Journal of Constructional Steel Research 138 (2017) 774–782

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Post-earthquake fire resistance of steel buildings

T. Jelinek [a], V. Zania [b], L. Giuliani [b],*

[a] Winning Steel s.r.o., Krizikova 72a, 612 00 Brno, Czech Republic
[b] Civil Engineering Department, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 3 August 2017
Accepted 21 August 2017
Available online xxxx

Keywords:
Multiple hazards
Post-earthquake fire
Fire scenarios
Steel structure
Moment-resistant frame

ABSTRACT

Current design procedures do not account for the concomitant or subsequent occurrence of earthquakes and fires, which has so far been justified by the low probability of occurrence of accidental actions. Nevertheless, fires are often triggered as a consequence of damage caused by the earthquake and are responsible for casualties and major additional damage to buildings and other constructions. Despite a number of research studies on the topic, it is at present unclear as to what extent the occurrence of a previous earthquake could affect the response of a structure to fire.

The response of a moment-resistant steel frame to post-earthquake fires (PEFs) is investigated and compared with the response of the undamaged frame exposed to fire only, by means of numerical analyses performed using a commercial finite element software. The frame considered as a case study is not insulated against fire, but it is designed to comply with the service damage limitation prescribed in EN1998-1 (2004). The nonlinear seismic response to 7 different earthquakes, scaled at the same peak ground acceleration (PGA), is analyzed; then two of these earthquakes are selected for the post-earthquake fire (PEF) computations and a number of critical fire scenarios are identified, based on the vicinity of the fire to the highest permanent deformation induced by the earthquakes. The structural elements involved in each fire scenario are considered to be exposed to a standard fire and the collapse mode and time are determined by means of large deformation analysis.

The comparison of the mode and time of the frame collapse for all the investigated scenarios shows a minor influence of the effect of the two considered earthquakes on the fire resistance of the frame. The current study shows that nonlinear geometric effects do not have a significant effect in the behavior of the building during fire, when the structure is designed to comply with the service damage limit states prescribed in EN1998-1 (2004).

1. Introduction

1.1. Design for accidental actions

Events such as fires, explosions, or impacts have a very low probability of occurrence within the lifetime of a building structure, but can have very high consequences in terms of both safety of the occupants and loss of the properties. The risk associated with those actions can therefore be high. Hence, most national and international standards [2,3,4] prescribe that the overall stability of the structural system must be ensured also under the occurrence of such low probability - high consequence events.

Due to the low probability of occurrence and the lack of statistical data for a probabilistic characterization of the actions associated with these events, the so called semi-probabilistic approach applied to ordinary design actions such as wind and earthquakes is not followed, but compliance with a special accidental design situation is required by the Eurocodes [5]. In the corresponding load combination, the concomitancy of two accidental actions is disregarded, in consideration of the rarity of such a concomitant occurrence of two low-probability events. While this assumption is sensible for statistically independent actions such as arsons and floods, it is not justified in case of interdependent events such as flood following a hurricane, or fire induced by explosions or by earthquakes [6].

The causes that may trigger a fire during or just after an earthquake are numerous: electrical and gas-related failures are most common fire triggering events, but also overturning or displacement of heat sources are likely [7]. For this reason, the timing of the earthquake plays a crucial role in the fire spread in buildings (e.g. home heating and electrical or gas appliances are used more in the evening hours and in the winter time), while large scale fire spread is instead significantly affected by the wind conditions. Fires that are directly caused by such earthquake-related failures should be therefore distinguished by other fires, such as e.g. those occurring in buildings that had previously been

---

* Corresponding author at: Section of Building Design, Department of Civil Engineering, Technical University of Denmark, Building 118, Kgs. Lyngby 2800, Denmark.
E-mail address: lugi@byg.dtu.dk (L. Giuliani).

http://dx.doi.org/10.1016/j.jcsr.2017.08.021
0143-974X/

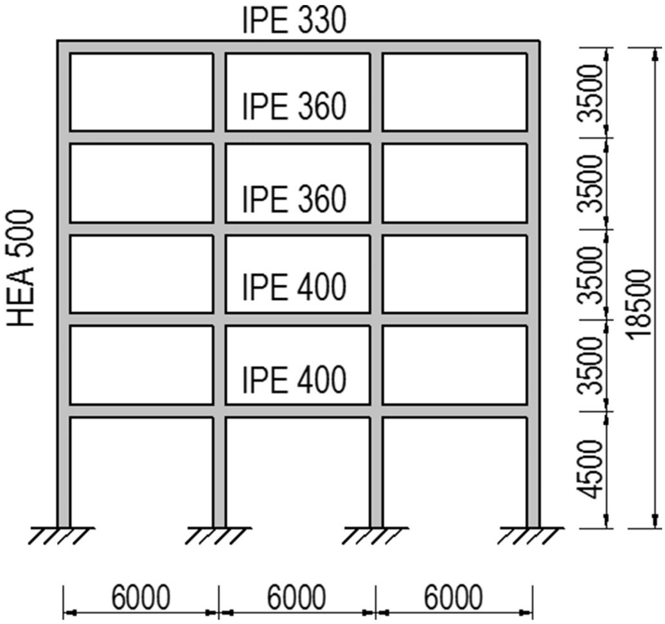

Fig. 1. Case study building geometry with dimensions in mm and section profiles.

damaged by an earthquake, before reparations are undertaken [8,9], by using a name such “earthquake-induced fires”. However, the terms Fire Following Earthquake (FFE) or Post-Earthquake Fire (PEF) are commonly used in literature and the latter is also adopted in this paper.

