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RECENT DEVELOPMENTS AND INTEGRATION OF DESIGN CODES FOR STEEL-CONCRETE COMPOSITE STRUCTURES IN FIRE

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Abstract. *This paper presents a review on the latest advances in the field of steel-concrete composite structures exposed to fire, studying the recent research in the area and developments of the design codes. The paper focuses in particular on concrete-filled steel tubular columns and slim-floor beams, topics where the authors have carried out extensive research during the last years. The more recent experimental and numerical studies are presented, as well as the currently available design methods for the calculation of isolated members in the fire situation. The use of advanced materials, such as high strength steel and concrete, stainless steel, lightweight concrete or geopolymer concrete is considered for the enhancement of the fire behaviour of concrete-filled steel tubular columns and slim-floor beams.*

1 INTRODUCTION

Steel-concrete composite construction has driven the attention of researchers during the last decades, leading to important developments in this field, what in turn has provided practitioners with new solutions and techniques for taking advantage of the combination of steel and concrete in new buildings.

Amongst the main advantages of composite construction, special mention should be done to their enhanced fire performance, owing to the heat sink effect provided by the concrete, which delays the temperature rise in composite sections as compared with bare steel solutions.

This paper focuses on the fire performance of steel-concrete composite structures, and is divided into two main parts: composite columns and composite beams, both of which have been studied by the authors through numerical models and extensive experimental testing. The recent developments and current trends in the use of composite solutions are reviewed in each part, as well as the current design provisions and available calculation methods. Although different configurations for composite columns and beams exist in the market (i.e. fully encased, partially encased, non-encased, etc.), only certain types of composite solutions will be studied in depth in this paper, those in which the authors have focused their research during the last years, being at the same time one of the most frequently used solutions for composite construction in practice. The first part of the paper is focused in particular on concrete-filled steel tubular (CFST) columns, while the second part of the paper specifically addresses a novel type of composite beams: the so-called slim-floor beam.

It must be mentioned in this point that the behaviour of an isolated member is different to that of the same member within the complete structure, therefore the recommendations given in this paper will be applicable to individual members, while the fire performance of the whole composite system should be evaluated through a global model that accounts for relevant aspects such as the stiffness of the connections, axial and rotational restraints, membrane action, fire exposure conditions, etc.

2 STEEL-CONCRETE COMPOSITE COLUMNS

2.1 Concrete-filled steel tubular columns

The use of concrete-filled steel tubes (CFST) has increased in recent decades, finding an important demand in the construction of high-rise buildings and bridges, owing to their high load-bearing capacity, good aesthetics and the significant fire resistance they can provide. Other applications where this typology can be found are industrial buildings, electricity transmitting poles, subways, open car parks, office or residential blocks [1].

Circular, square, elliptical and rectangular steel tubes are most commonly used to form these composite columns (see Fig. 1), although new shapes are emerging in the market, such as polygonal or round-ended sections. Even though the steel tubes can sometimes be filled with plain concrete, in most cases the concrete infill is reinforced with steel bars or with metal fibres.

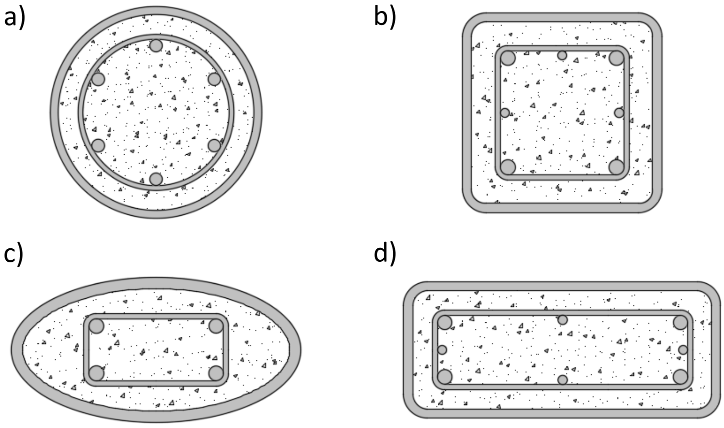

Figure 1: Typical CFST cross-sections: a) circular; b) square; c) elliptical; d) rectangular

These type of composite columns show an excellent structural performance, taking advantage of the combined effect of steel and concrete working together - the steel tube provides confinement to the concrete core, resulting in increased compressive strength, while the concrete core restricts inward deformation of the steel tube thus enhancing local buckling resistance and enabling the use of thinner cross-sections -.

Numerous examples of composite structures with circular or square columns, as external or internal structural members, can be mentioned.

In China, concrete-filled steel tubes have been employed in construction since 50 years ago, being used as the main compression resisting components [2]. Nowadays, CFST columns are being widely used in high-rise buildings, as the Canton Tower in Guangzhou (see Fig. 2a), comprising twenty-four inclined circular CFST members with a maximum diameter of 2000 mm and wall thickness of 50 mm.

