THIN-WALLED STEEL MEMBERS AT ELEVATED TEMPERATURES CONSIDERING LOCAL IMPERFECTIONS: NUMERICAL SIMULATION OF ISOLATED PLATES

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1. ABSTRACT

The local buckling capacity of fire exposed thin-walled steel cross sections is affected by the reduction in strength and stiffness due to elevated temperatures and the amplitude of the initial local imperfections. A usual method to estimate this capacity is the simulation of isolated plates (web: four sides simply supported plate, flange: three sides simply supported plate) that are subjected to in-plane compression until instability is observed. Several researchers have proposed design methods to calculate the capacity of these steel members at elevated temperatures based on isolated plate analysis, but they used different methodologies. This variability in hypotheses happens because there is no clear provision defining the numerical modeling procedure for fire design of steel plates in the codes (European or US). The paper proposes a methodology for finite element simulation of thin plates at elevated temperatures and its governing factors (amplitude of initial local imperfections, number of half-wave geometry of local imperfections, plate geometry (sides ratio a/b)).

2. INTRODUCTION

The use of slender steel sections, i.e. sections made of thin steel plates, has increased in recent years because they provide excellent strength to weight ratio; this trend has also

been favored by the development of higher steel grades. Yet, a major issue with slender sections is local buckling that may occur in zones subjected to compression: in the flange under compression for elements in bending and in the web for elements in compression. In very deep sections, shear can also trigger local buckling in the web if it is too slender.
Furthermore, past fire accidents have demonstrated local buckling failures in structural members with slender cross sections, like in WTC 5 [1] and Broadgate fire [2].
To take local instabilities into account, several design methods have been proposed by researchers based on finite element analyses of isolated plates [3], [4], [5], [6] or analytical methods [7]. As the current codes do not include a specific method for the calculation of the capacity of such structural members at elevated temperatures, the ambient temperature methods of EN 1993-1-5 [8] and AISC [9] can be used in conjunction with elevated temperature material models from EN 1993-1-2 [10] or AISC [9] respectively. A comparison of the plate capacity predicted by different proposed models, whether based on design codes or numerical analyses, is showed in Figure 1. The horizontal axis on the plot is the elevated temperature plate slenderness and the vertical axis is the strength reduction due to local buckling. Although these models give similar trends, the discrepancy in quantitative results is significant with a ratio in the order of 2 between the extremes. Table 1 shows the governing parameters (i.e. assumptions) used in the models based on numerical analyses. The parameters a, b and t are the length, width and thickness of the plate, respectively. It can be seen that different authors assumed different values for these parameters, which naturally lead to different results. The results are affected by the amplitude of the initial local imperfections [11], by the geometry of the local imperfections (number of half-waves) and by the dimensions of the plate (ratio a/b) [12]. Previous studies of the authors [11], [12] have discussed the effect of these parameters. The paper presents a methodology for the numerical modelling/simulation of steel plates at elevated temperatures.

Table 1. Governing analysis parameters used in the numerical simulations by different authors.

Reference	a/b	Number of half-waves	Amplitude of imperfections
[5]	flange: 2 web: 1	1	flange: b/50 = 0.020 b web: b/200 = 0.005 b
[3]	4	flange: 1, web: 4	flange: 80% b/50 = 0.016 b web: 80% b/100 = 0.008 b
[6]	5	flange: 3, web: 5	flange: 0.156 t web: 0.100 t

3. EFFECT OF AMPLITUDE OF LOCAL IMPERFECTIONS

Working in the European framework, one option is to use the equivalent geometric imperfections with amplitude defined as min(a/200, b/200) for flange and web plates, where a and b are the dimensions of the panel or the subpanel. Another option is to base the geometric imperfection on the manufacturing tolerance, and to also include in the analysis residual stresses for the structural imperfection. In the latter case, high geometric imperfections can be obtained for slender plates. Besides, the question of residual stresses has to be addressed.
At ambient temperatures, these two methods from EN 1993-1-5 [8] are giving very different results in terms of imperfection amplitude. The method combining imperfections as a function of manufacturing tolerance and residual stresses is unfavorable comparing

with the equivalent imperfections method. Indeed, the amplitude of imperfections calculated by the first method (80% of tolerance) is always higher than the amplitude calculated according to the equivalent method. Furthermore, the residual stresses are reducing further the strength of the plate, when they are combined with the unfavorable large imperfections. At elevated temperature, however, the effect of residual stresses has been shown to be very limited [13], so that the difference between the two methods becomes a bit less significant.

