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Damage and risk assessment for reinforced concrete wall panels subjected to explosive blast loading

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ABSTRACT

The structural integrity of reinforced concrete (RC) structures in blast events is important for critical facilities. In this paper, a structural reliability analysis is conducted to predict the damage and risk reduction for RC wall panels subjected to explosive blast loading. Due to considerable uncertainties associated with material properties, dimensions, structural response, blast loading, as well as expected damage, probabilistic methods are used in quantifying the probability of damage for conventional and blast-resistant RC precast cladding wall panels by incorporating spatial and non-spatial variables. The variability of blast loading is also taken into consideration. Monte Carlo simulation and numerical methods are utilized to predict damage of RC wall panels subject to various threat scenarios, based on a physics-based computer programme LS-DYNA to estimate maximum support rotations. It was found that spatial variability of concrete compressive strength and concrete cover has little effects on the structural reliability for precast concrete panels, and the blast-resistant wall has 5%–100% lower probability of hazardous failure than the corresponding value for a conventional wall.

1. Introduction

Reinforced concrete (RC) is a principal construction material used for civilian buildings and military constructions. These structures might be subjected to explosive blast loading from terrorist attacks, military ordnance, or other sources of explosions. This may lead to severe damage to RC structures and result in tremendous casualties and property loss. In recent years, significant worldwide efforts have been devoted to research on the performance of RC structures subjected to explosive blast loading.

RC precast wall panels are increasingly being used for residential and commercial buildings, and they are vulnerable to explosive blast loading. In recent years, much research has been conducted on the dynamic response of RC wall panels to blast loading. Remennikov and Kong [1] developed a numerical model to predict the flexural response of steel-concrete-steel panels subjected to blast and high-speed vehicle impact loading. Lin et al. [2] investigated the effects of charge weight, standoff distance, panel thickness, and reinforcement ratio on the blast resistance of RC wall panels by using LS-DYNA. Garfield et al. [3] conducted experiments for wall panels constructed by normal concrete and fiber reinforced concrete with a wide range of construction details under blast loading. Pan and Watson [4] reported the interaction between RC cladding panels and fixings under blast loading by using DYNA3D.

However, the deterministic research has not incorporated considerable uncertainties associated with material properties, structural dimensions, blast loading, as well as expected damage. Therefore, probabilistic and reliability theory methods are useful in quantifying the probability of damage. Only very few probabilistic and reliability analyses have been carried out for RC structures subjected to explosive blast loading (eg. Refs. [5–11]). This is in contrast to the approach that has been used very widely and successfully for other man-made and natural hazards (eg. [12]). Moreover, many of these reliability analyses used simplified probabilistic blast loading models and finite element models, and all assumed homogeneous material and dimensional properties. It is acknowledged that material and dimensional properties of a concrete structure will not be homogeneous due to the spatial variability of work practices and environment. Shi et al. [13] developed a procedure to assess the reliability of RC columns subjected to explosive blast loading, considering spatial random variables. Hence, a two-dimensional spatially variable reliability analysis is developed to predict the likelihood and extent of damage for RC wall panels subjected to blast loading. This model will consider the random spatial variability of concrete compressive strength and concrete cover.

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In this paper, Monte Carlo simulation iterations and numerical methods are used to estimate the damage of RC wall panels subjected to blast loading, based on the explicit finite element method software LS-DYNA. The prediction of damage is based on the support rotation of the structure. The reliability analyses of both non-spatial and spatial models are compared. The variability of blast loading is also taken into consideration. A terrorist Vehicle Borne Improvised Explosive Device (VBIED) scenario and a military Collateral Damage Estimation (CDE) scenario are considered to reflected the concerns and reality of current threats [14]. Expanded to include the probabilistic blast loading model developed by Netherton and Stewart [14] is the effect of charge shape. Hence, the blast scenarios considered herein are 50 kg (small VBIED), 116 kg (car-size) and 1000 kg (truck-size) of home-made Ammonium Nitrate Fuel Oil (ANFO), Mk82 General Purpose (GP) 500 lb bomb (89 kg Tritonal), and Mk83 GP 1000 lb bomb (202 kg Tritonal) detonated at various stand-off distance from a typical RC precast wall panel. The shape of charge assumed herein is a cylindrical explosive with aspect ratio of six to one. The TNT equivalent of 89 kg Tritonal and 116 kg ANFO are deterministically similar in peak reflected pressure. Additionally, the performance of conventional and blast-resistant wall panels will also be compared. The reliability analysis allows Blast Reliability Curves (BRCs) to be generated - these represent damage and collapse risks as a function of explosive mass and stand-off.

