Robustness in fire

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Chapter 12

Robustness in fire

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SCOPE OF CHAPTER

With the increasing number of complex and tall timber buildings with a significant area of unprotected timber surfaces, questions arise about the robustness of these buildings in extreme fire scenarios. In recent building projects, measures for robustness have been implemented on an ad hoc basis in agreement between the designers and the authorities. This chapter discusses general approaches to achieve structural robustness with regard to fire design and evaluates them to give guidance for robust fire design of timber structures.

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12.1 BASICS OF STRUCTURAL ROBUSTNESS

Regardless of the building material, structural robustness is an important characteristic of a structure that prevents damage that is disproportionate to the original cause (Agarwal et al., 2012). Structural robustness tends to be less important in areas subject to severe earthquakes because buildings designed for high seismic loads tend to have a high degree of inherent structural robustness for other load cases, including severe fires.

The mathematical definition for robustness can be described with the equation from Starossek and Haberland (2010) to describe disproportionate collapse $P(C)$ as in Equation 12.1:

$$P(C) = P(E) \times P(D|E) \times P(C|D) \qquad 12.1$$

where

$P(C)$ is the probability of disproportionate collapse
$P(E)$ is the probability of accident occurring or "Exposure"
$P(D|E)$ is the probability that damage occurs given this accident or "Vulnerability"
$P(C|D)$ is the probability that collapse occurs given the occurrence of damage

However, for the expression to be complete, the consequences of the said damage or collapse need to be evaluated. Without knowing the magnitude of the consequences, an insignificant progressive damage which is disproportionately larger than another insignificant initial damage can appear to be very serious according to Equation 12.1. The updated expression to include the direct consequences (C_{Dir}, caused by the initial damage) and indirect consequences (C_{Ind}, caused by the progressive damage) is given by the expectation of total consequences $\mathbf{E}[C]$ in Equation 12.2, as derived from Baker et al. (2008):

$$\begin{aligned}\mathbf{E}[C] &= \left(P(E) \times P(D|E)\right) \times C_{\mathrm{Dir}} \\ &+ \left(P(E) \times P(D|E) \times P(C|D)\right) \times C_{\mathrm{Ind}}\end{aligned} \qquad 12.2$$

We recommend the reader to refer to Voulpiotis et al. (2019) for further information on the state-of-the-art quantification of robustness.

For tall buildings, *collapse* is generally not acceptable, thus tall buildings must be designed with an extremely low probability of structural collapse, even in extreme loading. In case of fire, this may lead to the concept of *design to withstand burnout* (assuming failure of all other safety measures). The term "burnout" is discussed in Chapter 3. Robustness extends beyond only structural behaviour in fire, but also includes other performance objectives. For example, the extreme case of the fire in the Grenfell tower clearly shows that, even if collapse did not occur, many people died due to the uncontrolled fire spread in the building.

12.2 BASICS OF ROBUSTNESS AND FIRE SAFETY ENGINEERING

Fire safety engineering (FSE) incorporates many different aspects related to the performance of a structure in a fire situation, and the resulting safety for people and society. In European countries, the load-carrying capacity of timber members in a fire situation is mainly regulated in Eurocode 5 (EN 1995-1-2, 2004), while the fire loads are regulated in Eurocode 1 (EN 1991-1-2, 2002). Interestingly, in contrast to prior versions (ENV 1995-1-2, 1994), the latest version of Eurocode 5 does not contain a “system effect” in the fire situation, taking into account the robustness of a structural system. General guidance about FSE is available in handbooks such as the SFPE *Handbook of Fire Protection Engineering* (Hurley et al., 2015) with its section about timber design currently under revision.

In most countries, rules concerning the spread of fire in a structure (i.e. cladding, insulation materials, cavities, sprinklers, etc.), as well as serviceability considerations (i.e. the non-structural aspects related to the evacuation of a structure) are mostly regulated on a national level. Required fire safety concepts contain structural, organisational and active fire protection measures that must be designed in parallel. All of these measures are subject to uncertainty, which is an important aspect to consider in the planning of a robust fire safety concept, which aims at reaching a fire safety goal. This fire safety goal can be defined on a project basis, including all relevant stakeholders. Consequently, fire safety goals and accepted or tolerable risks are the basis for the definition of required safety measures. A holistic design approach towards the robustness of buildings in a fire situation can be achieved by tailoring the fire safety concept for the particular building and including fire-related risks and the fire safety goals.

