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Robustness Design For Tall Timber Buildings

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Abstract

With the ever-increasing height of timber buildings, the complexity of timber as a structural material gives rise to behaviors not previously studied by engineers. An urgent call is needed regarding their performance in damage scenarios: activating alternative load paths in tall timber buildings is not the same as in tall buildings made with steel and concrete. In this paper we propose a robustness framework covering all building materials, whose application in timber may lead to new conceptual designs for the next generation of tall timber buildings. Qualitatively, the importance of building scale and the distinction between localized and systematic exposures are discussed, and how existing supertall structures can be an example for future generations of tall timber buildings. Quantitatively, the robustness index is introduced alongside a method to calculate the performance of a given building regarding robustness, in order to find the most cost-effective structural solutions for improved robustness. A three-level application recommendation is made, depending on the importance of the building in question. Primarily, the paper highlights the importance of conceptual design to achieve structural robustness and encourages the practicing engineering community to use the proposed framework to quantitatively come up with the new generation of tall timber buildings.

Keywords: Disproportionate Collapse, Risk, Consequences, Modelling, Optimization, Tall timber building

1. Introduction

Structural robustness is an important characteristic of a structure that prevents initial damage to spread disproportionately. There are numerous case studies where lack of robustness in combination with an unforeseen event lead to catastrophic consequences. Two prime examples are the collapse of an entire corner of the 22 storey Ronan Point building in London in 1968 caused by a small gas explosion in an apartment (Bussell and Jones, 2010), and the progressive collapse of kilometers of power lines in Québec, Canada, following an extreme event of freezing rain in the winter of 1998 (Risk Management Solutions, 2008). More examples are presented in Agarwal, et al. (2011).

There are three distinct steps in any accidental scenario as seen in Figure 2 below:

Each event is statistically independent from each other, but since an exposure needs to happen for damage to occur, and damage needs to occur for collapse to happen, there is a conditional dependence described in Equation 1 (Starossek and Haberland, 2010):

$$P(C) = P(E) \times P(D|E) \times P(C|D) \quad (1)$$

P(C) is the probability of disproportionate collapse, P(E) the probability of an accident happening ("Exposure"), P(D | E) the probability that damage occurs given this accident ("Vulnerability"), and P(C | D) the probability that collapse happens given the occurrence of damage ("Robustness"). It is important to note that robustness is only concerned with the disproportionality of the progressive (indirect) consequences of some initial damage. Measures to protect a structure from being damaged in the first place may for sure contribute to structural safety by reducing its vulnerability, but do not contribute to its robustness.

There are three approaches to quantify robustness and design for it, listed in increasing complexity below. These approaches are presented in full detail in Adam, et al. (2018), Arup (2011), and Canisius (2011).

- Deterministic methods, such as Alternative Load Path Analysis (ALPA) and minimum tie forces. They aim to satisfy assumed damage scenarios like a column loss.
- Reliability approaches, which compare the failure probabilities of damaged and undamaged states.
- Risk approaches, which compare the direct and indirect consequences and their probabilities.

Existing building codes mostly focus on prescriptive deterministic rules, with little help to the designer (Mpidi Bita, et al., 2019).

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Figure 1. Sequence of events for structural damage.

2. Tall Timber Buildings: A Brief History

Tall timber buildings first appeared in the late 19th century in North America, using "heavy timber", that is very large solid wood sections from old growth forests (Koo, 2013). However, the availability and competitive pricing of concrete and steel, combined with fire phobia, caused the decline of tall timber buildings until the last two decades which have seen an unprecedented rise in modern tall timber buildings using advanced Engineered Wood Products (EWPs) such as Cross Laminated Timber. Due to their inherent sustainability benefits, and boosted by attractive prefabrication and rapid construction opportunities, medium to high-rise timber buildings can now be a competitive answer to the growing urbanization needs.

