THE RELEVANCE OF STRUCTURAL FIRE PERFORMANCE IN EARTHQUAKE DAMAGED STRUCTURES

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Abstract

Earthquakes and fires are low probability, high consequence events. Although, traditionally careful consideration is given to the design of structures to separately withstand the occurrence of both of these events, little or none attention is given to the potential structural vulnerabilities arising from their combined occurrence. Fires following earthquakes or post-earthquake fires can result in severe threats to the structure of a building and its lifeline. Several studies have actually shown that this combined event state is not a rare situation. This papers examines the potential relevance of structural fire performance, and the design for it, in earthquake damaged structural systems.

The mechanical degradation (e.g. reduced stiffness and load bearing capacity) of a structure after an earthquake can have a negative influence in the structural fire performance of the building. Prior studies on structural fire safety have concluded that thermally induced forces and deformations, and not mechanical degradation governs the structural fire performance. Furthermore, heating of structural elements may or may not be reduced by earthquake induced damage of the structural elements; e.g. cracking of concrete cover insulating reinforcement, effectiveness of steel intumescent coatings. Besides, damage generated by relatively large? deformations induced by earthquakes can result in fatal failure of non-structural components (e.g. fire-safe compartmentation, active fire protection systems); thus having a direct influence in the fire dynamics of a post-earthquake fire.

The design philosophy of both engineering practices (earthquake and fire engineering) can differ in essence. Earthquake engineering lays under the premise that the structure should withstand the full duration of a “design earthquake,” and it does so by explicitly limiting the structural response in the spatial-domain (e.g. inter-floor drift, acceleration). Contrary, structural fire engineers assess fire performance on the basis of rating of elements in the time-domain, i.e. time resisted during a fire resistance test; this last is known as the Fire Rating; 30, 60, 90 min or more.

Outcomes of this study evidenced the need for developing structural design guidelines explicitly considering the fire performance of structures after an earthquake. In addition, comprehensive analytical and numerical analysis tools need to be developed and validated against experimental data; the partial results of proposed studies are examined and discussed. Throughout the work presented herein, reinforced concrete structural systems are used as an exemplar to highlight the matter of analysis.

Keywords: structural fire safety; post-earthquake fire; engineering; structural design.

1. Introduction & Background

Earthquakes and fires are low probability, high consequence events. Although, traditionally careful consideration is given to the design of structures to separately withstand the occurrence of both of these events, little or none attention is given to the potential structural vulnerabilities arising from their combined occurrence. Fires following earthquakes or post-earthquake fires can result in severe threats to the structure of a building and its lifeline. Several studies have actually shown that this combined event state is not a rare situation [1]. This paper examines the potential relevance of structural fire performance, and the design for it, in earthquake damaged structural systems.

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2. The Fire 'Problem'

The need for optimization, energy efficiency, sustainability, novel architecture, and creativity are forcing rapid evolution in the use of new construction techniques, innovative materials, and ground-breaking designs in building construction. Modern building design occurs within a flexible and dynamic environment that supports iterative design processes in an open, knowledge-based, responsive dialogue [2]. Those charged with the design of fire safe structural systems are rarely (and often insufficiently) involved in this iterative process; all too often fire safety practitioners participate only on the periphery of the design process, sometimes with the goal of gaining regulatory approval – thus constraining the design to align with prescriptive fire safety measures which are presumed to provide adequate fire safety. The result is a sub-optimal relationship between the overall design (including earthquake resistant structures) and the structural fire safety considerations.

Since the development of early building codes [3], fire safety design and regulation of buildings has been founded on the concept of 'compliance,' wherein the design of individual building elements is required to comply with 'acceptability' criteria given in building codes to ensure that buildings provide a presumed, however typically unquantified, level of fire safety [4]. This non-integrated prescriptive approach presents fundamental issues for the current and future construction environment; in this context fire safety tends not to be part of the optimization process involved in design, but rather an additional set of requirements imposed on an otherwise optimised design process. In such a process, fire safety considerations will act as constraints and are likely to be perceived primarily as barriers to one or more other design goals such as material optimization, energy efficiency, sustainability, or architectural expression.

