Behavior of cellular beams protected with intumescent coatings

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Abstract

A new engineering practice in modern buildings is to use beams with web openings to allow the passage of services within the depth of the beam instead of underneath the beam. As the web post failure may occur before the section reaches the limiting temperature, usually an increase in the fire protection may be required for members with web openings in comparison to its equivalent solid section. The aim of this work is to present an experimental study of unloaded solid and cellular beams with circular holes in fire conditions with and without intumescent fire protection. These preliminary tests results are the basis for generating an elemental multi-temperature analysis needed to assess cellular beams with intumescent protection and give experimental results for calibration of further numerical simulations. The experimental results show that, considering the same nominal fire protection thickness, one can obtain a higher fire resistance time for solid beams when compared with cellular beams. The tests performed, with different hole diameters and web-post widths, points that to achieve the same fire resistance time, a cellular beam will need a higher fire protection compared to an equivalent solid beam. Also, a special care is needed when the intumescent coating is applied around the hole to avoid the intumescent contraction, applying for example an over coating.

Introduction

Cellular beams are widely used in multi-storey buildings, especially to achieve long spans and the same time providing passage for ducts, cables and other technical installations. These beams are steel sections with distributed circular openings that are produced by cutting and welding hot rolled steel sections (Westok method). The split halves are then offset and welded together to form a deeper beam with full circular or hexagonal shaped web openings. A different method, the Fabsec method, consists on cutting circular openings in a steel plate and the cellular beams are fabricated from welding three fabricated steel plates.

A cellular beam is a modern version of the traditional *castellated* beam. A hot rolled steel section is castellated which results in a beam approximately 40-60% deeper than its solid parent section[1] (Figure 1). The finished depth, cell diameter and cell spacing are very flexible. A cellular beam can have a bending resistance up to 2.5 times higher than its parent solid section and so improve the cost efficiency of a design. The cutting process and an application of cellular beams in buildings is illustrated in Figure 2.

For a beam with web openings at a design degree of utilisation, web post failure may occur before the section reaches the critical temperature of members in bending (Figure 3). This is due to the fact that the temperature of the web-post in a cellular beam increases at a faster rate compared to its equivalent (similar web size) solid beam. If the temperature of the web-post increases faster than expected, the cellular beam failure may occur by local buckling instability of the web-post between the openings or the Vierendeel bending at the opening.[2,3] In a fire situation the elastic modulus of steel reduces rapidly in comparison to its strength, which results in more rapid reduction of capacities based on buckling than those based on strength. Hence the buckling capacity of web-posts reduces more rapidly with temperature than those based on other failure types. Therefore web-post buckling tends in general to be the critical mode of failure in fire, even for beams with low web slenderness (d/t) ratios.[4] To avoid this premature collapse, in relation to the behaviour of equivalent solid beams, when a fire protection is used, an increase in the fire protection thickness may be required for members with web openings.

Traditionally the design guidance *Fire Protection for Structural Steel in Buildings* from the Association for Specialist Fire Protection (ASFP), known as the *Yellow Book*, until its 3rd edition,[5] indicates that a 20% increase in thickness of passive fire protection material should be used for members with web openings (the 20% being 20% increase in thickness from that required for the solid section). This 20% rule is for passive fire protection thickness, and has therefore been widely used for intumescent coating thickness (DFT) on cellular beams as their use has increased.

The fire resistance design of cellular beams was controversial in last decade, with most of the debate being concerned with their requirements for intumescent protection. The mentioned empirical prescriptive *rule* was subjected to criticism on the basis of the fire resistance test results on beams coated with intumescent products.[6] In fact, work by the Steel Construction Institute (SCI) showed that there are many other parameters that need to be taken into account when calculating the increase in the thickness required to protect these beams. The SCI issued a temporary guidance (RT 983) that gave some conservative advice until further tests could be carried out. A simplified document AD 269 was issued about the same time giving a more general method of calculating the increased DFTs. The cellular beams parameters used in AD 269 were: the ration of Span/depth, distance between holes and its diameter (S/do), the web-post width, the web hight to thickness ratio and the degree of utilization at cold design.[7]

From the fact that different intumescent coatings behaved differently, a testing procedure was developed to allow coatings manufactures to test their products on a set of specified cellular beams.[8] This methodology required that one loaded cellular beam and four short unloaded cellular beams were tested. From the tests, the temperatures of the web posts and bottom flanges were measured and the ratios of web post

temperature to bottom flange temperature calculated for each web post width. This data allows to draw a regression line of the ratios in function of web post widths and the failure temperature is converted to the required protection thickness using the multi-temperature loading tables defined for different fire resistant times and sections factors of the beam taken as 1400 divided by the web thickness.

