Comparative fire analysis of steel-concrete composite buildings designed following performance-based and U.S. prescriptive approaches

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ABSTRACT: Performance-based structural fire design provides a rational methodology for designing modern buildings with cost-effective solutions. However, in the United States, fire design still largely relies on design at the component level using prescriptive approaches. With performance-based approaches, there is an opportunity to benefit from increased flexibility and reduced cost in the design, but these advantages need to be explicitly described and disseminated to promote this shift in paradigm. In this paper, a comparative analysis is conducted on multi-story steel-concrete buildings designed following performance-based and U.S. prescriptive approaches. The steel-concrete composite structure allows taking advantage of tensile membrane action in the slab during fire, and therefore removing the fire protection on secondary beam elements. The nonlinear finite element software SAFIR® is used to model the behavior of the buildings under the standard ASTM fire and a natural fire determined using the two-zone fire model CFAST. The numerical simulations show that performance-based design can be used to achieve the required level of safety currently enforced in the U.S. prescriptive guidelines, while providing an opportunity for cost reduction in fire protection material.

1 INTRODUCTION

Current codes for fire design of structures in the United States are still based on design at the component level using prescriptive requirements, although performance-based approaches can provide efficient alternatives for designing modern buildings with cost-effective solutions. To promote the use of performance-based approach in practice, there is a need not only to develop the necessary knowledge and modeling tools, but also to demonstrate and exemplify the benefits of this approach on the fire design of typical structures.

This study compares the fire design of a typical office building using prescriptive and performance-based designs. The U.S. prescriptive approach is used as a benchmark for fire safety. This approach specifies the fire resistance rating required for each individual building structural elements, where the fire resistance rating is defined as the amount of time the element has to withstand when exposed to the standard fire. Then, alternative designs based on performance-based approach are studied. Evaluating the validity of the alternative designs requires the definition of a clear performance target. Here, it is assumed that the acceptable level of performance is the one that corresponds to the fire safety of the same structure designed based on the U.S. prescriptive guidelines. Under standard fire, the global stability of the structure should be ensured for at least the amount of time specified in the codes. Under natural fire, it is assumed that the global stability of the structure should be ensured until complete burnout of the fire.

A 9-story office building with steel frames and regular plan configurations with a composite floor system is used as the prototype structure. In the first part, the International Building Code is used to obtain the required fire resistance rating for the building structural elements based on current practice. The Underwriters Laboratory publications (UL, 2003) are employed to find the thickness of spray fire protection for the prescribed fire rating to be applied on the elements. Meanwhile, previous research shows that, when system-level performance is considered, fire protection on secondary beam elements is not necessary due to the development of a membrane action in the concrete slab during fire (Bailey and Moore, 2000; Gillie et al., 2002; Vassart et al., 2012). In the second part of this research, performance-based approach based on numerical simulations is adopted to design the fire protection in the building while taking into account the interaction of structural members at the system level. Different alternatives are studied considering different peripheral beam sections and amount of steel mesh in the slab.

Two types of fire exposure are considered, namely the standard ASTM E119 fire and a natural fire. The prescriptive design philosophy is based on the use of standard fire curves such as the ASTM E119 fire. Consideration of the same fire exposure for the structure designed with the performance-based approach allows comparing the response of the two designs for a same thermal load, hence focusing on the structural behavior. The safety level can be discussed in terms of amount of time that the structure withstands the applied loads under this standard fire. Yet, performance-based approach entails the possibility to consider a natural fire exposure evaluated by considering the real characteristics of the compartment. Natural fires are by nature very different from standard fire and therefore can lead to distinct structural response. So, this study also investigates the response of the different alternative designs under a natural fire which is determined using a two-zone fire model implemented in the computer program CFAST.

2 PROTOTYPE BUILDING

2.1 *Multi-story building*

The prototype building studied in this paper is a nine-story steel frame office building. The building is 45.72 m by 45.72 m in plan, consisting of five bays of 9.14 m in the two directions. The structure is composed of four moment resisting frames on the perimeter, as the lateral load resisting system, and four interior gravity frames, see Figure 1. The columns of the interior frames are continuous on the nine-story but the beams have pinned connections (statically determinate beams). The total height of the building is 37.18 m, divided between a 5.49 m high first floor and eight other floors each with a height of 3.96 m.