However, tall timber buildings come with certain challenges. On the material level, timber is sensitive to moisture, lightweight, orthotropic, generally brittle, and rather soft. This makes connection design difficult, especially if bending moments need to be transferred, vibration serviceability criteria challenging to fulfil, alternative load paths difficult to develop, and generally detailing becomes the most crucial part of the design. On the building level, the system, size, and time (creep) effects of timber are difficult to quantify. Accurately predicting the exact behaviour of such large structures is almost impossible due to lack of experience and difficulty with testing large-scale assemblies. Still, impressive efforts have taken timber structures to unprecedented heights while addressing the challenges as much as currently possible (Abrahamsen, 2018).

Robustness design is well researched and understood for concrete and steel buildings, however little research

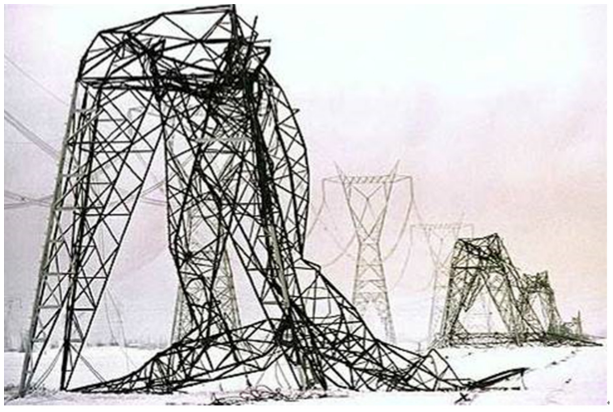


Figure 2. Series of collapsed pylons during the 1998 ice storm in Québec, Canada.



Figure 3. Mjøstårnet, Norway. At 85 m, the world's tallest timber building. ©Moelven Limtre

and almost no formal guidance exists for timber buildings (Huber, et al., 2019). With an increasing number of medium to high-rise buildings made in timber, and the structural challenges they present, it is of paramount importance to better understand their behavior in accidental scenarios, and prevent catastrophic events occurring from scaling up known systems to sizes not previously attempted, such as in the case of the Ronan Point building (Bussell & Jones, 2010). This paper presents an improved framework to consider robustness from the very first conceptual design steps, with a further attempt to quantify the qualitative results and prove their efficacy.

3. Qualitative Approach and the Modern Skyscraper

3.1. Scale

In the race for taller and more efficient buildings, the skyscraper saw a paradigm shift in the 1970s with the exploration of new conceptual designs. To a large extend influenced by Fazlur Khan, novel structural systems such as megaframes and tubes allowed the construction of high-performance buildings of unprecedented heights (Ali and Moon, 2007). With such building sizes it becomes easier to see a structural system in different levels of the scale: an entire building can be seen as a system of structural components (beams, columns, slabs, et cetera). Each component can also be seen as a system of sub-components (web, flanges, stiffener plates, et cetera). This component scale becomes clear in the design of the mega-columns of recent supertalls, such as those in Seoul's Lotte World Tower (von Klemperer, 2018), Tianjin 117 (Peng, et al., 2012), and Wuhan Centre (Bao, et al., 2015). The same applies to connections and their constituent parts. In low-rise buildings this scale distinction is less evident, but exists nonetheless.

The scale perspective is important because it is central in the current confusion and lack of clear guidelines for structural robustness. In the current state-of-the-art robustness formulation of Equation 1, the default interpretation of damage is that to the building components, for example the loss of a column, while progressive

