



# Performance of intumescent fire protection coatings applied to structural steel tension members with circular solid and hollow sections

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## ABSTRACT

Intumescent fire protection coatings are used to improve the fire resistance of steel members. Due to slender cross-sections typically used for tension members, high demands are placed on the effectiveness and reliability of the intumescent coatings. This paper describes real-scale fire tests of intumescent coatings applied to steel tension members with circular solid and hollow sections. First, the current regulations for the application of intumescent coatings on steel tension members are discussed. After that, a comparison between the foaming behaviour and failure mechanisms of intumescent coatings applied to steel tension members with different cross-sections and loading conditions is given. Next, the experimental setup and procedure of the performed fire tests are presented. In addition, the influences of various parameters on the performance of the intumescent coating are analysed, including the geometry of the steel profile, dry film thickness of the intumescent coating, load utilisation level as well as the orientation of the member. Based on the theoretical considerations and results of the fire tests, it is evidenced that mechanically loaded fire tests are essential to assess accurately the contribution of intumescent fire protection coatings to the fire resistance of steel tension members with circular solid sections.

## 1. Introduction

In civil engineering constructions, tension members are generally used for bracings, suspensions and underbracing systems. Typically, for tension members, slender sections are used with circular solid section (CSS). Because tension members often serve to stabilize the structure, in the event of a failure of these members, a collapse of the entire structure can happen. Under fire exposure, unprotected steel structures lose their load-bearing capacity at an early stage due to rapid heating. The use of reactive fire protection systems, or in short intumescent coatings, significantly reduces the heating rate of the steel. Thus, the fire resistance of steel members can be improved. In addition, the appearance of the slender tension members remains essentially unchanged as intumescent coatings are applied in relatively thin layers.

The application of intumescent coatings is regulated by National Technical Approvals (abZ and aBG) in Germany and the European Technical Assessments (ETA) in Europe. In Germany, the approvals are issued by the German technical assessment body, i.e. Deutsches Institut für Bautechnik (DIBt). Before an approval or assessment is granted, the fire resistance of the intumescent coating is examined with regards to its thermal protection and adhesion by fire tests on unloaded as well as

mechanically loaded steel members. Generally, the fire tests are carried out on steel beams and/or steel columns according to EN 13381–8 [1]. Therefore, the scope of application of intumescent coatings is usually limited to these steel members and the types of profiles used for them, i.e. I-profiles and hollow sections. In 2010, the regulations for National Technical Approvals in Germany were modified by DIBt based on a numerical comparison between the strains at the bending tension zone of a steel beam and those in a tension member, both with identical cross-sections and load utilisation factors. As a result, intumescent coatings tested on beams can also be used for tension members with open profiles such as I-, L-, T- and U-profiles as well as rectangular or square hollow sections under certain restrictions [2–5]. However, steel tension members with solid sections were excluded from the scope of application according to the German National Technical Approvals due to the lack of normative tests and assessment guidelines. For such members, the application of intumescent coatings must be verified on a case-by-case analysis.

To extend the scope of application of intumescent coatings on steel tension members with solid sections, a research project was conducted [6–8] at the Bundesanstalt für Materialforschung und -prüfung (BAM). The aim is to develop proposals and approval guidelines for the testing

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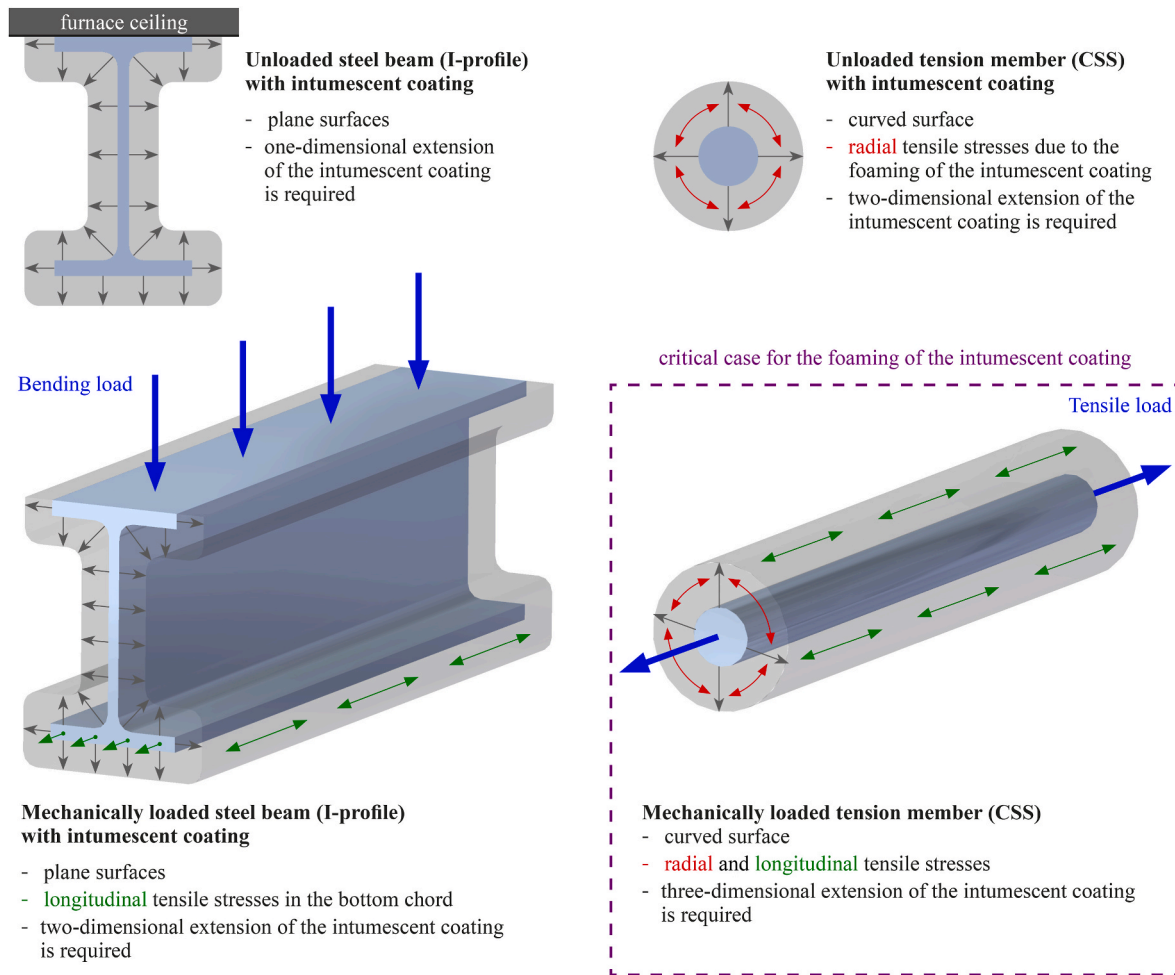


Fig. 1. Comparison of the foaming behaviour of intumescent coatings on beams with I-profile and tension members with circular solid section (CSS).

and assessment of intumescent coatings applied to steel tension members with solid sections by unloaded and mechanically loaded fire tests. In this paper, the current regulations for the application of intumescent coatings on steel tension members are discussed first. After that, the experimental setup, test procedure and results of the performed fire tests are presented. Furthermore, the influences of several parameters on the performance of the intumescent coating are analysed. They include the geometry of the steel profile, the dry film thickness of the intumescent coating, the load utilisation factor and the orientation of the steel member. Finally, the conclusions and outlook of the work are given.

**2. Behaviour of intumescent coatings – theoretical considerations**

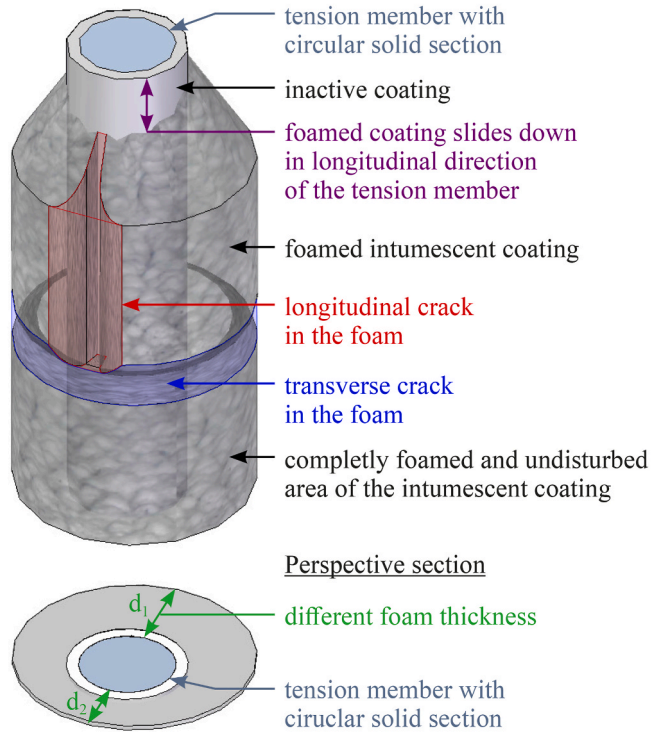
*2.1. Foaming behaviour of intumescent coatings on bending members compared to tension members*

