NUMERICAL AND EXPERIMENTAL ANALYSIS OF REACTIVE FIRE PROTECTION SYSTEMS APPLIED TO SOLID STEEL RODS IN TENSION

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Abstract

The application of intumescent coatings for fire protection of steel constructions is increasing. Thanks to the relative thin thickness of the coatings, the typical visual appearance of the structures can be preserved. In Germany, the applicability of the systems is regulated by the national as well as European technical approvals. According to the approvals, the application on steel members in tension is only allowed with limitations. Especially, the application on solid steel rods in tension is currently not covered. The paper will explain the actual state of the art of the application of reactive fire protection systems applied to steel structures. Physical and technical background information will be provided. After that, the latest scientific results of an on-going research project funded by the German National Institute of Building Technology (DIBt) and conducted by the Federal Institute for Materials Research and Testing (BAM) will be described.

Keywords: steel structure, solid rod, tension, fire protection, reactive fire protection systems, structural analysis, finite element method (FEM), experimental testing

INTRODUCTION

Unprotected steel structures exposed to fire can lose their load-carrying capacity at an early stage due to the relatively rapid heating rate. For steel structures that need to fulfill requirements concerning fire resistance, appropriate protection systems can be used in order to prevent a premature loss of the load-carrying capacity. In case of visible steel constructions, coatings with reactive fire protection systems are often used for architectural reasons. Thanks to the low thickness of the coatings, the visual appearance of the steel structure can be preserved. In case of fire, the increase of temperature causes a chemical reaction of the fire protection system that leads to expansion and the forming of a heat-insulating layer on the surface of the steel structure. This layer reduces the heating rate of the steel and thus delays the reduction in the load-carrying capacity.

Currently, the regulations in the European as well as in the German standards for the application and testing of reactive fire protection systems applied to solid steel members in tension are not adequately regulated. Therefore, a research project with the objective to explore the possibilities for the use of reactive fire protection systems applied to solid steel tension members is carried out at the Federal Institute for Materials Research and Testing (BAM) in Berlin. First results of this research are presented in this paper.

1 REACTIVE FIRE PROTECTION SYTEMS

According to the approval guidelines of the German Institute of Building Technology (DIBt, 1998), reactive fire protection systems can be applied as a coating on steel members to increase the fire resistance. Generally, a system consists of a primer and corrosion protection, a reactive component and a top coating. The reactive component may be an intumescent, an ablation, a sublimation or a combination of these products. The coating materials can be applied in one layer or several layers by spraying, brushing, dipping or in a similar vein.

1.1 General regulations

Since reactive fire protection systems are not regulated building and construction types, their application in Germany is based on technical approvals (abZ), European technical approvals (ETA) or approvals on a case-by-case basis (ZiE) (Stopp et al, 2011). In the scope of these approvals released by the DIBt, the use of reactive fire protection systems is defined. The application of reactive fire protection systems are currently limited to open and closed sections. In addition, the application is restricted to steel grades S235 and S355 and a particular range of the section factor A_m/V (according to ETA) or rather U/A (according to abZ). Further limitations arise from the maximum possible fire resistance of the individual reactive fire protection system and the static load type for the steel member, i.e. bending, compression or tension. Based on the mentioned criteria, the minimum dry film thickness of the reactive fire protection system that was assessed on the basis of fire tests can be determined. For applications of reactive fire protection systems different from the regulations given in the approvals, a case-by-case permission is required.

1.2 Application on tension members

In accordance with the approvals published by the DIBt until December 2010, which are in some cases still valid, the use of reactive fire protection systems on steel members in tension was not in the scope of the approvals and a verification by adequate tests was required. Starting from January 2011, the restrictions for all new approvals were changed in such a way that reactive fire protection systems can be applied also to tension members with open and closed profiles. However, the maximum load utilization factor (μ_{fi}) for the steel member is limited to 0.5 (Hothan, 2011). Tension members with solid cross-section are still excluded from the scope of the approvals (Stopp & Proschek, 2011). Currently a European standard for the implementation of fire tests on tension members with solid cross sections is an on-going works (CEN prEN 13381-10(V1), 2012).

