GEM – A SOFTWARE FOR STABILTY VERIFICATION OF NON-UNIFORM MEMBERS

Adaptation of the General Method procedure to fire design

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Abstract

There is currently no specific rules in Part 1-2 of Eurocode 3 for the stability verification of non-uniform members under fire conditions. For normal temperature, Part 1-1 of the same code provides a General Method to check the stability against lateral and lateral-torsional buckling for these type of members, though it requires some extensive calculations. It is here demonstrated in this paper how both problems can be addressed, by exposing a procedure that accounts for the modifications of the method at elevated temperatures, and by showing its implementation within a computer program. It is also shown how the program can be used to assess the study of the method itself, by applying it to a case of a web-tapered beam-column and comparing it to numerical results.

Keywords: Steel, Stability, Eurocode, Tapered, General Method

1 INTRODUCTION

The Part 1.1 of Eurocode 3 (EC3) (CEN, 2005a) presents the so-called General Method to assess the out-of-plane stability of steel members at normal temperature when the application of the expressions for flexural buckling (FB), lateral-torsional buckling (LTB) or their interaction, given in clauses 6.3.1, 6.3.2 and 6.3.3 respectively, is not possible, e.g. when the members are non-prismatic. This method assumes a separation of in-plane and out-of-plane behaviours, and the determination of a single generalized slenderness given by the in-plane resistance and the critical load amplifier for the out-of-plane instability. The overall resistance is then given by applying a reduction factor to the in-plane resistance that accounts for the out-of-plane buckling.

When dealing with fire design, there are currently no specific rules in Part 1.2 of EC3 (CEN, 2005b) regarding these types of members. Therefore, an adaptation of the method for fire design would be very welcomed, and a first take on the study of the method at elevated temperature has been done by Couto (2014), where it was shown that for the case of lateral-torsional buckling an adaptation of the General Method may yield good results.

The application of the General Method is involved in some difficulties, such as the need of knowing the location of the critical cross-section, which requires the determination of the resistant properties for a large number of cross-sections, making it impractical to use without the aid of automatic calculation tools. Another difficulty lies in the determination of the critical load amplification factor for the out-of-plane instability, which in most cases requires the use of Finite Element Models in order to estimate its value.

In this work it is presented the computer program *GeM*, which was developed at University of Aveiro in order to provide a tool that enables an easy application of the General Method. It is proposed an adaptation and implementation of the method to fire design according to the principles of Part 1.2 of EC3, namely by accounting the reduction of the strength and stiffness of steel under elevated temperatures. All the steps considered in the calculation are described as well as the options made available in the program. An example of the application of the program for the fire design of a web-tapered beam-column and comparison with numerical results is also presented, and conclusions about the usefulness of the program are drawn.

2 GENERAL METHOD

The general method allows to assess the overall stability of steel members at normal temperature by ensuring that:

$$\chi_{op} \cdot \alpha_{ult,k} / \gamma_{M1} \geq 1.0 \tag{1}$$

where $\alpha_{ult,k}$ is the minimum load amplifier of the design loads to reach the characteristic resistance of the most critical cross section of the structural component, considering its in-plane behavior without taking lateral or lateral torsional buckling into account however accounting for all effects due to in plane geometrical deformation and imperfections, global and local, where relevant;

χ_{op} is the reduction factor for the non-dimensional slenderness, to take account of lateral and lateral-torsional buckling.

The generalized slenderness $\bar{\lambda}_{op}$ is given by:

$$\bar{\lambda}_{op} = \sqrt{\alpha_{ult,k} / \alpha_{cr,op}} \tag{2}$$

where $\alpha_{cr,op}$ is the minimum amplifier for the in plane design loads to reach the elastic critical resistance of the structural component with regards to lateral or lateral torsional buckling without accounting for in plane flexural buckling.

The out-of-plane reduction factor χ_{op} may be taken as the minimum or by an interpolation of the values χ_z for out-of-plane FB and χ_{LT} for LTB, both calculated for the slenderness $\bar{\lambda}_{op}$.

