TEMPERATURE DISTRIBUTION IN THE COATBACK OF A PARTIALLY FIRE-PROTECTED MEMBER

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Abstract
Whenever fire unprotected steel members are attached to a fire-protected steel member and penetrate its passive fire protection, additional heat will be conducted to this member during a fire. This can result in a local hot spot in the primary member that may reduce the actual fire resistance. The wide variation in loss of fire resistance is because geometries can vary, and in particular because of the influence of the section factors of the attachments. The influence of the partial protection was experimentally and numerically studied at the Czech Technical University in Prague. Four partially fire-protected plates were heated according to the nominal standard fire curves in a small horizontal furnace. A Finite Element Analysis (FEA) was validated and was applied to a numerical study of an unprotected steel beam under fire separation sealing, which was connected to a steel column. A description was prepared of the development of heat for various fire exposures under fire protection of different lengths and nonlinear thermal conductivity with different section factors.

Keywords: steel structures, fire design, fire protection, beam, coatback.

1 INTRODUCTION

For extended exposure to fire, structural members may require thermal protection to restrict their temperature to levels at which sufficient member residual strength is retained. This protection often takes the form of interposing thermal insulation between the heating environment and the structural members. Fire protection for structural steel sections can be provided by a wide variety of passive fire protection systems, including suitable board systems, which generally form a boxed enclosure of the steel beams and columns, and by sprayed mineral cementitious systems, or by sprayed reactive coatings, which generally follow the profiled shape of the steel section. The primary heat transfer mechanisms are convection and radiation onto the exposed surface of the protected structural members. Heat also flows into the protected member by conduction from the (hotter) unprotected members connected to them. Part of the length of these unprotected members is insulated to reduce the temperature of the member and hence to reduce the heat conducted into the protected member. This protection of attached secondary members is referred to as coatback. The coatback length is set to control the flow of heat into the protected members and thus to delay strength and stiffness degradation.

A closed-form solution of the 1D heat conduction equation for determining the coatback length in offshore structures was developed by Yasseri (2002). The coatback length is a function of the size of the member, the intensity of the heating, the thickness and the properties of the fire coating, and the specified survival time. Parlor (2010) published recommendations for UK good practice confirmed by experience for protecting the adjoining 500 mm of unprotected structural steel to limit unwanted heat transfer. Ways in which different applications of passive fire protection influence the collapse time of Floating production storage and of the Offloading vessel module structure are presented in (Friebe et al, 2014). A series of heat analyses and thermal elasto-plastic FEA were prepared for various passive fire protection coatings, together with the resultant collapse time. The numbers of coatings are compared with each other. In a simplified example of a main girder to which secondary members are attached perpendicular, the use of a conventional coatback length of 450 mm for the secondary members was found to be adequate. A coatback length greater than 450 mm does not result in any substantial delay of an increase in temperature or of deflection growth.

Podolski (2017) confirms, when tensile membrane action is used in composite floor slabs, that the elimination of fire protection to the internal secondary beams can be justified. Podolski investigated how the coatback distance is influenced by various parameters, including the intumescent coating thickness, the steel section factor, the steel section depth, the thermal conductivity of the intumescent coating, and the limiting temperature. A fire protection length on the unprotected steel section is designed that gives a temperature at the end of the protection not more than 2 % higher than the temperature of the protected steel section. A simplified numerical method powered by a software tool that enables the required coat back length to be determined has been developed by (Breunese 2019). The method was verified by comparing the calculated steel temperatures with full three-dimensional simulations. The studies show that omitting coat backs significantly reduces the time to reach the critical steel temperature.

2 EXPERIMENT

The experiment consisted of four steel samples, which were loaded according to the standard temperature-time curve for 60 mins. The test took place in a small horizontal furnace at the University Center for Energy Efficient Buildings in Buštěhrad, Czech Republic. The dimensions of the samples were 300 x 60 x 8 mm. Half of the length of the sample was treated on three sides by fire spraying (Promat. 2021), the temperature parameters of which at elevated temperatures were tested in detail experimentally and numerically (Dobrovolny, 2021). The thickness of the fire protection was 10 mm for two of the samples and 20 mm for the other two samples. The walls inside the furnace were treated by spraying. The untreated side was attached to the ceiling of the furnace. Thermocouples were located on the protected and unprotected parts of the samples. The geometry of a sample is shown in Figure 1.