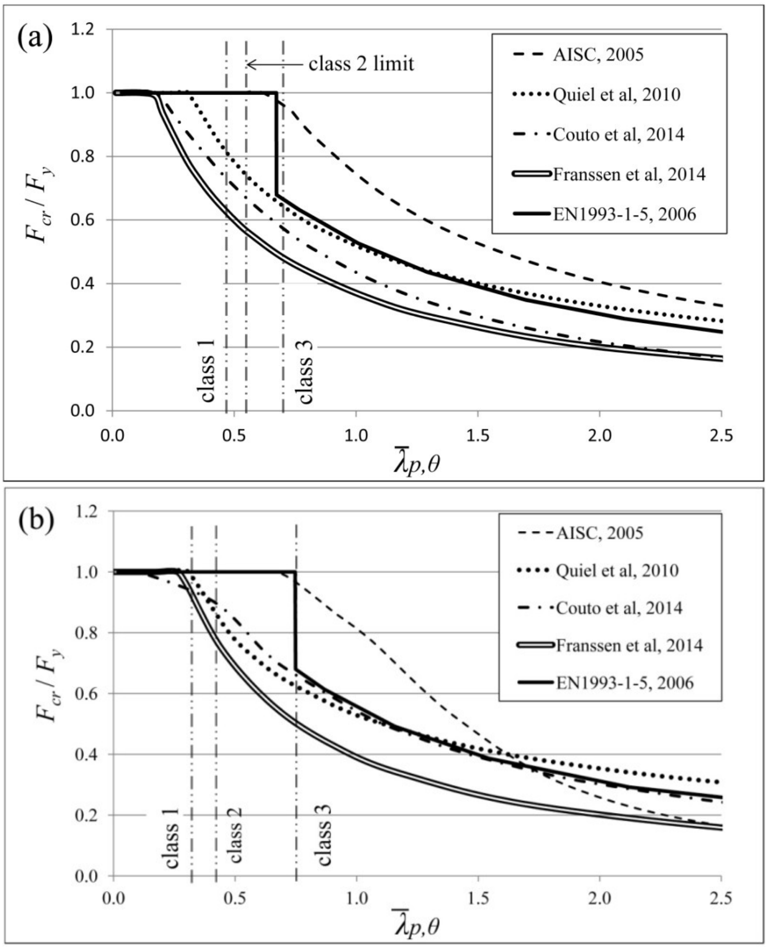

Fig. 1. Comparison of proposed design and code methods for capacity of slender plates at 500 ^{o}C, (a) for stiffened plates (web) and (b) for unstiffened plates (flange).

Previous sensitivity study of the authors [11] showed that the effect of the amplitude of local imperfections becomes less significant when this amplitude exceeds a b/100 limit, which can be derived from manufacturing tolerances. Also, the difference in results obtained following the two approaches of EN1993-1-5 is – generally – less than 10%. without considering the effect of the residual stresses. Typical analysis results are presented in Figure 2. Furthermore, the effect of the imperfection amplitude at elevated temperature is less significant than at ambient temperatures. [11] is proposed to adopt the equivalent local imperfection amplitude per EN 1993-1-5, 2006 (which here corresponds to: min(a/200, b/200)) and to use it for studies at elevated temperature. This definition of the amplitude has the merit of being simple, of incorporating implicitly the residual stresses, and being consistent with the approach of ambient temperature.