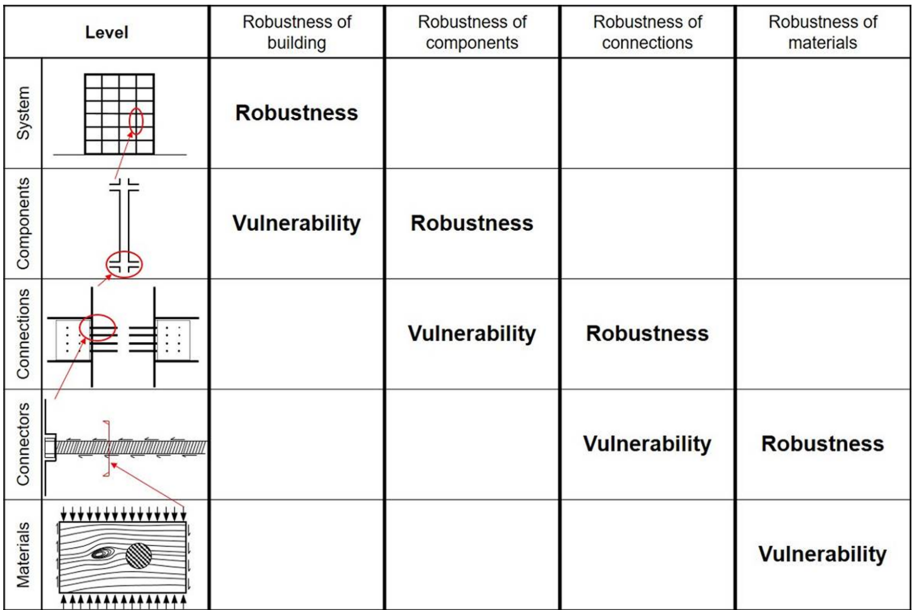


Figure 4. Robustness and vulnerability in different scales.

damage is considered in the whole building scale. It is however also possible to consider damage at a sub-component level (e.g. loss of a steel column web stiffener) and how this damage may progress up to the component level. In this view, it is possible to talk about robustness of a column, rather than robustness of a building. In a similar manner, one can talk about the robustness of a timber beam-to-column connection, by considering the effect of, for example, failed dowels.

By adopting such a multi-scale approach, the terms of Equation 1 (exposure, vulnerability, robustness) become scale-specific. The loss of a column is at the same time related to the vulnerability at the whole building scale and to the robustness at the component scale. This is shown in Figure 4 below:

As an example of how this perspective can help clarify certain aspects of robustness, consider the existing criticism for the key element design for robustness, one of the common deterministic methods. The criticism exists because key elements do not directly improve a building's robustness. That is true, however a key element should be designed for robustness at a component level, in other words it must be robust against damage in itself. Increasing the robustness of a key element is exactly the same as decreasing the vulnerability of the whole building, in both cases making the building safer by decreasing its probability of disproportionate collapse.

3.2. Exposures

In addition to the consideration of scale, a holistic robustness approach requires the consideration of the different types of exposures. When we talk about "accidental scenarios", the default consideration is that of a localized exposure, that is an exposure affecting one, or a small number of elements: an explosion, confined fire, or impact to a structural member. To design for robustness against these kind of exposures, the engineer must ensure that the structure is able to develop alternative load paths around the damaged portion.

However, there also exist systematic exposures, which affect a large number of elements, or the entire structure simultaneously. Examples of such exposures are earthquakes, systematic degradation (e.g. deteriorating glue throughout a structure), and human design or construction error. Addressing such exposures requires very different methods, such as compartmentalization. More importantly, robustness design methods which address localized exposures may actually be very dangerous when the same structure faces a systematic exposure. This was the case of the Bad Reichenhall Ice Arena in Germany, whose long span timber roof collapsed without warning in January 2006, 34 years after construction (Winter & Kreuzinger, 2008). The entire roof, made with 48 m long timber box girders, was weakened by severe degradation of the urea-formaldehyde glue used to produce the main girders. The failure started at one of the main girders, whose collapse pulled the rest of the roof down with it, via the strong secondary purlin connections between the main girders. A structural concept providing alternative load paths for localized exposures was the actual reason for disproportionate collapse.

Consider, on the other hand, how a lack of alternative load paths can help a structure survive: the case of the Siemens Arena in Denmark is an example of a long span timber roof collapse whose structure did not have a stiff secondary connection between main elements (Sørensen, 2011). The roof comprised 12 glulam trusses with a clear span of 73 m. Two of the 12 main trusses collapsed without



Figure 5. The Bad Reichenhall Arena collapse (left) and the Siemens Arena collapse (right).

warning in January 2003, only months after construction. The trusses were subject to several design errors, a systematic exposure. Since the purlins were only simply supported between the trusses, the collapse remained partial. Had the secondary connection system been strong and stiff, the entire roof would have collapsed since all the trusses were weak. The structure was unintentionally compartmentalized.