To demonstrate a problematic transfer of the results from fire tests of intumescent coatings on steel beams with I-profile to tension members with circular solid section, the foaming behaviour of an intumescent coating for an I-profile and a circular solid section is schematically shown in Fig. 1. The respective profile types have different demands on the foaming behaviour and thermal protection performance of the intumescent coating. Two scenarios of mechanical loading were considered, i.e. unloaded and loaded. Excluding the edges, an unloaded steel beam with I-profile requires mainly a one-dimensional foaming of the intumescent coating. The intumescent coating expands almost exclusively in the thickness direction, i.e. direction perpendicular to the

surface of the steel member. The performance of common intumescent coatings is optimized for this case. A possible reduction of the thermal protection of the intumescent coating due to cracking in critical areas, such as edged and curved areas, remain unconsidered according to EN 13381-8 [1], as the steel temperature measurement is carried out only in areas with flat surfaces. As a result, possibly higher steel temperatures at critical cross-sectional areas, for instance at the edges of the profile, are excluded from the assessment of the fire tests. In contrast to I-profiles, for an unloaded tension member with circular solid section, the curved surface and the increase of the circumference during the foaming process results in radial tension stresses of the intumescent coating. If these stresses are higher than the tensile strength of the foam of the intumescent coating, cracks occur. This phenomenon usually results in a reduction of the thermal protection of the intumescent coating. Therefore, the intumescent coating on tension members with circular solid section foams necessarily in two directions, i.e. thickness direction perpendicular to the member's surface as well as circumferential direction of the section. This requirement also applies to circular hollow sections.

Compared to the foaming in the thickness direction, the lateral expansion capacity of intumescent coatings is rather limited [7,9,10]. Based on the observations from fire tests, intumescent coatings tend to form cracks especially at cross-sectional edges as well as on convexly curved surfaces of steel profiles because of their limited lateral expansion capacity. As a result, there is usually a reduction of the thermal protection performance and a rapid rise of steel temperature in those areas. To avoid this, it is important that intumescent coatings also have a certain capacity to expand in the lateral direction, i.e. parallel to the

**Vertically oriented steel tension member with intumescent coating**



**Horizontally oriented steel tension member with intumescent coating**

A wide longitudinal crack in the intumescent coating on top of the tension member can cause the foam to slide downwards

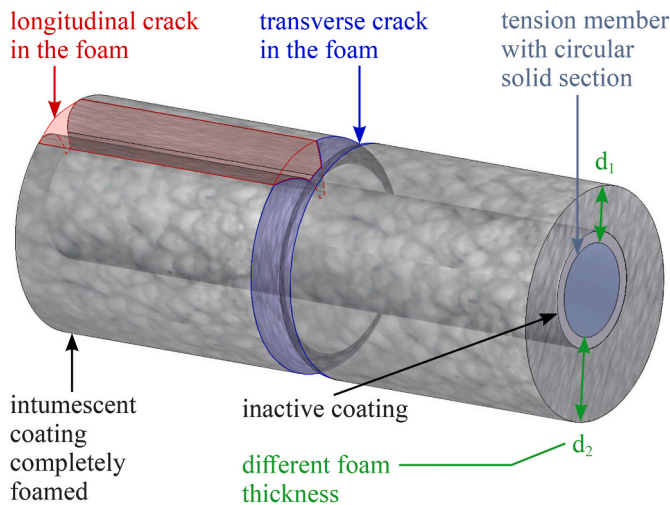


Fig. 2. Schematic presentation of possible failure mechanisms of foamed intumescent coating on vertically and horizontally oriented steel tension members with circular solid section.

member surface.

Beside the type of profile, the type of loading also influences the foaming behaviour of the intumescent coating. For a loaded beam with I-profile, the bending load results in longitudinal tensile stresses in the bottom flange of the beam. Due to the resulting strains, a foaming of the intumescent coating becomes necessary in two directions, i.e. direction

Table 1

Geometrical and mechanical properties of steel specimens in the fire tests.

Profile type	Designation	Diameter	Section factor	Material	Strength ( $f_{p0,2}/f_u$ )
Circular solid section	CSS D20	20 mm	200 m <sup>-1</sup>	Extruded cold-drawn steel S355 J2C + C	585/679 N/mm <sup>2</sup>
	CSS D30	30 mm	133 m <sup>-1</sup>		570/661 N/mm <sup>2</sup>
Circular hollow section	CHS D60	60 mm*	133 m <sup>-1</sup>	Hot-rolled steel S355 J2H	457.5/600.5 N/mm <sup>2</sup>

Note: For more detailed information see [7,11].

\*The profile has a wall thickness of 8.8 mm.

Table 2

Overview of the fire tests ( $\mu_n$ : load utilisation factor; DFT: dry film thickness).

Designation	Test series (TS)	Number of specimens		
		unloaded	mechanically loaded	
CSS D20	TS a (DFT = 1.5 mm*)	4	8	$(\mu_n = 0.15-0.65)$
	TS b (DFT = 2.5 mm)	4	8	
	TS c (DFT = 3.5 mm)	4	8	
CSS D30	TS d (DFT = 2.5 mm)	4	6	$(\mu_n = 0.15-0.65)$
	TS e (DFT = 3.5 mm)	4	6	
CHS D60	TS f (DFT = 2.5 mm)	3	3	$(\mu_n = 0.25-0.60)$
	TS g (DFT = 3.5 mm)	3	3	

Note: For more detailed information see [6,7].

\* On three of the mechanically loaded specimens with CSS D20 from "TS" a higher DFT was applied, i.e. 3.0 mm, 3.5 mm and 4.5 mm. The aim was to investigate the influence of higher DFT.

perpendicular to the surface and longitudinal direction of the beam. For loaded tension members, tensile stresses in longitudinal direction also occur additionally to those in radial direction due to the curved surface of circular solid sections typically used for tension members. Thus, for a mechanically loaded tension member with circular solid section, the intumescent coating requires a three-directional expansion in radial direction as well as in circumferential and longitudinal directions of the section. This places particularly high demands on the performance of the intumescent coating on mechanically loaded circular solid tension members, which represent the most critical case compared to other sectional profiles and loading conditions.

Another aspect to consider is that in contrast to beams, tension members have no stress transfer capability within the cross-section. Therefore, in the case of a fire, no additional load capacity reserves can be activated. In addition, based on numerical calculations comparing mechanically loaded beams and tension members of the same I-profile and identical load utilisation [2,3,5], the results show that at equal steel temperature, tension members have higher strains compared to the bending tension zone of beams. Since the level of strain affects the adhesion of the intumescent coating, this is a further evidence of higher stresses in the intumescent coatings applied to steel tension members compared to beams. Furthermore, not only hot-rolled steel is used for tension members with solid section, but also cold-drawn steel. Due to the manufacturing process, cold-drawn steel has different mechanical material properties than hot-rolled structural steel commonly used for beam and column profiles. Information regarding the mechanical properties of cold-drawn steel at elevated temperature are presented in [7,11].

To summarize, the results from fire tests of intumescent coatings on steel beams with I-profile cannot be straightforwardly transferred to steel tension members with circular solid sections. Moreover, a reliable assessment concerning the fire resistance of intumescent coatings applied to solid steel tension members requires mechanically loaded fire tests. Fire tests on unloaded tension members can overestimate the

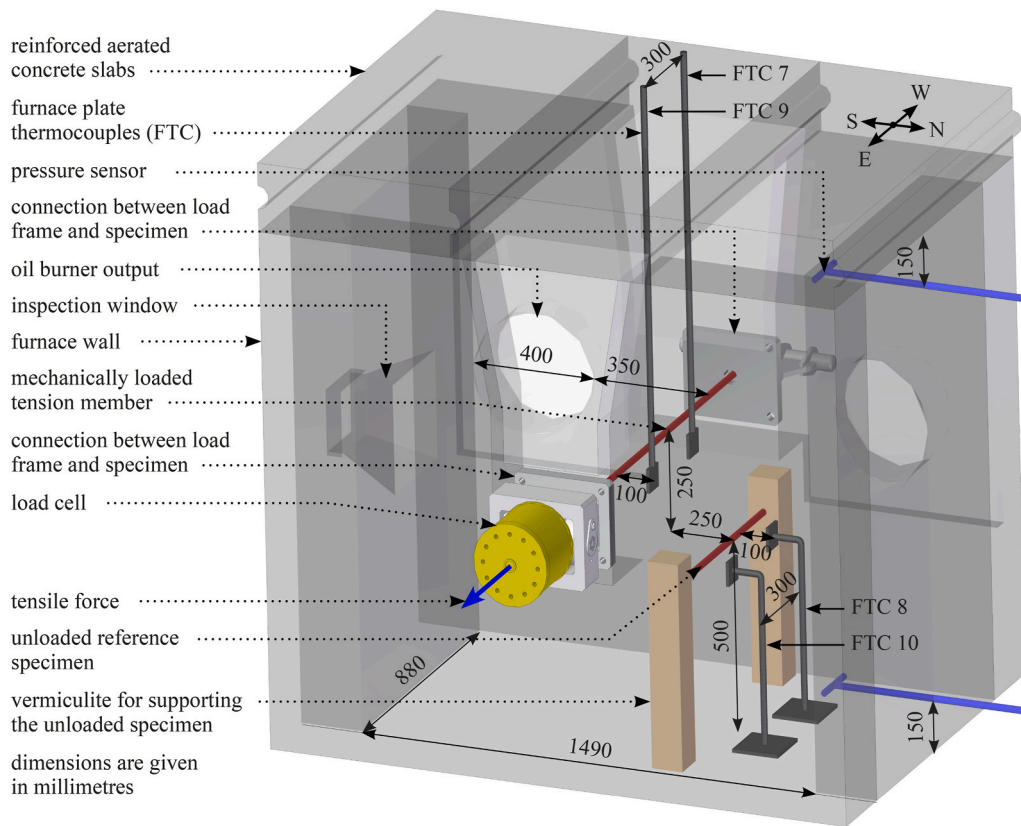


Fig. 3. Test furnace showing the mechanically loaded and unloaded steel tension members.

