COMPARISON BETWEEN EC3 AND THE ORIGINAL PROPOSAL FOR BEAM-COLUMNS IN CASE OF FIRE

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INTRODUCTION

As a result of the Buckling Curves in Case of Fire (BCCF) research project, funded by the European Convention for Coal and Steel (ECSC agreement: 7210 SA 316/515/618/931), a new procedure for the calculation of steel beam-columns interaction curves in case of fire was proposed in 1995. The outcomes were published by Talamona [1], Profil Arbed Recherche [2, 3], the European Commission [4] and in international journals (Franssen et al. [5] and Talamona et al. [6]). The proposed formulation was later accepted to become part of the Eurocode 3 part 1.2 to calculate the fire resistance of steel beam-columns. First it was adopted in the French National Annex, later in the ENV version of the EC3 and finally in the EN version [7].

It appeared that the equations published in the official version of EN 1993-1-2 [7] differ from the equations proposed in the original work [1, 2 and 4].

The motivation for this project is to clarify the doubt concerning the safety level of the Eurocode 3 created by the modification of formulae originally proposed in 1995. The objectives are to identify precisely the differences and to examine their consequences on the fire endurance of steel columns subjected to axial compression and bending.

1 FORMULATIONS

The original formulation proposed to calculate the fire resistance of steel beam-columns was published by the BCCF research partners in 1995 [1, 2 and 4]. In accordance with this proposal, elements with cross-sections in classes 1 and 2 submitted to bending and axial compression must satisfy the following condition in case of fire:

$$\frac{N_{fi,Ed}}{\chi_{min,fi}\cdot A\,\frac{k_{y,\theta}\cdot f_y}{\gamma_{M,fi}}}+\frac{k_{y,fi}\cdot M_{y,fi,Ed}}{W_{pl,y}\,\frac{k_{y,\theta}\cdot f_y}{\gamma_{M,fi}}}+\frac{k_{z,fi}\cdot M_{z,fi,Ed}}{W_{pl,z}\,\frac{k_{y,\theta}\cdot f_y}{\gamma_{M,fi}}}\le 1 \qquad (1)$$

The subscripts "*y*" and "*z*" refer to the major axis (or y-axis) and to the minor axis (or z-axis) respectively (except for f_y which is the yield strength and $k_{y,\theta}$ its reduction factor).

The interaction factors $k_{y,fi}$ and $k_{z,fi}$ should be determined by:

$$k_{y,fi}=1-\frac{\mu_{y,\theta}\cdot N_{fi,Ed}}{\chi_{y,fi}\cdot A\cdot k_{y,\theta}\,\frac{f_y}{\gamma_{M,fi}}} \quad \text{but } k_{y,fi}\le 3 \qquad (2)$$

$$k_{z,fi}=1-\frac{\mu_{z,\theta}\cdot N_{fi,Ed}}{\chi_{z,fi}\cdot A\cdot k_{y,\theta}\,\frac{f_y}{\gamma_{M,fi}}} \quad \text{but } k_{z,fi}\le 3 \qquad (3)$$

The differences between the original formulae and the ones in EN 1993-1-2 lie in the equations used to determine the values of coefficients $\mu_{y,\theta}$ and $\mu_{z,\theta}$. In EN 1993-1-2 they are given by *Eq. (6)* and *(7)*, which should be compared with *Eq. (4)* and *(5)* of the original proposal (see *Table 1*).

Table 1. formulae for $\mu_{y,\theta}$ and $\mu_{z,\theta}$

	Original proposal	Formulation from EN 1993-1-2
$\mu_{y,\theta} =$	$(2 \cdot \beta_{M,y} - 5)\bar{\lambda}_{y,\theta} + 0.44 \cdot \beta_{M,y} + 0.29$ but $\mu_{y,\theta} \le 0.8$ and $\bar{\lambda}_{y,20} \le 1.1$ (4)	$(1.2 \cdot \beta_{M,y} - 3)\bar{\lambda}_{y,\theta} + 0.44 \cdot \beta_{M,y} - 0.29$ but $\mu_{y,\theta} \le 0.8$ (6)
$\mu_{z,\theta} =$	$(1.2 \cdot \beta_{M,z} - 3)\bar{\lambda}_{z,\theta} + 0.71 \cdot \beta_{M,z} - 0.29$ but $\mu_{z,\theta} \le 0.8$ (5)	$(2 \cdot \beta_{M,z} - 5)\bar{\lambda}_{z,\theta} + 0.44 \cdot \beta_{M,z} - 0.29$ but $\mu_{z,\theta} \le 0.8$ and $\bar{\lambda}_{z,\theta} \le 1.1$ (7)