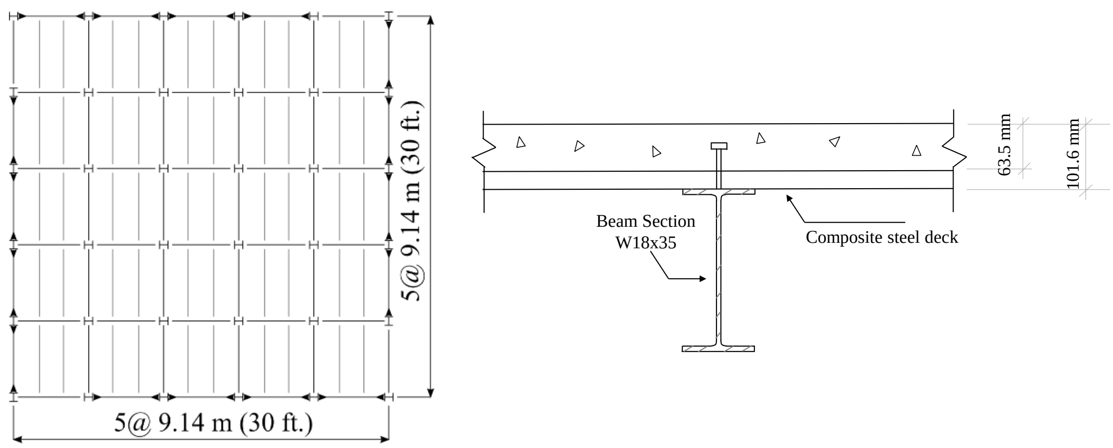

Figure 1. Plan of the 9-story frame and section of a beam and composite slab.

The perimeter frames, designed for lateral load resistance, are made of relatively heavy protected steel sections. Therefore, they are not likely to be affected significantly by a fire, as confirmed in a previous study (Elhami Khorasani et al., 2016). In contrast, gravity frames have a relatively high utilization ratio and they are most likely to reach their critical temperatures before the perimeter frames. Therefore, this work focuses on the effects of the fire on the gravity frames. The gravity frames are designed according to the ASCE 7-10 (ASCE, 2010) specifications and the AISC Steel Construction Manual (AISC, 2010). Table 1 provides the designed sections of the girders and columns for the interior frame, as well as the secondary beams.

Table 1. Section design of gravity frame.

Level	Beam	Girder	Column
9	W18x35	W18x40	W14x43
7-8	W18x35	W21x44	W14x53
5-6	W18x35	W21x44	W14x68
3-4	W18x35	W21x44	W14x82
1-2	W18x35	W21x44	W14x109

The composite floor slab is made of a cellular steel deck of 38.1 mm depth topped by a normal concrete slab of 63.5 mm depth with a single layer of reinforcing mesh. The nominal amount of reinforcement in the steel mesh is 503 mm^2/m in the spanning direction (i.e. parallel to the girders) and 168 mm^2/m in the orthogonal direction. The beams are designed to act compositely with the floor slab. The nominal values of the steel yield strength and Young modulus are 345 MPa and 200,000 MPa, respectively. The concrete compressive strength is 28 MPa.

2.2 *Floor design zone*

This study assumes that fire is limited to one compartment of the multi-story building. Compartment dimensions are assumed to be 9.14 m x 9.14 m, hence corresponding with the bays of the frame structure. The structural fire analysis focuses on the floor system comprising two girders, two boundary beams, two central beams and the steel-concrete composite floor, see Figure 2. This system constitutes a floor design zone as defined by the simple design method developed in the framework of the MACS+ research project (Vassart and Zhao, 2012). The sections for both the boundary and central beams are W18x35.

