FINITE ELEMENT ANALYSIS OF FIRE RESISTANT REINFORCEMENT ON END-PLATE STEEL CONNECTIONS

Konstantina Tsapara [a], Georgios A. Drosopoulos [b], Georgios E. Stavroulakis [a]

[a] Department of Production Engineering and Management, Technical University of Crete, GR-73132 Chania, Greece

[b] Institute of Continuum Mechanics, Leibniz University of Hannover, Germany

Abstract

In this paper the effect of fire resistant coatings on the mechanical behaviour of steel joints is studied using the finite element method. The proposed finite element model is an extension of a previous one developed for the study of the same connection in elevated temperatures, without fire reinforcement. In particular, the construction used consists of an end – plate steel connection which is covered with panels of lightweight concrete and gypsum board. The behaviour of those two fire resistant materials has been simulated in elevating mechanical and thermal conditions separately and simultaneously. Through this process it is examined the strength of the materials and of the overall construction. Specifically, the action of fire on the strength of the structure may result in an early collapse. In addition, the behaviour of the structure in the connection area and the opening of the interface is investigated.

Keywords: fire resistant, steel joint, thermal analysis, fem

INTRODUCTION

A significant number of scientific projects for the study of steel connections under elevated temperatures has been presented in the past. In particular, both analytical and experimental articles have been published (Lawson, 1990, Al-Jabri et al, 1998, Lien et al, 2009, Kalogeropoulos et al, 2012). On the other hand, scientific work related to the properties and behaviour of fire resistant materials, has been also presented (Jimenez et al, 2006, Weil, 2011, Rahmanian et al, 2012). In the present article an effort is made, for the coupling of structural elements (steel joint) and fire resistant materials (concrete or gypsum boards). Thus, a three dimensional, non-linear finite element model of an end-plate steel connection has been developed. The column, together with the critical bolted parts of the connection, are covered with a fire resistant material of either concrete or gypsum boards. Unilateral contact with friction has been used for the study of contact or separation of the connected parts. In addition, a thermomechanical analysis takes place, for the investigation of the behaviour of the structural system in high temperatures. According to the results presented here, the fire resistant coatings cause a significant reduction of the maximum temperatures developed on the structure, in comparison with the case of no fire reinforcement.

1 FIRE RESISTANT MATERIALS AND PROPERTIES

There are different materials available for protecting structural systems during a fire and providing a fire resistant rating. Among them are included insulating materials, which are often used for protecting structures from direct fire exposure. In particular, concrete and gypsum boards are considered to be good insulators and for this reason have been specifically used in this study.

The concrete has low thermal conductivity, and presents endothermic reactions in the cement mass. Under high temperatures, during a fire, a degradation of the mechanical characteristics of the concrete takes place. The compressive strength of the concrete decreases as the

temperature increases due to internal faults caused by the heating of the water and of the uneven distribution of the temperature in the mass of the concrete.
Systems of gypsum boards, as a mean of providing passive fire protection, are used in buildings as fire resistant coatings. The strength of such systems is attributed to the desired thermal properties of the gypsum, as a hygroscopic material.
The thermal properties of these two materials, as well as the mechanical ones slightly differ but in this analysis, the mechanical properties were considered equal, for simplicity. The thermal properties used for concrete and the gypsum boards are shown in Tab. 1.

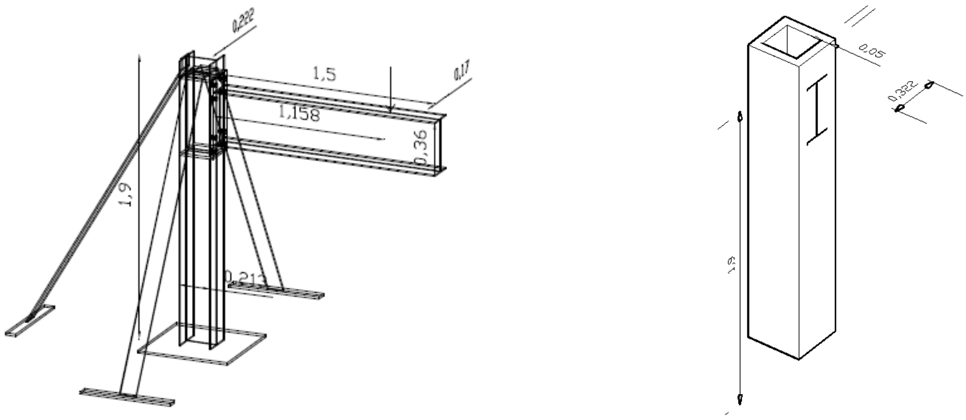
Tab. 1 Thermal properties of concrete, gypsum board and steel