After a great effort from the coatings manufactures to produce the DFT tables for cellular beams, and with the used of beams with rectangular and elongated holes, a more general protocol (engineering based) was established valid for rectangular and oval holes. This does not require the loaded beam to be tested and the major difference is that the web post temperatures are compared to the temperature of a plain web, instead of the bottom flange.[9] This assessment procedure was also on the basis for the establishment of the European standard prEN13381-9.[10]

temperatures depends on type and thickness of the intumescent fire protection.

It is recognised that the intumescent fire protection thickness required to provide a given fire resistance to a cellular beam depends on its web thickness, the hole shape and dimensions, the width of the web post, the degree of the beam asymmetry and the structural utilisation factor, as well as the protection efficiency of the intumescent coating.[8]

The assessment method of cellular beams protected with intumescent coatings needs a multi-temperature analysis (MTA) of the coating assessment on solid beams, for each fire protection period, performed accordingly to EN 13381-8.[13] The solid beam assessment provide a DFT baseline against which a suitable enhancement for cellular beams is added. Each fire test is carried out using five cellular beam sections, which enables a range of web post

widths and section factors to be evaluated, instrumented with thermocouples around the holes, web post and bottom flange, as standardized in prEN 13381-9.[10] The sections must be fabricated with welded plates to ensure a constant thickness, and a different set of standard cellular sections are specified for 60, 90 and 120 minutes fire resistance assessment.

This MTA shall be carried out on the web and bottom flange separately generating an elemental multi-temperature analysis (EMTA). The assessment procedure is used to establish: i) The thermal performance based on testing unloaded steel sections; ii) the temperature ratio between the web post and the web reference temperature; and iii) the EMTA from EN 13381-8 shall be reassessed and reported against elemental A/V for each fire resistance period (Figure 3).
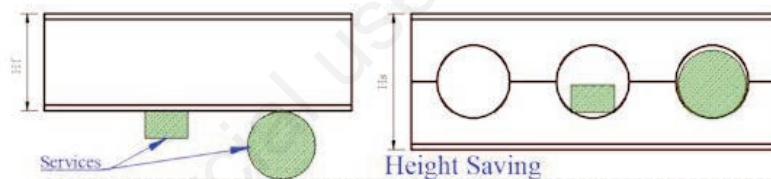
Materials and Methods

Assessment of cellular beams protected with intumescent coatings

The questions raised about the temperature of the web post being higher than a similar solid beam motivated the need of further experimental fire tests. These were mainly conducted by the coatings manufactures due to their necessity to supply their own loading tables, and its results were kept confidential.

The published work of Bailey about experimental fire resistance tests of unloaded solid and cellular beams showed that on beams without fire protection the flange and web post temperatures of the cellular beams were slightly lower than the corresponding temperatures of the solid beams.[11] The author justifies that this behaviour can be due to the influence of the flow of hot gases in the furnace.

Also the same author performs a set of fire resistance tests on unloaded solid and cellular beams, with circular holes, protected with intumescent paint. The results comparison shows that, in all the tests, the temperatures in the web post and flange temperatures were higher in the cellular beam than the corresponding temperatures of the equivalent solid beams. The author justifies this difference due to intumescence shrinkage around the circular hole perimeter, but he also refers the lack of protection within the holes, consistent with a deficient coating.[12] The results show that the difference between the web post and bottom flange

Figure 1. Ceiling height saving from ceiling-beam installation.

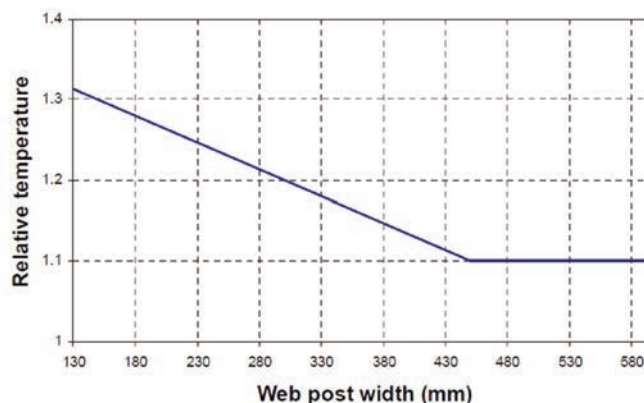**Figure 2. The cutting process of cellular beams.**

Figure 3. Plot of the relative temperature (°C) in function of the web post width.

