi-analytical finite strip analyses provide lower bounds for f_{crl}, f_{crd} and f_{cre} – exact values can only be obtained using either GBT or shell finite element (SFE) analyses. In this work, the SFE code ABAQUS [7] is used to determine both the critical stresses (f_{crl}, f_{crd}, f_{cre}) and the "exact" (numerical) ultimate strengths (f_n) of the columns experiencing L/D/G interaction.

The column cross-section dimensions and lengths were previously selected to ensure nearly coincident critical stresses (f_{cre}≈f_{crl}≈f_{crd}) and a wide range of (local, distortional and global) slenderness values, adopting the following procedure: (i) the cross-section dimensions were first chosen, by a trial-and-error procedure, to exhibit nearly coincident f_{crl} and f_{crd} values (equal minima), and (ii) the length was then selected to ensure that, for this critical stress level, the column also buckles in a global (flexural-torsional) mode. The steel sheet thickness is t=1.1 mm for all cross-sections and the column geometries obtained with this procedure are shown in Table 1 – b_w, b_f, b_s, L and A are the web height, flange width, lip width, column length and cross-section area. These cross-section dimensions fall into the $46 \leq b_w/t \leq 75$, $36 \leq b_f/t \leq 71$, $9 \leq b_s/t \leq 11$, $1.0 \leq b_w/b_f \leq 1.4$ and $0.15 \leq b_s/b_f \leq 0.25$ ranges – since the current DSM limits for pre-qualified columns are $b_w/t<472$, $b_f/t<159$, $4<b_l/t<33$, $0.7<b_w/b_f<5.0$ and $0.05<b_l/b_f<0.41$, one readily notices that all columns satisfy the geometrical requirements. Table 1 also displays the stress values corresponding to the first local (L), distortional (D) and flexural-torsional (FT) buckling modes, obtained from SFE analyses ($E=210\times10^3$ N/mm^2, $\nu=0.3$). With one exception (column C4), the maximum difference between the first ($f_{cr.1}$) and third ($f_{cr.3}$) buckling stresses never reaches 3%. The SFE column ultimate strength values were calculated by means of the following procedure:

(i) Columns C1 to C6: flexural-torsional initial geometrical imperfections with a very small amplitude (L/2000) and six yield stress values (f_y) were considered. Four of these values correspond to specific column flexural-torsional slenderness values (λ_e=1.0, 1.5, 2.0, 2.5, with $f_y = \lambda_e^2 f_{cre}$) and the remaining two are equal to f_y=265 and 340 N/mm^2. A total of 36 columns were analysed and Table 2 provides their yield stresses and numerically obtained ultimate stresses (f_u).

(ii) Columns C7 to C17: flexural-torsional initial geometrical imperfections with a small amplitude L/1000 and seven yield stresses were considered, four of them corresponding to flexural-torsional slenderness values λ_e=1.0, 1.5, 2.0, 2.5, and the remaining three equal to f_y=235, 350 and 520 N/mm^2. A total of 77 columns were analysed and Tables 3.1 (C7-C11) and 3.2 (C12-C17) show their yield and ultimate stresses.

Table 1: Cross-section geometries and critical stress values (f_{cr})

Column	b_w (mm)	b_f (mm)	b_s (mm)	L (mm)	A (mm^2)	$f_{cr.1}$ (N/mm^2)	Mode	$f_{cr.2}$ (N/mm^2)	Mode	$f_{cr.3}$ (N/mm^2)	Mode
C1	60	42	10	1380	180.4	366.4	L	371.4	D	372.7	FT
C2	76	60	10	2360	237.6	194.8	D	195.4	FT	199.5	L
C3	62	50	10	1600	200.2	289.3	D	292.2	FT	304.0	L
C4	52	47	11	1200	184.8	388.2	D	392.1	FT	425.1	L
C5	71	60	11	2100	234.3	221.2	D	221.5	L	221.5	FT
C6	75	65	11	2370	249.7	190.4	D	191.9	FT	195.3	L
C7	51	40	10	1100	166.1	441.5	D	444.4	FT	444.5	L
C8	62	50	10	1600	200.2	292.0	FT	293.0	D	295.1	L
C9	69	55	10	1950	218.9	234.7	D	238.7	FT	240.8	L
C10	76	60	10	2350	237.6	194.9	D	195.8	FT	199.5	L
C11	82	65	10	2750	255.2	166.2	D	166.9	FT	170.4	L
C12	52	47	11	1200	184.8	386.1	D	390.5	FT	396.1	L
C13	62	55	11	1650	213.4	275.4	D	278.7	FT	281.7	L
C14	71	60	11	2100	234.3	221.2	D	221.5	L	221.6	FT
C15	75	65	11	2350	249.7	190.4	D	194.5	FT	195.3	L
C16	82	70	11	2800	268.4	161.4	D	162.4	FT	164.4	L
C17	81	78	12	2850	287.1	149.4	D	152.7	L	153.6	FT

