WG1- Fire resistance

Member behaviour, analysis and design in fire

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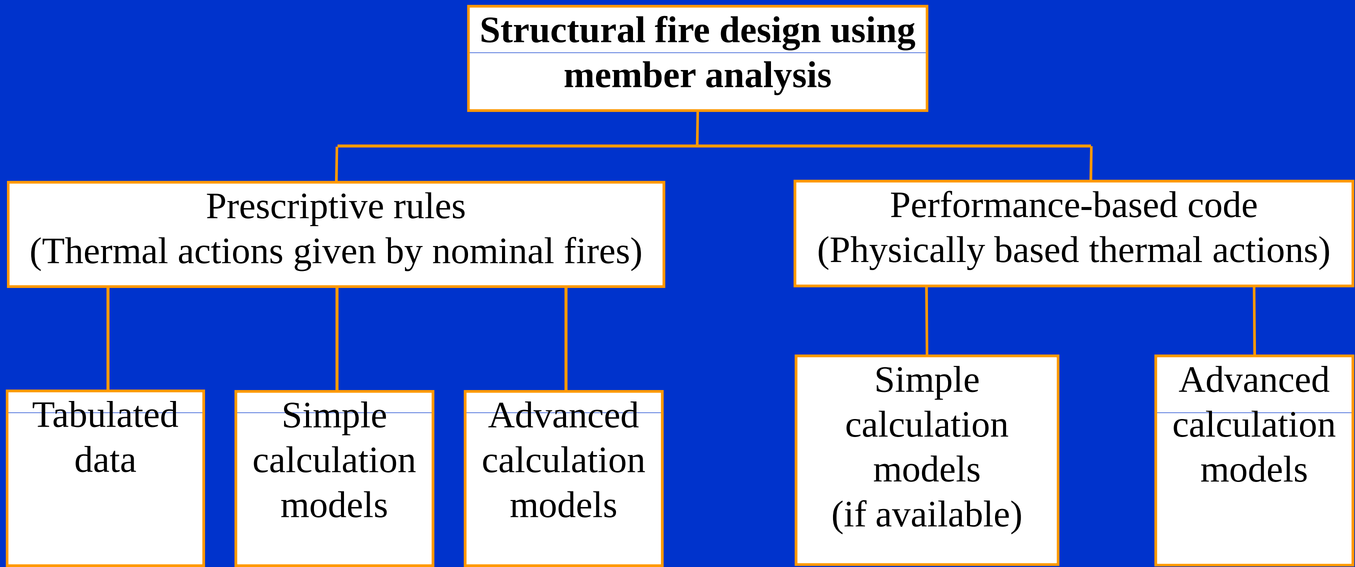
Structural member design in case of fire

N. Lopes[1]
P. Vila Real[1]
H. Bouchaïr[2]

1-University of Aveiro, Portugal
2-Blaise Pascal University, France

Structural member design in case of fire

➢According to the fire design part of Eurocode (EC) when a member is considered isolated indirect fire actions are not considered, except those resulting from thermal gradients.



➢In the EC are given simplified calculation methods for standard fire and parametric fire, however the material models apply only to heating rates similar to standard fire.

$$E_{d,fi} / R_{d,fi} \leq 1.0$$

- Structural member design in case of fire (part 1-2 of the EC)
  - Concrete member design (EC2)
  - Steel and stainless steel member design (EC3)
  - Composite member design (EC4)
  - Timber member design (EC5)
  - Aluminium member design (EC9)

Tabulated data

- EC may give recognised design solutions for the standard fire exposure up to 240 minutes. The tables have been developed on an empirical basis confirmed by experience and theoretical evaluation of tests.

Simplified calculation method

- Simplified cross-section calculation methods may be used to determine the **ultimate load bearing capacity** of a heated cross section (by reducing the mechanical properties at high temperature or in the case of timber reducing also the cross section) and to compare the capacity with the **relevant combination of actions**.

Advanced calculation methods

- In general, the Fire Parts of Eurocodes allow for advanced calculation methods that provide a realistic analysis of structures exposed to fire.

- Advanced calculation methods may be applied for the determining the:
  - **thermal response model**
  - **structural behaviour**

- Advanced calculation methods for the structural response should take into account the changes of mechanical properties with temperature and also, where relevant, with moisture.

Structural member behaviour and analysis in case of fire (contributions from the WG1)

N. Lopes[1]
P. Vila Real[1]

B. Uppfeldt[2]
M. Veljkovic[3]
L. Simões da Silva[4]
J-M. Franssen[5]
H. Bouchaïr[6]
J-P. Muzeau[6]
O. Vassart[7]
D. Bacinskas[8]
G. Kaklauskas[8]
V. Gribniak[8]
M.Cvetkovska[9]
L.Lazarov[9]
E. Nigro[10]
G. Cefarelli[10]

1-University of Aveiro, Portugal
2-The Sweden Institute of Steel Construction, Sweden
3-Luleå University of Technology, Sweden
4-University of Coimbra, Portugal
5-University of Liege, Belgium
6-Blaise Pascal University, France
7-ArcelorMitall, Luxembourg
8-Vilnius Gediminas Technical University, Vilnius, Lithuania
9-Civil Engineering Faculty, Skopje, Macedonia
10-Department of Structural Engineering, University of Naples, Italy

Class 4 Stainless Steel Box Columns in Fire

B. Uppfeldt
The Swedish Institute of Steel Construction, Stockholm, Sweden

M. Veljkovic
Luleå University of Technology, Sweden

Uppfeldt B. and Veljkovic M. (2007). *"Class 4 Stainless Steel Box Columns in Fire"*. Proceedings of the COST C26 Workshop in Prague, Czech Republic.

Uppfeldt B., Ala Outinen T. and Veljkovic M. (2008). *"A design model for stainless steel box columns in fire"*. Journal of Constructional Steel Research, 64, 1294–1301

Class 4 Stainless Steel Box Columns in Fire

- A study of **stainless steel cold-rolled box columns** at elevated temperatures is presented, which is a part of an RFCS project ”Stainless Steel in Fire”.

- Experimental results of six, **class 4**, stub columns at elevated temperature, were used to evaluate the FE model.

- The FE analysis obtained shows that the critical temperature **was closely predicted.**

- A parametric study was the basis to check the quality of prediction of a **newly proposed improvement for design rules** of class 4 cross-sections in fire according to Part1-4 and Part 1-2 of EC3 (stainless steel and fire design part respectively).

Class 4 Stainless Steel Box Columns in Fire

Elements

A general-purpose **shell element,** called S4R, within Abaqus/Standard was used.