Test program

The set of experimental tests performed at the Polytechnic Institute of Bragança to evaluate the behaviour of solid and cellular beams with and without fire protection is the presented in Table 1. The table shows the set of performed experimental tests considering solid beams with and without intumescent protection and also cellular beams with and without intumescent fire protection. Figure 4 shows different steps of the coating application process. The aim was to consider for all tested beams the same nominal intumescent DFT, equal to 1000 μm, but as can be seen in the table the coating of the test P4 has resulted in a little higher DFT. A water based intumescent coating supplied by International Coatings was used. Also were studied different combinations of the hole diameter and web post widths. All the sections are made from hot rolled IPE220 steel profiles with 600 mm length and in case of the cellular sections the circular holes cut directly from the web, resulting in a section with the same height, as represented in the Figure 5.

Experimental setup and element instrumentation

The fire resistance tests were performed on a fire furnace with interior dimensions of $1 \times 1 \times 1$ m^3, insulated with refractory bricks and ceramic fibber. It is a gas furnace with four gas burners in which the temperature evolution follows the specifications of the standard EN1363-1[14] and is controlled by a plate thermocouple.

For the analysis of the steel temperature evolution several thermocouples type K were used as recommended by the standard prEN13381-9,[10] positioned and numbered as shown in Figure 5. Two types of type K thermocouples were used. For the case of unprotected beams the thermocouples wires were welded to the steel surface, but for the sections with fire protection, the thermocouples were installed after coating the steel member and mineral insulated thermocouples with Inconel sheath were used by means of a drilled hole of 1.5 mm. By this procedure it was wanted to minimize the influence of the thermocouple wires on the coating expansion and therefore on the fire protection efficiency.

The protected and unprotected sections (3) were placed with the top flange fixed to the furnace roof (1) and with a ceramic mat layer of 50 (mm) in-between (2), simulating in all the cases a fire exposure by three sides (4). Also the beams ends were also insulated by an equivalent ceramic mat to avoid the heat transfer from the ends, as can be seen in Figures 6 and 7, for unprotected and protected beams, respectively.

Figure 4. Application of the primer and intumescent coating to the profiles.
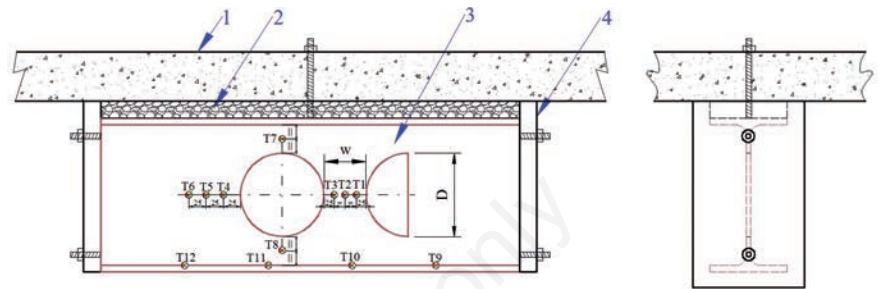
Figure 5. Test setup, position and numbering of the thermocouples.

Figure 6. Tests P12 and P15 before (left) and after (right) the test.

Table 1. Geometries and properties of the tested beams.

Reference	Beam type	DFT (μm)	Hole diameter (mm)	Web post (mm)	W/D
P1	Solid	-	-	-	-
P3	Solid	1047.3	-	-	-
P4	Solid	1187.5	-	-	-
P5	Cellular	-	120	60	0.5
P9	Cellular	-	120	75	0.625
P12	Cellular	-	160	80	0.5
P13	Cellular	993.7	160	80	0.5
P15	Cellular	-	160	100	0.625
P16	Cellular	943	160	100	0.625

DFT, Dry Film Thickness; W/D, web post width/hole diameter.

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Results and Discussion

The steel temperature evolution of the tests was measured by the attached thermocouples. The flange temperature is determined by the thermocouples T9 to T12 and the web post temperatures by the thermocouples T1, T2 and T3. The data obtained from T7 and T8 can be used to verify the non-uniform temperature distribution across the section due to the three-side fire exposure. During the test some of the thermocouple temperatures presented some unrealistic fluctuations, possibly due to an intermittent contact to steel and as a consequence were disregarded from the following graphs and analysis.

The temperature results from the unprotected solid and cellular beams are presented in Figure 8.

Considering for comparison the results of the tests P1 and P9, a solid and a cellular beam tested simultaneously, one can compare the evolution of the mean temperature of the web post temperature (WT), from T1 to T3, and the mean flange temperature (FT), from T9 to T12, presented in Figure 9. In both elements, the temperature of the cel-

lular beams in smaller than its equivalent solid beam. The web post average temperature after a fire exposure of 15 and 30 min is equal to 655.5 and 812.3ºC for the solid beam P1, and equal to 640.2 and 799.4ºC in the case of the cellular beam P9, respectively. The average temperature in the flanges for the same fire exposure periods are 650.7 and 811.7ºC for the solid beam P1, and 638.3 and 801.3ºC in the cellular beam P9, respectively.

