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EVACUATION MODELLING PROCEDURES FOR IMPROVING TIMBER FIRE DESIGN

Chorlton, B.[1] and Gales, J.[1,2]
[1] York University, Toronto, Canada
[2] jgales@yorku.ca

Abstract: Timber structures are undergoing a renaissance in Canada. Architects desire that the structures be left exposed, without encapsulation so as to exploit our natural psychological biophilia tendencies. This demand for leaving the timber members exposed and unencapsulated brings substantial challenges for the designer to ensure fire safe design. International practice for unencapsulated timber structures has subsequently moved to consider an increase in the prescriptive fire rating required for this type of building to compensate for the calculated increase in subsequent fire load (a transient fuel load calculated on the basis of charring rates). This procedure, with limitation, negates the effects of ventilation, oxygen supply, and response to realistic heat flux exposure, all which will influence the timber's actual contribution to the fire. Further, an argument can be raised that the required fire rating is increased on the premise of allowing for safe evacuation owing to the additional fire load present. Herein, the authors examine the current state of knowledge in Canada of a few of the variables that come into play in this complex coupled alternative solution process. We review fire dynamics and timber charring, human behaviour, and accessible design. Developing all of these factors and considering them together could provide designers with another tool for the specification of timber structures. Our hypothetical scenario involves how evacuation times can be modified due to increased considerations for human behaviour and accessibility, and therefore when assessed in parallel to the timber's increased fuel load, a determination can be made regarding how much of an increased risk the exposed timber actually presents – providing supporting research is advanced enough. Herein, a first-stage, rather provisional, framework is proposed of how a hypothetical unencapsulated timber building might be realized in the future and what research gaps are needed to enable subsequent framework phases.

1 INTRODUCTION

The recent advancements in engineered timber, and at the same time sustainability drivers in large urban centres, have created a market for timber hybrid structures as an alternative to traditional solely steel or concrete structures. This shift has challenged designers. For centuries the design of steel and concrete structures has been simplified due to the non-combustible nature of those products, where fire design would be treated predominately on a prescriptive basis, an acceptable solution. Timber on the other-hand has complicated behaviour in fire and the planning of these structures is not so simple for fire safety – particularly in the absence of dedicated education programmes in cities where these structures are desired (Toronto, Canada for example). Recent endeavours by designers have treated this complex behaviour through the consideration of advanced and alternative analysis techniques that are overly complicated and challenged at their fundamental level. For example; practice for unencapsulated timber structures has subsequently moved to consider an increase in the prescriptive fire rating required for this type of building to compensate for the calculated increase in subsequent fire load (a transient fuel load calculated on the basis of charring rates). This procedure, with limitation, negates the effects of ventilation and oxygen supply which will influence the timber's actual contribution to the fire. Further, an argument is made that the required fire rating is increased on the premise of allowing for safe evacuation owing to the additional fire load present. When these are considered, evacuation times could be lowered and therefore when assessed in parallel to the timber's increased fuel load, the increased fuel load is not a hindrance with respect to egress situations to ensure safety – providing of course there is supporting research to undertake such a calculation. An accurate demonstration of an alternative design solution then becomes achievable. Evacuation modelling while internationally is one of the most specified fire engineering consultancy activities, is relatively new within the context of Canadian practice. It is particularly challenged because of the dearth of data that exists for populations with accessibility needs. Improper quantification of this demographic often introduces significant complexities to architectural approvals, particularly when the combustibility of building materials becomes more complicated.

Herein, the authors introduce a review of current evacuation terminology and procedures that can be tailored specifically to the occupancy type as well as describe the fire risk of exposed timber providing future research supports this analysis. This paper, largely a review of the state of the art, concludes with a hypothetical first stage framework on how the synthesis of these topics can be considered and advance consultancy practice which may be expanded on in future work and direct practitioners to performing the necessary supporting research. Specific references to the author(s) research which support these alternative design methodologies are reviewed for context herein to help establish a framework of research in order to promote design solutions for tall timber construction in Canada. It is acknowledged that the bulk of research for timber structures has internationally accelerated over the last 6 years (since 2013), much of that research can feed into a second stage framework which is meant to follow this brief conference proceeding.

