RISK ASSESSMENT OF STEEL STRUCTURES UNDER FIRE

B. Faggiano[1], M. Esposto[2] and F.M. Mazzolani[3]

[1] *Assistant Professor, Dept. of Structural Engineering, University of Naples "Federico II", Naples, Italy*
[2] *PhD Student, Dept. of Structural Engineering, University of Naples "Federico II", Naples, Italy*
[3] *Full Professor, Dept. of Structural Engineering, University of Naples "Federico II", Naples, Italy*
Email: faggiano@unina.it; matteo.esposto@unina.it; fmm@unina.it

ABSTRACT :

Fire following earthquake is the one of the most concerning earthquake-related hazard in urban areas. In fact, in some cases it has been of catastrophic proportions. Actually, it is possible that particular building characteristics and density, meteorological conditions and other factors can combine to create a situation in which fire following earthquake is the predominant agent of damage. In addition, in case of fire following earthquake, the structural fire performances may be strongly impaired due to the presence of possible earthquake-induced damage, with consequent reduction of the fire resistance. In this context, this paper shows a preliminary brief overview of the most relevant research on the risk of fire following earthquake. Therefore, a methodology, conceived in the framework of the performance-based approach, for the assessment of the fire resistance of structures damaged by earthquake in relation to different structural damage levels is illustrated. As an example, it is applied to steel structures, with the aid of coupled temperature-displacement numerical analyses.

KEYWORDS: Fire following earthquake, risk assessment, steel structures, numerical investigations

1. INTRODUCTION

Fire following earthquake is the one of the most concerning earthquake-related hazard in urban areas. It has occasionally been of catastrophic proportions. Building characteristics and density, meteorological conditions and other factors can combine to create a situation in which fire following earthquake is the predominant agent of damage. Records from historical earthquakes even show that sometimes the damage caused by the subsequent fire can be much severer than the damage caused by the seismic action itself, this being true for both single buildings and whole regions (Scawthorn et al., 2005). For the sake of example, it is estimated that the loss due to the fires after the 1906 San Francisco earthquake is 10 times larger than that due to the ground motion; in addition, within the 1923 Tokyo earthquake, it is estimated that 77% of lost buildings were destroyed by fire (Fig. 1).
Despite the awareness about this hazard gained on the basis of historical surveys, large fires following earthquakes remain a problem, as clearly demonstrated by the more recent events as the 1994 Northridge (California, USA) and 1995 Kobe (Japan) earthquakes. The seriousness of this problem is also related to the probable multiple simultaneous ignitions which fire departments must respond to, such emergency being worsened by earthquake-induced impairing to communications, water supply and transportation leading to catastrophic scenarios characterized by structural collapses, hazardous materials releases and emergency medical aid (Scawthorn et al., 2005).
The behaviour in fire of structures which have been damaged by earthquakes represents an important investigation field since the earthquake-induced damage makes the structure more vulnerable to fire effects than the undamaged one. This is because the consequence of fire on a structural system is mainly a gradual decay of the mechanical properties as far as temperature grows. It is apparent that the more the structural behaviour is degraded after an earthquake the more time up to collapse due to fire is short (Faggiano et al., 2007). This problem is particularly felt in the case of steel structures, whose mechanical properties undergo extremely strong decay when temperature increases.

Figure 1 Effects of the fire following the 1906 San Francisco (California, USA) earthquake (Courtesy of The San Francisco Museum of Modern Art)

2. THE FIRE FOLLOWING EARTHQUAKE RISK MANAGEMENT

2.1. General

Fire following earthquake is a complex problem, characterized by many sequential and situational components. Several subjects are directly or indirectly involved in the related risk management activity, the complexity of the matter requiring a multi-disciplinary approach. It is arguable that, in the first instance, the leading role within the emergency is taken by fire service, local authorities, other utility organisations and research and hazard informative services. Other interested stakeholders may be the insurance industry, building owners and/or managers, environmental and community bodies and the general public (Wellington Lifelines Group, 2002).