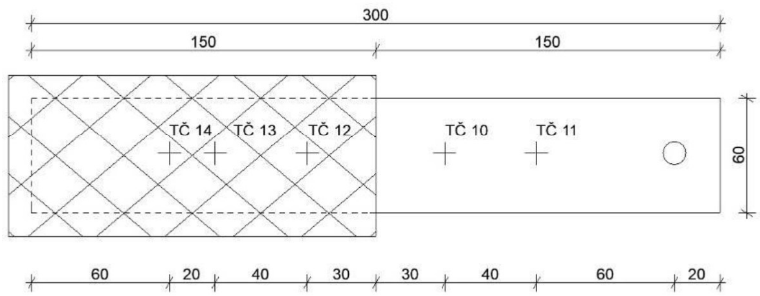

Fig. 1 The geometry of a sample and the position of the thermocouples

Fig. 2 The samples before and after the test

Five jacketed thermocouples 2.5 mm were designed for two of the samples and two jacketed thermocouples were designed for the other two samples. The samples before and after the test are shown in Figure 2. The measured temperature profile is shown in Figure 3, and the values for significant points are presented in Table 1.

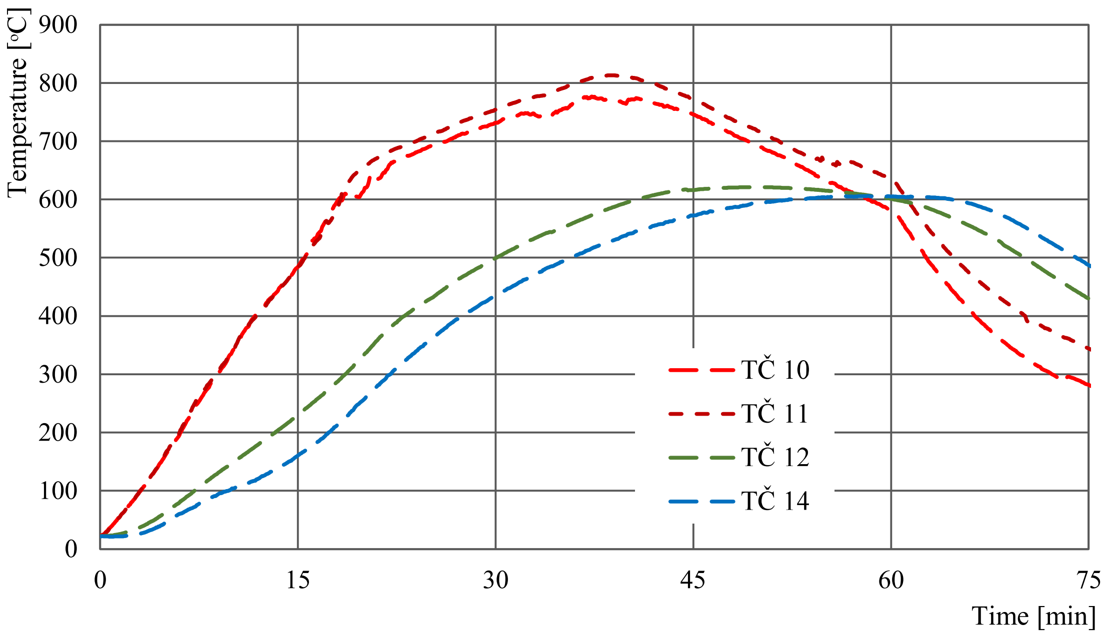

Fig. 3 Temperature distribution in sample 4 with protection thickness of 10 mm

Tab. 1 Temperature development in sample 4 with the protection thickness of 10 mm

t, min	TČ1	TČ2	TČ3	TČ10	TČ 11	TČ 12	TČ13	TČ14
15	483.2	213.4	645.3	484.1	483.8	230	312.4	160.5
30	676.8	480.2	796.7	731.6	754.4	499.7	543.9	436.2
45	714.7	600.3	737.1	745.8	771.2	616.2	573.8	572.7
60	608.0	613.1	540.7	582.1	636.8	601.1	359.9	605.3