2 LITERARY REVIEW OF FIRE DESIGN METHODOLOGIES

Timber structures are undergoing a renaissance in Canada. Architects desire that the structures be left exposed, without encapsulation so as to exploit both our natural psychological biophilia tendencies, and the health benefits associated with exposed timber structures (Kelz, Grote, and Moser 2011; Sakuragawa et al. 2005). Herein we systematically review the established understanding of the current state of research of both the fire dynamics of the structure and the behaviour of the occupants which moves us towards a first stage framework. A second stage framework would follow that would expand the research articles covered in these sections as well as point to new research to support new planning methodologies. This is discussed in Section 3.

2.1 Timber and Fire Dynamics

When timber is exposed to a fire, it begins to decompose and breakdown into char. This process is seen in Figure 1. A protective char layer forms on the wood, with a pyrolysis zone in between the charred and normal wood (a zone that has yet to completely char but is typically considered to have lost its strength). Methods have been proposed to determine the strength of a timber member post-fire, for example, the CSA O86-14 Annex B procedure describes a residual cross section method, in which the char depth is determined based on how long the timber is exposed to fire and using a charring rate specific to the timber product. An additional allowance is then added degradation effects, known as the zero-strength layer. This procedure assumes that that any charred portion of the timber, in addition to the zero-strength layer, has lost all of its strength, while the remaining cross sectional area is assumed to have retained most of its strength (CSA Group 2014). When designing for timber in fire, it is therefore crucial to have an accurate evaluation of the char depth.

Figure 1: Timber breakdown when heated (Laminated Veneer Lumber shown)

One of the challenges that arises with timber construction is that the presence of exposed (uncovered) timber provides an additional fuel load from the timber itself which is poorly understood. This additional fuel can then create a more severe fire (when proper ventilation conditions are present), which in turn could result in an increase in charring depth and rate (the research to support this is evolving). In contemporary calculation, many international designers currently follow a procedure that accounts for the exposed timber as a fuel in addition to other combustibles that may be present, and this procedure requires an iterative analysis before the final fuel load supplied by the exposed timber can be determined (this procedure is not yet commonly adopted in Canada to the knowledge of the authors). This can lead to an increase in corresponding fire resistance where equivalent comparison to steel and concrete structures can then be made. This iterative procedure is challenging to perform, and often neglects the effect of thermal gradients, as well as ventilation and oxygen, which will greatly influence how much the timber is actually contributing to the fire. Moreover, the particular geometry of the structure and the configuration of the exposed timber has been shown to influence the severity of the heat exposure (Bateman et al. 2018). Neglecting these and other considerations could potentially lead to being overly conservative in the degree of member sizing required to meet the new required rating. Having very large timber members may then become un-economical to a timber building project, leading to the use smaller timber members and achieving the required fire performance using fire rated gypsum board. Officials and authorities having jurisdiction may also be more likely to approve projects where non-combustible materials are used for encapsulation, however when the timber is encapsulated, many of the architectural, psychological, and physiological benefits are lost.

