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Progressive collapse fragility models of European reinforced concrete framed buildings based on pushdown analysis

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ABSTRACT

Structural safety for extreme loads that may cause local damage to single primary components or even the progressive collapse of the structure has been probabilistically assessed in a few studies, hence neglecting uncertainties in loads and system capacity. As such, this paper moves from a deterministic to a probabilistic framework, proposing new progressive collapse fragility models based on pushdown analysis of low-rise, reinforced concrete framed bare structures. Two building classes representative of structures designed for either gravity loads or earthquake resistance in accordance with current European codes were investigated. Monte Carlo simulation was used to generate random realizations of 2D and 3D structural models. Fiber-based finite element models were developed within an open source platform. The primary output consisted of fragility functions for each damage state of interest, given the loss of corner column at the ground floor. The fragility models were compared to those derived through incremental dynamic analysis (IDA) to assess the inaccuracy of progressive collapse fragility functions derived through pushdown analysis. Load capacity predictions provided by those analysis methods were used to develop regression models for a quick estimation of dynamic amplification factor at a given displacement/drift level. The analysis results show a significant influence of both seismic design and secondary beams on robustness of the case-study building classes.

1. Introduction

Accidental and man-made extreme events, such as impact, fire or explosion, can induce abnormal loads on structures, which in turn may suffer heavy damage or even collapse. In many instances, a significant propagation of direct damage to key structural components throughout the structure have produced a progressive collapse of residential, iconic and public buildings, resulting in huge losses of life and property [1–5]. Given that structural systems designed according to conventional approaches may not be able to withstand extreme actions, catastrophic cases of progressive collapse have strongly stimulated the research community to address such a system-level problem of structural safety. Following the early interest in blast- and progressive collapse-resistant design and assessment of buildings after the 1968 partial collapse of Ronan Point tower in UK [4], the occurrence of further dramatic accidents and deliberate attacks (either in urban or industrial environments) has led homeland security to become a primary concern for public authorities and stakeholders. Thus, the protection of structures against extreme loads has begun to have a great impact on economy and society.

Several definitions of progressive collapse have appeared in the literature [6–12], most of them assuming such a type of system failure to be characterized by a significant disproportion in size between the initial and final damage configurations. This has led to the more rigorous term of disproportionate collapse, which is a major indirect consequence of damage to single structural components subjected to abnormal loading. In order to ensure appropriate levels of structural safety and mitigate the progressive collapse risk in a cost-effective manner, nonstructural protective measures (e.g. external barriers, sacrificial elements, limitation or control of public access) have been reaffirmed to be crucial in reducing the building exposure. Major advances in protective design and structural response simulation under abnormal loading have recently made [13–39], allowing a standardization of analysis procedures and design methods in several guidelines published in the last two decades, particularly in the United States of America [13–16]. Moving from individual structural components to the entire structure, both direct and indirect design methods have recognized the key role of system-level requirements, such as

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robustness, integrity, continuity, redundancy and ductility [17–19]. A huge amount of theoretical studies on blast and progressive collapse phenomena have been done [11,12,17–35], allowing the influence of modeling assumptions and analysis techniques to be quantified. Shell or solid finite element (FE) [25,28,33,34], lumped plasticity [18,22–24,26,27,36] and spread plasticity [11,12,17,19,25,29–32,35,37–39] approaches have been developed and validated for progressive collapse analysis of different building typologies, ranging from civilian to strategic and military facilities. In this respect, both static and dynamic nonlinear analysis procedures have been explored using general-purpose codes or open platforms. In addition, experimental tests on structural subassemblages and framed prototypes have been carried out [34,40–44].

Despite the large number of deterministic investigations, probabilistic approaches have been applied to a lesser extent in this field and a few research works have appeared in the literature so far (see e.g. [1,6,45–53]), emphasizing the need for probabilistic assessment and management of disproportionate collapse risk to blast loads or sudden column loss scenarios. Brunesi et al. [50] developed a framework for fragility analysis of European reinforced concrete (RC) framed buildings, integrating Monte Carlo (MC) simulation for random generation of 2D and 3D structural systems with fiber-based FE modeling and incremental dynamic analysis (IDA). Dealing with RC buildings designed according to American building codes, Yu et al. [53] performed an interesting study on both sensitivity and fragility of 2D framed systems to sudden removal of exterior and interior columns, using pushdown analysis of macromodels. Nonetheless, the progressive collapse vulnerability of European buildings still needs to be evaluated and characterized, considering the specific construction features of those structures in accordance to past or modern codes.