1.3 Requirements

According to the approval guidelines of the DIBt, reactive fire protection systems have to fulfill different requirements (DIBt, 1997). These include, among other requirements, a durable effectivity against fire exposure, sufficient adhesion to the steel member and a perfect corrosion protection. Therefore, reactive fire protection systems have to fulfill certain thermal and mechanical requirements. For example, the thermal conductivity must be small enough to slow down the heating rate of the steel in order to keep the strength of the steel as long as possible. The determination of the mechanical and thermal properties of the reactive fire protection system is difficult due to the foaming behaviour. In particular, the adhesion to the steel surface is difficult to describe. Therefore, the adhesion of the reactive fire protection system to the steel (stickability) is considered sufficient when the coating remains on the surface of the steel for the entire length of the fire tests (DIN 4102-2, 1977). Another difficulty results from partially large differences in the behaviour and properties between the different products of the reactive fire protection systems, which makes it difficult to give general statements. Instead of determining the thermal properties of the reactive fire protection system, often the heating rate of the steel is used, which can be determined much easier by measurements (DIN EN 1993-1-2, 2010). The heating rate of the steel basically depends on the gas temperature in the furnace, the section factor of the steel section as well as the thermal properties and thickness of the reactive fire protection system. To determine the material properties of the steel, the heating rate is also important because it affects the creep behavior of the steel.

In contrast to the use of reactive fire protection systems on beams and compression members, other special aspects have to be taken into account for tension members. For instance, it must be verified whether the heating rates that occur for tension members meet the requirements given in the standard EN1993-1-2 (DIN EN 1993-1-2, 2010) in order to apply the material properties for steel recommended by this standard. Furthermore, circular solid sections are often used for tension members. The cross-sectional curvature and its effect on the adhesion of the reactive fire protection system have to be examined. Another issue for the adhesion results from the elongation of tension member. Moreover, the failure mechanism, i.e. local necking, and the influence of small defects and damages to the reactive fire protection system on the load bearing and deformation behavior of the tension members have to be investigated. Following, the robustness of the entire system can be assessed.

2 RESEARCH ON SOLID STEEL RODS IN TENSION

A research project funded by the DIBt and carried out by the BAM aims to develop recommendations and guidelines for the use and testing of reactive fire protection systems applied to solid steel members in tension. The investigation consists of fire tests and numerical simulations based on the finite element method (Hothan & Häßler, 2012).