The procedure for determining the sizing of the timber members is clearly restricted by many factors (described above), pointing to a number of research needs for timber structures in fire. Recently, the accuracy of commonly used charring rate models to predict the damage state of a timber member post-fire have been questioned. Recent studies have shown that models can only predict char depths within about 20% (Barber et al. 2018). This lack of precision stems from the basis of charring rates depending primarily on time exposed to fire, and not accounting for other factors such as heat flux. One of the challenges in performing experimental tests that will address many of these research needs is that it can be difficult to create a test setup that is representative of a real fire. A realistic fire may have a very severe heat flux (> 50 kw/m^2), which can often be difficult to control without the heat damaging much of the equipment. For that reason, it is common to see milder conditions reflected in various test programs. That said, there have been a few notable test series in which realistic (or potentially even more severe) fire exposures have been considered. To name a few, NIST performed a series of compartment tests examining the behaviour of a Cross Laminated Timber (CLT) compartment in which most of the walls are encapsulated with fire rated gypsum board (similar to previous fire designs of tall timber structures), with some of the tests in the series having one or more exposed CLT wall(s) (Su et al. 2018). A previous test by the authors has also been performed on a barn-style (exposed timber) structure, to examine the fire dynamics of a well-ventilated exposed timber structure, as well as the performance of multi-layer encapsulation using gypsum board. These tests have helped to identify some of the fire dynamics of a real fire involving exposed timber where instantaneous ignition was not observed but rather a fast spreading mechanism (Forrest et al. 2019) as well as gypsum board fall off at early stages of the fire. This test is described in brevity in Figure 2, details can be found elsewhere. There are at least 10 major research test programmes actively investigating fire dynamics in timber compartments to the knowledge of the authors. Another consideration unique to timber buildings, and especially buildings where the timber is exposed or unencapsulated, is the additional smoke produced during combustion. If the timber begins to contribute to the fire, additional smoke will be present, which presents an increased evacuation challenge to any occupants remaining in the building. This smoke may have additional toxins or compounds due to the timber's constituent contribution. Adhesives and their breakdown in fire still requires additional investigation to understand their chemical contribution to the smoke.

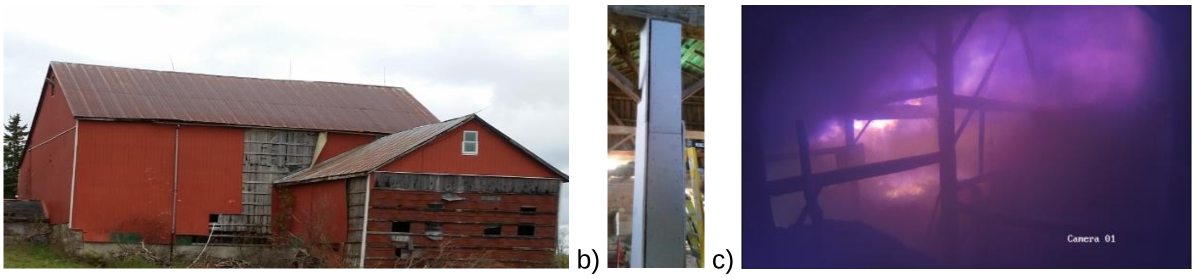
a) b) c)


Figure 2: a) The barn-style structure in consideration. b) The method of encapsulating the timber using multi-layered fire rated gypsum board, in a configuration identical to what is currently being used in contemporary Canadian tall timber buildings. One timber column only was encapsulated, the remaining structure was left exposed. c) Fire spread in the building, 22 minutes 30 seconds after ignition. In this photo, flaming can be seen in the distance near the ignition source, but none is observed yet on the timber near the camera

2.2 Human Behaviour in Fire

An important consideration when analyzing the fire design of a timber (or any) structure is anticipating how the occupants will behave in an emergency situation, such as in a fire, where an evacuation is required. Often, it is observed that humans do not always behave as predicted, for example while it may be expected that someone would begin to egress at the sound of an alarm, in reality there are a number of factors that may delay their beginning to egress, such as not feeling as though they are in danger, taking time to collect their items, finding a family member or friend, or a number of other protective actions. This period of time where an occupant has become aware of the alarm but not yet begun to evacuate, coupled with the time it takes for a fire to be detected and an alarm to be triggered, is known as the pre-evacuation time (Society of Fire Protection Engineers 2019). The pre-evacuation time, along with the time it takes from when a person begins evacuating until they egress to a safe location, is considered to be the required safe egress time (RSET) of the individual. A simple analysis to determine the adequacy of a fire design might include ensuring that the RSET is less the available safe egress time (ASET), that is, the amount of time after a fire is ignited until an occupant would become incapacitated. When all factors are considered, the ASET and RSET can either be prolonged or reduced based on the strength of the engineering solution; a strong engineering solution will have a large margin of safety, whereas a poor engineering solution may reduce that margin or have the RSET actually exceed the ASET. This can be visualized in Figure 3 below.