The general approach followed by the hazard and disaster management community during past years has consisted in operating almost solely on the relief programme. So, after the occurrence of a strong earthquake, eventually followed by a large fire, in the perspective of a response-based approach to disaster management, specially trained disaster managers (usually government officials), coordinate the relief efforts of both the affected community and the wider aid benefactors. In recent years, however, considering the high catastrophic consequences of a fire following earthquake, relief measures after impact have become increasingly inadequate to protect personal or community assets, safeguard social and economic investments. A new approach is felt, which should be aimed at identifying problems before they happen, by means of systematic process of analysis of risk and decisions about its acceptability. Such general decision-making process is commonly called Risk Management (Wellington Lifelines Group, 2002). Australia and New Zealand became, in 1995, the first Countries in the world to formally develop and adopt a General Standard on Risk Management. The Australian and New Zealand Risk Management Standard (AS/NZS 4360:1999 2nd Edition) provides a formalised, systematic decision-making process by which identifying solutions to issues concerning the vulnerability to natural hazards.

2.2. Main Risk Factors

Large urban areas prone to severe earthquakes may be susceptible to undergo catastrophic conflagrations following the shaking event.

The likelihood of fire following earthquake leading to a catastrophic scenario is related to the presence of RISK FACTORS (RF), which can be grouped with reference to the possible phases of the phenomenon (Wellington Lifelines Group, 2002) as follows:
- RF related to the direct earthquake effects: damage itself, displacement of dangerous contents, fracturing of gas and / or electricity connections and / or reticulations;
- RF related to the sources of ignition: open fires, hot surfaces, boilers, short circuits from structural damage, fallen live wires;
- RF related to the establishment of fire: fuel, failure of active suppression systems within buildings (like sprinklers);
- RF related to the spread of fire: high density of buildings, boundary barriers not designed to modern fire spread resistance (for instance, windows), direction and velocity of wind, damage to passive measures;
- RF related to the detection / containment / extinguishment of fire: uncertainty of fires location, impairment of fire brigade response, loss of water pressure due to reticulation damage.

3. RISK MANAGEMENT APPROACH

3.1. General

The fire following earthquake risk management requires an approach at two different scales (Chen et al., 2004): a local scale, referred to single buildings (Building Scale – BS), and a global scale, referred to a whole region (Regional Scale – RS). In both cases, multi-disciplinary approaches are useful.

3.2. Building Scale

At today's knowledge, the most correct design philosophy for integrating fire safety into the design process for structures appears to be the Performance-Based Design (PBD).
Such design approach has already been adopted by International Codes (USA, Australia, UK, New Zealand, Sweden, Eurocode system) in the field of structural fire safety. Performance-Based codes for fire safety change the standard of care from only meeting the code prescriptive requirements (height and area limits, fire-resistance ratings, egress, separations, etc.) to demonstrating, by means of specific calculations, that the building achieves the required safety performance (Johann et al., 2006; Bennetts and Thomas, 2002). As a general rule, the latter could be achieved by a multi-disciplinary approach including fire science, structural engineering and fire safety design tools.
In general, if a structure is exposed to gravity loads, extreme wind or earthquake, the safety of occupants is strictly related to the safety of the structure itself. On the contrary, in case of development of fire, the occupants may be threatened both directly by smoke and flames, and indirectly by the effect of the behaviour of the building structure under fire conditions (Bennetts and Thomas, 2002). This point involves to consider more stringent design objectives for structures that can be endangered by the combined hazard of earthquake and subsequent fire, aiming at facing the safety in terms of both the behaviour in fire and the direct effects of fires on people within the building.
In this perspective, design objectives for fire following earthquake scenarios may therefore include: (1) life safety of the occupants; (2) non-injury of occupants; (3) life safety of fire fighters; (4) non-injury of fire fighters; (5) prevention of damage to contents; (6) avoidance of damage to process; (7) prevention of damage to building; (8) prevention of collapse of building (Bennetts and Thomas, 2002).

