

# ON THE STRENGTH AND DSM DESIGN OF COLD-FORMED STEEL COLUMNS FAILING DISTORTIONALLY UNDER FIRE CONDITIONS

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**Abstract.** *This paper reports the results of an ongoing shell finite element investigation on the distortional post-buckling behaviour, ultimate strength and design of pinned and fixed cold-formed steel lipped channel and rack-section columns subjected to various (uniform) temperature distributions caused by fire conditions. The columns are axially compressed up to failure, making it possible to assess the influence of the temperature on their ultimate strength. The steel material behaviour at elevated temperatures is described by the model prescribed in Eurocode 3 for cold-formed steel. The failure load data gathered are then used to carry out a preliminary assessment on the applicability of the Direct Strength Method (DSM) to estimate the load-carrying capacity of pinned and fixed lipped channel and rack-section columns failing distortionally under fire conditions.*

## 1 INTRODUCTION

The use of cold-formed steel profiles in industrial or residential buildings has grown steadily in the last few years, mainly due to their high structural efficiency (strength-to-weight ratio), fabrication versatility and increasingly low production and erection costs. Therefore, it is important to assess the structural response of such profiles under high temperatures, namely those caused by fire – this has already been extensively done for hot-rolled (mostly) and welded steel members. However, the research effort devoted to cold-formed steel members under fire is still relatively scarce, as attested by the fairly small number of existing publications – the works of Kaitila [1], Chen & Young [2,3], Feng *et al.* [4] and Ranawaka & Mahendran [5] deserve a special mention. Moreover, only the last of these studies addresses members failing in distortional modes. Thus, the aim of this work is to report the available results of an ongoing shell finite element investigation on the post-buckling behaviour, ultimate strength and design of axially compressed pinned (simply supported) and fixed cold-formed steel lipped channel and rack-section columns failing distortionally at elevated temperatures caused by fire conditions. Since there are no specific rules available to predict the ultimate load of such cold-formed steel columns, ultimate load data concerning columns made from various steel grades (covering a wide distortional slenderness range) are obtained and then used to make a preliminary assessment on the applicability of the Direct Strength Method (DSM [6]) to perform this task for pinned and fixed lipped channel and rack-section columns.

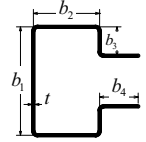
## 2 NUMERICAL ANALYSIS

### 2.1 Column geometry and buckling behavior

The cold-formed steel lipped channel and rack-section columns analysed in this work exhibit the cross-section dimensions and elastic constants displayed in table 1. These cross-section dimensions make it possible to select column lengths ensuring distortional critical buckling modes for both simply supported (locally and globally pinned end sections that may warp freely) and fixed (locally and globally fixed end sections prevented from warping) columns. The buckling analyses required to identify the above column geometries were carried out in the code *GBTUL* [7], based on a recently developed *Generalised Beam Theory* (GBT) formulation [8].

Table 1. Column cross-section dimensions and elastic constants

Column	$b_1$ (mm)	$b_2$ (mm)	$b_3$ (mm)	$b_4$ (mm)	$t$ (mm)	$E$ (GPa)	$\nu$
Rack	134.7	80.8	24.2	47.1	2.3	210	0.3
Lipped C	130	100	12.5	--	2.0	205	0.3



The curves depicted in figures 1(a)-(b) provide the variation of the elastic critical buckling stress  $\sigma_{cr}$ , normalised with respect to the critical (distortional) buckling at room temperature ( $\sigma_{cr,D,20}$ ), with the column length  $L$  (logarithmic scale) and temperature  $T$ , for pinned and fixed rack-section and lipped-channel columns – 4 temperatures are considered: 20/100°C (“room temperature”), 500°C, 600°C and 800°C. Also shown are the critical (distortional) buckling mode shapes of the four column sets analysed. One readily observes that, within each set, (i) a given buckling curve is obtainable through a “vertical translation” of the top one, with a magnitude that depends exclusively on the Young’s modulus erosion due to the rising temperature (Poisson’s ratio  $\nu$  is deemed temperature-independent and equal to 0.3), and that (ii) the critical distortional stress ( $\sigma_{cr,D,T}$ ) corresponds to the same length ( $L_D$ ) for each column set. Table 2 indicates the values of  $L_D$  and  $\sigma_{cr,D,20}$  concerning the four column sets dealt with in this work.