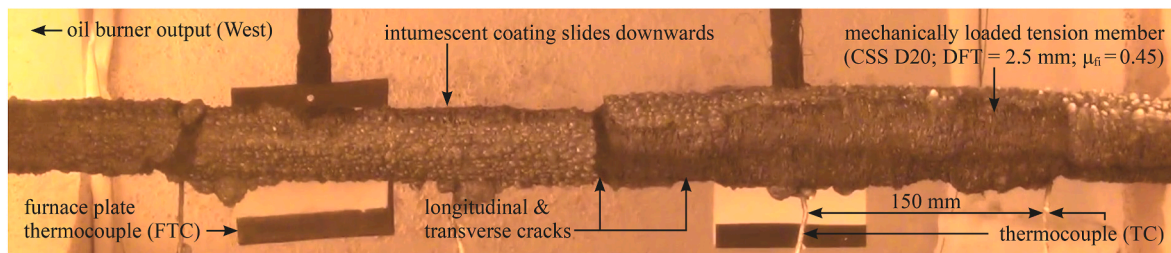


Fig. 4. Transverse and longitudinal cracks and partial sliding of the intumescent coating at a mechanically loaded steel tension member.

thermal protection performance of the intumescent coatings due to missing tensile load or resulting stress in the intumescent coating. Therefore, they are not sufficient to evaluate critically the fire resistance corresponding to the actual loading situation in the building constructions. Mechanically loaded fire tests, on the other hand, are able to consider appropriately the most critical case. Thus, they are necessary for an accurate assessment of the fire resistance of intumescent coatings in practice.

### 2.2. Failure mechanisms of intumescent coatings

From fire tests on steel beams and columns with intumescent coating, it is known that cracks in the intumescent coating can occur due to the foaming process for both unloaded and mechanically loaded steel members. The progression of the cracks, their length, width as well as depth vary and generally cannot be predicted. At areas with cracks, the thermal protection of the intumescent coating is reduced. Thus, the temperature of the steel increases and results in an earlier failure of the steel member. For steel tension members with circular solid section, possible failure mechanisms of foamed intumescent coating are shown in Fig. 2. Considering horizontally oriented tension members, a

broadening of longitudinal cracks on top of a circular solid member can lead the intumescent coating to slide down. For vertically oriented tension members, sliding can occur downward due to the self-weight of the intumescent coating (see Fig. 2). This phenomenon is critical because it results in relatively large unprotected areas. As a consequence, there can be a rapid heating and an early loss of the load-bearing capacity of the tension members.

## 3. Experimental study

### 3.1. Specimens and test programme

The fire tests of steel tension members with intumescent coating were carried out in real-scale. The test programme was designed to assess the different factors that influence the behaviour of the intumescent coating specifically, i.e. the profile geometry and orientation of the tension member, dry film thickness (DFT) of the intumescent coating and the tensile stress level in terms of the load utilisation factor in case of fire ( $\mu_{fi}$ ).

Concerning the profile geometry, as slender profiles are generally used for tension members, among that circular sections represent the

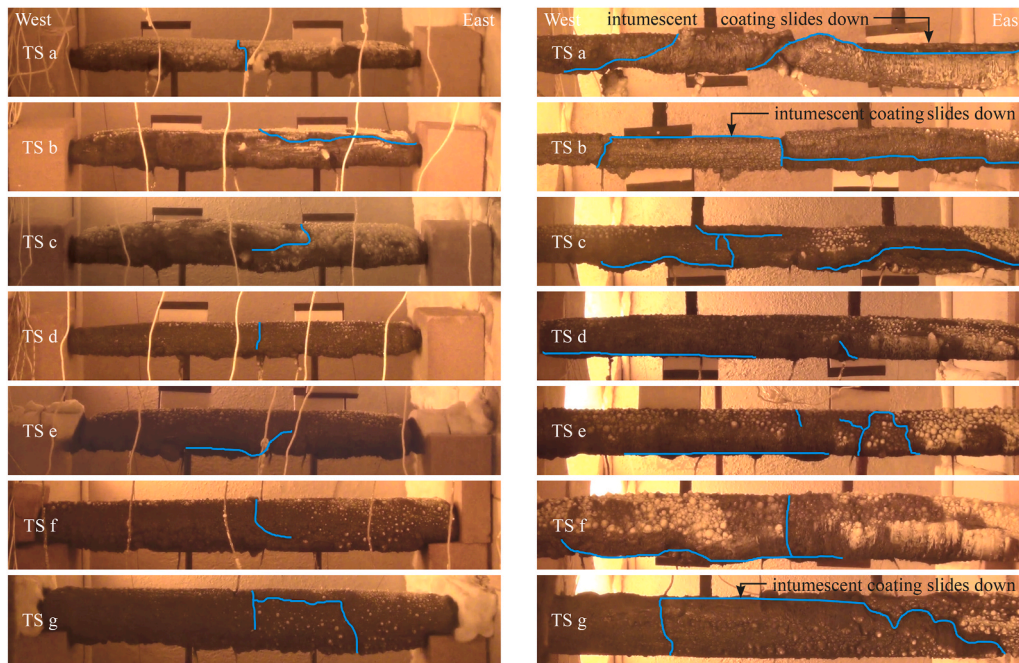


Fig. 5. Comparison of the foaming behaviour and crack formation of the intumescent coating of unloaded (left) and mechanically loaded steel tension members (right); the crack pattern is highlighted by light blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

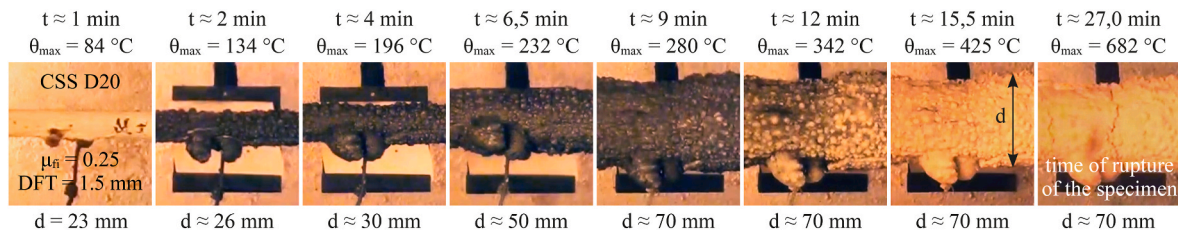


Fig. 6. Foaming process of the intumescent coating during the fire test of a mechanically loaded steel tension member.

most critical cases compared to other sections, circular solid sections with a diameter of 20 and 30 mm (D20 and D30) were used in the fire tests. In addition, to investigate the influence of larger bar diameters without exceeding the maximum allowable tensile force of the test facility, circular hollow sections (CHS) with a diameter of 60 mm (D60) and a wall thickness of 8.8 mm, whose section factor is the same as that of the CSS D30, were tested. For all specimens, steel grade S355 was used. The solid profiles were made of extruded cold-drawn steel, the hollow profile of seamless finished hot-rolled steel. The geometrical and mechanical properties of the steel specimens are provided in Table 1. The section factor is equal  $A_m/V$ , where  $A_m$  is the surface area of the steel section exposed to fire per unit length and  $V$  is the sectional volume per unit length. The steel members with the same profiles were taken from the same batch and therefore have identical material properties. The steel strength was determined by small-scale material tests. The first strength value in Table 1 refers to the offset yield point of 0.2%-proof stress ( $f_{p0.2}$ ) and the second value to the tensile strength ( $f_{tR}$ ). To ensure a good adhesion between the steel members and the intumescent coating, a surface preparation grade SA 2½ according to DIN EN ISO 8501-1 [12] was created for the specimens by sandblasting. Regarding the member orientation, the fire tests were performed in most cases for horizontally oriented tension members. To identify the effect of the orientation of the tension members on the performance of the intumescent coating, generally two unloaded vertically oriented specimens of each test series were tested.