3.3. Regional Scale

At the regional level, Geographic Information Systems (GIS) based approaches for earthquake hazard mitigation may be used. Such tools attempt to provide a decision support tool for assignment and routing optimization of emergency vehicles after earthquake, considering the geographic distribution of ignited fires and injuries, locations of emergency response facilities, earthquake damage to the facilities and the

transportation system (Chen et al., 2004).
The management of the fire following earthquake emergency at regional scale involves understanding and correlating the main aspects of the problem, well keeping in mind that one of the most relevant key factors is time (Scawthorn et al., 2005).
The essential steps of the process, as indicated by Scawthorn et al. (2005) are listed hereafter:
- Occurrence of the earthquake: it may presumably cause damage to buildings and contents, including simple but dangerous knockings of things such as candles or lamps;
- Ignition: whether a structure has been damaged or not, ignitions may occur due to earthquakes, the sources of ignitions being numerous (overturned heat sources, abraded and shorted electrical wiring, spilled chemicals having exothermic reactions, etc.);
- Discovery: at some point, the fire resulting from the ignition will be discovered, if it has not self-extinguished yet; the discovery may require a time period longer than that necessary in ordinary conditions, due to the confusion usually following an earthquake;
- Report: if it is not possible for whom discovers the fire to immediately extinguish it, fire department intervention is required;
- Response: the fire department has to respond to the help request;
- Suppression: the fire department then has to suppress the fire; if the fire department is successful, they move on to the next incident; if the fire department is not successful, they continue to attempt to control the fire; the process ends when the fuel is exhausted, namely when the fire comes to a firebreak.

In a long-term perspective, in general the Emergency Management spans routine periods as well as emergency periods. During the former, the task of the emergency manager is to facilitate sustainable hazard management practices that lead to community resilience. During emergency periods, emergency management focuses on coordinating response and recovery requirements (Wellington Lifelines Group, 2002).

4. STRUCTURAL ANALYSIS AND DESIGN ASPECTS AT BUILDING SCALE

4.1. Prior Research

The integration of the fire structural design in a Performance Based Approach is a very attractive study field and so several studies are ongoing all over the world on this subject. In the following, two important contributions for such integration are briefly outlined.
Chen et al. (2004) make a proposal of a procedure consisting in four major steps: (1) hazard analysis, (2) structural and/or non-structural analyses, (3) damage analysis and (4) loss analysis. One of the key points in the proposed procedure is that structural and/or non-structural analyses are repeated when fire follows the earthquake. In fact earthquake and fire are two different hazards occurring sequentially and, consequently, after the earthquake, the actual status of the building needs to be evaluated. In particular three kinds of damage should be considered: damage to structures, damage to fire protection of structural members and damage to non-structural fire protection system. Re-evaluating the fire hazard is also very important because the damage to the fire protection systems may affect the development of the fire hazard.
Johann et al. (2006) propose a framework developed to integrate structural fire safety into the design of structural framing systems. It consists in a series of flowcharts to identify and organize the specific functions for involvement of fire performance expertise, including design by calculation. In the perspective of PBD fire safety integration into the structural design process, the following five activities are considered: (1) Structural design for gravity and lateral loads; (2) Modifications during service life; (3) Definition of design fire conditions within the building; (4) Analysis of structural response to the design fire conditions; (5) Evaluation of the acceptability of the predicted performance.
With reference to the behaviour of steel structures damaged by earthquake and subjected to fire, an important contribution is provided by Della Corte et al. (2003), who studied steel portal frames and multi-span multi-storey frames, with the aim of determining the fire resistance rating reduction of frames as a function of the maximum residual inter-storey drift angle and of the seismic intensity. Their work is developed in two main

phases: (1) Dynamic time histories seismic analyses aiming at the damage identification; (2) Fire analysis on the structural configurations distorted due to the seismic damage carried out by means of an ad-hoc software.