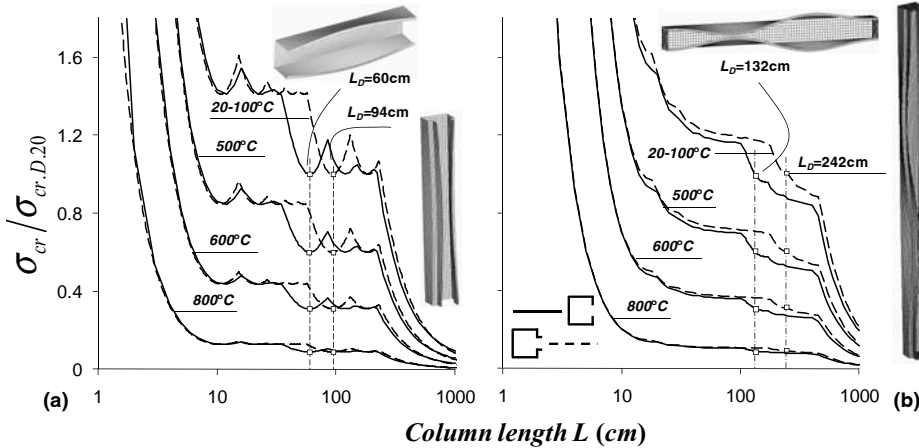


Figure 1: Variation of the buckling curve ( $\sigma_{cr}/\sigma_{cr,D,20}$  vs.  $L$ ) with  $T$  for (a) pinned and (b) fixed rack-section and lipped channel columns.

Table 2. Column lengths and critical stresses

Cross-section	Rack		Lipped Channel	
	Pinned	Fixed	Pinned	Fixed
$L_D$ (cm)	94	242	60	132
$\sigma_{cr,D,20}$ (MPa)	210.4	253.7	155.4	191.5

## 2.2 Shell finite element post-buckling analyses

The column post-buckling analyses were carried out in the code ANSYS [9] and employing a shell finite element model previously validated by the authors [10] that involves column discretisations into fine SHELL181 (ANSYS nomenclature) element meshes – thin-shell four-node elements with six d.o.f. per node. A parametric study was carried out with the aim of assessing how the (elevated) temperature influences the post-buckling and ultimate strength behaviour of pinned and fixed lipped channel and rack-section columns buckling in distortional

modes. The analyses (i) were performed by means of an incremental-iterative technique combining Newton-Raphson's method with an arc-length control strategy and (ii) simulate the response of columns subjected to a uniform temperature distribution (they are deemed engulfed in flames and, thus, share the temperature of the surrounding air [11, 12]) and subsequently axially compressed up to and beyond failure – *steady state* analyses providing *failure loads*. At this stage, it is worth noting that the authors [10, 12] have recently shown that the failure loads yielded by the *steady state* analyses match the more realistic *failure temperatures* obtained through the “corresponding” *transient* analyses (axially compressed columns heated up to failure), which means that the column (distortional) failure under fire conditions can be fully investigated by resorting only to failure loads.

The columns analysed contained initial geometrical imperfections with a critical-mode (distortional) shape and amplitude equal to 10% of the wall thickness  $t$  – due to the column distortional post-buckling asymmetry (e.g., [13]), these initial imperfections involve outward (lipped channel columns) and inward (rack-section columns) flange-lip motions, which are those leading to lower post-buckling strengths. These columns were made of different steel grades, whose constitutive relations were assumed to vary with the temperature according to the model prescribed in Eurocode 3 (Part 1.2) [14].

The column end sections were either (locally and globally) *pinned* or *fixed* (torsional rotations prevented in both cases) – the latter condition was modelled by means of rigid end-plates attached to the cross-section centroids and only allowed to exhibit axial translations. Finally, the axial compression was applied by means of either (i) two sets of concentrated forces acting on the both end section nodes (pinned columns) or (ii) two point loads acting on the end-plate points corresponding to the cross-section centroids (fixed columns) – these loadings were applied in small increments, making use of the ANSYS automatic load stepping procedure.

