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Analytical assessment of steel frames progressive collapse vulnerability to corner column loss

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ABSTRACT

Most of the approaches to the progressive collapse analysis of steel frames have focused so far on computational methods which try to capture the solution of the system responding to localized damage. For the case of progressive collapse, damage is included in the model through the removal of a key element of the structure. The computational difficulty of these approaches, however, makes it very hard for practicing engineers to perform these analyses. For that reason, it is very important for the engineering community to develop simple and reliable analytical tools which could provide useful information on the response of a structure to a column loss. This paper applies a threat-independent analytical method regarding the corner column loss case, which has been presented by the author in previous papers to a wide range of symmetric and non-symmetric steel moment-resisting (sway) frames. The analytical and simple method can indicate the collapse mechanism of a steel frame for the case of a corner column loss through the development of critical ductility curves. The impact of the number of floors, the column removal location, the vertical irregularity and the design of the frames is also studied.

1. Introduction

The assessment of the vulnerability of structural systems to localized damage is the main objective of progressive collapse analysis. Damage, however, can appear in a structure in many different ways and can have many different consequences to the integrity of a system and that is why the analysis of damaged structures is still an area of extensive research [1–9]. Most of the approaches to the progressive collapse phenomenon are typically considered threat-independent in the attempt to investigate the response of a structure to the appearance of local damage and generally assess the redundancy of a specific structure. If a specific threat is identified and defined, a more detailed threat-dependent method can be followed. As a result of many of the research efforts, two regulative documents have been produced [10,11] which aim at reducing the potential of progressive collapse for structures that experience localized structural damage through extraordinary events [10].

As explicitly defined in [10], the progressive collapse design options for a practicing engineer are the indirect design approach, the alternate path direct design approach and the specific local resistance approach. The specific local resistance method requires that the structure or a specific part of it has enough strength to resist specific load [10] while the alternate path method requires that the structure has enough strength to resist the removal of a key element. Although the assumption of an element removal is very generic, it is used to provide a simple way to introduce local damage in the structure. While this assumption is under discussion, the alternate load path method has been most commonly used by researchers and practitioners due to its closest connection to the response of a structure during an abnormal event. The method involves the utilization of computational structural analysis tools which can be used to determine the vulnerability of a structure, the mode through which a potential collapse would occur and possible design measures to prevent the collapse.

Most usually, the vulnerability of damaged structures can be assessed only through computationally expensive and tedious methods involving intense nonlinear response of many kinds. With few exceptions, it is almost certain that when damage appears in a structural system, the response of the system will undergo several nonlinear phenomena which can only be captured by a material and geometric nonlinear analysis. Although there are many references in progressive collapse literature which have identified several collapse mechanisms and the computational methods to capture them, there are very few instances providing analytical tools which can be used to evaluate the potential for progressive collapse or to identify the progressive collapse mechanism [12].

This paper applies the analytical method presented in [13], also compactly presented in this paper, to the set of steel moment-resisting (sway) frames presented in [14]. The work presents an extensive parametric study on the response of steel frames to corner column removal, for vertical downward loading, as in a common push-down method. The analytical tool identifies the governing progressive collapse mechanism through simple calculations which can be easily performed by practicing engineers. Two collapse mechanisms are

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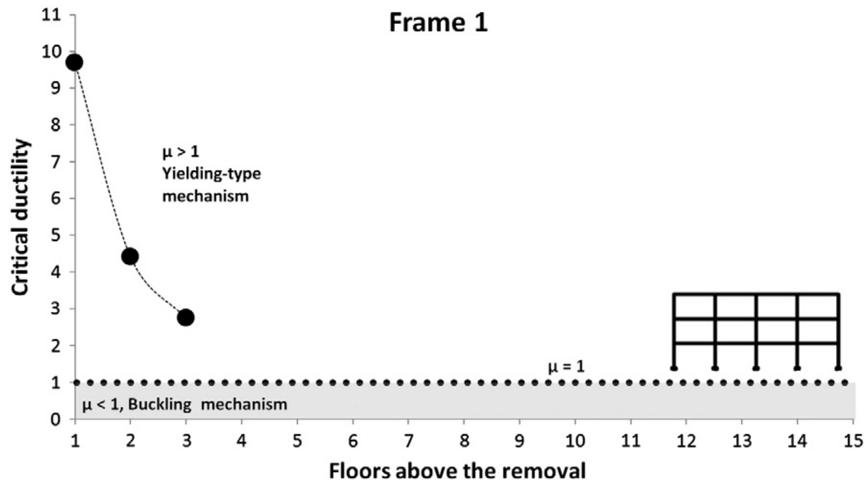