	Conductivity (W/m.°C)		
Temperature (°C)	Concrete	Gypsum board	Steel
20	0.988	0.200	53.33
100	0.938	0.183	50.67
200	0.875	0.120	47.34
300	0.813	0.100	44.01
400	0.750	0.120	40.68
500	0.688	0.123	37.35
600	0.625	0.130	34.02
700	0.563	0.137	30.69
800	0.500	0.147	27.30
900	0.500	0.160	27.30

The thermal expansion for the steel parts is taken equal to $12x10^{-6}/^{o}C$, while the thermal expansion for the bolts is considered equal to $13x10^{-6}/^{o}C$. For the thermal reinforcement, the thermal expansion is chosen equal to $18x10^{-8}/^{o}C$.

2 GEOMETRY AND THE FINITE ELEMENT MODEL

The end-plate steel connection consists of an IPE-360 beam section, an HEA-220 column section, an extended end-plate and eight high strength M20 bolts with average yield and ultimate stresses Fy = 600 N/mm^2 and Fu = 800 N/mm^2 obtained from coupon tests, were used. The beam, the column, and the end-plate were made of steel having average yield and ultimate stresses Fy = 314 N/mm^2 and Fu = 450 N/mm^2, respectively, also obtained from relevant coupon tests. The Young Modulus for the steel parts and the bolts is equal to 120 GPa and the Poisson’s ratio to 0.3.



(a) (b)

Fig. 1 Geometry of (a) the steel joing and (b) the fire resistant coating

The column, together with the bolted parts of the connection, are covered with a fire resistant panel of steady thickness. The geometry of the connection and the fire resistant coating, are shown in Fig. 1.
For the numerical analysis, three-dimensional 8-node brick finite elements have been used. The mesh of the model becomes denser around the area of the connection. The mesh of the structure is presented in Fig. 2. For the numerical solution of the non-linear problem the Newton–Raphson incremental iterative procedure has been used. For the interfaces between the column, the end-plate and the fire reinforcement, the friction coefficient is taken equal to 0.4.

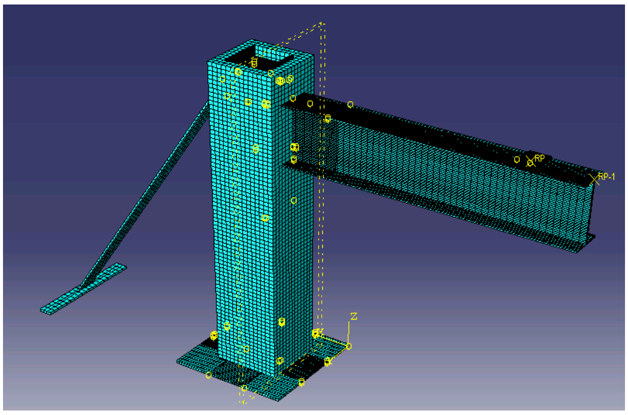


Fig. 2 Mesh of the end-plate connection and the fire resistant coating

Concerning the mechanical properties of the steel material, degradation of the Young Modulus has been considered according to Eurocode 3 (Eurocode 3). The stress–strain laws have been also considered at elevated temperatures (Eurocode 3). Moreover, large displacement analysis as well as the v. Mises plasticity model have been used in the numerical scheme. Finally, for the implementation of the contact and friction laws the penalty method has been chosen.

3 CONCEPT OF THE THERMOMECHANICAL ANALYSIS

The numerical analysis has been performed in two phases. In the first phase the pure heat transfer problem is solved. The results of the thermal analysis are imported as a predefined field, into the mechanical finite element model and the thermal-stress analysis is carried out.
It is possible to import the data obtained from the thermal analysis, into any of the steps developed within the thermomechanical model, thus creating the possibility of multiple load steps either thermal or mechanical which will alternate between them with any desired sequence each time. In particular, three main different load cases have been considered for two different fire resistant materials: concrete and gypsum board. In the first case, the thermal and a concentrated mechanical load are concurrently applied in the same analysis step. Within the second load case the thermal load precedes the point loading. The total mechanical load forced is 200 KN. According to the third load case, at the first step half of the initial thermal load is applied (1 KW/m^2), then follows a mechanical load of 50 kN, in the next step the remaining thermal load is forced (1 KW/m^2) and finally a mechanical load of 150 kN.
It has to me mentioned that the self-weigh has been applied before any other load, at the beginning of the process. It is also noted that for the above load cases, the rate of increase of both the mechanical and the thermal load is linear, within each analysis step.
Among other, in this study are examined:

- The behaviour of the two fire resistant materials and of the overall structure under thermal and mechanical loads.