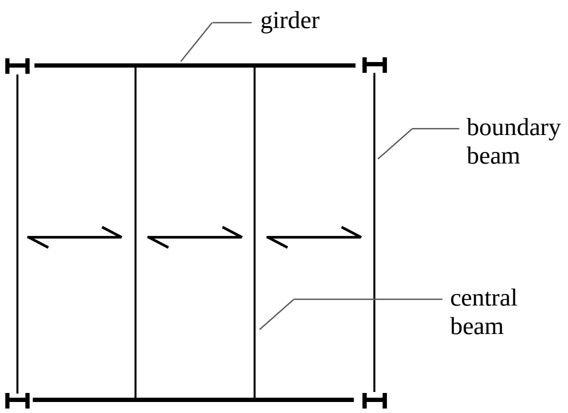

Figure 2. Floor design zone modeled in the study.

3 BUILDING FIRE DESIGN

3.1 *Prescriptive design*

The current practice was closely followed during the design of the prototype structure in order to have a reasonable representation of a real-life design. The current practice follows a prescriptive guideline for designing the thickness of spray fireproofing on all structural elements (considered as individual elements). Therefore, this prescriptive approach, as described in the International Building Code (IBC, 2012) and the AISC Design Guide 19 (AISC, 2003), is used to find the fireproofing thickness for the prototype structure. The IBC is used to define the general construction classification and the fire rating for building elements. The 9-story steel frame, as an office building, is classified as a structure with non-combustible material, and with a required 2-hour fire rating for beams and columns in the frame. No special modification, such as firewalls or partitions, is foreseen in the design. It is conservatively assumed that the beams are part of an unrestrained assembly, which leads to thicker fireproofing. It is not uncommon to make the conservative assumption of unrestrained assembly.

Having determined the required fire resistance rating, the Underwriters Laboratory publications (UL, 2003) are then used to find the thickness of fireproofing. The UL publications provide the results for the required fireproofing thickness given a fire rating for a large set of test specimen. The test configuration that is closest to the construction of the assembly under study should be used to find the proper thickness. The provided thickness from the UL test is only valid for the beam size used in the test; however, a simple formula based on the ratio of beam weight to heated perimeter is used to adjust the thickness to be applicable for the beam size under study. The ratio is referred to as W/D, where W is the weight per foot in pounds and D is the heated perimeter in inches.

The fireproofing for the beams in this study is designed based on the N823 UL configuration with an unrestrained beam and normal weight concrete. A dry mix CAFCO Blaze-Shield II from Isolatek is used with product specification and design aid provided by the manufacturer (Isolatek, 2014). Table 2 shows the thickness of fireproofing corresponding to 2-hour rating for the beam and column sizes.

Table 2. Thickness of fireproofing for frame sections.

Section Size	W/D	2-hr thickness of SFRM (cm)
W18x35	0.67	2.22
W18x40	0.76	2.06
W21x44	0.74	2.06
W14x43	0.75	3.65
W14x53	0.91	3.18
W14x68	1.04	3.02
W14x82	1.23	2.70
W14x109	1.29	2.70

3.2 *Performance-based design taking advantage of tensile membrane action*

The main assumption of the prescriptive approach is that the tested elements in standard furnace tests subject to the standard fire curve will provide the required safety level when become part of the structural system during a real fire event. Given that the building system will behave differently under fire compared to the isolated elements, the actual level of safety of the building is not evident.

The performance-based design is an alternative approach that enables new structural designs by defining the required performance, rather than prescribing how the building should be constructed. In the case of fire engineering, the perception for the acceptable level of safety may vary, since well-established regulatory standards for performance-based design are not available. For the purpose of this study, the prescriptive guidelines are assumed to provide the benchmark for fire safety; therefore, the acceptable level of fire safety when the design is based on performance-based approach is assumed to be guaranteed only when it exceeds the fire safety of the same structure designed based on the U.S. prescriptive guidelines.

In the case of steel frame buildings, as discussed in Section 3.1, the prescriptive approach requires insulation for beams, girders, and columns of the structural frame. Using performance-based design, it is possible to reduce some of the insulations on the steel members. Previous studies (e.g. Bailey, 2004) show that a composite floor system can retain stability during fire without insulation on the central secondary beams. A number of studies and researchers have identified the membrane action of the slab provides additional resistance during fire (e.g. O'Conner et al., 2003; Vassart et al., 2012). This concept will now be investigated for the prototype building designed according to the U.S. specifications.

