Structural Safety 53 (2015) 13–25

Contents lists available at ScienceDirect

Structural Safety

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

Spatial reliability analysis of explosive blast load damage to reinforced concrete columns

Yufeng Shi *, Mark G. Stewart

Centre for Infrastructure Performance and Reliability, The University of Newcastle, New South Wales 2308, Australia

ARTICLE INFO

Article history:
Received 15 July 2014
Accepted 22 July 2014
Available online 8 January 2015

Keywords:
Spatial analysis
Reliability analysis
Explosive blast
RC column
Random field
Terrorism

ABSTRACT

Columns are the key load-bearing elements in frame structures and exterior columns are probably the most vulnerable structural components to terrorist attack. In this paper, a spatial reliability analysis is conducted to predict the damage for reinforced concrete (RC) columns subject to explosive blast loading. The spatial variability of material and dimensional properties of RC columns are modelled by stationary and non-stationary random fields. The variability of blast loading is also taken into consideration. Monte Carlo simulation and numerical methods are used to derive Blast Reliability Curves for RC columns under explosive loading for a number of terrorism threat scenarios, based on a high–fidelity physics-based computer programme LS-DYNA to estimate design and residual axial load-carrying capacity of RC columns. It was found that spatial variability has a significant effect on structural reliabilities and the spatial model will lead to more accurate predictions of damage and safety risks.

1. Introduction

Accidental or malevolent explosions can cause serious damage to civilian and military infrastructure as well as inflicting personal injury or death. Blast loads and its impact on safety and performance of structures have received considerable attention in recent years. The US Army, Navy and Air Force combined manual TM5-1300 [1] contains a comprehensive background and empirical relationships for blast load to predict structural performance developed from extensive experimental data. Since reinforced concrete (RC) is the principal material used for civil and military engineering structures [2], many investigations have been conducted on the dynamic response of RC structures subject to blast loading. Wu [3] investigated the dynamic response of simply supported RC slabs subject to explosive blast loading, using finite difference analysis. Remennikov [4] conducted research on predicting the effectiveness of blast wall barriers using experimental data and a neural network-based model.

Columns are the key load-bearing elements in frame structures and exterior columns are probably the most vulnerable structural components to terrorist attack. Failure of a critical column can lead to progressive collapse and large loss of life. The preferred method of attack continues to be Improvised Explosive Devices (IEDs), often through suicide tactics, against buildings and transport infrastructure. Moreover, military planners are under greater scrutiny to ensure that unintended damage or injury to civilians (collateral damage) by targeted ordnance is minimised. Hence, predicting the likelihood and extend of infrastructure damage and casualties due to explosive blast loading is topical focus for research, for both terrorist attack and targeted ordnance delivery. In recent years, much research is conducted on RC columns subject to explosive blast loading. Shi et al. [5] proposed a numerical method to generate pressure-impulse diagrams for RC column damage to blast loads. Bao and Li [6] and Wu et al. [7] conducted field tests using near-field explosive charges on two RC column specimens to validate their numerical simulations, then an extensive parametric study was developed to investigate the relationship between residual axial capacity and structural and loading parameters. Fujikake and Aemlaor [8] qualitatively and quantitatively investigated the damage of RC column by blast tests. Hao et al. [9] developed numerical simulation of blast wave interaction with RC columns, using AUTODYN 3D. Li et al. [10] analysed progressive collapse of RC frame structures by considering failure of columns induced by blast loading.

However, there are considerable uncertainties associated with material properties, dimensions, structural response, blast loading and expected damage which are not considered in those deterministic studies. Structural reliability and the inclusion of stochastic methods in structural simulations have been well developed, but there are few applications in explosive blast loading. Low and Hao [11,12] considered the stochastic parameters describing

* Corresponding author. Tel.: +61 2 49216156.
E-mail address: yufeng.shi@uon.edu.au (Y. Shi).

http://dx.doi.org/10.1016/j.strusafe.2014.07.003
0167-4730/

explosive loads and computed probabilities of failure for RC slabs. Stewart et al. [13] described a general framework for probabilistic and structural reliability analysis of structural systems. Stewart and Netherton [14,15] and Al-Hababheh and Stewart [16], using probabilistic analysis, modelled the damage and safety risks of monolithic glazing and unreinforced masonry to explosive blast loads. Hao et al. [17] conducted a structural reliability analysis of RC columns using regression functions to correlate changes in parameter values to changes in RC resistance. Eamon [18] developed a procedure to assess the reliability of concrete masonry unit infill walls subjected to blast loading. Recently, Kelliher and Sutton-Swaby [19] combined Monte Carlo methods with a simplified but conservative progressive collapse RC structural model. However, many of these studies used simplified probabilistic blast loading models and finite element models, and all assumed homogeneous material and dimensional properties. Due to the spatial variability of workmanship, environmental and other factors, it is recognised that the material and dimensional properties of a concrete structures will not be homogeneous (eg. [20,21]).