1.2. Historical perspective

In the last century several post-earthquake fires (PEFs) grew into disastrous dimensions [10]. The 7.8 Mw earthquake that struck San Francisco in 1906 and the 7.9 Mw earthquake that hit Tokyo in 1923 were followed by fires that are considered to belong to the most destructive ones during a peaceful time [10]. Other countries that experienced severe PEFs were New Zealand, where a 7.8 Mw earthquake hit Napier in 1931, and Turkey, hit by a 7.8 Mw earthquake in Izmit, in 1999. United States were again struck by PEFs after the 7.1 Mw Loma Prieta earthquake in 1989 and the 6.7 Mw Northridge earthquake in 1994. Japan was also struck by severe PEFs after the 7.9 Mw earthquake that hit Kobe in 1995, as well as after the 9.0 Mw earthquake that struck the east coast in 2011, which also caused a tsunami and the Fukujima nuclear disaster [11].

Even though not all strong quakes are followed by major fires (this is e.g. the case of the 7.1 Mw and 6.2 Mw earthquakes that hit Christchurch, New Zealand, in 2010 and 2011, respectively [12]), post-earthquake fires often cause more damage than the quake itself. In the above mentioned cases of the San Francisco and Tokyo earthquake, for example, the PEFs were responsible of ca. 80% of the total damage.

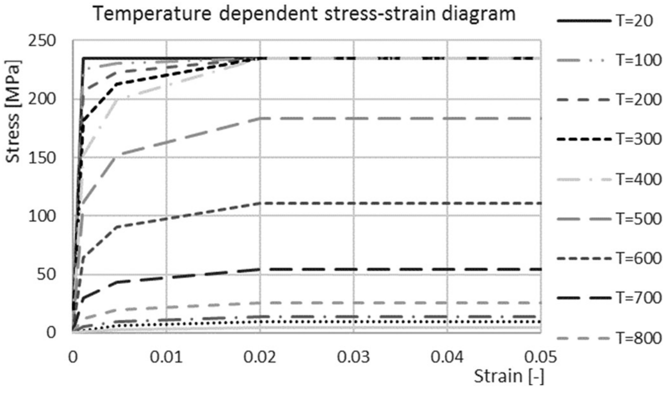

Fig. 2. Quadrilinear stress-strain diagram for steel at elevated temperatures.

Since the current seismic design philosophy allows for plastic damage of the load-bearing structure (EN1998-1, 2004), while the fire design is carried out by assuming undamaged structural elements, a reduced fire resistance of a building subjected to a prior earthquake can be expected. Likely, damage to active fire systems (e.g. water hoses or sprinklers) as well as passive fire measures (such as fire compartmentalization or element insulation) would further reduce the fire resistance. The development of design methodologies and procedures for designing building capable to resist PEFs and their inclusion in codes and guidelines seems therefore an urgent issue.

1.3. State of the art

The majority of research on PEFs has been performed during the past two decades. The vast majority of published numerical studies indicate that PEFs can impair the structural integrity of steel buildings. However, the fire scenarios and material modeling assumed in the investigations along with the computed impact of a PEF vary amongst the different studies.

Della Corte et al. [13] carried out one of the first comprehensive studies on PEF response of unprotected moment-resisting steel frames. By means of a parametric study of simple frames and a numerical analysis on two multi-story frames, Della Corte et al. [14] showed that the fire resistance is reduced by increasing damage caused by an earthquake on the examined frames.

Other studies have reached a similar conclusion, by employing a push-over analysis to determine the seismic response of unprotected moment-resisting steel frames designed according to Eurocode (EN1998–1, 2004) and by considering both standard and natural curves as fire exposure [15,16]. Vertically travelling fires in tall steel structures were also investigated by Behnam and Ronagh [17], while Behnam [18] compared the PEF performance of regular and irregular tall steel structures, demonstrating that irregular buildings suffered more damage during earthquakes than regular ones and hence showed a lower fire resistance after the earthquake.

Faggiano and Mazzolani [19] investigated the structural performance of steel frames exposed to PEFs by means of a robustness assessment method, based on the consideration of the seismic performance levels indicated in FEMA 356 [20] and on the evaluation of the consequences of potential subsequent fires. A study on 3-dimensional steel frame performance subjected to post-earthquake fire was conducted by Pantousa and Mistakidis [21]. Their parametric study explored the influence of strains and rotations in plastic hinges induced by earthquake on fire resistance and concluded that the fire resistance of a structure is reduced by earthquake induced permanent deformations.

Only Memari et al. [9] reached different conclusions, by focusing on the effect of a reduced beam section in the beam-column connection of a moment-resistant unprotected frame. The analysis was conducted using nonlinear dynamic analysis to determine the seismic response and uncoupled thermal-mechanical analysis to assess the effects of subsequent parametric fires with cooling phase. The results showed that the global performance of the investigated frames was not affected by the earthquake. However, even though the extension of the fire in the

Table 1
List of selected accelerograms.

No.	Code name	Location	Magnitude M_w	Duration
1	Artificial	–	–	30 s
2	Montenegro E-W	Ulcinij, Montenegro	6.9	40 s
3	Turkey N-S	Izmit, Turkey	7.6	20 s
4	Italy E-W	L'Aquila, Italy	6.2	30 s
5	Hollister	Hollister, USA	6.9	40 s
6	Northridge	Northridge, USA	6.7	40 s
7	Loma Prieta	Loma Prieta, USA	6.9	40 s