RESEARCH PRIORITIES FOR MAINTAINING STRUCTURAL FIRE RESISTANCE AFTER SEISMIC DAMAGE

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ABSTRACT :

This paper will systematically outline and prioritise the research needed to develop this important and hitherto neglected area. Fires are a relatively likely event consequent to earthquakes in urban locations and in general are an integral part of the emergency response strategies focussed on life safety in most developed economies. Similarly building regulations in most countries require engineers to consider the effect of seismic and fire loading on the structures and provide an adequate level of resistance to these hazards, however only on a separate basis. To the authors knowledge there are no current regulations that require buildings to consider these hazards in a sequential manner to quantify the compound loading and design for the required resistance. It is accepted that in many cases this may not be feasible or even desirable, but on the other hand there will be many high value structures where it would be economically and technically sensible to provide such resistance. This paper will focus on the research needs for developing consistent methodologies for addressing this issue from a structural engineering perspective. The nature of the compound hazard will be analysed first and the research effort required to adequately quantify the risk posed by this hazard will be discussed. The second part of the paper will deal with the research required for identifying possible strategies for managing the risk, which may or may not involve developing new analysis and design procedures.

KEYWORDS: Fires after an earthquake, fire resistance, seismic damage, risk assessment

1. INTRODUCTION

The risk of fires in the aftermath of earthquakes is well known. The fires following the 1906 San Francisco and the 1923 Tokyo earthquakes led to major conflagrations and widespread devastation resulting in far greater damage than caused by the original shaking. Fortunately the scale of those events have not been repeated, however there have been many major earthquakes which have been followed by fires. Nearly all major Californian earthquakes have been followed by multiple ignitions, most notably, the 1971 San Fernando and 1994 Northridge earthquakes were both followed by over 100 ignitions. The 1995 Hanshin (Kobe) earthquake was also followed by over 100 ignitions in Kobe City and a similar number of fires in other cities in a highly populated area (over 2 million) and several conflagrations developed. Scawthorn *et al.* (2005) provide a relatively comprehensive treatment of the post-earthquake fires from an emergency response, societal preparedness and disaster mitigation point of view and include discussions of the major historical fire following earthquake (FFE) events.

Another thing that comes out rather starkly from the study of FFE events is that the risk of FFE is very non-uniform. Many recent earthquakes were not followed by widespread fire events, for example 1999 Izmit (Turkey) (although a number of crude and naptha tanks burned), 2001 Gujrat (India), 2005 Kashmir (Pakistan and India) and 2008 Wenchuan (China) earthquakes were not followed by significant fire events. The level of urbanization and industrialization may be an obvious factor which possibly explains this anomaly (most certainly for the relatively remote and backward mountainous regions of Kashmir – even here, however, the main market in the town of Uri suffered a major fire following the earthquake which caused extensive damage). There may be other factors that are responsible for this apparent anomaly but a full explanation perhaps requires a careful and detailed study of the kind by Scawthorn *et al.* (2005). If urbanization (and concomitant density of gas, fuel and electrical supply networks) is indeed one of the key reasons, the risk of fire after earthquakes must be considered as a rapidly increasing risk to life, livelihoods and to the sustainability of growth and development in some of the world's most densely populated regions. With an increasing integration of the world economy major disasters of the future could have repercussions far beyond the local region. FFE events have the potential to create such disasters and should certainly be considered in the overall disaster mitigation strategies by governments and agencies with such a remit. This clearly includes issues concerning preparedness, emergency response and management, short term relief and reconstruction etc. however this is not the focus of this paper.

This paper specifically intends to highlight another major anomaly that currently exists in structural engineering practice. Although structural engineers in seismic regions of the world have access to the most sophisticated design tools and technologies for ensuring structural safety in the event of an earthquake, they routinely stop short of considering how a post earthquake fire might affect the ultimate performance of an otherwise efficient energy-dissipating design, often achieved at the cost of some residual damage in the structure. This does not mean that the structures in earthquake regions are not designed for fire, indeed they are, the problem however is that the fire design is currently completely independent of the seismic design. If one considers that the risk of occurrence of a fire is significantly greater after an earthquake, than under normal conditions, it has to be accepted that the current state of affairs, where an FFE event is completely ignored in all routine seismic design, is indeed a strange anomaly.