2.1 Experimental Analysis

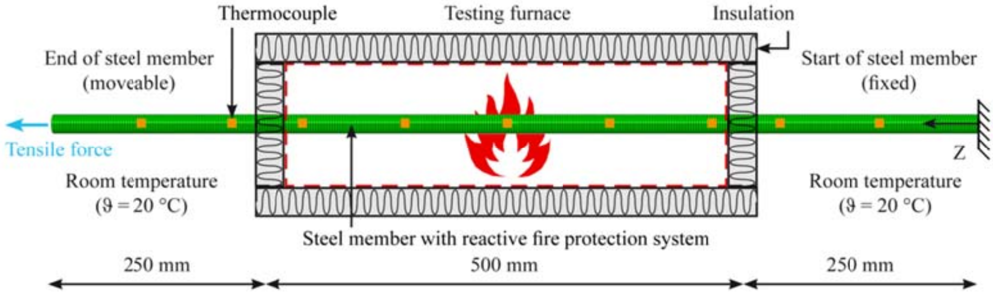

Fig. 1 Schematic experimental setup for the real scale fire tests

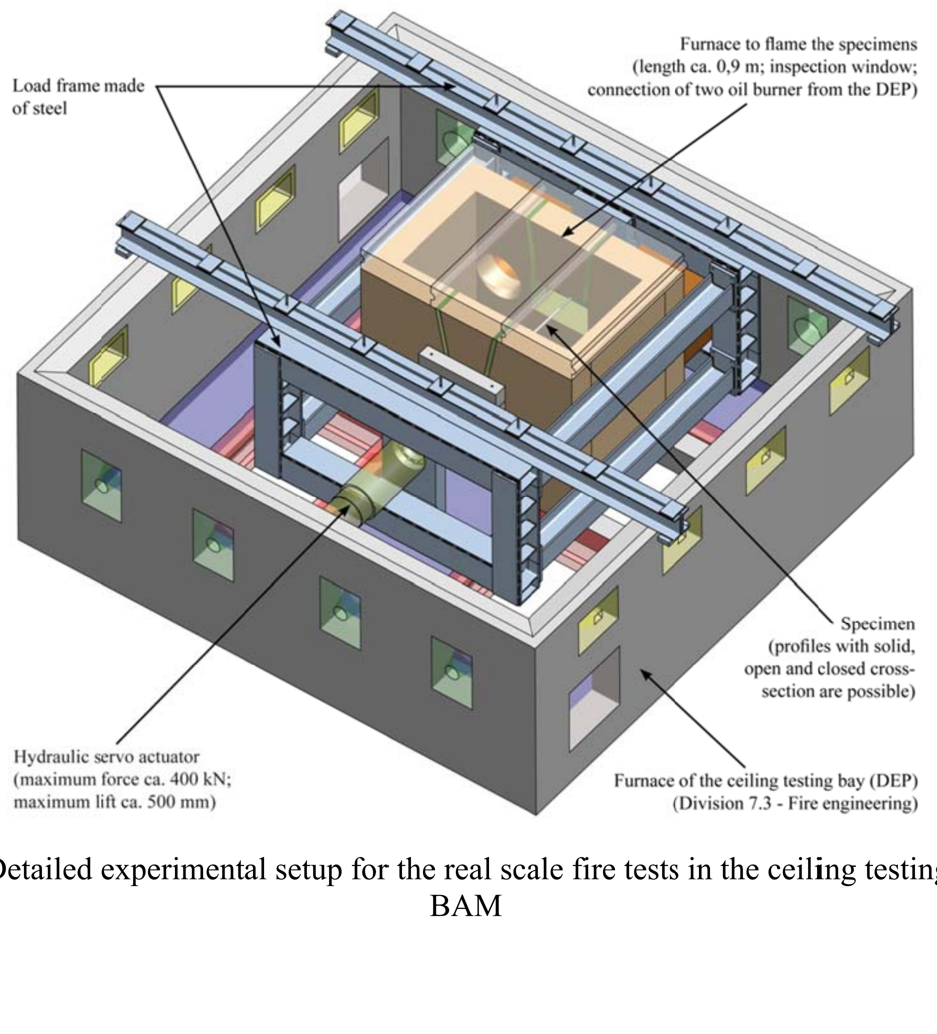

Fig. 2 Detailed experimental setup for the real scale fire tests in the ceiling testing bay of BAM

Currently no studies exist for the use of reactive fire protection systems applied to solid steel tension members. Therefore, appropriate experimental tests as well as numerical analysis will be carried out. For the experimental analysis, real scale fire tests on steel members subjected to tension will be performed at the testing facilities of BAM. The experimental setup is schematically presented in Fig. 1. A reactive fire protection system will be applied and tested on various solid steel sections. Especially, circular cross-sections, which are typically used for tension members, will be analysed. The specimens consist of steel S355. Thermocouples on the surface of the steel specimen are used to measure the temperature during the experiment. In Fig. 2, a detailed 3D-model of the entire testing bay at BAM is presented. In addition to the real scale tests, small scale tensile tests at room and elevated temperatures will be performed in order to characterise the relevant material properties of the steel.

2.2 Numerical Analysis

In addition to the fire tests, the applicability of reactive fire protection systems on tension members with solid cross-section will be also analysed by numerical simulations. For this purpose, a numerical model based on the finite element method (FEM) will be developed in order to describe the behaviour of the specimens used in the real scale fire tests. The data obtained in the fire tests will be used as input for the numerical simulation as well as for the validation of the finite element model. Afterwards, the validated numerical model will be used for parametric studies. The aim of the comparison between the experimental and numerical analysis is to develop an appropriate design method for the application of reactive fire protection systems to tension members with solid cross-section.