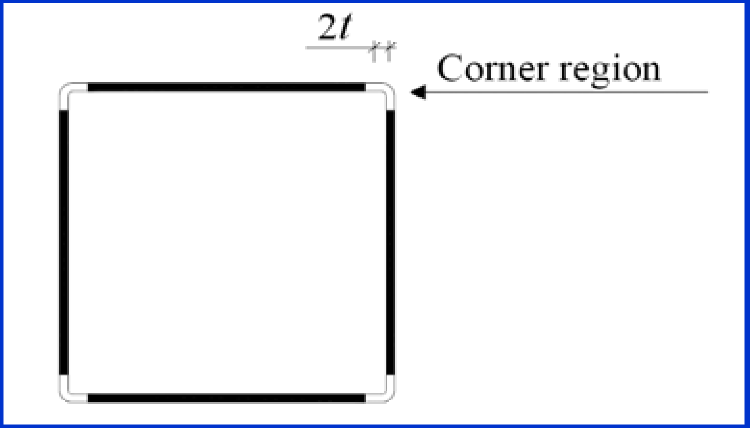
Imperfections

The two types of geometrical imperfections that have to be considered are, **global imperfections** and **local imperfections**.

For the modelling of the tested stub columns the measured local imperfections were used and no global imperfections were introduced.

Material

It is well established that the mechanical properties of stainless steel are strongly influenced by the level of cold-work.



Class 4 Stainless Steel Box Columns in Fire

Residual stresses

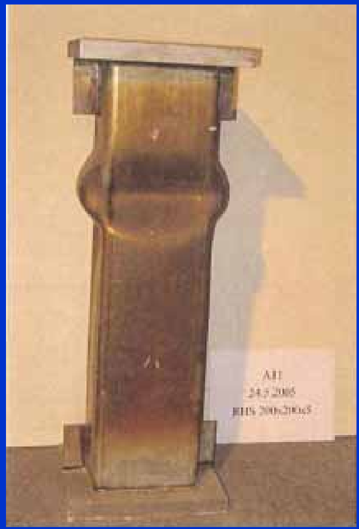
No residual stresses were introduced in the modelling of the tested columns.

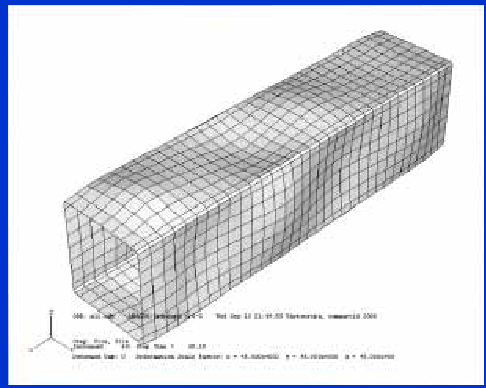
Validation

No. specimen Cross-section	Experiment Temp. °C	FEA Temp. °C	$Temp_{FEA}/Temp_{exp}$
1. 150x150x3	676	716	1.06
2. 150x150x3	720	758	1.05
3. 150x150x3	588	593	1.01
4. 200x200x5	609	482	0.79
5. 200x200x5	685	645	0.94
6. 200x200x5	764	732	0.96

It is concluded that the FE-model predicts the failure temperatures with **good accuracy** for all tests but specimen No. 4 and the general conclusion is that the model is reliable for parametric study.

Class 4 Stainless Steel Box Columns in Fire





➢Comparison between experiments at the elevated temperature and results obtained from FEA indicates that

- ➢- assumptions made for the influence of the **material properties** in the **corners** are **realistic**;
- ➢- assumptions for the shape and level of the local buckling, b/200, and global imperfections, L/1000, are consistent with assumptions established at ambient temperature.

➢The proposed design model is an **improvement** compared to the design model on EN 1993-1-2.

Steel and Stainless steel elements in case of fire

Nuno Lopes; Paulo Vila Real
University of Aveiro, Portugal

Luis Silva
University of Coimbra, Portugal

Jean-Marc Franssen
University of Liege, Belgium

Vila Real P., Lopes N., Silva L., Franssen J.-M. (2007). *"Parametric analysis of the Lateral-torsional buckling resistance of steel beams in case of fire"*. Fire Safety Journal, vol. 42 / (6-7) , 416-424 .

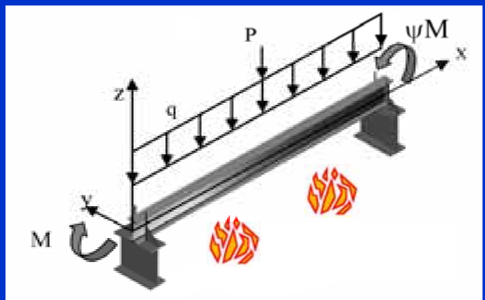
Vila Real P., Lopes N., Silva L., Franssen J.-M. (2007). *"Lateral-torsional buckling of stainless steel I-beams in case of fire"*. Journal of Constr. Steel Res., 64, 1302-1309.

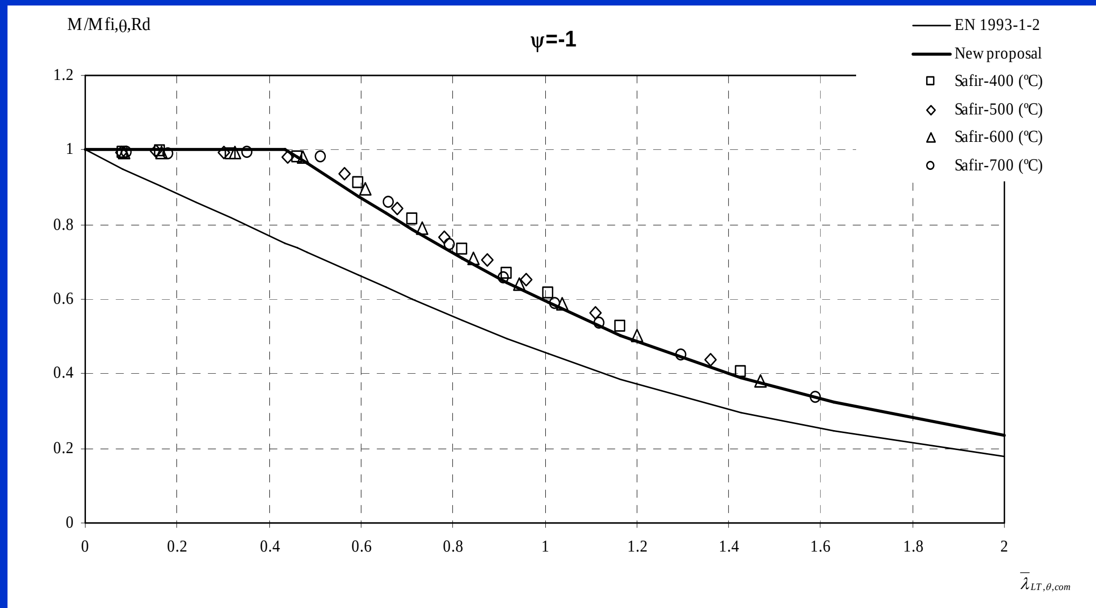
Lopes N., Vila Real P., Silva L., Franssen J.-M. (2008). *"Duplex stainless steel columns and beam-columns in case of fire"*. Proceedings of the 5th Structures in Fire (SiF'08), Singapore.