For comparability reasons, all fire tests were carried out with the same intumescent coating that is a water-based conventional product with a valid European technical assessment [13]. The use of this product is to fire protect various sizes of structural steel ‘H’ and ‘I’ beams and columns as well as rectangular hollow sectioned columns for a fire resistance classification of up to R120. The system consists of a primer and an intumescent layer. A topcoat was omitted in the fire tests. Since the principle of the behaviour of intumescent coatings under fire is not dependent on the particular product used, the findings obtained from the performed fire tests are of general nature.

For the examination of the effect of the DFT on the performance of the intumescent coating, two different thicknesses were applied to all specimens, i.e. 2.5 and 3.5 mm. In addition, for the specimens with CSS D20, coating thicknesses of 1.5, 3.0 and 4.5 mm were analysed.

Table 2 gives an overview of the test programme. The test series (TS) were designed to combine specimens with the same DFT in one group. To take into account the critical cases, the test programme was specified to consist of mainly mechanically loaded fire tests. In total, 42 mechanically loaded and 26 unloaded steel tension members with intumescent coating were tested. The load utilisation factor in case of fire of the mechanically loaded tension members  $\mu_{fi}$  was varied from 0.15 (low capacity) to 0.65 (full capacity, i.e. full utilised tension member under normal design temperature) at an interval of 0.1. Beside the amount of the applied tensile load, the influence of the timing of the applied load was considered. In general, the tensile load can be applied before or after

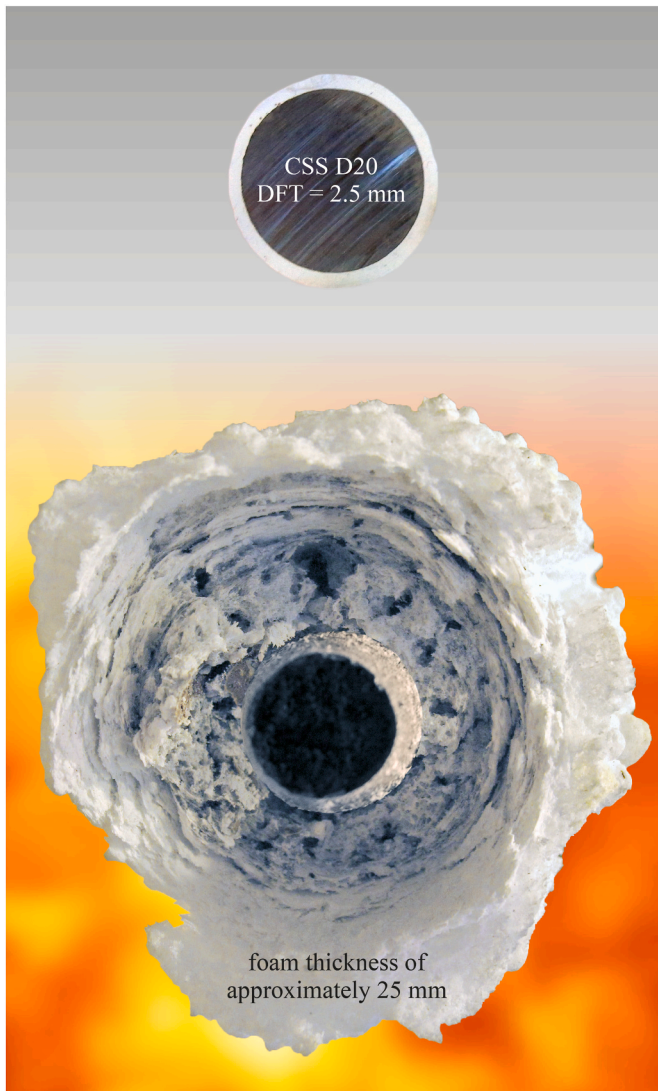


Fig. 7. Cross-section of a mechanically loaded steel tension member with circular solid section D20 showing the intumescent coating before (top) and after (bottom) the fire test.

the application of the intumescent coating on the members. The latter case is considered more critical because the application of the tensile load can result in the formation of micro-cracks in the already hardened intumescent coating, which could have a negative effect on the performance of the intumescent coating. To examine the more critical testing condition for the intumescent coating, the tension members were first coated with the intumescent coating, i.e. factory coating, and the mechanical tensile load was applied after curing.

### 3.2. Setup and execution of the fire tests

A three-dimensional model of the furnace showing the installed mechanically loaded and unloaded steel tension members is presented in Fig. 3. Thermocouples (TC) were used to measure the steel temperature of the specimens as well as the gas temperature in the furnace during the fire tests. The setup of the tension members in the actual testing furnace and the position of the furnace plate thermocouples (FTC) to measure the gas temperature are described in [6–8]. In the fire tests, the flamed length of the mechanically loaded tension members was approximately 1 m. The ISO 834 standard temperature/fire curve [14] was applied.

### 3.3. Results

#### 3.3.1. Tension members with CSS D20 (“TS a” to “TS c”)

About 2 minutes after the start of the fire tests, the intumescent coating started to foam. The surface of the intumescent coating turned black and bubbles developed. The blackening resulted from the carbon that was released during the foaming process. Because of the large volume expansion and the increase of the circumference, cracks were formed in the intumescent coating in longitudinal and transverse directions of the tension members (see Fig. 4). For specimens with high DFT, crack healing abilities of the intumescent coating could be activated. Thus, cracks could be partly closed-up by after-foaming of not yet fully reacted coating material. In the absence of this crack healing ability, a widening of cracks could be observed. Consequently, the thermal protection of the intumescent coating was reduced in the cracked areas and the steel temperature increased rapidly. In general, mechanically loaded tension members showed a more intensive cracking than unloaded specimens (see Fig. 5).

The crack formation and crack healing were confined to the foaming process of the intumescent coating. Due to longitudinal cracks at the top of horizontally oriented mechanically loaded specimens in some fire tests, the intumescent coating slid down (see Fig. 5). In such areas, the specimens were nearly unprotected, which resulted in a rapid rise of the steel temperature and a premature failure of the mechanically loaded specimens. It was observed that the intumescent coating slid down only at mechanically loaded tension members, in comparison to unloaded ones. Especially at the mechanically loaded specimens of the test series “TS a” with a small bar diameter of 20 mm and a comparatively small DFT of 1.5 mm, the intumescent coating slid down often. The risk that the intumescent coating slides down relates to the DFT, the crack healing ability of the intumescent coating and the profile geometry of the bar as well as the tensile stress level. The theoretical failure mechanisms of the intumescent coating (see Fig. 2) were in agreement with the performed fire tests. Depending on the profile geometry and the DFT, the largest expansion of the foaming was reached after about 10–20 minutes of fire duration. Thereafter, the surface of the foamed intumescent coating began to ash and turn white. New carbon-rich compounds were not formed and the foaming process ended. The white crust-like surface of the intumescent coating changed its appearance during the further duration of the fire test insignificantly. The foaming behaviour of the intumescent coating during the fire duration is shown

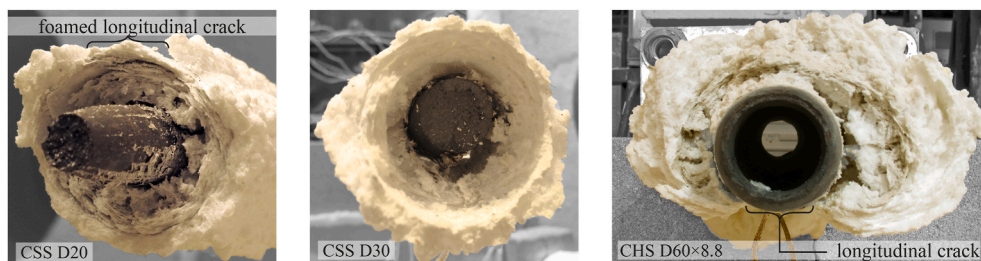


Fig. 8. Foaming behaviour of the intumescent coating on mechanically loaded steel tension members.

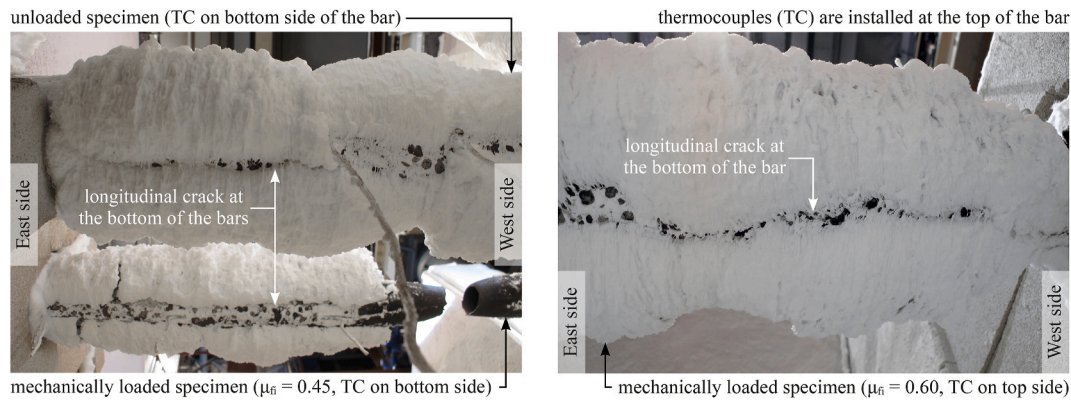


Fig. 9. Bottom view of the mechanically loaded and unloaded tension members tested in horizontal orientation showing the longitudinal cracks (CHS D60; DFT = 2.5 mm).