The analyses are conducted using numerical finite element modeling. The floor design zone extracted from the 9-story frame building is studied for different alternative designs:

1. Prescriptive design where all members are protected with thermal insulation according to Table 2.
2. Performance-based design where central beams are not protected; all other design parameters are kept identical to the prescriptive case.
3. Performance-based design, identical to case 2, but where the amount of reinforcement in the slab is increased to 503 mm²/m in both directions.
4. Performance-based design, identical to case 3, but where the boundary beam sections are increased to W21x44.

In all cases, columns are protected and it is assumed that the vertical supports endure loading capacity during fire. All cases are studied under standard ASTM E119 fire and under a natural fire described in Section 4. The results are provided in Section 6.

4 FIRE MODEL

The structure is first analyzed under standard fire exposure. Since the focus of this paper is on the comparison between performance-based and U.S. prescriptive design, the ASTM E119 fire curve is adopted. This allows defining the standard fire resistance time of the structure in accordance with the prescriptive approach in American codes.

In the second step, it is interesting to analyze the behavior of the structure under natural fire exposure. Indeed, natural fires are more realistic as they account for the cooling phase. Besides, the use of a two-zone model approach such as the one implemented in CFAST (NIST, 2016) allows considering the real features of the compartment, such as the dimensions, openings, fire load, etc., when calculating the evolving distribution of temperature throughout the compartment during the fire. Here, the fire analysis considers a fire compartment of 9.14 m x 9.14 m, with a floor to ceiling height of 2.8 m. The walls and ceiling are lined with gypsum boards. There are 9 m² of openings in total in the walls. Assuming office occupancy, the characteristic fire load is taken as 511 MJ/m² with a Rate of Heat Release density (RHR_f) of 250 kW/m² and a medium fire growth rate (i.e. the fire develops 1 MW after 5 min). The fire can develop on the entire surface of the compartment. Figure 3 plots the evolution of the gas temperature in the hot zone computed by CFAST, alongside the standard ASTM E119 fire curve.

The performance target adopted in case of natural fire exposure is that the structure should survive until complete burnout of the fire.

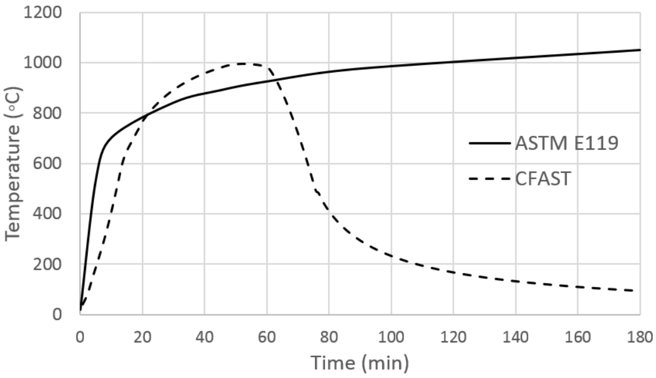

Figure 3. Fire curves used in the analyses.

5 NUMERICAL MODEL OF THE STRUCTURE

The composite slab is modeled in the non-linear finite element software SAFIR (Franssen, 2005; Franssen and Gernay, 2017) developed at University of Liege. SAFIR allows conducting a thermal analysis of the sections of the structural members, followed by a transient structural analysis of the building at high temperature. Here, the response of the 9.144 m x 9.144 m composite floor design zone shown in Figure 2 is studied.

The thermal finite element analyses of the beams and girders uses cross-sections that are discretized with two-dimensional quadrangular elements, which will then form fibers in the beam elements used in the structural model. The thermal modeling of the beam section includes a 2.3 m effective width of concrete slab, i.e. one quarter of the span, as shown in Figure 4. For the slab, the thermal analysis is unidirectional and uses 25 elements across the thickness. The thermal boundary condition is given as a time-temperature evolution of the gas that surrounds the section. The time-temperature relationships are defined to correspond to the standard ASTM E119 fire and then to the natural fire computed with the two-zone model CFAST.