Table 2: Columns C1 to C6: yield (f_y) and ultimate (f_u) stresses and DSM estimates (f_n) – N/mm^2

Column	f_y	f_u	f_{nd}	f_{nd}/f_u	f_{ne}	f_{ne}/f_u	f_{nle}	f_{nle}/f_u	f_{nde}	f_{nde}/f_u	f_{nlde}	f_{nlde}/f_u
C1-1.0	363	286	275	0.96	242	0.84	235	0.82	212	0.74	212	0.74
C1-1.5	818	329	430	1.31	326	0.99	288	0.88	257	0.78	245	0.75
C1-2.0	1454	337	570	1.69	327	0.97	288	0.86	258	0.76	245	0.73
C1-2.5	2272	355	702	1.98	327	0.92	288	0.81	258	0.73	245	0.69
C1-265	265	234	225	0.96	197	0.84	197	0.84	183	0.78	183	0.78
C1-340	340	275	264	0.96	232	0.84	228	0.83	206	0.75	206	0.75
C2-1.0	193	146	145	1.00	128	0.87	125	0.86	112	0.76	112	0.76
C2-1.5	435	169	227	1.34	171	1.01	153	0.91	135	0.80	130	0.77
C2-2.0	773	187	301	1.61	171	0.92	153	0.82	135	0.72	130	0.70
C2-2.5	1208	197	370	1.88	171	0.87	153	0.78	135	0.69	130	0.66
C2-265	265	161	175	1.08	150	0.93	140	0.87	124	0.77	123	0.76
C2-340	340	167	200	1.20	164	0.98	149	0.89	131	0.79	128	0.77
C3-1.0	287	220	216	0.98	190	0.86	188	0.85	166	0.75	166	0.75
C3-1.5	646	256	337	1.32	256	1.00	230	0.90	201	0.79	195	0.76
C3-2.0	1148	278	447	1.61	256	0.92	230	0.83	201	0.72	196	0.70
C3-2.5	1794	309	550	1.78	256	0.83	230	0.75	201	0.65	196	0.63
C3-265	265	211	206	0.97	181	0.86	181	0.86	161	0.76	161	0.76
C3-340	340	236	239	1.01	209	0.89	200	0.85	177	0.75	177	0.75
C4-1.0	385	297	290	0.98	255	0.86	255	0.86	223	0.75	223	0.75
C4-1.5	866	353	453	1.28	344	0.97	313	0.89	270	0.77	266	0.75
C4-2.0	1540	378	600	1.59	344	0.91	313	0.83	270	0.72	266	0.70
C4-2.5	2407	383	738	1.93	344	0.90	313	0.82	270	0.71	266	0.69
C4-265	265	233	228	0.98	200	0.86	200	0.86	187	0.80	187	0.80
C4-340	340	276	268	0.97	237	0.86	237	0.86	211	0.77	211	0.77
C5-1.0	219	165	165	1.00	145	0.88	141	0.86	127	0.77	127	0.77
C5-1.5	494	192	258	1.34	194	1.01	172	0.90	153	0.80	147	0.76
C5-2.0	878	199	342	1.72	194	0.98	172	0.87	153	0.77	147	0.74
C5-2.5	1372	204	421	2.06	194	0.95	172	0.85	153	0.75	147	0.72
C5-265	265	178	184	1.04	161	0.90	152	0.85	136	0.76	135	0.76
C5-340	340	186	212	1.14	179	0.96	163	0.88	145	0.78	142	0.76
C6-1.0	189	142	142	1.00	125	0.88	123	0.86	109	0.77	109	0.77
C6-1.5	425	165	222	1.35	168	1.02	150	0.91	132	0.80	128	0.77
C6-2.0	755	180	294	1.63	168	0.93	150	0.83	132	0.74	128	0.71
C6-2.5	1180	185	362	1.96	168	0.91	150	0.81	132	0.72	128	0.69
C6-265	265	158	173	1.09	149	0.94	138	0.87	122	0.77	121	0.77
C6-340	340	163	198	1.21	162	0.99	146	0.90	129	0.79	126	0.77

