First-Order Robustness, Higher-Order Mechanics

Bassam A. Izzuddin[1]

[1]*Department of Civil and Environmental Engineering, Imperial College London*
Exhibition Road, London SW7 2AZ, United Kingdom
e-mail: b.izzuddin@imperial.ac.uk

Abstract

This paper establishes the basic first-order requirements for the assessment of structural robustness, with particular focus on multi-storey buildings. Starting from the definition of structural robustness as the resistance to disproportionate collapse, the paper considers the significance of predictability towards the adequacy of assessment. It is proposed that the assessment of robustness for realistic structures should operate outside the conventional strength limit but within the ductility limit state. Nevertheless, the conditions of predictability require the exclusion of certain scenarios from practical consideration, particularly those that are highly influenced by uncertainty in the loading, structure and/or response model. It is also argued that realistic robustness assessment requires models based on higher-order mechanics, including capabilities for modelling geometric and material nonlinearity as well as the interactions of various components within the overall structural system. A multi-level approach recently developed at Imperial College is shown to offer a practical design-oriented assessment framework which fulfils the aforementioned requirements. Finally, the paper highlights important outcomes arising from the application of this framework to multi-storey buildings.

Keywords: robustness, progressive collapse, structural mechanics, large deformations

1. Introduction

The past decade has witnessed a substantial renewed interest in defining and assessing structural robustness. It is now widely accepted that robustness implies the ability of a structure to withstand local damage scenarios, particularly those arising from unforeseen extreme dynamic events, without undergoing collapse that is disproportionate to the original cause.

Several alternative approaches have been proposed since the Ronan Point collapse in 1968 for the assessment of structural robustness, and these vary greatly in terms of applicability and sophistication. This paper aims at elucidating the prerequisites for a rational assessment of robustness, which are linked to computational modelling requirements and demonstrated through a design-oriented assessment framework for multi-storey buildings recently developed at Imperial College [4].

2. First-order robustness

There is a wide spectrum of robustness assessment methods that have been proposed, including some which have been adopted in design codes, ranging from prescriptive to performance-based and varying in terms of modelling sophistication. Focus is given here to establishing the basic 'first-order' requirements for a rational assessment method of structural robustness that can be realistically applied in design practice.

A rational assessment method should be based on models of i) the structural properties, ii) the applied actions, and iii) the structural response, with the adequacy of the overall method directly linked to the degree of predictability in all three models.

Prescriptive methods for robustness design, such as the tying force requirements still used in the Building Regulations [5], make only an implicit reference to the applied actions and involve no prediction of the structural response. Therefore, these cannot form the basis for a rational robustness assessment.

Performance-based methods, on the other hand, involve consideration of the structure, applied actions and response, but can vary greatly in the models adopted for each. In the context of building structures subject to an extreme event that causes local damage, basing the ensuing response on a plane frame idealisation is typically inadequate. Indeed, the interactions between the slabs, beams, columns and connections within the overall 3D structural system should normally be considered. Furthermore, even non-structural components that are ignored in conventional structural design, such as infill wall panels, can make a significant contribution to robustness. However, the inclusion of such components in robustness assessment must depend on the predictability of their properties and response.

With regard to applied actions, consideration must be given to those arising from the extreme event that causes local damage and those that persist on the structure afterwards. The latter types of action are typically gravity loads, which are largely predictable. On the other hand, actions due to the extreme event, such as blast or impact loads, are typically known with much less certainty, and this is particularly true for malicious events. Since robustness assessment and design are concerned with unforeseen events, this appears on the face of it to rule out a performance-based approach. However, it is still possible for a rational assessment method to be based around local damage scenarios and establishing that these do not progress to disproportionate collapse. One such scenario is the loss of a column, which has been considered in several design codes [1,5], although some consider the loss to be static [5] while others consider it to be instantaneous [1] leading to dynamic effects. Clearly, the latter assumption is much more realistic since column loss/damage would typically arise from short duration extreme dynamic events. Furthermore, while detailed modelling of the action due to an extreme event is not justified on the basis of the aforementioned uncertainty, it is of interest to study the correlation between such actions and sudden member loss. Towards this end, recent work [2] has shown that sudden column loss presents an upper bound on the influence of column damage caused by blast loading, which adds further weight to the benefits of this scenario in robustness assessment and design. Of course, other types of local damage scenario may also be considered, with the overall objective of ensuring that these do not lead to disproportionate collapse.

3. Higher-order mechanics

In addition to the aforementioned issues related to structural properties and applied actions, the type of model used for the structural response, particularly following the onset of local damage, is of paramount importance to robustness assessment.

Since extreme events are very rare, structures subject to such actions should be allowed to undergo relatively large inelastic deformations that would not be tolerated for normal loading conditions. Indeed, construction economy demands that this be the case. Therefore, elastic and even conventional strength-based elasto-plastic analysis would be unrealistic for robustness assessment. Instead, models that account for both geometric and material nonlinearity in the structural response should be used, allowing the modelling of such phenomena as compressive arching, tensile catenary/membrane action and material strain-hardening.