For the case of solid (P3 and P4) and cellular beams (P13 and P16) tested with

intumescent fire protection, the temperature evolution is presented in Figure 10. The curves present a higher non-uniformity of the temperature in the elements, when compared to the unprotected beams.

A comparison is presented in Table 1 for all tested beams, regarding the fire exposure time, in completed minutes, to reach a reference temperature of 550ºC, and the beam temperature for 30 minutes of fire exposure. Considering the global mean temperature of the beams, the time to reach a temperature of 550ºC is 36 and 49 minutes for the solid

Figure 7. Tests P4 and P3 before (left) and after (right) the test.
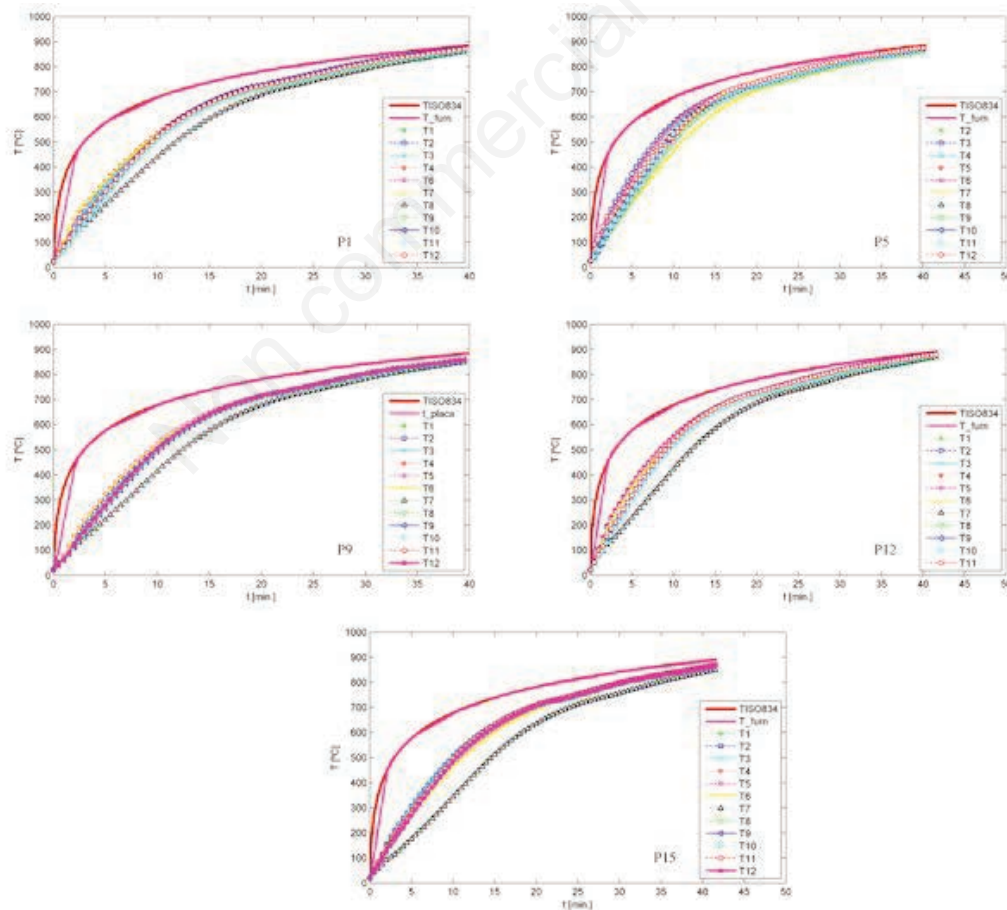

Figure 8. Temperature evolution results of unprotected solid and cellular beams.

beams P3 and P4, respectively, but for the cellular beams P13 and P16 the time decreases significantly to 28 minutes in both beams.

The intumescent coating expansion of the cellular beams P13 and P16, protected with a DFT of intumescent coating close to 1000 μm, measured at the web post and after the test end was equal to 30 mm. The expansion measured at the web of the solid beams P3 and P4, with a DFT equal to 1047 μm and 1187 μm, respectively, was significantly higher, resulting in 85 and 75 mm, respectively. The carbonaceous char layer thickness of these beams can be seen in Figure 11, verifying generally a smaller expansion in the case of cellular beams, a decrease of this expansion close to the beam edge and also around the hole edge. Also, due the intumescent char contraction around the hole of the beam P16 one can verify a small area of steel without fire protection, leading to a faster steel temperature increase. This behaviour suggests that, to achieve the same fire protection level as for equivalent solid beams, a higher intumescent DFT is needed.

