The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 2.3
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.2.3

Rational Robustness Assessment and Design of Multi-storey Buildings

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Abstract

This paper presents two rational methods for the robustness assessment of building structures subject to the sudden loss of a vertical load bearing member. The first is a multi-level assessment framework which offers a practical alternate load path approach based on nonlinear static analysis combined with a simplified dynamic assessment approach. Besides applicability at various levels of structural idealisation, a key feature of the proposed approach is its utilisation of the energy balance principle in simplified dynamic assessment, leading to the notion of the pseudo-static capacity as a rational measure of structural robustness. An important feature of this approach is it application to various types of nonlinear static pushdown response, avoiding prescribed dynamic increase factors which are typically unsafe for a nonlinear static response characterised by tensile catenary/membrane action and/or compressive arching action. The second method is a recently developed simplified tying approach which recognises the inadequacy of the prescriptive tying force requirements originating from the UK Building Regulations and currently considered in the Eurocodes. The new horizontal tying force method recognises the significance of the system deformation capacity, accounts for various types of loading and sources of tying, and allows for dynamic amplification. Moreover, it comes with supplementary methods that consider the interaction of the affected floors system with the surrounding structure. The relative simplicity of the proposed tying force method, which has been validated for different forms of building construction, renders it a suitable for prescriptive tying force requirements in the next generation of the Eurocodes.

Keywords: robustness, building structures, alternate load path method, tying force method, sudden member loss, ductility.

1 Introduction

The robustness assessment and design of building structures has re-gained prominence after the catastrophic collapse of the WTC towers on 11 September 2001, with earlier considerations traced back to the progressive collapse of Ronan Point in 1968. From a structural engineering perspective, the widely accepted notion of structural robustness is the ability of the structure to arrest local damage from progression towards disproportionate collapse.

Following Ronan Point, the UK led with the formulation of robustness design guidance, which was incorporated in the Approved Document A of the Building Regulations for the avoidance of disproportionate collapse [1]. This guidance was subsequently adopted, largely unchanged, in the Eurocodes [2], which carried forward much of the inherent shortcomings of the original guidance. Most significantly, this guidance lacks a rational basis for the various recommended means of ensuring structural robustness, including the notional member removal, key element design, and prescriptive tying force requirements [3]. On the other hand, recent design codes in the US [4,5], while drawing inspiration from the UK Building Regulations, have adopted a more transparent and rational treatment of structural robustness. Most significantly, this is reflected by the introduction of alternate load path assessment for local damage scenarios considering sudden column loss, and by the formulation of tying force requirement that recognise the importance of ductility and deformation capacity.

In recognition of the need for a more rational and improved treatment of robustness, new guidance has been developed for the next generation of the Eurocodes under mandate M515 of CEN/TC 250. This paper presents an overview of a rational multi-level robustness assessment framework for multi-storey buildings, which offers an effective alternative load path method for the sudden column loss scenario, avoiding some of the shortcomings of the most recent US design codes [4,5]. Furthermore, a novel horizontal tying force method, developed by the author as part of WG6 PT2 commissioned under mandate M515, is outlined, highlighting its rational basis as a replacement for existing prescriptive tying force requirements. Together, the two approaches have the potential to offer two crucial pillars for robustness assessment and design in the next generation of the Eurocodes.

The paper proceeds by providing an outline of the two proposed methods, making reference to validation studies that have been undertaken in support of their application to various forms of building construction, and drawing comparisons against some other methods that are commonly applied in robustness design and assessment practice.

2 Methods

One of the most applied local damage scenarios for the robustness assessment and design of multi-storey buildings is the sudden loss of a column, where the objective is to establish whether the structure can accommodate the resulting maximum dynamic deformations. This scenario has been adopted by recent USA codes [4,5], and it may be seen as an event-independent scenario that offers a standard test of structural robustness.

In order to avoid the complication of nonlinear dynamic, a multi-level framework was proposed by the author for alternate load path assessment [6], applicable at various levels of structural idealisation, which utilises nonlinear static analysis coupled with a simplified dynamic assessment approach. As illustrated in Fig. 1, nonlinear static analysis can be performed at the level of the affected bay, floor system above the lost column, individual floor, and individual beam, depending on the structural regularity and desired sophistication, besides applicability at the full structural level. Once the characteristic nonlinear static push-down response of the structure, excluding the affected column, has been established, simplified dynamic assessment based on energy balance is performed to obtain the pseudo-static response representing the maximum dynamic deformations under sudden column loss, as illustrated in Fig. 2. This leads to the notion of the pseudo-static capacity, which is the maximum pseudo-static resistance before the structure achieves its ductility limit, as a rational measure of robustness combining the effects of ductility, energy absorption capacity, redundancy and dynamic behaviour [6].