Table 3

Increase in the fire duration [min] until the rupture of the mechanically loaded tension members by increasing the bar diameter from 20 to 30 mm ( $\mu_{fi}$ : load utilisation factor; DFT: dry film thickness).

$\mu_{fi}$ [-]		0.15	0.25	0.35	0.45	0.55	0.65	Average value
DFT	2.5 mm	+19.3	+15.8	+16.2	+15.3*	+14.8	+13.1	+15.7 min
	3.5 mm	+26.4	+22.0	+21.1	+19.8	+18.2	+18.1	+20.9 min

\* The CSS D30 was tested with a reduced load utilisation factor of  $\mu_{fi} = 0.42$ . The time is calculated based on the time value of CSS D30 minus the time value of CSS D20.

Table 4

Reduction in the heating rate of the steel [K/min] of the mechanically loaded tension members by increasing the bar diameter from 20 to 30 mm ( $\mu_{fi}$ : load utilisation factor; DFT: dry film thickness).

$\mu_{fi}$ [-]		0.15	0.25	0.35	0.45	0.55	0.65	Average value
DFT	2.5 mm	-5.5	-5.8	-6.9	-6.2	-6.1	-7.0	-6.3 K/min
	3.5 mm	-7.4	-6.0	-7.3	-7.4	-9.6	-7.6	-7.5 K/min

\* The CSS D30 was tested with a reduced load utilisation factor of  $\mu_{fi} = 0.42$ . The value is calculated based on the value of CSS D30 minus the value of the CSS D20. The heating rate of each specimen is calculated for temperatures ranging between 350 and 550 °C, which corresponds to the foamed condition of the intumescent coating.

in Fig. 6.

The rupture of the tested mechanically loaded tension members was usually indicated by several transverse cracks in the foamed intumescent coating and occurred at the location of the maximum steel temperature. Therefore, the assessment of the fire tests always refers to the maximum measured steel temperature of the tension member. Because of the large strains and longitudinal deformations that occurred near the time of rupture of the tension member, the crack width in the intumescent coating increased. Based on the location of the transverse cracks and the measured maximum steel temperature, the position of the rupture can be predicted relatively well. Depending on the load utilisation factor, the DFT and foaming behaviour of the intumescent coating, the mechanically loaded tension members failed approximately after 21 to 46 minutes. An example of the foaming behaviour of the intumescent coating is presented in Fig. 7 and Fig. 8. Because of the impact at the rupture of the loaded specimen, the intumescent coating partially fell apart from the steel.

### 3.3.2. Tension members with CSS D30 (“TS d” and “TS e”)

The specimens CSS D30 showed a similar behaviour compared to CSS

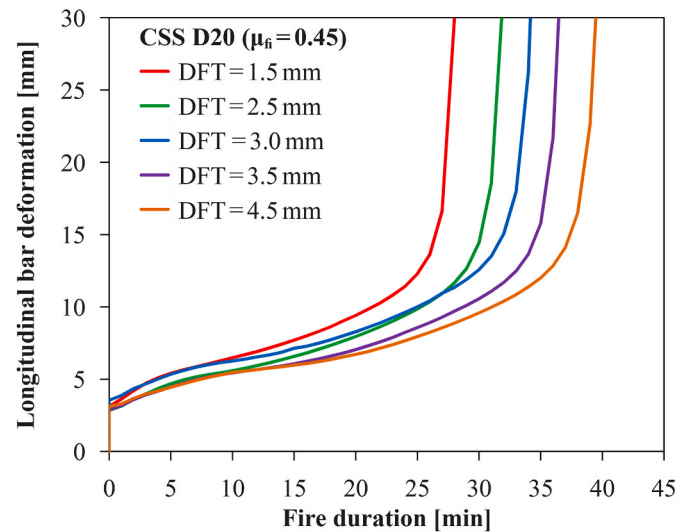


Fig. 10. Influence of the dry film thickness on longitudinal bar deformation and time until the rupture of the mechanically loaded tension members with CSS D20.

D20. The increased diameter of the specimens allowed a more uniform foaming behaviour and better crack healing abilities of the intumescent coating. Cracks in longitudinal and transverse direction also occurred in the intumescent coating, but usually they could be closed due to the after-foaming effect of the coating material. In addition, because longitudinal cracks mainly occur at the bottom of the rods, the intumescent coating did not slide down. In general, mechanically loaded tension members showed a more intensive cracking formation than unloaded specimens. The rupture of the mechanically loaded specimens occurred between 42 and 72 minutes. The foaming behaviour of the intumescent coating is exemplary presented in Fig. 8.

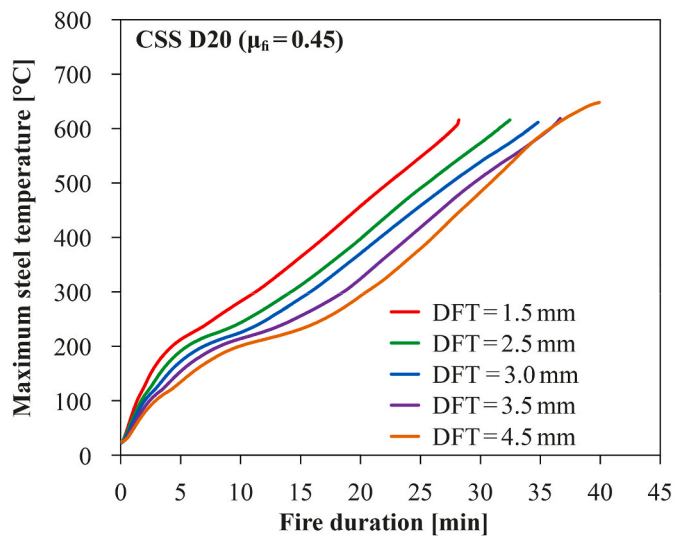


Fig. 11. Influence of the dry film thickness on maximum steel temperature of the mechanically loaded tension members with CSS D20.

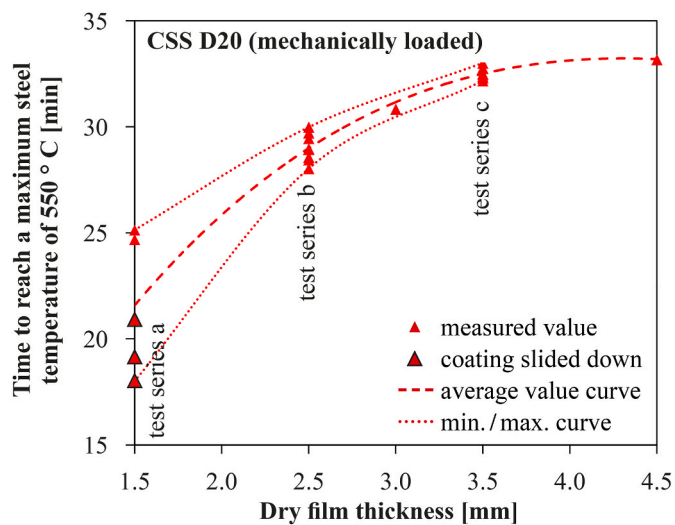


Fig. 12. Time to reach a maximum steel temperature of 550 °C (CSS D20, test series "TS a" to "TS c").

### 3.3.3. Tension members with CHS D60 ("TS f" and "TS g")

The foaming behaviour and crack formation of the intumescent coating on tension members with CHS D60 was observed similarly to that on the circular solid sections (CSS). Other than expected, the bigger diameter and the resulting lower surface curvature of the circular hollow section did not reduce the cracking formation. In some cases, the cracking in the intumescent coating was even increased. It should be noted that this observation was based on a comparison of two different section types, i.e. CSS and CHS. Moreover, relatively wide longitudinal cracks also occurred at the bottom of the specimens. To exclude the effect of the thermocouples that are located at the bottom of the tension member to the cracking formation, the thermocouples were installed at the top of some specimens. Fig. 9 presents the longitudinal cracks at the bottom of the specimens. Some mechanically loaded tension members also experienced the phenomenon that the intumescent coating slid down. Even though the tension members with CHS D60 have the same section factor and DFT as the specimens with CSS D30, the measured maximum steel temperature curves of the mechanically loaded CHS D60 showed significantly stronger scattering between the individual tests.

The mechanically loaded tension members failed after about 37 to 90 minutes. A cross-sectional view of a specimen with CHS D60 after the fire tests is presented in Fig. 8.

### 3.4. Factors affecting the performance of the intumescent coating

The cracking and foaming behaviour, the thermal protection performance of the intumescent coating, the time until rupture as well as the heating rate of the tension members were analysed based on the fire tests. The most important factors affecting the behaviour of the intumescent coating and the tension members were investigated. These factors are identified as the profile geometry, the DFT of the intumescent coating, the level of tensile stress resulted from applied tensile load and the orientation direction of the tension member. The influence of each factor is discussed next.