3 APPLICATION TO FIRE DESIGN

As demonstrated by Couto (2014), in order to be used in fire design the aforementioned method must be adopted to accommodate the differences that arise when dealing with elevated temperatures, such as the appearance of the reduction factors for the yield strength, $k_{y,\theta}$ (for classes 1, 2 and 3) or $k_{0.2p}$ (for class 4), and for the elasticity modulus, $k_{E,\theta}$, and to account for the different buckling curves found in EC3-1-2.

In order to overcome the difficulties and extensive calculations involved in the application of the General Method, a software named *GeM* was developed by the authors. This software makes use of the program *LTBeamN* (Galéa, 2003) to determine the internal forces and moments and the critical amplifiers that are needed.

3.1 Description of the procedure

A description of each one of the steps involved in the procedure at elevated temperature, as carried out by *GeM,* is shown. This procedure is an adaptation of the one found in Bureau (2007), and assumes that the member being analysed is isolated from the rest of the structure, after a global analysis has been performed (considering global imperfections and global 2nd order effects (P-Δ)).

Step 1: Discretization of the member

In first place a division of the member is done in a number of elements that may be sufficient to emulate its behaviour in a Linear buckling Analysis (performed in *LTBeamN*) as well as to find the critical cross-section for the in-plane analysis.

Step 2: Determination of the internal forces and properties for each cross-section

For each one of the cross-sections resulting from the discretization made at step 1**,** internal forces are calculated in a 1st order analysis of the internal forces, considering the value for E affected by the reduction factor for the elasticity modulus, $k_{E,\theta}$, and the geometrical properties (area, A, and section modulus about y-y, W_y) for each one of the cross-sections are calculated taking into account their class, and by accounting for the reduction factors for the yield strength, $k_{y,\theta}$ (for classes 1, 2 and 3) or $k_{0.2p}$ (for class 4). *GeM* can determine the class by three different approaches (Vila Real, 2014), in which the ultimate limit state is reached by: a) increasing only N_{Ed}; b) increasing both N_{Ed}

and $M_{y,Ed}$ with the plastic limit given by Eq. 6.36 of EC3-1-1; c) increasing both N_{Ed} and $M_{y,Ed}$ with the plastic limit given by the plasticity theory.

Step 3: equivalent geometrical imperfection, e_0 (if e_0 is considered)

The program offers three alternatives for the estimation of e_0: a) to use the values from Table 5.10 of EC3-1-1; b) to calculate e_0 from equation 5.10 of EC3-1-1; c) to calculate e_0 with a modified version of equation 5.10 of EC3-1-1 that accounts for the imperfection factor α_θ and the non-existence of a plateau for the buckling curves at elevated temperature, given by:

$$e_0 = \alpha_\theta \cdot \bar{\lambda}_{y,\theta} \cdot M_{y,Rk,\theta} / N_{Rk,\theta} \tag{3}$$

$$\alpha_\theta = 0.65 \cdot \sqrt{235/f_y} \tag{4}$$

$$\bar{\lambda}_y = \sqrt{\alpha_{ult,k,\theta,N} / \alpha_{cr,ip,\theta,N}} \tag{5}$$

where $\alpha_{ult,k,N}$ is the amplification factor for N_{Ed} to reach the characteristic resistance to compression $N_{Rk,\theta}$,

$\alpha_{cr,ip,N}$ is the amplification factor for N_{Ed} to reach the in-plane elastic critical buckling,

$M_{y,Rk,\theta}$ is the characteristic resistance to bending.

GeM determines $N_{Rk,\theta}$ by multiplying the area A by f_y and the reduction factor $k_{y,\theta}$ (or A_{eff} and $k_{0,2p\theta}$ for Class 4 cross-sections), and uses the value for $\alpha_{cr,ip,\theta,N}$ evaluated by *LTBeamN*.

Along with these options, *GeM* also lets the user set the value of e_0.

