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Fragility analysis for the Performance-Based Design of cladding wall panels subjected to blast load

Pierluigi Olmati [a,*], Francesco Petrini [b], Konstantinos Gkoumas [b]

[a] Faculty of Engineering and Physical Sciences, University of Surrey, GU2 7XH Guildford, UK
[b] Sapienza University of Rome, Department of Structural and Geotechnical Engineering, Via Eudossiana 18, 00184 Rome, Italy

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ABSTRACT

This paper presents a probabilistic method to support the design of cladding wall systems subjected to blast loads. The proposed method is based on the broadly adopted fragility analysis method (conditional approach), widely used in Performance-Based Design procedures for structures subjected to natural hazards like earthquake and wind. The cladding wall system under investigation is composed by non-load bearing precast concrete wall panels. From the blast design point of view, these wall panels must protect people and equipment from external detonations. The aim of this research is to compute both the fragility curves and the limit states exceedance probability of a typical precast concrete cladding wall panel considering the detonations of vehicle borne improvised explosive devices. Moreover, the limit states exceedance probability of the cladding wall panel is estimated by Monte Carlo simulation (unconditional approach) in order to validate the proposed fragility curves.

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1. Introduction

Designing structures to withstand blast loads is common practice for many government and commercial buildings. Generally in the design practice, a set of design scenarios are selected and the integrity of the blast-resistant structural members and of the protective elements is assessed by using non-linear dynamic analyses with an equivalent single degree of freedom (SDOF) method. In such a way (adopting a deterministic approach for the hazard characterization), the probability of exceeding a particular limit state is not evaluated. In addition to the above, in designing a structural component subjected to blast loads, the current state of practice is to assume that the capacity is deterministic.

The adoption of deterministic values for the demand is principally due to a lack of knowledge of the hazard probability density function. This is common for Low Probability–High Consequence (LPHC) events [1]. As a partial consideration of the uncertainty affecting the blast load, simplified approaches are usually adopted. For example, in [2] the use of a magnification coefficient of 20% is applied on the assumed amount of explosive. However, this is limited to explosive storage facilities. In an antiterrorism design, the amount of explosive is characterized by elevated uncertainty depending on both technical and socioeconomic factors. These uncertainties lead the engineering community toward the implementation of probabilistic methods [3], something that is now crucial for both academics and practitioners.

With specific reference to blast-resistant structures, some authors started carrying out investigations about the use of probabilistic methods for the assessment and design of structural components and structural systems. In [4], results of a parametric investigation on the reliability of reinforced concrete slabs under blast loading are presented, in order to establish appropriate probabilistic distributions of the resistant parameters. In [5], the extension of probabilistic approaches from the performance-based earthquake engineering to the blast design problems are provided, also by suggesting appropriate variables for the intensity measures IMs, the damage measures DMs, and the response parameters definition. In [6], Monte Carlo simulations are performed in order to estimate the failure probability of windows subjected to a blast load made by a vehicle bomb. In [7], the fragility curves are presented for two kinds of glazing systems. In [8], the design in a probabilistic way of a sacrificial cladding for a blast wall is described, deployed to protect vulnerable objects against an accidental explosion.

Due to the above considerations, the definition of appropriate frameworks for the probabilistic design of blast resistant structures is an important objective for the engineering scientific community. To this regard, during the last decade Performance-Based Design (PBD) has been recognized as a powerful methodology for verifying the achievement of design performance objectives of structural systems during their design life [9]. Probabilistic approaches have been extensively implemented in the state of the art methods for

* Corresponding author.
E-mail address: pierluigi.olmati@gmail.com (P. Olmati).

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the PBD of structures under different kind of hazards such as earthquake [10,11], wind [12–14], and hurricanes [15]. The last case is an example of multi-hazard situation that is expected to be one of the main directions of PBD approaches in the future [16].

In the PBD context, a powerful tool is represented by the fragility analysis (see for example [17–19]). As it is well known, the structural fragility is expressed as the cumulative probability distribution of attaining a certain Damage Measure (DM) conditional to the Intensity Measure (IM) of the hazard. The efficiency of the fragility approach is strictly related to the appropriateness of the IM in terms of "sufficiency" and "efficiency", meaning that the IM must accurately describe all pertinent hazard sources (see [20]).

Despite the above, a rigorous approach that is consistent with the well-established PBD frameworks adopted in presence of other hazards has not been defined for blast resistant structures. This paper is an effort in that direction with a specific focus on the fragility analysis. The fragility analysis is applied in order to compute the probability of exceeding a limit state ("probability of exceedance") of a precast wall panel subjected to blast loads (in particular far-field surface-blast loads [2]) in a PBD perspective.