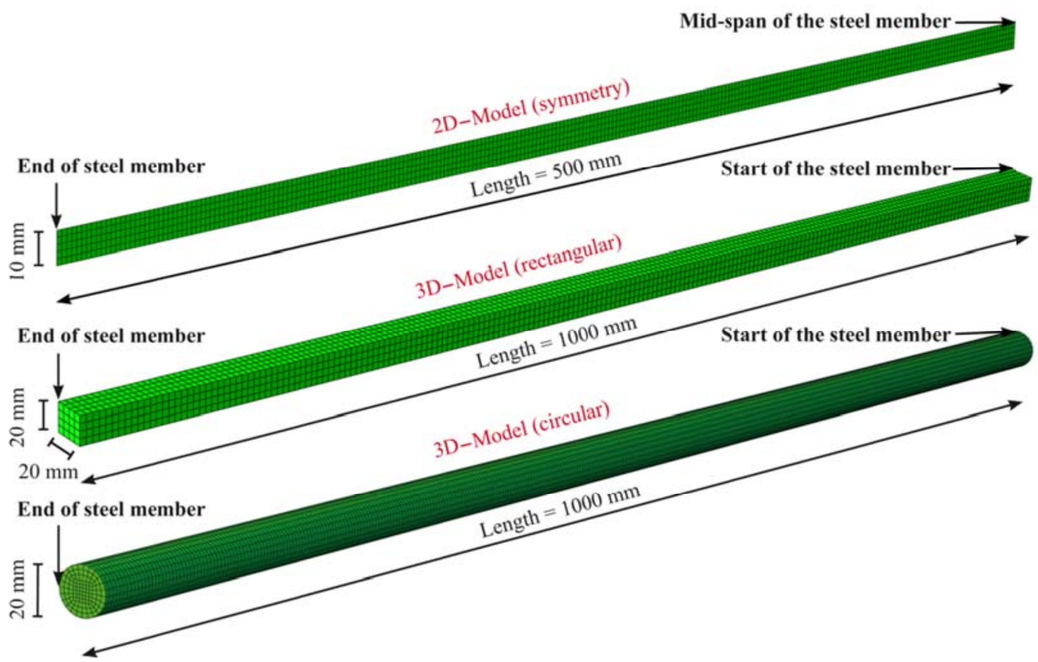

Fig. 3 Overview of the developed numerical models

At the present time, several two and three dimensional finite element models of solid tension members were developed using assumptions in the material properties. In total, there are three models with different cross-sections. Because the small scale tensile tests were not yet carried out in laboratory, as a first assumption the material properties for steel at room and elevated temperatures were assumed according to DIN EN 1993-1-2 (DIN EN 1993-1-2, 2010). An overview of the created FEM models is presented in Fig. 3. The finite element program ABAQUS© was used.

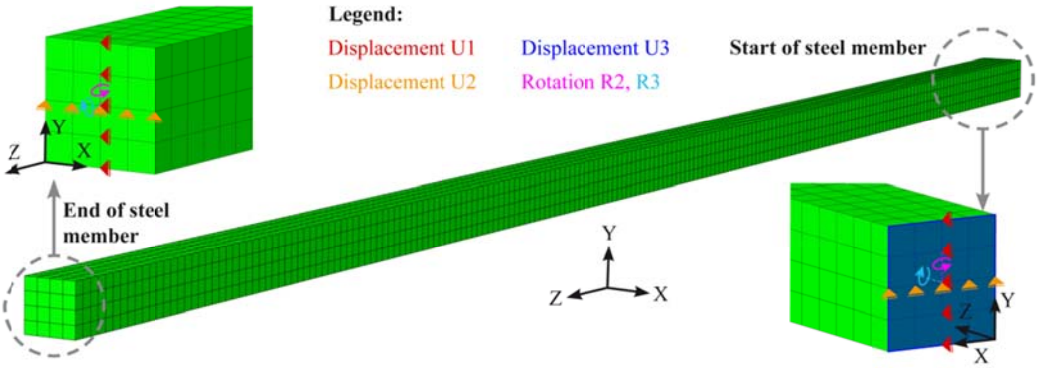

Fig. 4 Example of the applied restraints to the 3D-model with rectangular cross-section