In this study, the authors modify the fragility analysis procedure by Brunesi et al. [50] to evaluate the progressive collapse vulnerability of modern European RC framed buildings through pushdown analysis techniques, which are used more frequently than nonlinear dynamic analysis for progressive collapse assessment.

The main scope of this research was threefold: (1) to derive progressive collapse fragility models based on pushdown analysis of low-rise RC framed buildings that are designed according to Eurocode 2 (EC2) [54] and Eurocode 8 (EC8) [55]; (2) to develop regression models for prediction of the dynamic amplification factor (*DAF*) to use in pushdown analysis of the European buildings; and (3) to assess the inaccuracy of pushdown-based fragility models with respect to their IDA-based counterparts. The selected structures define two distinct classes of the European building heritage, namely, EC2-conforming buildings designed only to gravity loads and EC8-conforming buildings designed for earthquake resistance.

2. Research methodology

This study falls within a general framework for probabilistic risk analysis (PRA) of structures and infrastructure systems threatened by extreme events, namely, low probability-high consequence (LPHC) events. Either in hazard- or scenario-based approaches, the annual probability of disproportionate collapse can be obtained through the probabilities of exceeding the following conditional limit states: (1) local damage to a single or small number of structural components given an extreme event, which is a direct consequence of abnormal loading; and (2) partial or total collapse of the structure given a local damage, which is an indirect consequence of abnormal loading [6,47,51]. These two conditional probabilities can be quantified using a multilevel analysis where uncertainties related to abnormal loading and structural system are modeled and propagated. The probability of damage to structural components and systems can be derived by means of reliability computations in which demand is convolved with capacity [56]. As such, PRA is a quantitative and rational tool that fosters risk-informed decision making for LPHC events. Although this is a well-established approach in earthquake disaster risk mitigation (see e.g. [57–61]), only a few applications have been made in case of abnormal loads [45–53]. After initial studies on probabilistic robustness assessment [45–47], the vulnerability of structural members (see e.g. [51,62]) and buildings [49,50,52,53] to abnormal loads has been usually investigated through fragility analysis. The output of the latter analysis consists of fragility functions, each of which describes the conditional probability of exceeding a prescribed performance limit state given the load intensity. The limit state is defined through a damage measure (DM), whereas the level of loading by means of an intensity measure (IM). Therefore, the characterization of progressive collapse risk depends on one hand on the fragility of single components to blast, impact or other abnormal loads, and on the other on the fragility of the structure given damage to one or more components. The latter contribution to physical vulnerability is termed 'progressive collapse fragility' and is investigated herein according to the following assumptions and methodology.

Two classes of low-rise, modern, European RC framed buildings were selected: gravity-load designed buildings according to EC2 [54] and earthquake-resistant buildings according to EC8 [55]. All buildings were assumed to be used for housing, composed of bare framed structural systems with one-way joist slabs, and subjected to sudden removal of single corner column at the ground floor. The loss of corner column was considered because usually it is the most demanding single-column removal condition in the case of a framed building.

For each building class, the procedure for characterization of progressive collapse fragility consisted of the following main steps as summarized in Fig. 1:

- Definition of multiple limit states by means of different DMs and thresholds.
- Modeling of uncertainties in material properties, geometry and loads.
- Generation of the building population through random sampling of RVs from their probability distributions, producing a large number of building realizations.
- Nonlinear fiber force-based FE modeling and pushdown analysis of each building realization, based on alternative structural representations and load distributions.
- Damage analysis and fragility estimation at each IM level and limit state, according to MC simulation method.
- Derivation of analytical fragility curves for each structural model under investigation through a regression analysis procedure.

The parameters that mainly influence the extreme response of the selected structures to column loss scenarios were assumed to be random variables (RVs) with appropriate statistics and probability distribution functions. Other parameters were considered as deterministic variables or deterministic transformations of RVs.

Fiber-based modeling of structures was selected because it is currently used in earthquake engineering [58,61,63–65] and progressive collapse simulation [11,12,17,19,25,29–32,35,37–39,50]. The downward load on beams, which is here denoted as Q_b, was assumed to be the IM. This is motivated by the fact that the abnormal load causing loss of columns vanishes instantaneously, so the residual structure should be able to resist gravity loads acting in that moment.