Next, the structural analysis is performed. The slab is meshed using 576 shell elements of 0.38 x 0.38 m². Each beam and girder is meshed using 24 three-dimensional beam elements of 0.38 m length. The three-dimensional structural model is shown in Figure 5. The structural analysis takes into account geometrical and material non-linearity, including large deflections. The evolution of thermal and mechanical properties for steel and concrete at high temperature is adopted from Eurocode (EC2, 2004; EC3, 2005). The stress-strain relationship for concrete is based on a plastic-damage formulation and takes into account explicitly the transient creep strain (Gernay et al., 2013; Gernay and Franssen, 2015).

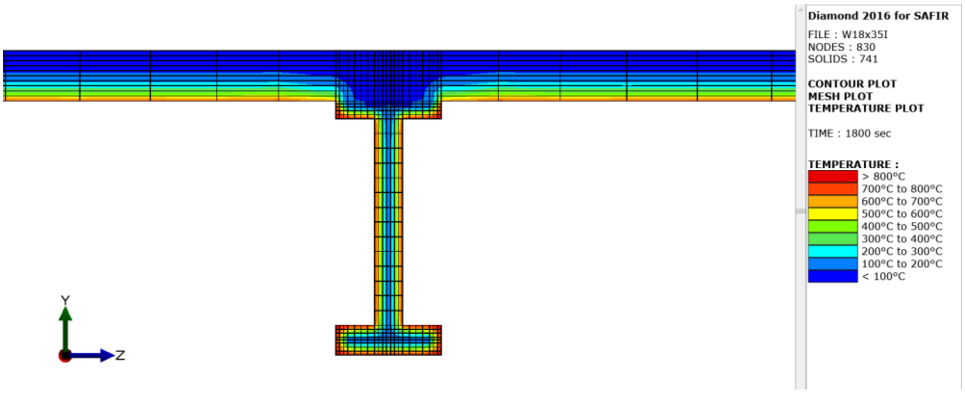

Figure 4. Thermal analysis of the protected beam after 30 minutes of ASTM E119 fire exposure.

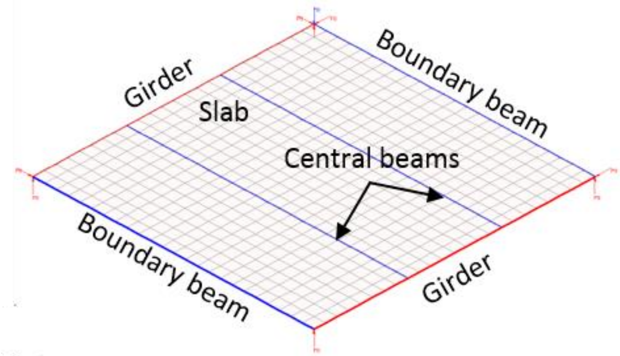

Figure 5. Finite element model for the floor system.

6 RESULTS

6.1 *Prescriptive design under ASTM fire*

This section provides the results for the case where all the beams in the floor design zone (Figure 2) are protected based on the design discussed in Section 3.1. Figure 6 shows contours of the vertical deflection at room temperature in comparison to the deflection at elevated temperature at time 123 minutes, just passing the required 2 hours fire rating. At this time, the average temperature in the central beams and the girders are approximately 573 and 580 °C respectively. Figure 6b shows that, just before failure, deflection at mid-span reaches about

0.7 m. At failure, steel girders at the perimeter are yielded and have strains that exceed 0.15, hence entering the descending branch of the stress-strain material law.

6.2 *Performance-based design under ASTM fire*

This section discusses the design for the case where the central (interior) beams are not protected, taking into account the full floor system behavior and the effect of tensile membrane action. First, the fire protection on the central beams is removed. The behavior of the floor system is then tested without any other changes. The results show that the floor system can only endure the fire for about 45 minutes, which is considerably shorter than the required 2-hour fire resistance. Failure occurs by yielding of the steel reinforcement, which is perpendicular to the girders.