Using the equivalent uniform moment factors $\beta_{M,y}$ and $\beta_{M,z}$ defined as:

$$\beta_{M,i} = 1.8 - 0.7 \cdot \psi_i \qquad (8)$$

and the non-dimensional slenderness estimated at elevated temperature:

$$\bar{\lambda}_\theta = \bar{\lambda}_{20} \cdot \sqrt{\frac{k_{y,\theta}}{k_{E,\theta}}} \qquad (9)$$

In *Eq. (8)*, the subscript "*i*" is defined as "*y*" or "*z*" depending on the buckling axis considered.

2 COMPARISON OF THE TWO FORMULATIONS

Fig. 1 and *Fig. 2* show a comparison of the evolution of the ratios $\mu_{y,\theta}$ and $\mu_{z,\theta}$ as function of the relative slenderness calculated at elevated temperature ($\bar{\lambda}_\theta$) and of the shape of the bending diagram ($\beta_{M,y}$ and $\beta_{M,z}$)

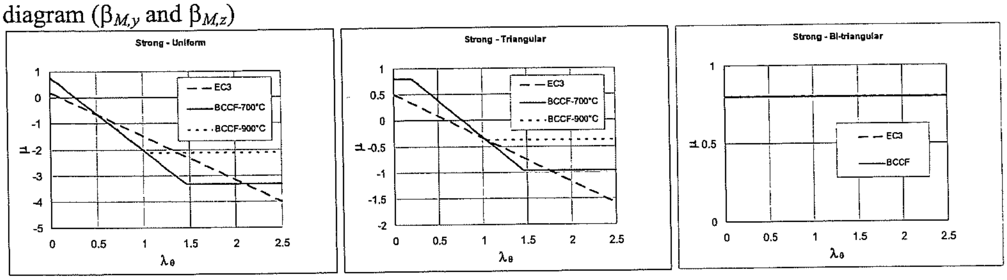


Fig. 1. $\mu_{y,\theta}$ as function of $\bar{\lambda}_{\theta,y}$

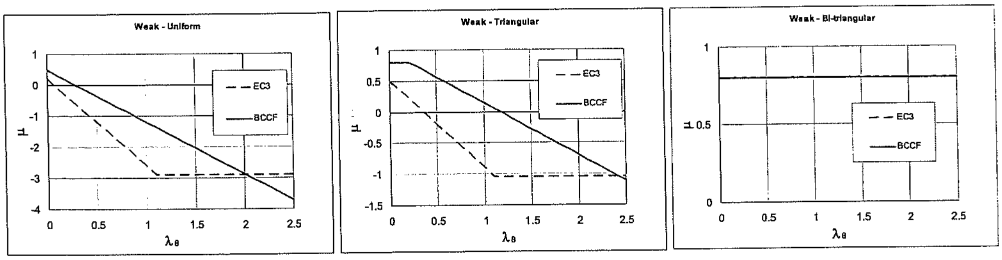


Fig. 2. $\mu_{z,\theta}$ as function of $\bar{\lambda}_{\theta,z}$

Eq. (4) of the original proposal has a limitation of the slenderness expressed at room temperature, $\bar{\lambda}_{20} \le 1.1$, which creates a variation of $\mu_{y,\theta}$ as function of temperature for uniform and triangular bending moment distributions, as can be seen *Fig. 1*. The curves established at 700°C and 900°C represent the maximum and minimum values of the ratio $\sqrt{k_{y,\theta}/k_{E,\theta}}$ (1.33 and 0.9428 respectively).