- The ultimate external vertical load on the beam before failure, the vertical displacements and the force-displacement diagrams.
- The behaviour of the contact–friction interface between the column and the end-plate of the beam (opening and sliding modes).

Finally, for the heat transfer analysis temperature boundary conditions have been applied as shown in Fig. 3. Also, a heat flux equal to 2 KW/m^2 has been applied to the beam's top flange as it is shown in Fig. 4.

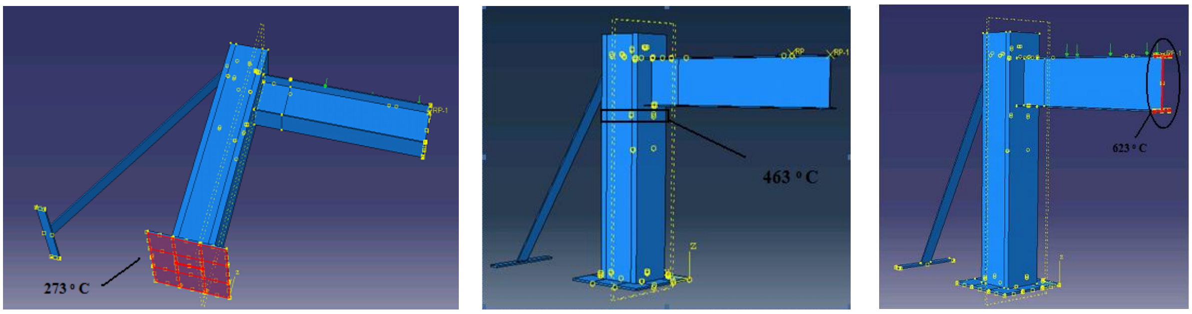


Fig. 3 Temperature boundary conditions

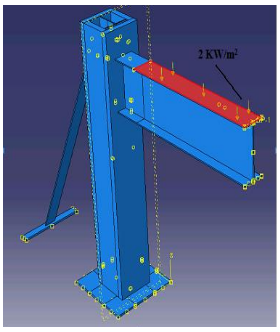
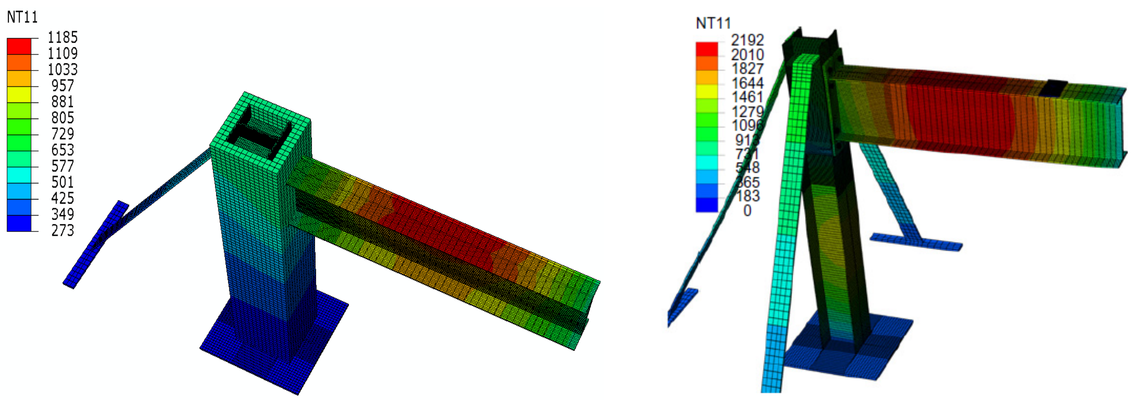


Fig. 4 Thermal heat flux

4 RESULTS AND DISCUSSION

4.1 Study of the influence of the sequence of thermal and mechanical loads



(a) (b)

Fig. 5 Temperature distribution for the model (a) with and (b) without thermal reinforcement