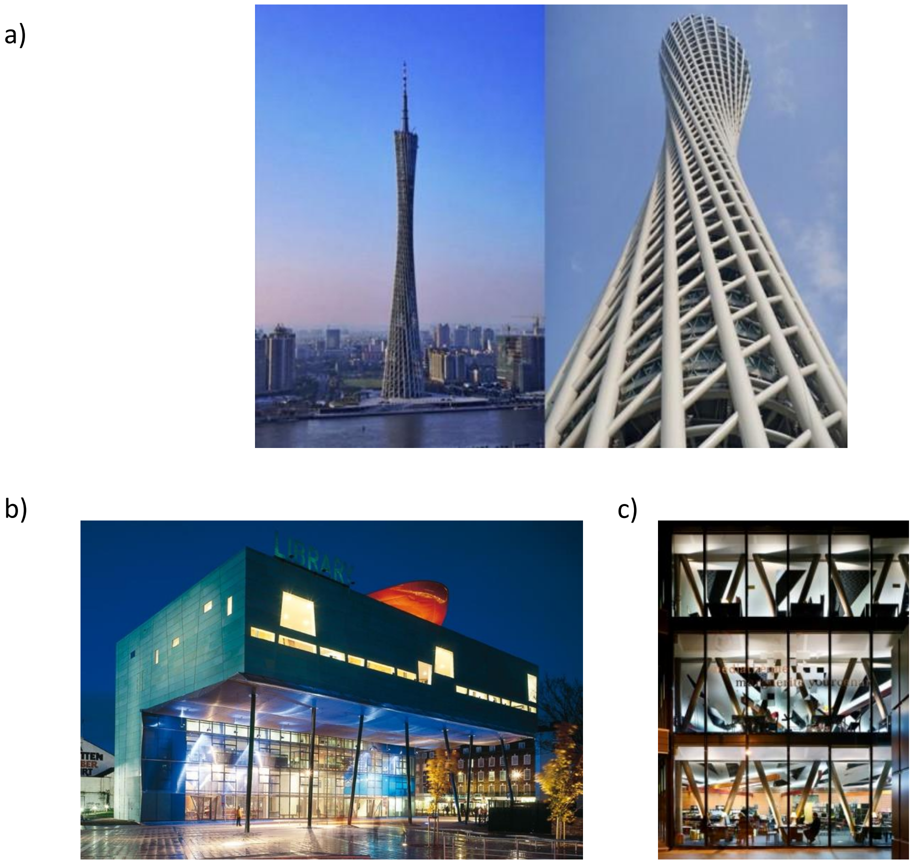

Figure 2: Examples of buildings using CFST columns: a) Canton Tower (Guangzhou, China); b) Peckham library (London, UK); c) Marguerite Yourcenar Media Library (Paris, France) [6]

Further examples can be found in Northern America [3]. In the Museum of Flight at King County Airport (Seattle, Washington, USA) bar-reinforced concrete filled hollow sections are used for the columns supporting the roof of the exhibit hall, allowing to fulfil the required fire resistance without the need of sprayed fire protection. Another application can be found in the St. Thomas Elementary School (Hamilton, Ontario, Canada), where concrete filled CHS columns with different concrete strengths are used, achieving one hour fire resistance rating.

In Australia, the Riverside Office Building can be cited [4], using concrete filled bar-reinforced CHS columns of 600 mm diameter which were required to fulfil a 120-minute fire resistance. The Commonwealth Centre in Melbourne, the Forrest Centre, Exchange Plaza and Westralia Square in Perth are additional examples of such type of construction in Australia.

Several examples can also be mentioned in Europe, mostly in the United Kingdom, such as NEO Bankside, the Fleet Place or the Rochdale bus station [4]. The Peckham Library is another example of such type of construction in London. Seven external circular CFST columns support the building at the front (see Fig. 2b). The inclined 18 m long columns meet the 60-minute fire rating required without any external protection.

In Marguerite Yourcenar Media Library (Fig. 2c), circular CFST columns are utilised, typically 273×10 mm S355 steel tubes, filled with C40 to C50 concrete and 16 mm S500 steel bars. The 3.90 m long inclined columns achieve the 120-minute fire resistance required. The Tecnocent Building (Oulu, Finland) makes use of circular and square bar-reinforced concrete filled hollow section columns [4]. The Mjärdevi Centre in Sweden is a twelve-storey office building with 200 mm diameter circular CFST columns, continuous over 3 storeys. ArcelorMittal Steel Centre in Liege, Belgium is a five-storey office building comprising external unprotected circular columns. In Germany, the City Gate in Düsseldorf is a high-rise building composed of two sixteen-storey towers connected by a 3-storey attic to a portal. Circular CFST columns are used, in combination with concrete partially encased beams (R90).

Concrete-filled steel tubular members have also been applied in many types of bridges [1], such as arch bridges, cable stayed bridges, suspension bridges, and truss bridges. CFST members can serve as piers, bridge towers and arches. An important advantage of using CFST in an arch bridge is that, during the stage of erection, the hollow steel tubes can serve as the formwork for casting the concrete, which significantly reduces the construction cost.

Although the described construction examples give an idea of the good fire performance of CFST columns, in applications which require a high slenderness combined with important bending moments, the magnification of the second order effects question their applicability. A previous RFCS funded project – FRISCC "Fire Resistance of Innovative and Slender Concrete Filled Tubular Composite Columns" – [6], highlighted the limited fire resistance of CFST columns with high slenderness. An extensive experimental programme was carried out within the FRISCC project, consisting of 36 fire tests. The studied parameters were the cross-section shape, sectional dimensions, member slenderness, load eccentricity and reinforcement ratio. An example of one of the columns before and after test can be seen in Fig. 3.

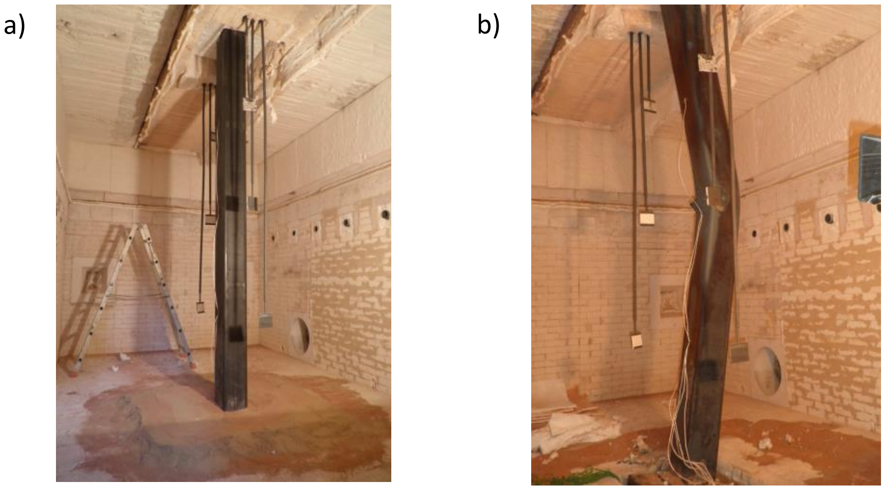

Figure 3: View of a square CSFT column before (a) and after (b) the fire test [6]

The premature failure in slender columns was found to be due to a local behaviour which occurs close to the column ends, an issue which must be solved for optimizing their fire response. Therefore, innovative solutions are needed which help improving the performance of this typology of composite columns in the fire situation.

2.2 Innovative composite columns

Recently, innovative steel-concrete composite solutions have been developed, which can solve the current limitations of slender CFST members when exposed to fire. At the same time, as the construction of high-rise buildings increases worldwide, solutions which allow for higher capacities at room temperature are sought by designers. One of these solutions are the so-called concrete-filled double-skin tubes (Fig. 4a), which have the potential to be used as columns in high-rise buildings, bridge piers or transmission towers [1],[7]. In this tube-in-tube configuration, the inner steel tube is thermally protected by the outer concrete ring and therefore its degradation when exposed to fire is delayed, which may help resisting the applied load for a longer period of time, solving the aforementioned problems of slender CFST columns in the fire situation.