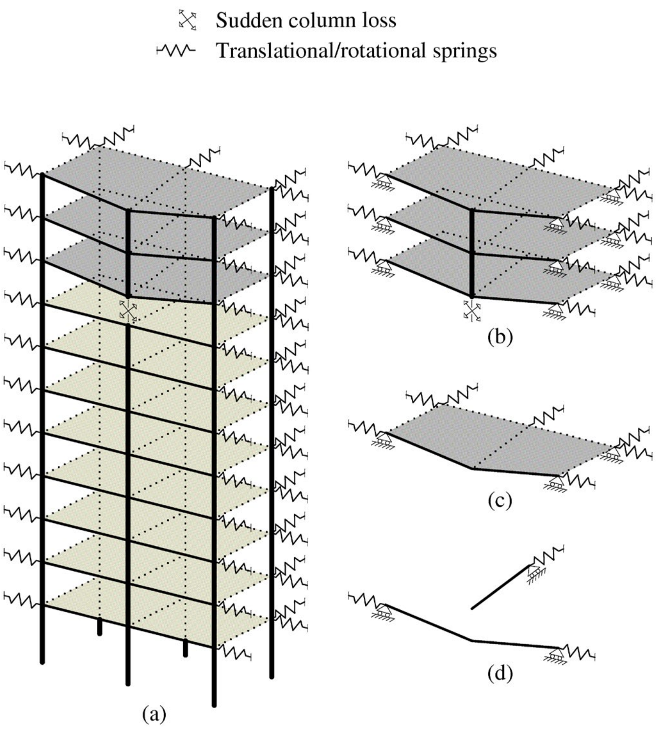


Figure 1: Sub-structural levels for robustness assessment.

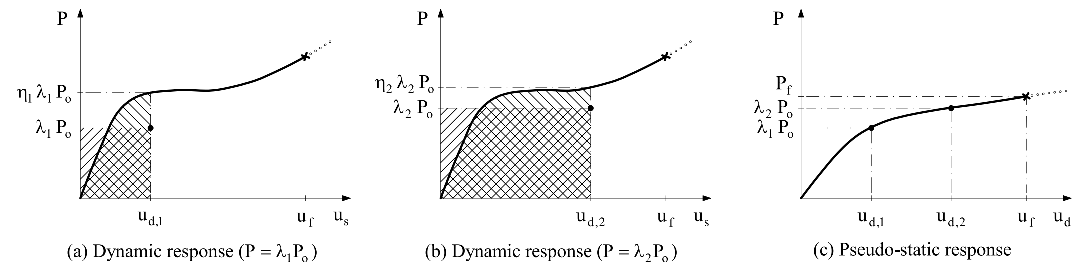


Figure 2: Simplified dynamic assessment and pseudo-static response.

As a more simplified approach, a novel horizontal tying force method was recently proposed by the author [7], which benefits from a rational basis centred around the ability of the floor system to resist gravity loading under the sudden loss of a vertical load bearing member [3]. The new method addresses the unrealistically low tying forces of the prescriptive approach currently considered in the Eurocodes [2], which completely neglects deformation capacity, and offers a much more comprehensive treatment that the latest US codes [4,5] with the consideration of different types of loading, sources of tying and levels of ductility in addition to dynamic effects. The proposed simplified tying force method is encapsulated by the following requirement:

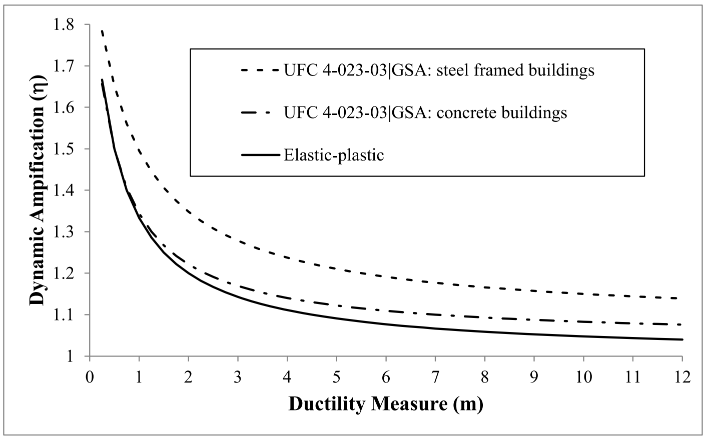
$$T \geq \eta\, \rho \left(\frac{i_f}{\bar{\alpha}} \right) P, \quad \bar{\alpha} = \frac{\alpha}{0.2}, \quad (\alpha \text{ in rad}) \tag{1}$$