By studying the results obtained from the different load cases, it was found that the sequence of the application of thermal and mechanical loads significantly affects the strength of the

overall structure as well as the ultimate load which can be developed, before collapse. Starting with the concrete, in the first case where the thermal and the mechanical load were simultaneously applied the overall temperature reaches the 750 ^{o}C. In the second load case where the thermal load precedes a point loading of 200 kN the temperature reaches the 1.185^{o}C. In the last load case, where as mentioned above four steps were applied alternating thermal and mechanical loads, the maximum temperature is equal to 926.6 ^{o}C. It has to be mentioned that the third step of this load case, where a thermal load of 1 KW/m^2 is applied to the structure, was not completed while the fourth step of the mechanical loading never started.
It is worth noticing that the model of the same joint without fire reinforcement, for the second load case where the thermal load precedes the mechanical one, reached a maximum temperature almost twice bigger than the temperature of the model with the fire reinforcement, Fig. 5. This is an important advantage for the structure with fire reinforcement.
For the reinforcement with the gypsum board, the temperature distribution was only slightly different from the previous case of concrete board reinforcement.
According to the load-displacement diagrams on Fig. 6 for the concrete it is shown that the strength is drastically reduced when the thermal load is applied first and the mechanical point load follows. On the contrary, when the thermal and the mechanical loads are concurrently applied the collapse load is of six times greater than the previous case. Also in the third case with the four steps (Fig. 6) the failure load is 50 kN and the connection reaches its highest level of resistance.
The results obtained by using the gypsum board, are similar to the above mentioned results. As it would be expected, the response of the structure is improved when no thermal loading is applied to the structure.

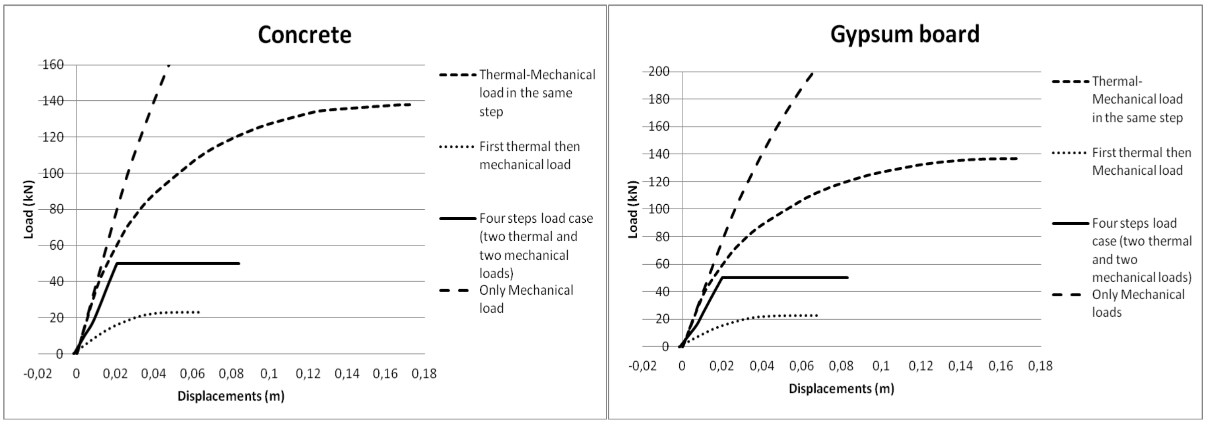
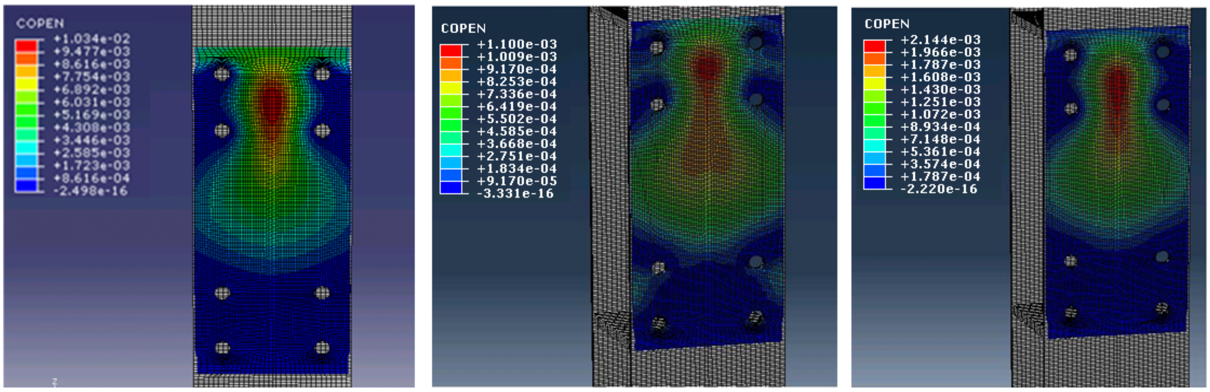