While many structures will examine the fire design and pedestrian movement independently, this procedure involves comparing the two. There are several limitations on this ASET vs. RSET procedure. For one, determining the RSET of the occupants requires an in-depth examination into how they will behave, both in the pre-evacuation phase and in the movement phase. While there is some information available regarding pre-evacuation times, movement speeds, etc. it is difficult to transfer this data to a population other than the one that was observed in a particular experiment, as there are an immense number of variables that must be considered. Moreover, the movement speeds themselves are often governed by aspects other than the speed at which a person walks, for instance, it is not uncommon to see significant queuing at bottleneck locations (such as at entrances to stairwells), which has the potential to significantly increase the time it takes for a person to egress the building. There are various movement parameters available that have been determined from previous studies, as well as hand and computational procedures for determining the human behaviour aspect of an evacuation (Society of Fire Protection Engineers 2016).

While valuable, there are still many scenarios which have yet to be addressed, for instance the behaviour of vulnerable populations is explicitly acknowledged as a high priority research need in the SFPE Roadmap (Society of Fire Protection Engineers 2018).

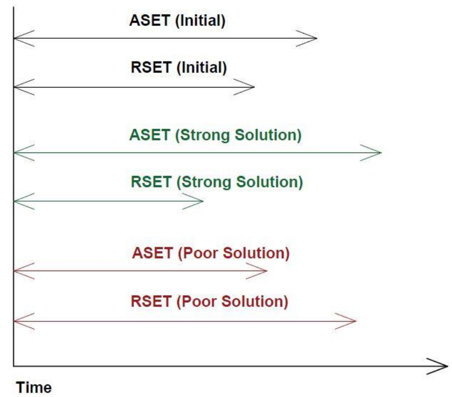


Figure 3: Possible ASET and RSET outcomes for strong and poor engineering solutions (taking both structural, behaviour and disability into account)

It is difficult to extrapolate information determined from other buildings and other populations, and therefore when relevant data is not available, one of the only ways to really understand what to expect in a particular evacuation event is to observe one such event. Of course, this also carries a multitude of challenges such as requiring permission of the building operator to observe the occupants, and possibly shutting down building operations in order for a drill to occur and subsequent (lengthy) analysis of the data. It may also require an ethics approval or consent of the occupants, especially if any filming or recording should occur. Moreover, if observing the population in either general circulation or in a drill, the occupants will likely behave differently than in a real emergency, as there will be less of a perceived threat. Vulnerable populations and people with disabilities will also need to be considered, and it can be very difficult and more stressful for them to participate in a drill, even though their behaviour would be some of the most useful to understand.

2.3 Accessibility in Canada

The current movement accessibility framework that exists in Canada with relation to Fire Engineering relies predominately on codifications found in the National Building Code of Canada. Provision of this guidance is mostly given towards those with visible disabilities, such as wheelchairs. It negates specific guidance in detail to providing support towards those with invisible disabilities (such as a chronic or mental illness) and instead refers to those with obvious physical or sensory limitations. Other countries, such as the UK, have advanced standard provisions to normative clauses that include provisions for disabilities that are more difficult to plan for, and these can be taken into account within a required and acceptable safe egress time calculation. While Canada has made some excellent contributions to Fire Engineering and human behaviour, there are few studies currently underway on this topic beyond the authors work regarding communities, stadia, care homes and museums, etc. (see Aucoin et al. 2018; Champage et al. 2019; Folk et al. 2019). Nevertheless, for the application of the structure it is very important to understand the demographics that will be contained therein. For example, the study by Champagne et al., 2019, identified the importance of determining the demographics unique to the building of interest. In that study, a cultural centre (museum) was examined during three separate evacuation events. In the context of a cultural centre, there were many people present that had their mobility limited in some capacity, for example, parents pushing strollers, carrying young children, and people with service dogs were all observed. The nature of the building brings together people from all walks of life, and this would need to be accounted for in determining the accessibility requirements for egress. This same principle would need to be applied to many public places, be it a university, hospital, or even a place of commercial business.