### 2.3 Column post-buckling behaviour and ultimate strength

Figure 2 shows geometrically and materially non-linear equilibrium paths ( $\sigma/\sigma_{cr,D,20}$  vs.  $v/t$ , where  $\sigma$  is the applied stress and  $v$  is the maximum vertical displacement along the flange-stiffener longitudinal edges) concerning pinned and fixed lipped channel and rack-section columns made of two steel grades (*S355* and *S700*) and subjected to four uniform temperatures ( $20/100^\circ\text{C}$ - $300^\circ\text{C}$ - $500^\circ\text{C}$ - $700^\circ\text{C}$ ). The circles located on the curves indicate the ultimate stress ratios  $\sigma_u/\sigma_{cr,D,20}$ . The observation of these sets of post-buckling results prompts the following remarks (some of which were already partially addressed in [10, 15]):

- (i) Obviously, the ultimate stress decreases as the temperature  $T$  rises, both for the pinned and fixed columns.
- (ii) The post-critical strengths of the fixed columns are considerably higher than those exhibited by the pinned columns – for  $T=700^\circ\text{C}$ , this difference is less perceptible due to the low  $\sigma/\sigma_{cr,D,20}$  values.
- (iii) For all the pinned columns, the collapse occurs either (iii)<sub>1</sub> immediately after the onset of yielding and at relatively small deformation levels (*S355*) or (iii)<sub>2</sub> following a well pronounced equilibrium path plateau, *i.e.*, is preceded by a fair amount of ductility (*S700*).
- (iv) For all the fixed lipped channel columns, the collapse occurs for fairly high deformation levels. Nevertheless, failure is not preceded by a visible equilibrium path plateau (*i.e.*, there is a well defined maximum stress value) –

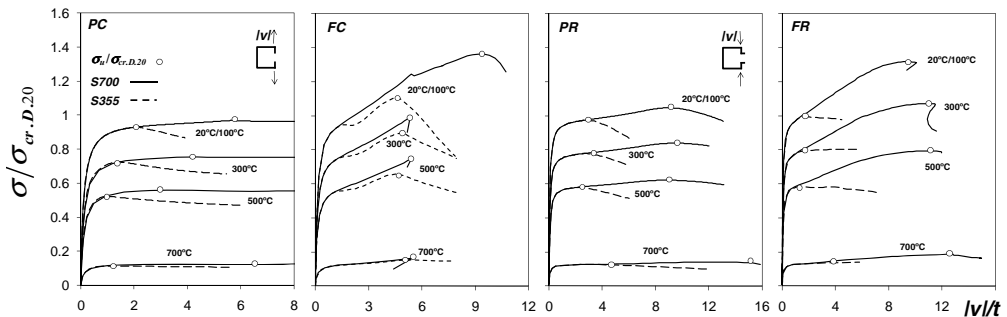


Figure 2: Distortional post-buckling equilibrium paths of pinned (P) and fixed (F) lipped channel (C) and rack-section (R) columns made of *S355* and *S700* steels and subjected to temperatures  $20/100$ - $300$ - $500$ - $700^\circ\text{C}$ .

the S355 columns exhibit a small snap-through phenomenon following the onset of yielding<sup>1</sup>.

- (v) In the case of the fixed rack-section columns, there is a marked difference between the collapse behaviours of those made of S355 and S700 steel. While the latter behave like their lipped channel counterparts, the former fail immediately after the onset of yielding (*i.e.*, do not exhibit the snap-through phenomenon mentioned above).
- (vi) There is no clear trend concerning the variation of the deformation level at collapse with the temperature.

### 3 COLUMN DSM DESIGN

This section presents a preliminary assessment of the applicability of the Direct Strength Method (DSM), already included in the North American Specification for cold-formed steel structures [6], to predict the ultimate strength of pinned and fixed lipped channel and rack-section columns failing distortionally at room and elevated temperatures. At *room temperature*, the nominal ultimate load of cold-formed steel columns experiencing distortional collapses is given by the DSM equation (curve)

$$P_{n,D} = \begin{cases} P_y & \text{for } \bar{\lambda}_D \leq 0.561 \\ \left[ 1 - 0.25 \left( \frac{P_{cr,D}}{P_y} \right)^{0.6} \right] \left( \frac{P_{cr,D}}{P_y} \right)^{0.6} P_y & \text{for } \bar{\lambda}_D > 0.561 \end{cases} \quad (1)$$