The fire safety community (both in research and in practice) has also recognized the need for integration and has reacted to the on-going evolution of buildings and the building design process. During the past few decades, global efforts have been made to develop and implement performance-based approaches for fire safety design [5-8]. The use of performance-based fire engineering design approaches is now commonplace in many jurisdictions (e.g. [9]). However, many building design professionals (e.g. structural engineers, architects, etc.) still fail to recognize fire safety as an explicit design variable [10]. Notwithstanding a small number of particularly enlightened building design firms, fire safety practitioners are rarely considered integral members of the larger design team. Despite the efforts and resources expended, the fundamental regulatory constraint of designing for a presumed equivalent level of safety as that 'demonstrated' by structural elements in a standard fire resistance test simply results in 'sophisticated' tools being used to design against a simplified performance criterion; i.e. design a structural element so as to achieve a prescribed time to 'failure' during a fire resistance test, rather than design a structural system to perform 'satisfactorily' in a real fire.

2.1 Post-earthquake fire dynamics

While from a structural point of view a successful earthquake proof design requires the building to withstand the consequences of a certain design earthquake without the rupture of any load bearing elements, it does not require internal compartmentation to be maintained. This can potentially have severe consequences from a fire dynamics point of view. Compartmentation is usually an integral part of performance based design strategies, that allows for an effective way of smoke management and fire containment. If internal walls fail due to the action of an earthquake, a potential fire might spread out of control, and otherwise safe egress paths might be filled with smoke, thus compromising the evacuation of occupants from the building.

2.2 Concrete – A fire safe material?

Structural engineers have historically relied on concrete's inherent fire safety characteristics (e.g. non-combustibility, non-flammability, high thermal inertia) for the fire safe design of concrete structures. As described above, structural fire resistance testing is characterized by the use of outdated procedures developed many decades ago. The construction industry is, however, evolving rapidly on an ongoing basis. Versatility, ease of construction, low skilled workmanship in production, 'good' mechanical properties and "inherent fire endurance" have all contributed to concrete becoming amongst the most widely used construction materials in the world [11]

Most contemporary advances in concrete technology have been driven by the need to build faster and higher, to reduce cost, and to increase structural service life. As in various other areas of engineering, the need to produce a more environmentally friendly material with lower embodied energy and carbon footprint has become an increasingly relevant driving force in the building construction industry [12]. Rapid advances in the engineering properties of both fresh and hardened concrete have partly been achieved by research and development into its constituents and admixtures. An example of this is the use of cementitious admixtures (i.e. supplementary cementing materials) such as silica fume and fly ash, which were previously considered waste materials but have become common for partial replacement of Portland cement in concrete [13,14].

The fire performance of typical reinforced concrete structural systems is generally accepted as being defined in terms of the temperature of reinforcement and hence the concrete cover provided. The required concrete cover to achieve a certain fire resistance can be obtained directly from design guidelines [15], or by assessing the heat transfer within the depth of the concrete elements. However, for earthquake damaged structures, the above presents a drawback as it does not account for the concrete cover has undergone some damage prior to a thermal load, nor the potential for a reduced load-bearing capacity; this is discussed later in the paper.

3. Structural Fire Safety Engineering

Fire safety considerations in the design of buildings' structural systems have traditionally been based on the concept of 'compliance,' wherein the design of individual structural elements is required to comply with specified 'acceptability' criteria, with little consideration to the ideal iterative, knowledge based process described above; this is likely to result in inefficient and sub-optimal designs. A broader view of the potentials for integrated fire safety design considerations throughout the design of contemporary buildings has been presented by Maluk [16]. This general idea is clearly not unique to fire safety design in buildings, as others have extensively reflected upon the current state and potential benefits of an integrated approach to design on structural optimization, life cycle cost, energy saving, climate control, lighting, acoustics, and various other relevant design considerations [17,18]

The current building construction industry has ‘solved’ most problems by operating within a structure in which architects and structural engineers, whether aware of it or not, have the means to design, with little or no rational engineering judgement, structural elements that comply with the prescribed fire safety performance criteria defined by the regulatory authority having jurisdiction (e.g. [19]). More than a century of research and development in structural fire testing has essentially converged into widespread use of the standard fire resistance test (i.e. large scale furnace test) as the means to experimentally rate (in the artificial time domain of ‘fire resistance’) the load bearing capacity of a structural element exposed to a ‘standard’ fire. The result is a simplified, comparative regulatory system in which the true performance of materials and structures in real fires is rarely questioned (or known, or acknowledged). Additionally, while structures admittedly fail only very rarely in fires, when they do fail it is almost always for reasons that would not be expected on the basis of standard fire resistance testing (e.g. unexposed column that grows eccentric because of thermal expansion due to fire in an adjoining beam). This shows that the complexities of real fires in real buildings are not captured in standard fire resistance tests [20].

