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The influence of beams design and the slabs effect on the progressive collapse resisting mechanisms development for RC framed structures

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ABSTRACT

Using numerical approaches, this paper investigates the structural response of RC framed buildings subjected to accidental/abnormal loads (explosion, impact, etc.). Beside the contribution of the beams, currently considered in the progressive collapse analyses, the effect of the slab structural element through its specific resisting mechanisms (Flexural Action, Yield Line Mechanism, Membrane Action) is also assessed. In addition, the influence of three distinct beam design parameters (the ductility class of the beam longitudinal reinforcement, the beam flexibility in terms of beam height over the beam clear span ratios, respectively the beam longitudinal reinforcement ratio) on the progressive collapse behavior of RC structures is evaluated. Based on previously calibrated numerical models, a consistent series of nonlinear push-down advanced analyses are performed using the Finite Element Method approach. The results indicate that the slab influence is significant at the internal forces transfer and load redistribution mechanisms level: it completely changes the resisting elements behavior when considered in the numerical model. Original findings based on the conducted parametric studies are drawn and compared with results currently available in technical literature.

1. Introduction

Explosions, wind gusts, fire, terrorist attacks or design flaws cause the disproportionate or even total collapse of buildings leading to significant human causalities and material damages. The most recent event occurred on 19 January 2017 in Tehran, Iran where the Plasco Building, a 17-story high rise structure (Fig. 1) considered an iconic landmark of the Tehran skyline collapsed due to a fire started at the ninth floor. Twenty firefighters have been reported to have been killed and at least 70 others were injured by the collapse [1]. Other well-known progressive collapse events with significant casualties occurred at Rana Plaza commercial office complex in Savar, Bangladesh (2013–1129 deaths and 2515 injuries), World Trade Center buildings in New York City, USA (2001–2752 deaths), Sampoong Department Store in Seoul, South Korea (1995–501 deaths and 937 injuries) [2].

Nowadays, the behavior of structures subjected to abnormal loads such as those previously mentioned is a high interest research topic among civil engineering researchers. ASCE7 [4] defines the Progressive Collapse phenomenon as “the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it”, definition also assumed by DoD (2009) [5] Guidelines.

The progressive collapse behavior of RC structures is analyzed in recent experimental and theoretical studies considering the

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Fig. 1. Plasco Building, Tehran, Iran [3].

successive occurrence of several resisting mechanisms [6–9]. When subjected to abnormal loads that lead to the failure of a vertical structural element, the RC structure activates load-carrying capacity resources through beam and slab resisting mechanisms.

Depending on the structural design, the beams can develop the resisting mechanisms known in technical literature as: **F**lexural **A**ction (FA) – explicitly considered in the design phase of a structure, **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 large displacements and deformations of beams [8].

Experimental and numerical studies [10,11] emphasize that three main resisting mechanisms occur for slabs: **F**lexural **A**ction (FA) - explicitly considered in the design phase of a structure, **Y**ield **L**ine **M**echanism (YLM) - the ultimate stage of flexural behavior, characterized by the appearance of plastic strains concentration along linear patterns, respectively **M**embrane **A**ction (MA) - "consisting of a peripheral compressive ring of concrete supporting tensile membrane action in the central region" [12]. When the progressive collapse risk of RC structures is assessed using models capable to numerically represent the slab elements, the load-carrying capacities assured by the previously described slab resisting mechanisms can be also accounted for.

The structural elements design has direct consequences on the progressive collapse behavior of structures. The boundary conditions of beam's end sections influence on the resisting mechanisms developed in beams are investigated in an authors' previous paper [9]. The importance of accurately considering these conditions in the numerical progressive collapse analysis is emphasized. The progressive collapse resisting mechanisms developed in beams (FA, CAA, CA) could also be influenced by the following main design parameters: the ductility class of the beam longitudinal reinforcement, the beam flexibility in terms of beam height over the beam clear span ratios and the beam longitudinal reinforcement ratio. Their influence was also investigated by other research groups interested in the progressive collapse topic [6,13]. Most of technical papers available draw conclusions regarding these aspects based on analyses performed on RC sub-assemblages. A significant improvement would be to assess the influence of the previously mentioned parameters on the supplementary resistance resources activated through FA, CAA and CA by using complete RC framed models. Since experimental studies on entire structures are difficult to perform due to technical and cost efficiency issues, the first objective of the current study is to investigates these aspects through numerical methods.

Furthermore, the accuracy of the progressive collapse resisting capacity assessment could be significantly improved when the slab is considered in the numerical models. In addition, the influence of beam-slab interaction on the progressive collapse resisting mechanisms, according to authors' knowledge, is not covered extensively in the available research studies. Consequently, the second objective of the current paper is to estimate the additional load-carrying capacity of an RC framed structure when the slab is added in the numerical model as a primary structural element. Also, the influence of the slab presence on the activation and development of beam PC resistance mechanisms is investigated.

2. Analysis procedure and PC resisting mechanisms

According to both main progressive collapse guidelines [5,14] the collapse risk can be assessed using three different analysis methods: Linear Static Analysis (LSA), Nonlinear Static Analysis (NSA) and Nonlinear Dynamic Analysis (NDA). Due to their complexity and the high demands in terms of computational power, the dynamic procedures are not widely used for the progressive risk assessment of real, complete structures. Different approaches, such as the use of a Dynamic Increase Factor (DIF), have been proposed [15–17] to account for the dynamic effect while performing a static analysis. However, all the previously mentioned procedures account only for the Flexural Action (FA) developed in the structural elements (beams and slabs), since the plastic rotation values are limited for RC beams and slabs to 0.10 rad by the provisions of DoD(2009) [5]. Experimental studies [10,18] indicate that load-carrying capacities could be activated, through CAA and CA in beams, respectively through YLM and MA in slabs, even when the plastic rotations exceed the limit values prescribed in progressive collapse assessment guidelines [5,14].

Compressive **A**rch **A**ction (CAA) could be considered an enhancement of the **F**lexural **A**ction (FA) mechanism and it is typical only for RC structures. The supplementary load-carrying capacity associated with CAA can be activated for structural deformations corresponding to the small displacements domain [7]. **C**atenary **A**ction (CA) occurs when the beams no longer act as structural elements subjected mainly to bending; the vertical loads are instead transferred to the adjacent vertical structural elements through