#### 3.4.1. Influence of the profile geometry

The influence of the profile geometry was analysed based on the mechanically loaded specimens with circular solid sections (CSS D20 and CSS D30). For this profile type, the section factor ( $A_m/V$ ), which is commonly used in fire engineering, depends only on the bar diameter. The CSS D20 has a section factor of  $200 \text{ m}^{-1}$ , while the CSS D30 has a section factor of  $133 \text{ m}^{-1}$ . An increase of the bar diameter decreases the section factor. Because of the direct correlation between the section factor and bar diameter, only the bar diameter had to be considered. The effect of the bar diameter can be evaluated based on the fire duration until rupture of the tension member as well as the heating rate of the steel and the cracking and foaming behaviour of the intumescent coating.

An increase of the bar diameter from 20 to 30 mm results in higher fire durations until the rupture of the mechanically loaded tension members occurs (see Table 3). Depending on the load utilisation factor in case of fire and the applied DFT, the time until rupture could be increased by approximately 13 to 26 minutes. In addition, by an increase of the bar diameter, the heating rate of the steel could be reduced by approximately 5.5 to 9.6 K/min (see Table 4). An influence of the bar diameter on the foaming behaviour and crack formation of the intumescent coating can also be observed by the fire tests (see Fig. 5). In general, the tension members with CSS D30 showed a more uniform foaming of the intumescent coating in longitudinal and circumferential directions than the specimens with CSS D20. However, the foaming thickness depends mainly on the applied DFT of the intumescent coating rather than on the bar diameter. The increase of the bar diameter improves the crack healing ability of the intumescent coating so that the thermal protection of the intumescent coating can be maintained.

#### 3.4.2. Influence of the dry film thickness

The influence of the dry film thickness (DFT) was examined based on the mechanically loaded tension members with CSS D20 and a load utilisation factor in case of fire of  $\mu_{fi} = 0.45$ . The DFT varied from 1.5 to 4.5 mm. In Fig. 10, the rupture of the loaded tension members is characterised by high deformation values and the almost vertical course. In Fig. 11, the rupture time is equal to the end of the temperature measurement. Both figures show that an increase of the DFT of the intumescent coating increases the fire duration until the rupture of the mechanically loaded tension members occurs. This results from the improved thermal protection of the intumescent coating that increases with higher DFT. Thus, the heating rate of the steel can be reduced and its strength can be maintained for a longer time. Because all analysed loaded tension members have the same load utilisation in case of fire, the DFT has no effect on the maximum steel temperature at the rupture time (see Fig. 14). Except for the specimen with a DFT of 4.5 mm, where the location of the temperature measurement and the rupture is different, the temperature at rupture was about 615 °C.

To assess the influence of the DFT, the time to reach a maximum steel temperature of 550 °C was determined for all mechanically loaded



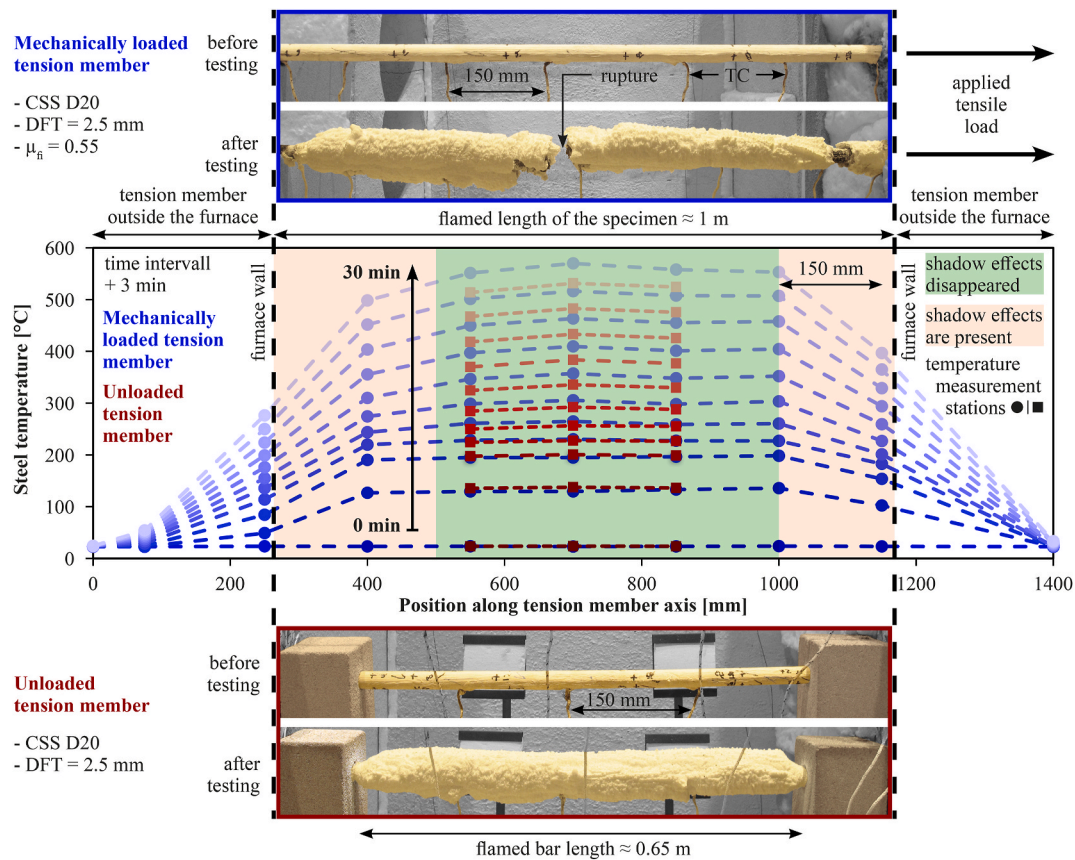


Fig. 13. Comparison of mechanically loaded and unloaded tension members tested in horizontal orientation.

tension members with CSS D20 (see Fig. 12). This reference temperature almost corresponds to the rupture temperature of a fully utilised tension member ( $\mu_{fi} = 0.65$ ). In general, the time to reach a temperature of 550 °C increases with higher DFT. However, the increase in time is getting smaller with increasing DFT. Consequently, the improvement of the thermal protection of the intumescent coating by increasing the DFT is limited. The gain in time develops under-proportional to the increase of DFT.

Because of the different cracking and foaming behaviour of the intumescent coating within a test series (TS), time differences to reach the reference temperature occurred. The relatively large time difference in “TS a” resulted from longitudinal cracks on top of some specimens, where the intumescent coating began to slide down partially. An increase of the DFT improved the crack healing ability and results in a more uniform foaming of the intumescent coating. Thus, the time differences within a test series could be reduced. For example, in “TS a”, the difference between the minimum and maximum time to reach the reference temperature of 550 °C was about 7 minutes; in “TS b” it reduced to 2 minutes and in “TS c”, it was only 1 minute. The described statements on the influence of the DFT can be also applied to other steel temperatures.

### 3.4.3. Influence of the load utilisation level

To investigate the influence of the tensile stress on the temperature development in each test series, two fire tests with a simultaneously tested mechanically loaded and unloaded tension member were carried out. All specimens were horizontally installed in the furnace. Except the member length, the corresponding number of attached thermocouples and the applied tensile load to both specimens are identical. To minimize shadowing effects, the two specimens were positioned with a certain distance to each other, i.e. 250 mm in horizontal and vertical direction (see Fig. 3). This complies with the requirements of the

regulations given in DIN EN 1363–1 [15].

Fig. 13 presents a comparison of a mechanically loaded tension member and an unloaded one before and after the fire tests as well as the measured steel temperatures along the member axis. Both specimens have a circular solid section (CSS) with a diameter of 20 mm. An intumescent coating with a DFT of 2.5 mm was applied. The mechanically loaded tension member has a load utilisation factor in case of fire of  $\mu_{fi} = 0.55$ . The measured steel temperatures along the member axis are given in a time interval of 3 minutes. The rupture of the loaded specimen occurred near mid-span after about 30 minutes. The maximum steel temperature at the position of failure was about 570 °C. At the same point of time, the temperature of the simultaneously tested unloaded specimen was approximately 50 °C less than that of the loaded specimen, i.e. 520 °C. This confirms that the testing of mechanically loaded tension member places particularly higher demands on the performance of the intumescent coating compared to unloaded fire tests.

Due to the relatively close distance between the thermocouples, i.e. 150 mm, local temperature differences along the member axis could be detected. These temperature differences could be resulted from different foam thicknesses and cracks in the intumescent coating as well as from shadow effects near the furnace walls and local fluctuations of the gas temperature in the furnace. The evaluation of the measured steel temperatures in Fig. 13 shows that the temperature near the furnace walls was reduced due to edge effects. However, from about 150 mm to the furnace wall, these effects were largely diminished. In the centre of the furnace, an approximately 500 mm long undisturbed bar area with an almost constant steel temperature was present. Thus, the selected flamed length of the mechanically loaded and unloaded tension members was sufficient.