> *“Most of the existing tests had to be developed by trial and error, and they are open, it is true to the objection that they do not truly indicate how a material will behave in an actual fire. They may tell us which is the better of two materials, but not whether one or both is good enough for the job.”* [21]

3.1 Fire Resistance Rating

The late 19th Century, an era of rapid innovation within the construction industry, brought on by novel structural designs with structural configurations and materials developed in an effort to save space and build higher, promoted the early developments of supposed “fire-resistant” construction [22]. So-called “fire and water” tests became common practice for manufacturers of these emerging fire resisting materials and systems, who attempted to advertise their products’ “fire proof” characteristics by resorting to whatever they considered a satisfactory means of demonstration (e.g. [23]); this approach soon (and predictably) became unreliable [16].

The subsequent establishment of federal, municipal, and private experimental testing facilities, with recognised credentials and purported impartiality, introduced an environment in which testing facilities could systematically test materials and systems under presumed ‘uniform’ conditions, initially for the purposes of comparative examination only. At the time that these test methodologies were conceived, no standard failure criteria were defined for tested elements, although techniques for the assessment of load bearing capacity, integrity, and insulation where already common practice [24].

At the turn of the 20th Century, efforts were made both by American and European testing organizations, as well as by other stakeholders involved in the building construction community, to define a uniform ‘standard’ fire resistance test (e.g. [23,24]). As indicated by Ira Woolson, then Chairman of the National Fire Protection Association’s (NFPA) Committee on Fire-Resistive Construction, the overarching goal of these efforts was to “unify all fire tests under one single standard and remove an immense amount of confusion within the fire testing community” [25].

In 1903, at the International Fire Prevention Congress held in London, UK, Edwin Sachs presented a set of suggested standards for a fire resistance test which proposed the use of an essentially arbitrary “fierce” fire represented by a sustained minimum temperature over a defined period of time (1500°F or 1800°F, equivalent to 816°C or 982°C, respectively), as well as suggesting minimum requirements for ‘fire resistance’ of structural elements, for which the level of ‘protection’ was classified as ‘temporary’, ‘partial’ or ‘full’ [26].

In the US, a standard testing methodology was gradually adopted during the 1920s, as seen in transcripts of the discussions which took place at several annual NFPA meetings [25]. At the 1917 NFPA annual meeting, Woolson stated that; “we want to get it as nearly right as possible before it is finally adopted, because, after it is adopted by these various associations, it will be pretty hard to change it” [25]. A tentative standard time-temperature curve was proposed at the 1917 NFPA annual meeting and presented for final adoption in the subsequent annual meeting [27]. The time-temperature curve (see Fig. 1) was delineated by "points on the graph" defined by a committee composed by numerous technical bodies with 'interests' in the subject (e.g. NFPA, American Society for Testing and Materials, Underwriters' Laboratories, Association Factory Mutual Fire Insurance Companies, American Institute of Architects, American Society of Civil Engineers, American Concrete Institute). The actual source behind the selected "points on the graph" remains unknown by the author of this thesis. Since it was originally adopted in 1918, the standard time-temperature curve has been basically unchanged and is now widely used in modern fire resistance testing standards (e.g. [28,29]).