where (i)  $P_y$  and  $P_{cr,D}$  are the column squash and distortional critical buckling loads, and (ii)  $\bar{\lambda}_D = \sqrt{P_{cr,D}/P_y}$  is the column distortional slenderness. Figures 3(a)-(b) compare the ultimate loads predicted by the above DSM curve with (i) numerical values obtained in this work and (ii) experimental values reported by Ranawaka [16], for pinned (fig. 3(a)) and fixed (fig. 3(b)) rack-section and lipped-channel columns. While the numerical values deal with (i) both end support conditions and (ii) several yield stresses<sup>2</sup>, making it possible to cover wide distortional slenderness ranges (the minimum and maximum values achieved were 0.77 and 2.89), the experimental values concern only a few fixed columns, namely one lipped channel column pair and three rack-section column pairs<sup>3</sup>. The observation of the columns ultimate strength results prompts the following (preliminary) remarks:

- (i) First of all, one readily notices that the ultimate load estimates provided by the DSM distortional curve for the pinned columns with moderate-to-high slenderness considerably overestimate the numerical values yielded by the ANSYS analyses – indeed, safe (and fairly accurate) predictions only occur in a low slenderness range. This confirms earlier findings by authors [10, 15], which performed similar numerical analyses for other pinned (simply supported) lipped channel and rack-section columns failing in distortional modes.
- (ii) Concerning the fixed columns, the first remark is that the DSM distortional curve estimates either match almost perfectly or slightly underestimate (particularly the stockier columns) the ultimate loads of the 8 columns tested by Ranawaka [16]. As for the numerical ultimate loads provided by the ANSYS analyses, they are also quite close to the DSM distortional curve predictions, even if there is a slight overestimation in the high slenderness range (both for the lipped channel and rack-section columns).
- (iii) There is no significant difference between the “quality” of the DSM distortional curve estimates concerning the lipped channel and rack-section columns. Indeed, the ratios between the DSM predictions and the numerical

<sup>1</sup> It is worth noting that numerically difficulties prevented reaching a well defined clear ultimate load/stress in the fixed lipped channel columns at elevated temperatures (the equilibrium path descending branch appears very abruptly). This also explains why, at 700 °C, the S355 and S700 fixed lipped channel columns exhibit identical ultimate loads/stresses (the latter is certainly underestimated).

<sup>2</sup> The following room temperature yield stresses were considered: (i)  $\sigma_y = 150-235-355-600-700-1000$  MPa (pinned lipped channel columns), (ii)  $\sigma_y = 150-250-355-550-700-1200$  MPa (pinned rack-section columns), (iii)  $\sigma_y = 250-355-550-700-1000-1600$  MPa (fixed lipped channel columns) and (iv)  $\sigma_y = 250-355-550-700-1000-1200$  MPa (fixed rack-section columns).

<sup>3</sup> Results concerning the following column dimensions and room temperature yield stresses were reported in [16]: (i)  $b_1=30, b_2=30, b_3=5, t=0.60$  mm,  $\sigma_y=315-675$  MPa and  $L=20$  cm (lipped channel columns) and (i)  $b_1=40, b_2=30, b_3=5, b_4=10, t=0.60-0.80-0.95$  mm,  $\sigma_y=250-550$  MPa and  $L=22-24-28$  cm (rack-section columns).

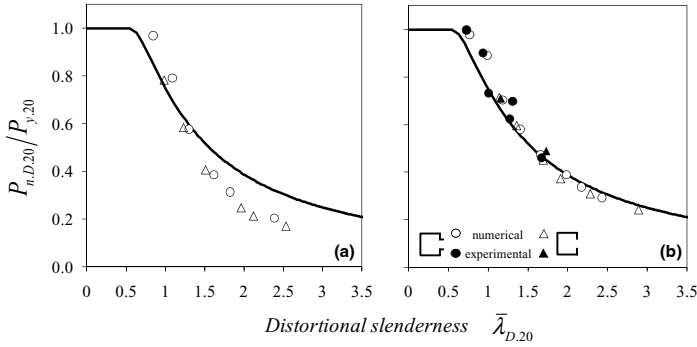


Figure 3: Comparison between the DSM distortional curve predictions and the numerical (obtained in this work) and experimental (reported in [16]) ultimate loads for (a) pinned and (b) fixed columns at room temperature.

ultimate loads for both column geometries differ by less than 5%. The lipped channel ultimate load ratios are generally (slightly) smaller, most likely due to the higher flange-to-web width ratio ( $0.77$  against  $0.60$ ) – note that a higher ratio corresponds to a “weaker” flange, thus leading to a lower post-critical strength.