In addition, the structural response following local damage is typically dynamic, due to the relatively short duration of the initiating extreme event. Accordingly, nonlinear dynamic analysis is often required, though simplified dynamic assessment can be undertaken for sudden member loss as discussed in the next section. Furthermore, even though the gravity driven response following member loss is of relatively larger duration compared to the initiating event, material rate sensitivity could still play an important role [6] and should therefore be modelled.

By relying on the residual dynamic resistance beyond the conventional strength limit, ductility issues become paramount, and a robustness limit state would thus be defined in terms of ductility demand exceeding supply, either on the basis of first component failure or successive component failures [3]. It is also conceivable that the structural response model may account for the progression of structural discontinuity, formation of debris and the transfer/impact of such debris on other parts of the structure so as to assess the extent of damage progression. However, such models are typically prohibitively expensive, and their predictive capacity is questionable for a phenomenon that is likely to be chaotic, add to which the recent finding that even the impact of one failed floor on top of another is likely to trigger progressive collapse in typical multi-storey buildings [7]. Accordingly, it is proposed that the scope of robustness assessment is restricted to the range over which structural response models offer good prediction capabilities, even if this were to require further computational developments and validation against physical testing.

4. Multi-level robustness assessment framework

A design-oriented framework has been recently developed at Imperial College London [4], which fulfils the above discussed first-order requirements of robustness assessment for multi-storey buildings. The proposed framework considers sudden column loss as an event independent scenario for robustness assessment, accounts for the interaction of components in the 3D structural system, and can be applied at various alternative levels of structural idealisation, as illustrated in Figure 1. Towards this end, significant modelling benefits arise for regular building structures, where assessment can be performed at lower levels of idealisation within an affected bay.

The proposed approach can accommodate simplified as well as detailed nonlinear models of the various system components. Even in the latter case, simplified assembly procedures can be employed to establish the system nonlinear response at higher levels from that of the lower levels, where only the nonlinear static response under gravity loading is required

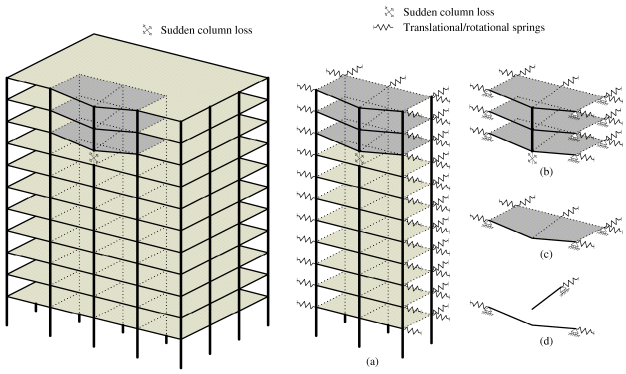

Figure 1: Alternative levels for robustness assessment [4]

Dynamic effects under sudden column loss are dealt with using a simplified assessment procedure based on energy balance, leading to the notion of a pseudo-static response which provides the maximum dynamic displacement corresponding to different levels of loading. It is contended that the pseudo-static capacity of the overall system provides a rational measure of structural robustness, which combines the influences of redundancy, ductility and energy absorption capacity.

The paper elaborates on the application of the proposed robustness assessment framework, including outcomes from recent case studies which have considered such additional influences as infill masonry panels and material rate sensitivity. In particular, it is noted that both these effects can significantly enhance the robustness of typical multi-storey buildings, though a combination of physical testing and detailed numerical modelling is still required to achieve good predictability.

References

[1] Department of Defense, *Unified facilities criteria, Design of buildings to resist progressive collapse*, UFC 4-023-03, Washington, DC, USA, 2009.

[2] Gudmundsson, G.V. and Izzuddin, B.A., The 'sudden column loss' idealisation for disproportionate collapse assessment, *The Structural Engineer*, 88, pp. 22-26, 2010.

[3] Izzuddin, B.A., Simplified assessment of structural robustness for sudden component failures, *1st Workshop on Robustness of Structures, COST Action TU0601*, Zurich, Switzerland, 2008.

[4] Izzuddin, B.A., Vlassis, A.G., Elghazouli, A.Y. and Nethercot, D.A., Progressive collapse of multi-storey buildings due to sudden column loss – Part I: simplified assessment framework, *Engineering Structures*, 30, pp. 1308-1318, 2008.

[5] Office of the Deputy Prime Minister, *The Building Regulations 2000, Part A, Schedule 1: A3, Disproportionate Collapse*, London, UK, 2004.

[6] Pereira, M. and Izzuddin, B.A., Assessment of progressive collapse in multi-storey buildings – influence of material rate sensitivity, *Proceedings of the 6th International Conference on Advances in Steel Structures*, ICASS'09, Hong Kong, 2009.

[7] Vlassis, A.G., Izzuddin, B.A., Elghazouli, A.Y. and Nethercot, D.A., Progressive collapse of multi-storey buildings due to failed floor impact, *Engineering Structures*, 31, pp. 1522-1534, 2009.