Engineering Structures 117 (2016) 457–469

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Simplified fragility-based risk analysis for impulse governed blast loading scenarios

Pierluigi Olmati [a,*], Francesco Petrini [b], Dimitrios Vamvatsikos [c], Charis Gantes [c]

[a] Tokyo Polytechnic University, Atsugi, Kanagawa, Japan
[b] Sapienza University of Rome, School of Civil and Industrial Engineering, Rome, Italy
[c] National Technical University of Athens, School of Civil Engineering, Athens, Greece

ARTICLE INFO

Article history:
Received 23 October 2014
Revised 27 October 2015
Accepted 14 January 2016

Keywords:
Performance-based design
Fragility analysis
Safety factor
Steel built-up blast resistant door
Simplified SDOF model
Monte Carlo simulation

ABSTRACT

Blast-loaded structures are presently assessed and designed following a deterministic approach, where only a set of structural analyses under worst-case design scenarios are carried out in order to verify each limit state. As a rational alternative, a conditional probabilistic approach is introduced to offer comprehensive risk assessment and to allow the design with user-defined confidence in meeting performance targets in view of uncertainties. To simplify the probabilistic consideration of the uncertain parameters, the determination of the blast hazard and the structural response are decoupled into the evaluation of blast hazard curves and structural fragilities curves, respectively, by introducing a single conditioning intensity measure. This is chosen to be the impulse density, shown to be sufficient for impulse-governed scenarios, achieving a reduction of the computational effort by several orders of magnitude without introducing bias. Furthermore a problem-specific safety factor formulation is introduced to incorporate the influence of uncertainties in a simple manner, akin to current engineering practice. As a proof-of-concept test, a steel built-up blast resistant door is subjected to an accidental detonation of mortar rounds in a military facility. The equivalent single degree of freedom model is adopted in order to conduct the structural analyses, while detailed finite element analyses are carried out for validation. Finally, the conditional approach risk analysis on the steel door is compared against the results obtained through the comprehensive (probabilistic) unconditional approach, showing the validity of both the proposed intensity measure and safety factor formulation.

1. Introduction

As for any structural problem, in order to assess the response of structures subjected to a detonation the following tasks must be achieved:

(a) Hazard (blast) analysis [1,2].
(b) Structural demand assessment (i.e. structural analysis) [2].
(c) Structure/component capacity assessment [2].
(d) Safety assessment (i.e., comparison of demand and capacity) [3].

Usually the execution of all of the above steps is conducted in a deterministic rather than a probabilistic way. At the scale of the structural system the global response can be assessed by considering pertinent damage scenarios [4,5] while at the scale of the single structural element detailed numerical models are employed for the correct prediction of both blast demand [6,7] and damage pattern of the structural element [8].

While, generally, the deterministic approach is preferred in order to design structures under blast loads, a number of works can be useful in order to calibrate probabilistic models and bound the uncertainties affecting the design of blast resistant structures. Stewart and Netherton [9] studied two types of window glazing system and investigated the crucial issue of selecting an appropriate intensity measure for computing the fragility curves for blast loaded structures. The fragility curves are developed as a function of two different intensity measures (the explosive weight and the stand-off distance) and several fragility curves are computed for specific cases of study. Netherton and Stewart [10] investigated the accuracy of the blast loading prediction model, concluding that the overall risk is sensitive to uncertainties of the blast load model. An example regarding the complexity of the blast load modeling is shown in the work of Ballantyne et al. [6] where the clearing effect for finite width surfaces is investigated. In the study of Wu et al.

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

http://dx.doi.org/10.1016/j.engstruct.2016.01.039
0141-0296/© 2016 Elsevier Ltd. All rights reserved.

[11] a series of different kinds of concrete slabs are tested in order to both compare their blast resistance and evaluate the uncertainty affecting the pressure estimation procedures provided in the Unified Facilities Criteria (UFC) 3-340-02 [2] manual. Chang and Young [12] used Monte Carlo simulations in order to estimate the probability of failure for windows subjected to blast load induced by a vehicle bomb. Low and Hao [13] presented results of a parametric investigation on the reliability of reinforced concrete slabs under blast loading in order to establish appropriate probabilistic distributions of the resistance parameters. Olmati et al. [14] carried out fragility analyses for the performance-based design of cladding wall panels subjected to blast load by adopting the scaled distance as intensity measure, and presented a discussion about the effectiveness of this choice.

The difference between deterministic and probabilistic approach is that in the first case only one blast load scenario is considered in order to define the hazard, usually taken to be representative of the worst case. Then, a single structural model realization, typically incorporating average or characteristic material properties, is analyzed to obtain the corresponding Demand (D) value. Similarly the Capacity (C) is assumed to be a single value describing an upper threshold in the response parameter of interest (e.g. rotation or strain), which when exceeded determines the violation of the limit state. The safety comparison is performed through the well-known equation $C > D$; as a consequence, the result is a binary "safe" or "unsafe" answer.

