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# A simplified approach for modelling failure propagation of steel structures

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## ABSTRACT

Assessing the likelihood of progressive collapse in buildings resulting from the local failure of individual structural elements is challenging, especially in steel buildings. Engineers invest significant effort in modelling various connections between structural members, requiring detailed 3D solid elements. The complexity and computation time increase exponentially when analysing an entire building instead of local subassemblies. This study presents a practical methodology for modelling steel structures to predict progressive collapse rapidly. It adopts the distributed plastic hinges approach and is able to accurately simulate large deformations expected in collapse scenarios. Suitable experimental tests were selected to validate the proposed methodology, revealing the sensitivity of predictions to modelling assumptions such as the positioning of the hinges, the plastic length of each hinge, the cross-section discretisation and the material definition. Finally, a set of recommendations for the simplified modelling of steel structures is provided for practising engineers working in the progressive collapse domain.

*Keywords: Progressive collapse, Steel structures, Modelling strategies, Computational modelling, Simplified approach.*

## 1. INTRODUCTION

In some buildings, the local failure of primary structural components can lead to the progressive collapse of the entire structure if other components cannot withstand additional loads redistributed to them following the initial failure. This has been observed in the collapse of large steel structures like the Plasco Building (Tehran, Iran) and The Twin Towers of the World Trade Center (NY, USA). Engineers usually need to develop detailed and complex models that require high computational costs to analyse such scenarios.

This article proposes a simplified but sufficiently accurate approach to assess the possibility of progressive collapse occurring due to the initial failure of primary structural components. The aim is to reduce computational costs and model complexity while still being able to reliably predict the successive failure of structural components. To achieve this, the numerical models must be able to capture key failure modes of beams and columns under the combined effect of axial loads and bending moments. As such, the predicted structural response using the proposed approach is compared in this article to that observed during suitable experimental tests to verify that the resulting errors are acceptable.

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## 2. SIMPLIFIED MODELLING STRATEGY

The proposed simplified modelling strategy provides insight into the overall behaviour of a building up to the initiation of collapse. Collapse is a systems problem, requiring a good representation of the interaction between elements to assess their failure.

The modelling approach involves representing the steel structure using 2D elements (frame objects). For this study, primary beam-column connections are considered as being entirely rigid (suitable for overstrength joints), while joints between secondary and primary beams are modelled as pinned.

### 2.1. Fiber Hinges

The nonlinear behaviour during the collapse of a steel building is evaluated by using fiber hinges. These hinges discretize the cross-section into fibers with different constitutive relations, allowing changes in the moment-rotation behaviour and plastic deformation to be considered. Each hinge is defined by its length, by the number of fibers in the cross-section, and by a material constitutive law for each fiber. The hinge length determines the distance over which the element's plastic properties (rotation and axial deformation) develop [1]. The area of each fiber depends on a geometric ratio, which is always kept below five and preferably below three. This ratio indirectly determines the number of fibers making up the section. Additionally, the material's constitutive relationships are established based on the stress-strain curve of steel. Adequate definition of the number of hinges, their location, the material's constitutive relationships, and hinge length are crucial to ensure computational efficiency and accuracy.

### 2.2. Modelling of columns

As the main vertical loadbearing elements of a framed building, it is of the utmost importance to accurately represent the failure of columns. These elements are subjected to high axial loads, so their failure is governed either by their first buckling mode or by yielding. Experimental tests on two different column specimens with three different pairs of boundary conditions [2] have been chosen to assess the suitability of the proposed approach. The columns have the following characteristics: $L_1$=1.15 m, $f_{y,1}$=292.3 MPa (height and yield strength of the first type of column specimens); $L_2$=1.42 m, $f_{y,2}$= 281.3 MPa (height and yield strength of the second type of column specimens). In the first study (Pin-Pin), failure always occurs due to buckling. In the second (Pin-Fix) and third studies (Fix-Fix), the failure is produced by yielding of the steel profile.