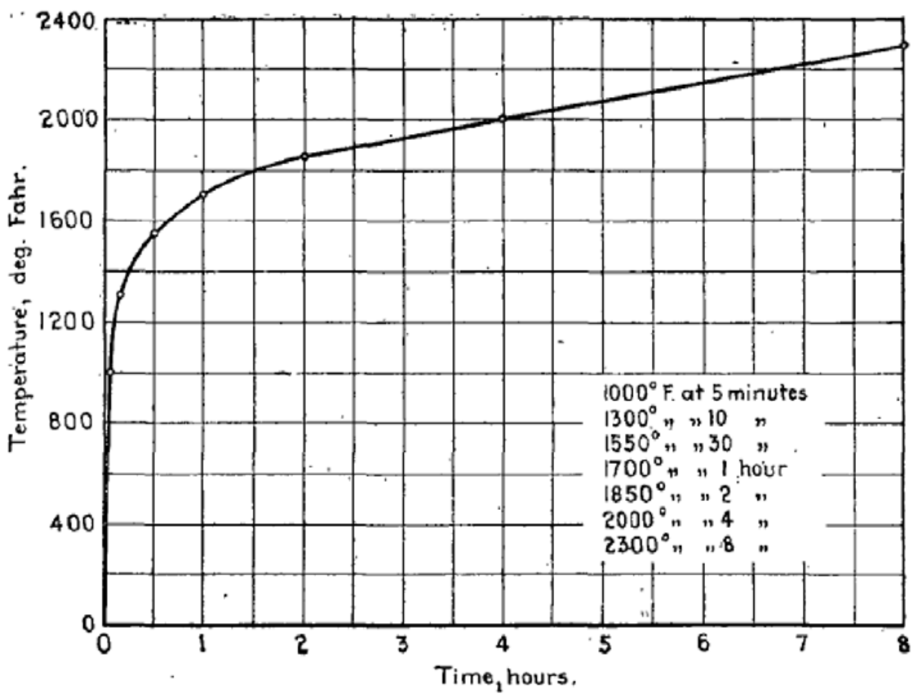

Fig. 1 – Standard time-temperature curve presented for adoption at an NFPA annual meeting (NFPA 1918).

With an agreed standard fire resistance test methodology, subsequent decades saw the fire testing community experience considerable growth (and thus to develop considerable inertia) in the number and cost of standard fire testing facilities and the amount of large scale experimental studies carried out around the world. Early versions of 'standard' testing furnaces were capable of testing mechanically loaded specimens during heating [30].

In 1928, based on recognition that the standard time-temperature curve was not a 'real' fire, Simon Ingberg presented a method for quantifying a fire's 'severity' resulting from burnout of all the combustible contents in a compartment [31]. Ingberg attempted to correlate this to the severity of heating imposed during the standard fire resistance test. To do this he introduced the 'Equal Area Concept', which in theory allowed designers to define the required time of standard fire resistance (derived from a furnace test) for structural elements based on the actual fuel load within a given compartment [32]. This was accomplished by equating the total area under the real fire's time-temperature curve (measured during numerous full scale fire tests in compartment fitted with office furniture) to the area under the standard fire curve for a given duration of standard fire exposure (see Fig. 2).

Despite it not being obvious at the time, Ingberg's publications on this topic fundamentally (and unfortunately) linked the concept of 'time' to the performance objectives used to define the 'fire resistance' of structural elements. In the decades that followed, alternative severity metrics were introduced, and in some cases adopted, by the structural fire engineering community. These included: the 'Maximum Temperature Concept', the 'Minimum Load Capacity Concept', and the 'Time Equivalent' Formulae (e.g. [33]); however, all of these were fundamentally linked to results from isolated elements tested under the 'standard' time-temperature curve.