in which P is the total equivalent load, T is the total equivalent tying force, i_f is a tying force intensity factor, α is the chord rotation capacity, η is a dynamic amplification factor, and ρ is a reduction factor that allows for contributions additional to tying [3].

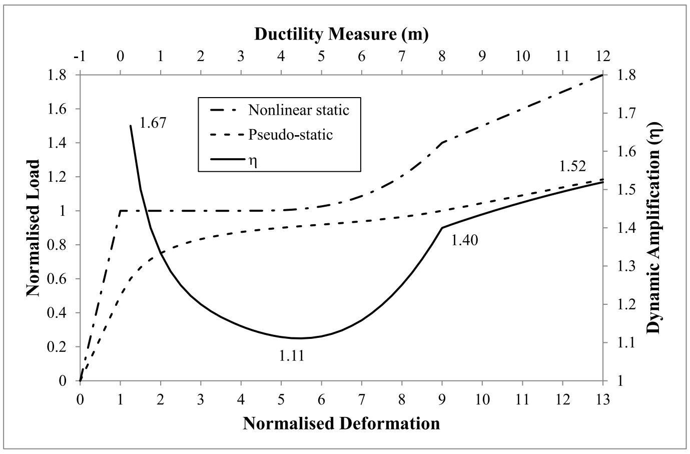
3 Results

The proposed multi-level robustness assessment framework provides an alternate load path approach with nonlinear static analysis that benefits from a realistic and simplified dynamic assessment via energy balance. Unlike the latest US codes [4,5], where a dynamic increase factor (DIF) is prescribed in terms of the ductility limit of the locally damaged structure, the proposed energy balance approach provides a more realistic treatment for different types of nonlinear static response, including compressive arching and tensile catenary action. In this respect, the provisions of the US codes [4,5], while reasonable for an elastic perfectly plastic pushdown response, can be grossly unsafe for a pushdown response characterised by tensile membrane/catenary action, as illustrated in Fig. 3. Importantly, the proposed pseudo-static assessment approach has been extensively applied, verified and validated [8-12]; moreover, it lends itself naturally to the consideration of successive component failures in the robustness assessment of floor systems under sudden column loss [3].

On the other hand, the simplified tying force method accounts for different types of loading and sources of tying in 1D beam and 2D floor slab systems, with the corresponding parameters utilised in (1) illustrated for selected systems in Table 1. Importantly, besides the rational basis centred around ensuring the ability of the beam/floor system to resist gravity loading under the sudden loss of a vertical load bearing member, the new tying force method comes with supplementary methods that consider i) the minimum deformation capacity for the activation of fully tying action, ii) the requisite planar stiffness from the surrounding structure to ensure the activation of full tying action for specific level of deformation capacity, iii) a more realistic dynamic amplification factor η than the default of 2 when accounting for flexural action, and iv) the dynamic amplification of redistributed gravity loading to the surrounding structure [7]. The proposed tying force method has been verified against detailed numerical models [7], and it has been further validated for reinforced concrete [13] as well as post-and-beam timber building structures [14]. While benefitting from a rational basis, the proposed tying forces method maintains the simplicity of application which renders it a suitable candidate for replacing prescriptive tying force requirements in the next generation of the Eurocodes.



(a) Comparison of elastic-plastic dynamic amplification



(b) Dynamic amplification for pushdown response with membrane/catenary action

Figure 3: Comparisons of dynamic amplification factors.