The fire performance of these columns can be enhanced even more by adding concrete inside the inner tube, constituting the so-called double-tube columns (Fig. 4b), where both the inner and outer tube are filled with concrete. Filling the inner steel tube with concrete contributes to increase the load-bearing capacity of the column, while it delays the temperature rise within the column cross-section and therefore lengthens its fire resistance. This solution can be found in practice, being a good example the Queensberry House in London (UK) [4], a six-storey office and commercial building where the columns use a tube-in-tube system in which one CHS section is placed inside a larger one with all the voids grouted after erection of the floor structure. No external fire protection was needed, as the internal composite column had enough load-bearing capacity by itself in the fire limit state.

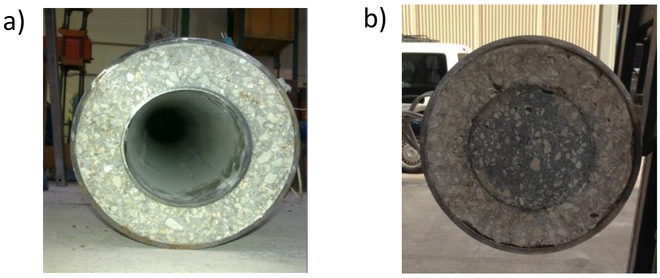

Figure 4: Different types of concrete-filled dual steel tube sections: a) double-skin section; b) double-tube section [8]

An extensive experimental campaign consisting of 30 concrete-filled dual steel tube column tests was carried out by the authors [8], where the effects of two parameters was analysed: strength of concrete (normal strength and ultra-high strength concrete) and the ratio between the thicknesses of the steel tubes. From these tests, six of them were performed under fire conditions.

Normal (C30) and ultra-high strength (C150) concrete were used for filling the columns. The influence of filling the inner tube with concrete (i.e. double-tube section) was studied, as well as the variation of thicknesses of the outer and inner steel tubes. It was found that a good design strategy for CFST columns is to split the outer tube into two different steel tubes (outer + inner) with the same total steel area (and thus same steel usage), placing the thinner tube in the outer part of the section and the thicker tube in the inner part, so as to be thermally protected by the concrete ring (see Fig. 5). Moreover, it is recommended that both rings are filled up with concrete for an enhanced fire performance.

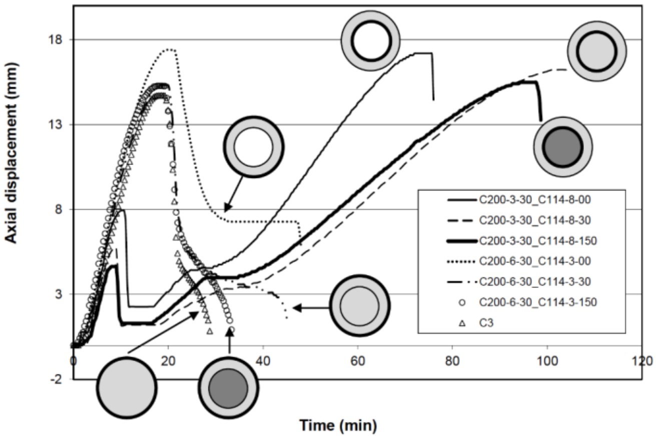

Figure 5: Comparison of test results for different concrete-filled dual steel tube columns tested under fire, against the CFST reference column (C3) [8]

An alternative and innovative solution consists in embedding a steel profile within the concrete-filled steel tubular section. An example of the use of this solution is the Millennium Tower in Wien, Austria (see Fig. 6a). It is a fifty-five storey, 202 m high building, with external and internal CFST columns. These columns are made of outer circular S355 steel tubes with a C40 to C60 concrete infill. In order to increase their load-bearing capacity, the internal columns were provided with embedded H profiles.

Figure 6: Examples of buildings using innovative composite columns: a) Millennium Tower (Wien, Austria), b) Highlight Towers (Munich, Germany) [6]

In the Netherlands, the Amsterdam Mees Lease Building is a four-storey office building using 323 mm CHS columns with a fire resistance rating of 60 minutes in combination with concrete encased HEA beams [4].

Other types of innovative solutions have recently emerged for optimising the cross-section of composite columns. Those columns consist of a hollow steel section, a massive embedded steel core and concrete infill in between. This cross-section type comes along with a significantly increased load bearing capacity compared to other types with identical outer dimensions. In consequence, either higher loads can be applied or columns can be designed with smaller dimensions.

This innovative cross-section has been recently used in projects of high-rise buildings. Two engineering companies in Germany can be cited, which have developed patents using this new type of cross-section: Spannverbund GmbH[1] and Stahl+Verbundbau GmbH[2].

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[1] Geilinger-StützeTM, Spannverbund GmbH (Germany): http://www.spannverbund.global/english/geilinger-stuetzesuptmsup/

[2] "s+v Stuetzensystem" Stahl+verbundbau GmbH (Germany): http://www.stahlverbundbau.de/cms/sundv/index1db8.html?page=leistungen_stuetzensystem

The Highlight Towers in Munich, finished in 2004 (see Fig. 6b), are one example of the use of innovative CFST columns with embedded steel cores, meeting a fire resistance class R120. 750 out of a total number of 1400 columns have a massive steel core encased in concrete with an outer hollow steel profile. The embedded steel cores range from simple circular cross-sections to stepwise welded massive steel plates (see Fig. 6b).

The fire performance of these innovative solutions has been studied through a numerical model by the authors [9]. Fig. 7 compares the fire performance of several innovative steel-concrete composite columns, against a reference CFST column with a fire resistance of 28 minutes (a) tested in a previous experimental campaign. This CFST section of dimensions 273×12.5 mm is chosen as a reference, and it is used to generate other three innovative sections with inner profiles, maintaining the total amount of steel. As it can be seen, the embedded steel core solution (e) lengthens the failure time slightly, up to 36 minutes. In turn, with the embedded HEB solution (d), the fire resistance of the column is increased up to 47 minutes. Finally, if the steel tube is split into two tubes, generating the CFDST column with the ticker tube in the inner part of the section, the fire resistance is significantly improved to 77 minutes (b), provided that the inner tube is infilled with concrete (i.e. double-tube). In the case of not using concrete inside the inner tube (i.e. double-skin), there is still an improvement in terms of fire resistance to 63 minutes (c), although not as significant as that obtained with the double-tube solution.