12.3 NORMATIVE FRAMEWORK AND ROBUSTNESS

There are three approaches to quantify robustness and design for it, in increasing complexity. They are listed in the following and discussed in more detail in Adam et al. (2018):

1) Deterministic methods, such as Alternative Load Path Analysis (ALPA) and minimum tie forces. They aim to satisfy assumed damage scenarios such as failure of a single column.

2) Reliability approaches, which compare the failure probabilities of damaged and undamaged states.
3) Risk approaches, which compare the direct and indirect consequences and their probabilities.

Today, most standards for robustness in the built environment are written on a prescriptive rule basis, which is implementing deterministic methods only. There is, however, room for performance-based design in cases where the choice of verification is agreed between parties, e.g. building owner, designer, insurance and authority representatives. The help that building codes provide to the designer of robustness is known to be notoriously vague, and sometimes no explicit requirement for robustness design exists (Huber et al., 2019). A survey carried out by Bita et al. (2019) studied the experience of practising structural engineers in the field of robustness and came to the conclusion that although prescriptive design is the current primary approach to implementing robustness design in building codes, a performance-based design approach would be preferred.

The Eurocode EN 1991-1-7 (2010) defines robustness as “the ability of a structure to withstand events such as fire, explosion, impact or the consequences of human error so as not to cause damage that is disproportionate to the cause of the damage.” The corresponding ISO standard (ISO 2394) gives further possibilities to increase robustness:

(i) By avoiding critical events
(ii) By dimensioning of individual components
(iii) By enabling alternative load paths
(iv) By reduction of the consequences

In general, it can be stated that in order to increase the robustness of a structural system, the methods or strategies selected must either

(1) reduce the probability of failure or
(2) limit the consequence of a failure

For the former, the designer can increase the size of certain structural members or reduce the probability that the damage occurs in the first place. For the latter, which is not well addressed in literature, a sound conceptual design is required, for example a design concept that uses compartmentation effectively to keep the fire within a room without further spread.

12.4 EXPOSURE TYPES

Considering the different types of exposure is paramount for an effective robustness design. Exposure may be from structural actions such as accidental loading or material weakness, or from unplanned events such as explosions or unexpected fires. While distinctions such as whether the exposure is static or dynamic, cyclic or monotonic, short term or long term are useful when considering the conceptual design of a building, the primary distinction that needs to be taken into account for robustness design is whether the exposure is localised or systematic.

A localised exposure is one that affects only one, or a very small number of elements. A systematic exposure is one that affects many or all elements (e.g. columns located in one fire compartment). It is very important to realise that the vast majority of known and acceptable robustness measures are only addressing localised exposures. Worse, if a systematic exposure occurs in the structure, those robustness measures may actually worsen, rather than improve, the performance of the structure. A well-known example of the described systematic exposure in timber engineering is the background of the collapse of the Bad Reichenhall Arena, where a so-called progressive collapse behaviour appeared, i.e. the failure of an individual main support led to the chain-reaction collapse of the entire arena roof structure (see Winter and Kreuzinger, 2008).

Fire exposure is more complex than other accidental loads. Both local and systematic exposures need careful consideration before robustness measures are implemented. In general, a fire load starts as a localised exposure in the initial stages (localised exposure), but can spread quickly to become a large event (systematic exposure). Its extent is typically determined by taking into account multiple variables, e.g. the type of fire load (with randomly distributed total value and a heat release rate within certain bounds), the failure modes of the glazing, the availability of combustible surfaces arranged vertically and/or horizontally, the size and efficiency of the fire compartment and countermeasures. In general, it must be made clear that fire design is actually addressing a calculated accidental load case where certain aspects have been investigated in the past, as opposed to generic robustness for “unforeseen events.” Therefore, different strategies may be needed to address robustness in localised and systematic cases, and some of these strategies may be contradictory.

