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Structural fire performance of earthquake-resistant composite steel–concrete frames

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ABSTRACT

Seismic and fire design of a building structure may be two very demanding tasks, especially if included in a performance based design philosophy. For the time being, the necessary harmonization on the regulations concerning these two design fields is almost missing, thus preventing the effective possibility of an integrated design. Besides, while many countries have already moved towards the use of performance-based codes for seismic design, the application of such methodologies for the fire design of structures is still limited in scope. Within this framework, the development of suitable procedures introducing structural fire performance issues for a comprehensive design methodology is needed.

In this paper, a numerical investigation for the assessment of the structural fire performance of earthquake resistant composite steel–concrete frames is presented. With reference to a case study defined in the framework of a European Research Project, a great effort was devoted to the identification of the key structural parameters allowing for a possible correlation between the predictable performances under seismic and fire loadings, when these two are considered as independent actions.

At the conceptual design level, the most suitable structural solution with respect to both design actions was chosen, including composite beams and circular steel concrete-filled columns. The frame was designed in order to resist severe seismic action according to the ductile design approach provided by Eurocode 8; the parameters affecting members' sizing were outlined in this phase. Afterwards, the seismic performance of the designed frame was investigated by means of non-linear static analyses; once the seismic performance objectives were met, in order to evaluate the structural fire performance of the whole frame a set of criteria was defined. To this purpose, thermo-mechanical analyses under different boundary conditions were developed and in order to identify the possible mechanisms leading to structural failure, the state of stress at the critical cross-sections at different times of fire exposure was investigated. Another point of main concern was represented by the assessment of the influence of different restraining conditions on the achieved fire resistance rating and kind of structural failure.

Moreover, the proposed methodology allowed making an estimate of the amount of axial restraint provided to the heated beams by the surrounding structure; in this view, the importance of choosing column elements in function of their flexural stiffness was revealed, in order to correlate it with the predictable performances under both seismic and fire loadings.

1. Introduction

The adoption of a performance-based philosophy in the design of building structures can be a very demanding task since each potential event has to be specifically considered in order to define the related performance objectives and the way to quantify them. However, it is only by following such an approach, that it is possible to take advantage of all the resources possessed by a structure thus allowing for cost-effectiveness of the adopted solutions.

In this framework, obtaining a well-engineered structure with respect to both seismic and fire loadings may be a very difficult process requiring expertise in many fields and presenting many shortcomings [1]. As a matter of fact, actual code provisions such as the Eurocodes develop seismic and fire design of structures according to completely independent tools preventing the possibility of obtaining an integrated design. Secondly, while a performance-based approach to seismic design has widely developed in the last years and introduced by many countries into standards and regulations, the same cannot be said for performance-based design of structures in fire. Its application in fact, is still limited in scope being fire design of structures mainly conducted according to simplified models which unfortunately are not able to represent the real behavior of structural elements [2]

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thus often underestimating their performance. Therefore, a double effort is needed in order to develop a suitable performance-based procedure allowing not only to set a correlation between seismic and fire design of building structures but also to introduce the principles of structural fire engineering since the early design stages so that an advantage can be taken from the understanding of the real structural behavior under thermal action. It is only in recent years, moved by the necessity of eliminating expensive fire protection systems, that alternative design methods have been developed [3,4] accounting for the introduction of the behavior of heated elements at large displacements in fire.

Within this framework, the potentialities offered by composite steel–concrete frames were deeply investigated. Several studies conducted in past researches [5] report on their ability of resisting severe seismic actions through the hysteretic behavior of some of their components thanks to their high available ductility and decreased sensibility to buckling phenomena. At the same time, the full-scale fire tests developed at Cardington [6] gave the possibility of observing the key structural phenomena developing in a heated building revealing the importance of the stability of column elements for its surviving as well as the possibility of adopting unprotected steel beams. Moreover, a series of experimental tests [7,8] conducted at the National Research Council of Canada (NRCC) on composite concrete filled columns in order to investigate the significant factors affecting their behavior under thermal action, showed their inherent good resistance in fire. Unfortunately, a general analytical framework within which to analyze these many factors involved in both seismic and fire design situations is still missing.

In present work, a suitable methodology for the assessment of the structural fire performance of earthquake resistant composite moment frames is presented.

In a first stage of the research, the reference case study was defined and different structural solutions were investigated in order to choose the most suitable with respect to both seismic and fire loadings. To this purpose, the possibility of considering or not the composite action with the slab for the main beams was evaluated and the inherent fire resistance of two kinds of composite columns including partially encased and concrete filled sections was investigated.

