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# Probabilistic progressive collapse analysis of steel frame structures against blast loads

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ABSTRACT

This study investigates the failure probability of steel frame structures against terrorist attack from Vehicle Borne Improvised Explosive Device (VBIED). A two-step approach is used to evaluate the collapse potential of structures against blast loads. In the first step, the damage degree and responses of structural members under blast loads are determined based on an equivalent single–degree of freedom system. In the second step, the post-blast collapse behavior of steel frame structures is investigated using a 3-D non-linear macro-based numerical model. To improve the computational efficiency, the failure probability is calculated using subset simulation method cooperated with an advanced Delayed Rejection Adaptive Markov Chain Monte Carlo simulation algorithm. The variability of blast load, vertical gravity load and structural material properties are considered. The computational framework is applied to a prototype 10-story steel frame to study the failure risk against VBIED. The results show that the reliability assessment framework used in this study provides an accurate and more efficient prediction of failure risk of structures against blast loads compared with the direct Monte Carlo simulation method. The framework also presents an approach for determination of effective measures in protecting structures against blast loads.



## 1. Introduction

Terrorist attacks against civilian structures have been more frequently reported during the last decades. The explosions cause damage to the structural components and might lead to a disproportionate collapse of the building. Protection of civilian structures against blast loads has become a hot research topic [1].

A steel frame structure is a conventional structural system in the regions with high-seismic intensity. Research on the progressive collapse analyses of steel frame structures have attracted many researchers [1]. To reduce the collapse potential of structural buildings against blast loads, a number of protection techniques have been developed. Generally, there are three kinds of protective approaches [2]: (1) to reduce the blast loads by setting protective perimeters (2) to design structural members blast-resistant (3) to improve the integrity of structures. For a civilian structure located in urban area, it might be impossible to increase the standoff distance or it is uneconomical to make all the structural members be blast-resistant. Therefore, it is appealing for engineers to improve the integrity of structures so that the loss of structural components will not lead to a disproportionate collapse [2]. The strengthening measures include steel cables [3], CFRP cables [4] and steel connections with high rotation capacities [5].

However, the previous discussed studies are carried out with deterministic blast loads and structural properties. In reality, due to the influence of detonation point, charge shape, explosive material and even temperature and pressure, considerable variations have been observed in blast loads, as indicated by the studies from Netherton and Stewart [6] and Low and Hao [7]. In addition to the randomness of blast loads, material properties are also inevitably fluctuating. Therefore, the responses of structural member under blast loads are facing with uncertainty. Furthermore, considering the complex behavior of progressive collapse, the post-blast progressive collapse behavior of the damaged structure is subjected to much more uncertainties [8]. Therefore, reliability analyses of structural members and building under blast loads have received much attention. Using a coupled-SDOF system, Low and Hao [7] studied the direct shear and flexural failure probability of RC slabs under blast load. Stewart and Netherton [9] presented a risk assessment framework and studied the failure probability of glazing under explosions. Based on the developed pressure-impulse curves, Hao et al. [10] studied the effect of FRP on reducing failure risk of RC columns under blast loads. Olmati et al. [11] presented a fragility analysis of cladding wall panels against blast load.

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Recently, Shi and Stewart [12] investigated the effect of material random field on failure probability of RC columns against blast loads. Compared with reliability analyses on structural members, research on structural buildings under blast loads are limited. Kelliher and Sutton-Swaby [13] studied the failure probability of RC-shear wall structure against blast loads with a homogenized material model. Asprone et al. [14] investigated the collapse risk of RC frame considering both seismic motion and blast loading. Ding et al. [15] developed a probabilistic connection model and investigated the reliability level of composite floor systems against column loss. Olmati et al. [16] studied the punching shear failure probability of plat slab concrete building under accidental actions. Based on a multi-scale cohesive model, Xue and Le [17,18] carried out a stochastic progressive collapse analysis using alternate load path method. Although no blast loads are considered in [15–18], much of the collapse behaviors are similar to those under blast loads.

It should be mentioned that the reliability analyses of structural members and systems against blast loads are conducted using the Monte Carlo simulation (MCS) method, which is the most conventional methodology for predicting the failure probability of uncertain structural systems. The main drawback of the MCS method is its inefficiency in estimating a small failure probability. Fortunately, experimental tests from Chen et al. [19] and Xiao et al. [20] indicated that the collapse potential of structures designed with modern codes is relatively small. Generally, structural buildings are resistant to collapse under blast loads with the exception of the extraordinary large blast scenarios [21], such as a terrorist attack from Vehicle Borne Improvised Explosive Device (VBIED) comprising home-made ANFO [6]. Therefore, it is computationally inefficient to estimate the failure probability of structures under blast loads using MCS method, especially when the MCS method is cooperated with time-consuming numerical simulations. To overcome the limitations of the MCS method, Au and Beck [22] proposed an advanced subset simulation (SS) method intended for computing failure probability with smaller sample size. The basic principle of SS method lies in the fact that small failure probability can be represented by a product of a series of large conditional probabilities. This makes the method very attractive in predicting the failure probability of structures.