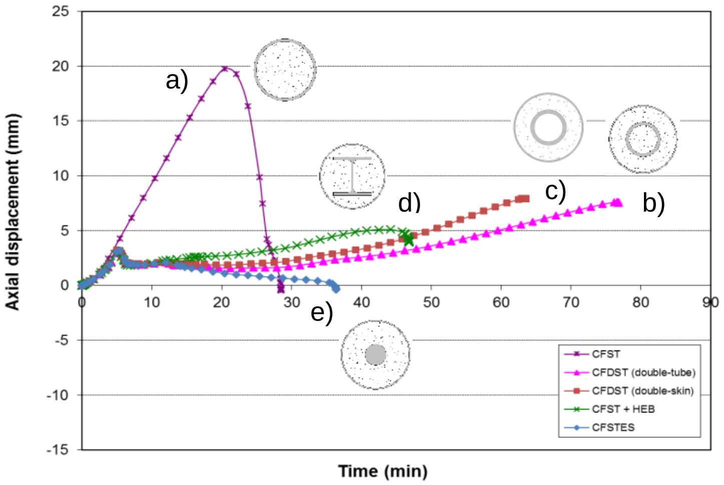


Figure 7: Comparison of the fire response of different innovative composite cross-sections: a) CFST; b) CFDST (double-tube); c) CFDST (double-skin); d) Embedded HEB; e) Embedded steel core [9]

2.3 Advanced materials

The previously exposed advantages of composite structures can be exploited with an efficient use of advanced materials emerging in construction, such as high strength steel (HSS), stainless steel (SS), high strength concrete (HSC) or geopolymer concrete (GC). These materials may enhance the fire performance of composite steel-concrete solutions, depending on the part of the section where the advanced material is applied. Moreover, a more rational and efficient use of the material may lead to important savings, as a higher load-bearing capacity allows for section reduction. Also the combined use of “green concrete”, such as the geopolymer concrete, may decrease the carbon footprint.

In structural steelwork, high strength steels enable less material to be used, which reduces the costs associated with construction, transport and assembly. However, regarding their behavior at elevated temperature, little information exists in the literature and the building codes do not include design recommendations for this type of steels in the fire situation. EN1993-1-12, related to HSS up to S700 grade does not provide any additional information on the fire design of such steel grades, and practitioners are referred to EN1993-1-2, valid up to S460 grade. Very limited research has been done to date on the fire behaviour of HSS. Amongst the existing work, results from Lange and Wohlfeil [10], Schneider and Lange [11] and Outinen [12] on HSS S460, or Chen and Young [13] and Chiew et al. [14] for HSS S690 can be found. Recently, Qiang et al. [15], investigated the properties at elevated temperatures of HSS S460, S690 and S960, proposing reduction coefficients of the mechanical properties of these steels at elevated temperature based on experimental results. Other recent investigations by Choi et al. [16] have focused on the thermal and mechanical properties of HSS at elevated temperatures.

The presented advantages of high strength steels opens a new range of possibilities regarding their application in CFST columns, where they can improve the problem of the limited fire resistance of slender members. In fact, Tondini et al. [17] presented recently the results of a fire test on a CFST column using HSS, where the superior performance of composite columns made of HSS was proved.

Taking advantage of the improved properties of HSS and using the appropriate steel share between the outer tubes and inner profiles, it may be possible to obtain an elevated fire resistance without the need for external protection, which will lead to subsequent cost and time savings.

Previous investigations performed by Espinós et al. [9] confirmed that a good strategy for enhancing the fire resistance of these composite columns is to improve the steel grade of the inner profile without reducing the total steel area (see Fig. 8). The use of inner steel profiles made of HSS offers an alternative to applying intumescent coatings, with better external appearance, zero maintenance, same steel usage and thus similar cost.

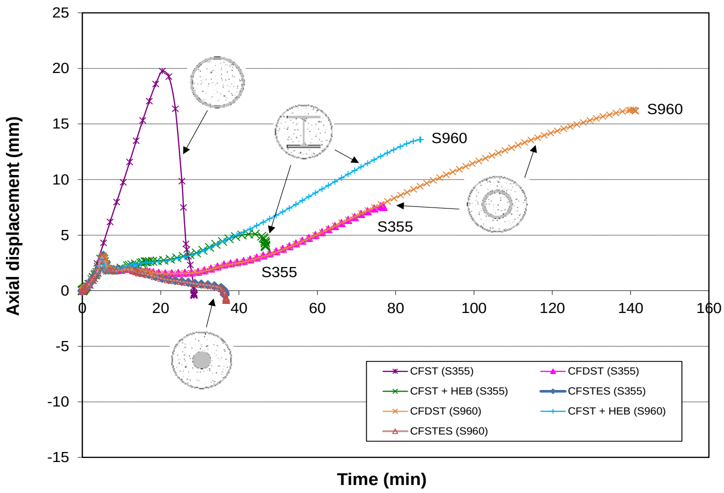


Figure 8: Comparison of the fire behaviour of composite columns with innovative sections, using different steel grades at the inner profiles: S355 vs S960 [9]

Singular buildings of recent construction have used HSS, such as the “Freedom Tower” in New York (USA), the Olympic Stadium “Bird’s Nest” in Beijing (China) or the Millau viaduct (France). In Japan, a new building in Kiyose City uses CFST columns combining 700 MPa HSS with ultra-high strength concrete. The design guide from Liew and Xiong [18] includes a list of buildings using HSS in combination with HSC.

Other material whose potential can be used in the fire situation is stainless steel (SS) [19]. The reduction in strength and stiffness at elevated temperature is slower than for carbon steels [20], thus stainless steel can be exposed to higher temperatures without significantly altering its properties. Authors such as Tao et al. [21] and Han LH et al. [22] performed experimental tests on CFST columns with hollow steel tubes made of stainless steel, where their fire resistance was found to be much higher than those columns with carbon steel. A recent publication by Han et al. [23] reviewed the latest research on the topic and highlighted the benefits of the use of stainless steel in CFST columns.

Apart from taking advantage of advanced materials at the outer tubes or inner profiles, the fire resistance enhancement of composite columns can be achieved by a better performance of the concrete. High-strength concrete (HSC) may be used as infill in conventional CFST columns, as well as in double-skin or double-tube columns. Previous research by the authors on double-tube columns using ultra-high strength concrete (UHSC) up to 150 MPa [8] revealed that HSC results beneficial at elevated temperatures when placed at the outer ring of the double-tube column, however filling the inner tube of high concrete grades does not provide a significant enhancement in fire resistance.

The use of other types of novel concretes, such as geopolymer concrete has also been considered in recent research. This type of concrete is an aluminosilicate binder with reduced associated CO_2 emissions and energy requirements, being a sustainable alternative to Portland cement concrete [24]. Regarding its fire resistance, geopolymer concrete presents a lower thermal conductivity and higher strength retention at elevated temperature than conventional concrete [25], thus resulting attractive for fire requirements. A previous investigation by the authors highlighted the potential of such type of concrete for increasing the fire resistance of innovative composite columns [26].