There are historic reasons for this anomaly, which are primarily to do with widely prevalent and continuing inadequacies in the practice of ensuring the safety of structures in fire. This has typically been the domain of the architect or the fire protection engineer (in the United States) often with no involvement from a structural engineer beyond perfunctory specification of fire protection based on simple look-up table type code prescribed rules. For example, consider the following facts:

1. Barring rare exceptions nearly all structural design for fire is carried out without any demand or capacity calculations
2. Structural fire resistance (capacity) is almost universally described in terms of material behaviour at

high temperature and design of a structural member is restricted to providing sufficient "passive fire protection" to ensure that it does not reach some limiting temperature over a code-specified time period when subjected to a code-specified "standard" fire in a test furnace.

3. Standard fires do not represent natural fires (actual demand), therefore the design fire resistance time (such as 90 minute fire resistance) has no meaning in the real world and at best it can be seen as a relative rating between two systems, but only if it could be assumed that the test furnaces the systems are tested in, provide the same exposure (which is also doubtful, as it has been shown on numerous occasions that supposedly identical standard fire exposures in any two given furnaces can vary significantly in practice).
4. As fire resistance design is exclusively focused on material properties at high temperature, it fails to account for two very important aspects of structural response to fire: a) whole structure response, as no account of structural redundancy and alternative load carrying mechanisms is taken; and b) the geometric changes in structural members to heating, as thermal expansion effects that can have a profound effect on the overall system response are completely ignored.
5. Although generally conservative, because of the reasons discussed above the traditional design process cannot provide any reasonable estimate of the real performance of the structure in a real fire and therefore the level of safety available against the risk of limit states, such as collapse, is simply unknown.
6. The cost of fire protection, especially for steel frame composite structures, constitutes a substantial proportion of the structural frame cost and represents poor value for money. In most cases quantifiably safer designs could be achieved, at much lower overall cost, if passive fire protection is more selectively applied using proper demand and capacity calculations as part of a rationally developed performance based design framework (very much like it is done for earthquake or wind loads, for instance).

Considerable research has been undertaken around the world in the last decade and a half (perhaps most notably in Europe, for example University of Edinburgh (2008) and University of Manchester (2008)) to expand the knowledge base and develop methods and technologies that would enable the development of a proper performance based approach for design of structures in fire. However relative to earthquake engineering, structural fire engineering is still in its infancy and there is a huge need of coordinated research covering the whole spectrum of issues. This paper will look at some of the specific issues that need to be addressed for the particular case of FFE and make recommendations for the kinds of research that should be undertaken to advance this field leading to the eventual integration of seismic and fire design practice. There is very little existing literature in this area. Most of it focuses on lifelines issues and on reducing the frequency and severity of FFE events and does not directly consider the effect of fire on structures damaged in earthquakes. Two works that briefly discuss this issue, while maintaining the broader lifelines focus, are Mousavi *et al.* (2008) who provide a review of the current state-of-the-art and make recommendations for research for buildings subjected to post-earthquake fires. Taylor (2003) offers a New Zealand perspective of the problem. This paper will endeavour to retain its focus and discuss this problem from a purely structural engineering perspective and offer recommendations for future research so that this problem can be addressed in a rational and systematic manner.

2. SEISMIC DAMAGE CHARACTERISATION FOR ESTIMATING FFE RESPONSE

Response of structures subjected to an FFE event will depend very much on the magnitude, location and type of structural damage caused by the precursor event (earthquake). Clearly this is a very broad and complex issue as it depends upon a very large range of factors, such as:

1. Type of structure (commercial or residential multi-storey buildings, very tall buildings, industrial structures, transport structures – all of these could be exposed to FFE events unlike normal fires which tend to occur in enclosures or "compartments")
2. Material of construction (steel, concrete, composite, timber, masonry, retrofitted structures etc.)
3. Type of structural system (low-redundancy structures to high-redundancy moment-resisting frame,

braced frame, shear-wall frame etc.)

4. On a local level connections details in particular structures could be seen as another important and separate issue as seismic damage is often located at or near connections. Connections also play an important role in structural response to fire.

The permutations of the above present an enormous range of complexity to be investigated. It is beyond the scope of this paper (and the ability of the author) to cover the implied range of problems with any level of completeness and this will remain work in progress within the small (and hopefully growing) community of FFE researchers. To set the ball rolling some problems that the authors considers most important are discussed in the following subsections.

