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Improving the accuracy of progressive collapse risk assessment: Efficiency and contribution of supplementary progressive collapse resisting mechanisms

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ABSTRACT

This paper investigates the structural response of RC framed buildings subjected to accidental/abnormal loads (explosion, impact and other hazards). Several existing national or international design codes (GSA 2003, DoD 2009, 2013) provide limited guidelines for the assessment of progressive collapse resistance in the design process and the alternate load path method is widely used in current structural design codes. Since the progressive collapse is a dynamic and nonlinear event the structural components undergo nonlinear deformations before failure. In this study the nonlinear procedures (NSA and NDA) are applied. These types of analyses imply significant computational power and time costs. In addition, the reinforced concrete framed structures are able to develop multiple post flexural resisting mechanisms. These are currently not considered in the structural analyses performed according to GSA2003 and DoD2009 provisions. Thus, the first objective of this paper is to identify by numerical computation the presence and contributions of such supplementary resisting mechanisms. A further objective is to determine what will be the influence on the accuracy of results when, starting from the original structure, the number of its bays is successively reduced; also, what is the efficiency in saving run-time costs when such simplified models are considered in the analysis. The study reveals that in order to resist abnormal loads, RC structures are able to develop supplementary resisting mechanisms beyond the flexural behavior and respectively, important time savings are obtained without significantly affecting the results accuracy.

1. Introduction

Progressive collapse represents, according to GSA (2003) Guidelines [1], a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. This topic captured the attention of the research community after the catastrophic event that took place in 1968 at Ronan Point apartment building. Due to an explosion generated by a gas leak at 18th floor, a significant part (entire south-east corner) of a 22 story apartment building collapsed. The topic continues to be of interest to researchers, mainly due to the relatively recent progressive collapse events: A. Murrah Federal Building in Oklahoma City, U.S. – 1995, World Trade Center in New York City, U.S. – 2001 (Fig. 1a), Windsor Tower in Madrid, Spain – 2005 (Fig. 1b).

In this paper, the progressive collapse is considered to be a dynamic and nonlinear event in which structural components undergo nonlinear deformations in a short time frame before failure. Although progressive collapse can be identified through three types of structural analysis (linear static analysis – LSA, nonlinear static analysis – NSA and nonlinear dynamic analysis – NDA), the most accurate results are based on three dimensional (3D) nonlinear dynamic analyses. For the latter, the models involve a large number of structural members (beams, columns and slabs), and after discretization, a large number of finite elements. Applying such a procedure can lead to significant computational power and run-time requirements even for low-rise buildings (e.g. 3-story buildings). For this reason, certain researchers prefer to consider the non-linear dynamic nature of the progressive collapse phenomenon using simplified approaches, for both reinforced concrete structures [2,3], respectively for steel structures [4,5].

The numerical procedures (LSA, NSA and NDA) are proposed by the main guidelines regarding progressive collapse risk assessment: GSA (2003) [1] and DoD (2009) [6]. The provisions of these two guidelines [1,6] where most attention has been devoted to the behavior of beams bridging over the removed column, the progressive collapse potential is assessed by considering only the flexural

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(a) (b)

Fig. 1. (a) World Trade Center, U.S. and (b) Windsor Tower, Spain.

behavior of such elements [7]. Recent experimental and theoretical studies [8–11] have shown that the dominant load resisting mechanism in RC framed structures is represented by a combination of several actions: **F**lexural **A**ction (**FA**) in beams – currently considered in the current progressive collapse analysis, **C**ompressive **A**rch **A**ction (**CAA**) – developed in beams which tends to elongate as they experience large flexural deformation, cracking and yielding, **C**atenary **A**ction (**CA**) – acting only under very large displacements and deformations of beams and finally, **V**ierendeel **F**rame **A**ction (**VFA**) – characterized by double curvature deformations of a 3-D structural system formed of beams, slabs and columns [12,13]. Advanced analyses should consider not only the main (classic) progressive collapse resisting mechanism (**FA**) but also the contribution of certain supplementary mechanisms that can be mobilized sequentially to mitigate progressive collapse and these are: **CAA**, **CA** and **VFA**. These three mechanisms are still not incorporated in the current design codes or guidelines. If the contribution of floor slabs (as primary components) is considered in the load-carrying capacity of the structural system, then also the membrane actions of slabs and not only the flexural or yield-line capacity has to be taken into account [7,14,15]. The membrane action (tensile membrane in the central deflected area, peripheral compressive ring, transition flexural zone) of RC slabs is not considered.

This paper investigates the structural response of RC framed (beams and columns) buildings subjected to accidental/abnormal loads (explosion, impact, terrorist attack, and other hazards). Based on the previous remarks, the present study has two main objectives. The first objective is to identify the presence and contributions of two possible supplementary resisting mechanisms (**CAA**, **CA**) acting beyond the frame flexural capacity. The second objective is to determine the influence on the accuracy of results when the number of structure's bays is successively reduced and which is the efficiency in saving run-time costs when simplified substructures models are considered in the advanced nonlinear analyses.

In order to maximize the accuracy of the results, only nonlinear analyses (NSA and NDA) are carried out, since the general opinion expressed in the technical literature is that these types of analyses provide most accurate results [2,3,16]. In these analyses concentrated respectively distributed plasticity concept are used.

This paper is an extension of Botez et al. paper [17], and includes the following supplementary studies:

- numerical validation of the concentrated plasticity concept and the distributed plasticity concept used in the numerical models to describe the FA, CAA and CA in the RC frame beams. The numerical models are checked against the experimental study carried out by Yi et al. [8];
- refinement of the numerical analyses performed in the original study [17] for typical reinforced concrete framed structures in order to identify the contribution of supplementary progressive collapse resisting mechanisms, based on the numerical validation results;
- extension of the proposed simplification techniques to four missing column scenarios specified in DoD (2009) [6], in order to enhance the efficiency in assessing the progressive collapse potential of typical reinforced concrete framed structures.

2. Identification of supplementary progressive collapse resisting mechanisms

The progressive collapse potential, based on DoD (2009) [6] Guidelines, depicts only the bending behavior of the analyzed structures.

Experimental studies [8,9] have shown that the structures have supplementary resistance capacities that can be developed through other mechanisms: **C**ompressive **A**rch **A**ction (**CAA**) – developed in beams which tend to elongate as they experience large flexural deformation, cracking and yielding and **C**atenary **A**ction (**CA**) – acting only under very large displacements and deformations. Several studies [12,13,18] define the **V**ierendeel **F**rame **A**ction (**VFA**) – characterized by double curvature deformations of beams, slabs and columns – as the **F**lexural **A**ction (**FA**), **C**ompressive **A**rch **A**ction (**CAA**) and the transition towards the **C**atenary **A**ction (**CA**).

While the technical literature contains multiple numerical investigations based on experimental studies [19–21] that emphasize the contribution of the previous mentioned mechanisms on the progressive collapse resistance of reinforced concrete sub-assemblages, there is a limited number of numerical studies