2.4 Design guidance and development of new calculation methods

There are a number of design codes and specifications worldwide that address the design of concrete-filled steel tubular members subjected to fire.

The Chinese Code DBJ13-51 [27] establishes an equation to calculate the thickness of the external fire protection required to achieve a certain fire resistance time and is based on a research carried out by Han et al. [28].

Another approach, which is in use in North America, was developed by Kodur and co-workers [3] and has been incorporated into the National Building Code of Canada [29], ASCE/SFPE 29-99 [30] and ACI 216 [31]. This approach consists of a single design equation, which includes the main parameters affecting the fire resistance of CFT columns.

In Europe, the most extended methods for calculating the fire resistance of CFST columns are those included in EN 1994-1-2 [32], comprising three levels of design: a) tabulated data, b) simple calculation models and c) advanced calculation models. Option a) is available in Clause 4.2.3.4 in the form of a selection table which provides the minimum cross-sectional dimensions and reinforcement ratio that a CFST column must have in order to achieve a rated standard fire resistance time under a certain load level. This approach is the most simplistic and its results are highly conservative.

A specific method for unprotected CFST columns is also given in Annex H of the same code. However, this method was found unsafe for slender columns [33] - which is a frequent situation for columns in car-parks, high-rise, commercial or industrial buildings -, leading to the approval of an amendment by the European Committee CEN/TC250/SC4 which limits the relative slenderness at ambient temperature to 0.5 in the application of Annex H. In the previously referred research project FRISCC [6], funded by the Research Fund for Coal and Steel (RFCS) of the European Union, an extensive experimental and numerical database was generated for stablishing the basis for the development of a new simplified design method [34] that solves the shortcomings of the current Annex H of EN 1994-1-2. The new method includes innovative shapes such as elliptical hollow sections and provides safe predictions for columns with relative slenderness at ambient temperature up to 2. It is also valid for large eccentricities, extending the current scope of Annex H.

A key contribution of the new simplified calculation method is to assume that the effects of non-uniform temperature in the CFST cross-section can be represented by an equivalent uniform temperature for each of the different components (steel tube, concrete infill, reinforcement) of the CFST cross-section (see Fig. 9). Simplified equations were developed for providing practitioners with equivalent temperatures that can be used for evaluating the capacity of the columns in fire without the need of performing advanced heat transfer calculations.

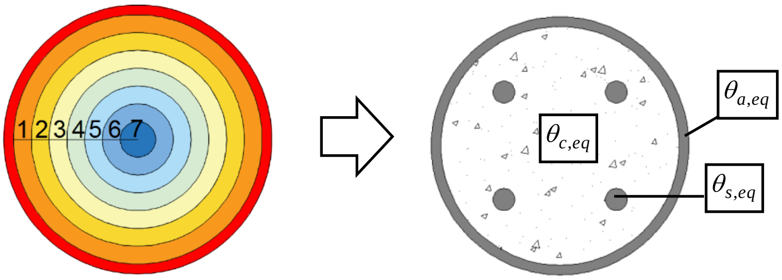


Figure 9: Definition of equivalent temperatures within a CFTS cross-section

The new simplified calculation method for CFST columns has been recently revised and extended by a specific Project Team SC4.T4 appointed by the European Committee of Standardization (CEN) to redefine the current Annex H and, after the recent approval of the final draft, it will be available in the next generation of the Eurocodes. Additionally, the simple calculation method has been further extended for its application to different bending moment distributions [35], ranging from single curvature to double curve bending. The proposed new design method is applicable to concentric load and uniaxial bending and is in line with the cold design method in EN1994-1-1 [36], making use of interaction diagrams for elevated temperature, as in the example given in Fig. 10. Extension of the simplified design method for biaxial bending moment is currently underway.

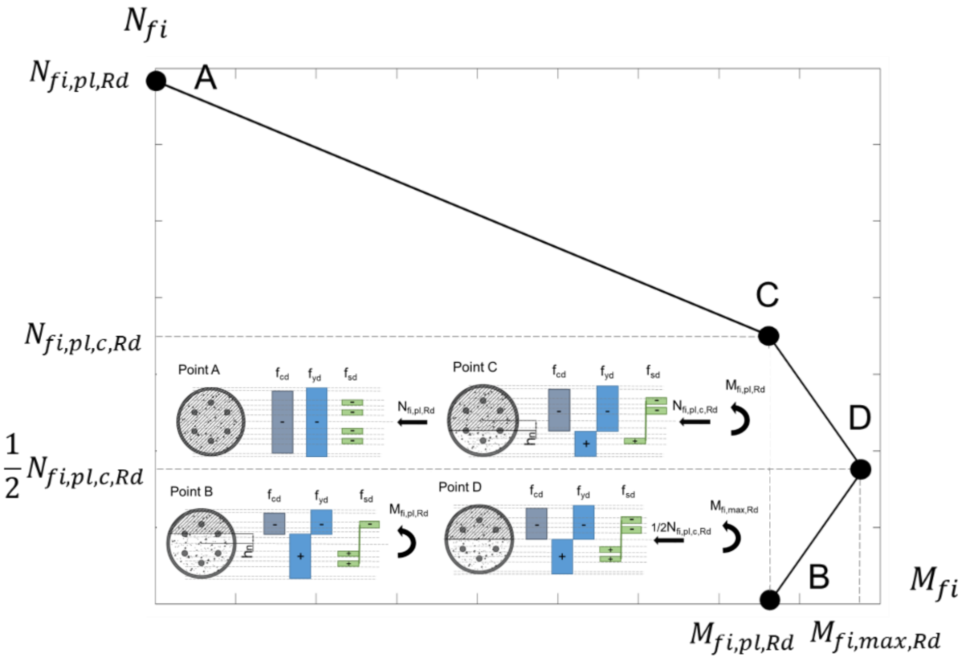


Figure 10: Example of an interaction diagram for the calculation of eccentrically loaded CFST columns at elevated temperature

3 STEEL-CONCRETE COMPOSITE BEAMS

3.1 Slim-floor beams

Traditionally, steel-concrete composite beams have been built up by connecting composite, precast or in-situ concrete slabs on top of a solid steel beam (i.e. non-encased composite beam) or with a partially encased configuration where the beam downstands under the floor. A novel type of composite steel-concrete beams fully embedded in floors (slim-floors) have emerged in the market, in which the floor slabs are incorporated within the depth of the steel beams. The special arrangement of these types of beams makes it possible to place the slab elements directly onto the lower flange of the beam, resulting in an integrated and shallow solution. This configuration offers important advantages such as the floor thickness reduction, the increase of the working space and the ease for under-floor technical equipment installation. Because of these advantages, slim-floor beams are increasingly used in industrial and commercial buildings.