12.5 CONSEQUENCES RESULTING FROM A FIRE EVENT

In the event of a fire, active fire protection and organisational measures might be sufficient to fight the fire before any flashover occurs, in which case only a limited and localised fire exposure will occur. If a fully developed fire or a travelling fire happens, the fire will affect several structural and separating members, which means that the structural fire safety measures and the firefighting strategy are of key importance. Firefighter access may be compromised in some cases, after a major earthquake for example.

Smoke, elevated temperatures and fire spread are among other relevant consequences that must be addressed. As the strategies to fight the fire in the fire growth phase and the fully developed fire phase are significantly different, it is apparent that both cases must be considered separately, i.e. very different goals are followed, e.g. during evacuation and after flashover in the same fire compartment.

Selected different direct and indirect consequences related to a fire event can be structured, as presented in Figure 12.1 and given as examples in Table 12.1 (please note that this list is not intended to be exhaustive and can be extended).

12.6 EVALUATION OF IMPROVEMENTS PERFORMED IN PRACTICE

In the following, the direct application of a robustness measure taken from normal-temperature design is presented. This is followed by a general view on the robustness and finally its application for the fire situation for tall timber buildings. Additional robustness is not necessary for low-rise timber buildings because the consequences of failure are less severe.

12.6.1 Prevention of progressive collapse for the fire situation

Recently, several tall timber buildings have been finished, among others being Mjøstårnet in Norway (see Figure 12.2) and HoHo in Austria.

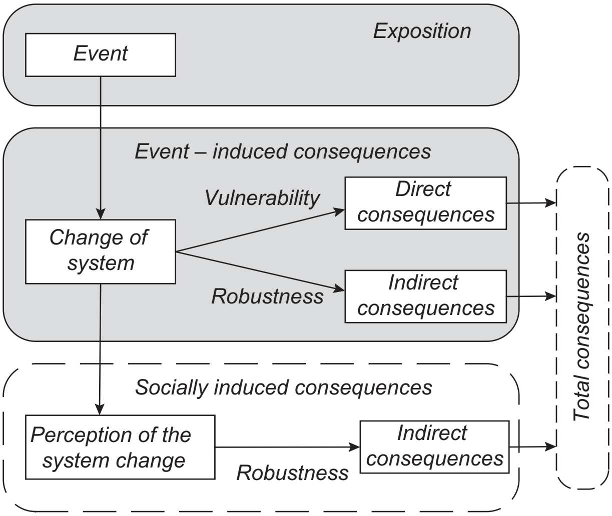

Figure 12.1 Overview of consequences (modified from JCSS 2001 and Schubert 2009).

Table 12.1 Examples of potential fire events, direct and indirect consequences and related robustness measures

Event	*"Failure" and direct consequence*	*Indirect consequence*	*Robustness measures*
Fire	Combustion	Creation of toxic gas and smoke, fire spread	Reduction of combustible surface material, compartmentation, sprinkler system, fire detection system
Failure of manual suppression	Increased fire	Increased risk for tenants	Fire protection measures, training, fire detection system
Failure of secondary elements	Localised failure	Alternative load paths might be activated	Include alternative load-paths, over-dimensioning of structure
Smouldering combustion	Continuation of fire after burnout	Reignition and later collapse	Fill gaps/voids with non-combustible materials and create airtight joints
Failure of integrity	Spread of fire (vertically and/or horizontally)	More systematic exposure	Increased resistance to fire spread. Extra inspection of workmanship
Fire detector failure	Delayed evacuation, delayed filling of dry sprinkler pipes and delayed alert of fire brigade	Personal injury and property damage, limited effect of sprinkler	Regular integrated tests of detector systems, improvement of automated fire detection
Sprinkler failure	Fully developed fire	Damage of complete compartment and possible further spread	Regular integrated tests of sprinkler systems, no reduction of fire resistance of structural system due to sprinklers
Spread of fire	Larger effected area and more members	Change from localised to systematic exposure	Change robustness concept
Exposure to elevated temperature	Reduction of strength and stiffness	Failure of member and connection	Encapsulation of members and connections
Early failure of encapsulation	Charring of timber, reduction of anticipated failure time	Failure of connection and/or member	Design structure with additional fire resistance. Inspection of encapsulation
Fire exposure	Charring of timber, additional fuel load	Failure of member, increase of temperature and extension of fire	Increase of load-bearing capacity/fire resistance *R* of all or selected members, limit the share of visible combustible surfaces
Combustion volatiles (gas/smoke)	Leakage of smoke, visibility	Increased number of fatalities	Improved compartmentation, improved design for reaction to fire
Collapse or partial collapse of timber building	Singular monetary loss	End of success story of tall timber buildings	Perform adequate fire safety engineering for all timber buildings