In this paper, Monte-Carlo simulation iterations and numerical methods are used to predict the damage of RC columns subjected to blast loading based on the explicit FEM software LS-DYNA. The prediction of damage is based on load-bearing capacity of the structure. The structural reliability analysis calculates: (i) variability of structural response and (ii) damage and collapse risks for RC columns subject to various explosive threat scenarios. Concrete compressive strength and cover are taken as spatial variables in this research and the reliability analysis of both non-spatial and spatial models are compared. The variability of blast loading is also taken into consideration. A terrorist VBIED (Vehicle Borne Improvised Explosive Device) scenario is considered to reflect the concerns and reality of current terrorist threats [22]. Therefore the blast scenarios considered herein are 50 kg (small VBIED), 100 kg (car-size) and 1000 kg (truck-size) of home-made ANFO (Ammonium Nitrate Fuel Oil) detonated at various stand-off distances from a typical RC column. The reliability analysis allows Blast Reliability Curves (BRC) to be generated – these represent damage and collapse risks as a function of stand-off.

If protective measures, such as bollards or other perimeter security measures, allow the stand-off to be increased, then BRCs obtained from structural reliability and probabilistic methods may be used to assess risk reduction due to these protective measures. A decision analysis can then consider threat likelihood, cost of security measures, risk reduction and expected losses to compare the costs and benefits of security measures to decide which security measures are cost-effective, and those which are not. For additional and wider-ranging assessments of the issues raised and the approaches used, see Stewart [23-25] and Mueller and Stewart [26,27].

2. Stochastic finite element analysis

2.1. Structural reliability

The probability of damage to infrastructure conditional on the occurrence of a specific threat is

$$Pr(D|T) = Pr[G(\mathbf{X}) \leq 0] \quad (1)$$

where $G(\boldsymbol{X})$ is the limit state function, and $\boldsymbol{X}$ is the vector of all relevant variables. Structural systems damage or collapse takes place when load effects (S) exceeds resistance (R), so $G(\boldsymbol{X}) = R{-}S$ where $G(\boldsymbol{X}) = 0$ defines the boundary between the 'unsafe' and 'safe' domains [28]. The limit state functions can be expressed in terms of structural damage, safety hazards or casualties.

2.2. Probabilistic modelling of structural response

The RC column is representative of a ground floor central column of a two storey RC frame building (Fig. 1). The RC column is H = 4.6 m high and is of rectangular cross-section (Figs. 2 and 3). Table 1 shows the design (nominal) material and dimensional properties of the RC column.

2.2.1. Finite element model

The finite element model used herein is identical to the one developed by Shi et al. [5]. Eight-node solid hexahedron elements of 50 mm are used to represent concrete, while the steel bars are modelled explicitly by 50 mm-long beam elements connected to the concrete mesh nodes. The restraint at the top end of the column provided by secondary floor beams and slabs is modelled as a stiff block, while the bottom end restraint is modelled as a fixed support. In the numerical model, the top end of the column is only allowed to move vertically in z direction, while at the other end all degrees of freedom are constrained. Thus a header and a footing, as shown in Fig. 3, are used in the numerical model to provide higher fidelity for constraints. The outer vertical faces of the head and footing are constrained against horizontal motions, and the bottom face of the footing is constrained against vertical motion [7].

The Karagozian and Case (K&C) material type 72R3 (MAT_CONCRETE_DAMAGE_REL3) concrete model is utilised in the present study to model concrete. It is a plasticity-based model, using three shear surfaces and includes damage and strain-rate effects. The model characterizes all aspects of concrete by a single input parameter, namely uniaxial unconfined compressive strength. Previous studies have proved that this model is able to provide robust representation of complex concrete laboratory response and be employed in structural response analysis subjected to blast loading [29]. Steel is modelled by the material model PLASTIC_KINEMATIC, which is a strain rate sensitive elastic–plastic material model, accounting for strain rate sensitivity and stress–strain history dependence.

The bond-slip interactive effect between longitudinal steel bars and surrounding concrete is considered in this numerical simulation because stress transfer behaviour between the reinforcement and concrete plays a significant role in the dynamic response of RC structures [30]. Thus, a one-dimensional slide line, which is intended for use in modelling bond slip in LS-DYNA, is applied to model the bond slip between steel bars and concrete. A string of

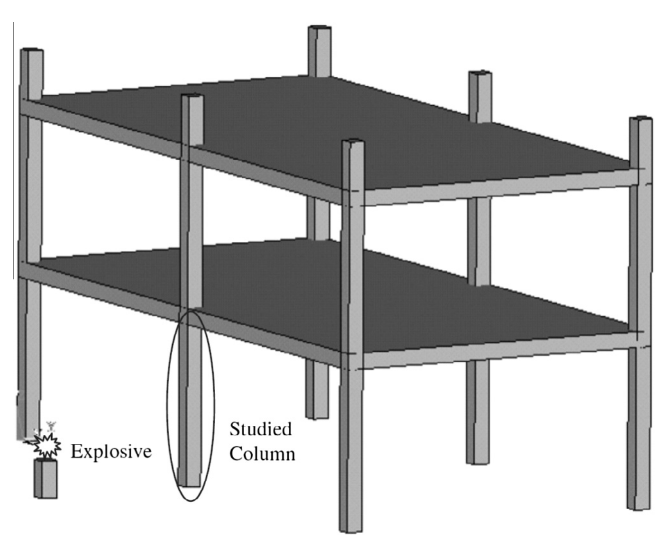

Fig. 1. Schematic diagram of column position [5].