Steel and Stainless steel elements in case of fire

- Numerical modelling of the **lateral–torsional buckling** (LTB) of **steel** beams at elevated temperature has shown that the beam design curve from EN 1993-1-2 is over-conservative in the case of **non- uniform bending**.

- An improved proposal was presented that addresses the influence of the:
  - loading type,
  - the steel grade,
  - the pattern of the residual stresses (hot-rolled or welded sections)
  - and the ratio h/b

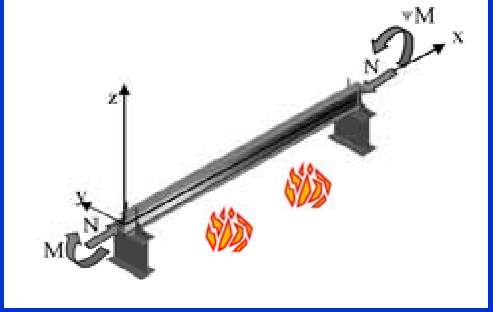




- This proposal achieves **better agreement** with the numerical behaviour and maintains **safety**.

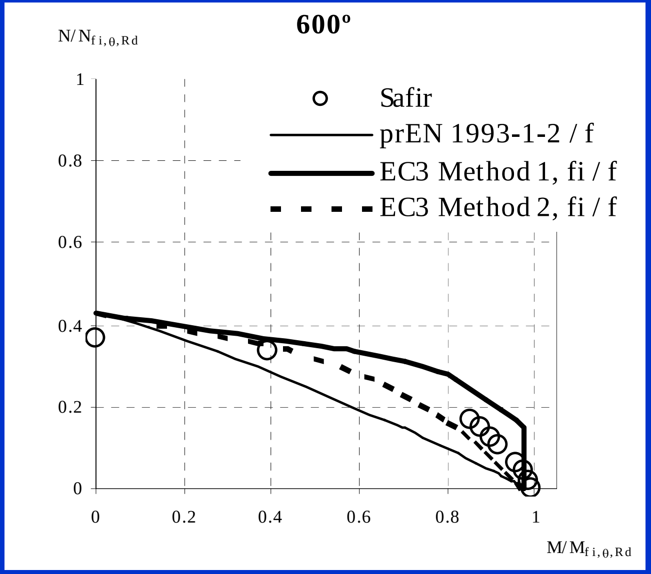
Steel and Stainless steel elements in case of fire

➢Two new formulae for the design of **steel** beam-columns at room temperature have been proposed in EN 1993-1-1 as the result of extensive work by two working groups that followed different approaches, namely, a French-Belgian team and an Austrian-German one.



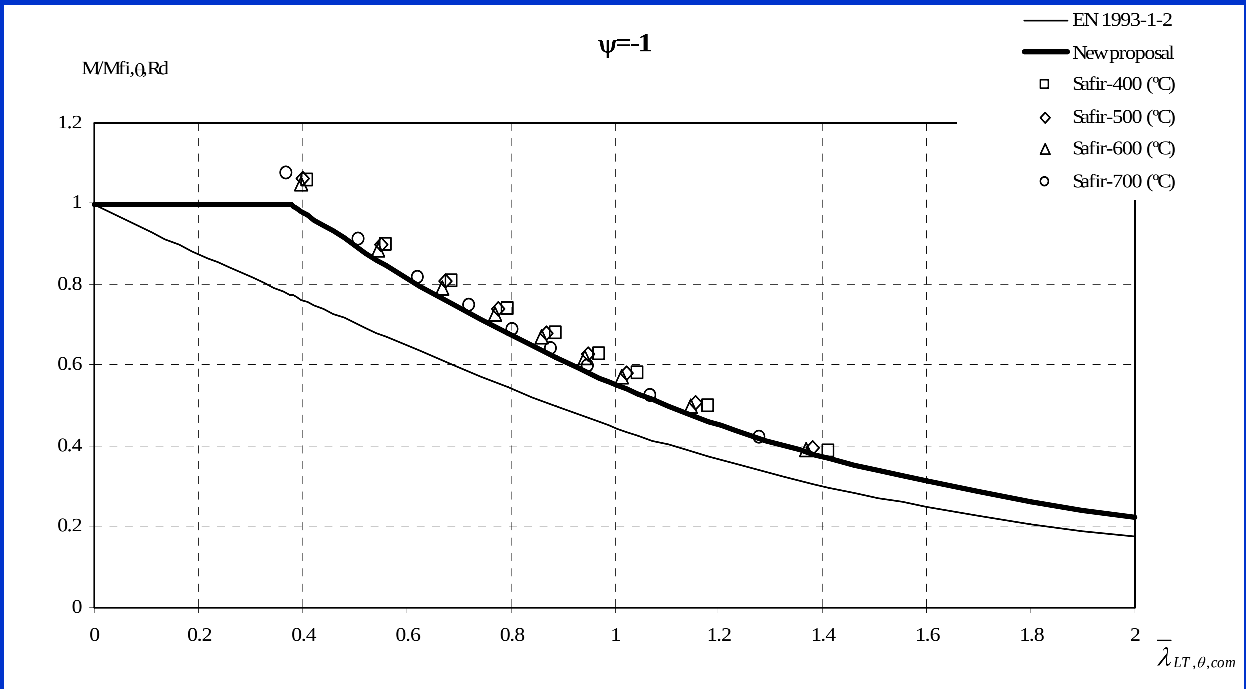
➢Under fire conditions, in EN 1993-1-2, the proposed formulae for the design of beam-columns in case of fire have not changed and are still based on ENV 1993-1-1.

➢ In order to study the possibility of having, in parts 1-1 and 1-2 of the EN version Eurocode 3, the same approach for beam-columns, a numerical investigation was carried out, with the conclusion that it **is possible** to use the formulae from the **part 1-1** provided that some **factors are modified** to consider high temperatures.



Steel and Stainless steel elements in case of fire

➢New formulae for **LTB**, that approximate better the real behaviour of **stainless steel** structural elements in case of fire were proposed.