Figure 12.2 (a) Mjøstårnet, Norway. At 84.5 metres, it is currently one of the world's tallest timber buildings (photo Peter Lang, Rothoblaas). (b) HoHo in Austria (photo proHolz Austria / Bruno Klomfar).

In projects such as the HoHo, the robustness in fire has been addressed by activating alternative load paths, where it was shown that any single column could fail without leading to a progressive collapse. Other projects are applying this approach by verifying design where one or more members can be assumed to have failed. This deterministic approach gives information of the behaviour of the structure with regard to well-defined exposures, but little or no information on the effectiveness of certain measures to increase robustness.

It should be stated that timber structures often use columns with pinned supports and single span beams; thus, they are sensitive to disproportionate overall structural failure in the event of a single element failure. Such a structural design concept should not be applied to tall timber buildings.

Evaluating the actual structural boundary conditions, it should be highlighted that structural elements such as simply supported beams and columns are fixed in their position not only by frictional forces, but also by engineered connections. Thus, these connections allow the transfer of additional tensile and shear forces which could be activated in case of the failure of one member, see schematic illustration in Figure 12.3. In that example, the stabilising effect is created by the additional resistance of the diagonals and their connections, generating forces not considered in the normal design.

Figure 12.3 shows that a failure of an element does not lead immediately to a total collapse of the system when the actual connection design activates alternative load paths (ALPA). However, in the fire accidental case, the scenario that only one member is exposed is quite unrealistic since travelling

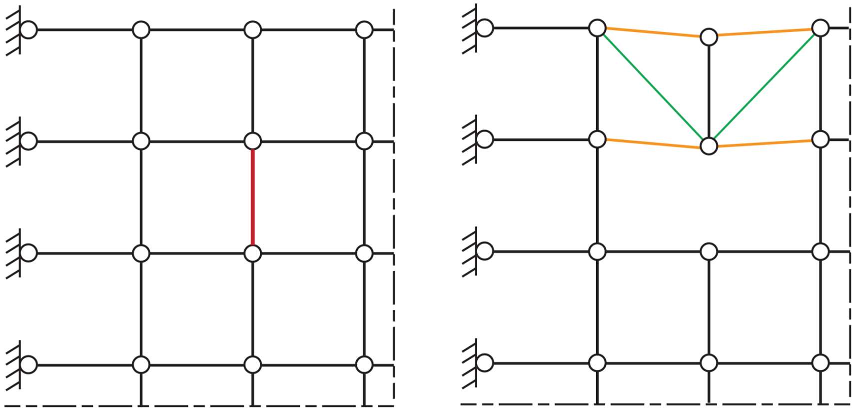

Figure 12.3 Static system with pinned supports of beams and columns before failure of the column in the fire compartment (left) and after column failure with additional diagonal elements (right).

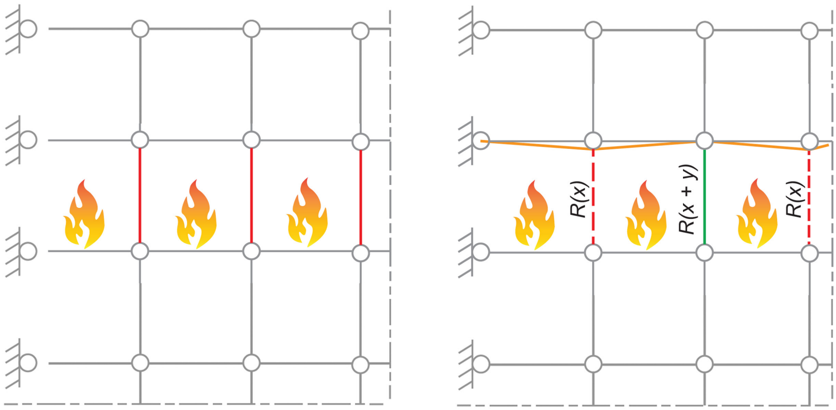

Figure 12.4 Static system with pinned supports in fire (a) and a possible situation at an advanced stage (b) where a member with increased fire resistance *R*(*x* + *y*) is arranged. Note that all exposed columns are in the same fire compartment.

fires or full compartment fires are quite likely when a significant share of combustible structure is present. Figure 12.4a illustrates a more realistic scenario with a significant area of a compartment in fire.

