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RC beams under blast load: Reliability and sensitivity analysis

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ABSTRACT

The effects of blast loading on structures can be very dangerous: damages and failures are expected with serious threats to structural safety and human life. Materials stresses and strains are often pushed to the limit and the modelling of these phenomena can be very complex. In order to design blast-resistant structures it is very important to determine what are the key parameters of this problem.

This paper presents a reliability and parametric analysis of the response of reinforced concrete (RC) beams under blast loads. The main aim is to highlight the key parameters of the problem in order to produce information useful for the design of reliable blast-resistant RC structures. The beam has been idealised as an equivalent SDOF system, in which strain-rate effects are accounted for. This approach is convenient from a computational point of view and it has been validated by a direct comparison with a more sophisticated finite element model and with experimental results found in literature. Then a sensitivity analysis of the parameters involved in beam response under blast load has been developed. Slenderness (which has a direct effect on stiffness) and peak load prove to be the most important parameters, but span length (which has an important influence on the mass) is also a key parameter. Other variables such as concrete strength and reinforcement ratio do not seem to have a strong correlation with the beam response.

1. Introduction

Nowadays, the issue of structural safety under blast loading has become a dramatic problem. The tragic news of the terrorist attacks of recent years (9/11/2001, New York; 7/7/2005, London; 7/23/2005, Sharm El Sheik; 20/09/2008, Islamabad 1/24/2011, Moscow; etc), raise important, urgent questions regarding the real safety and reliability of our buildings. Extreme loads such as impacts, explosions, etc., can occur in everyday life with unexpectedly high frequency. Actually, the problem of terrorist attacks, so important for strategic and military building design, has been linked to residential and industrial building explosion accidents.

The effects of blast loading on structures can be very dangerous, damages and failures are expected with serious treats to structural safety and human life. Materials stresses and strains are often pushed to the limit and the modelling of these phenomena can be very complex. The peculiarities of damages induced by blast load can be treated as "fingerprints" and allow to estimate the load characteristics in a back analysis process. This issue is well presented in the review paper [1] where the explosion aftermath analysis can be synthetized by two main questions: what damage is seen? What does the damage mean? In this way, important lessons can be learned also by real case studies: for example in [2] the real blast-induced collapse of bridge is investigated. Its failure was due to a firework explosion and important information about the explosive charge and its real location were assessed looking at the damages.

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As said before the structural response under blast load is not trivial. In the scientific literature several papers were devoted to the study of simple structural elements like beams and columns. The most elementary dynamic model consists of schematizing the beam with a Single Degree of Freedom (SDOF) system. This approach simplifies the theoretical formulation of the problem and its solution. It has a quite low computational cost but it usually requires the introduction of empirical formulas and, in addition, it does not provide full information on beam response.

A first example of this approach is reported in the pioneering work by Frankland [3] which presents an early, simple model: purely undamped elastic SDOF. In a quite recent paper, [4], Morison distinguishes two main SDOF approaches:

– Modal Method.
– Equivalent SDOF Method

The modal method was first presented in 1946 in the US Manual EM 1110-345-405, and, in 1965, re-issued as TM5-855-1 [5]. This method assumes that the elastic forced response of the real element is approximated by its first mode of free vibration. In case of elastic-pure plastic resistance function, the equation of motion can be solved in a closed-form, and referring to an idealised blast load, with triangular/rectangular time-history, maximum deflection can be easily calculated.

In the fifties, knowledge in this field increased, and the elastic–plastic model was considered. In an early work, Seiler et al. [6] modelled, by means of SDOF, a simply-supported beam under impulsive loading. They assumed that the initial velocity was a half sine wave. In this case, a simple mass-spring system can model the behaviour of elastic–plastic and rigid-plastic beams in order to develop a comparison between the two approaches. Then, Brooks and Newmark, in [7], investigated numerous dynamic structural problems. In particular, Newmark [8,9] was an influential proponent of the modal method, having calculated several modal period formulas and corresponding stiffness and strength expressions.

