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Blast fragility and performance-based pressure–impulse diagrams of European reinforced concrete columns

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ABSTRACT

Terrorist attacks and accidental explosions can induce abnormal loads on building structures, producing local damage to single primary components or even progressive collapse. Few probabilistic investigations have been carried out to assess the risk of blast damage to structural components and progressive collapse. This study aims at evaluating the blast fragility of reinforced concrete columns for two classes of European residential buildings: those designed only for gravity loads according to past codes and those designed for earthquake resistance according to Eurocode 8. After uncertainty in material strengths, column dimensions, reinforcement ratios and blast capacity model was characterised, Monte Carlo simulation was performed. Blast capacity was defined through pressure–impulse equations that establish a relationship between the dynamic nature of blast load and damage. The output was the derivation of blast fragility surfaces and probabilistic pressure–impulse diagrams at multiple limit states which may be used for quantitative risk analysis and performance-based design/assessment.

1. Introduction

Civilian and military infrastructure may suffer heavy damage under accidental or bomb explosions, resulting in significant loss of life. Explosions are low-probability/high-consequence (LPHC) events as they induce abnormal loads that may cause partial or total collapse of the structure as a result of the propagation of direct damage to key components. This type of collapse is termed progressive or disproportionate collapse as it is characterised by a distinct disproportion in size between the initial and final damage configurations [1,2].

Early interest in progressive collapse probably started with the 1968 partial collapse of Ronan Point tower in UK [3–5] where a structural failure caused by a gas explosion at the 18th floor triggered the pancake collapse of an entire building corner [6]. The occurrence of further deliberate attacks and dramatic accidents in both urban and industrial environments generated a significantly increasing attention by the general public, governments, industry and researchers to the protection of structures against extreme loads. Guidelines for progressive-collapse-resistant design, assessment and retrofit of structures were published [7–9] and some building codes included rules for structural integrity and robustness against abnormal loads [10–13]. Besides, a large number of analytical studies on progressive collapse resistance were carried out particularly on steel structures (e.g. [14–20]) and reinforced concrete (RC) framed structures (e.g. [21–28]).

Despite the huge amount of deterministic analyses, a few investigations on the probabilistic features of progressive collapse were performed. In this respect, it is emphasised that probabilistic risk analysis (PRA) is a quantitative and rational approach that allows risk-informed decisions for disaster mitigation. Ellingwood and Leyendecker [4] carried out a pioneering work on the vulnerability of structural systems to specific damage scenarios, advocating the alternate load path analysis as a robustness assessment method. Other researchers proposed formulations for assessing the probability of progressive collapse [29–31]. According to a general framework for progressive collapse risk analysis in case of LPHC events [32], the annual probability of progressive collapse can be calculated and rationally reduced by different structural and non-structural measures. Either in hazard- or scenario-based approaches, the probability of progressive collapse can be computed by characterising the conditional probabilities of two limit states: local damage given an extreme event and disproportionate (global) collapse given a local damage. Such conditional limit state probabilities can be effectively determined by means of a multi-level analysis where uncertainties related to abnormal loading and structural system are modelled and propagated. The probability of blast damage to structural components and systems can be

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quantified through reliability computations where blast demand is convolved with blast capacity. The latter can be assessed by means of fragility analysis, which is a well-established tool in earthquake engineering [33] and was also recognised as an efficient means to separate and identify resistance and load uncertainties in blast risk assessment and management [34]. More recently, blast fragility analysis was applied either to structural components [35] or to structural systems subjected to column loss scenarios at the ground floor [36].

The present study is focused on blast fragility of European RC columns of the following building classes: (1) gravity-load designed buildings in compliance with past (non-seismic) codes and practice rules in the Euro-Mediterranean region [37–39], and (2) earthquake-resistant buildings designed in compliance with Eurocode 8 – Part 1 [40]. According to Stewart et al. [34], uncertainties in blast capacity of columns was modelled without considering aleatory and epistemic uncertainties in blast load. Then, probabilistic simulations were carried out to investigate the probability of exceeding multiple damage levels (or performance limit states) given a vector-valued blast demand measure defined in terms of peak overpressure P and impulse I. The primary scope of fragility analysis was to develop uniform-probability pressure–impulse (P–I) diagrams for performance-based design and assessment of the RC columns under study. Those P–I diagrams were characterised at multiple probability levels and three performance limit states. To account for the dynamic nature of blast load, structural response and damage, the blast capacity of columns was modelled through P–I diagrams which were developed and validated in other studies (see e.g. [41]).