The calculation of the temperatures of the steel resulting from fire exposure (temperature model) is separated from that according to the mechanical behaviour due to the axial load and elevated temperatures (mechanical model). Both models have the same geometry mesh. However, the type of element used in the models is different. For the investigation, time and local variable temperature fields were studied. Because the temperature data from the experiment was not available at the current moment, the steel temperature was assumed to be the same as in the Standard ISO 834 fire curve. After carrying out the real scale real scale fire tests the steel temperature can be taken directly from the measurements of the thermocouples, which are located on the surface of the specimens. As an advantage of this method, it is not necessary to model the difficult foaming process of the reactive fire protection system. One end of the specimen is fixed and the other end can move in longitudinal direction. The axial tensile force is applied at the moveable end of the steel member. In all models, stresses from the applied restraints were minimised. In Fig., the boundary conditions for the 3D-model with rectangular cross-section are presented.

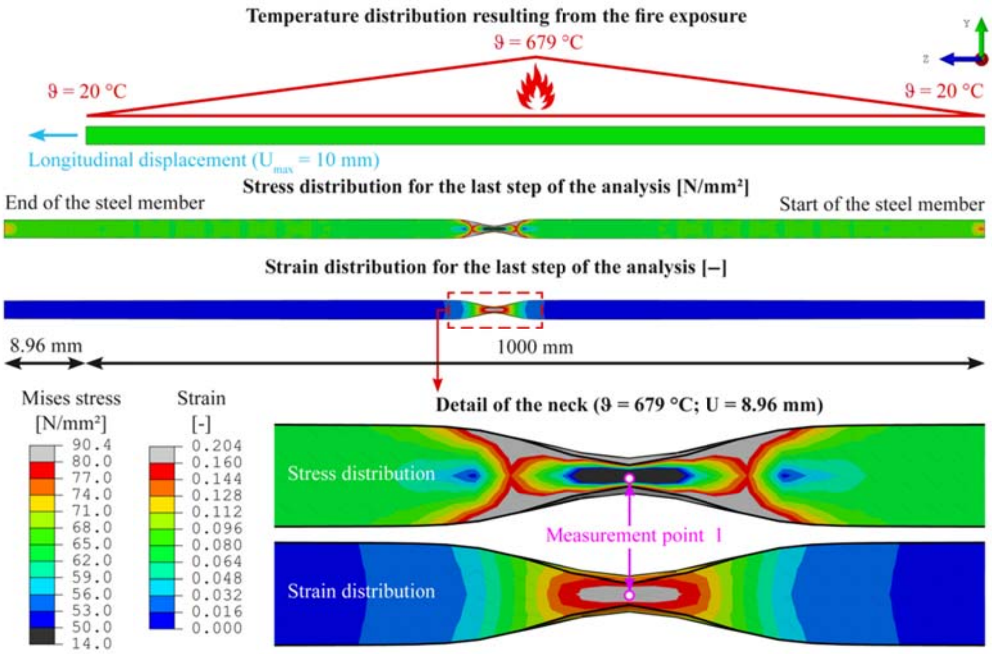

Fig. 5 Stress and strain distribution at the time of failure [last analysis step, scaling factor = 10]

In addition to the magnitude of the loads, the sequence of the loads can be also changed. This allows the simulation of non-stationary (σ = const., $\vartheta \neq$ const.), as well as stationary ($\sigma \neq$ const., ϑ = const.) tensile tests. In the numerical simulation, the failure of the tension member is emerged by the formation of a neck. Because of its complexity, the fracture mechanism occurring in reality is not included in the developed numerical models. In the simulation, the process terminates automatically when no more convergence in the calculation can be achieved. Fig. 5 shows the stress and strain distribution of a tensile test at elevated temperatures at the time of failure. After the temperature field resulting from the fire exposure was applied to the steel member, an additional longitudinal displacement started at the end of the specimen (stationary tensile test). The calculation stopped before reaching the maximum displacement of 10 mm due to the high temperatures in the mid-span of the steel member and the resulting low strength of the material. The failure of the specimen is announced by the formation of a neck.