The equivalent SDOF method appeared in 1957 in the US Army Corps of Engineers manual: see [10,11]. This method relies on the calculation of SDOF parameters based on the equivalence of energy: the equivalent mass must have equal kinetic energy, the equivalent resistance must have equal internal strain energy and the equivalent loading must have equal external work to the real distributed element. These equivalent factors can be calculated for different structures with different boundary and loading conditions. A thorough presentation of this method is proposed in the well known Biggs book [12], which is a milestone for this kind of problems.

Most of recent SDOF models (see [13–17]) are based on the latter approach, their reduced computational time is a key characteristics that makes them very convenient, in comparison with more advanced numeric and analytic models, when it is necessary to develop an high number of dynamic analyses. However when it necessary to have more information on the beam response (e.g. time history of the distribution of displacements and curvature along the span) Multi Degree Of Freedom (MDOF) and continuous beam models are more effective: see [18–23] for Timoshenko beam theory, and [24] for Euler-Bernoulli beam theory.

Actually the development of numeric methods and in particular of Finite Element Analysis (FEA) has improved the reliability of this approach. In the case of blast and impulsive loading a very efficient code is LS-Dyna which is considered as a standard for both concrete structures (e.g. [25–27]) and steel structures (e.g. [28]). Furthermore some very interesting papers dealing with blast effects on glass structures and their design have been recently published by Amadio and Bedon: [29–31].

Experimental test of reinforced concrete elements subjected to blast load is of paramount relevance to set benchmark data necessary to validate the numerical model, however they are costly and difficult to carry out. In addition the spread of these results is often limited for defence purposes. Thus field results published in the international scientific literature are very important.

Magnusson et al. ([32–36]) subjected many reinforced concrete beams, with or without steel fibres, to air blast loading using a shock tube. One of the main important results is that the beams with a high reinforcement ratio and without steel fibres failed in shear, while those with a low reinforcement ratio failed in flexure. In addition, an explicit non-linear numerical model is developed in [37] with the aim of interpreting and describing the above mentioned experimental results. The effects of explosion on reinforced concrete beams strengthened by carbon fibres polymers were studied also in [38] by Hudson and Darwin.

It is important to mention also the experimental works by Remennikov and Kaewunruen [39], Fujikake et al. [40], Zhan et al. [41] and Tachibana et al. [42], in which reinforced concrete beams under impact loads were investigated. In [43], Giovino et al. subjected a set of RC panels to open-field blast in order to study the response of RC cladding under impulsive load due to external bomb. One way RC slab under blast load is also tested and modelled by FEA in [44].

An interesting study is presented in [45] where different strategies to strengthen RC elements are developed and tested with field experiment in order to prevent blast-induced failure, but very important results for close-in blast load are presented also in [46]. Indeed, in the latter work, an empirical scale law is proposed and it can be suitable for design purpose.

Blast load due to accidents or terroristic attacks cannot be forecasted in a deterministic way. Thus design procedures that consider explosion load must take into account the randomness of the threatening and of the load scenario. In addition, also the mechanical characteristics of materials cannot be assessed in a deterministic way and this is particularly important in case of RC structures. Therefore, when the randomness of these parameters is accounted for, the structural response assumes a probabilistic nature, making it necessary to look at reliability analysis. The probabilistic approach to structural reliability in the case of a blast load is a current topic in structural engineering. Due to the important computational effort to develop such kind of analysis the SDOF model becomes very convenient. For example in quite an early work [47], Low and Hao presented results from a parametric investigation of the reliability of reinforced concrete slabs under blast load. The authors considered an equivalent non-linear SDOF system, also taking into account the strain-rate effect. In [48], Rong and Li developed a probabilistic analysis of maximum displacement and ductility factors for a reinforced concrete flexural member under explosion load, using a non-linear dynamic