Conclusions

This work presents the results of a set of experimental tests on protected and unprotected solid and cellular beams subjected to a fire exposure on three sides. The parametric analysis allows comparing the performance of an intumescent coating as a fire protection material using beams with and without intumescent protection. Additionally, it is also studied the effect of intumescent thickness, the hole diameter and the web post width in the case of cellular beams.

The experimental tests are carried out with reference to the standards EN13381-8 for solid beams protected with intumescent paint and prEN13381-9 for the analysis of cellular beams protected with intumescent paint. The experimental temperature results show intumescent coating efficiency when applied to solid beams and also for cellular beams, resulting from its application an increase fire the resistance time in both cases. Considering for example the time required for the steel to reach 550ºC, with the application of a nominal thickness of 1000 μm, an increase of the fire resistance time of 25 minutes is achieved for solid beams, while for cellular beams with a hole diameter of 160 mm the increase is equal to 17 minutes.

Tests performed in cellular beams with web posts of 80 and 100 mm does not show any significate temperature difference neither in relation to the fire resistance time. For both beams, when is applied a nominal
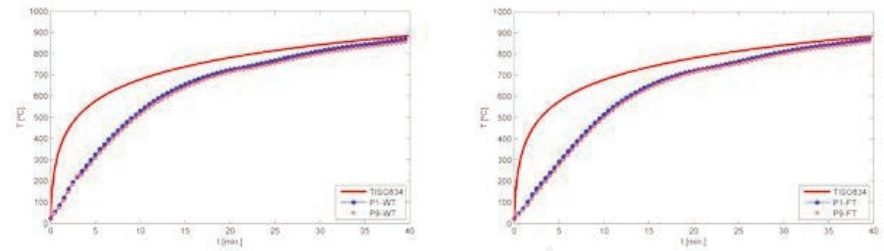

Figure 9. Evolution of the mean temperature registered on the web post and flanges of test P1 and P9.
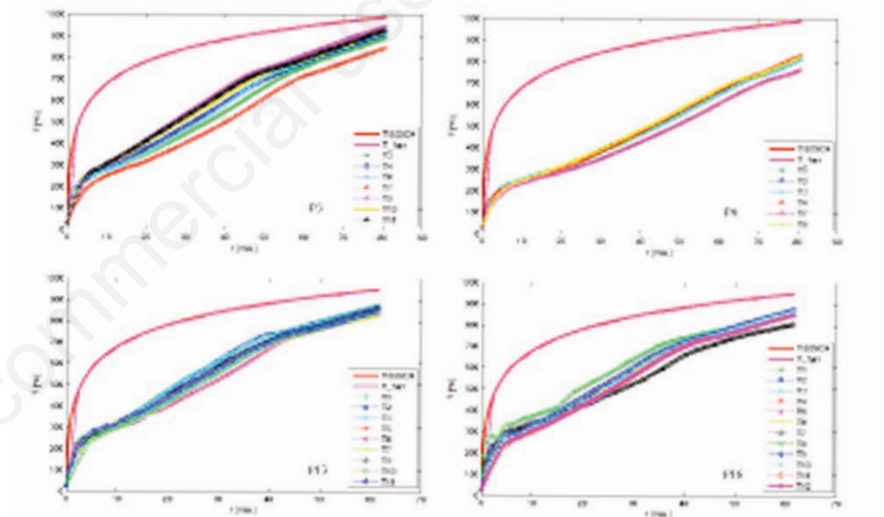

Figure 10. Temperature evolution results of intumescent protected solid and cellular beams.

Figure 11. Intumescent coating expansion of test P4 (left), P13 (middle) and P16 (right) after test.

DFT equal to 1000 μm, the temperature of 550ºC is achieved after 28 minutes. For longer fire exposure periods a slight difference can be already verified.

The intumescent char expansion shows a localized effect, a known edge or board effect that limits the char expansion in the case of tested cellular beams. Also, specifically in beam P16, a small contraction of the intumescent char around the circular hole was occur, leaving a small area of steel directly exposed to fire. These two behaviours lead to a need of higher DFTs values for cellular beams in comparison to equivalent beams to achieve the same fire protection.

This study is being extended to a wider parametric analysis considering different cellular beams geometries and intumescent coatings thicknesses to allow for a general elemental multi-temperature analysis (EMTA).

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