2.1. Concrete constitutive models at ambient and elevated temperatures

Adequate constitutive models exist for characterising mechanical deformations under loading for most materials that can be used in computational structural mechanics models. The development of better models for concrete has historically dominated this research. At ambient temperature we now have relatively good models for concrete that perform quite well under a large range of loading conditions (accounting for multi-axial stress states and damage during load reversals). These models (such as Feenstra and de Borst 1996) can capture the key features of behaviour (for example strain softening and localisation effects are captured by relating the softening parameter to the ratio of fracture energy and some measure of element size ensuring that the results are mesh size independent). A good description of plasticity based concrete models appears in Jirasek and Bazant 2002. More advanced models combining plasticity and damage mechanics (continuum damage mechanics) have become popular over the last two decades and are still developing. At elevated temperatures ambient temperature constitutive models are typically extended using uniaxial test data (widely available for steel and concrete). The author is not aware of any multi-axial testing of materials at elevated temperatures that could assess the adequacy of this approach. There are other well-known in issues that are unique to material response at high temperatures. Both steel and concrete exhibit accelerated creep at high temperature. This effect is particularly strong in concrete under high compressive stresses (called transient thermal creep). Another big issue in concrete at high temperature, for which there are currently no reliable models, is spalling (from mild scouring to violent ejection of surface layers of concrete outside the reinforcement cage to, in some cases, explosive ejection of large volumes of concrete in deeper layers through the reinforcement cage – seen in tunnels, perhaps in sections under high compressive stresses). This effect seems to depend upon the moisture content and compressive stress in the concrete. No adequate constitutive models exist that could model these phenomena properly and constitute a major research challenge for advancing structural performance estimation in FFE events.

2.2. Effect of damage in materials on thermo-mechanical response

Clearly FFE response of structures will depend significantly upon the seismically induced damage in the materials that make up the structure. There is large repository of knowledge about structural performance in real earthquakes and possibly and equally large database of results from dynamic testing of structures around the world and therefore the level of damage that a given earthquake may inflict on a given engineered construction is probably relatively well understood. This damage level can also perhaps be adequately simulated using currently available material models (particularly continuum damage mechanics based ones) and computational software. It is however unclear what effect a fire will have on a structure with an arbitrary level of damage. It is reasonable to assume that a lightly damaged structure will typically perform better that a heavily damaged structure, however the limits of what light or heavy damage means in this context needs to be defined. This work is clearly fundamental to developing our understanding in this area. Here again if we are dealing with RC buildings new constitutive models may have to be developed for damaged reinforced concrete under multi-axial stress states at elevated temperatures.

2.3. Structural failure mechanisms on exposure to FFE events

The previous two subsections focused on material damage issues at elevated temperatures, which typically are of pivotal importance in terms of the global structural response and the eventual failure mode in earthquakes (often through formation of a sufficient numbers of hinges creating a mechanism). Global structural failures are less common as a result of fires, it is however unclear if fire played a major role in structural failures in past earthquakes, and if so, what sort of failure mechanisms manifested themselves. This question can only be answered by carrying out carefully designed experiments on structural frames with varying levels of damage and subjecting them to fire and of course analysing the results with the aid of computational models of the experiments. Hybrid simulation and testing of the type carried out by the Nees consortium in the USA (see for example http://nees.colorado.edu/Presentation.php) can be an excellent tool for understanding fire induced failure of earthquake damaged structural frames. Such modelling makes possible the testing of a full-scale sub-structure connected to actuators which are driven by a numerical model representing the rest of the structure, in real time, if required. The earthquake damage could first be applied to the sub-structure followed by a fire. Parts of the substructure exposed to the fire could be enclosed in a fire-proof containment in order to protect the actuators and other equipment or heating could be applied locally to appropriate components of the sub-structure by radiant heaters.