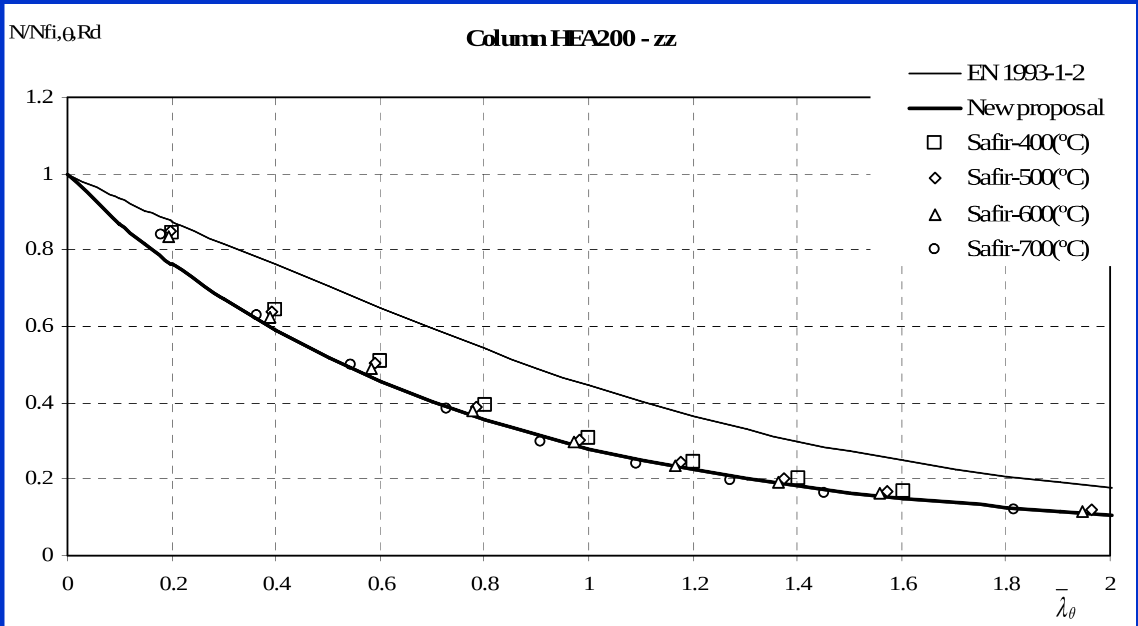


Structural member behaviour and analysis in case of fire

Steel and Stainless steel elements in case of fire

➢It were evaluated the accuracy and safety of the currently prescribed design rules in part 1.2 of EC3 for the evaluation of the resistance of **stainless steel columns** and **beam-columns**. This evaluation was carried out by numerical simulations on Class1 and 2 stainless steel H-sections.

➢It was considered buckling in the **two** main cross-section **axis** and, in the case of the beam-columns, different bending moment diagrams.



➢The results presented shown that EC3 formulae for the evaluation of the fire resistance of columns and beam-columns **need to be improved**.

Numerical and analytical models for cellular beams

O. Vassart
ArcelorMitall, Luxembourg

A. Bouchair; J.-P. Muzeau
Blaise Pascal University, France

Vassart O., Bouchair A., Muzeau J.-P. (2007). *"Analytical model for the web post buckling in cellular beams under fire",* Proceedings of the COST C26 Workshop in Prague, Czech Republic.

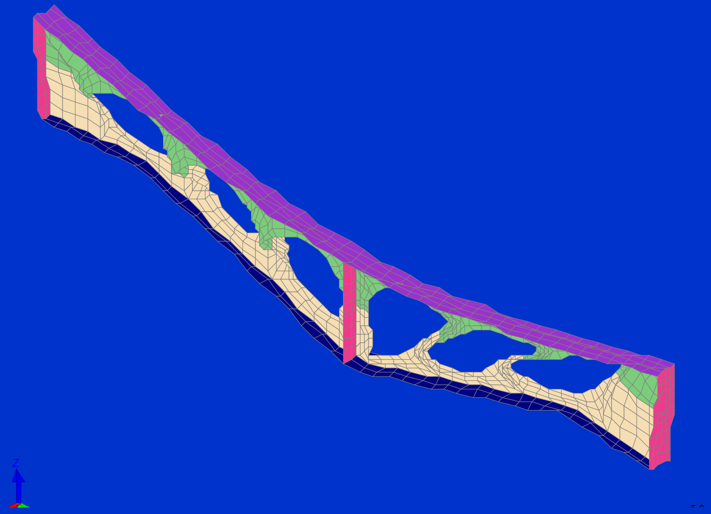
Numerical and analytical models for cellular beams

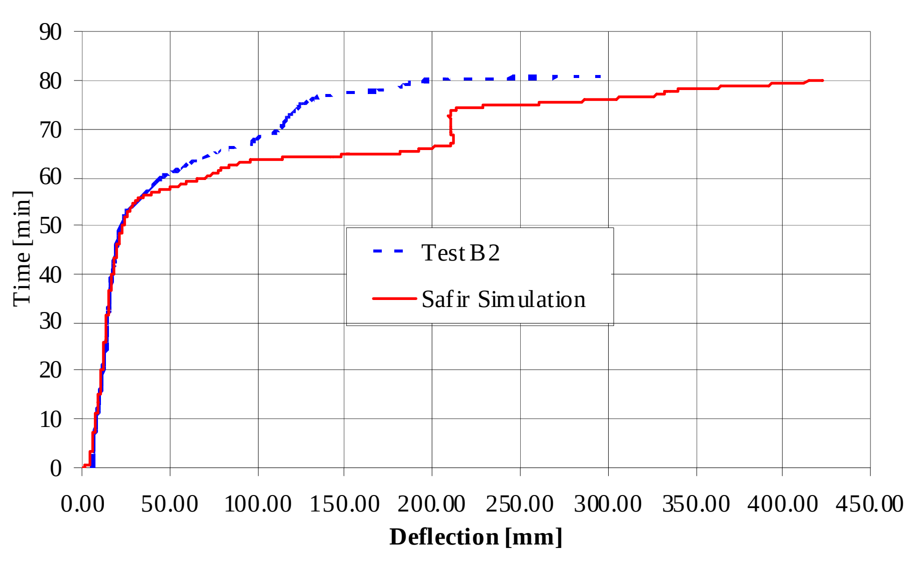
- An analytical model representing the web post buckling for **cellular beams** in case of fire is developed on the basis of that for cold conditions.

- The analytical model is checked using a finite element model (SAFIR) considering both material and geometrical non-linearity. This model is calibrated on the basis of **experimental results** (failure modes, stiffness, strength).

- During fire tests, the main failure mode is web-post buckling. The numerical model is able to simulate the behaviour of composite cellular beams in both cold and elevated temperature conditions with a relatively **high accuracy**.

Numerical and analytical models for cellular beams





Numerical and analytical models for cellular beams

- The analytical model used to evaluate the critical temperature of the web-post gives **accurate** and **safe** sided results compared to the experimental tests and FEM model for cellular steel beams.

- Further improvement must be done in order to take into account the **composite cellular beams** in the analytical model and define its limits of validity.

Simplified grid model for analysis of reinforced concrete members

Viktor Gribniak; Darius Bačinskas; Gintaris Kaklauskas
Vilnius Gediminas Technical University, Lithuania

Gribniak V., Bačinskas D., Kaklauskas G. (2007). *"Non-linear modelling of reinforced concrete beams subjected to fire"*. Proceedings of the COST C26 Workshop in Prague, Czech Republic.