3 NUMERICAL SIMULATION

The numerical model is processed in the ANSYS Mechanical program (Lawrence, 2020). A partially protected connection of the beam to the column is proposed. When modelling, the column is considered to be perfectly insulated. Heat is supplied to the column from the beam. Heating of the protected and unprotected parts of the beam are considered to be from three sides. The structure of the ceiling is assumed to be perfectly insulated from the upper side. The column is protected at the connection point of the beam by fire protection of the same thickness as the beam. The model is shown in Figure 4. Loading by heat transfer and radiation takes place according to the standard nominal temperature curve. The SOLID 70 element, which has eight nodes and one degree of freedom, is used for the numerical solution. The thermal properties of the steel were considered according to EN 1993-1-2:2005. The fire protection material was simulated as multilinear, see Table 2.

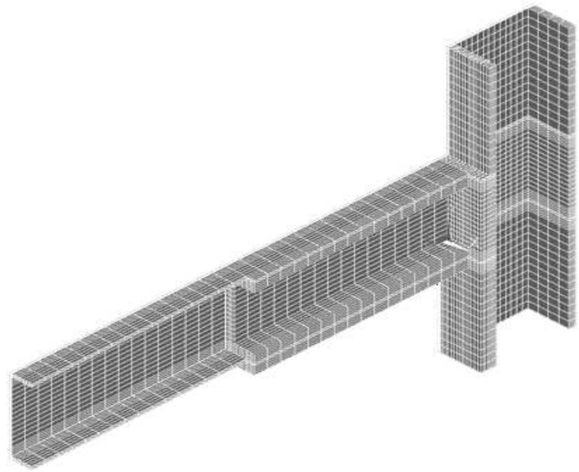

Fig. 4 Column and beam in the FEA model

Tab. 2 The multilinear characteristics of the fire protection material (Protocol, 2004)

Temperature [°C]	20	200	400	600	800	1000
Specific heat capacity [J/kg×K]	924	968	1032	1112	1208	1320
Thermal conductivity [W/m×K]	0.079	0.096	0.137	0.212	0.330	0.500
Density [kg/m^3]	440					

A mesh sensitivity study and subsequent validation approved thirty-two thousand nodes as appropriate for prediction. The model was validated on the results of a fire test until one hour after the start of loading. The results are shown in Figure 5. The differences are due to heating of the samples during the experiment from the top edges, which was not fully prevented, while the numerical model does not assume heating from these edges. The level of accuracy is mainly dependent on the accuracy with which the thermal properties of the fire protection material can be defined (Wang et al, 2012).