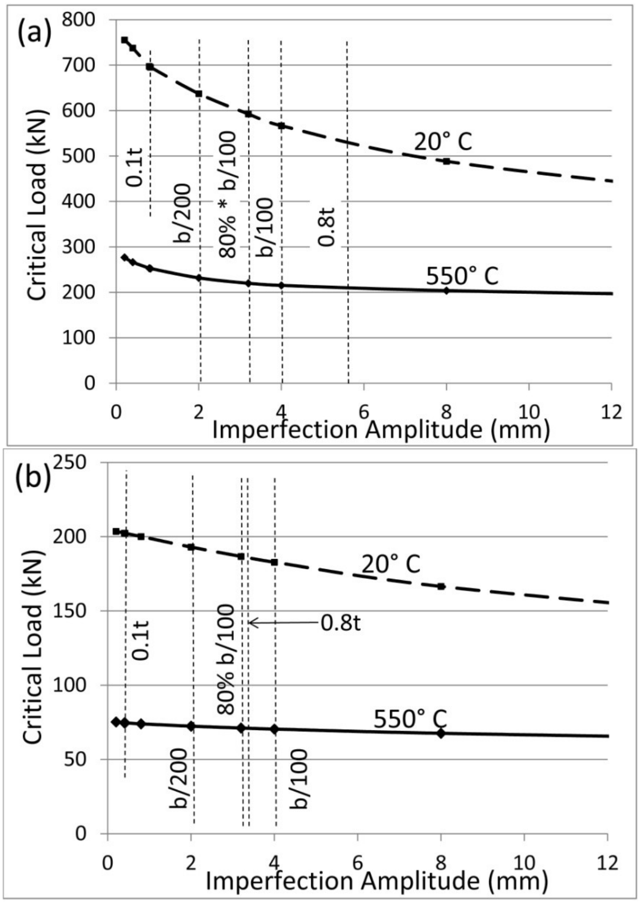

Fig. 2. Critical load vs local imperfection amplitude for four sides simply supported plates with (a) $\lambda_{p,\theta}$=1.0 and (b) $\lambda_{p,\theta}$ =2.0 at 20 °C and 550 °C.

3. EFFECT OF GEOMETRY OF LOCAL IMPERFECTIONS (NUMBER OF HALF WAVES)

3.1 Theory of perfect & imperfect plates

For long rectangular plates, the critical stress is given by the equation [14]:

$$\sigma_{cr} = k\,\pi^2\,E / 12\,(1-\nu^2)(b/t)^2 \qquad (1)$$

Where σ_{cr} is the critical stress, k is the plate buckling coefficient, E and ν are the modulus of elasticity and the Poison ratio of the elastic material, b is the width of the plate and t is the plate thickness.

The plate buckling coefficient k depends on the applied boundary conditions. When the plate is short in the direction of the compressive stress, there exists an influence in the critical buckling stress due to the fact that the buckled half-waves which take integer values are forced into a finite length plate (Figure 3a). Therefore for short plates, the plate buckling coefficient is also a function of the size of the plate (ratio a/b) and the number of half-waves m (Figure 3b).

As with all steel structures, plate panels contain residual stresses from manufacture and subsequent welding into plate assemblies, and are not perfectly flat (they have imperfections). The previous discussions about plate panel behaviour all relate to an ideal, perfect plate. As shown in Figure 4 these imperfections affect the behaviour of actual plates.