(iii) Columns C18 to C20: to enable a fruitful comparison between the above two column sets, the columns C1, C4 and C6 (see Table 1) were also analysed with a flexural-torsional initial imperfection with amplitude L/1000 (instead of L/2000). To avoid confusion with the previous columns, these three new columns are labelled as C18, C19 and C20. The seven yield stresses described in the previous item (columns C7-17) were considered, which corresponds to a total of 21 columns analysed – their yield and ultimate stresses are given in Table 4.

The relations between the elastic modulus ($E=210\times10^3$ N/mm^2) and the adopted yield stress values fall into the range $76 \leq E/f_y \leq 1405$. Note that, since the current DSM limit for pre-qualified columns is $E/f_y>340$, 48 out of the 134 columns analysed do not satisfy this material requirement – nevertheless, these columns were considered, in order to cover high slenderness values. The above tables also include the DSM estimates, namely (i) distortional (f_{nd} – Eq. (3)), (ii) global (f_{ne} – Eq. (1)), (iii) local/global (f_{nle} – Eq. (4)), (iv) distortional/global (f_{nde} – Eq. (6)) and (iv) local/distortional/global (f_{nlde} – Eq. (7)) ultimate strengths, as well as their ratios with respect to the numerical values (f_u). Finally, Figure 1 shows the five DSM design curves (distortional, global, local/global, distortional/global and local/distortional/global), as well as the variation of the numerical ("exact") f_u/f_y values with the global slenderness λ_e (note that $\lambda_e \approx \lambda_d \approx \lambda_l$) – the black circles, white circles and grey triangles correspond to the C1-C6, C7-C17 and C18-C20 columns. The analysis of these numerical and predicted results prompts the following remarks:

(i) Obviously, the DSM predictions decrease as one travels from the distortional (D) to the local/distortional/global (LDG) design curves, following the order given above.

Table 3.1: Columns C7 to C11: yield (f_y) and ultimate (f_u) stresses and DSM estimates (f_n) – N/mm^2