2.4. Other important issues relating to response of structures to FFE events

In many seismic regions of the world that are not so developed as USA and Japan, there are a large number of structures that have not been designed or even constructed properly and represent virtual death traps for their occupants. Even in USA and Japan there is a lot of older building stock that is likely to sustain significant damage in an earthquake. In these countries and other developed countries however there has been a steady growth in retro-fitting and strengthening such structures to improve their expected performance. These structures will have their own peculiar problems when exposed to an FFE event depending upon the scale and type of strengthening carried out. For example if a concrete column has been repaired using FRP wraps to provide confinement, it may see off the earthquake with little externally apparent damage, however a fire later on could burn the FRP off very quickly, possibly exposing badly damaged concrete inside exposed and lead to collapse through loss of confinement. Masonry and timber structures will also present different challenges and will require a similar effort in understanding their performance in FFE events. In less developed areas of the world FFE events may not be as likely, however in rapidly developing economies such as China and India FFE threat will continue to increase and sooner or later will have to be addressed. In the interim perhaps their overwhelming priority must be to upgrade the seismic performance of the large majority of their existing building stock in order to minimise life loss and major destruction in a future big earthquake.

3. FFE DEMAND CHARACTERISATION

Type and source of fire exposure in an FFE event can potentially vary a great deal (internal – as in ignition inside the structure, external – as in ignition outside in close vicinity of the structure through gas leaks, electrical short circuits, smouldering or open flame household appliances or decorations, flammable liquid spillage etc.). This means that FFE demand must be handled in a risk-based framework, where the most likely causes of ignition and sources of fuel could be identified a-priori and risk reduction measures be undertaken in a systematic manner including designing the structure to perform adequately in an FFE event. It is doubtful if the usual fire safety provisions in a building can be relied upon following an earthquake. One could perhaps rely upon fire protection on structural members (foam, board, intumescent paint etc. – clearly some may perform better than others) to remain intact, however the same could not be said about other passive measures such as compartmentation and active measures such as sprinklers or electrically operated devices such as fans and vents. Kobe City Fire Department (1995) reports that from 10 to 40% of fire all active fire protection systems in the city surveyed were found damaged and inoperable. All of these should be considered in assessing the FFE risk to a structure and estimating demand. For estimating structural response, the fire exposure must also be translated to structural temperatures, which will typically only affect parts of the structure at a time and could be relatively non-uniform in space and evolve over a period of time.

4. PERFORMANCE BASED ENGINEERING

As mentioned earlier, the overwhelming complexity of the FFE problem demands clever and novel approaches to achieve satisfactory solutions. The PEER (Pacific Earthquake Engineering Research Centre - see http://peer.berkeley.edu/index.html) performance based earthquake engineering (PBEE) methodology is an excellent example of such an approach (see for example Kunnath (2007)). The PEER-PBEE evaluation framework is shown in Figure 1 below. This represents a holistic approach to the problem and takes into account the whole range of associated issues, from: probabilistic quantification of the hazard in terms of intensity measures (IM) based on local seismological characteristics; followed by structural analysis to determine probable structural response (given specific IM) in terms of engineering demand parameters (EDP); EDP are then used to make probabilistic estimates of damage (DM); and finally using DM estimation of losses and repair costs etc. are arrived at, which serve as probabilistic decision variables (DV) and help stakeholders to make informed decisions about the level of performance they require from the structure.

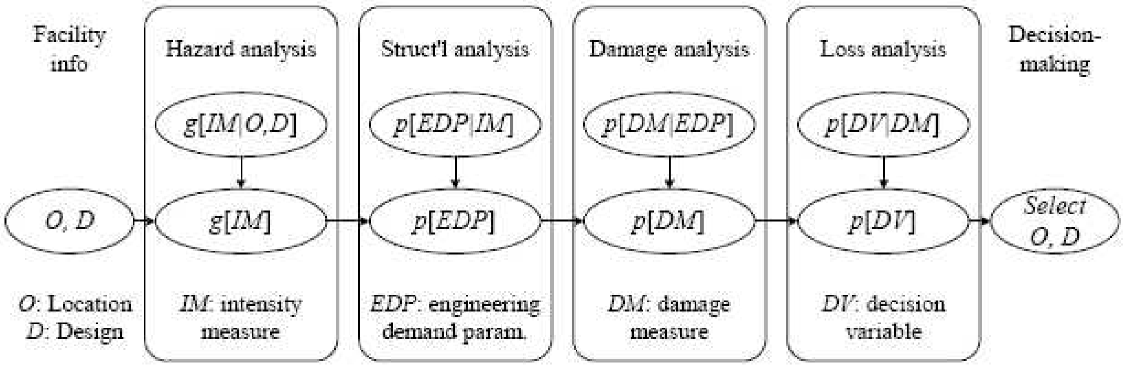

Figure 1. PEER-PBEE framework (from Kunnath (2007))