- (iv) At this stage, note that the calibration and validation of the DSM distortional curve involved almost exclusively fixed columns (*e.g.*, Schafer [17]), since it is extremely difficult to test pinned columns failing in distortional modes – in particular, it is virtually impossible to ensure that the column end sections are able to warp freely.
- (v) In view of the above facts, it seems fair to conclude that there are significant differences in the distortional post-critical strengths of pinned and fixed columns, which are not adequately reflected in the corresponding (distortional) critical buckling stresses<sup>4</sup>.

Taking into consideration the above assessment of the performance of the DSM distortional curve to predict the ultimate strength of lipped channel and rack-section columns at room temperature, the suitability of this DSM approach to estimate column (distortional) ultimate loads at elevated temperatures is addressed next. Accordingly, the methodology followed in this work, which was already (partially) explored by other researchers [2, 3, 5] (and also by the authors [10, 15]), consists of modifying equation (1) to account for the influence of the temperature on  $P_{cr,D}$  and  $P_y$  – this influence is felt through the values of the Young’s modulus and yield stress, which are reduced as the temperature increases due to the fire conditions. In other words, one replaces  $P_{cr,D}$  and  $P_y$  (or  $\sigma_y$ ) by  $P_{cr,D,T}$  and  $P_{y,T}$  (or  $\sigma_{y,T}$ ) – note that  $\bar{\lambda}_D$  also varies with  $T$ .

Figure 4 concerns pinned columns and shows a comparison between the ultimate loads predicted by the modified DSM curve and the numerical values obtained in this work. It includes 8 plots, each corresponding to a different temperature ranging from  $20/100$  °C (room temperature – results already presented in fig. 3(a) and included here for comparison) to  $800$  °C. The yield stress variation considered makes it possible to cover a wide slenderness range: from  $0.98$  to  $3.4$ , for the lipped channel columns, and from  $0.84$  to  $3.2$ , for rack-section columns. Keeping in mind that it has been shown that the available DSM distortional curve consistently overestimates the ultimate loads of the pinned columns with moderate or high slenderness values, at room temperature, the observation of the sets of results presented in figure 4 leads to the following comments, concerning the applicability of the modified DSM approach to predict column (distortional) ultimate loads at elevated temperatures:

- (i) Regardless of the temperature, the modified DSM curve ultimate strength predictions generally overestimate the numerical ultimate loads ( $P_{u,D,T}$ ) considerably – there are only a few exceptions, all concerning stocky columns at room temperature (mostly),  $T=200$  °C and  $T=300$  °C. As for the amount of overestimation, it ( $i_1$ ) increases with  $T$  up to  $400$  °C and ( $i_2$ ) remains practically constant from then on (*i.e.*, for  $T \geq 400$  °C).

<sup>4</sup> In the context of lipped channel and rack-section columns affected by local/distortional/global mode interaction, Dinis & Camotim [18-20] showed that there are marked differences between the post-buckling behaviour and strength of pinned (simply supported) and fixed columns.