Step 4: Equivalent load for the imperfect shape, q_0 (if e_0 is considered):

GeM considers the geometrical imperfect shape by applying one uniformly distributed load q_0 along the length of the member, with its value given by (see 5.3.2(7) from EC3-1-1):

$$q_0 = (8N_{Ed} \cdot e_0)/L^2 \tag{6}$$

where L is the total length of the bar.

The direction of this load is defined according to the maximum value found in step 2 for the deflection, i.e. positive if the maximum deflection is positive and negative if the maximum deflection is negative.

Step 5: In-plane analysis (accounting for q_0 if considered)

In this step, *GeM* runs *LTBeamN* again performing a 1st order or a 2nd order analysis depending on the user's choice, and stores the new values for the internal forces.

Step 6: Amplification factor for the characteristic in-plane resistance $\alpha_{ult,k,\theta}$

$\alpha_{ult,k,\theta}$ is determined by a cross-section verification. For each one of the cross-sections *i*, *GeM* determines the coefficient $\alpha_{ult,k,\theta}$ by proportionally and simultaneously increasing N_{Ed} and $M_{y,Ed}$ until the ultimate limit state is reached, and saves the one with the smallest value as the critical one, as well as its position within the member's length. Depending on the class of each cross-section, $\alpha_{ult,k,\theta}$ is determined by a linear interaction for cross-sections of Classes 3 and 4, and for Classes 1 and 2 two options are given (Vila Real, 2014): a) to consider the bilinear curve from EC3-1-1, which is an approximation to the theory of plasticity; b) to consider a conservative linear interaction.

Step 7: Amplification factor for out-of-plane instability, $\alpha_{cr,op,\theta}$

In case the user does not choose the input the value of $\alpha_{cr,op}$ himself, *GeM* considers the value returned by *LTBeamN* in the analysis made at step 2. Similarly to the previous step, the determination of $\alpha_{cr,op}$ is carried out in *LTBeamN* by proportionally and simultaneously increasing N_{Ed} and $M_{y,Ed}$.

Step 8: Normalized slenderness for the out-of-plane instability, $\bar{\lambda}_{\theta}$

$\bar{\lambda}_{\theta}$ is calculated by:

$$\bar{\lambda}_{op,\theta} = \sqrt{\alpha_{ult,k,\theta} / \alpha_{cr,\theta,op}} \quad (7)$$

Step 9: Reduction factor for the out-of-plane instability, $\chi_{op,\theta}$

At elevated temperature, the difficulties related to the choice of the curve and of a value for χ_{op} among the ones for LTB and FB that occur for normal temperature do not exist, as there is a single curve for both buckling behaviours, which only depends on the steel grade f_y. Therefore:

$$\phi_{\theta} = 0.5 \cdot \left[1 + \alpha_{\theta} \cdot \bar{\lambda}_{op,\theta} + \bar{\lambda}_{op,\theta}^{2}\right] \quad (8)$$

$$\chi_{z,\theta} = \chi_{LT,\theta} = \chi_{op,\theta} = 1/(\phi_{\theta} + \sqrt{\phi_{\theta}^{2} - \bar{\lambda}_{op,\theta}^{2}}) \quad (9)$$

Step 10: Resistance criterion

Finally, the following expression is used to check the overall stability of the member:

$$\chi_{op,\theta} \cdot \alpha_{ult,k,\theta} / \gamma_{M1} \geq 1.0 \quad (10)$$

3.2 Overview of the procedure

In Figure 6 it is shown a flowchart with all the steps involved in the procedure, as well as each option made available in the program.

