Towards a Multi-hazard Framework for the Design of Taller Timber Structures

Christian Viau[1](✉), Onur Kaplan[2], Abla Krouma[3], Gabriele Tamagnone[4], Daniel Brandon[5], Felix Wiesner[6], Tuba Tatar[7], and Daniele Casagrande[8]

[1] Department of Civil and Environmental Engineering, Carleton University, Ottawa, ON, Canada
christian.viau@carleton.ca
[2] Institute of Earth and Space Sciences, Eskisehir Technical University, Eskisehir, Turkey
[3] Department of Civil Engineering, University of Ottawa, Ottawa, ON, Canada
[4] Mechanics and Civil Engineering Laboratory, University of Montpellier, Montpellier, France
[5] Division of Fire Safety Engineering, Lund University, Lund, Sweden
[6] Department of Wood Science, University of British Columbia, Vancouver, BC, Canada
[7] Department of Civil Engineering, Sakarya University, Sakarya, Turkey
[8] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy

Abstract. Multi-hazard events, though infrequent and rare, are responsible for a substantial portion of global economic losses. This book chapter investigates the complexities of multi-hazard events and explores the design challenges and methodologies in multi-hazard risk assessment and structural resilience for wooden structures. Special attention is given to the interaction between earthquakes, fires, and blast loads on timber structures, highlighting the state of the art, the gaps in current research, and the potential for probabilistic design and analysis approaches to enhance understanding and improve structural resilience and robustness. The limitations of existing design codes and standards are reviewed and frameworks for assessing cumulative damage and risk under multi-hazard scenarios are discussed. The book chapter aims to provide the state of the art on the topic and guide future research and practical applications in designing timber structures capable of enduring multiple hazards, thereby enhancing the safety and sustainability of the built environment.

Keywords: Timber · Seismic · Fire · Blast · Multi-hazard · Design

1 Introduction and Background

Multi-hazard events, which involve the simultaneous, cascading, or cumulative occurrence of multiple natural hazards, pose a serious threat to human lives and property. This danger arises mainly from the cumulative and cascading impacts caused by the interaction of different natural hazards across space and time. However, identifying these events is difficult due to the complex interactions between hazards and the limited availability of multi-hazard data. Globally, about 19% of the 16,535 disasters recorded

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in the EM-DAT Database in the last decade are classified as multi-hazard events [1]. The identified multi-hazard events were reclassified into four distinct categories: (1) preconditioned/triggering events, (2) multivariate events, (3) temporally compounding events, and (4) spatially compounding events. These multi-hazard categories were primarily based on the typology that classified compound events into preconditioned, multivariate, temporally compounding, and spatially compounding categories [2]. Despite their lower occurrence, these events are responsible for nearly 59% of the estimated global economic losses, while single hazard events tend to result in higher fatalities [1]. Most multi-hazard events are associated with floods, storms, fires, and earthquakes, with landslides frequently emerging as secondary hazards, often triggered by these primary events. The majority of these multi-hazard events display preconditioned/triggering and multivariate characteristics. Multi-hazard events are more common in Asia and North America, whereas Europe sees a higher occurrence of temporal overlaps of multiple hazards. The Great Lisbon Earthquake of 1755, the Typhoon Nina-Banqiao disaster in 1975, and the 2010 Haiti earthquake are key examples of multi-hazard events. The Lisbon earthquake led to widespread structural destruction from ground acceleration, followed by a tsunami, fires, and aftershocks. Typhoon Nina in China caused heavy rainfall and winds, leading to the failure of 61 dams and severe flooding. Similarly, the Haiti earthquake triggered cascading hazards, including landslides, a tsunami, and aftershocks, amplifying its impact.