Accounting for visible and invisible disabilities is essential to ensuring that the RSET of a building is accurate. In many public places, there is a large presence of people with accessibility limitations. For example, a recent study was done by the authors at a major sporting event at the York University Stadium (daily capacity approximately 12 500) in Toronto. In this study, video cameras were set up by the authors to observe the general circulation of people within the stadium, as well as their movement through the entrance and exit. Figure 4 shows the number of persons observed over the course of two days that had a visible physical hindrance or mobility aid. Figure 4 serves only as a count of the number of people that fall into this category and is not meant to be a movement study. Every one present had consented to being filmed, as was stated as a requirement for their entry on their ticket. This video footage was then reviewed, and all cases of some sort of physical hindrance was documented. Of course, this only accounts for people with a visible disability or hindrance. The actual number of people with some sort of disability will not include those with invisible disabilities, and will therefore the final count could be much larger than is reported in Figure 4 for this general circulation study. It does suggest that nearly 10% of all occupants in this structure have specific needs relating to mobility.

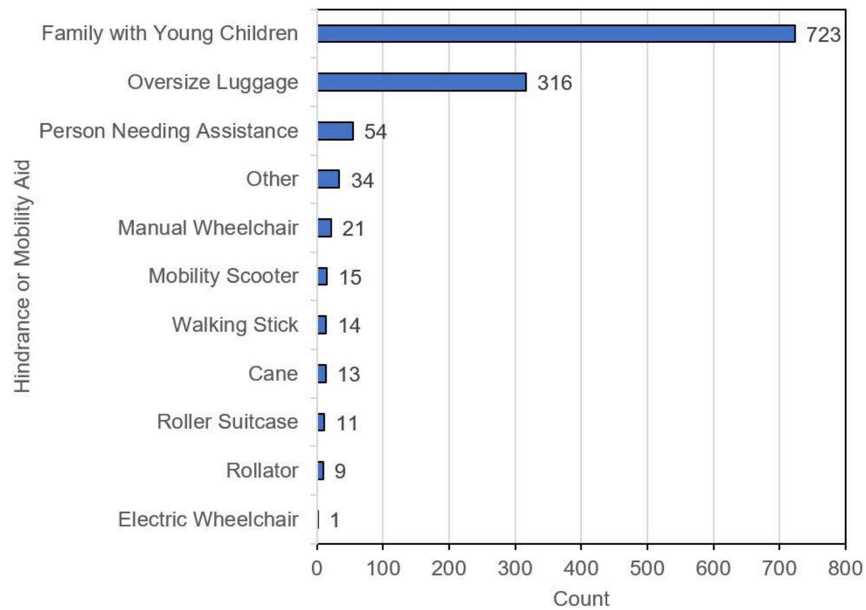


Figure 4: Day sampling of West End of campus into the York University Building

When a structure is specified with accessibility in mind, then all the occupants should be able to egress in a reasonable amount of time. If accessibility is not considered, or is considered too late in the planning process, then these occupants will take significantly longer to egress the building, increasing the RSET. By ensuring that accessible design is at the forefront of the planning process and all different types of people are being accommodated, the RSET may then begin to decrease.