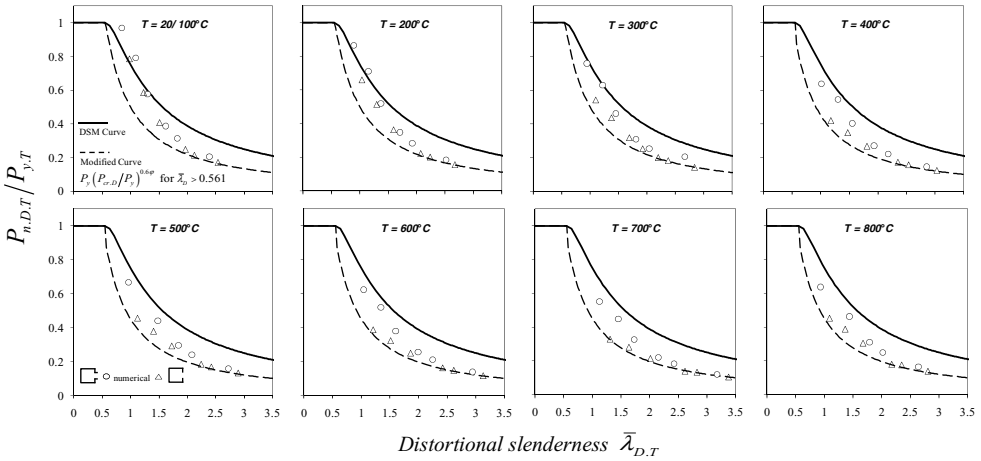


Figure 4: Comparison between the modified DSM distortional curve estimates and the numerical ultimate loads for pinned columns at temperatures 20/100-200-300-400-500-600-700-800 °C.

- (ii) Nevertheless, it may be said that the various sets of  $P_{u,D,T}/P_{y,T}$  values remain fairly “aligned” with a Winter-type curve, which suggests that it is possible to further modify equation (1) in order to achieve a better correlation with the numerical column ultimate loads determined in this work. Just for the sake of illustration, each plot in figure 4 includes also a very simple/crude exponential curve (dashed line), that does not clearly underestimate any of the numerical values (while remaining as close to all of them as possible) and was obtained by adopting the following modification of equation (1): (ii<sub>1</sub>) eliminate the term with the 0.25 coefficient and (ii<sub>2</sub>) multiply the power of the remaining term (0.6) by a slightly temperature-dependent parameter  $\phi$  – one has either  $\phi=0.5$  (if  $T \leq 300$  °C) or  $\phi=0.45$  (if  $T > 300$  °C).
- (iii) The fact that the  $\phi$  values given in the previous item are much smaller than 1.0 stems from the combined influence of (iii<sub>1</sub>) the temperature effects and (iii<sub>2</sub>) the “inherent lack of safety” of DSM design curve predictions for pinned columns. Moreover, since those  $\phi$  values are governed by the slender column estimates, it is just logical that the modified curves considerably underestimate the numerical ultimate loads of the columns with low and intermediate slenderness values (more so for the lower temperatures).
- (iv) Finally, note that the lipped channel column  $P_{u,D,T}/P_{y,T}$  values are also slightly smaller than the rack-section ones for elevated temperatures. The differences become more pronounced for  $T \geq 300$  °C and high slenderness values.

Figure 5 display similar results for fixed columns, but now the ultimate loads predicted by the modified DSM curve are compared with both numerical (obtained in this work) and experimental (reported in [16]) values. The latter concern 8 column geometries and four temperatures (20/100-200-500-800 °C) and it should be noted that these 32 columns do not exhibit the same material behaviour as the remaining ones – indeed; they follow an experimentally obtained stress-strain law [16], and not the model prescribed in EC3-1.2 that was adopted to obtain the numerical ultimate loads. As before, plots corresponding to 8 different temperatures are presented and the yield stress variation considered now enables covering the following slenderness ranges: 1.13 to 3.56 (lipped channel columns) and 0.77 and 2.9 (rack-section columns). Recalling that the available DSM distortional curve provides fairly accurate ultimate load estimates for fixed columns at room temperature, the observation of the results displayed in figure 5 prompt the following remarks on the suitability of the modified DSM approach to predict column (distortional) ultimate loads at elevated temperatures:

- (i) Again regardless of the temperature, most of the modified DSM curve ultimate strength predictions now slightly overestimate the numerical ultimate loads ( $P_{u,D,T}$ ) – the few exceptions still concern stocky columns at room temperature (mostly),  $T=200$  °C and  $T=300$  °C. As for the pinned columns, the amount of overestimation, (i<sub>1</sub>) increases with  $T$  up to 400 °C and (i<sub>2</sub>) remains practically constant for  $T \geq 400$  °C.