4.2. Modelling Issues

One of the main concerns and source of aleatority for the evaluation of the structural behaviour in fire and the protection strategies, aiming at the design, is the modelling of the fire event, which can be carried out by following several methods, affected by different levels of refinement and complexity. The most spread models are the following ones:
- The nominal standard temperature-time ISO 834 model: it does not take into account any physical parameter, and can be far away from reality; from the beginning, the nominal model supposes that the entire compartment is in the flashover phase and the temperature is increased continuously, without taking into account the cooling phase;
- The parametric fire model: it considers the cooling phase and gives the temperature-time curve function of the fire load density and openings; this model is, however, limited to the surface and the height of the fire compartment considered, and supposes that the temperature is the same on the entire compartment, from the beginning of the fire;
- The combined "Two Zone" and "One Zone" model: it is a modern fire model approach; in this natural fire model, during the pre-flashover phase, the fire compartment is divided in a hot upper zone and a cold inferior one; for each zone, with uniform temperature, mass and energy equations are solved; after the flashover, the temperatures is considered uniform and it is determined by solving the equations of mass and energy of the compartment, taking into account walls and openings.

Different analytical tools are available for the assessment of the structural response in fire. For the sake of example, it is possible to use numerical programs able to perform only the analysis in fire, resulting in the evaluation of the fields of temperature within the structural members. This requires the use of other programs for the structural analyses, for the evaluation of both the stress and strain states taking into account the temperature variation. Currently, some programs, able to carry out the temperature and displacement analyses in a unique structural model, are available. Such approach has the advantage of considering the thermal and mechanical aspects of the problem in a unique model, so that the mutual interactions may be easily caught (Faggiano et al., 2007).

4.3. Methodology for the Assessment of the Fire Resistance of Structures Damaged by Earthquake

This section introduces a methodology for the assessment of the fire resistance of steel structures damaged by earthquakes, conceived in the framework of the Performance-Based approach.
First of all, the seismic damage on the structures is determined according to the Performance-Based Earthquake-Resistant Design (SEAOC, 1995), which states the acceptability of various levels of damage on the basis of the consequences on the user community, related to the expected return period of the earthquake. In particular, four performance levels are considered:
1 Fully Operational (FO), in which no damage occurs – the consequences on the building user community are negligible;
2 Operational (O), in which moderate damage to non-structural elements and contents, and light damage to structural elements occurs – the damage does not compromise the safety of the building for the occupancy;
3 Life Safe (LS, damage state), in which moderate damage to structural and non-structural elements occurs – the structure's lateral stiffness and ability to resist additional lateral loads is reduced, but some safety margins against collapse remain;
4 Near Collapse (NC, extreme state), in which the lateral and vertical load resistance of the building is substantially compromised – aftershocks could result in partial or total collapse of the structure.
The corresponding engagements in terms of inter-storey drift (δ/h, where δ is the inter-storey lateral displacement and h is the inter-storey height) and plastic rotations (Θ) are also indicated; they are reported in Table 1.

Table 1 Damage state corresponding to the performance levels

Performance level	Inter-storey drift (δ/h)	Plastic rotations (Θ, rad)
FO	0.002 – 0.005	0 (elastic range)
O	0.002 – 0.01	≈ 0 (negligible damage)
LS	0.01 – 0.02	0.01 – 0.03
NC	0.02 – 0.04	0.02 – 0.05

The analysis procedure is articulated in three different phases:

1 Seismic pushover analysis of structures subjected to vertical loads;

2 Identification of the performance levels, according to the mentioned SEAOC indications;

3 Analysis under fire of the structures already damaged by earthquake, starting from each previously defined performance level.