The key in developing the tensile membrane mechanism in the slab is to have the capacity to sustain large in-plane tensile forces at the center, while in-plane compressive forces form a supporting "ring" around the perimeter of the slab (O'Conner et al., 2003). This mechanism develops at large displacements. The concrete slab relies on the steel reinforcement mesh in order to sustain the in-plane tensile forces. In the prescriptive design, 503 mm²/m of steel is provided in the primary direction of the slab, i.e. in the direction of the short span, whereas only the minimum temperature/shrinkage reinforcement of 168 mm²/m is provided in the secondary direction. Such amount of reinforcement is satisfactory when the slab is supported by the protected secondary beams during fire, e.g. in prescriptive design. However, when the unprotected beams are heated and the slab deforms in membrane action, the amount of reinforcement in the secondary direction (168 mm²/m) is not enough to support the tensile forces. In order to take advantage of the mechanism, the design is adjusted with the steel reinforcement in the slab being increased to 503 mm²/m in the secondary direction.

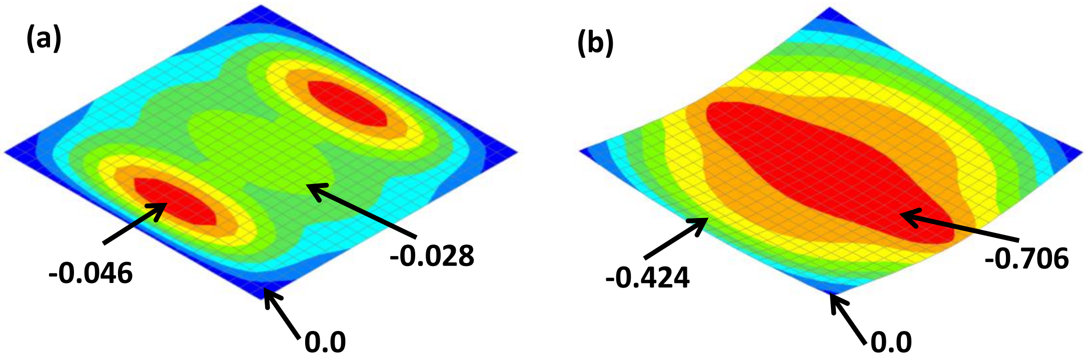

Figure 6. Vertical deflection [m] for the prescriptive design at (a) room temperature and (b) elevated temperature after 123 min of ASTM fire exposure (failure by yielding of the girders).

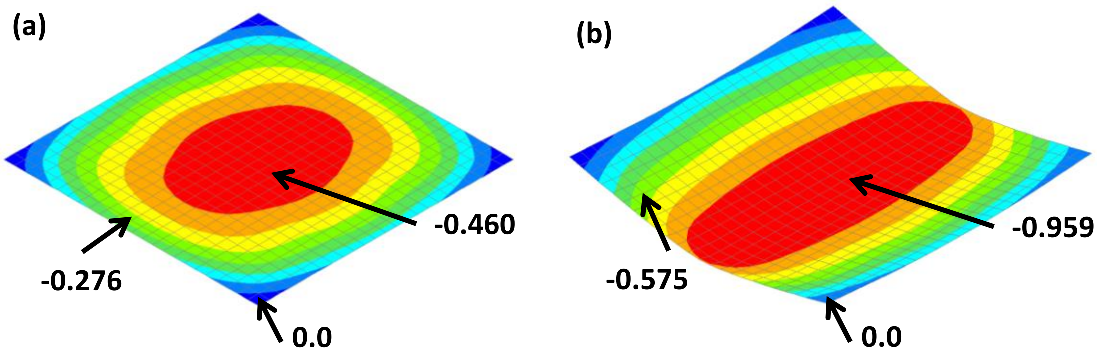

Figure 7. Vertical deflection [m] for the performance-based design after (a) 90 min and (b) 120 min of exposure to ASTM fire (failure by yielding of the boundary beams).