2. Finite element analysis

The RC precast wall panel is shown in Figs. 1 and 2, and Table 1 shows the design material and dimensional properties for conventional and blast-resistant wall panels. The hydro code LS-DYNA is utilized to analyse the wall panel damage to blast loading. Eight-node solid hexahedron elements of 50 mm are used to represent the concrete, and the Lagrangian formulation is employed in the analysis. In the Lagrangian formulation, the nodes of the numerical mesh are attached to the material, and they move and deform with the material. Therefore, there is no material transportation between elements, and the boundary conditions and interface between materials can be precisely defined [15]. A numerical

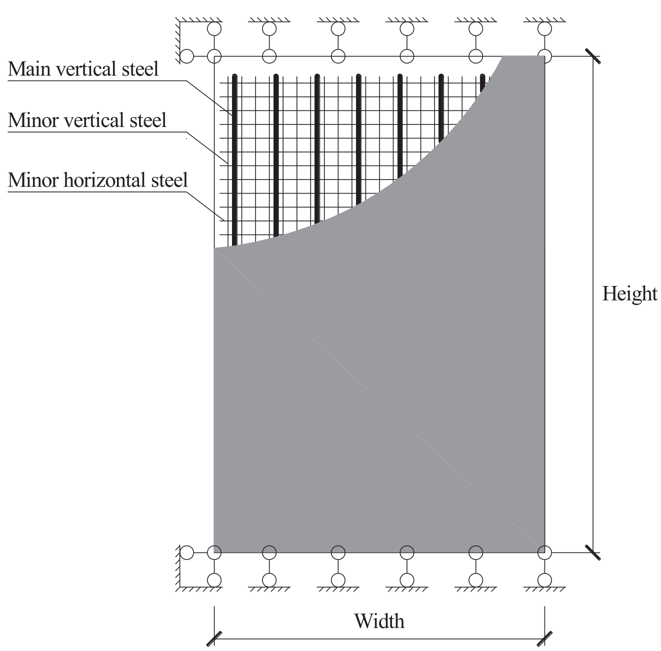

Fig. 1. Precast wall panel details.

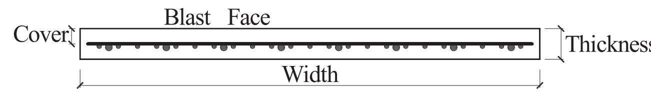

Fig. 2. Cross-section of the wall panel.

convergence study shows that further decrease of the mesh size has little effect on the numerical results but leads to a much longer calculation time. Therefore, a mesh size of 50 mm is used in the study.

The steel bars are modelled explicitly by 50 mm-long beam elements connected to the concrete mesh nodes. The bond-slip interactive effect between main vertical steel and surrounding concrete is also incorporated in this simulation to provide more accurate RC structural performance [16,17]. The bond strength has been investigated by pull out experiments and was found that the bond stress due to static friction and chemical adhesion between the concrete and reinforcing steel is 6.6 MPa for quasi-static loading, 18.0 MPa for dynamic loading, and 22.0 MPa for impact loading [18]. Shi et al. [19] used 18.0 MPa as the maximum bond strength for RC column subjected to explosive blast loading, since in blast event the bond strain reach the maximum value later than the direct pull out test. Therefore, 18.0 MPa is also employed herein as the maximum bond strength between concrete and reinforcement. As for the boundary conditions of this RC precast wall panel, the restraint of the top and bottom is modelled as a simple support, since it is a cladding wall.

2.1. Material models

In this LS-DYNA model, concrete is represented by the Karagozian & Case Concrete Model-Release III (MAT72 R3) [20,21]. It is a three-invariant model where three shear failure surfaces are used with damage. Strain rate effects are incorporated in this model, and different dynamic increase factors (DIFs) can be employed for concrete in compression and tension to simulate the desired rate effect. 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 [21].

Reinforcing steel is modelled by the Plastic Kinematic Model (MAT3) which is suited to simulate isotropic and kinematic hardening plasticity with the option of including rate effects. The Cowper-Symonds model [15] is used to incorporate strain rate

Table 1
Material and dimensional properties for RC wall panel.

Parameter	Design value	
	Conventional wall	Blast-resistant wall
Wall width	2400 mm	2400 mm
Wall height	3600 mm	3600 mm
Wall thickness	160 mm	160 mm
Main vertical steel	8 × 12 mm diameter	8 × 18 mm diameter
Minor vertical steel	N.A.	8 mm @ 100 mm spacing
Minor horizontal steel	N.A.	8 mm @ 100 mm spacing
Yield strength of main steel	413.7 MPa (Grade 60)	517.1 MPa (Grade 75)
Yield strength of minor steel	N.A.	413.7 MPa (Grade 60)
Fracture strain of hoops and cross-ties	10%	10%
Cover (C_n)	74 mm	71 mm
Concrete Compressive Strength (F'_c)	40 MPa	50 MPa