Column	f_y	f_u	f_{nd}	f_{nd}/f_u	f_{ne}	f_{ne}/f_u	f_{nle}	f_{nle}/f_u	f_{nde}	f_{nde}/f_u	f_{nlde}	f_{nlde}/f_u
C7-1.0	442	313	331	1.06	291	0.93	284	0.91	254	0.81	254	0.81
C7-1.5	993	382	517	1.35	390	1.02	346	0.91	307	0.80	294	0.77
C7-2.0	1766	411	685	1.67	390	0.95	346	0.84	307	0.75	294	0.72
C7-2.5	2759	423	842	1.99	390	0.92	346	0.82	307	0.73	294	0.69
C7-235	235	207	218	1.05	188	0.91	188	0.91	183	0.88	183	0.88
C7-350	355	277	289	1.04	254	0.92	254	0.92	231	0.83	231	0.83
C7-520	520	335	365	1.09	319	0.95	302	0.90	270	0.81	269	0.80
C8-1.0	293	200	220	1.10	193	0.96	188	0.94	168	0.84	168	0.84
C8-1.5	659	245	343	1.40	256	1.05	228	0.93	202	0.83	194	0.79
C8-2.0	1172	273	455	1.67	256	0.94	228	0.84	202	0.74	194	0.71
C8-2.5	1831	267	559	2.09	256	0.96	228	0.85	202	0.76	194	0.73
C8-235	235	178	192	1.08	168	0.94	168	0.94	153	0.86	153	0.86
C8-350	355	217	246	1.13	213	0.98	201	0.93	180	0.83	179	0.83
C8-520	520	236	303	1.29	247	1.05	222	0.94	198	0.84	191	0.81
C9-1.0	235	161	176	1.09	156	0.97	152	0.94	135	0.84	135	0.84
C9-1.5	528	200	275	1.37	209	1.05	186	0.93	164	0.82	158	0.79
C9-2.0	939	226	364	1.61	209	0.93	186	0.82	164	0.73	158	0.70
C9-2.5	1467	222	448	2.02	209	0.94	186	0.84	164	0.74	158	0.71
C9-235	235	162	176	1.09	156	0.96	152	0.94	135	0.84	135	0.84
C9-350	355	185	223	1.21	190	1.03	175	0.94	155	0.84	152	0.82
C9-520	520	200	273	1.36	209	1.04	186	0.93	164	0.82	158	0.79
C10-1.0	195	133	146	1.10	128	0.97	126	0.95	112	0.84	112	0.84
C10-1.5	439	166	228	1.37	172	1.03	153	0.92	135	0.82	130	0.79
C10-2.0	780	187	302	1.62	172	0.92	153	0.82	135	0.72	130	0.70
C10-2.5	1218	209	372	1.78	172	0.82	153	0.73	135	0.65	130	0.62
C10-235	235	143	163	1.14	142	0.99	135	0.94	120	0.84	120	0.84
C10-350	355	156	205	1.31	166	1.07	150	0.96	133	0.85	129	0.82
C10-520	520	173	249	1.44	172	0.99	153	0.89	135	0.78	130	0.75
C11-1.0	166	111	125	1.12	110	0.99	107	0.97	96	0.86	96	0.86
C11-1.5	374	136	195	1.43	146	1.08	131	0.96	115	0.85	111	0.82
C11-2.0	665	158	258	1.63	146	0.93	131	0.83	115	0.73	111	0.70
C11-2.5	1039	162	317	1.96	146	0.90	131	0.81	115	0.71	111	0.69
C11-235	235	127	152	1.20	130	1.03	121	0.95	107	0.84	106	0.83
C11-350	355	139	189	1.36	146	1.05	130	0.94	115	0.83	111	0.80
C11-520	520	152	229	1.51	146	0.96	131	0.86	115	0.76	111	0.73

Table 3.2: Columns C12 to C17: yield (f_y) and ultimate (f_u) stresses and DSM estimates (f_n) – N/mm^2