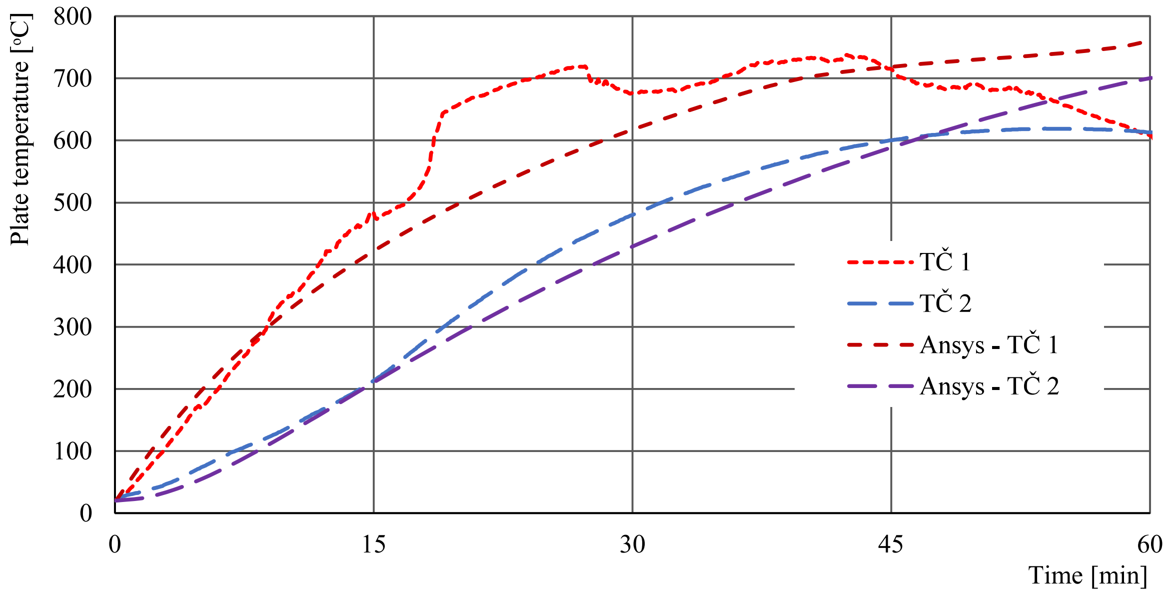

Fig. 5 A comparison between the temperature course of the numerical model and the temperature course of the experiment, protection thickness 20 mm

The sensitivity study focused on the influence of the cross-sectional coefficient of the column, the beam, and the fire protection of the beam on the length of fire protection. The temperature distribution under fire protection is presented in Figure 6 for beam IPE220, column HEB300, coatback 500 mm, 15 min fire exposure. Figure 7 presents the temperature development under fire protection when changing the cross-section of the beam, column HEB300, length of fire protection 500 mm and thickness 20 mm, exposure to fire for 90 min. The graphs show the rapid decrease in temperatures under fire protection confirmed by experiments and by accidents described in the literature. The table shows that the generally-used fire protection length of 500 mm can be considered sufficient. When 500 mm protection length is used for various cross-sections, the temperatures in the numerical model are shown in Table 3.

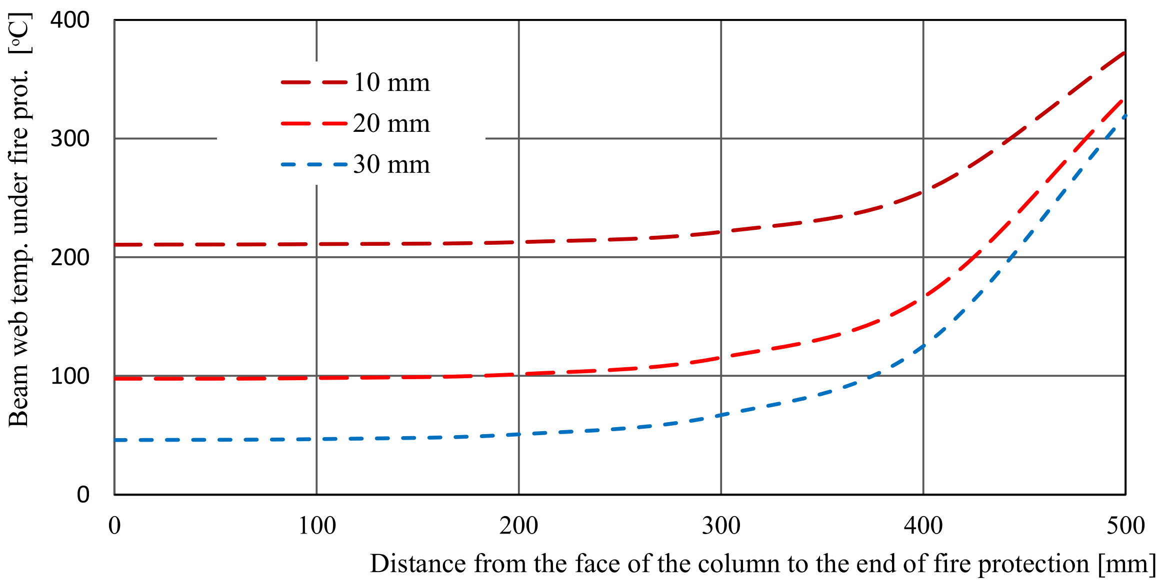

Fig. 6 Temperature development under fire protection for different thicknesses of fire protection, beam IPE220, column HEB300, coatback 500 mm, fire exposure for 15 min