Slim-floor beams can be used in combination with different flooring systems, such as in-situ concrete slabs, profiled steel decks or precast concrete slabs (Fig. 11). This last option provides additional benefits, such as its fast erection and structural efficiency for long spans. Moreover, the slab configuration itself changes the incidence of the thermal action to the composite beam, i.e. the hot air between the ribs in a profiled steel deck facilitates the advance of temperatures in the beam section as compared to a floor configuration with concrete slabs.

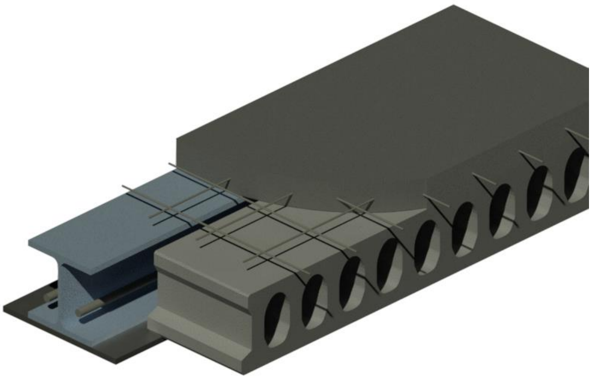


Figure 11: Slim-floor beam with hollow core slabs. 3D general view [42]

Two main types of slim-floor beams can be distinguished: Integrated Floor Beam (IFB, Fig. 12a) and Shallow Floor Beam (SFB, Fig. 12b). The former is made of a half I-section where a wider bottom plate is welded to the bottom of the web in replacement of the lower flange. The latter consists of a full I-section with a bottom plate attached and welded to its lower flange. A suitable fire behaviour of these beams is expected, since the steel beam is totally embedded in the concrete floor and thus it results only exposed to fire from its lower flange. Additionally, the SFB configuration presents the advantage in fire of a thermal gap that appears at the interface between the steel profile lower flange and the bottom plate, which delays the temperature rise of the section, as observed experimentally by Newman [37]. Fellinger and Twilt [38] suggested that this air gap should be ensured in manufacturing the SFB specimens in order to increase the slim-floor fire resistance in practice.

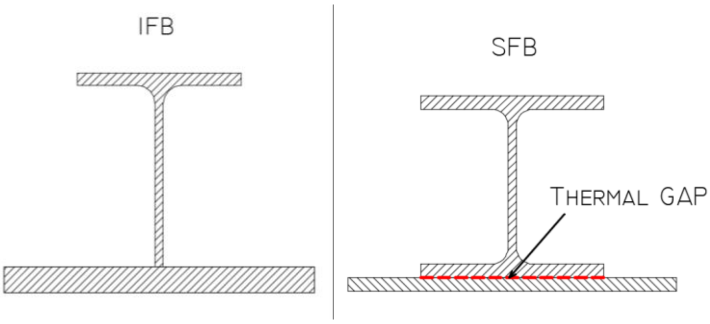


Figure 12: Types of slim-floor beams: a) IFB, b) SFB

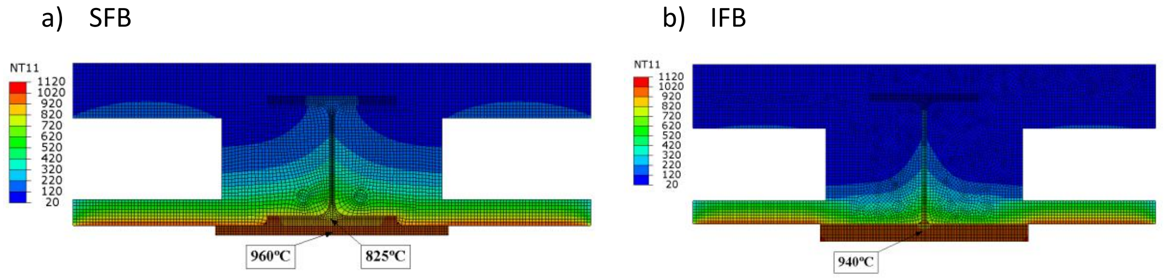
The flexural behaviour of slim-floor beams exposed to fire has been studied through experimental testing over the last decades, although not many fire test results are available to date. Two standard fire tests were conducted by the Warrington Fire Research Center [39] with a SLIMDECK system using an IFB configuration. Significant fire resistance times of 75 and 107 minutes were achieved, for load ratios of 0.43 and 0.36, respectively. Fire tests were also reported by Ma and Mäkeläinen [40] using an IFB configuration under different load ratios. It was observed that fire resistance periods over 60 minutes could be reached for load ratios under 0.5 without additional fire protection.

Given the lack of experimental results on SFB configuration, recent elevated temperature tests have been carried out in the testing facilities of ICITECH (Concrete Science and Technology Institute) at UPV Valencia, Spain [41], as part of a wider experimental campaign currently underway. In this experimental program, an electrical radiative furnace was used, shown in Fig. 13. The main objective of this experimental campaign was to obtain a better understanding of the thermal behaviour of slim-floor beams and investigate the influence of different parameters over their fire performance. The fire performance of equivalent IFB and SFB sections was compared. For the SFB configuration, a HEB200 beam welded to a steel plate of dimensions 360x15 mm was used, while for the IFB configuration ½ IPE450 was welded to a steel plate of 360x30 mm. In this way, the thickness of the bottom steel plate of the IFB profile was equal to the sum of the bottom plate plus lower flange thickness of the SFB. These tests provided evidences about the different thermal behaviour between SFB and IFB due to the thermal contact resistance in the gap between bottom plate and lower flange.

Figure 13: Experimental setup for elevated temperature slim-floor tests at UPV, Valencia (Spain) [42]

Previous parametric studies carried out by the authors [42] by means of a finite element model confirmed that the fire resistance of composite beams embedded in floors can be significantly enhanced by splitting the lower steel flange of an IFB section into two steel plates, generating the so-called SFB type. The thermal gap between the lower flange and the bottom plate delays the temperature rise and therefore lengthens the fire response of the beam for the same load level, as compared to the IFB configuration.

Fig. 14 shows the temperature field of two equivalent SFB and IFB configurations exposed to standard ISO834 [43] fire curve for 120 min. It can be observed that, while the IFB bottom plate reaches 940 ºC after 120 minutes of fire exposure, the lower flange of the SFB steel profile remains at a lower temperature of 825 ºC, what proves the significant influence of the thermal gap.


a) SFB

b) IFB

Figure 14: Comparison of the temperature field of SFB and IFB configurations after 120 minutes fire exposure [41]

Fig. 15 shows the temperature evolution along the fire exposure time of the IFB bottom steel plate and the SFB lower flange. It can be observed that due to the thermal gap in SFB, the temperature difference is maintained around 100-120ºC, showing however a moderate decrease at high fire exposure times caused by thermal inertia.