The growing interest in multi-hazard risk assessment and structural resilience has led to diverse methodologies and frameworks. Building taxonomy for multi-hazard risk assessment (GEM4ALL) [3], methodologies for assessing cumulative damage from sequential multi-hazard events [4], risk analysis methods for multi-hazard scenarios [5] are just some of the directions pursued by researchers around the globe to investigate the subject. However, researchers have also highlighted the infancy of multi-hazard engineering, noting the need for integrated resilience strategies [6], the shortcomings of current design codes [7], and the necessity of tailored multi-hazard criteria for enhancing structural stability against combined threats [8]. Lou et al. [9] and Meacham [10] developed material-agnostic performance-based frameworks for Post-Earthquake Fires (PEF) assessment, emphasizing the importance of a more extensive database, fragility curves for multi-hazard resilience, and collaboration between fire and seismic engineering. Studies on fire-induced material degradation indices [11], fragility curves [12], and full-scale testing under combined earthquake and fire loading [13] offer valuable knowledge. Other key factors to consider are damage to passive fire protection systems from seismic events impact fire resistance [14] as well as the very factors leading to PEF [15]. In an attempt to implement the performance-based design approach in the case of post-earthquake fire, Meacham [16] conducted shake table tests on a full-scale, five-story reinforced concrete building and proposed a model to performance-based seismic and fire design.

The dynamic behaviour of reinforced concrete (RC) slabs was investigated under simultaneous fire and explosion, and it was found that fire reduces the RC slab's ability to withstand blast loading [17]. Xue et al. [18] proposed a novel damage assessment methodology for shear wall structures facing earthquake–explosion disaster chains, revealing that initial seismic damage exacerbates vulnerabilities to subsequent explosions, often elevating damage levels to severe states. Verma et al. [19] examined reinforced concrete structures under combined earthquake and blast scenarios, demonstrating that such multi-hazard conditions result in the most severe structural responses due to compounded localized and widespread impacts. Finally, Quiel and Marjanishvili [20] examined progressive collapse in steel-framed buildings following blast and fire, underscoring the necessity of multi-hazard approaches for enhancing structural resilience.

While extensive research has been conducted on timber structures concerning individual hazards such as earthquakes, blast loads, or fires, the complex interactions between multiple hazards remain underexplored and are mostly limited to other structural materials and forms. The exception to this is work by Tesfamariam [21], in which the design of taller timber buildings is discussed for earthquake and wind loads within a multi-hazard performance-based design framework. This gap in the literature limits understanding of how tall timber structures respond when exposed to the cumulative or triggered effects of more than one hazard. This book chapter aims to guide and provide a succinct overview of pertinent literature and design considerations on the subject through the existing knowledge.

2 Overview of Accidental Load Situations

Accidental load situations, such as earthquakes, fires, and blast loads, represent extreme events that can pose significant challenges to the integrity and safety of structures and occupants. These loads are rare but have the potential to cause catastrophic damage if not properly accounted for in the design and evaluation process. Designers and building officials consider these load scenarios individually, as each has unique characteristics, mechanisms, and impacts on structural behaviour. Understanding the specific demands and responses associated with each accidental load is critical before exploring their potential interactions or cascading effects. This foundational knowledge allows engineers to implement appropriate design strategies and ensure compliance with safety standards, ultimately enhancing the resilience of built environments.

2.1 Earthquakes

Timber lateral load-resisting systems are recognized to be a viable alternative to other structural types in seismic-prone areas, even those of moderate to high seismicity. Several studies have shown that timber buildings perform well under strong ground motions primarily because of their high strength-to-mass ratio [22] and ability to dissipate energy in ductile metal connections. However, throughout history, timber structures have exhibited varying degrees of resilience to seismic activity shaped by structural types, material properties, and design regulations.