Consider the structure shown in Figure 12.4a where the fire severity exceeds that considered in the prescriptive design. If the fire duration exceeds the column's fire resistance, e.g. *R*(*x*) (providing *x* min load-bearing resistance), failure of the all exposed columns can be expected. In consequence, collapse of the entire structure could be expected, unless the overall structure is designed in a way to survive the failure of all columns in the fire compartment. The resulting consequences will be disproportionate to the marginal exceedance of fire severity. The challenge is to identify the most effective measure to increase the robustness of this structure for such an accidental scenario.

One possible solution shown in Figure 12.4b is to prevent disproportionate collapse by designing key elements, e.g. every second column with additional fire resistance (indicated as $R(x + y)$), allowing redistribution of loads from the failed columns to the remaining columns.

An alternative solution would be to design all the columns with additional fire resistance and thus as reinforced elements (indicated as $R(x + y)$), which would be much less effective and lead to much higher costs. This would still lead to failure of all the columns if the fire severity exceeds the design scenario; however, the probability of this exceedance is greatly reduced. Further, it should be noted that this can be achieved as well by combining active fire protection with enhanced structural fire engineering provisions.

12.6.2 Approaches for improved robustness for timber buildings

The key element approach is addressing the vulnerability of the structure as per Equation 12.1. Because of this, and along with other challenges of key elements (e.g. architectural, element protection), it has been a long debate whether “the key element approach” should be considered a valid “robustness measure” or not. More details on this debate are presented by Voulpiotis et al. (2021).

The focus for improving robustness must be on reducing the overall probability of disproportionate collapse of the building without having to debate the categorisation of the individual approaches. Robustness improvements should be assessed considering the particular project’s boundary conditions.

Contrary to the typical robustness designs which address the probability of collapse given damage $P(C|D)$ for the fire situation, the safety measures may also need to address

(1) the reduction of the probability of the occurrence of events (exposure), $P(E)$, and/or
(2) the reduction of the structure’s vulnerability $P(D|E)$.

An optimised combination of measures can be most beneficial. In particular, the following measures can be considered:

(i) Reduction of the probability of critical fire events by sprinklers, including further measures such as independent water supplies, redundant piping and pumps

(ii) Selected load-bearing timber elements are designed to meet a prescriptive $R(x + y)$ requirement, while other elements are designed for $R(x)$

(iii) All load-bearing timber elements are designed to meet a prescriptive $R(x + y)$ requirement, although this may imply over-dimensioning

(iv) Use of fire-resistant detailing and creation of additional or redundant load path (as mentioned above): e.g. beams and slabs supported by direct bearing rather than supported by connections which are vulnerable to fire attack

(v) The dimensioning of the supporting system for the case of fire is carried out with more realistic fires instead of the simplified standard fire exposure

(vi) The structural fire protection and active fire protection are carried out in parallel holistically, e.g. without reducing the structural fire design requirements because of the introduction of sprinklers.

12.6.3 Improvement of the robustness for structural timber buildings

In the following, the potential improvements for the robustness of buildings with major elements made from timber are presented. While most of the approaches diverge only very little from non-combustible buildings, some ideas address the combustibility of wood.

For the following consideration, structural collapse is defined as a failure mode, which should be avoided. This implies that a fire with limited consequences is still an acceptable event. For the evaluation and analysis of the risk that structural collapse is reached, an event tree may be created, as shown in Figure 12.5.