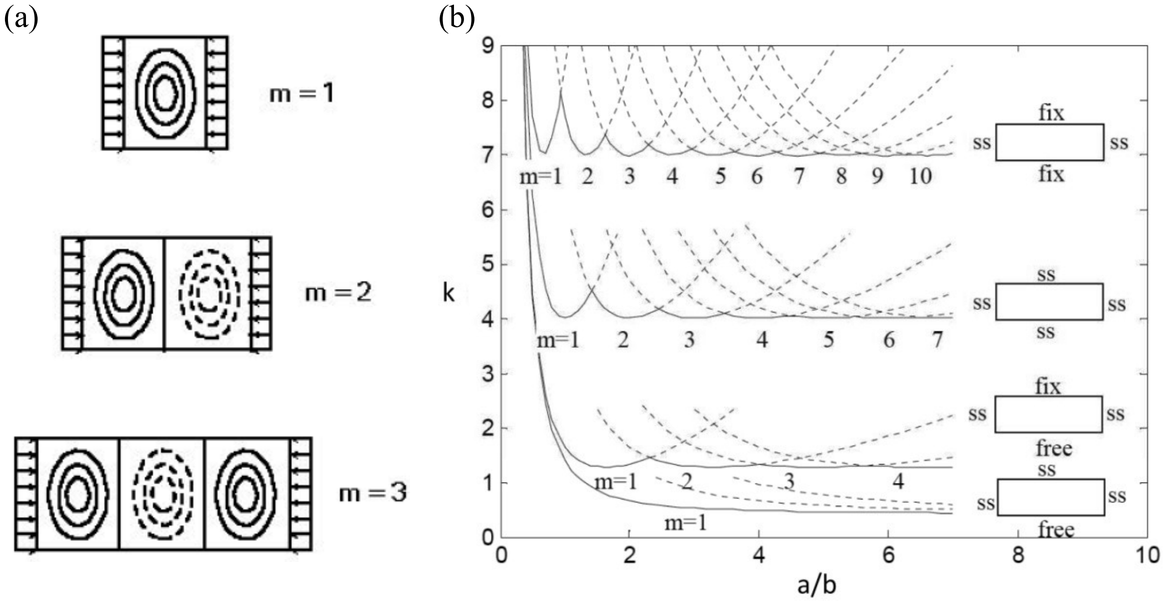

Figure 3. (a) Different buckling modes (m is the number of half-waves) for different a/b ratios of 4 sides simply supported plates and (b) buckling reduction factor for plates in compression as function of the shape of the plate a/b, the boundary conditions and the number of half-waves m [14].

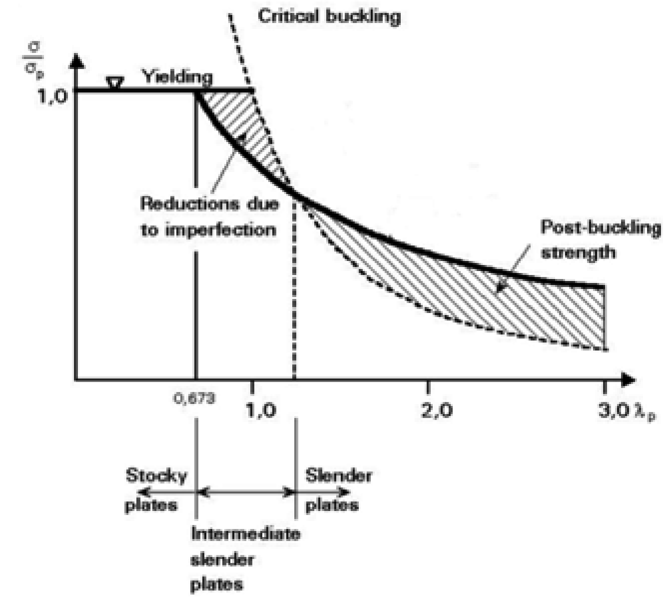

Figure 4. Relationship between plate slenderness and strength in compression.

3.2 Results from parametric analysis

A detailed parametric analysis performed in [12]. Detailed information regarding the numerical modelling is presented in the same paper. The effect of the plate shape (a/b sides ratio) and of the number of half-waves of imperfections m has been studied for four sides simply supported and three sides simply supported plates. The studied values of these parameters were $1 \leq a/b \leq 6$ and $1 \leq m \leq 5$.

It has been found that the four side simply supported plate, which simulates web, can be simulated accurately and with minimised computational time with $a / b = m = 1$.

The situation with the three sides simply supported plate, which simulates flange, is complicated. Although the shape of the plate must be long ($a / b \geq 5$), the number of half-waves of imperfections cannot defined with a single value. In Fig. 5, comparison of results for different m values are presented. It is clear, the results of the analysis with m=4 are unfavourable (and so safe) for $\lambda_{p,\theta} > 1.25$ (approximately) and similarly the results for m=1 are safe for $\lambda_{p,\theta} < 1.25$. Comparing Figure 5 with Figure 4, the reasons of this unexpected behaviour can be estimated. The plate with one half-wave is giving unfavorable results at the slenderness range where the imperfections are affecting with a major way the plate capacity. At the other side, the plate with m=4 has unfavorable shape of imperfections, so it buckles under higher force than the plate with m=1. For $\lambda_{p,\theta} > 1.25$, where the imperfections do not affect severally the slender plates, post-buckling behaviours are present. When m=4, the effect of post-buckling affect the plate capacity with a minor way. At the opposite, when m=1, the post-buckling effects increase the plate capacity that much that the configuration is giving unsafe results. The limit of slenderness is not always 1.25 as in Fig. 5, as it depends of the definition of slenderness, the temperature and the steel grade.