A comparison of the measured maximum steel temperature for each test series is shown in Fig. 14. For each test series, the pair of a mechanically loaded specimen and an unloaded one with the highest

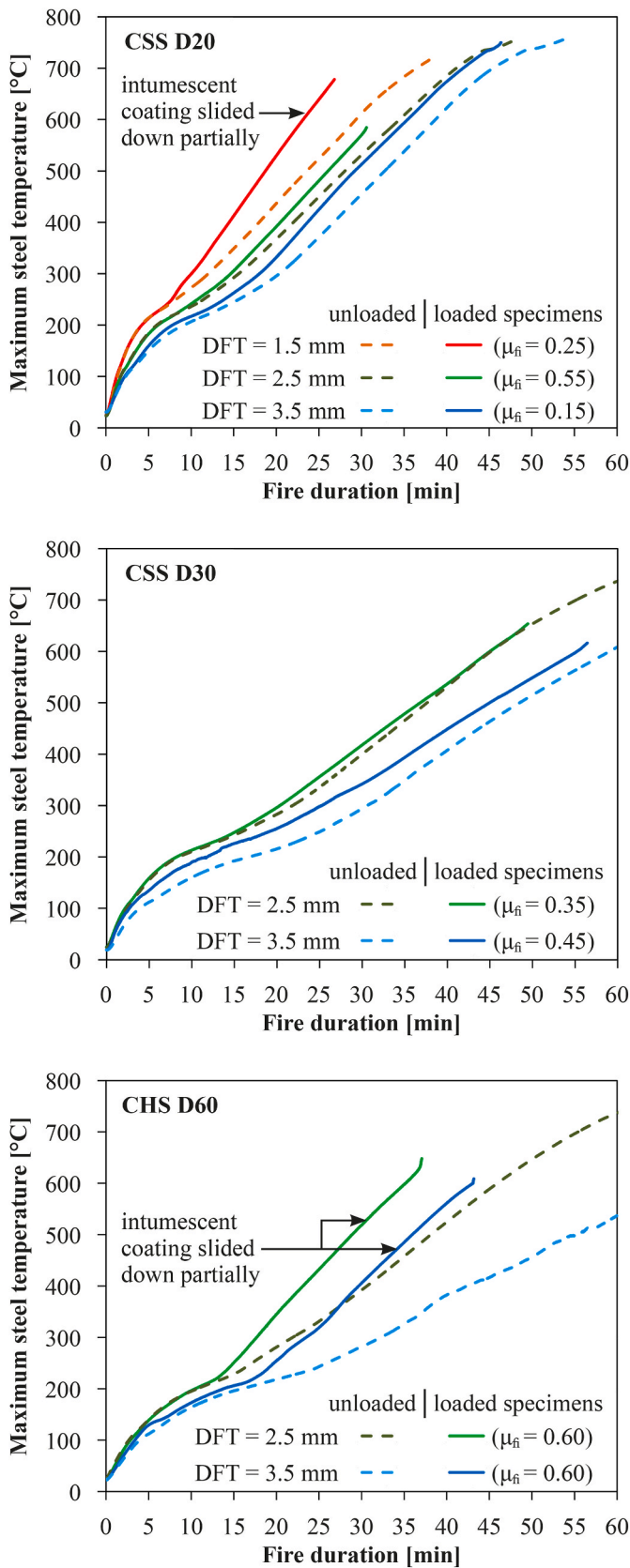


Fig. 14. Comparison of the maximum steel temperature measured at mechanically loaded and unloaded tension members tested in horizontal orientation.

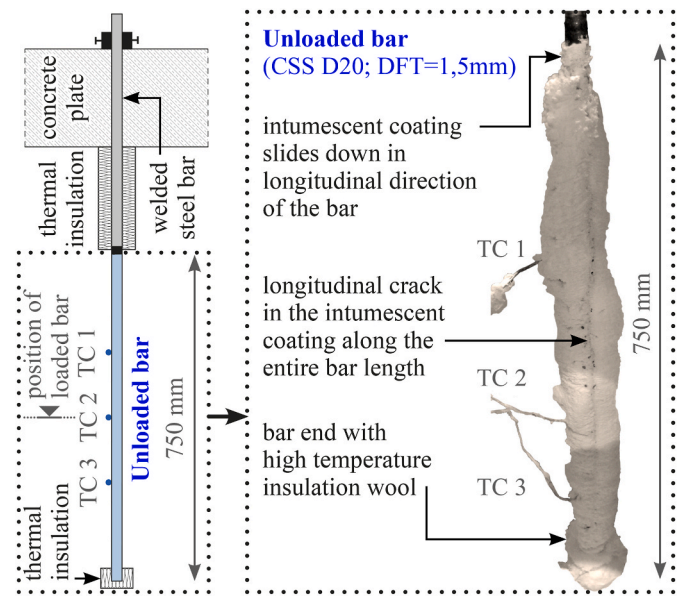


Fig. 15. Unloaded tension member tested in vertical orientation (left: principle sketch; right: view of the foamed intumescent coating after the fire test).

temperature difference was selected. Because of the identical profile geometry and DFT of the intumescent coating, the maximum steel temperature–fire duration curves were principally similar for the pair of loaded and unloaded tension members. For the mechanically loaded tension members, the end of the temperature measurement corresponds to the time of rupture of the specimen. In general, the thermal protective effect of the intumescent coating and thus a slower heating of the steel could be obtained by increasing the DFT or the cross-section of the tension member. Based on the results shown in Fig. 14, mechanically loaded tension members have higher maximum steel temperatures than unloaded specimens. This resulted from the increased tendency of cracking in the intumescent coating due to the applied load and corresponding tensile stress. Consequently, the thermal protective effect of the intumescent coating was reduced and the heating rate of the steel was increased. Furthermore, for mechanically loaded tension members, the intumescent coating slid down partially during the fire test, which resulted in nearly unprotected areas of the steel with a fast increase of the steel temperature.

#### 3.4.4. Influence of the tension member orientation

Based on fire tests of unloaded tension members with circular solid sections installed in horizontal direction (see Fig. 3) and vertical position (see Fig. 15), the influence of the member orientation on the behaviour of the intumescent coating was analysed. The results of the measured maximum steel temperature are given in Table 5. In the fire tests, the tension members in vertical direction heated up faster than those installed in horizontal position. Due to the different orientation of the specimens, a difference in the steel temperature occurred already after about 15 minutes. The reason for the fast heating of the vertically installed unloaded tension members were intensive longitudinal cracks and an uneven distribution of the foamed intumescent coating over the cross-section (see Fig. 15). The longitudinal cracks normally ran over the entire length of the bar and reached the surface of the steel. Because of these cracks, the thermal protection of the intumescent coating was significantly reduced. The unloaded tension members that were tested in horizontal orientation also showed longitudinal cracks in the foam. However, these cracks were usually at the bottom of the specimens and could be closed during the foaming process by the crack healing ability of the intumescent coating.

For some vertically tested specimens, the intumescent coating slid down in longitudinal direction, particularly at the upper end of the

**Table 5**

Comparison of the measured steel temperatures between the unloaded tension members tested in horizontal and vertical orientation.

Fire duration	15 min					30 min					45 min				
	CSS D20		CSS D30			CSS D20		CSS D30			CSS D20		CSS D30		
<b>Test series</b>	<b>TS a</b>	<b>TS b</b>	<b>TS c</b>	<b>TS d</b>	<b>TS e*</b>	<b>TS a</b>	<b>TS b</b>	<b>TS c</b>	<b>TS d</b>	<b>TS e*</b>	<b>TS a</b>	<b>TS b</b>	<b>TS c</b>	<b>TS d</b>	<b>TS e*</b>
DFT [mm]	1.5	2.5	3.5	2.5	3.5	1.5	2.5	3.5	2.5	3.5	1.5	2.5	3.5	2.5	3.5
$\theta_{\text{horizontal}}$ [°C]	368	295	238	241	203	651	541	463	418	357	–	742	694	601	549
$\theta_{\text{vertical}}$ [°C]	465	329	246	275	–	754	617	482	470	–	–	–	712	652	–
$\Delta\theta_{\text{vertical-horizontal}}$	97	34	8	34	–	103	76	19	52	–	–	–	18	51	–

\* Only specimens in horizontal orientation were tested.

The values are based on the measured maximum steel temperature of the tension members.

Base value for the temperature difference ( $\Delta\theta$ ) of each test series is the specimen tested in vertical orientation.

specimens (see Fig. 15). For these areas, an increase of the steel temperature was expected. Since the distance between the end of the bar and the attached thermocouples was about 225 mm, the temperature measurement was not affected. The behaviour that the intumescent coating slides down due to its self-weight is known from fire tests for columns protected with intumescent coating.

The temperature difference between the horizontally and vertically oriented unloaded tension members with circular solid section in Table 5 shows that with increasing fire duration, the temperature difference also increased. This resulted from the differences in the heating rates of the steel, which are a measure of the thermal protection performance of the intumescent coating. In general, tension members in vertical orientation have higher heating rates than specimens tested in horizontal direction. By an increase of the DFT of the intumescent coating or higher bar diameters, the differences in the steel temperature and heating rates between the horizontally and vertically oriented tension members could be reduced. This is due to the better crack healing ability and the decreasing cracking risk of the intumescent coating.