For bi-triangular bending moment distribution ($\psi = -1$), the coefficients $\mu_{y,\theta}$ and $\mu_{z,\theta}$ are equal to the maximum value of 0.8 for both formulations. In this case, as the two formulations have the same $\mu_{y,\theta}$ and $\mu_{z,\theta}$ as input coefficients, the same ultimate temperature will be predicted. Thus this load case will be left out of this investigation.

3 COMPARISON OF THE ULTIMATE TEMPERATURES

A comparison of the ultimate temperatures obtained with both formulations has been performed using the following assumptions:

- Twelve reduced slenderness have been considered ($\bar{\lambda}_{20}$ = 0.2 to 2.4 with an increment of 0.2)
- Six M/N ratios (0.05, 0.1, 0.5, 1.0, 3.0 and 5.0 multiplied by the radius of gyration about the buckling axis considered)
- Buckling about the major and minor axis
- Two bending moment distributions (uniform: $\psi = 1$ and triangular: $\psi = 0$)
- Failures temperatures between 400 °C and 860 °C (for both formulations)
- Profiles in class 1 and 2 in compression and bending have been considered (382 profiles).
- Steel S235 with reduction of the yield strength depending on the thickness of the flanges
    - ➢ 235 MPa for $t_f \leq 16$ mm
    - ➢ 225 MPa for $t_f \leq 40$ mm
    - ➢ 215 MPa for $t_f \leq 100$ mm
    - ➢ 195 MPa for $t_f \leq 150$ mm

Note that axially loaded columns and bi-triangular ($\psi = -1$) bending moment distribution have not been considered, as these load cases are not affected by the modification introduced in the EC3.

Fig. 3 shows a comparison of the failure temperatures predicted by both formulation for selected loading cases and slenderness. The title of each graph represents, the buckling axis (strong or weak), the bending moment distribution (uniform and triangular for $\psi = 1$ and $\psi = 0$ respectively) and the relative slenderness at room temperature.

As can be seen *fig. 3* there is no major difference between the temperatures predicted. The biggest differences in ultimate temperatures are obtained for short columns submitted to a triangular bending moment and heavily loaded (failure temperatures under 600 °C). These discrepancies are due to the fact that under these conditions the value of $\mu_{y,\theta}$ and/or $\mu_{z,\theta}$ is between 0.8 and -1 and it has been shown [1, 2 and 6] that for the values the M-N interaction curve is extremely sensitive to a variation of $\mu_{y,\theta}$ or $\mu_{z,\theta}$. As a general rule it can be stated that: the smaller the value of $\mu_{y,\theta}$ or $\mu_{z,\theta}$ (-2, -3 etc.) the less sensitive the M-N interaction curve.

The most sensitive case is a HE 100 AA + (steel S235) with a relative slenderness at room temperature equal to 0.2 axially loaded (N = 150160 N) and with a triangular bending moment distribution ($M1 = 10 \cdot i_z \cdot N$ at one end and M2 = 0 at the other end). Where i_z is the radius of gyration in the z-axis. The models predict ultimate temperatures for the EC3 model and the BCCF model of 410 °C and 512 °C respectively. To achieve a failure temperature of 512 °C with the EC3 model, the load should be decreased by 24% (keeping the same M/N ratio) and to achieve a failure temperature of 410 °C with the BCCF model the load should be increased by 31%. Using the formula available in the previous version of Eurocode 3 part 1.2 [8] and maximum load of 165000 N can be calculated. This means that under the initial conditions the columns was loaded at 91% of its ultimate load at room temperature which is not realistic.

These types of unrealistic calculations have been computed as the program was developed to calculate the failure temperatures aimed to compare the two formulations at elevated temperature. Therefore no systematic check of the loading at elevated temperature against the maximum load at room temperature has been preformed automatically.