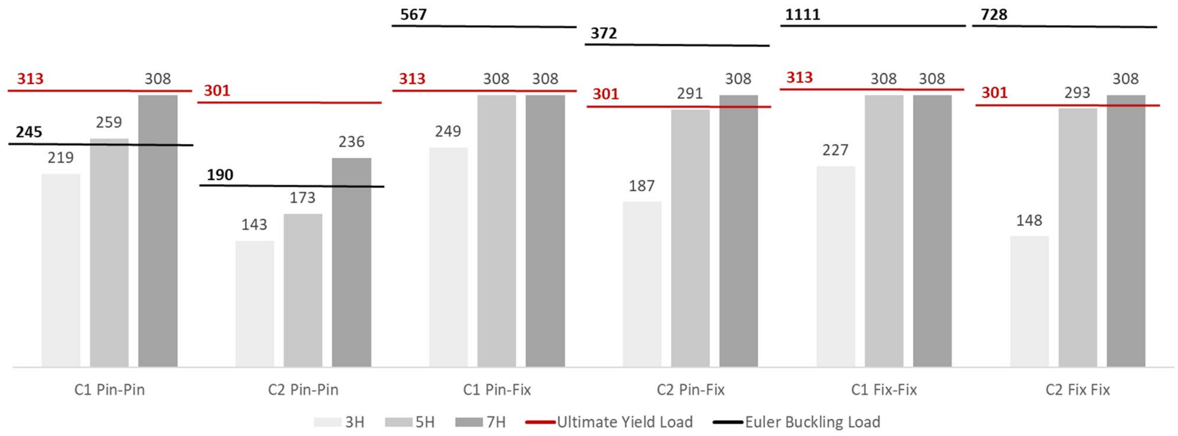

**Figure 1.** *Comparison of the ultimate load obtained with different simplified models (with 3,5 and 7 fiber hinges along the column height) and those obtained in the experimental tests. All values in kN.*

In Figure 1, different simplified models are evaluated for each of the previously described experimental studies, where the columns have 3, 5, and 7 equally distributed hinges along their height. The results reveal that it is most suitable to use 5 hinges, leading to a relative error of less than 3% for all tests.

### 2.3. Modelling of beams

The behaviour of beams under extreme events is dominated by catenary actions, unlike normal conditions where bending governs. The experimental test involving the substructure shown in Figure 2 (a) was chosen to evaluate the proposed simulation strategy. The test involved removing the central column and applying a constant downward load until the beam element ruptures. The specimen was designed with rigid joints to avoid connection failure during the test [3].

Appropriate definition of material properties is crucial for the simulation to produce accurate predictions. Parameters such as the yield strength and strain, the stress and strain at the onset of necking, and the ultimate strength and strain must be defined. Ideally, having the complete stress-strain curve of the materials would be best, although this is sometimes not possible. Figure 2 (c) shows the vertical load-displacement relation recorded at the node of the removed column during the experiment compared to those predicted by simplified models with different material properties. All these models were defined with 21 hinges per beam (Figure 2 (b)). The different materials evaluated are: S355 Minimum (defined based on minimum ductility requirements specified in [4]), S355 Global (defined based on mean characteristics of steel elements reported in [3]), and S355 Local (each member defined with its mechanical material characteristics as reported in [3]). Results reveal that knowing at least the average characteristics of the steel used is essential to accurately evaluate the overall behaviour of the entire structure. The S355 local material was chosen for the analysis presented in the remainder of this section since it corresponds to the most accurate representation of the test specimen.