Following the 1994 Northridge Earthquake, light-frame timber buildings attracted the attention of structural engineers and researchers due to the significant damage observed especially in two to three-storey apartment buildings [23]. Most wood-frame buildings in the area were poorly engineered and lacked a seismic-force-resisting system, triggering significant losses in wood-frame constructions. Consequently, in order to minimize earthquake losses to wood-frame construction and develop specific performance-based seismic design (PBSD) approaches, in 1998 the CUREE project [24] was launched as a series of coordinated and comprehensive scientific investigations in North America. In 2002, Filiatrault and Folz [25] conducted a comprehensive literature review on force-based seismic design, showing a strong correlation between inter-storey drift during an earthquake and the subsequent damage to wood-frame structures. Rosowsky & Ellingwood [26] and van de Lindt & Walz [27] established the performance levels in terms of inter-storey drift limits to control non-structural and structural damage in wood-frame timber buildings and developed specific design procedures accordingly. In 2005, the NEESWOOD research project [28] aimed at developing a PBSD approach for mid-rise wood-frame constructions. Shake table tests on a two- and a six-storey light-frame building were conducted [29, 30] (including tests on some damping systems and half-scaled base-isolation tests [23]) and a specific non-linear time history analysis software package, was developed. Moreover, a proposal for the application of a direct displacement design (DDD) approach to wood-frame buildings was presented. In Italy, Tomasi et al. [31] investigated the seismic performance of multi-storey light-frame timber buildings through a shake table test conducted on a three-storey timber light-frame building. A highly dissipative behaviour, with most plastic deformations concentrated in the sheathing-to-framing joints and the hold-downs and angle brackets, was observed.

The studies on the seismic performance of mass timber (e.g. Cross-Laminated Timber - CLT) structural systems started in the early 2000s, showing significant differences with those conducted on wood-frame buildings. The energy dissipation in CLT buildings is in fact concentrated in the mechanical anchors (i.e. hold-down, angle brackets) when single-panel shearwalls are used whereas vertical joints are designed to dissipate energy in segmented shearwalls [32]. Within the SOFIE [33] and SERIES [34] projects, shake-table tests were conducted on a seven- and three-storey building made with multi-panel and single-panel shearwalls, respectively. Gavric et al. [35] and Flatscher et al. [36] conducted experimental tests on hold-down and angle brackets showing a ductile failure mechanism when hold-downs were subjected to tensile loads and angle brackets to shear load.

Despite most of the current design standards for the seismic design of timber buildings (e.g. Eurocode 8 [37]) primarily follow a deterministic force-based procedure, in the last decade, several studies have applied risk-based approaches to investigate the seismic performance of timber buildings and determine the structural behaviour q-factors (i.e. R-factors in North America) of different structural types. For CLT structures, for example, Van de Lindt et al. [38] calculated the R-factor for CLT platform-type buildings using the FEMA P695 [39] procedure while Rinaldi et al. [40] used a risk-consistent approach to verify the values of q-factors reported in the second generation of Eurocode 8 according to the q-factor estimation methodology [41]. Tesfamariam et al. [42] assessed the R-factor for a 10-storey hybrid timber-reinforced concrete building while non-linear incremental dynamic analyses (IDA) were conducted by Morshedi et al. [43] to assess the R-factors of light-timber frame shearwalls.

2.2 Fires

Timber buildings have burned down in the past mainly because they lacked proper fire safety features. These features include adequate fire compartments, detection systems, and suppression methods. Historical disasters like The Great Fire of London in 1666 and The Boston Fire in 1872 happened because the fire safety technology at the time could not stop small fires from propagating. Many building regulations today, which limit the height of timber buildings to about four stories, were created in response to these massive urban fires from the past [44]. Modern structural systems and technologies for detecting and suppressing building fires suggest no continuing reason to limit the permissible heights of timber buildings prescriptively [22].

In most jurisdictions, fire safety regulations follow a deterministic approach, designing buildings to withstand specific, standardized fire exposures, typically a fire resistance test (e.g., EN1363-1) for a set duration. However, this method does not account for variations in fire scenarios: many buildings may not experience significant fires, while some may encounter more severe events than anticipated within the deterministic approach. In a deterministic approach, it is not straightforward to quantify the effect of risk-reducing measures, such as sprinklers, fire-stopping, and/or improved firefighting access. Instead, deterministic regulations are adjusted over time based on experience [45], such as by high-consequence fire incidents or lack thereof.

A probabilistic approach may enable societal cost optimization concerning acceptable losses, as a deterministic approach applied to all buildings can be overly conservative and costly. Probabilistic fire safety design aims primarily to ensure life safety but can also address property protection. A possible approach for fire safety engineering is the use of Farmer's diagrams, better known as F-N curves, which set limits on the frequency (F) of incidents with a specific number of casualties (N). These curves emphasize that the likelihood of multiple fatalities should be extremely low, with incidents causing more than 10 fatalities considered nearly unacceptable, as shown in Fig. 1. The ALARP principle (As Low as Reasonably Practicable) allows designs to bypass strict F-N curve limits if compliance is infeasible.