Fig. 1. Ductility limit state graph for frame 1.

taken into account: the collapse triggered by the failure of a column adjacent to the location of the removal and the collapse triggered by the plastification/hardening of beam members above the removal.

2. Analytical vulnerability assessment method

2.1. Collapse modes

The response of a steel moment-resisting (sway) frame after the loss of one of its corner columns depends on the properties of the structure. It is therefore not easily clear which collapse mode will be activated and how will damage evolve throughout the structural system. Although there have been several different collapse modes identified in the progressive collapse literature, the specific work is limited to the two major ones:

- the column mode and
- the yielding-type beam mode.

The column mode involves the failure of one of the adjacent to the removal columns. This phenomenon can potentially happen as elastic buckling (for tall and slender columns), inelastic buckling (for the most common intermediate-type columns) or material failure (for very short columns). On the contrary, the yielding-type collapse mode involves the progression of damage through the beams above the removed column. This mode is governed by the beam flexural response and the formation of plastification/hardening zones.

This work distinguishes the potential loss-of-stability phenomenon (buckling of an adjacent-to-the-removal column) which can follow the removal of a column. Most of the researchers have so far concentrated on the investigation of the propagation of damage through yielding-type failures of connections/beams/slabs while the buckling of columns has not received the necessary attention. Additionally, the yielding-type beam mode has clearly more redundancy since the redistribution of the loads can occur in several ways, while the buckling of a column is a far more catastrophic damage in the system.

2.2. Analytical modeling

The following analytical method is compactly presented here for the sake of completeness. The method is described in detail in [13].

2.2.1. Column mode of collapse

The compression capacity P_{Ri} of a column element i of a steel frame can be defined as follows:

$$P_{Ri} = \begin{cases} P_{Eul} = \dfrac{\pi^2 \cdot E \cdot I_i}{(k \cdot H)_i^2}, & \text{for slender columns and } P_{Eul} < A_i \cdot f_y \\ A_i \cdot f_y, & \text{for intermediate columns and } P_{Eul} > A_i \cdot f_y \\ A_i \cdot f_u, & \text{for short and stocky columns and } P_{Eul} > A_i \cdot f_y \end{cases} \tag{1}$$

where I is the moment of inertia, H is the height, A is the cross section area and k is the column effective length factor of the column

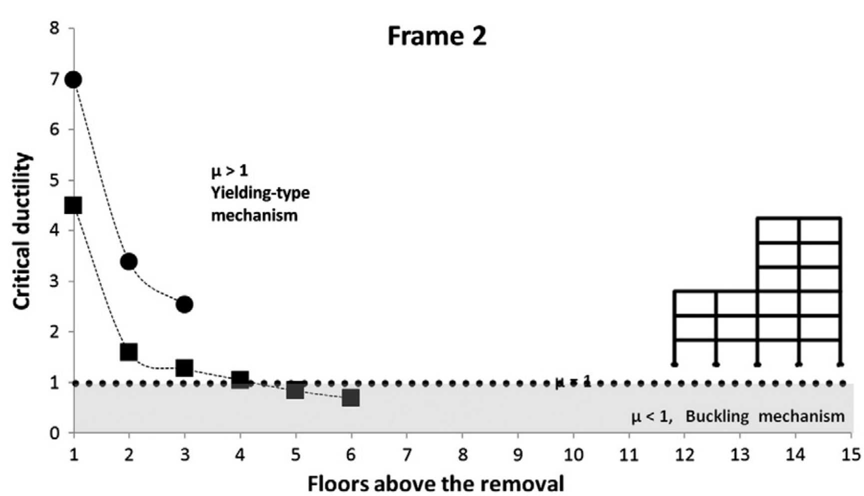

Fig. 2. Ductility limit state graph for frame 2.