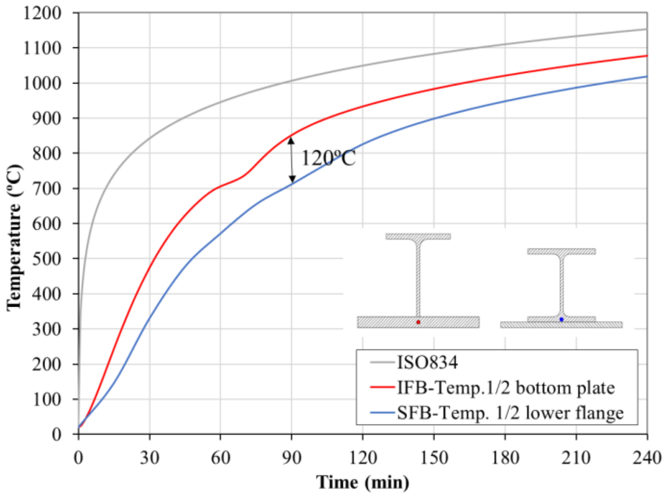


Figure 15: Comparison of the temperature evolution at the bottom steel plate (IFB) - lower flange (SFB) [41]

3.2 Advanced materials

The beneficial properties at elevated temperatures of the advanced materials previously exposed in Section 2.4 can be also used for enhancing the fire performance of slim-floor beams. Previous research by the authors [44] has shown that the use of high strength steel is favourable under fire loading, provided that it is placed in the steel profile rather than in the bottom plate. Its usage in this position does not provide a significant increase of the bending capacity, as it results directly exposed to fire and thus its strength is rapidly affected by high temperatures.

As can be seen in the example of Fig. 16, using HSS of grade S960 increases the bending moment resistance for fire exposure times lower than 30 minutes, regardless the position of HSS - bottom plate or inner profile -. Nevertheless, placing HSS in the bottom plate does not result effective for fire exposure times higher than 60 minutes. In turn, placing HSS in the inner profile maintains the bending moment improvement for higher fire exposure times.

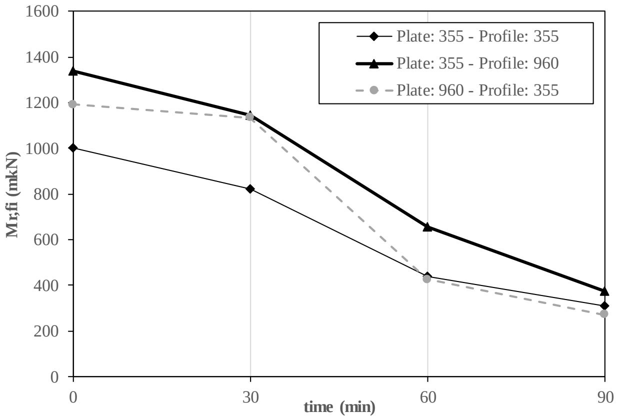


Figure 16: Influence of HSS in over the bending moment resistance of SFB during fire exposure [44]

The use of lightweight concrete in the slim-floor encasement has been also assessed in previous investigations [42], [44] concluding that, for this typology of composite beam, the advantage provided by this type of concrete depends on the degree of reinforcement. The lower thermal conductivity of lightweight concrete and its consequent delay of the temperature rise in the concrete mass causes a localized temperature increase in the bottom steel plate and thus a reduction of its contribution to the bending moment capacity. In turn, lightweight concrete provides an additional heat insulation for the reinforcing bars and therefore increases their mechanical contribution in fire. Thus, in shallow floor beams configurations where the amount of reinforcement is significant, this additional protection offered by lightweight concrete may counteract the unfavourable effect of the reduction of strength of the bottom plate and help increasing the total bending capacity of the cross-section in fire.

As commented before in Section 2.3, the performance of stainless steel under fire conditions has been assessed through extensive research over the last years [20], showing a better strength retention at elevated temperatures and a lower emissivity, which may delay the cross-section heating. Being aware of this potential, experimental [44] and numerical [46] investigations have been carried out for testing the fire performance of slim-floor beams using stainless steel, proving that the use of this material offers a considerable increase in fire resistance as compared to traditional composite beams made of carbon steel. In particular, it results convenient to locate the stainless steel part in the bottom plate of slim-floor beams, in order to take advantage of its enhanced mechanical properties in fire. Apart from a better fire performance, the use of stainless steel in slim-floor beams may also provide an improved durability and aesthetic finishing. Further experiments are currently underway in the authors' research group for confirming this beneficial effect.

3.3 Code provisions and design recommendations

While simplified models are available for partially encased and non-encased composite beams in EN 1994-1-2 [32] Annex F and Clause 4.3.4.2.2, respectively, this standard does not provide any simplified model to evaluate the fire behaviour of slim-floor beams. Project Team SC4.T5 has been appointed by the European Committee for Standardization (CEN) for the development of design rules for shallow floor beams in fire and their integration into the next generation of the Eurocodes, work which is currently underway.

In the absence of any specific method for assessing the temperature development in slim-floor beams exposed to fire, different proposals have been developed during the last years in order to provide models that allow predicting the temperature field in slim-floor composite beams.

Zaharia and Franssen [47] developed simple equations for the calculation of temperatures within the cross-section of an IFB, providing formulas for the assessment of the temperature at the bottom plate, web of the steel profile and reinforcing bars. Cajot et al. [48] defined a set of formulas to determine the thermal field in slim-floor beams based on the existing equations in EN 1994-1-2, with particular assumptions for IFB and SFB configurations. Romero et al. [49] compared the previous simplified models and defined a methodology for the evaluation of temperatures based on the existing formulas in EN 1994-1-2 for the different parts of the slim-floor cross-section combined with the use of the Zaharia and Franssen equations for the prediction of the lower flange temperature. More recently, Hanus et al. [50] proposed specific analytical equations to predict the temperature of longitudinal reinforcing bars embedded in slim-floors.