Figure 7 shows the results for the case where the central beams are unprotected and the amount of reinforcement in the slab is 503 mm²/m in both directions. The figure shows the vertical deflections at elevated temperatures after 90 minutes and 120 minutes of exposure to ASTM fire, respectively. After 90 minutes, the deflected shape is that of a membrane, indicating the development of tensile membrane action as the load bearing mode. At this time, the temperature in the central beams reaches 1000°C. It is clear that, at this temperature, the central beams are not providing any support to the slab; yet the development of tensile membrane action allows the floor system to withstand the loads. The structure can sustain the applied loads for 120 minutes, yielding a fire resistance similar to the prescriptive design. At failure, the deflections increase quickly as a result of excessive yielding of the boundary beams.

It is interesting to compare Figure 6b, where failure occurs by yielding of the girders, with Figure 7b, where failure occurs by yielding of the boundary beams. After increase of the amount of steel reinforcement, the 'weak' elements in the floor system acting in tensile membrane action become the boundary beams. Indeed, these beams were initially designed to withstand the load applied on a slab width of 3.05 m. However, in the performance-based fire design, the central beams lose their strength and the boundary beams have to withstand significantly larger vertical reactions from the slab. Therefore, the failure mode is by yielding of these boundary beams.

In an alternative design, the boundary beam sections are increased to W21x44, i.e. the same as the girders. The other parameters are kept the same as in the previous design, notably a reinforcement of 503 mm²/m in both directions. In this case, the fire resistance time is increased up to 135 min. Failure occurs by yielding of the girders.

Figure 8 plots the evolution of the vertical deflection at the centre of the slab for the four cases listed in Section 3.2 for which the results have been discussed here. The structural integrity can be maintained for 2 hours using the performance-based design, indicating a safety level equivalent to that of the prescriptive design, provided the amount of steel reinforcement in the slab is increased in the direction parallel to the central beams (i.e. the direction of the long span at ambient temperature, which is not activated). It is evident that the performance-based design (labelled as PBD in the figure) experiences deflections larger than the original design from the very beginning of the fire. This is consistent with previous experimental studies. However, deflection limit has not been a performance criterion for as long as the structural system is able to sustain the load and maintain stability. The PBD allows for a reduction in the amount of thermal protection on the steel structure, which can lead to cost reduction.

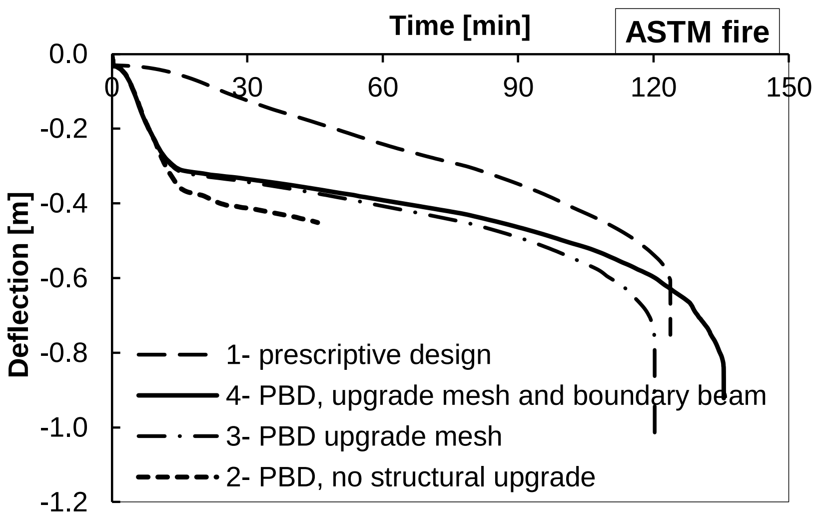

Figure 8. Evolution of vertical deflection at center of the slab under standard ASTM fire for different designs of the floor system.