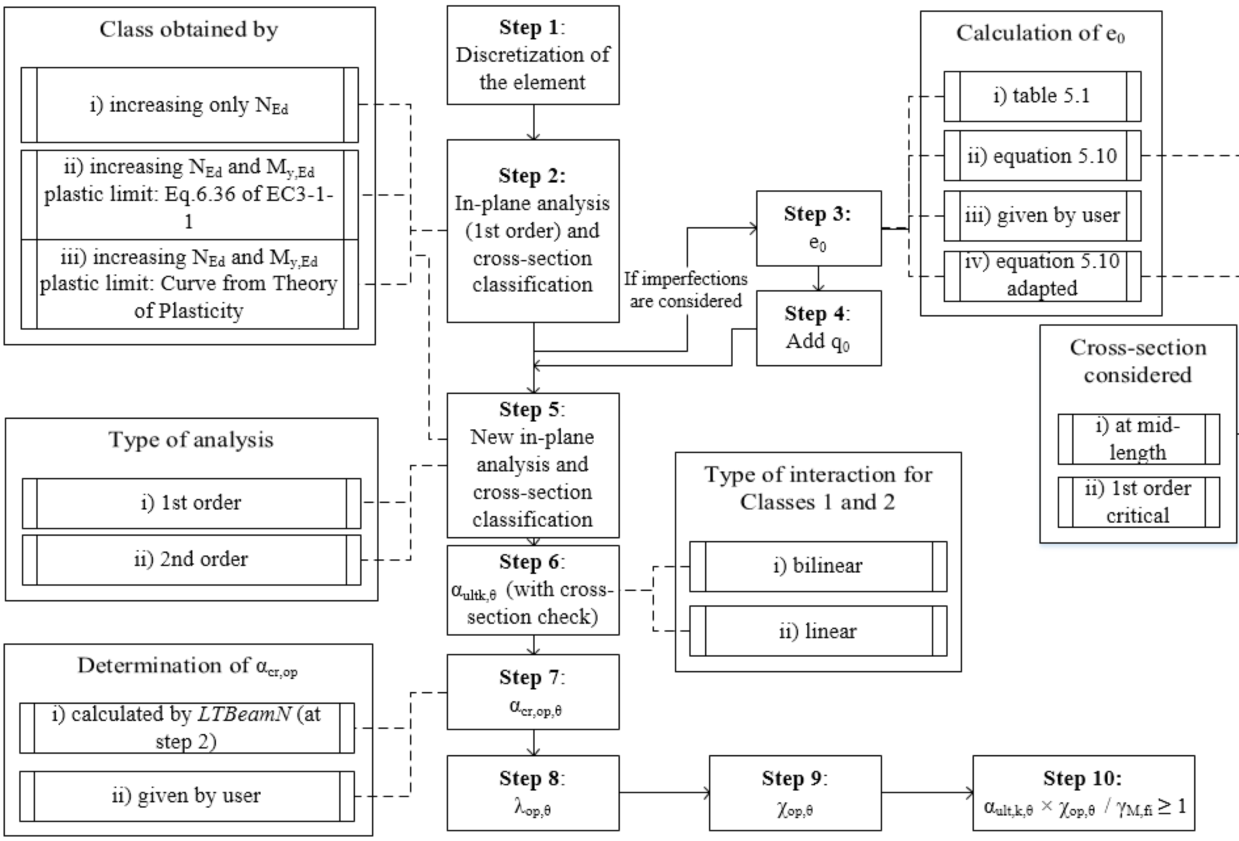

Fig. 1 Flowchart of the General Method procedure adopted in *GeM* at elevated temperature

4 EXAMPLE OF APPLICATION

An example of application and comparison to numerical results is here presented to better expose the utility and purpose of the program.

4.1 Case studied

The example deals with a welded I-shaped beam-column with constant web thickness and variable web height. The length of the column is 8000 mm with its cross-sections aligned by the top, which have the following dimensions: the full height h is variable from 200 mm to 400 mm; the web width b is 100 mm and the flange and the web thicknesses are, respectively, 8.5 mm and 5.6 mm.
The member is considered to have fork supports at both ends and has 3 lateral restraints placed at the middle of the web, equally spaced along the length of the member. It is subjected to a linear bending moment diagram that varies from M_{Ed} = -28 kN.m at the end with the bigger cross-section to M_{Ed} = 12.6 kN.m at the opposite end, and to a constant compression value of N_{Ed} = 89.6 kN. The steel grade used is S355, the elasticity modulus E is 210 GPa and the Poisson's factor is 0.3.