Based on the previous investigations, a simplified approach for the evaluation of the plastic bending moment of a slim-floor beam after a certain period of fire exposure can be given, consisting of the subdivision of its cross-section into different zones with representing temperatures. In particular, 7 zones can be defined, as indicated in Fig. 17. Zone 1 considers the lower flange of the steel profile plus a portion of the bottom steel plate with the same width. In turn, zone 2 comprises the outermost areas of the bottom plate. In turn, the web of the steel profile is divided into two parts: zone 3, with temperatures over 400ºC and zone 4, below 400ºC. Zone 5 corresponds to the upper flange of the steel profile, while zone 6 is the top concrete compression area and zone 7 includes the longitudinal reinforcing bars.

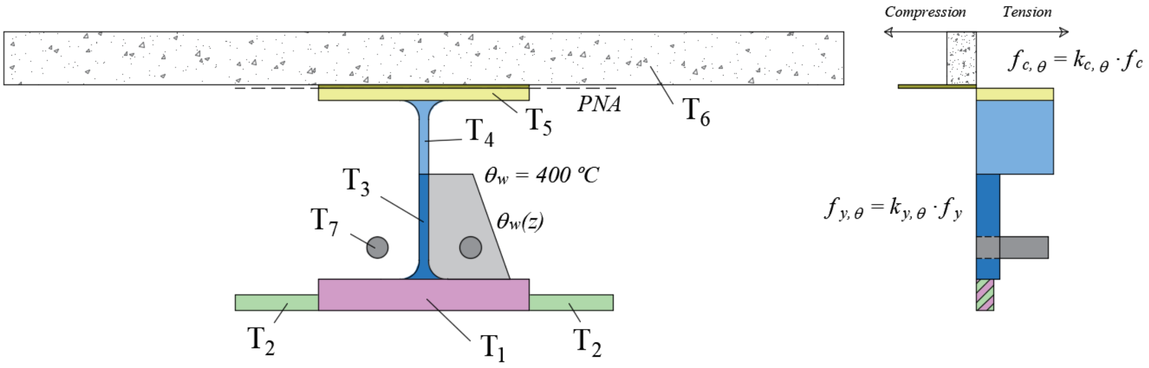


Figure 17: Subdivision of a SFB cross-section into different temperature zones

The previously described simplified models [48], [49], [50] provide equations for obtaining the temperature at each of the denoted parts. Once these temperatures are known, the corresponding strength reduction factors for the different parts can be obtained from EN 1994-1-2. Using the reduced mechanical properties at elevated temperature, the position of the plastic neutral axis (PNA) and the value of the plastic bending resistance of the cross-section can be finally computed by applying the equilibrium equations.

In the experience of the authors [42], the simplified calculation model safe-sided, since the predicted temperatures resulting from the application of the above-described equations are normally higher than the realistic temperatures obtained from experimental tests or finite element models. In particular, it was found in previous investigations that the available formulas for predicting the temperature of the reinforcing bars are overly conservative. Therefore, further research is needed for developing new simplified formulas for the reinforcing bars in slim-floor beams. Additionally, specific formulas for the prediction of the temperatures at the lower flange and bottom plate of SFB configurations are needed, as the temperature difference caused by the thermal gap is not well captured with this simplistic approach, which uses a single temperature for representing zone 1.

A more precise approach to evaluate the flexural capacity of composite beams at elevated temperature consists of discretizing the cross-section for evaluating the realistic temperature field (i.e. by means of a heat transfer sectional model) and afterwards applying a fibre-based model for computing the ultimate bending moment by equilibrium. In a first instance, the cross-section is meshed and a heat transfer analysis is conducted, an example is given in Fig. 18.

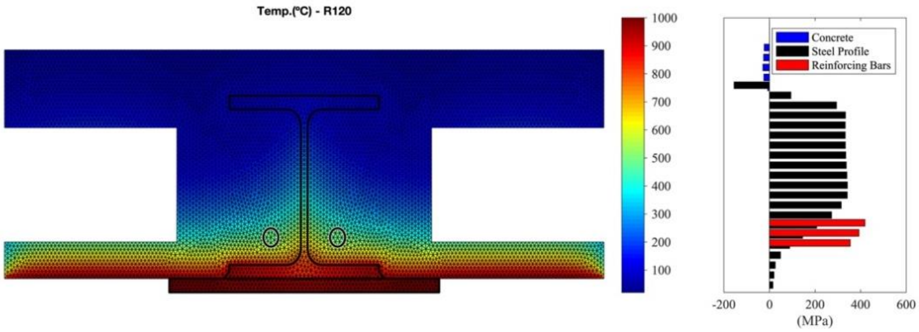


Figure 18: Evaluation of the ultimate bending moment of a SFB cross-section after 120 minutes fire exposure by means of a fibre-based model

Each cell of the mesh is then characterized by its position and its temperature. Using the reduced mechanical properties of steel and concrete at the representative temperature of each cell, the contribution of each fibre to the axial force is computed and the position of the PNA is determined by equilibrium. Once the PNA location for a given temperature is known, the plastic bending resistance of the cross-section can be easily computed by taking moments from each fibre.

This approach is similar to the previously described simplified model, but in this case the finer discretization of the cross-section allows for a more accurate assessment of the bending capacity of the composite beam, providing more realistic predictions.

4 CONCLUSIONS

This paper has reviewed the latest developments for steel-concrete composite structures in the fire situation. In particular, the more recent investigations on the fire behaviour of concrete-filled steel tubular columns and slim-floor beams have been presented.

Innovative solutions that may help improving the fire performance of traditional CFST columns have been presented, such as double-skin or double-tube configurations, as well as CFST columns with embedded steel profiles or massive steel core. The superior capacity of these innovative solutions when exposed to fire has been proved by means of both numerical studies and experimental testing.

The differences between IFB and SFB configurations for slim-floor beams have been highlighted, and the improved fire behaviour of the latter option has been shown by means of numerical and experimental results.

The use of advanced materials, such as high strength steel, stainless steel, high strength concrete, lightweight concrete or geopolymer concrete has been considered as a way for enhancing the fire performance of these composite members. Design recommendations have been given for a rational use of these materials, in order to take advantage of their improved mechanical properties at elevated temperatures.

The available calculation methods in the design codes as well as from the reviewed literature have been presented. For CFST columns, a recently developed method by the authors and co-workers from the CEN Project Team SC4.T4 that will replace EN 1994-1-2 Annex H has been presented, while for slim-floor beams a simplified approach which combines the use of adapted equations from EN 1994-1-2 and specific temperature equations from other authors is given. These two methods provide an integrated framework for designers for the calculation of global structural systems made up of composite steel-concrete elements.

Although the potential into fire conditions of isolated composite members has been demonstrated in this paper, further studies that consider the global behaviour of composite steel-concrete solutions, including the realistic modelling of the connections and the consideration of the composite effect should be carried out, in order to provide designers with a fully integrated composite construction system.

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