The main message of these two examples is that different methods to design for structural robustness are required for localized and systematic exposures. The well-known ALPA method alone is not sufficient to address systematic exposures. This distinction is very important to make and not immediately obvious.

3.3. Holistic Approach

The multi-level scale approach and the distinction between localized and systematic exposures are the two key notions that combine to form the proposed improved framework to design for structural robustness. Addressing both localized and systematic exposures is most easily done in different levels of the scale: alternative load paths for the former and compartments for the latter. Key element design, or better "robust component design", is a good method to create the compartment borders. This is illustrated with an example high-rise building in Figure 6: robustness for localized exposures can be addressed with frames able to develop alternative load paths. These frames can be separated with key elements, forming strong-border compartments which address the systematic exposures: an entire frame may collapse due to a widespread error, but the compartment borders will not allow this damage to spread to the rest of the building.

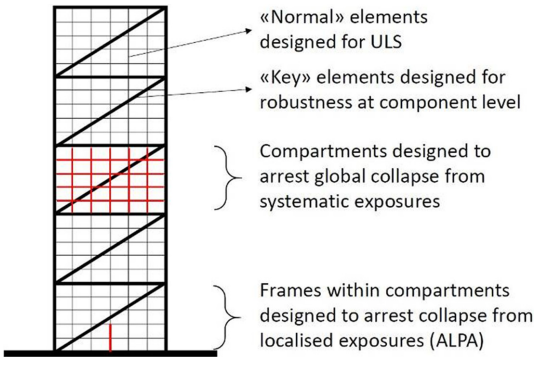


Figure 6. Framework qualitatively applied to a tall building.

The resulting mega-component-based compartmentalized structure is a common theme in supertall buildings, such as the China Zun Tower, Tianjin 117, and Guanghzou West Tower (Bao, et al., 2015). The underlying reasons for these conceptual designs seem, however, to be material economy (Jianlong, et al., 2014) and performance in highly seismic regions (Chung & Sunu, 2015). Robustness as an achievement of a compartmentalized structure is only explicitly mentioned in the publication for the design of the China Zun Tower (Peng, et al., 2016). With the explicit presentation of this qualitative robustness framework, we hope to continue shifting the attention of the structural engineering community to these very high-performance supertall buildings. While timber buildings of increasing height are being constructed without yet having a performance-based robustness design, the timber engineering practice can learn a lot from the current supertall trends. Two conceptual designs of timber skyscrapers following the steps of the modern skyscraper have already been proposed, the River Beech Tower (Sanner, et al., 2017), and the Oakwood Tower (Ramage, et al., 2017).

Using the robustness framework described above, the final list of scales is shown in Figure 8 below. A sound conceptual design should consider if damage propagates upwards in the scale. The primary design methods that address robustness in each level of the scale are also indicated. It should be noted that the responsibility to enable these methods in a structure lies beyond the role of the chief structural engineer. While he or she may come up with a robust concept for the entire structure, the engineer responsible for the detailed design shall be taking care of the robustness at the connection level, while the supplier of connectors and materials is expected to provide products to specification and standard. The responsibilities discussed here are not exhaustive; they show that the structural engineer need not control every



Figure 7. Left to right: China Zun Tower, Tianjin 117, River Beech Tower, Oakwood Tower.

level of the scale. Conceptual design is a collaboration of engineers, architects, contractors, and many others.

While there are a number of unresolved details for the construction of tall timber buildings, it is obvious that conceptual design at the early stages of a project is where robustness considerations can be addressed most effectively and economically. This is a fundamental conclusion of the qualitative approach to robustness and potentially enough for the practicing engineer to consider in his or her designs. However, the framework is not complete without a quantitative approach to confirm the qualitative findings. A novel quantification scheme is described in the following chapter.