4.2 Options considered

The member was discretized into 200 elements. It was considered that the class of the cross-sections is obtained by increasing proportionally N and M, and that an equivalent imperfection e_0 is given by eq. (3), considering the values of N_{Ed} and $N_{Rk,\theta}$ for the 1^{st} order critical cross-section. In the calculation of $\alpha_{ult,k,\theta}$ a bilinear interaction between N and M was admitted and the value of $\alpha_{cr,op,\theta}$ was set to be determined by *LTBeamN*. A partial safety factor $\gamma_{M,fi}$ = 1 was introduced.

4.3 Results from *GeM*

The results obtained with the program are shown in Figure 2. On the left side are presented the main output values, whereas on the right side a display of the results from the in-plane analysis is shown.

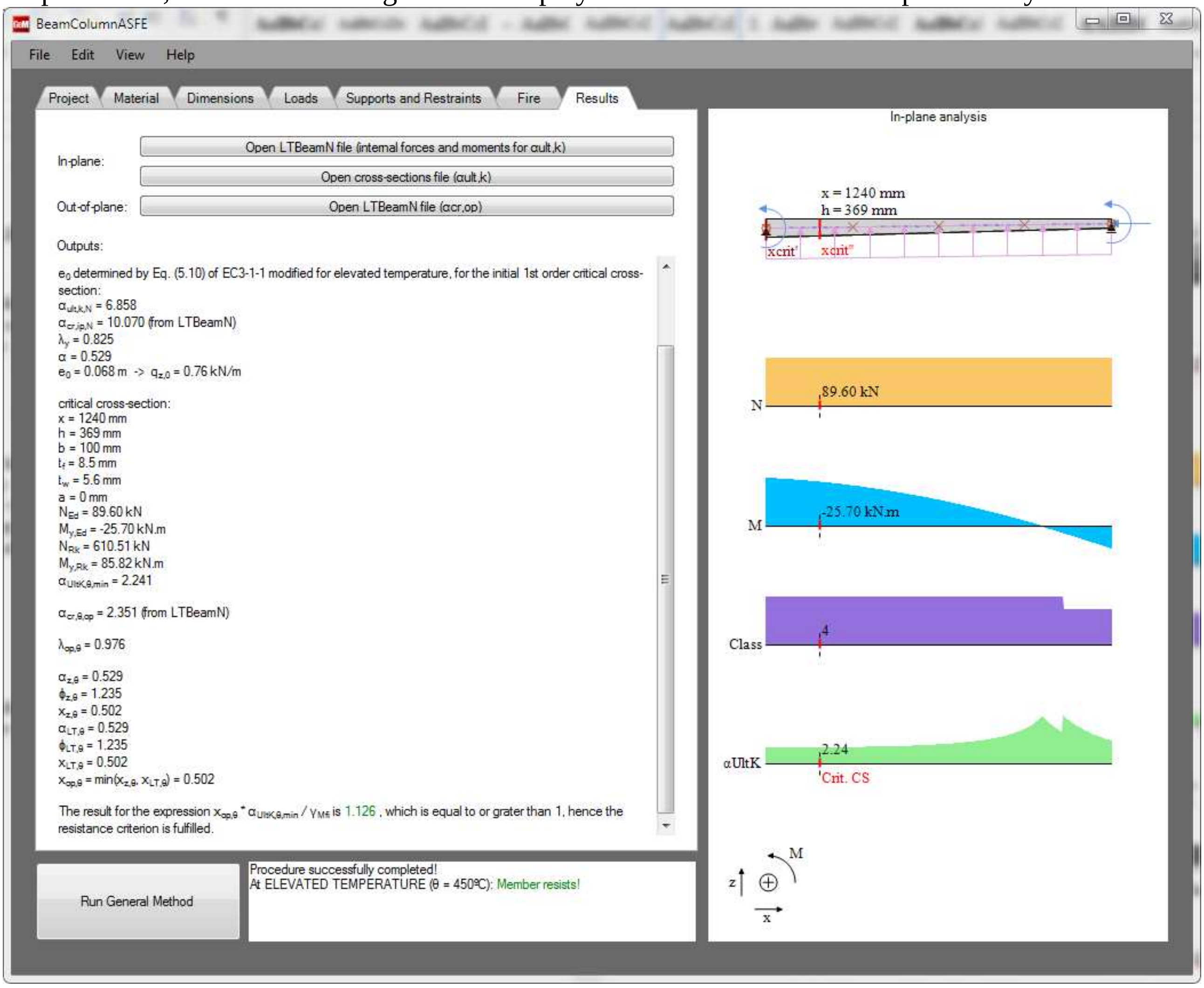

Fig. 2 Overview of the main window of *GeM* after calculation has been performed

4.4 Comparison with numerical results

In Table 1 is found a comparison between the results obtained numerically - by running an in-plane and full GMNIA analysis with the program SAFIR (Franssen, 2005) and a LBA analysis with Cast3M (CEA, 2012) - and *GeM*.

Table 1 Comparison of results obtained numerically and with *GeM*

Form of analysis	**In-plane**			**Out-of-plane**	**Overall**		
	$\alpha_{ult,k}$	utilization rate	$\Delta_{in\text{-}plane}$ (%)	$\alpha_{cr,op}$	$\alpha_{failure}$ / Eq. (10)	utilization rate	$\Delta_{overall}$ (%)
Numerical	2.74	0.36	-	2.40	1.31	0.76	-
GeM	2.24	0.45	22.27	2.35	1.13	0.89	15.32

The results show that for the studied case (given the options considered) differences of 22.27% for the in-plane and 15.32% for the overall utilization rates were found, both on the safe side, confirming that the General Method is normally conservative.

5 CONCLUSIONS