2. Methodology

2.1. General probabilistic framework

This research falls within a general probabilistic framework for progressive collapse risk analysis where the annual probability of progressive collapse due to an extreme event H is estimated as follows [32]:

$$\Pr[C] = \Pr[C|LD]\Pr[LD|H]\lambda_H \tag{1}$$

In Eq. (1), LD is the event that local damage occurs as a result of H, C is the event of progressive collapse induced by LD, λ_H is the mean annual rate of occurrence of H that is numerically interchangeable with the annual probability of occurrence for randomly occurring events with rates less than 10^{-2}/year, $\Pr[LD|H]$ is the conditional probability of local damage given H, and $\Pr[C|LD]$ is the conditional probability of progressive collapse given LD. According to this framework, the probability of progressive collapse is decomposed in three terms, highlighting two conditional probabilities that define the probability of progressive collapse given H, namely $\Pr[C|H]$, which is multiplied by λ_H. If multiple hazards and damage states are possible, Eq. (1) can be generalised to:

$$\Pr[C] = \sum_H \sum_{LD} \Pr[C|LD]\Pr[LD|H]\lambda_H \tag{2}$$

This probabilistic formulation allows the structural engineer to carry out a performance-based design/assessment so that $\Pr[C] \leqslant p_{th}$, where p_{th} is the *de minimis* risk defining the acceptable risk level below which society normally does not impose any regulatory guidance. Pate-Cornell [42] took evidence that p_{th} is in the order of 10^{-7}/year. Stewart [43] defined three risk acceptance criteria based on fatality risks, failure probabilities and cost-benefit assessment, extending Eq. (2) to the annual probability of loss (risk). Stewart and Melchers [44] found that an annual fatality risk of less than 10^{-6} is generally accepted. PRA has great impact because assessing $\Pr[C]$ gives room to effective risk mitigation procedures aimed at minimising hazard (non-structural measures), the likelihood of initial damage (local structural measures), the likelihood that initial damage will propagate to a disproportionate damage (global structural measures), or some combination of the last effects. If the conditional probability of loss given C is equal to unity, the annual loss associated with progressive collapse can be simply derived as $\Pr[C]$ times an exposure measure, thus providing the consequence of H [45]. If λ_H cannot be quantified with sufficient confidence, a scenario-based procedure can be applied so that Eq. (1) can be replaced by:

$$\Pr[C|\text{Scenario}] = \Pr[C|LD]\Pr[LD|\text{Scenario}] \tag{3}$$

as a decision measure. In that case, the scenario is regarded as a specific event that may trigger a disproportionate collapse of the structure.

Scaling down the problem formulation from the overall structure to a single primary component (i.e. a column in case of framed systems), probabilistic analysis turns out to be focused on $\Pr[LD|H]$. If H is assumed to be a blast event, its magnitude can be quantified by an intensity measure (IM). For instance, in case of bomb detonations, a vector-valued IM is usually defined in terms of stand-off distance R and mass of explosive W, which can be synthesised into the scaled distance $Z = R/W^{1/3}$ to be used as scalar IM. The effect of blast load on a structural component is measured through an engineering demand parameter (EDP), which is a two-component vector including peak overpressure and impulse. Therefore, $\Pr[LD|H]$ can be replaced by $\Pr[LD|IM]$ and decomposed as follows:

$$\Pr[LD|IM] = \Pr[LD|EDP]\Pr[EDP|IM] \tag{4}$$

leaving the definition of the annual probability of occurrence of R and W, that is λ_{IM} instead of λ_H as a challenging task [34]. Eq. (4) gives evidence of the blast fragility $\Pr[LD|EDP]$ for a structural component, namely the cumulative distribution function of blast resistance. Conversely, $\Pr[EDP|IM]$ describes the variability in blast demand given a type and magnitude of blast load, and can be derived through a probabilistic blast demand analysis. It is worth noting that different estimates of blast demand are obtained for different types of blast event, such as bomb detonation, natural gas deflagration inside a building, and gas pipeline explosion. As such, different IMs may be selected according to the blast event under study. For instance, in case of gas distribution pipeline explosions, both peak overpressure and impulse do not depend on a scaled distance but rather on other event-specific factors such as type and size of pipeline, type and operating pressure of gas, type and extent of pipeline rupture, gas discharge properties, wind velocity, and distance between structure and pipeline. As structural response depends on the physical mechanisms and uncertainties related to the generation and propagation of a prescribed blast event, the fragility model proposed herein is based on the assumption that the explosive event ideally produces a uniform blast load on column surface. Therefore, other fragility models should be used to assess localised damage induced by close-in bombs such as vehicle-borne improvised explosive devices or suitcase bombs [46,47]. This calls for the use of different fragility models when the total risk of a structural component/system associated with several blast hazards must be evaluated.

2.2. Single-component fragility analysis and performance-based P–I diagrams

Fragility analysis was carried out on column prototypes representative of those typically detected in two building classes. Appropriate P–I equations were assumed as blast capacity model at multiple performance limit states (see Section 1). The reliability