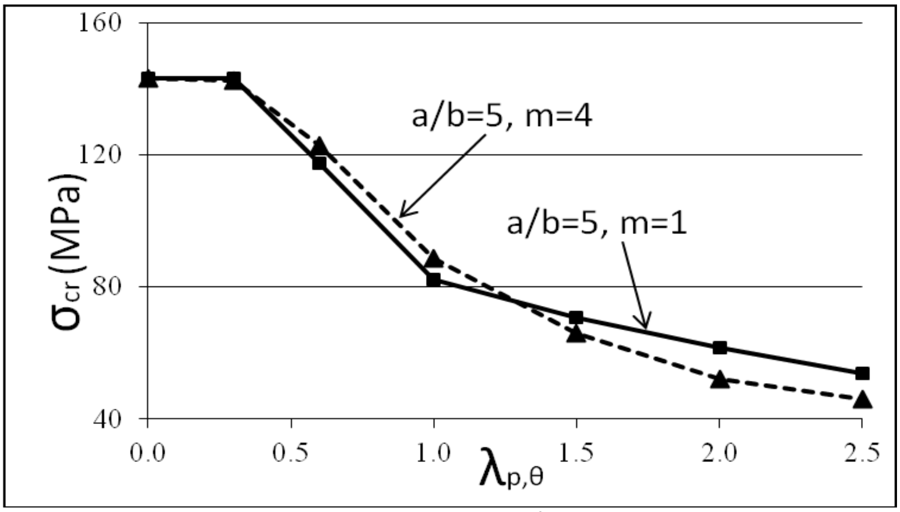

Figure 5. Analysis results for plate (S235, 500 °C, a/b=5) with different shape of imperfections (number of half waves m).

4. CONCLUSIONS

The proposed analysis parameters for the numerical simulation of isolated thin-walled steel plates at elevated temperatures are:

- The amplitude of local imperfections is proposed to considered as the equivalent geometric imperfections are defined in EN 1993-1-5, eg min(a/200, b/200) for flange and web plates, where a and b are the dimensions of the panel or the subpanel.
- For four sides simply supported isolated plates (web simulation), m = a / b = 1 is recommended, where m is the number of half-waves of imperfections and a/b is the side ratio.
- For three sides simply supported isolated plates (flange simulation), the shape of the recommended plate should have a / b ≥ 5. As the shape of imperfections, in terms of half-waves, affects the results with a complex way, the minimum critical stress can be obtained from a pair of analysis with m = 1 and m = 4, where m is the number of half-waves of imperfections.

5. ACKNOWLEDGMENTS

This research was supported by the University of Liege and the EU in the context of the FP7-PEOPLE-COFUND-BeIPD project.

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ΛΕΠΤΟΤΟΙΧΑ ΜΕΤΑΛΛΙΚΑ ΔΟΜΙΚΑ ΣΤΟΙΧΕΙΑ ΣΕ ΥΨΗΛΕΣ ΘΕΡΜΟΚΡΑΣΙΕΣ ΜΕ ΤΟΠΙΚΟ ΛΥΓΙΣΜΟ: ΑΡΙΘΜΗΤΙΚΗ ΠΡΟΣΩΜΟΙΩΣΗ ΜΕΜΟΝΟΜΕΝΩΝ ΠΛΑΚΩΝ

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ΠΕΡΙΛΗΨΗ

Η αντοχή σε τοπικό λυγισμό των λεπτότοιχων μεταλλικών διατομών υπό την επίδραση φωτιάς, επηρεάζεται από την απομείωση της αντοχής και της ακαμψίας του υλικού σε υψηλές θερμοκρασίες και το μέγεθος των τοπικών ατελειών. Μία συνήθης μέθοδος για τον προσδιορισμό της αντοχής αυτής είναι η προσομοίωση μεμονωμένων πλακών, οι οποίες βρίσκονται σε θλίψη εντός επίπεδου μέχρι την εμφάνιση λυγισμού. Διάφοροι ερευνητές έχουν προτείνει μεθόδους σχεδιασμού για τέτοια μεταλλικά δομικά στοιχεία σε υψηλές θερμοκρασίες βασιζόμενοι σε αναλύσεις μεμονωμένων πλακών, αλλά χρησιμοποιούν διαφορετικές μεθοδολογίες. Αυτές οι διαφοροποιήσεις εκτιμάται ότι οφείλονται σε μη ξεκάθαρες οδηγίες για την προσομοίωση των μεταλλικών πλακών σε φωτιά από τους κανονισμούς. Η εργασία προτείνει μία μεθοδολογία για την προσομοίωση με πεπερασμένα στοιχεία των λεπτότοιχων πλακών σε υψηλές θερμοκρασίες και των παραμέτρων που επηρεάζουν τα αποτελέσματα (μέγεθος και γεωμετρία ατελειών και γεωμετρία πλάκας).