Hamilton *et al.* (2002) have proposed the application of such a methodology for fire as shown in Table 1 below. This methodology can conceivably be extended to provide a suitable framework for FFE design by including FFE specific issues at all stages (examples of this are shown in italics in Table 1). To achieve this, a considerable amount of work needs to be done as this methodology, although considered to be state-of-the-art, is still very much in the realm of research and development. Much work is being done, particularly by North American earthquake engineering researchers to develop case studies demonstrating applications of this methodology to real engineering problems, see for example Kunnath (2007) and the PEER (2008) funded projects webpage. None of this work has so far been extended to structures in fire, although some aspects of this work overlaps with the general area of *probabilistic safety analysis* (PSA), for example see Fullwood (1999). Some of the key developments that need to occur for the PEER methodology to be extended to include FFE events and to be widely accepted by practicing engineers are:

- a comprehensive characterisation of uncertainties related to fire hazard and structural response to fire;
- extending this to the compound FFE hazard (likely to be a considerably more complex problem);
- developing fire and FFE damage fragility functions for structures of interest;
- developing a database of case studies applying PEER methodology to structures in fire and FFE events;
- providing a public domain software (such as OpenSees (2008), after upgrading it to also model structures in fire) to help engineers perform most of the required deterministic and probabilistic calculations

Each of the above items involve research tasks that would require 100s of man years of work ideally carried out by multiple teams in international collaborations involving theoreticians, numerical modelers and experimentalists with good lab facilities for FFE type testing (practically none exist for this specific purpose).

PROCESS	VARIABLE	DISCIPLINE	PARAMETERS	EXAMPLES
Fire Hazard Analysis *including FFE hazard*	IM	fire protection engineering *or fire safety engineering* *seismology/geotechnics/ building services engineering*	- likelihood of flashover fire compartment geometry and thermal properties - ventilation - fuel load & burning rate - fire insulation - structural configuration and fire exposure - *potential FFE ingnition sources, compartmentation loss and fire spread* - *likelihood of conflagration*	• maximum temperature of steel/*concrete* • compartment gas time-temperature curve • normalized heat load … • *mapping of structural fire exposure against corresponding damage*
Structural Analysis	IM→EDP	structural engineering	- structural model - fire scenario & steel/*concrete* temperature distribution - steel/*concrete* mechanical and thermal properties *(before and after damage)* - applied gravity loads	• component forces • inelastic deformations • deflections • *mechanical & thermal deformations & strains*
Damage Assessment	EDP→DM	Structural and fire prot. engineering; construction *& building services*; architecture; loss modeling	- damage fragility curves of smoke and thermal barriers *(or compartmentation)* - damage fragility curves of structural components *for compound seismic and fire actions*	• strength limit states • structural damage (repair) states • barrier breach • local or global collapse
Loss & Risk Assessment	DM→DV	construction & cost estimating; risk assessment; loss modeling	- occupancy - alarms and egress efficiency *(or quality of emergency response)* - fire duration/endurance - *external factors (e.g. risk of conflagration)*	• casualties (occupants, first responders) • direct $ losses • repair time/downtime

Table 1. PEER-PBEE framework applied to structures in fire (from Hamilton *et al.* (2007)) *including FFE*

5. CONCLUSIONS

A very brief overview of the problem of structural performance in FFE events has been provided with a view to encourage debate and foster new ideas for initiating good quality research in this area. Admittedly this is by no means a thorough analysis of the research needs in this area however it is hoped that it will be a useful first attempt for initiating discussion towards developing a comprehensive research program on an international level. The complexity of the problem clearly demands such an approach that will involve specialists in many areas coming from all corners of the world as much of the research to be undertaken on structures subjected to FFE events will be cross-disciplinary.

One of the major spin-off benefits of increased activity in FFE research will be the energising of the traditional structural fire engineering discipline which will help it to develop much faster by significantly augmenting the number of researchers in this area and by importing ideas and technologies from earthquake engineering and bringing structural fire engineering squarely within the domain of the structural engineering, where it surely belongs.

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