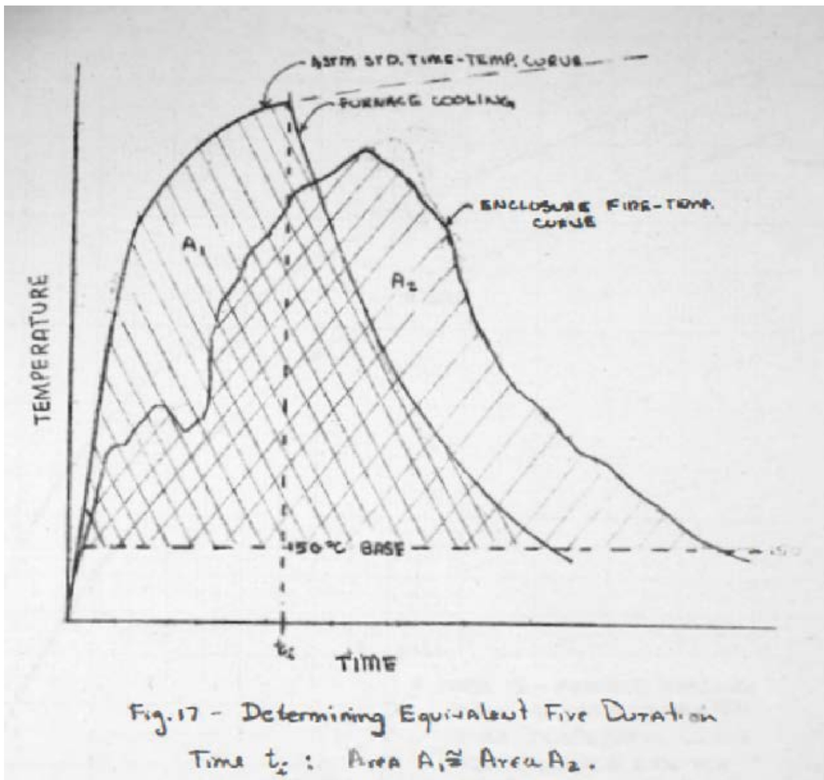

Fig. 2 – Illustration of the 'Equal Area Concept' concept for determining equivalent fire duration; at time t_i area under the curve $A_1 \approx A_2$ [32].

4. Post-Earthquake Structural Fire Performance

The hazard associated with a fire event following an earthquake is associated to the probability of the events. The occurrence and the magnitude of earthquakes are defined by various factors, which boil down to return periods. The probability and severity of a fire event following an earthquake can be based on a range of potential fire scenarios. To yield an appropriate design, the fire safety strategy of the building is done with a level of redundancy and reliability. The integrity of the structural system as a whole is essential so the structural system may resist until complete burnout of the fire. Furthermore, recent studies clearly show that novel structural systems (e.g. optimized, with high level of utilization, slender) may not exhibit the typical level of fire performance as that of conventional structures [16], nevertheless these systems are increasingly used in seismic regions. Adequate research is needed in this area to ensure that these structural systems can be used with confidence in seismic regions.

Structural loads, such as earthquakes, may cause widespread damage to structural and non-structural components. For example, when designing earthquake resistant load-bearing reinforced concrete structural systems there is an allowable capacity for plastic deformations to occur. Localised effects, such as tensile cracks at the fibres in tension, can arise from plastic deformations yield during an earthquake; thus potentially compromising the insulation capacity of the concrete cover. This simple concept results in a major discrepancy for applying traditional design guidelines for designing fire safe concrete, when dealing with earthquake damaged concrete structures.

A simplified assessment of the structure can be made in the mechanical domain; with damage being quantified by means of strength and stiffness reduction, in areas of the structure which undergo plastic deformation. The cyclic loading, in the plastic range, during earthquake also induces a reduction of mechanical properties. Nevertheless, if the structure is sufficiently strong, plastic deformation demand could be relatively small also for the design earthquake. It is apparent that, in such a case, the mechanical type of damage is actually negligible.

The fire response of the structure is defined by thermally-induced changes of the mechanical properties, and the developments of thermal expansion [34]. However, the interaction of these two parameters has a significant impact on the response of a structure. This interaction is a function of the bulk temperature increase within the material and thermal gradients. The temperatures and thermal gradients are a function of the thermal boundary condition, which is in essence the “size of the fire”. Where the temperature distribution of an unrestrained structural element is simplified to a one-dimensional (through- or in-depth) heat transfer analysis, a linear thermal gradient will result in a member curvature. Where a thermal gradient is non-linear, this will result in the development of internal mechanical strains within the depth of the structural element; these strains (or rather, the force and moment induced by them) must be resolved in order to maintain static equilibrium of the structural element. As described herein, the level of complexity required for assessing fire performance of structural systems is not simply based on the concept of rating induvial elements in the time domain.

5. Concluding Remarks

The outcomes of the work presented herein evidenced the need for developing structural design guidelines explicitly considering the fire performance of structures after an earthquake. In addition, comprehensive analytical and numerical analysis tools need to be developed and validated against experimental data; the partial results of proposed studies are examined and discussed.

The concept of the standard fire resistance test, a central pillar of the contemporary compliance-based structural fire safety design of buildings, is not aligned with the need for explicitly quantified performance required for the analysis of post-earthquake structures. Poor repeatability, unrealistic and/or inappropriate boundary conditions, and poor statistical confidence are problematic issues regarding the use of standard fire resistance tests, both for regulatory compliance of contemporary construction techniques and materials, and for rational, scientific structural fire engineering research.

Finally, damage generated during an earthquake can have fatal failure of non-structural components (e.g. fire-safe compartmentation, active fire protection systems); thus having serious effects the fire dynamics of a post-earthquake fire. The thermal insult and fire spread in a fire where compartmentation cannot be assured may be significantly different to that yield by a fire where compartmentalization can be assured.

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