As an example of application, the methodology is applied to the case of simple steel portal frames, whose behaviour in fire after earthquake is studied through coupled temperature-displacement numerical analyses, carried out by means of the multi-purpose computer program ABAQUS (2004). Details on such analysis are given in Faggiano et al. (2007).
Four study cases are considered (Fig. 2). They are simple steel portal frames, characterized by two different steel grades (S235 and S275) and different span over height (L/H) ratios (L/H = 1 and L/H = 2).

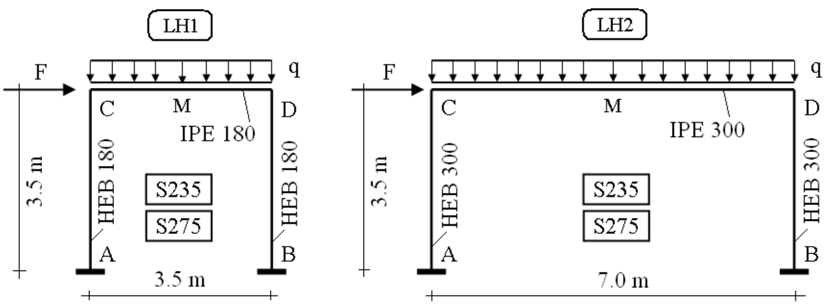

Figure 2 The study steel portal frames

The study structures are designed at both ultimate (ULS) and serviceability (SLS) limit states according to European standard rules for seismic design (CEN, 2004). The dead load is $G_k = 4.5$ kN/m^2 and the live load is $Q_k = 2.0$ kN/m^2. For the seismic design, a PGA equal to 0.35g and an A-type soil are considered. The assumed inter-axis is 3.0 m.
The design of structures is carried out considering the steel grade S235, besides the same portal frames, made of steel grade S275 are examined, allowing for a larger structural overstrength. The latter is quantified as the inverse of the exploitation ratio σ_{Sd}/f_y (defined as the ratio between the maximum and the yielding stresses at ULS). As far as the overstrength is larger, the fire resistance increases. In fact, since the fire effects on the structures mainly consist in a strong reduction of the material mechanical properties, the overstrength gives a useful information about the resistance reserves in the structure: the more the structure is endowed with such resistance supply, the more the resistance reduction (and the fire duration) must be large for reaching the collapse.
The adopted analysis procedure is different from the one usually applied in thermal analyses where, for the sake of simplicity, the heat transfer analysis and the structural one are performed separately (uncoupled analyses). In particular, in such cases, the heat transfer analysis is carried out as preliminary step, in order to evaluate the temperature – time law within the structural elements; subsequently, the structural analysis under design loads is carried out, by imposing to the member the temperature variation obtained in the first step. On the contrary, the analyses carried out by means of the sophisticated finite element program ABAQUS v.6.5 (2004) allow to perform fully coupled temperature – displacement transient analyses, in which the mechanical and thermal

aspects of the problem can be treated simultaneously and the mutual interactions can be caught.
The materials are modelled considering the dependence of their physical and mechanical properties on the temperature, according to the indications of Eurocode 3, part 1-2, related to the structural fire design of steel structures (CEN, 2003).
Fixed restraints are imposed at the base of the columns; moreover an internal tie constraint, which prevents relative motions between the adjacent surfaces, is applied to the beam-to-column connection, in order to model a rigid node. Tridimensional linear thermally coupled solid finite elements with reduced integration (C3D8RT) are used in the models, which are endowed with both translational and thermal degrees of freedom.
The vertical loads on the structures are modelled through a uniform distributed pressure on the top face of the beam flange, whereas for the pushover analyses increasing lateral displacements are imposed at the top of the column.
The fire phenomenon is modelled by means of the ISO834 standard curve, which represents the ambient temperature during the fire as a function of time. The heat transmission due to radiation from the ambient where the fire develops to the external surfaces of the structural members is also modelled. All the members surfaces are considered as exposed to fire. The emissivity of steel is assumed equal to 0.5, which is an intermediate value between those of zinc-plated and oxidized steel. The temperature transmission within the structural members is modelled by assigning the thermal conductivity, the mass density and the specific heat of the material, as a function of temperature according to Eurocode 3, part 1-2 (CEN, 2003).
The seismic pushover analyses of the study structures in presence of vertical loads are carried out in order to define the state of earthquake-induced damage corresponding to the pre-fixed performance levels. In particular, the considered performance levels are quantitatively defined as it follows:

Fully Operational (FO): $\delta/h = 0.5\%$;
Operational (O): $\delta/h = 1.0\%$;
Life Safe (LS): $\delta/h = 2.0\%$;
Near Collapse (NC): $\delta/h = 3.0\%$ (NC_1); also the maximum plastic hinge rotation equal to 0.05 rad (NC_2) is considered.

The damaged states of the structures, characterizing the performance levels, are considered as initial configurations for the fire analysis, aiming at the evaluation of the effect of the seismic induced damage on the fire resistance and the collapse mode of the study structures. The seismic damage to the structure is produced by imposing, at the top of the column, a displacement corresponding to the selected performance level. Then, the imposed displacement is removed and the elastic part of that displacement recovered. As an example, a pushover curve referred to one of the study cases is shown in Figure 3, where the damage extent is indicated.

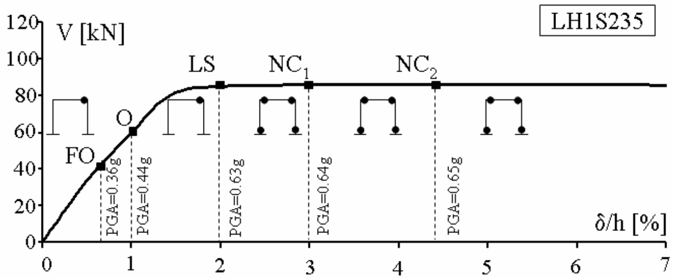

Figure 3 Example of pushover curve for the determination of the earthquake-induced damage

The fire is applied on the obtained permanent deformed configuration. The performance levels considered as starting points for the fire applications are FO, O, LS and NC_1. In all cases the collapse condition, assumed for the determination of the fire resistance of the structure, is the NC_2, i.e. achievement of a 0.05 rad plastic rotation in at least one hinge of the structure.
General results show that only in case of Life Safe and Near Collapse (NC_1) performance levels after earthquake, where the damage is significant, there is a reduction of the fire resistance, as respect to the undamaged structure, and the collapse condition, corresponding to the achievement of the maximum plastic rotation in the beam, changes, the 0.05 rad plastic hinge moving from the beam mid-span to the beam-to-column node.

5. CONCLUSIVE REMARKS AND FURTHER DEVELOPMENTS

In this paper an overview on the risk assessment of steel structures in seismic areas, which may be subjected to fire following earthquake, is briefly presented. The importance of a multi-disciplinary approach to face up the problem is recognised and underlined. The necessity of considering both a building scale and a regional scale for the management of the emergency is also pointed out.
With regard to the building scale, the necessity of integrating the fire design of steel structures into the general design process is recognised, and the Performance-Based Design is assumed as the most suitable technical approach. In this respect, some important contributions are indicated.
With regard to the regional scale, some GIS-based studies are indicated and the main peculiarities of the problem are summarized.
At last, a methodology, conceived in the framework of the Performance-Based approach, for the assessment of the fire resistance of structures damaged by earthquake in relation to different structural damage levels is illustrated. As an example of application, the study of simple steel portal frames, which applies fully coupled temperature-displacement numerical analyses, is shown.
Further studies are needed. At the regional scale, maybe one of the most important issues is the refinement of the predictive correlations between the expected PGA and the fire occurrence. At the building scale, it is compulsory to consolidate the suitable definition of performance criteria and integrated design procedures.

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