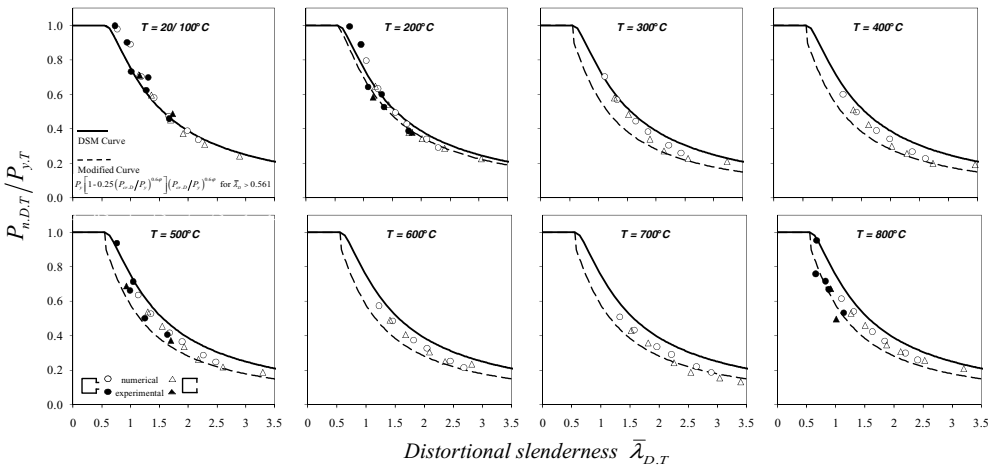


Figure 5. Comparison between the modified DSM distortional curve estimates and the experimental (reported in [16]) and numerical ultimate loads for fixed columns at temperatures 20/100-200-300-400-500-600-700-800 °C.

- (ii) Concerning the experimental  $P_{u,D,T}/P_{y,T}$  values, the DSM curve estimates (ii<sub>1</sub>) slightly underestimate them at room temperature, (ii<sub>2</sub>) slightly overestimate them at  $T=200$  °C and (ii<sub>3</sub>) fairly overestimate them at  $T=500$  °C and  $T=800$  °C – in these last two cases, the experimental ultimate loads are below the numerical ones.
- (iii) As before, each plot in figure 5 includes an exponential curve (dashed line) that does not significantly underestimate any of the *numerical* values but remains as close to all of them as possible – one has now  $\varphi=1.0$  (room temperature),  $\varphi=0.9$  ( $T=200$  °C) and  $\varphi=0.7$  ( $T\geq 300$  °C). Note that these  $\varphi$  values are much closer to 1.0 than those obtained for the pinned columns, due to the fact that they stem from the sole influence of the temperature effects (there is no “inherent lack of safety” of DSM design curve predictions for fixed columns).
- (iv) Only 2 out of all experimental  $P_{u,D,T}/P_{y,T}$  values fall below the dashed lines – they both concern  $T=800$  °C.
- (iv) Once more, the numerical lipped channel column  $P_{u,D,T}/P_{y,T}$  values are slightly smaller than the rack-section ones, with the differences being again more pronounced for  $T\geq 300$  °C and high slenderness values.

Obviously, further research is required in order to confirm the preliminary assessment presented here – in particular, it is indispensable to obtain additional numerical and experimental columns ultimate loads at elevated temperatures, involving different cross-sections and temperature-dependent steel material behaviours. Then, it will be possible to progress towards developing new DSM design curves to predict the distortional failure of (pinned and fixed) columns subjected to elevated temperatures, namely those caused by fire conditions – on the basis of the available results, it seems that such curves should be mildly dependent on the temperature.

#### 4 CONCLUDING REMARKS

This paper reported the available results of an ongoing shell finite element investigation on the distortional strength and design of pinned and fixed cold-formed steel lipped channel and rack-section columns at elevated temperatures. The variation of the material behaviour with the temperature followed the EC3-1.2 model for cold-formed steel, and the geometrically and physically non-linear shell finite element analyses were carried out in the code ANSYS. Then, the suitability of modified DSM design curves to predict the ultimate strength of columns subjected to elevated temperatures and failing in distortional modes was addressed. A preliminary assessment was presented, on the basis of the comparison between the above DSM curves estimates and numerical (pinned and fixed column ultimate loads analysed in this work) and experimental (fixed column tests reported in [16]) ultimate loads. Although a fairly large amount of research work is required before this preliminary assessment can be confirmed, it seems that an efficient DSM design will have to be based on new curves mildly dependent on the temperature.

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