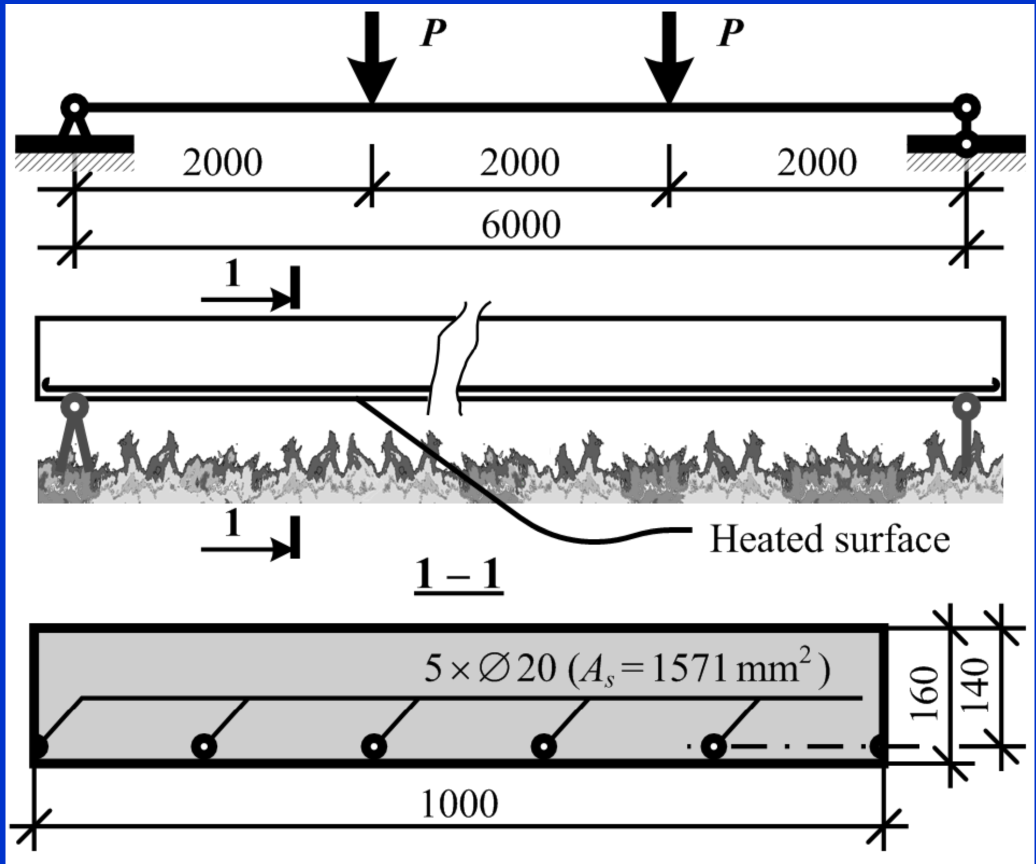
Simplified grid model for analysis of RC members

- Analytical and computational methods have been extensively developed in the field of **reinforced concrete** (RC) building exposed to high temperature or accidental fire.

- Advanced non-linear mechanical models based on the 2D or 3D FEM which were rapidly progressing within last decades are based on universal principles and can include all possible effects. However, such models are computationally too demanding.

- This research is aimed at developing a **simple computationally effective technique** based on formulas of materials strength and grid approach employing temperature dependant material diagrams.

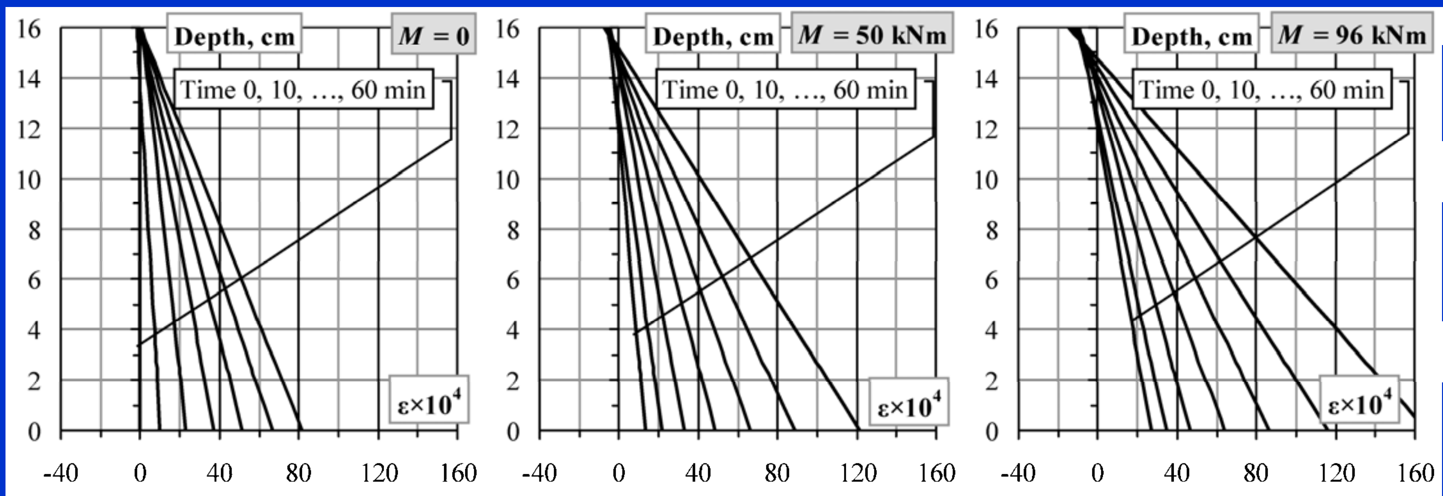
Simplified grid model for analysis of RC members



Simplified grid model for analysis of RC members

- The beam's cross-section is divided into a number of horizontal and vertical layers comprising a **grid** section. Each grid element may have different material properties.

- A **step-by-step nonlinear** sectional analysis is performed under the external mechanical loads for a given temperature distribution obtained from thermal analysis. Starting with the cross-sectional strains and stresses due to the initial mechanical load a new strain and stress distribution is calculated at any time of the transient thermal analysis.