4. Quantitative Approach

4.1. Mathematical Formulation

According to Figure 1, Equation 1 can be transformed to Equation 2 if the direct consequences due to the initial damage, C_{Dir}, and indirect consequences due to the propagating damage, C_{Ind}, are included in the calculation. Here, E[C] is the expectation of total consequences (= total risk).

$$E[C] = (P(E)\times P(D|E))\times C_{Dir} + (P(E)\times P(D|E)\times P(C|D))\times C_{Ind} \quad (2)$$

Given the definition of robustness as the (lack of) disproportionality of consequences given damage, the robustness index is defined as the ratio of the direct consequences to the total consequences, and simplifies to Equation 3:

$$I_{Rob} = \frac{E[C_{Dir}]}{E[C]} = \frac{E[C_{Dir}]}{E[C_{Dir}]+E[C_{Ind}]} = \frac{C_{Dir}}{C_{Dir}+P(C|D)\times C_{Ind}} \quad (3)$$

The index cannot be below zero (all consequences are indirect, i.e. no robustness), or above one (all consequences are direct, i.e. total robustness). Further details on the definition of the robustness index can be found in Voulpiotis, et al. (2019), and Baker, et al. (2007). We recommend the use of this robustness index for the quantification of robustness in buildings, for which three analysis steps are required:

1. Create a sufficiently accurate structural model, be it analytical (for a very specific case), or numerical (to study a variety of cases). For robustness analyses, a nonlinear dynamic finite element model is preferred.
2. Use the appropriate probabilistic inputs and propagate the uncertainties in the model using an appropriate uncertainty quantification technique. This is used to calculate the probability of further damage given an initial damage, P(C|D). Various methods exist, from the simple (but expensive) Monte Carlo Simulation, to the most efficient sparse polynomial chaos expansion models (Sudret, 2007). For a variety of methods, there exists in-house software developed at ETH Zurich (Marelli, et al., 2019).

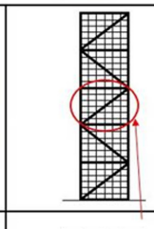
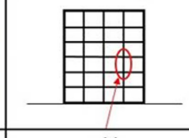
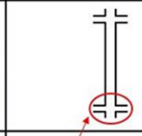
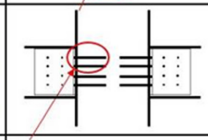
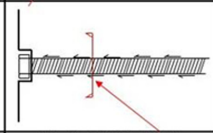
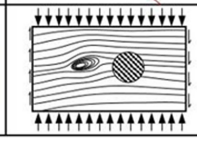
Level		Design Method	Responsibility
Whole building		Compartmentalisation	Structural Engineer (Conceptual Design)
Compartments		Alternative Load Path Design	Structural Engineer (Conceptual Design)
Components		Key Element Design	Structural Engineer (Conceptual Design)
Connections		Robust Connection Design	Structural Engineer (Detailed Design)
Connectors		Key Connector Design	Supplier
Materials		Material Grading / Robust Manufacture	Supplier

Figure 8. Multi-scale robustness approach with design methods and responsibilities.

3. Estimate the consequences C_{Dir} and C_{Ind} from the results of the model run. This can be simplified by measuring consequences in terms of the floor area of the failed part of the building.

4.2. Complete Quantification Framework

As shown in Figure 9 below, the robustness index is a term relative to a specific damage scenario only, therefore the sequence of steps shall be repeated for many damage scenarios. Each robustness index calculated shall be then weighted with the probability of occurrence of the respective damage scenario. In addition, this entire procedure may be repeated for several different concept designs of the same building, in order to compare their robustness performance. For k different concepts and n different damage scenarios, the k^{th} average robustness index is given in Equation 4:

$$I_{Rob(k,av)} = \frac{1}{n}\sum_{i=1}^{n} P(E_i) \times P(D|E_i) \times I_{Rob(k,i)} \quad (4)$$