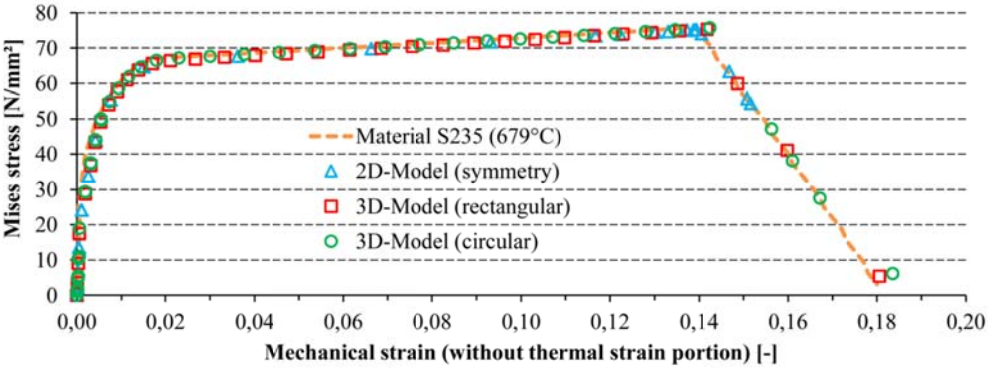

Fig. 6 Stress-strain diagram for measurement point 1

In order to check the three developed numerical models for accuracy, the stress-strain relationship in measurement point 1 was analysed. The corresponding curves are presented in Fig. 6. For all models, the stress-strain curves follow the material behaviour of S235, which was implemented in the numerical models. In addition, it can be noticed that only the 3D-models are capable to display the fracture area up to nearly no stress. The calculation of the 2D-model is already stopped shortly after reaching the maximum stress. To conclude, all developed numerical models are capable to describe the structural behaviour of the steel member subjected to tension and fire exposure.

3 SUMMARY

The application of reactive fire protection systems to tension members in Germany is currently only regulated by European and national technical approvals for open and closed profiles. As an additional restriction, the maximum load utilisation factor in the case of fire is limited to $\mu_{fi} \leq 0.5$. This corresponds to a load utilisation in the normal design situation of 0.78. The regulations given in the current approval are based on numerical analysis of a comparison between the deformation of bending members and tension members (Hothan, 2011). For higher load utilisation factors and for profiles with solid cross-sections, a use of reactive fire protection systems can only be allowed in an approval on a case-by-case basis, which requires in general additional experimental investigation. In particular, the adhesion of the intumescent coating on the surface of the steel member (stickability) has to be proved. A research project funded by the DIBt and carried out by the BAM aims to develop recommendations and guidelines for the use and testing of reactive fire protection systems applied to solid steel members subjected to tension. The investigation consists of fire tests and numerical simulations based on the finite element method (Hothan & Häßler, 2012). Numerical models have been already created and the first results have been explained in this paper. The models are able to describe the global load-deformation behaviour at elevated temperatures as well as local effects, such as the failure by necking. The appropriate material properties used as input for the numerical analysis will be determined by small scale tensile tests in laboratory. In particular, the effect of different heating and load rates will be studied. Real scale fire tests on unloaded and loaded tension members with reactive fire protection system will be performed to validate the numerical models. Based on the result of the research project, an extension of the scope of the technical approvals might be possible. The practicability, relevance and expected benefits from the project encourage the possibility of a technical and substantial cooperation of BAM with third parties, especially producers of reactive fire protection systems.

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