Property protection, a secondary goal of fire safety engineering, accepts certain probabilities of failure. However, regulations do not explicitly specify limits for failure probabilities due to fires. Some regulations indirectly offer property protection, such as Eurocode 0 [46], which specifies a reliability index of $\beta = 3.8$, equating to a probability of approximately $P = 7.23 \times 10^{-5}$ over 50 years for moderate structural failure. Notably, no reliability index is provided for more substantial failures such as progressive collapse.

Implementing performance-based design faces significant challenges due to a lack of data, the complexity of required analyses, and inherent uncertainties. Probabilistic design depends on statistical data, such as fire load densities, and fire growth rates. However, fires are relatively rare and poorly documented events and outliers are poorly represented in statistical distributions, limiting the ability of a probabilistic design approach to foresee high-consequence events. The ALARP principle adds complexity, requiring a balance between financial feasibility and life safety, which is hard to quantify. Additionally, many stakeholders, including fire brigades, local authorities, and designers, often trust deterministic regulations more than probabilistic approaches due to a limited understanding of risk-based methods.

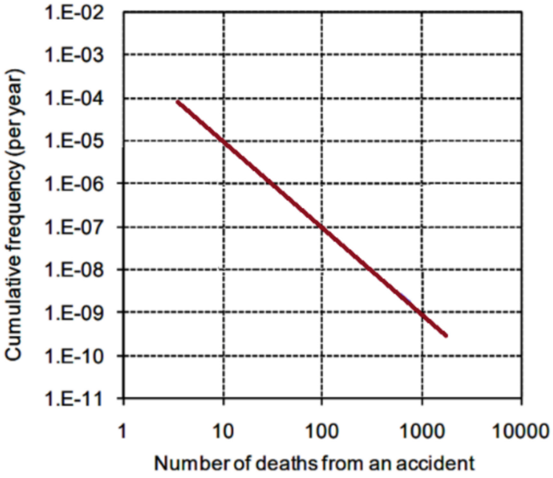

Fig. 1. F-N curve for fire events in the Netherlands.

2.3 Blast Loads

Blast loads tend to occur nearly instantly and release enormous amounts of energy, leading to a dynamic response, localized damage, and a high strain rate effect of the wood material. Examples of an explosion followed by a fire are the Oklahoma City bombing (USA, 1995) and UNBC's Wood Innovation Research Laboratory Explosion and Fire (Canada, 2023), while the case of a fire followed by an explosion is the Port of Beirut Explosion (Lebanon, 2020). The behaviour of timber elements under blast loading has been investigated in recent years, and the design of timber structures subjected to blast loads is explained thoroughly in another Book Chapter. It is important to note that design against blast loads is not required in the standards, but it is upon request of the owner or government authorities.

3 Multi-hazard Scenarios

When combined load effects, such as those from fire, earthquakes, and blast loads are considered in the multi-hazard design framework, performance-based design becomes a necessity. Performance-based design liberates the designer and provides opportunities to communicate with the public (e.g., owners, insurers, occupants) to understand the needs and expectations better and allows the designers to provide solutions not being limited to prescriptive regulations that are not capable of delivering required or expected performance, especially in the multi-hazard scenarios. Multi-hazard events often have more severe impacts than single-hazard events and present challenges for traditional design. In addressing multi-hazard events, adopting a probabilistic approach, despite its inherent challenges, becomes increasingly necessary. Rare, high-impact events—where the primary goal is to prevent mass casualties—present unique scenarios where lower-probability outcomes, such as moderate structural damage or minimal casualties, may already align with acceptable thresholds. This stems from the rarity of such events inherently limiting their overall risk. By focusing on mitigating catastrophic outcomes, probabilistic methods provide a rational framework for balancing safety and resource allocation in the face of complex, multi-hazard scenarios.