If, in addition, we obtain some measure of the base cost of each of the k conceptual designs (for example, the volume of material used), we can define the Normalized Geometry Rating (NGR) as per Equation 5, a numerical value for the change in robustness (with consideration of the cost) when comparing design improvements to a base geometry, or a starting concept design:

$$NGR_k = \frac{I_{Rob(k,av)}}{I_{Rob(1,av)}} \times \frac{V_1}{V_k} \quad (5)$$

This is exactly the basis of the proposed framework: the goal is not to analyze a large number of completely different structures which fit the remit of a building design and compare their robustness performance, but rather explore the effectiveness of design decisions for improving the robustness of an initial conceptual design, whose base geometry has been selected according to numerous other factors such as location, project size, architecture, local materials and expertise, et cetera.

The entire procedure is summarized in Figure 10. The quantification framework can be connected back to the scale approach described earlier by categorizing each design improvement by its respective scale. For example, the stiffening of the connections would be a concept improvement in the connection scale, while the rearrangement of compartment borders would be a concept

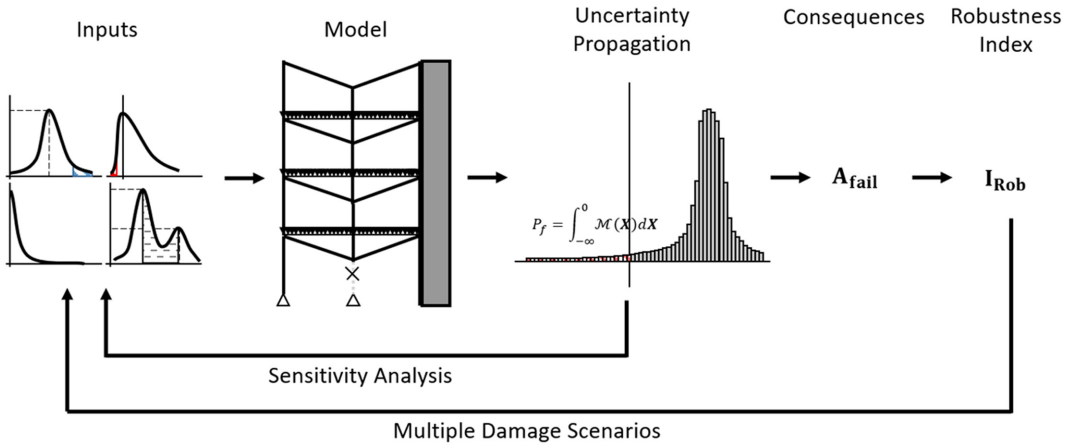


Figure 9. Algorithm to calculate the robustness index for a given structural concept.

Robustness Optimisation	Scenario 1	Scenario 2	...	Scenario n	**Average I_{Rob}** (Separate for localised and systematic exposures)	Measure of base cost, e.g. material volume	**Normalised Geometry Rating (NGR)**
Base Concept	$I_{Rob(1,1)}$	$I_{Rob(1,2)}$	...	$I_{Rob(1,n)}$	$\mathbf{I_{Rob(1,av)}}$	V_1	$\frac{\mathbf{I_{Rob(1,av)}}}{\mathbf{I_{Rob(1,av)}}} \times \frac{\mathbf{V_1}}{\mathbf{V_1}} = \mathbf{1}$
Concept 2	$I_{Rob(2,1)}$	$I_{Rob(2,2)}$	...	$I_{Rob(2,n)}$	$\mathbf{I_{Rob(2,av)}}$	V_2	$\frac{\mathbf{I_{Rob(2,av)}}}{\mathbf{I_{Rob(1,av)}}} \times \frac{\mathbf{V_1}}{\mathbf{V_2}} = ?$
...	...	...	...	...	...	...	...
Concept k	$I_{Rob(k,1)}$	$I_{Rob(k,2)}$	...	$I_{Rob(k,n)}$	$\mathbf{I_{Rob(k,av)}}$	V_k	$\frac{\mathbf{I_{Rob(k,av)}}}{\mathbf{I_{Rob(1,av)}}} \times \frac{\mathbf{V_1}}{\mathbf{V_k}} = ?$
	$\mathbf{I_{Rob,av(1)}}$	$\mathbf{I_{Rob,av(2)}}$	...	$\mathbf{I_{Rob,av(n)}}$			

