Journal of Constructional Steel Research 150 (2018) 60–75

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Progressive collapse of 3D steel composite buildings under interior gravity column loss

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ARTICLE INFO

Article history:
Received 9 May 2018
Received in revised form 3 August 2018
Accepted 4 August 2018
Available online xxxx

Keywords:
Progressive collapse
Stability
Structural failure
Gravity column removal
Robustness
3D

ABSTRACT

This paper presents a novel analytical framework on the quasi-static robustness assessment of 3D steel and concrete composite gravity framed buildings subjected to an interior gravity column loss scenario. The analytical method takes into consideration the two most presumable collapse mechanisms which can be activated in such a case, denoted as the *yielding-type* and the *stability* collapse mode. The proposed framework is formulated upon a series of elastic analyses on appropriately selected and accordingly modified structural idealizations of the building, allowing the method implementation by any structural engineering software regardless of the user experience. The method is capable of estimating the damage propagation path within the structural system, assess the gravity connections failure load including the influence of a failed connection to the system response, account for the transition from the composite to the membrane action, assess the potential for column instabilities, determine the gradual system stiffness degradation as the gravity load increases and finally calculate the ultimate collapse load and the corresponding characteristic vertical displacement on the onset of collapse. The analytical method is applied on a 9-story prototype structure performing 9 interior gravity column removal scenarios along the same column row, and the numerical validation of the method demonstrates the excellent agreement among the analytical and numerical results.

1. Introduction

The performance of a steel and concrete composite building exposed to progressive collapse conditions has been investigated by many researchers within the past decades primarily oriented around 3 directions: developing numerical models ([1–5]), conducting experiments on the member- or single-story level under loading conditions which are representative of a real column loss scenario ([6–11]), and formulating analytical methodologies to describe the structural response based on closed-form expressions ([12–14]). The latter direction has attracted comparatively to the first two significantly less interest by the research community, mainly due to the prominent complexity in the development of analytical methods which address highly nonlinear phenomena, such as structural progressive collapse. As a result, the engineers in practice are not equipped with reliable and easy-to-handle methodologies in order to assess the structural robustness of a building under progressive collapse conditions, and this in turn increases their dependency on commercially available software which produce results beyond their verification capabilities.

The scope of this study is the expansion of the analytical tool developed in [14, 15], with respect to interior gravity column removal scenarios in 3D steel framed and concrete composite buildings. The new tool evaluates the progressive collapse mode and the ultimate capacity of the structure by applying a push-down approach up to collapse. The method accommodates two collapse mechanisms, namely the *yielding-type* and the *stability* mechanism which are the most prominent collapse modes of a steel framed composite building subjected to an interior column loss. The proposed methodology confronts all these concepts which increase the complexity of the phenomenon, such as the transition from the slab flexural to the membrane action, the damage propagation path and the successive gravity connections failures leading to the system stiffness degradation, potential instability issues, etc. The analytical method sheds light on the response at both the member level (beam, connection, column) and the system level. A major advantage of the proposed methodology is that it is based on a sequence of elastic analyses in appropriately selected and modified geometries of the gravity system. This key feature allows the method implementation by any commercially available structural engineering software, regardless of the user experience level. At the end of the paper, the method is validated against high fidelity finite element models of the entire building, providing sufficiently satisfying agreement regarding the rationale and the assumptions entailed by the method.

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https://doi.org/10.1016/j.jcsr.2018.08.003
0143-974X/© 2018 Published by Elsevier Ltd.

2. Analytical method background rules

The proposed method can be implemented on steel framed and concrete composite buildings with a lateral load resisting system comprised of moment frames, while the vertical load framing system consists of the gravity columns, the main girders, the secondary gravity beams (perpendicular to the girders, whereas there are two secondary beams within each bay), rotationally pinned connections and a concrete slab spanning rectangular bays. This structural system is widely employed in current design practices and a typical plan view of this system can be seen in Fig. 1. The proposed tool adopts the threat-independent *Alternate Path Method* (APM), as prescribed in the present guidelines (GSA [16], DoD [17]). According to the APM, the robustness of a building against progressive collapse can be evaluated utilizing the notion of a load-bearing vertical component being removed from the structure, in this case a column is lost. The analytical method assesses the building robustness when an interior gravity column is excluded from the structural system (locations C3, D3, C4 and D4 in Fig. 1), while the slab is continuous on the boundaries of the region which is immediately adjacent to the removed column. For the remaining of this study, this region will be termed as *2 × 2 area*, since it spans two bays in each direction around the removed column. It is indicated by the hatched area of Fig. 1, assuming a C3 column removal scenario. The system in Fig. 1 has the moment frames at the building perimeter, however the method is also applicable on structural systems with a different placement of the moment frames as long as the removed column and the immediately surrounding columns belong to the gravity system.

In agreement with the APM specifications, the analytical method assumes that the gravity load is the only loading scheme present in the analysis. The APM allows for three different types of analyses: a) linear static, b) nonlinear static and c) nonlinear dynamic. The proposed method evaluates the progressive collapse response of the building by applying a static *push-down* approach. In this framework, the gravity load is incrementally increased from zero up to a load where predefined failure criteria are met. The latter regard members of the structural system (gravity connections, wire mesh, steel deck, gravity columns) and their limit state signifies that they are no longer capable of contributing to the building capacity. The analytical method incorporates two collapse mechanisms, denoted as the *yielding-type mode* and the *stability mode*. Each of these collapse mechanisms is associated with different failure criteria and the collapse mechanism satisfied for the minimum applied load is the dominant one. The structural components that the method particularly focuses on are the gravity (or shear) connections, the slab steel components and the building gravity columns.