Each analyzed structural solution was preliminary designed to sustain vertical loadings, afterwards Eurocode 8 [9] was applied. Seismic design was made for high seismicity regions, adopting a peak ground acceleration (PGA) equal to 0.35g and the simplified lateral force method of analysis was adopted; moreover, the ductile design approach given by Eurocode 8 was followed and a high ductility class was chosen. Each frame was designed with reference to a global collapse mechanism corresponding to the "strong column–weak beam" concept. Given the importance of the stability of column elements in fire, preliminary analyses were developed in order to evaluate their load bearing capacity at elevated temperatures. Finally, a "full" composite solution including steel beams connected to a profiled steel sheeting composite deck and circular concrete-filled columns was chosen.

In a second stage of the research, both seismic and structural fire performance of the adopted frame solution were evaluated. For what concerns seismic actions, static non-linear analysis under different sets of horizontal loads were developed. Once seismic performance objectives were met, the structural fire performance of the frame was evaluated by means of thermo-mechanical analyses on a planar model under different thermal boundary conditions. In doing so, particular attention was posed to the identification of the main load carrying mechanisms and to the adequate representation of the restraining conditions offered by the surrounding structure to the heated elements. To this purpose, the behavior of four isolated heated beams under ideal support conditions was investigated and compared with the behavior of the same beam in the complete frame, outlining the influence of axial restraint on the fire resistance rating and kind of structural failure. Besides, in order to quantify such an influence, the behavior of rotationally restrained heated beams with varying degrees of axial restraint was investigated setting a qualitative correlation between the amount of axial restraint and the flexural stiffness of column elements. In this way, the proposed methodology allowed pointing out the most important parameters affecting seismic design in order to evaluate and to quantify their possible influence on the structural fire performance, thus setting the desired correlation between the two design fields.

2. Choice of the structural scheme and optimized solution

In the choice of the structural scheme, particular attention was given to the definition of the geometric layout, in order to obtain an optimized solution which offered a good compromise between satisfactory structural performance and cost effectiveness. As a result, the main frame was made out of two bays spanning 7.5 and 10 m, respectively; the adoption of quite long spans for the main beams imposed the realization of secondary beams, in order to avoid the presence of propping systems for the composite deck. The secondary beams, spanning 7.5 m each, were placed at a distance of 2.5 m and were designed according to a simply supported scheme so that the frame resulted braced in transverse direction. For what concerns the elevation, a medium-rise solution was adopted including five floors with 3.5 m inter-storey height; the schematic of the adopted layout is shown in Fig. 1.

With reference to the defined geometry, different structural solutions were considered, in order to choose the most suitable with respect to both design actions. In particular, partially encased (type A) and concrete filled (type B) sections were analyzed for column elements, while bare steel (type 1) and composite (type 2) sections were analyzed for beam elements. Therefore, four different structural solutions were investigated, each one including the same composite deck made out of a concrete slab cast on a 55 mm profiled structural steel sheeting which was checked at both ultimate and serviceability limit states. Design actions used for verification were 4.72 kN/m^2 for dead loads and 3.00 kN/m^2 for imposed loads kN/m^2 (corresponding to category B for office buildings); for the roof floor lower values were applied equal to 3.72 kN/m^2 for dead loads and 2.50 kN/m^2 for imposed loads. For each analyzed structural solution, preliminary calculations were developed for vertical loadings following both Eurocode 3 [10] and Eurocode 4 [11] provisions; vertical loads were applied on main beams as pointed loads coming from secondary beams. Afterwards, the lateral force method for seismic analysis provided by Eurocode 8 was applied; floor weights were computed according to Eurocode 8 provisions resulting in 1671 kN for all levels except for the roof whose applied load was equal to 1331 kN; besides, the ductile design approach was followed adopting a behavior factor $q = 6$ corresponding to high ductility class. The seismic design was developed applying the capacity method with reference to the "strong column–weak beam" concept requiring the formation of plastic hinges at the end of beams' spans and at the base of ground storey columns. To this purpose, the validity of the resistance hierarchy criterion was checked but in no case its application represented a conditioning design issue. The main outcomes in terms of members' sizing for the two design stages are summarized in Table 1.

The obtained results for the static combination of actions showed that the use of a composite section for the main beams would not seem the most appropriate choice since no substantial reduction in the steel profile size with respect to the bare steel solution was possible. This was due to the fact that the adoption