Robustness assessment for multiple column loss scenarios

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Abstract

This paper focuses on assessing the robustness of multi-storey buildings subject to multiple column loss scenarios, where progressive collapse is more likely to be triggered by column instability rather than joint failure as considered in the original ductility-centred framework developed at Imperial College. For this purpose, the original framework is enhanced so as to consider the requirements for simplifying the MDOF system into an equivalent SDOF system and the stability of surrounding columns. In order to demonstrate that the modified approach can effectively capture the surrounding frame instability, the removal of two adjacent peripheral columns is considered for a benchmark composite building. The application study compares simplified and detailed slab models for appraisal of the floor load capacity and load redistribution. More importantly, it is shown that extreme events leading to the loss of two columns may indeed be followed by the buckling of surrounding columns prior to joint failure, thus demonstrating the need for improving the ductility-centred method for progressive collapse assessment under different triggering events.

Keywords: progressive collapse, robustness, stability, steel structures.

1. Introduction

Current codes [1,2] propose notional member removal scenarios for robustness assessment. These scenarios evaluate the integrity of a structure subjected to the loss of a single load-carrying member, and this is typically based on a subsequent first failure of a member or a joint. Therefore, in structures where continuity is provided by highly ductile connections, surrounding member failure might trigger disproportionate collapse.

This hypothesis is even stronger for multiple column loss events, for which not only the frame load-carrying capacity is drastically reduced but the column pull-in (P-Δ effect) is more significant. Serving as a classical example of disproportionate collapse, the bombing of the Alfred P. Murrah Building caused the destruction of a couple of columns by direct blast effect. Nonetheless, this was sufficient to induce buckling in the surrounding columns, triggering the collapse of the structure [3].

In order to quantitatively assess the structural robustness of multi-storey buildings in a simple design-oriented approach, the ductility-centred framework, recently developed at Imperial College London [4], uses nonlinear static analysis and simplified dynamic assessment at any appropriate level of structural idealisation. The efficacy of the multi-level framework relies on the high computational savings in detailed modelling of only the system components at lower levels of idealisation, where the structural response of higher levels can be obtained by the compatible assembly of the component response based on energy balance between a system and its constituents. Since dynamic amplification under gravity loading is mainly experienced in the multiple floors above and vertically aligned with the lost column [1,4], the full rendering of this system corresponds to the highest level of structural idealisation in the ductility-centred method, which considers the surrounding frame by means of boundary conditions [4].

This paper aims to enhance the ductility-centred framework to capture surrounding frame instability in a multiple column loss scenario, thus extending the adequacy of this approach in the design of building structures against progressive collapse.

2. Simplified dynamic assessment for multiple column loss

The ductility-centred framework [4] uses a simplified dynamic assessment approach in order to obtain the nonlinear dynamic response of an affected bay subject to a single sudden column loss from its nonlinear static response. The main feature of this simplified approach is based on rendering column loss as gravity load applied to the affected bay, in order to perform work balance at any level of structural idealisation. Hence, by assuming a deformation mode correspondent to a piecewise linear/planar rigid-plastic mechanism, work balance is simply satisfied in terms of a single degree-of-freedom (SDOF), typically the vertical displacement at the lost column position (Figure 1a).

However, for multiple columns loss, as shown in Figure 1b, a SDOF collapse mechanism can become rather inaccurate, with the deformation mode not only dependent of the load pattern, frame geometry and stiffness but also sensitive to the achieved level of structural deformation.

Therefore, a modification of the ductility-centred method in the simplified dynamic assessment is necessary in order to determine the nonlinear dynamic response of a structure affected by multiple column loss from its nonlinear static response.

Nevertheless, in some cases, a constant relationship between vertical displacements can be established, which leads to an effective SDOF mode. Figure 1c illustrates a symmetric frame (in geometry and loading) subject to the simultaneous sudden loss of two columns, where a prominent trapezoidal deformation mode is observed up to system failure, i.e. equal dynamic vertical displacements at the lost column positions. Another example, shown in Figure 1d, consists of an

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asymmetric frame where columns provide negligible in-plane rotational stiffness and large floor displacements are associated with significant joint rotations. For this specific frame, a triangular deformation mode is consistently observed up to system failure, allowing once again the approximation of the frame collapse mechanism as a SDOF mode. Further examples highlight the importance of load distribution and joint configuration for the evolution of the collapse mechanism during system deformation.

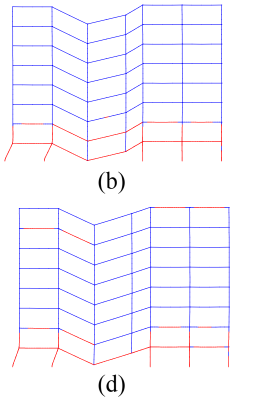

Figure 1: Frames subject to (a) single column loss and (b,c,d) two column loss

The extension of this approach to a multi-level application follows by using work balance between vertically compatible sub-systems. Finally, verification against nonlinear dynamic analysis is made using ADAPTIC [5] to demonstrate the effectiveness of the enhanced dynamic assessment proposed.

3. Grillage analogy for multiple column loss

For large vertical displacements, the floor system provides planar membrane action which is not accounted for in the grillage analogy [6]. A linear deformation mechanism used for compatibility of the individual floor beams in their assembly has also been shown to underestimate the floor capacity.

With regard to composite action, the use of a concrete flange effective width according to EN 1994-1-1 in the grillage model is only adequate for linear elastic analysis of a floor system and neglects further reinforcement area mobilised during the tensile catenary stage. Since code-prescribed effective width is proportional to the span length, for an adjacent columns loss scenario in a symmetric frame, it assumes a twice as wide concrete flange, leading to an incongruous higher floor capacity for two column losses. Therefore, in order to understand the effect of load redistribution and the adequacy of a grillage approximation for the floor response prediction, comparison between a detailed slab model and a grillage model using full slab width is undertaken with ADAPTIC [5] using cubic elasto-plastic elements to represent the steel beams and flat shell elements to represent the reinforced concrete slab.

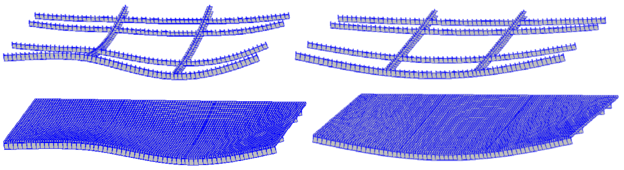

Figure 2: Deformed shape of grillage and detailed floor systems subjected to peripheral single and double column losses

The obtained results demonstrate a good agreement between the two representations, thus justifying the use of the floor grillage analogy in the multi-level framework.

4. Surrounding frame instability

Since the ductility-centred framework considers the full structure at different levels of idealisation imposing compatibility between the sub-systems, it is important to ensure the integrity of each structural sub-system. Floor axial restraint considered in the main sub-system is provided by the surrounding frame. Therefore, by enforcing compatibility and equilibrium between the main affected bay and surrounding bays in the boundary region, it is possible to verify the robustness of the full structure [7].

For a multiple adjacent column loss scenario in an individual floor, the span of the affected bay increases and the number of surrounding bays reduces by the number of lost columns. This induces greater column pull-in for a reduced number of load-carrying columns in the surrounding frame and simultaneously lowers the level of axial restraint in the main sub-system, as observed in Figures 1a-b.

The application study uses the comparison between a single peripheral column loss and double adjacent peripheral columns loss to illustrate a scenario where column failure occurs prior to joint failure. Furthermore, the assessment of the surrounding frame instability under multiple column loss is extended so as to consider the 3D interactions in a multi-storey building.

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