Column	f_y	f_u	f_{nd}	f_{nd}/f_u	f_{ne}	f_{ne}/f_u	f_{nle}	f_{nle}/f_u	f_{nde}	f_{nde}/f_u	f_{nlde}	f_{nlde}/f_u
C12-1.0	386	269	290	1.08	255	0.95	250	0.93	222	0.83	222	0.83
C12-1.5	869	336	452	1.35	342	1.02	305	0.91	269	0.80	259	0.77
C12-2.0	1544	365	599	1.64	342	0.94	305	0.84	269	0.74	259	0.71
C12-2.5	2413	388	737	1.90	342	0.88	305	0.79	269	0.69	259	0.67
C12-235	235	198	210	1.06	183	0.92	183	0.92	174	0.88	174	0.88
C12-350	355	257	275	1.07	243	0.94	241	0.94	215	0.84	215	0.84
C12-520	520	302	344	1.14	298	0.99	278	0.92	246	0.82	244	0.81
C13-1.0	275	187	207	1.10	182	0.97	178	0.95	159	0.85	159	0.85
C13-1.5	620	236	322	1.37	244	1.04	218	0.92	192	0.81	185	0.78
C13-2.0	1102	259	427	1.65	244	0.94	218	0.84	192	0.74	185	0.71
C13-2.5	1721	283	525	1.86	244	0.86	218	0.77	192	0.68	185	0.65
C13-235	235	171	187	1.10	165	0.97	165	0.97	148	0.87	148	0.87
C13-350	355	206	239	1.16	208	1.01	195	0.95	173	0.84	172	0.84
C13-520	520	226	294	1.30	238	1.05	214	0.95	189	0.84	183	0.81
C14-1.0	221	149	166	1.11	146	0.98	142	0.95	127	0.85	127	0.85
C14-1.5	498	186	259	1.39	194	1.05	172	0.93	153	0.82	147	0.79
C14-2.0	885	201	343	1.71	194	0.97	172	0.86	153	0.76	147	0.73
C14-2.5	1383	197	422	2.14	194	0.99	172	0.88	153	0.78	147	0.74
C14-235	235	153	172	1.12	151	0.99	145	0.95	130	0.85	130	0.85
C14-350	355	174	217	1.25	182	1.04	165	0.95	147	0.84	143	0.82
C14-520	520	188	265	1.41	194	1.03	172	0.92	153	0.82	147	0.78
C15-1.0	190	128	143	1.12	126	0.99	124	0.97	110	0.86	110	0.86
C15-1.5	428	163	223	1.37	170	1.05	151	0.93	133	0.82	128	0.79
C15-2.0	762	181	295	1.63	171	0.94	152	0.84	134	0.74	128	0.71
C15-2.5	1190	184	363	1.97	171	0.93	152	0.82	134	0.73	128	0.70
C15-235	235	140	161	1.15	142	1.01	134	0.95	119	0.85	118	0.85
C15-350	355	154	202	1.31	165	1.07	148	0.96	131	0.85	127	0.82
C15-520	520	170	246	1.44	171	1.00	152	0.89	134	0.79	128	0.75
C16-1.0	161	107	121	1.13	106	1.00	104	0.97	93	0.87	93	0.87
C16-1.5	363	137	189	1.38	142	1.04	127	0.93	112	0.82	108	0.79
C16-2.0	646	152	250	1.65	142	0.94	127	0.83	112	0.74	108	0.71
C16-2.5	1009	170	308	1.81	142	0.84	127	0.75	112	0.66	108	0.63
C16-235	235	123	150	1.22	128	1.04	118	0.96	105	0.85	103	0.84
C16-350	355	154	187	1.21	142	0.92	127	0.82	112	0.73	108	0.70
C16-520	520	170	226	1.33	142	0.84	127	0.75	112	0.66	108	0.63
C17-1.0	149	98,5	112	1.14	99	1.01	97	0.99	86	0.88	86	0.88
C17-1.5	336	128	175	1.37	135	1.05	119	0.93	105	0.82	101	0.79
C17-2.0	598	145	232	1.60	135	0.93	119	0.82	105	0.73	101	0.70
C17-2.5	934	158	285	1.80	135	0.85	119	0.76	105	0.67	101	0.64
C17-235	235	115	145	1.26	124	1.08	113	0.98	100	0.87	97	0.85
C17-350	355	129	180	1.39	135	1.04	119	0.92	105	0.82	101	0.78
C17-520	520	139	217	1.56	135	0.97	119	0.86	105	0.76	101	0.73

(ii) The distortional DSM estimates are generally very unsafe and highly scattered – the f_{nd}/f_u values have average and standard deviation equal to 1.37 and 0.32. Only a few C18-C20 columns with low slenderness have f_u/f_y values lying above the DSM distortional curve.

(iii) The global DSM predictions are generally quite accurate and exhibit a rather low scatter – the f_{ne}/f_u values have

Table 4: Columns C18 to C20: yield (f_y) and ultimate (f_u) stresses and DSM estimates (f_n) – N/mm^2