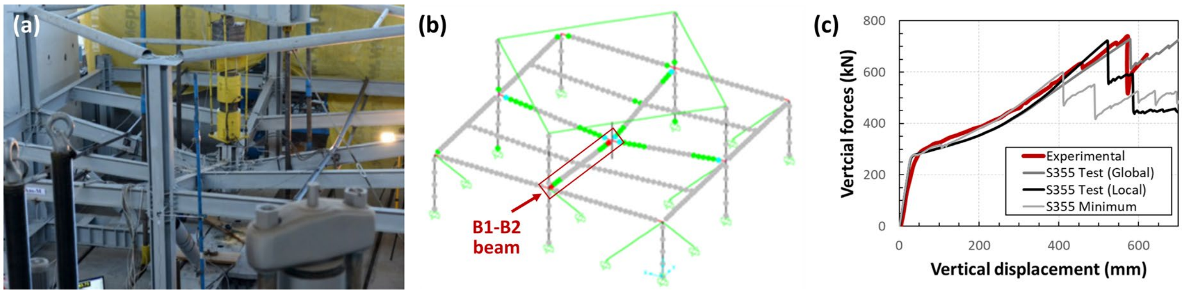

**Figure 2.** *(a) Specimen at the end of the test [5]; (b) Simplified model at initial rupture of a member; (c) Comparison between experimental and model results in beam B1-B2 with different* $\sigma - \varepsilon$ *curves.*

It is crucial to evaluate yielding along the entire beam length using a sufficient number of hinges to detect beam failure. This is because of the specific features of cross-sections used for steel structures and the material's remarkable ability to absorb plastic energy. As a result, a section that is yielding experiences substantial deformations that can significantly affect the behaviour of adjacent elements. Figure 3 compares measured responses during the experimental test to the predictions of simplified models with 11, 21, and 31 hinges along each beam length. Specifically, the evolution of vertical forces, bending moments, and axial loads as the vertical displacement of the central beam increases are reported. Based on the results, the 21-hinge model is deemed as being the most suitable choice as it exhibits lower relative errors overall.

It is worth highlighting that the behaviour of the hinges at each end of the beam is particularly important due to stress concentrations that occur at the connection locations. This behaviour depends strongly on the hinge length defined for these hinges. Through iteration, it has been found that it is suitable to set the hinge length at these locations to one-third of the depth of the beam section. As shown for the case of 11 hinges in Figure 3, incorrect results are obtained in the failure evaluation if this adjustment is not implemented.

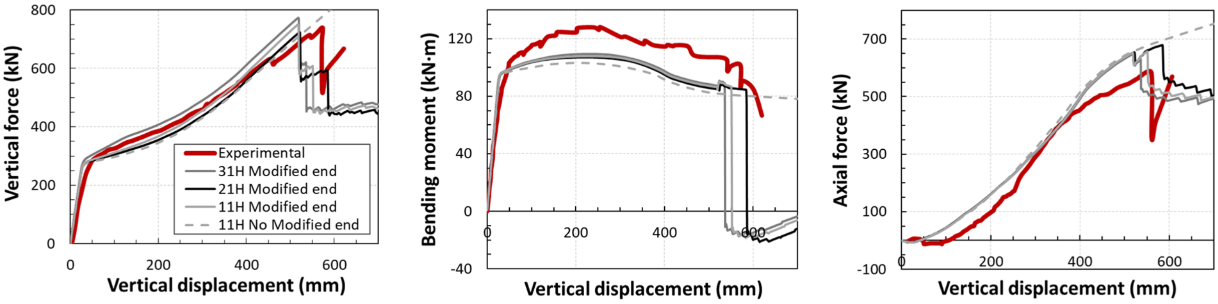

**Figure 3.** *Comparison between experimental results and model results with different numbers of hinges: 11 (with and without modified end hinges), 21 and 31. Vertical force, bending moment, axial force - vertical displacement, in beam B1-B2 (left to right).*

## 3. CONCLUSIONS

Evaluating building collapse typically requires complex simulations involving tedious modelling and high computational costs. A simplified modelling approach using fiber hinges has been proposed to assess the failure of steel-framed buildings. It has been found that using 5 hinges in columns and 21 hinges in beams can predict the behaviour of these components with sufficient accuracy during the early stages of collapse. This configuration significantly reduces computational costs, while still providing sufficient accuracy to facilitate a clear and simple identification of the failure initiation.

## ACKNOWLEDGEMENTS

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