Strain distribution across the depth of the slab under different time and loading

Centrically and eccentrically loaded columns

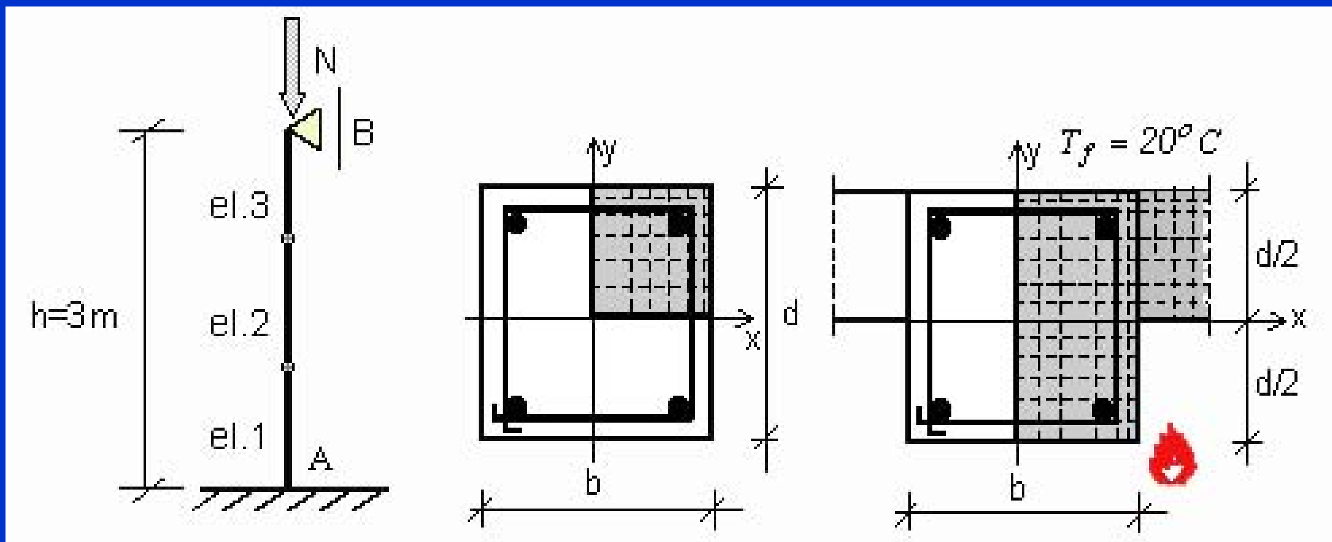
M. Cvetkovska; L. Lazarov
Civil Engineering Faculty, Skopje, Macedonia

Cvetkovska M., Lazarov L. (2004). *"Non-linear stress strain behaviour of RC columns exposed to fire". Proc. of Inter. Conf., Lifetime-Oriented Design Concepts*, *Germany.*

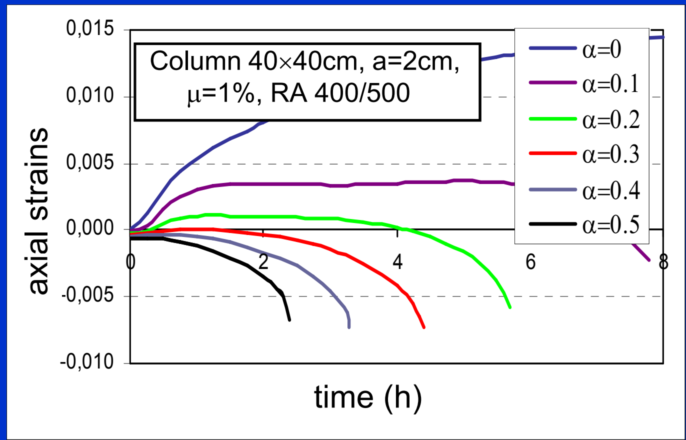
Cvetkovska M., Lazarov L. (2005). *"Nonlinear stress-strain behaviour of RC elements exposed to fire"*. *Proc. of Impr. of Build. Struct. Qua. by New Tech., COST C12*.

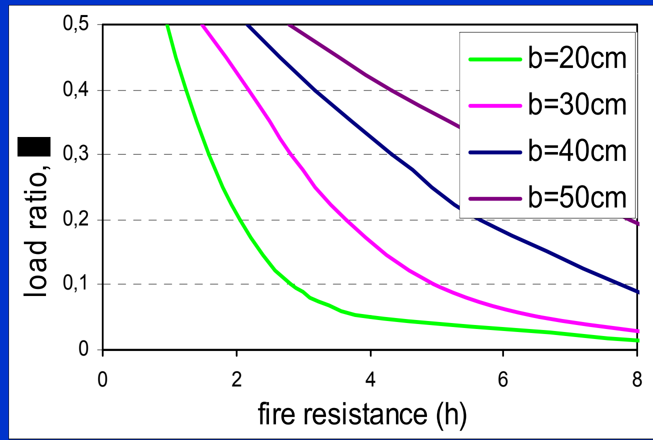
Centrically and eccentrically loaded columns

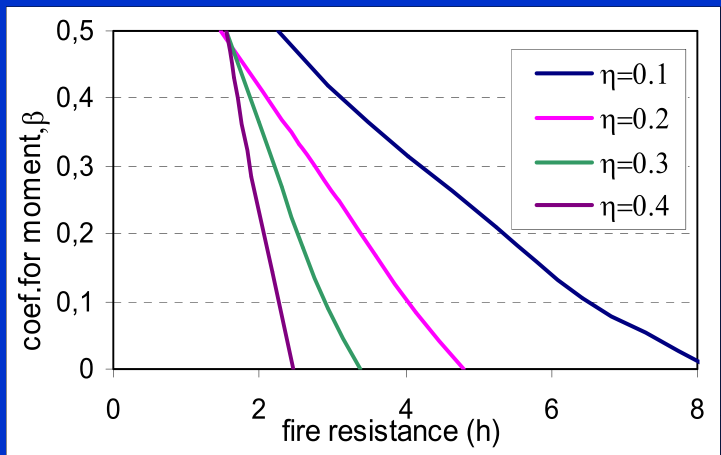
➢A **computational procedure** for the nonlinear analysis of a **RC** elements and plane frame structures subjected to fire loading is developed. The program FIRE carries out the nonlinear transient heat flow analysis (modulus FIRE-T) and nonlinear stress-strain response associated with fire (modulus FIRE-S). The solution technique used in FIRE is a FEM coupled with time step integration.

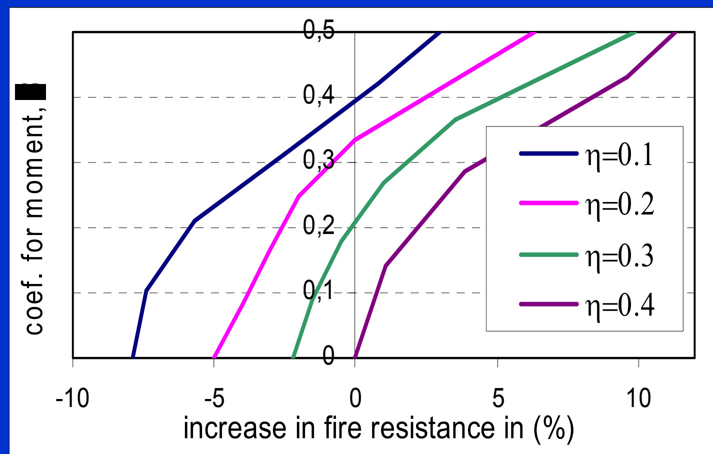


Centrically and eccentrically loaded columns









Centrically and eccentrically loaded columns

- **Analytically** achieved results for the fire resistance of centrically loaded RC columns exposed to fire from all sides and eccentrically loaded RC columns incorporated in a wall for separating the fire compartment are presented in this study.