In this paper it was shown how the General Method can be applied to the fire design of non-uniform members against buckling. It was seen that two of the major difficulties that exist in the application of the method at normal temperature (the choice of the cross-section properties for determining the buckling curve and the choice of a value for χ_{op} between the ones for LTB and FB) are avoided, as currently in EC3-1-2 the choice of the buckling curve only depends on the yield strength f_y. It was concluded that the program developed enables a quick application and study of the General Method, and that it may prove to be a very useful tool in the validation of the method in the context of fire design.

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REFERENCES

Bureau A., 2007, *Résistance au flambement et au déversement d’un poteau à inertie variable selon l’en 1993-1-1*, *Révue Construction Métallique nº3*, CTICM, (in French).

Couto C, Vila Real P., Ferreira J., Lopes N., 2014, *Numerical validation of the general method for structural fire design of web-tapered beams*, Eurosteel 2014, September 10-12, Naples, Italy.

CEA, 2012, *CAST 3M is a research FEM environment; its development is sponsored by the French Atomic Energy Commission* http://www-cast3m.cea.fr/.

CEN, 2005a, EN 1993-1-1, *Eurocode 3: Design of steel structures - Part 1-2: General rules and rules for buildings*, European Committee for Standardisation, Brussels.

CEN, 2005b, EN 1993-1-2, *Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design*, European Committee for Standardisation, Brussels.

Franssen J.-M., 2005, *SAFIR, A Thermal/Structural Program Modelling Structures under Fire*, Eng. Journal, A.I.S.C., vol. 42, no. 3, pp. 143–158.

Galéa Y., 2003, *Elastic critical moment for lateral-torsional buckling of steel beams – introduction of the software LTBeam*, Révue Construction Métallique nº2, CTICM (in French).

Vila Real P., 2014, *On the classification of cross-sections under bending and axial compression at elevated temperature*, Commemorative publication on the occasion of Prof. Peter Schaumann’s 60th birthday - Leibniz Universität Hannover, pp. 221–230.