Column	f_y	f_u	f_{nd}	f_{nd}/f_u	f_{ne}	f_{ne}/f_u	f_{nle}	f_{nle}/f_u	f_{nde}	f_{nde}/f_u	f_{nlde}	f_{nlde}/f_u
C18-1.0	378	264	281	1.07	247	0.94	239	0.90	215	0.81	215	0.81
C18-1.5	850	317	439	1.38	327	1.03	288	0.91	258	0.81	245	0.77
C18-2.0	1512	336	581	1.73	327	0.97	288	0.86	258	0.77	245	0.73
C18-2.5	2362	336	714	2.13	327	0.97	288	0.86	258	0.77	245	0.73
C18-235	235	199	208	1.04	180	0.91	180	0.91	171	0.86	171	0.86
C18-350	355	256	271	1.06	238	0.93	233	0.91	210	0.82	210	0.82
C18-520	520	294	338	1.15	290	0.99	266	0.90	239	0.81	233	0.79
C19-1.0	388	268	291	1.09	257	0.96	256	0.96	223	0.83	223	0.83
C19-1.5	873	343	454	1.32	344	1.00	313	0.91	270	0.79	266	0.77
C19-2.0	1553	376	602	1.60	344	0.91	313	0.83	270	0.72	266	0.71
C19-2.5	2426	384	741	1.93	344	0.90	313	0.82	270	0.70	266	0.69
C19-235	235	199	210	1.06	183	0.92	183	0.92	174	0.88	174	0.88
C19-350	355	257	276	1.07	243	0.95	243	0.95	215	0.84	215	0.84
C19-520	520	302	345	1.14	298	0.99	284	0.94	247	0.82	247	0.82
C20-1.0	190	127	143	1.12	126	0.99	123	0.97	110	0.86	110	0.86
C20-1.5	428	162	223	1.38	168	1.04	150	0.93	132	0.82	128	0.79
C20-2.0	762	179	295	1.65	168	0.94	150	0.84	132	0.74	128	0.71
C20-2.5	1190	201	363	1.81	168	0.84	150	0.75	132	0.66	128	0.63
C20-235	235	139	161	1.16	141	1.01	133	0.96	118	0.85	118	0.85
C20-350	355	153	202	1.32	164	1.07	147	0.96	130	0.85	126	0.82
C20-520	520	169	246	1.45	168	1.00	150	0.89	132	0.78	128	0.75

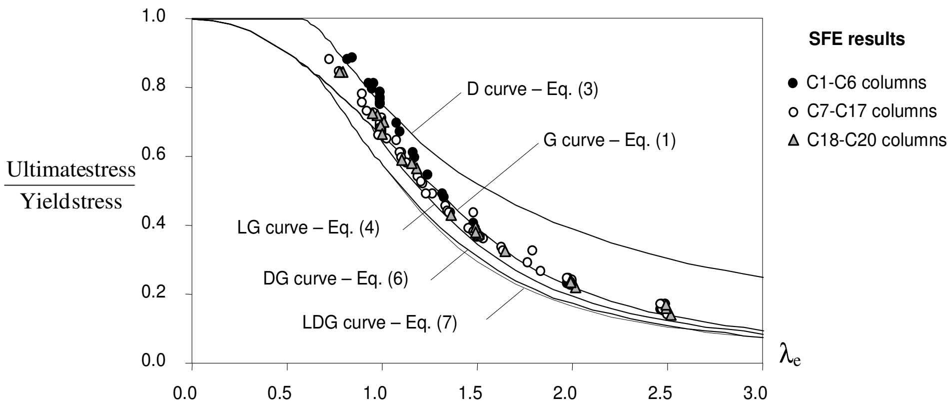

Figure 1: DSM design curves and variation of numerical f_u/f_y values with the global slenderness λ_e

average and standard deviation equal to 0.96 and 0.06. Almost all of the unsafe estimates correspond to columns with moderate slenderness ($1.0<\lambda_e\leq1.5$).

(iv) All DSM estimates associated with interactive failure (LG, DG and LDG) are safe and exhibit the same low scatter (0.06 standard deviation). However, they are increasingly less accurate (overly conservative) – the averages of the f_{nle}/f_u, f_{nde}/f_u and f_{nlde}/f_u values are equal to 0.89, 0.79 and 0.77.

(v) The DSM global estimate ratios f_{ne}/f_u are (v_1) less accurate (slightly safer) for the C1-6 columns (0.92 average and 0.06 standard deviation) and (v_2) more accurate (and still safe) for the C7-17 columns (0.98 average and 0.06 standard deviation). The C18-20 columns are in an intermediate situation (0.96 average and 0.05 standard deviation).

(vi) The DSM local/distortional/global curve is clearly too conservative, even when f_y is much higher than $f_{crl} \approx f_{crd} \approx f_{cre}$ and there is enough room for elastic coupling effects to develop before yielding causes the column failure. This is due to the fact that the small (almost negligible) global post-buckling strength governs the column behaviour collapse, which precludes the occurrence of a meaningful interaction between the global buckling mode and the local and/or distortional buckling modes.