- The influence of: element geometry, concrete cover thickness, steel ratio and intensity of the axial force and bending moment are analyzed and the results are presented by curves.

- As a result of parametric studies, the following conclusions are made:
  - dimensions of the cross section, intensity of the axial force (load ratio) and the type of the aggregate (siliceous or carbonate) are significant factors affecting fire resistance of **centrically loaded columns** exposed to standard fire from all sides.
  - When the load ratio is increased, the fire resistance is decreased, and opposite.
  - If carbonate aggregate concrete is used instead of siliceous aggregate concrete, the fire resistance is increased for 30% in average.

Centrically and eccentrically loaded columns

- **Eccentrically loaded** columns that are part of a wall for separation the fire compartment have the lowest fire resistance.

- Dimensions of the cross section; concrete cover thickness; steel ratio; support conditions; fire scenario and intensity of the axial force and bending moment are significant factors affecting fire resistance of these columns.

- The effect of increasing the steel ratio is positive. It was not a case when the column was centrically loaded.

- When the bending moment is increased and the axial force is decreased the positive effect is more expressive.

- For optimally loaded columns the concrete cover thickness has a positive effect in increasing the fire resistance, but not more than 5% for columns with small dimensions, and up to 10% for larger columns.

Steel and concrete composite beams

E. Nigro; G. Cefarelli
Department of Structural Engineering, University of Naples “Federico II”, Italy

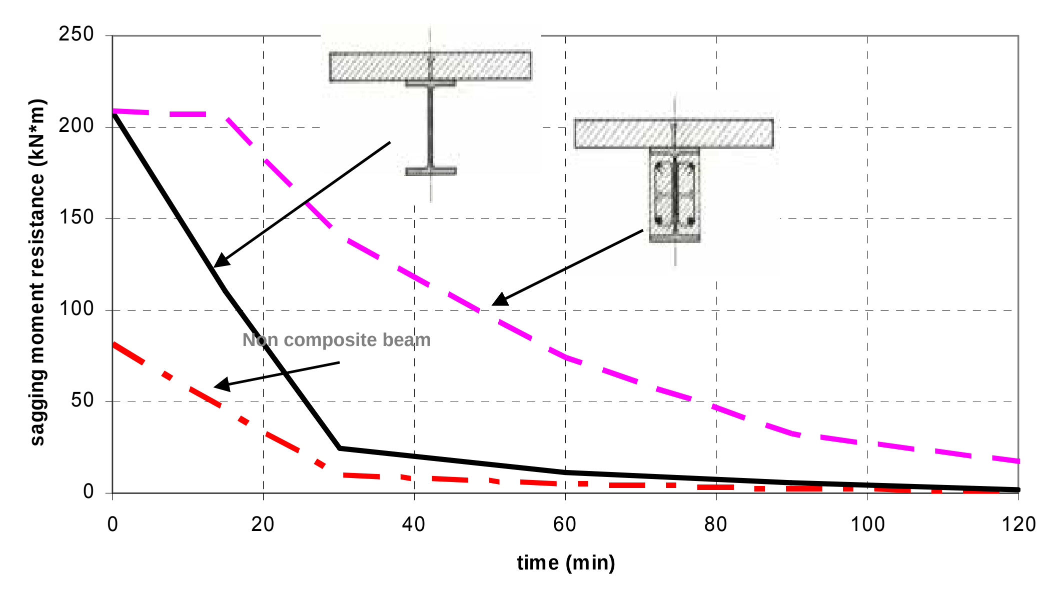
Nigro E., Cefarelli G. (2007). “Some Remarks on the Simplified Design Methods for Steel and Concrete Composite Beams”, Proceedings of the COST C26 Workshop in Prague, Czech Republic.

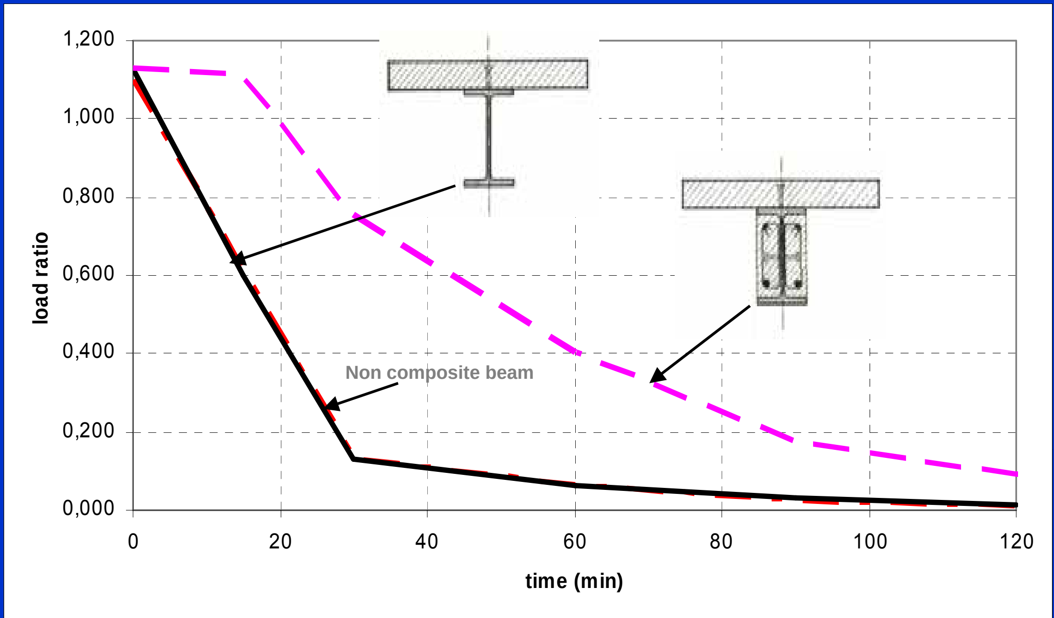
Steel and concrete composite beams

This work recalls the main characteristics of a general numerical approach to assess the ultimate bearing capacity of steel and concrete composite beams in fire conditions. The behaviour of the **composite beams** during a **standard fire exposure** is investigated.

- It is shown the comparison of resistance between **steel beam, composite beam and composite beam with partial concrete encasement**.
- The following features affecting the resistance of the composite beam with partial concrete encasement are firstly investigated: influence of the beam dimensions and effectiveness of the reinforcing bars in concrete encasement.