As case study, a precast concrete cladding wall panel with the dimensions of 3500 mm in length and 1500 mm in width, with a cross sectional thickness of 150 mm is considered. The panel is subjected to a blast load generated by a vehicle borne improvised explosive device. The wall under investigation is a non-load bearing precast concrete wall panel used as exterior cladding for buildings. Typically, the length and the width of these walls are subject to specific architecture requirements while their thickness is approximately 15 cm. The steel reinforcements are generally placed in the middle of the cross section. This kind of wall panels should be designed in order to protect occupants and equipment from external detonations.

Non-linear dynamic analyses are carried out by the well-established method of the equivalent non-linear SDOF system, where the precast concrete wall panel is modeled by an equivalent non-linear SDOF on the basis of energetic considerations. Furthermore, both the fragility curves and the probabilities of exceedance are computed using Monte Carlo simulations.

The fragility curves are evaluated for the case-study wall panel for each defined limit state called here Component Damage Level (CDL). Then the fragility curves are used in order to estimate the probability of exceedance of the cladding wall panel subjected to blast load scenarios (vehicle borne improvised explosive devices). Finally, the probability of exceedance of the wall panel subjected to the same scenarios is estimated by the unconditional approach (based on a single Monte Carlo simulation) in order to validate the obtained results (see [4,11]).

In addition to the fragility analysis of the examined structural member typology (an innovative aspect of the paper), some preliminary indications on the selection of a sufficient and efficient IM for PBD of blast-resistant structures are provided.

2. Fragility analysis

As previously stated, the fragility of a structure under the action of a certain hazard is expressed as the cumulative probability distribution of a certain DM conditional to the IM of the considered hazard. Probabilistic PBD approaches identify the generic structural performance by means of acceptable occurrence frequencies for some threshold values (representing structural limit states) of an appropriate DM during a reference period of time [21,22]. The determination of such occurrences is affected by large amounts of uncertainty. The fragility approach allows the designer to express in a synthetic and efficient manner this uncertainty by making use of conditional probability relations and by highlighting the dependences of these occurrences from the IM.

In earthquake engineering, the fragility approach has been mostly developed during last twenty years and applied for PBD purposes. The fragility curves have been developed also for structures subjected to flood [23], fire [24], and windborne debris in hurricane prone regions [25]. The fragility curves are nowadays extensively used for the state of practice methods of structural risk evaluation for structures under natural hazards.

Among other techniques proposed for the evaluation of the fragility curves, Monte Carlo analysis is extensively used [26].

Two main issues need to be addressed primarily in order to develop fragility curves under a single hazard by Monte Carlo approaches. These are due to the fact that: (i) the computational effort required in order to obtain the desired level of approximation is often challenging [27]; and, (ii) the individuation of an efficient and sufficient scalar IM for fragility representation is needed.

The last point is essential since, in case of a vectorial IM, the structural fragility needs to be represented in terms of surfaces, something that is required for example in the case of performance analysis under multiple hazards (see for example [28]). In this paper, this issue is discussed focusing the attention on the criticism of choosing a scalar IM.

As a first step, the uncertainties characterizing blast-engineering problems need to be properly individuated and addressed (Fig. 1). These uncertainties can be divided into three main groups:

- hazard uncertainties (e.g. explosive, stand-off distance);
- structure uncertainties (e.g. stiffness, dimensions, damping, material characteristics, damping, etc.);
- interaction mechanism uncertainties (e.g. the reflected pressure, pressure duration, etc.);

This classification of the uncertainties in three groups (load, structure, interaction mechanisms) is generally valid for many engineering fields.

The IM in general should be chosen among the first group of uncertain parameters or as a combination of those parameters, while the entity of the blast action given a certain IM is determined by the parameters characterizing the interaction between the IM and the structural parameters. In probabilistic terms, hazard and structural parameters can be characterized as unconditional with respect to parameters belonging to one of the other two groups, while parameters representing the interaction mechanisms must be usually characterized in conditional probabilistic terms with respect to the hazard and the structural parameters [12].

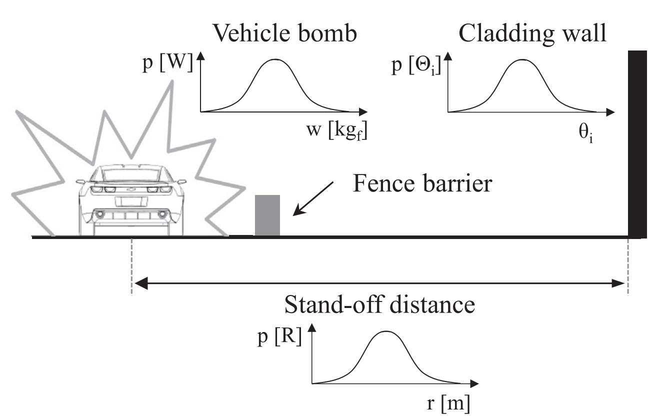

Fig. 1. Uncertaint parameters of vehicle borne improvised explosive device scenarios.

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