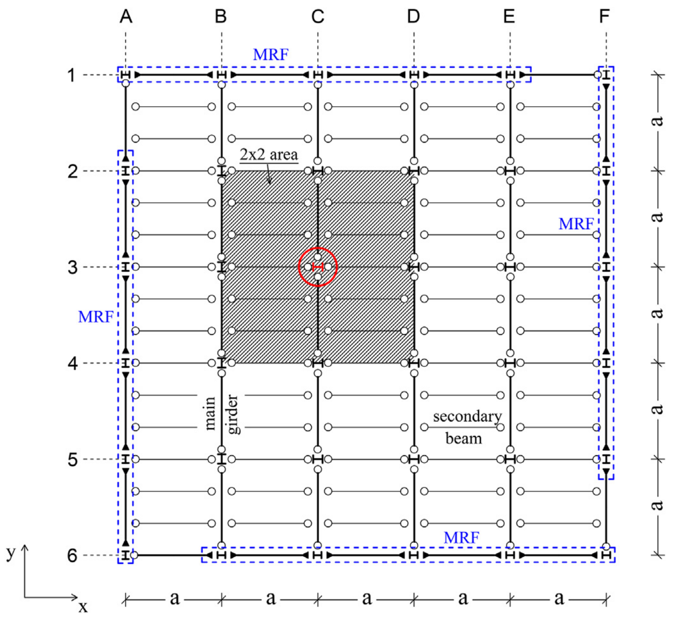

Fig. 1. Typical floor plan view of a steel framed and concrete composite building. Lateral load-resisting moment frames are enclosed by the dashed blue lines. The gravity system is comprised by the gravity columns, the main girders (y-axis), the gravity beams (x-axis) and the rotationally pinned connections (denoted with circles). The column at location C3 is removed and the hatched region is termed as 2 × 2 area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The shear connections of the beam grillage are considered a highly vulnerable component of the gravity floor system. These connections are intended to transfer only shear forces, however in a progressive collapse scenario they are exposed to additional significant axial demands towards which they have not been designed. Shear connection types which are commonly used in practice include shear-tab, welded-bolted or bolted-bolted single-angle and double-angle connections, etc. Each connection type has different stiffness, strength and ductility characteristics and therefore a generalization over all the different connection types can not be easily drawn. In the present study, the method is implemented in the prototype structure assuming bolted-bolted double-angle connections; however the method can be applied utilizing any connection type which shares similar response features. These features are the following: a) the gravity connections are taken as rotationally free, so that bending moments can not be transferred through them, b) they are assumed to be rigid with respect to the shear forces and c) they have a bilinear axial force-displacement diagram, with the post-peak branch of the tensile force-displacement behavior following an abrupt drop to zero forces once the connection maximum tensile capacity is attained. A *perfectly-plastic* post-peak branch is assumed for the compressive force-displacement behavior. The assumption regarding the tensile force-displacement behavior implies that a brittle failure mode governs the response of the double-angle in tension and it is based on experimental findings by Oosterhof and Driver [9]. Their experimental setup was comprised of a column, a gravity connection (shear-tab, welded-bolted single-angle, bolted-bolted single-angle, bolted-bolted double-angle) and the beam at which the connection was attached. They exposed their assemblies to a combination of moment, shear and tensile force and the failure mode of the bolted-bolted double-angle connections was dictated by the propagation of a tear along the angle, which in some cases was manifested in a sudden, brittle manner. Therefore an immediate drop to zero force values was adopted for the tensile force-displacement diagram of the connections. The bilinear perfectly-plastic behavior of the compression force-displacement response of the gravity connection is also adopted in other studies, such as the one by Foley et al. [18] (bolted-bolted double-angle connections) and by Sadek et al. [19] (single-plate shear connections). Additionally, the axial capacity of the connections is significantly less than the axial capacity of the gravity beams or girders. Therefore, the gravity beams are not expected to experience failure prior to their respectively attached tensile connections, rendering the tensile connections the *weak link* of the beam grillage (a similar assumption is adopted in the design-oriented model proposed by Alashker and El-Tawil [13]).

Apart from the connections, an additional source of the gravity floor robustness stems from the slab steel components. These are the wire mesh reinforcement, which is located close to the top slab fiber acting in both directions and the steel deck, which is located at the bottom slab fiber and it is assumed to act only in one direction, parallel to the flutes (along the y-axis in Fig. 1). The contribution of the steel deck perpendicular to the deck ribs is considered negligible ([1, 13]). The current study adopts a bilinear elastic-perfectly plastic stress-strain relationship for the wire mesh and the steel deck materials. Finally, the method accounts for the behavior of the building gravity columns, emphasizing on the importance of investigating instability phenomena in a progressive collapse loading scheme. After a column removal, the gravity load previously carried by the lost member is now distributed to the immediately adjacent columns at the perimeter of the 2 × 2 area. These structural components are not designed towards this additional demand and