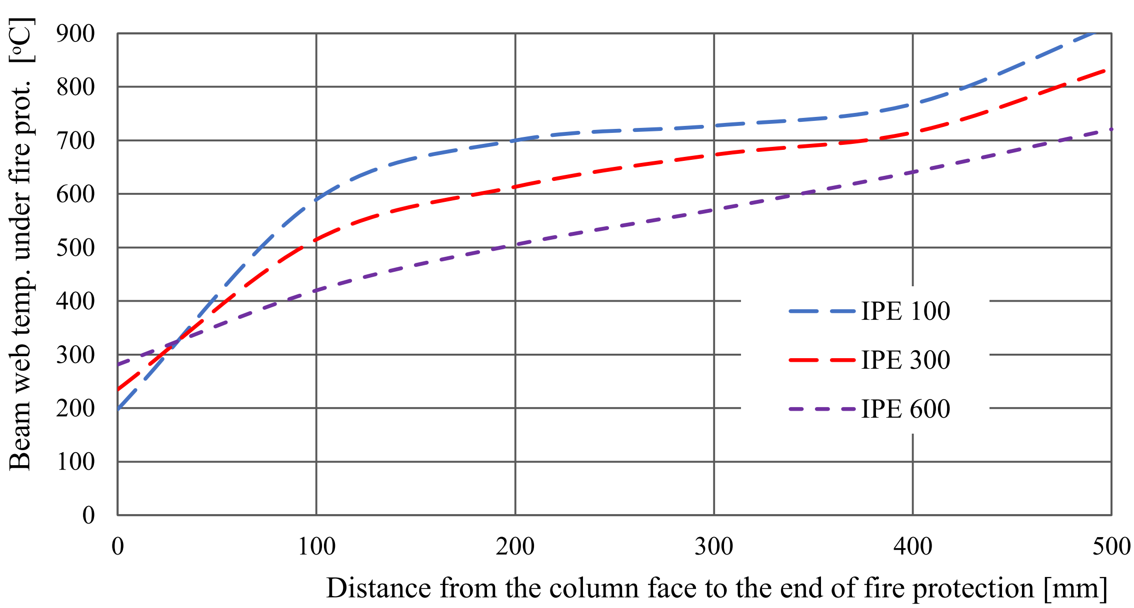

Fig. 7 Temperature development under fire protection when changing the cross-section of the beam, column HEB300, length of fire protection 500 mm and thickness 20 mm, exposure to fire for 90 min

Tab. 3 Beam temperatures in the connection to the column
for various fire time exposures and coatback lengths

Beam	Section factor A_m/V	Protection length / Profile height	Time exposure/coatback length The temperature at a connection to the column [°C]			
			15 min/ 100 mm	30 min/ 200 mm	60 min/ 200 mm	120 min/ 500 mm
IPE 160	269	3.13	246	365	398	275
IPE 220	221	2.27	226	337	416	331
IPE 300	188	1.67	209	312	421	351
IPE 330	175	1.52	203	304	421	377
IPE 500	116	1.00	173	260	425	415

4 CONCLUSIONS

The potential for heat transfer from unprotected structural steel into protected structural steel should be taken into consideration. A sensitivity study (Dobrovolný, 2021) has shown that there is no simple direct relationship between the height of the cross-section, the section factor of the members, or the thickness of the fire protection and the necessary coatback length.

The study showed a rapid decrease in the temperature under fire protection. For fire protection designed for a certain temperature of the column, the predicted temperature is observed to be about 250 mm from the beginning of the fire protection.

The results of our study confirm that a good estimate of the coatback length based on European best practice is 450 mm or 500 mm up to 120 mins for members that are fire protected for expected fire resistance. For short time exposure, up to 30 mins, the length is conservative and may be shortened (Breunese, 2019).

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