Based on the results of the fire tests, the orientation of the tension member affects the thermal protection of the intumescent coating. A direct transfer of the temperature data between tension members with horizontal and vertical orientation is therefore not recommended. Hence, the scope of application of the intumescent coating has to be identical to the orientation of the tested tension member. Due to the limited number of tested specimens, further investigation on this topic is necessary.

#### 4. Conclusions and perspective

The fire tests show that intumescent coatings can be applied to steel tension members with circular solid section to improve their fire resistance. Because of relatively slender cross-sections that are typically used for tension members and the missing stress transfer capability, high demands are placed on the performance and reliability of the intumescent coatings. Due to the lack of a scientifically sound basis, a direct comparison between the bending tension zone of a mechanically loaded steel beam with I-profile and a loaded tension member with circular solid section is not possible.

In the numerous fire tests carried out at BAM, the cracking, crack healing and foaming behaviour of the intumescent coating as well as the heating and the maximum steel temperatures of the tension members were analysed. Particularly, cracks in longitudinal direction of the tension members, together with the phenomenon that the intumescent coating slides down, reduced significantly the thermal protection of the coating. By applying a sufficiently high dry film thickness (DFT), crack healing effects can be activated. Thus, cracks that arise during the foaming process can be closed and the thermal protection of the intumescent coating can be maintained.

The assessment of the fire tests shows that the profile geometry, the DFT, the tensile stress level and the orientation direction of the tension member have a significant influence on the thermal protection of the intumescent coating. In addition, these factors interact with one another

[7,8]. Generally, the fire resistance of the tension members can be improved by an increase of the bar diameter, a reduction of the section factor, an increase in the DFT of the intumescent coating or a lowering of the tensile stress level, i.e. load utilisation factor in case of fire. In the fire tests, the horizontally oriented unloaded tension members showed a better thermal protection of the intumescent coating compared to the specimens tested in vertical orientation. Due to the limited number of tested specimens, the generality of this statement has to be verified by further investigation.

Based on the results of the fire tests and theoretical considerations, it is evidenced that the necessary three-dimensional foaming direction of the intumescent coating applied to members with circular solid sections subjected to tension results in the highest stress level in the coating in comparison to unloaded members or loaded members of other types of cross-sections. Therefore, to analyse and assess the fire resistance of intumescent coatings, fire tests of mechanically loaded tension members are necessary.

Recommendations on the implementation of fire tests for intumescent coatings applied to mechanically loaded and unloaded tension members are described in [6,7,15]. Based on this research, the German building authority, i.e. DIBt, has defined the national safety level and extended the national approval principles for intumescent coatings applied to steel tension members with solid sections. A summary of the current regulations in Germany for the application of intumescent coatings on steel tension members is described in [16,17], in which mechanically loaded tests are mandatory. The German mirror committee for standardization has prepared a proposal for the testing and assessment of intumescent coatings applied to steel tension members with solid sections [18]. Based on this proposed testing procedure, an intumescent coating has firstly obtained a national approval in Germany for the application on steel tension members with circular solid and hollow sections [19]. In addition, a proposal for a European testing standard of intumescent coatings applied to steel tension members with solid section is currently developed as part of an ongoing research project at BAM [20]. In this project, the influence of different member orientations on the thermal performance of the intumescent coating is investigated, as well as the transferability of the results from members with circular solid section to those with rectangular or square solid sections is evaluated. Findings regarding the behaviour of intumescent coatings on the associated connecting components of tension rod systems can be found in [10,21,22].

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#### References

- [1] EN 13381-8, Test Methods for Determining the Contribution to the Fire Resistance of Structural Members – Part 8: Applied Reactive Protection to Steel Members, CEN, Brussels, 2013.

- [2] S. Hothan, Grundlagen zur Erweiterung des Anwendungsbereiches für reaktive Brandschutzsysteme auf Stahlbauteilen im nationalen Zulassungsverfahren, DIBt Mitt. 42 (2011) 187–189. Berlin, Ernst & Sohn Verlag.
- [3] S. Hothan, Numerische Voruntersuchungen zur Anwendung von reaktiven Brandschutzsystemen auf zugbeanspruchten Stahlbauteilen, Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, 2010.
- [4] V. Stopp, P. Proschek, Reaktive Brandschutzsysteme auf Stahlbauteilen mit reiner Zugbeanspruchung, DIBt Mitt. 42 (2011) 190–191. Berlin, Ernst & Sohn Verlag.
- [5] S. Hothan, D. Häßler, Zur Anwendung reaktiver Brandschutzsysteme auf Stahlzuggliedern. Bauphysik, 6, Ernst & Sohn Verlag, Berlin, 2012, pp. 275–285.
- [6] S. Hothan, D. Häßler, Numerische und versuchstechnische Untersuchung zur Anwendung von reaktiven Brandschutzsystemen auf Zuggliedern aus Stahl. Abschlussbericht, Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, 2015.
- [7] D. Häßler, Verhalten reaktiver Brandschutzsysteme auf kreisförmigen Zuggliedern aus Blank- und Baustahl, Dissertation, Leibniz Universität Hannover, 2016.
- [8] D. Häßler, S. Hothan, Fire tests of reactive fire protection systems applied to steel tension members with solid circular section, 9th Int. Conf. Struct. Fire (2016) 1099–1106. Princeton, USA, 8.-10. June.
- [9] E. Raveglia, Grundlagen der Bemessung von intumeszierenden Brandschutzsystemen im Stahlbau. Dissertation, ETH Zurich, 2008.
- [10] M. Häßler, D. Häßler, S. Hothan, S. Krüger, Fire tests of steel tension rod systems with intumescent coating, J. Struct. Fire Eng. (2019) 1–11. Emerald Publishing Limited.
- [11] D. Häßler, S. Hothan, Mechanische Hochtemperatureigenschaften von Stahlzuggliedern aus kaltverformtem Blankstahl der Festigkeitsklasse S355. Stahlbau, 5, Ernst & Sohn Verlag, Berlin, 2015, pp. 332–340.
- [12] DIN EN ISO 8501-1: Vorbereitung von Stahloberflächen vor dem Auftragen von Beschichtungsmitteln – Visuelle Beurteilung der Oberflächenreinheit. Teil 1: Rostgrade und Oberflächenvorbereitungsgrade von unbeschichteten Stahloberflächen und Stahloberflächen nach ganzflächigem Entfernen vorhandener Beschichtungen, Beuth Verlag, Berlin, 2007.
- [13] ETA-12/0050, European Technical Approval for the Reactive Fire Protection System "HENSOTHERM® 420 KS", Warrington Certification Limited, Warrington, 2013.
- [14] ISO 834-1: Fire-Resistance Tests – Elements of Building Construction – Part 1: General Requirements, International Organisation for Standardization, 1999.
- [15] DIN EN 1363-1, Feuerwiderstandsprüfungen. Teil 1: Allgemeine Anforderungen, Beuth Verlag, Berlin, 2012.
- [16] D. Häßler, S. Hothan, Vom Brandversuch zum Feuerwiderstand: Neues Prüf- und Bewertungsverfahren für filigrane Stahlzugglieder mit reaktivem Brandschutzsystem. Stahlbau, 1, Ernst & Sohn Verlag, Berlin, 2018, pp. 2–9.
- [17] D. Häßler, S. Hothan, Überblick zur Anwendung reaktiver Brandschutzsysteme auf Stahlzuggliedern. Stahlbau, 1, Ernst & Sohn Verlag, Berlin, 2018, pp. 61–66.
- [18] A.A. Na 005-52-02, German Proposal for Determining the Fire Resistance of Steel Tension Bars with Fire Protection Systems Based on Mechanically Loaded Fire Tests, Deutsches Institut für Normung (DIN), 2015.
- [19] Nr AbZ, Z-19.11-2194: Allgemeine bauaufsichtliche Zulassung für das reaktive Brandschutzsystem „HENSOTHERM® 420 KS“ zur Anwendung auf Stahlzuggliedern, Deutsches Institut für Bautechnik, Berlin, 2015.
- [20] Bundesanstalt für Materialforschung und -prüfung (BAM), Development of a European Test Standard for the Determination of the Fire Resistance of Steel Tension Members with Intumescent Fire Protection Coating Based on Loaded Fire Tests (FIRESTEMIC), WIPANO research Project, Berlin, 2020, 2022.
- [21] M. Häßler, D. Häßler, S. Hothan, S. Krüger, Performance of intumescent fire protection coatings on steel tension rod systems, Belfast, UK, 10th Int. Conf. Struct. Fire 6–8 (2018) 649–654. June.
- [22] D. Häßler, M. Häßler, S. Hothan, S. Krüger, Leistungsfähigkeit reaktiver Brandschutzsysteme auf Zugstabssystemen und deren Anschlusskonstruktionen, Stahlbau 11 (2018) 1049–1056. Berlin, Ernst & Sohn Verlag.