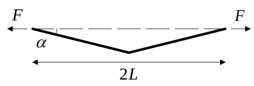
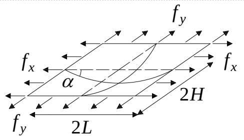
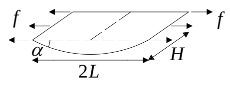
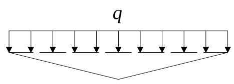
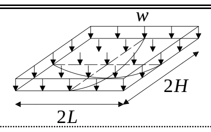
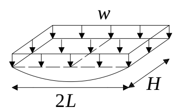
	Tying via beam	Two-way tying via floor	One-way tying via floor
			
Intensity factor: i_f	2.5	3.125	3.125
Equivalent tying force: T	F	$f_x H + f_y L\left(\frac{L}{H}\right)$	$\frac{f\,H}{2}$
Loading			
Equivalent load: P	qL	wLH	$\frac{wLH}{2}$
Redistributed load amplification	$0.25 + 0.75\eta$	$0.3056 + 0.6944\eta$	$0.3056 + 0.6944\eta$

Table 1: Tying parameters and redistributed load amplification for selected 1D/2D systems [7]

4 Conclusions and Contributions

This paper presents two rational methods for the robustness assessment of building structures subject to the sudden loss of a vertical load bearing member. The first is a multi-level assessment framework which offers a practical alternate load path approach based on nonlinear static analysis combined with a simplified dynamic assessment approach. Besides applicability at various levels of structural idealisation, a key feature of the proposed approach is its utilisation of the energy balance principle in simplified dynamic assessment, leading to the notion of the pseudo-static capacity as a rational measure of structural robustness. An important feature of this approach is it application to various types of nonlinear static pushdown response, avoiding prescribed dynamic increase factors which are typically unsafe for a nonlinear static response characterised by tensile catenary/membrane action and/or compressive arching action.

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References

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

[2] CEN, "EN 1991-1-7, Eurocode 1 - Actions on structures - Part 1-7: General actions - Accidental actions". European Committee for Standardization (CEN), Brussels, Belgium, 2006.

[3] Izzuddin, B.A., "Rational Robustness Design of Multi-Storey Building Structures". Journal of Structural Engineering, ASCE, 148(3), 04021279, 2022.

[4] Department of Defense, "Unified Facilities Criteria, Design of Buildings to Resist Progressive Collapse, UFC 4-023-03, Change 3, November 2016", Washington, DC, USA, 2009.

[5] General Services Administration, "Alternate Path Analysis & Design Guidelines for Progressive Collapse Resistance, Revision 1, January 2016", Washington, DC, USA, 2013.

[6] Izzuddin, B.A., Vlassis, A.G., Elghazouli, A.Y., Nethercot, D.A., "Progressive Collapse of Multi-Storey Buildings due to Sudden Column Loss — Part I: Simplified Assessment Framework", Engineering Structures, 30(5), 1308-1318, 2008.

[7] Izzuddin, B.A., Sio, J., "Rational Horizontal Tying Force Method for Practical Robustness Design of Building Structures", Engineering Structures, 252(1), 113676, 2022.

[8] Vlassis, A.G., Izzuddin, B.A., Elghazouli, A.Y., Nethercot, D.A., "Progressive Collapse of Multi-Storey Buildings due to Sudden Column Loss — Part II: Application", Engineering Structures, 30(5), 1424-1438, 2008.

[9] Xu, G., Ellingwood, B.R., "Disproportionate Collapse Performance of Partially Restrained Steel Frames with Bolted T-stub Connections", Engineering Structures, 33(1), 32-43, 2011.

[10] Fu, Q., Tan, K.H., "Numerical Study on Steel-Concrete Composite Floor Systems under Corner Column Removal Scenario", Structures, 21, 33-44, 2019.

[11] Pham, A.T., Tan, K.H., "Static and Dynamic Responses of Reinforced Concrete Structures under Sudden Column Removal Scenario Subjected to Distributed Loading", Journal of Structural Engineering, ASCE, 145(1), 04018235, 2019.

[12] Ding, L., Van Coile, R., Botte, W., Caspeele, R., "Quantification of Model Uncertainties of the Energy-Based Method for Dynamic Column Removal Scenarios", Engineering Structures, 237, 112057, 2021.

[13] Ravasini, S., Sio, J., Franceschini, L., Izzuddin, B.A., Belletti, B., "Validation of Simplified Tying Force Method for Robustness Assessment of RC Framed Structures", Engineering Structures, 249, 113291, 2021.

[14] Martinelli, P., Izzuddin, B,A., "Validation and Application of Rational Tying Method for Robustness Design of Ppost-and-Beam Timber Buildings", Wood Material Science & Engineering, DOI: 10.1080/17480272.2022.2035433, 2022.