6.3 *Natural fire exposure*

The structure is then subjected to the natural fire described in Section 4. Figure 9 plots the evolution of the vertical deflection at the centre of the slab for the four different designs of the composite floor system. Failure occurs only for the case where the central beams are unprotected and the mesh remains at 168 mm²/m in the direction perpendicular to the girders (Case 2). All other designs are able to survive the natural fire until complete burnout. The residual deflection is smaller for the prescriptive design, because the slab did not have to develop tensile membrane action, which causes extensive cracking.

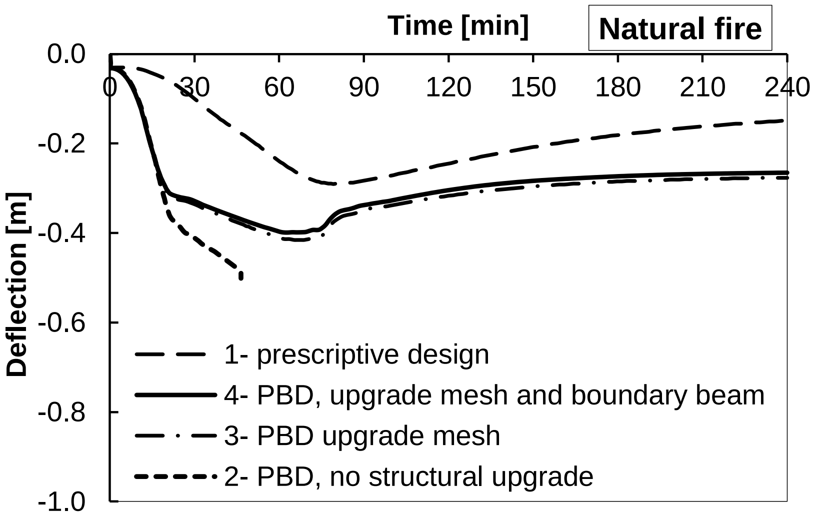

Figure 9. Evolution of vertical deflection at center of the slab under natural fire (CFAST) for different designs of the floor system.

Table 3 summarizes the results obtained for the fire analysis of the floor design zone under standard fire and natural fire.

Table 3. Results.

Fire	#	Design approach	Central beam (insulation)	Steel mesh (mm²/m)	Boundary beam (section)	Failure time (min)	Failure mode / residual deflect.
ASTM E119	1	Prescriptive	insulated	503 / 168	W18x35	123	girder yielding
	2	Performance	no insulation	503 / 168	W18x35	45	mesh yielding
	3	Performance	no insulation	503 / 503	W18x35	120	boundary beam
	4	Performance	no insulation	503 / 503	W21x44	135	girder yielding
Natural CFAST	1	Prescriptive	insulated	503 / 168	W18x35	no failure	0.15 m
	2	Performance	no insulation	503 / 168	W18x35	46	mesh yielding
	3	Performance	no insulation	503 / 503	W18x35	no failure	0.28 m
	4	Performance	no insulation	503 / 503	W21x44	no failure	0.27 m

7 CONCLUSION

This study provides a comparative analysis of the fire performance of a steel-concrete composite floor system part of a multi-story office building, for different designs and fire exposures. The objective is to compare the use of the prescriptive approach currently practiced in the U.S. codes with a performance-based approach based on advanced numerical analysis.

The performance-based approach, which takes into account the interaction of structural members at the system level, allows removing the fire protection of the central beams. Numerical simulations show that tensile membrane action develops in the slab at elevated temperature, providing a satisfying performance with a fire resistance duration under standard fire similar to that of the prescriptive design. The only design upgrade which is needed to achieve this behavior is an increase in the steel mesh reinforcement in the direction which is not activated at ambient temperature (i.e. the large span of the slab). In a performance-based approach, it can also be justified to replace the standard fire by a more realistic fire evaluated through an analysis that takes into account the real characteristics of the compartment. In this study, a natural fire curve was obtained using the two-zone model software CFAST and applied to the structure. The results show that both the prescriptive and the performance-based designs are able to survive this natural fire until burnout.

As a conclusion, this study shows that performance-based design provides an alternative to the prescriptive approach, which, for a similar level of performance, offers more flexibility and potentially cost reductions, owing to the fact that it takes into account system behavior and/or more realistic fire exposure.

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