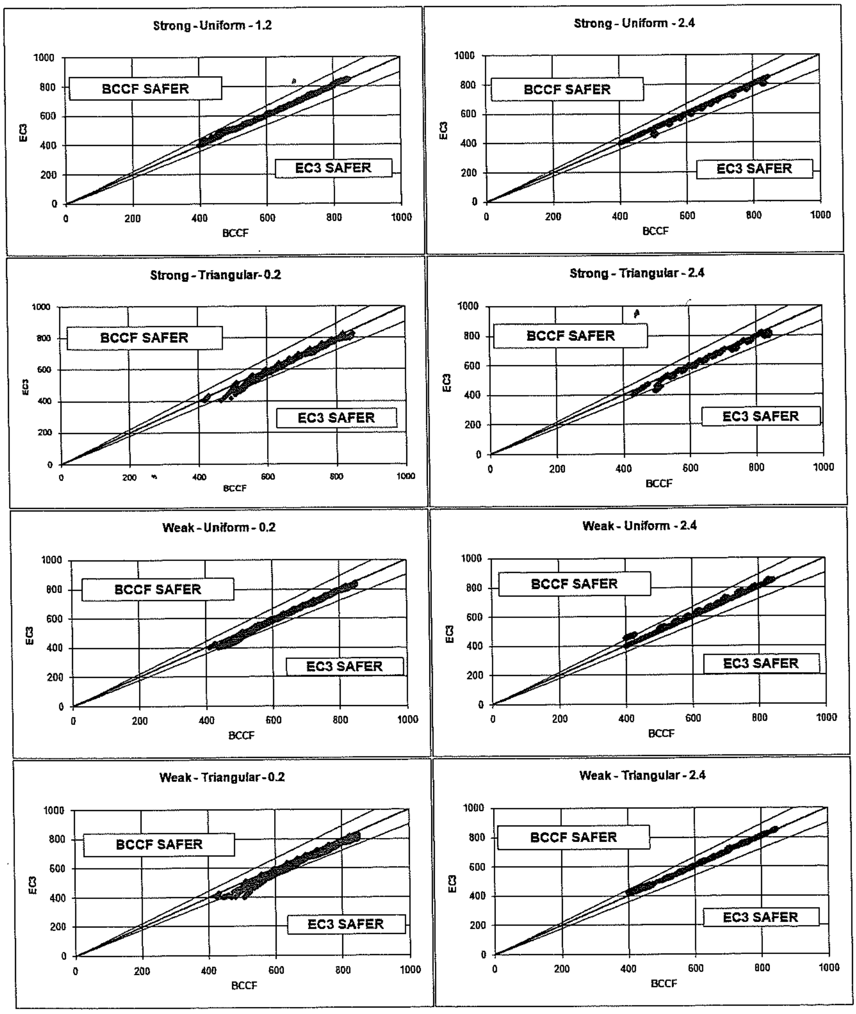
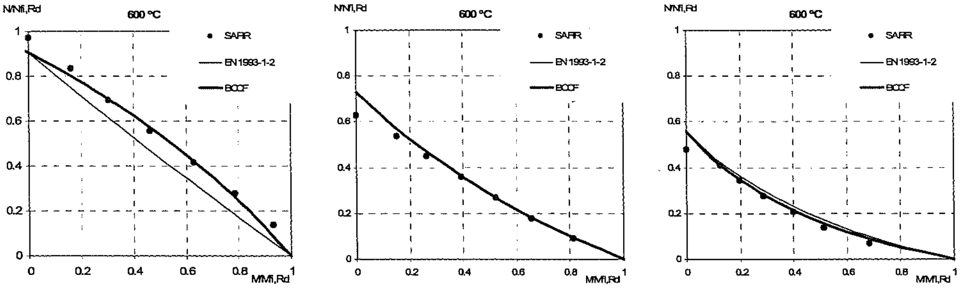


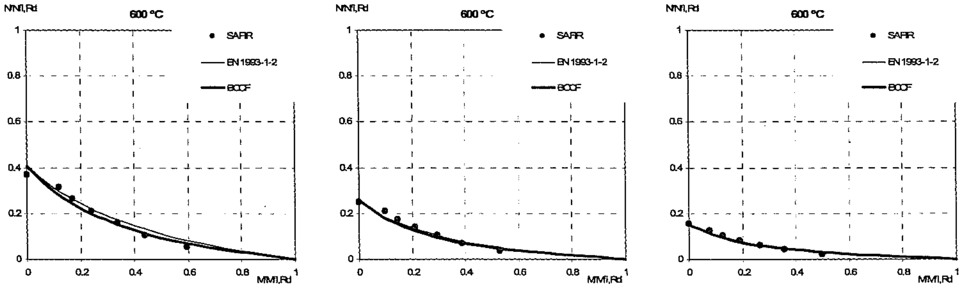
Fig. 3. Comparison of the ultimate temperatures