3 RESEARCH NEEDS TOWARDS ALTERNATIVE SOLUTIONS USING FIRE DESIGN FOR TIMBER STRUCTURES

Thoroughly accounting for each of these different factors (human behaviour in fire, timber and fire dynamics, and accessibility) is paramount to being able to confidently implement exposed timber into innovative and tall buildings. One of the challenges that arises from this procedure is that all these topics are relatively specialized and are not widely taught in the Canadian engineering education system, nor adequately researched, or not necessarily recognized professionally yet in Canada. For instance, some schools offer a graduate or undergraduate course that may address timber but may not address timber design as thoroughly as would be needed to justify a timber fire design through an alternative solution. Human behaviour in fire and accessibility are rarely taught within the Canadian engineering education system, though it would be beneficial for practitioners to realize the importance of these aspects and how to account for them. And lastly fire engineering is treated as a sub discipline of Mechanical or Civil Engineering professionally rather than its own unique form. It is critical to consider that the specification and planning of timber buildings may be in effect interdisciplinary. Such a framework cannot yet be used as illustrated in this paper. Using this hypothetical first stage (provisional) framework along these lines requires additional research, education, and professionalism.

Many of the buildings currently proposed to be tall timber structures are located on University campuses (such as the George Brown College Arbour Building and the University of Toronto Academic Tower). These campuses will undoubtedly have occupants with a very wide range of movement abilities, so taking precautions to accurately understand exactly who will be using these buildings will be crucial to understanding what the actual required safe egress time will be. To determine accessibility requirements, the accessibility needs of current and recent students must be considered. Further research providing information on how these people can egress a building in an emergency would be very useful in assessing how much time they will take to exit. A multitude of different evacuation strategies may be used for these persons, for example the use of a tool such as an evacuation chair, and the strategy that will be implemented in a given building should be reflected in the required safe egress time.

Moreover, aside from considerations for persons with accessibility needs, there is further a need to understand human behaviour in fire specific to the context of interest. In keeping with the theme of University buildings, for a tall timber building to be implemented as an educational building, and especially if the timber were to be exposed, there needs to be a clear understanding of how students will behave in an evacuation. While there is some information available on this topic, many of these previous studies occurred in other countries, and human behaviour in fire tends to vary somewhat between cultures. In Canada, and especially in cities like Toronto where many of these timber buildings are either proposed or beginning to appear, the population is very diverse. The implication of this is that the occupants may respond in many different ways when they hear an alarm or signal to evacuate, further complicating the determination of how these occupants will egress the building. A better understanding of how people will behave in a context tailored to the building in consideration will be useful.

The architectural design of a building must also be carefully planned in a tall and/or exposed timber building. In this context, much of the egress time of the occupants could potentially be reduced if the architecture were designed in such a way that the queueing was minimized, so that the architecture of the building will not govern the required safe egress time. This analysis may be facilitated through the use of a model and examining where common problem bottlenecks are occurring in similar buildings. The timber and fire dynamics also have several research areas which could be expanded upon. Of particular interest would be determining to what extent does exposed timber actually contribute to the fuel load of the fire, and once this is determined, a detailed description of a calculation or modelling method that can be applied would be extremely useful. Ventilation and the supply of oxygen would also need to be considered when determining how much the timber will contribute. This analysis will help to assess how much of increased risk is actually posed by the presence of timber within a building.

By accounting for human behaviour in fire, as well as accessibility needs early in the planning process of a timber building, the RSET could be altered, and in some cases may significantly be reduced. If designers are able to show that all occupants are able to safely egress the building in a reduced amount of time, then any increase risk posed by exposed timber could become less of a concern. Should it be determined that the timber reduces the ASET of the structure, meanwhile human behaviour and accessibility considerations reduce the RSET of the structure, then the margin of safety remains the same in this analysis, and the occupants would not be at any additional risk over a non-combustible building where human behaviour in fire or accessibility are not considered. It is possible of course that this analysis may show that the RSET exceeds the ASET, and that building requires additional proposed safety, and in this case the analysis will have helped the designers to realize that they need to make some alterations such that it can be ensured that the occupants have sufficient time to safely egress. If all of these considerations and supporting research is performed and are all well understood and accurately assessed, the ability to plan these advanced tall exposed timber buildings with a novel second-stage framework becomes more of a possibility in the future.

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