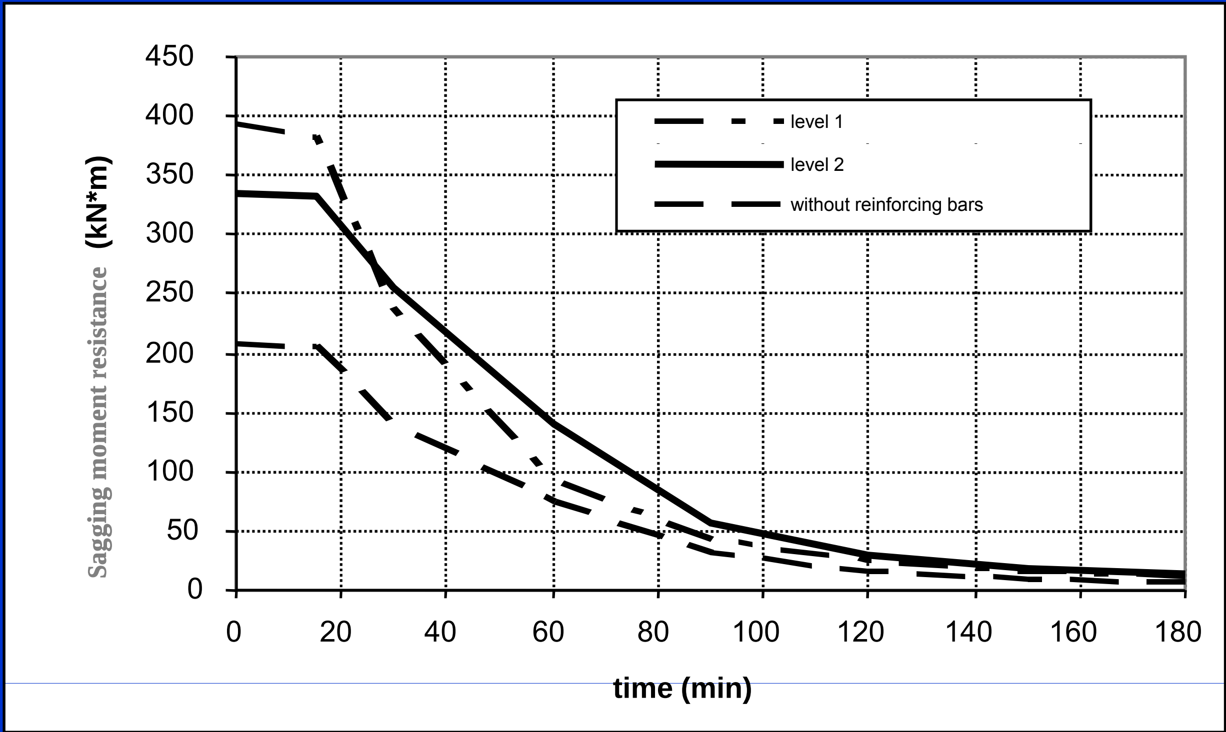
Steel and concrete composite beams



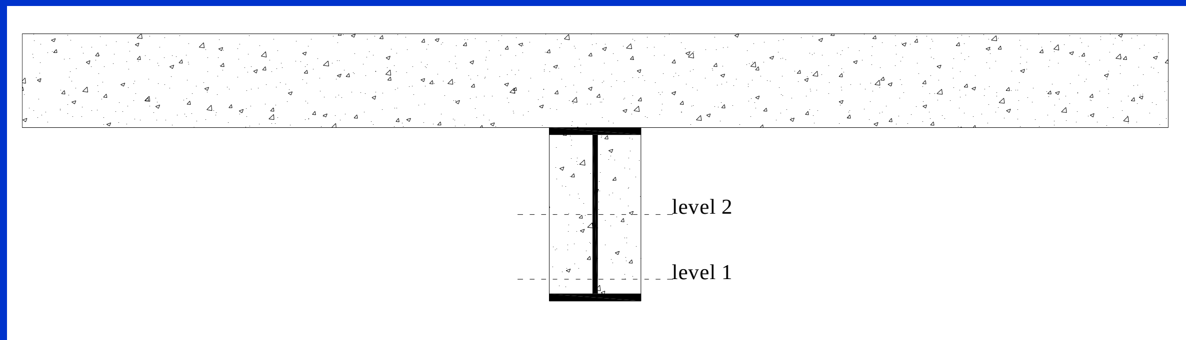


The comparison in resistance field shows the better behaviour of composite members; however, in load ratio field, the composite beam without concrete encasement shows a similar behaviour to non-composite beam. This is due to, both in the composite beam without concrete encasement and non-composite beam, the moment capacity depends on loss of strength of metallic part exposed to fire. In the case of composite beam with partial concrete encasement, it is shown a quite better behaviour, thanks to lower temperature values in the steel beam.

Steel and concrete composite beams

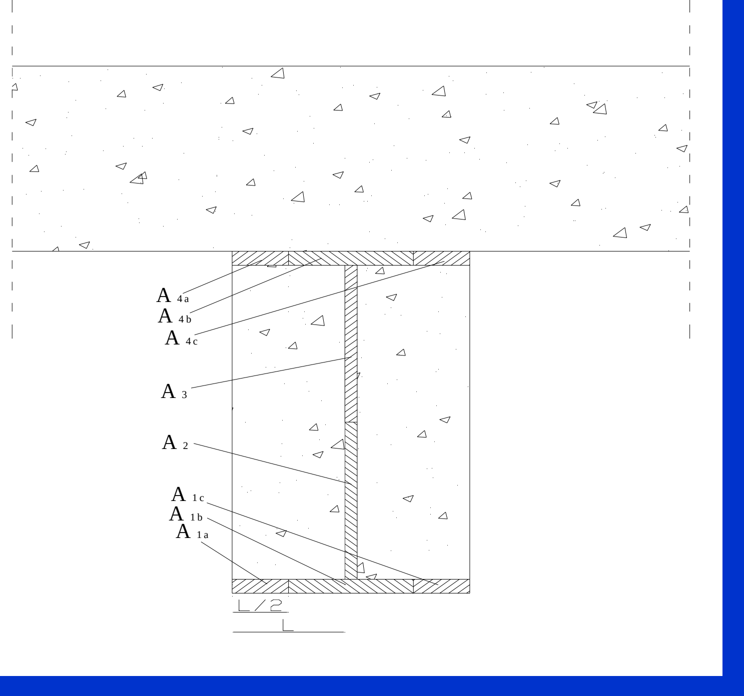


It is clear how the reinforcement to level 1 provides a better performance in ambient condition, but it provides a worth performance in fire condition, compared to the case of reinforcement placed to level 2.



Steel and concrete composite beams

- Finally, it is **proposed a simplified plastic method** for evaluating the sagging moment resistance of the composite beam with partial concrete encasement in fire conditions.



Final considerations

➢It was summarized the research contributions from the **COST-WG1 members** the topic of the behaviour and analysis of **structural elements in case of fire**.

Thank you for your attention