3.1 Earthquakes and Fires

Both earthquakes and large building fires are relatively rare events, although they are not statistically independent with fires often starting in the aftermath of earthquakes. A joint deterministic approach for combined earthquakes and fires would be prohibitively costly, both in terms of test requirements and design implementation. This also highlights the opportunities for a probabilistic approach to combine these events.

While conventional fire design is heavily focused on deterministic solutions, earthquake design usually involves probabilistic events and design against expected earthquakes (rather than a ‘standard earthquake’). There are also design aspects between earthquakes and timber fire design that are fundamentally opposed. For example, earthquake design has a clear sacrificial order in which limited damage from major earthquakes is part of the design in order to prevent overall collapse. Paired with repair considerations this favors exposed, easily accessible connections that absorb damage from deformations but can rapidly be accessed and repaired. In contrast for timber design in fire, connections are often placed within timber elements to avoid heating and the resultant weakening of steel components and the timber adjacent to this steel.

Wood is combustible, which distinguishes it from other materials that are commonly used for tall buildings, such as steel or concrete. In most current design approaches the amount of exposed timber is limited by encapsulation with fire-rated plasterboard. This can help to ensure that self-extinction of timber can be achieved and limits the overall fire size [47, 48]. Therefore, beyond the direct effects of combined earthquakes and fires on the structure, the potential contribution of timber due to damage to encapsulation must be considered in probabilistic analysis. This can also include damage to other fire safety measures and the lack of fire service intervention.

3.2 Blast Loads and Fires

The design and analysis of structural elements subjected to blast loading in CSA S850 [49] defines the dynamic strength, S_D, provided as:

$$S_D = S_S \times SIF \times DIF \tag{1}$$

Where SIF is the strength increase factor, DIF is the dynamic increase factor, and S_S is the specified static strength. While the DIF incorporates the effects of high strain rates onto the material properties, which tend to be beneficial (i.e., greater or equal to unity), the SIF acts to transform design-level specified strengths to near-average strength values. The use and magnitudes of the SIF in blast design resemble the current Canadian [50] and European [51] wood design provisions for fire scenarios.

There are currently no design standards or guidelines for cases of succeeding or simultaneous fire and blast scenarios. In addition, due to the extreme rarity of both loads acting concurrently, no documented case study nor literature exists on the topic of timber structures. With that being said, engineering judgement can be applied to develop rational design approaches for determining potential interaction effects for pre- and post-blast fires. Fires may occur as a direct or indirect result of an explosion or may be the source of an explosion (e.g., fire causing a gas line to ignite and explode). Concerning the former, localized deformations in structural and non-structural elements brought on by the blast event may jeopardize the integrity of fire compartments and otherwise safe evacuation routes, particularly in light-frame wood assemblies. While structural elements may only be subjected to superficial damage levels following blast loading, such cracks may present a potential path for fire development to penetrate through walls and other compartments. In such cases, one may conservatively assume failure of compartmentalization. If consideration of potential cases of blast events is required, for example, for high-profile assets or proximity to high-profile assets, one may plan evacuation routes to be outside the perimeters of the building, to move them as far as possible to the effects of the shockwaves.

For the latter (i.e., blasts occurring due to a fire event), designers should consider the potential loss of cross-sectional area and mass, both of which would contribute to an element's response to a blast load. Estimating the effective cross-section depends on the zero-strength layer and char depth, which can be obtained from the charring rate and fire exposure time.

4 Outlook

The increasing number of taller timber structures and the need for more resilient and safe tall structures require addressing the complex challenges posed by multi-hazard scenarios. Experimental testing for scenarios of fire and explosions is highly complex due to cost and testing conditions. The ability to predict materials' behaviour and damage level under explosions and fire is uncertain, and many factors play a role in this, such as the sequence of events and type of Engineered Wood Products (EWP) being used in the design. The current knowledge available in case of fire and explosion events was mainly developed using advanced analysis using FE packages. Additionally, the behaviour of connections under such combined or successive events is not investigated. With the current lack of comprehensive design guidelines for multi-hazard design or studies on the response of the building under such events, redundancy and robustness of taller timber structures are paramount, and the design in such cases should be towards including alternative load paths to prevent progressive collapse.

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