Figure 10. Algorithm to calculate the normalized geometry ratings for a given structure.

improvement in the whole building scale, according to Figure 8. Given enough design improvement concepts, each with its calculated NGR, the scale with the maximum NGR indicates where the structural engineer should invest resources in making the base structure more robust, more economically. Alternatively, sensitivity indices of each scale may be calculated from the various NGRs, however this will not be discussed further in this paper. The connection to the scale approach is shown in Figure 11.

5. Conclusions – The Timber Skyscraper

This paper presented a conceptual design tool for structural robustness on two levels: qualitative and quantitative. For the qualitative level, we have highlighted the importance of building scale and the distinction between localized and systematic exposures. For the quantitative level, we have presented a risk-based method to calculate the average robustness index for a given structure, and its Normalized Geometry Rating (NGR) when compared to a base geometry.

The proposed robustness framework, both at qualitative, as well as at a quantitative level, is an invitation to the practicing engineering community to consider robustness from the very beginning of the conceptual design. Not all projects, however, require the entire risk analysis presented in this paper: for a building of increasing importance class, three robustness approaches

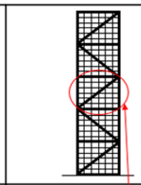
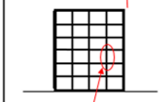
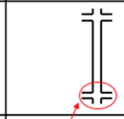
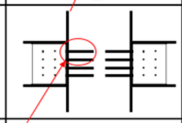
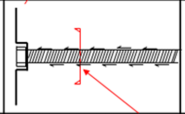
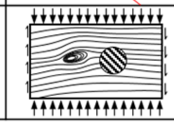
Level		Design Method	Responsibility	Max(NGR)	Level Sensitivity
Whole building		Compartmentalisation	Structural Engineer (Conceptual Design)	NGR_{system} NGR_{local}	$S_{building}$
Compartments		Alternative Load Path Design	Structural Engineer (Conceptual Design)	NGR_{system} NGR_{local}	$S_{compartment}$
Components		Key Element Design	Structural Engineer (Conceptual Design)	NGR_{system} NGR_{local}	$S_{component}$
Connections		Robust Connection Design	Structural Engineer (Detailed Design)	NGR_{system} NGR_{local}	$S_{connection}$
Connectors		Key Connector Design	Supplier	NGR_{system} NGR_{local}	$S_{connector}$
Materials		Material Grading / Robust Manufacture	Supplier	NGR_{system} NGR_{local}	$S_{material}$

Figure 11. Complete scale-based robustness framework with quantification.

are recommended:

1. Qualitative Approach only: this may apply to most low to medium-rise buildings where a quantification of robustness is not necessary. The conceptual methods described in chapter 3 are enough to design a sufficiently robust building.
2. Quasi-Quantitative Approach: this may apply to any building whose structure is relatively common. We suggest the calculation of the NGRs in Figure 11 for common structure types, such as moment resisting frames, typical core & outrigger structures, et cetera. The engineers may then be able to refer to the table of values and invest resources in improving the appropriate scales in their given building.
3. Full Quantitative Approach: this may apply to any unique, high importance building, such as most supertalls, and new tall timber buildings. The engineers should carry out a full quantification of the risks according to this paper and make specific improvements to the structure. Building codes may impose a minimum average robustness index that the design must satisfy.

These recommendations are only tentative and up for discussion in both the practicing and academic community. Most importantly, the unprecedented rise of timber as a primary loadbearing material in high-rise buildings is calling for new measures to design for robustness. The presented framework applies to buildings of all materials, however the resulting optimal structures may significantly differ when timber is loadbearing. We hope the engineering community engages in the topic and helps to define and design the new generation of tall timber buildings.

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