Conceptually, the probabilistic approach can be considered to be a repetition of the deterministic assessment over many (ideally all) possible scenarios. Then, the safety assessment becomes an evaluation of the probability that the demand exceeds the capacity, formally $\mathrm{P}(C < D)$, also known as the probability of exceedance of the limit state that is tied to the capacity. For example, if one considers N_b equally probable blast loadings, N_s equally probable realizations of the structure and N_c equally probable capacity values, then $\mathrm{P}(C < D)$ is the fraction of the $N_b{\cdot}N_s{\cdot}N_c$ scenarios where the demand exceeds the capacity.

Both the advantages and disadvantages of using the probabilistic approach are well-discussed in the literature [15–17]. They mainly revolve around the complexity of applying a probabilistic analysis versus the additional insight, reliability and often economy offered when one takes into account all pertinent uncertainties. The emergence of performance-based engineering and present abundance of computational resources have allowed the adoption of probabilistic methods in many fields of the civil engineering [18–23], a trend that is, nowadays, also moving into blast [9,10,14,24]. In view of such advancements, a streamlined method for probabilistic performance-based blast analysis is proposed here for impulse-governed loading of first-mode-dominated structures. Essentially it confers all of its advantages while removing its perceived complexity by having a low computational footprint and closed-form solutions for safety assessment.

2. Probabilistic basis for performance assessment

Assessing the probability of exceedance for any limit state of interest, $\mathrm{P}(C < D)$, can be achieved by several procedures that can be broadly categorized in two classes: the unconditional (UA) and conditional (CA) approach. In the unconditional approach, samples of blast scenarios, model realizations, and potential capacity values are generated, then combined in order to determine $\mathrm{P}(C < D)$ by a single Monte Carlo simulation. The unconditional approach is exactly the generation of the $N_b{\cdot}N_s{\cdot}N_c$ scenarios described earlier, from which the fraction that violates (exceeds) the limit state is evaluated. The main disadvantage of the unconditional approach is the need for performing $N_b{\cdot}N_s$ structural analyses, if the value of capacity is assumed not to influence the structural response, or $N_b{\cdot}N_s{\cdot}N_c$ otherwise. This has led to the adoption of the so-called conditional approach, widely used in earthquake engineering [25,26]. Therein, an interface variable, called intensity measure (IM), is introduced to be able to fully represent the characteristics of the hazard in a single scalar (or rarely vector) variable. Formally, IM needs to be "sufficient" [27]. Then, hazard analysis needs to assess the distribution of IM arising from the potential blast scenarios, while structural analysis is reduced to computing the distribution of structural response conditioned on the value of the (scalar) IM.

A blast scenario depends on multiple parameters (stand-off distance, charge weight, height of the detonation, presence of barriers, etc.). Conversely, an unconditional approach would involve the determination of structural response over the vector of hazard parameters, leading to a large number of blast scenario realizations N_b and corresponding structural analyses. By introducing a scalar IM, the conditional approach effectively reduces the structural analysis effort by several orders of magnitude. Perhaps the only downside is that the probability of exceedance of the limit state is no longer a simple fraction but instead necessitates the integration through the application of the total probability theorem:

$$\mathrm{P}(C < D) = \int_0^{+\infty} \mathrm{P}(C < D|IM)\mathrm{f}(IM)\mathrm{d}IM \tag{1}$$

The target of structural analysis now becomes the assessment of the conditional probability of exceeding a limit state, $\mathrm{P}(C < D|IM)$, the so-called limit state fragility curve or function [28]. $\mathrm{P}(C < D|IM)$ is determined for a range of IM, ideally from a value of $IM = 0$ to a value that causes the probability of exceedance to become 1, essentially guaranteeing failure. $\mathrm{f}(IM)$ is the probability density function (PDF) of encountering a given IM value and its determination is the target of the blast hazard assessment. Thus, the problem is efficiently divided in two parts with the benefit that the complete structural characterization, achieved by the fragility curve, can be used for any blast scenario (different charge weights, stand-offs, etc.). As both the demand D and the capacity C are random variables, the actual evaluation of the probability of exceedance can become more complex than Eq. (1) implies. Following simplifying assumptions and methods from performance-based engineering [29] a useful IM for performance-based blast assessment and design will be presented, together with the analytical evaluation of Eq. (1) in a format that is useful for practical applications.

3. The impulse density as intensity measure

Two of the main parameters that determine the blast load on structures are: the scaled distance (Z) and the amount of explosive or charge weight (W). Fig. 1a shows their effect on blast pressure (p) and blast impulse (i) both taken as load parameters for the case of surface burst explosions [2]. The stand-off distance R is measured from the target to the explosive source, while the scaled distance Z is obtained by dividing R by the cube root of the explosive charge weight W. p_0 is the side-on pressure, p_r is the reflected pressure, i_0 and i_r are the side-on and reflected impulse densities, respectively [2]. Based on the UFC 3-340-02 [2] manual the blast load can be defined as an equivalent triangular pulse as indicated in Fig. 1a, where t_d is the equivalent triangular pulse duration. Via the functional relationships shown in Fig. 1a in terms of the scaled distance and explosive weight, a direct dependence of the blast load on both peak pressure p_{peak} (p_r in the case of Fig. 1a) and impulse density (i) can be observed.

Fig. 2a represents an iso-response curve, i.e., a curve of constant structural demand D (in this case referring to the support rotation