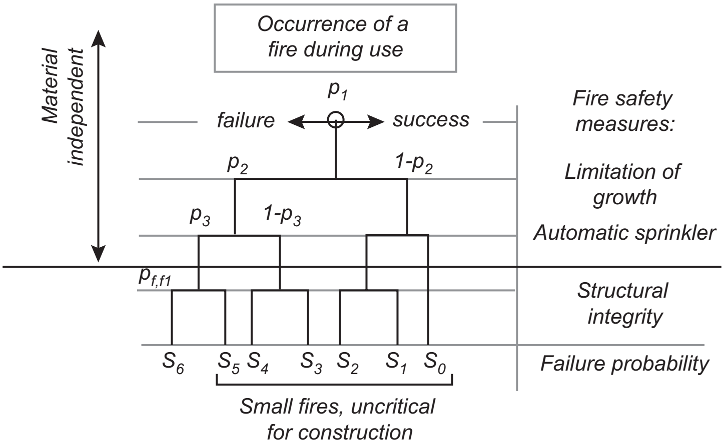

Figure 12.5 Event tree analysis of a fire event, with the probability of occurrence P_i and the individual event failure probability S_i.

For simplicity reasons, Figure 12.5 focuses on the fully developed fire (in contrast to the growth phase where evacuation can be ensured) and does not show details such as early failure of the passive fire protection of structural members (e.g. gypsum plasterboards). From Figure 12.5, it can be seen that many elements above the horizontal heavy line are material-independent. Looking at the event tree, it becomes further apparent that many elements of the event tree are important before reaching the demand of the structural fire design for the fully developed fire (e.g. fire occurrence or starting fire, failure of occupants and fire brigade in stopping the fire, failure of sprinkler in stopping the fire). This is case S_6 in Figure 12.5, whereas $P_{\mathrm{f,fi}}$ is the probability of a failure in a fully developed fire. Consequently, any measure as presented in Section 12.6.2, may only be favourable for this case. As long as this measure is not replacing other measures (e.g. redundant sprinkler feed), it may be an improvement of the overall robustness.

In the following, the focus is the probability of collapse (case S_6), when the structural fire design must provide for structural survival in the fully developed fire after failure of all other fire safety measures. The main difference between structural timber and other building materials is the combustibility of wood.

Structural timber contributes to the structural fuel corresponding to the fire development, i.e. the more severe the fire, the higher the additional fire load from exposed wood surfaces. Design must ensure that the additional fuel load from the consumption of timber members does not lead to structural collapse. Further, the consumption of the combustible structural elements might increase the fire duration and, consequently, challenge other measures (e.g. service penetrations, compartmentation walls, fire curtains and also the protection of load-bearing steel elements in the same compartment). It is not always clear if a long fire with limited peak temperatures (e.g. due to limited ventilation) or a short fire with high peak temperatures (e.g. due to increased ventilation) is more severe for the structural elements. Consequently, a parametric study would be essentially needed to answer this question for the particular design case (i.e. the building, storey, compartment or part of the compartment). In the parametric study, both fuel- and ventilation-controlled fires should be considered and eventually assessed. To do so, the particular facade design should also be taken into account.

12.7 DESIGN OF TIMBER BUILDINGS FOR REUSE AFTER A FIRE

The design of a timber building for reuse after a fire is a relatively new topic in research. The motivation for reuse rather than demolition will depend on the extent and severity of any fire. Limited information is available, see e.g., Matzinger (2019), but in-depth information or planning guidelines are missing. In general, the consideration to reuse a timber structure must consider load-bearing and compartmentation aspects as well as smoke damage. Furthermore, possible damage induced by extinguishing water might be relevant. In the design process, the reuse after a fire scenario might be considered with additional covering of the timber members, and design to replace some load-bearing and non-load-bearing elements after the fire. Charring and possible water damage must be taken into consideration and the structural integrity reassessed. Furthermore, indoor air quality and the functionality of any fire safety measures must be checked. In general, it seems that a well-thought-through design-for-deconstruction approach that allows the de-installation of structural members seems to be beneficial in this context.

12.8 DISCUSSION AND CONCLUSION

The need for robustness in fire design increases as the height and complexity of the building increase.

On one hand, robustness in fire design can be increased by reducing the likelihood of a fire event. This appears to be independent of the building material. However, considering the severity of a fire event, the combustibility of a building material may have an influence, e.g. when looking at the fire spread on combustible, vertical exterior surfaces (e.g. timber facades). This hazard may be addressed by reducing the time to flashover or by considering the increased possibility for a full compartment fire rather than a travelling fire.