(vii) Figure 1 shows that the numerical values correlate fairly well with (ii_1) the DSM global curve, for $\lambda_e > 1.5$ (high slenderness), and (ii_2) the DSM local/global interactive curve, for $1.0 < \lambda_e \leq 1.5$ (moderate slenderness). In the low slenderness range ($\lambda_e \leq 1.0$), the f_u/f_y values lie well above DSM global curve and, moreover, they approach the DSM distortional curve as λ_e decreases.

(viii) Recalling that 12 C1-6 and C18-20 columns only differ in the initial imperfection amplitude (L/2000 vs. L/1000), the comparison between the corresponding f_{ne}/f_u values makes it possible to assess how imperfection-sensitive are the DSM estimates. The maximum percentage difference between the two sets of f_{ne}/f_u values is equal to 11.0% and occurs for C1-1.0/C18-1.0, C4-1.0/C19-1.0 and C6-1.0/C20-1.0, which means that the DSM estimates are more imperfection-sensitive for columns with low slenderness ($\lambda_e \leq 1.0$). This can be confirmed by looking at Figure 1, where the black circles and grey triangles are slightly more apart in the low slenderness range.

(ix) There was also good numerical/DSM agreement for the 48 columns not satisfying $E/f_y > 340$ (high slenderness). This preliminary study indicates that this requirement may be too restrictive for high strength steels.

3 CONCLUSION

A numerical (shell finite element) investigation on the ultimate strength and DSM design of fixed lipped channel columns experiencing local/distortional/global interaction was reported. A total of 134 columns were analysed, all exhibiting nearly coincident L, D and G buckling stresses, containing low or moderate imperfections and displaying a wide range of slenderness values. The following aspects deserve to be highlighted:

(i) For the imperfections considered (global with L/1000 or L/2000 amplitudes), good (always safe and fairly economic) ultimate stress predictions are provided by the DSM local/global design curve. However, for $\lambda_e < 1.0$ (stocky columns), these predictions are overly conservative and the DSM global curve becomes a better choice.

(i) Although the DSM local/distortional/global design curve yields excessively conservative estimates, it should be noted the consideration of higher (probably "more realistic") imperfection amplitudes will inevitably lower the column ultimate strengths, thus bringing the numerical results closer to this design curve.

Finally, the authors recognise that experimental investigations are crucial to confirm and/or improve the findings presented in this study. In this context, fixed lipped channel column experimental tests were recently performed [6] and further tests are currently under way, as reported in another paper included in these Proceedings.

REFERENCES

[1] Schafer BW, "Local, distortional and Euler buckling in thin-walled columns. *Journal of Structural Engineering* (ASCE), **128**(3), 289-299, 2002.

[2] Yang D., Hancock G.J., "Compression tests of high strength steel channel columns with interaction between local and distortional buckling", *Journal of Structural Engineering* (ASCE), **130**(12):1954-1963, 2004.

[3] Silvestre N, Camotim D, Dinis PB, "Direct strength prediction of lipped channel columns experiencing local-plate/distortional interaction", *International Journal of Advanced Steel Construction*, **5**(1):49-71, 2009.

[4] Kwon YB, Kim BS, Hancock GJ, "Compression tests of high strength cold-formed steel channels with buckling interaction", *Journal of Constructional Steel Research*, **65**(2):278-289, 2009.

[5] Dinis PB, Camotim D, "Local/distortional/global buckling mode interaction in cold-formed steel lipped channel columns", *Proceedings of SSRC Annual Stability Conference* (Phoenix, 1-4/4), 295-323, 2009.

[6] Dinis PB, Camotim D, Batista E, Santos E, "Local/distortional/global mode coupling in fixed lipped channel columns: behaviour and strength", *Proceedings of 6th International Conference on Advances in Steel Structures* (ICASS'09 – Hong Kong, 16-18/12), SL Chan (ed.), 19-34, 2009.

[7] DS Simulia Inc. *ABAQUS Standard* (version 6.7), 2007.