4 COMPARISON WITH SAFIR

Fig. 4 and *Fig. 5* show the interaction curves for the case of a welded HEA 200 in S235, at 600 °C submitted to flexural buckling around the y-y axis and the z-z axis respectively. The spans for the calculation are comprised between 1 and 14m. These figures show that for the major buckling axis the BCCF method predicts results which are closer to the SAFIR calculation than the model from Eurocode 3. But when the minor axis is considered the Eurocode 3 perform better than the BCCF model. Nevertheless on average both formulations provide similar results when compared to finite element calculations..

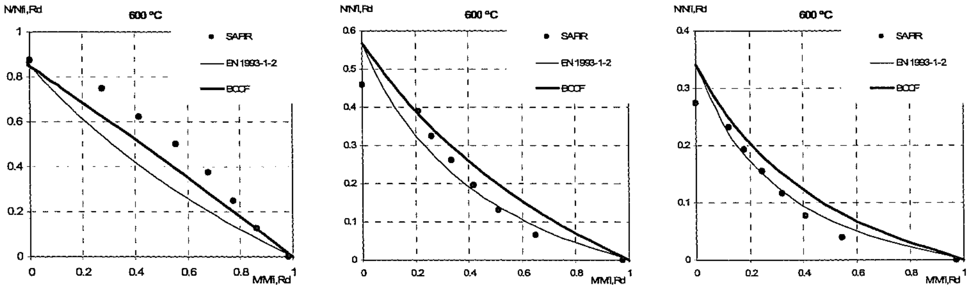


L=1000mm; $\overline{\lambda}_{y,\theta} = 0.159$ L=3000mm; $\overline{\lambda}_{y,\theta} = 0.477$ L=5000mm; $\overline{\lambda}_{y,\theta} = 0.795$

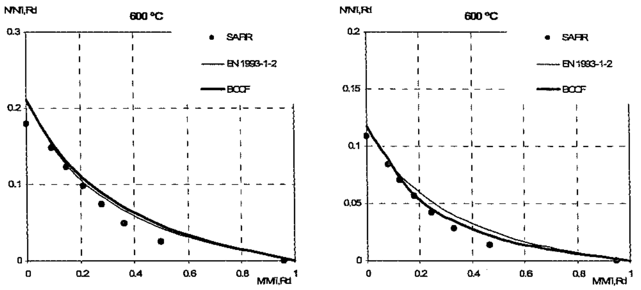


L=7000mm; $\overline{\lambda}_{y,\theta} = 1.112$ L=10000mm; $\overline{\lambda}_{y,\theta} = 1.589$ L=14000mm; $\overline{\lambda}_{y,\theta} = 2.225$

Fig. 4. Interaction curves at 600 °C for beam column with bending around the major axis, (N+M_y)



L=1000mm; $\overline{\lambda}_{z,\theta} = 0.258$ L=3000mm; $\overline{\lambda}_{z,\theta} = 0.773$ L=5000mm; $\overline{\lambda}_{z,\theta} = 1.289$



L=7000mm; $\overline{\lambda}_{z,\theta} = 1.804$ L=10000mm; $\overline{\lambda}_{z,\theta} = 2.578$

Fig. 5. Interaction curves at 600 °C for beam column with bending around the minor axis, (N+M_z)

CONCLUSIONS

From this investigation, it can be concluded that the formulations from the Eurocode and BCCF research project are:

- Usually similar in terms of failure temperatures
- When differences are observed they are usually conservative
- When the new formulation is not conservative the difference in terms of load variation is less than 5%
- Both formulations provide similar failure temperatures when the predicted temperatures are above 600°C
- The examples in this article highlight that the larger differences in failure temperatures are observed for heavily loaded columns (low failure temperatues), which are not likely to be found in constructions.

From the results presented in this paper it can be concluded that the new formulation is not likely to decrease the safety level of constructions. More investigation needs to be performed to assess the impact of these modifications on the competitiveness of steel structures.

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