On the other hand, robustness of a structure can be increased by increasing the redundancy of structural elements. In this case, a simplified event tree analysis may help to find out redundant and complementary elements in the case of a fully developed fire.

Looking at the design of structural members made from timber, increased robustness can come from an extended parametric study in the course of a performance-based fire design which looks more closely at effects of single parameters affecting the fire severity, e.g. ventilation conditions.

In general, it can be stated that comprehensive fire design and the creation of a robust fire safety concept can be used to increase the robustness of a structure. The concept must be able to guarantee the safety of the occupants and fire brigades for all considered fire scenarios. It must be recognised that measures to achieve robustness against fire can be very different from measures to achieve robustness against some other localised accidents. This is because fire is a systematic exposure, which potentially affects a large number of elements simultaneously. Therefore, the conceptual design of the structure and the structural detailing are keys to providing a robust structure. This is valid independent of the structural material.

REFERENCES

Adam, J.M., Parisi, F., Sagaseta, J. and Lu, X. (2018) Research and Practice on Progressive Collapse and Robustness of Building Structures in the 21st Century. *Engineering Structures*, 173, pp.122–149.

Agarwal, J., Haberland, M., Holický, M., Sykora, M. and Thelandersson, S. (2012) Robustness of Structures: Lessons from Failures. *Structural Engineering International*, 22(1), pp.105–111.

Baker, J.W., Schubert, M. and Faber, M.H. (2008) On the Assessment of Robustness. *Structural Safety*, 30(3), pp.253–267.

Bita, H.M., Huber, J.A., Voulpiotis, K. and Tannert, T. (2019) Survey of Contemporary Practices for Disproportionate Collapse Prevention. *Engineering Structures*, 199, p.109578.

EN 1991-1-2 (2002) Actions on Structures. General Actions. Actions on Structures Exposed to Fire. In *European Standard CEN*. European Committee for Standardization.

EN 1991-1-7 (2010) Actions on Structures Part 1–7 General Actions: Accidental Actions. In *European Standard CEN*. European Committee for Standardization.

EN 1995-1-2 (2004) Design of Timber Structures Part 1–2 General: Structural Fire Design. In *European Standard CEN*. European Committee for Standardization.

ENV 1995-1-2 (1994) Design of Timber Structures: Part 1–2 General Rules: Structural Fire Design. In *European PreStandard CEN*. European Committee for Standardization.

Huber, J.A., Ekevad, M., Girhammar, U.A. and Berg, S. (2019) Structural Robustness and Timber Buildings: A Review. *Wood Material Science & Engineering*, 14(2), pp.107–128.

Hurley, M.J., Gottuk, D.T., Hall Jr, J.R., Harada, K., Kuligowski, E.D., Puchovsky, M., Watts Jr, J.M. and Wieczorek, C.J. eds. (2015) *SFPE Handbook of Fire Protection Engineering*. Springer.

ISO 2394 (n.d.) *General Principles on Reliability of Structures. International Standard*. International Organization for Standardization.

JCSS (2001) *Probabilistic Model Code*. Joint Committee on Structural Safety.

Matzinger, I. (2019) *Brand- und Wasserschadensanierung, Presentation at Beiratssitzung des Österreichischen Ingenieurholzbauverbandes (IHBV)*. Ingenieurholzbauver band

Schubert, M. (2009) *Konzepte zur informierten Entscheidungsfindung im Bauwesen* (Vol. 322). vdf Hochschulverlag AG an der ETH Zürich.

Starossek, U. and Haberland, M. (2010) Disproportionate Collapse: Terminology and Procedures. *Journal of Performance of Constructed Facilities*, 24(6), pp.519–528.

Voulpiotis, K., Köhler, J., Jockwer, R. and Frangi, A. (2021) A holistic framework for designing for structural robustness in tall timber buildings, Engineering Structures. DOI: https://doi.org/10.1016/j.engstruct.2020.111432.

Winter, S. and Kreuzinger, H. (2008) The Bad Reichenhall Ice-Arena Collapse and The Necessary Consequences for Wide Span Timber Structures. In Proceedings WCTE 2008 Conference, Miyazaki, Japan.