On the other hand, explosion is an accidental event with a low probability but the loss may be huge. The response of structures under blast loads needs a quantitative evaluation of failure risk [6]. As mentioned above, the previous researches are conducted with deterministic parameters. No attempts have been made at reliability analysis of steel structures against blast loads. Furthermore, although a number of protective measures have been developed, engineers may still be faced with problems on how to choose the most effective measures in blast-resistant design. Motivated by these limitations, this study conducts a probabilistic progressive collapse analysis of steel structures against terrorist attack from VBIED. The main objectives of this paper are (1) to present an efficient framework for reliability analysis of structural buildings against blast loads and (2) to provide an approach for determination of effective protective measurers based on the reliability analysis results.

This paper is organized into five sections. Following this introduction, the paper presents the reliability assessment framework for structural buildings against blast loads. The following section illustrates the 10-story prototype structure and random variables considered in the study. After that, the computational framework is applied to the 10-story steel frame structure as an example. The reliability analysis results are given and discussed in detail. Finally, some conclusions are made by discussing the applicability of the framework.

## 2. Reliability assessment framework

Fig. 1 shows the flowchart of the reliability assessment framework. The framework combines the SS method and a two-step progressive collapse assessment approach. The SS method is intended to predict the failure probability of the uncertain structural system while the two-step approach is employed as a deterministic analysis to check if the sample point falls into the failure region. In SS method, an advanced Markov Chain Monte Carlo (MCMC) algorithm is used to generate conditional samples from intermediate failure regions. Based on the reliability analysis results, an approach is presented for determination of effective measures in protecting structures against blast loads.

### 2.1. Two-step progressive collapse assessment approach

One of the intrinsic characteristic of the blast loads is its high magnitude and short duration. For these reasons, the responses of the structural buildings under blast loads can be divided in two stages [2]. In the first stage, the direct response of structure against blast loads is mainly associated with structural components. Due to the large mass of floor slabs, which provide large inertia resistant to blast, the responses at the floor level are small [2]. In the second stage, if the structural member loses its load-carrying capacity, structural progressive collapse might be triggered due to the insufficient of structural integrity [1]. Therefore, the analysis of structural building under blast load involves the following three steps: (1) determine the blast load (2) calculate the structural member response against blast loads (3) post-blast assessment of the damaged structure.

#### 2.1.1. Determine the blast load

Terrorist scenarios of Vehicle Borne Improvised Explosive Device (VBIED) are considered to reflect the reality of current terrorist threat [21]. Since the main objective of this study is concentrated on risk of structural collapse, the blast scenarios considered herein is truck-size home-made Ammonium Nitrate Fuel Oil (ANFO), detonated at various stand-off distances from the building. Based on the location of the detonation point and the equivalent TNT mass, the blast loads acting on the structural members are determined according to the flowchart of TM5-1300 [23]. A surface blast explosion is considered in this study which typically refers to a detonation point close to or on the ground. This is a reasonable assumption with respect to VBIED. Using the reflected pressure, the reflected impulse and the arrival time, the blast loads are simplified into a triangle loading function.

#### 2.1.2. Calculate the structural member response

The response of structural member under blast loads is calculated based on an equivalent single-degree-of freedom (SDOF) system. Structural column is the most important component in resisting vertical load. In this study, only the responses of columns under blast loads are determined. Fig. 2 shows the schematic of the equivalent SDOF system. The SDOF model used in this study considers the flexural failure and global instability of a steel column under blast loads. It should be noted that the SDOF model cannot consider shear failure and flexural-shear failure. The shear failure and flexural-shear failure of steel columns can be further considered according to the Timoshenko beam theory [24]. Neglecting the effect of damping, the equation of dynamic motion of the equivalent SDOF system under blast loads can be written as:

$$K_M M\ddot{y} + K_L R(y) = K_L F(t) + K_L \eta(t) \quad (1)$$

where $\ddot{y}$and $y$ are the acceleration and displacement of the equivalent SDOF system, and they are equal to the horizontal acceleration