Fig. 6 Force-displacement diagrams

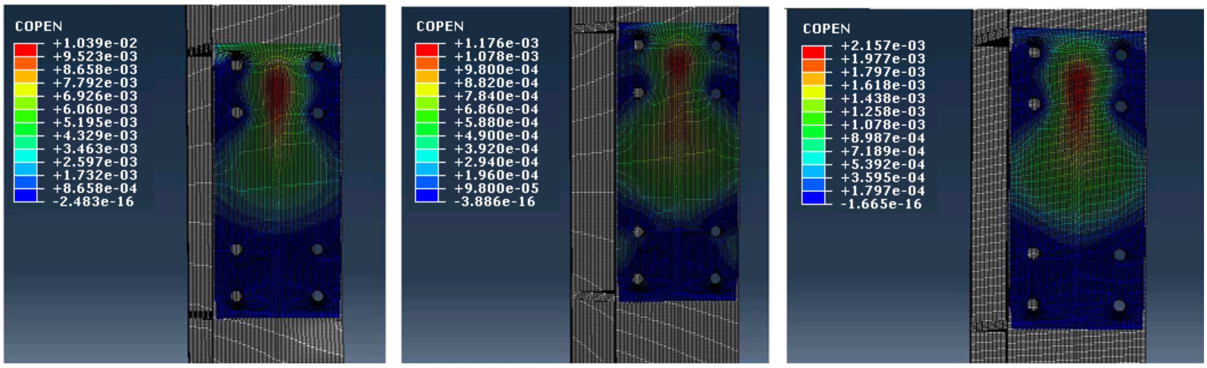
4.2 Behaviour of the contact-friction interface

For the analysis with the concrete fire resistant material and the first load case (Fig. 7a), where the thermal and the mechanical loads are applied simultaneously, the maximum opening of the beam to column interface is 10.3mm. For the second load case, where only the thermal load has been applied to the joint and before the application of the mechanical load, a small opening of 1.1 mm appears (Fig. 7b). This opening appears only due to the heating of the interface, Kalogeropoulos et al, 2012.
For the third load case the maximum opening of the interface becomes approximately five times smaller (2.1mm, Fig. 7c) compared to the first load case. This is attributed to the fact that half of the thermal load is applied first.
Similar opening values for the contact-beam interface is obtained from the model with gypsum board fire reinforcement, Fig. 8.



(a) (b) (c)

Fig. 7 Opening of the interface (concrete) for the (a) first, (b) second, (c) third load case



(a) (b) (c)

Fig. 8 Opening of the interface (gypsum board) for the (a) first, (b) second, (c) third load case

5 CONCLUSIONS

The usage of a fire resistant covering from either concrete or gypsum board in the column of a steel end-plate connection, results in a significant reduction of the maximum temperatures, in comparison with the temperatures developed in the same joint, when no fire reinforcement is applied. The maximum temperature reached 1194 ^{o}C in the second load case, for the gypsum board reinforcement.

In addition, it was proved that the resistance of the structure depends on the sequence between the thermal and the mechanical loading. When the thermal and the mechanical load are simultaneously applied to the same step the connection withstands greater load and has increased resistance before it collapses, relative to the case that the thermal load precedes the mechanical one. For this load case, an opening of the column to beam interface appears, when only thermal loads have been applied to the structure, before the application of any mechanical load.

Moreover, when the thermal and the mechanical load are in the same step the displacements become sufficiently large (for application of the both fire coating materials), compared to the case where the thermal load precedes the mechanical one.

Finally, the opening of the column to beam interface for the concrete and the gypsum board reinforcement shows only small differences.

REFERENCES

Lawson R. M., Behaviour of steel beam-to-column connections in fire, The Structural Engineer, 1990.

Al-Jabri K. S., Lennon T., Burgess I. W., Plank R. J., Behaviour of steel and composite beam-column connections in fire, Journal of Constructional Steel Research, 1998.

Lien K. H., Chiou Y. J., Wang R. Z., Hsiao P. A., Nonlinear behaviour of steel structures considering the cooling phase of a fire, Journal of Constructional Steel Research, 2009.

Kalogeropoulos A., Drosopoulos G. A., Stavroulakis G. E., Thermal-stress analysis of a three-dimensional end-plate steel joint, Construction and Building Materials, 2012.

Jimenez M., Duquesne S., Bourbigot S., Intumescent fire protective coating: Toward a better understanding of their mechanism of action, Thermochimica Acta, 2006.

Weil E. D, Fire-protective and flame-retardant coatings - A state-of-the-art review, Journal of Fire Sciences, 2011.

Rahmanian I., Wang Y.C., A combined experimental and numerical method for extracting temperature-dependent thermal conductivity of gypsum boards, Construction and Building Materials, 2012.

Eurocode 3, Design of steel structures part 1.2: general rules structural fire design ENV 1993-1-2, Brussels (Belgium): European Committee for Standardization, 2001.