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Modelling the response of reinforced concrete panels under blast loading

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ABSTRACT

A finite element model is developed for the simulation of the structural response of steel-reinforced concrete panels to blast loading using LS-DYNA. The effect of element size on the dynamic material model of concrete is investigated and strain-rate effects on concrete in tension and compression are accounted for separately in the model. The model is validated by comparing the computed results with experimental data from the literature. In addition, a parametric study is carried out to investigate the effects of charge weight, standoff distance, panel thickness and reinforcement ratio on the blast resistance of reinforced concrete panels.

1. Introduction

Reinforced concrete is a principal construction material used for civilian buildings and military constructions. These structures might be subjected to extreme loadings during their service life, such as blast and explosive loading which could produce an overload much greater than the design load of a structure in a very short period of time. This may result in severe damage to the reinforced concrete structure and cause tremendous casualties and property loss. In particular, for strategically important infrastructure such as government and defence buildings, a high level of blast resistance is required due to the increasing risk of terrorist attacks. In addition, industrial explosion is another cause of such accidents. Therefore, it is of great significance to investigate the structural response of reinforced concrete structures to blast loading so as to provide reliable design guidelines to resist blast loads.

The analysis of structures made of brittle materials, such as concrete under blast loading is a very complex issue. Short duration and high magnitude loading can significantly influence the structural response. The frequencies of explosive loads can be much higher than that of the conventional loads, and short duration dynamic loads exhibit strong spatial and time variations, leading to sharp stress gradients in the structures and a varying strain rate for the duration of the analysis [1]. A few experimental studies on the reinforced concrete panels subjected to blast loading have been reported, such as the blast loading trials on simply supported reinforced concrete panels with openings conducted by Mays et al. [2], the test of the clamped reinforced concrete panels subjected to explosive loading carried out by Razaqpur et al. [3], the blast test on a simply supported one-way reinforced concrete panel done by Sun [4], the air blast tests on steel fibre reinforced concrete panels with various fibre types and boundary conditions carried out by Lok and Xiao [5]. In addition, the blast responses of sandwich panels consisting of mild steel face plates and aluminium honeycomb cores were investigated by Chi et al. [6].

However, full scale experimental test is usually costly and time consuming. A simplified single degree of freedom (SDOF) system has been widely used to predict the dynamic response of a structural member under blast loads. Naito and Wheaton [7] used a combination of a static finite element analysis and an equivalent SDOF dynamic analysis to determine the response of a reinforced concrete shear wall under blast loading. A corrugated stainless steel wall subjected to blast loading was analysed by Fallah and Louca [8] using the SDOF model with the resistance curve extracted from finite element analysis. In Low and Hao's study [9], a reinforced concrete slab was simplified to an equivalent SDOF system, and the peak dynamic response of the SDOF system to blast loads was solved dynamically. The response of a SDOF idealised model is an approximation of the displacement at some important point in a real structure. Parameters used to describe a SDOF model are converted from the original continuous structure by utilising an admissible function and application of the principle of virtual displacements [8]. Although the SDOF model has been proven to yield satisfactory overall structural response, the predictions are found to be very conservative [10], moreover, it cannot give an accurate indication of local damage of a structural component [11,12].

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In order to obtain more accurate predictions of structural behaviour of reinforced concrete structures and structural members under blast loading and avoid large numbers of repetitive experimental tests, many efforts have been made in recent years to the development of reliable numerical techniques. So far, the commercial numerical hydrocodes such as LS-DYNA and AUTODYN have been used in several studies. A 3D finite element model was proposed by Xu and Lu [1] using LS-DYNA for modelling of reinforced concrete plates subjected to blast loading, in which solid elements were used for modelling the concrete while the effect of reinforcements on the reinforced concrete behaviour was simulated by a mixture model in which the bulk modulus was contributed by both concrete and reinforcements. Different degrees of damage in concrete were investigated, and empirical equations were proposed in their study as spallation criteria. The blast resistance of reinforced concrete slabs was also investigated by Nam et al. [13] using LS-DYNA. Solid and beam elements with rate dependant material models were used for modelling the concrete and reinforcing bars respectively, and the mid-span displacement and the maximum strain of the concrete slabs were reported. Pereira et al. [14] investigated the blast resistance of cracked steel structures repaired with carbon fibre-reinforced polymer (CFRP) composite patch using LS-DYNA. The steel box was modelled using quadratic shell elements, and CFRP patch was modelled with a layered thin-shell element. The effects of patch thickness, patch size and laminate design were reported in their study [14]. The response of a reinforced concrete slab to blast loading was estimated by Zhou et al. [11] using AUTODYN, where the blast wave propagation was modelled in a 2D simulation, and then the results obtained from the 2D calculation were remapped to a 3D model to consider the interaction between the blast wave and the concrete slab. A dynamic material model for concrete was modified and employed in their numerical model. The blast pressure and the damage on concrete slabs were predicted. Luccioni et al. [15] simulated the structural collapse of a reinforced concrete building under blast loads using AUTODYN. Instead of modelling the concrete and reinforcements separately, a homogenised elasto-plastic material model that considered the collaboration of the reinforcements in tension was used in their study to simulate the behaviour of reinforced concrete components.

Although previous studies have made progress in the numerical modelling of reinforced concrete structures under blast loading, the numerical developments are still far from being sufficient due to the complexity of dynamic response of reinforced concrete structures. In addition, the effects of different parameters on the blast resistance of reinforced concrete structures are rarely reported. In this study, a finite element model is developed for the simulation of the structural behaviour of steel-reinforced concrete panels under blast loading. In particularly, the dynamic material model of concrete under blast loading is studied in details, considering the element size effect and strain-rate effect. The commercial software package LS-DYNA is applied to carry out the nonlinear finite element analysis using explicit time integration, and the developed finite element model is validated by comparing the computed results with test data from literature. In addition the effects of a series of parameters such as charge weight, standoff distance, panel thickness and reinforcement ratio on the blast resistance of reinforced concrete panels are also investigated using the validated finite element model.

2. Material model for concrete under blast loading

An appropriate concrete material model, which can describe the characteristics of concrete behaviour at high strain rate, is essential for the reliable numerical prediction of the response of a reinforced concrete structure to blast loading. It is generally accepted that the failure strength of concrete is rate dependent although the exact physical mechanisms responsible for the rate effect are currently not clearly known [1]. Both tensile and compressive strengths of concrete can be increased significantly under dynamic loading. Further, the strain-rate effect was found to be nonlinear and different for tensile strength and compressive strength [11]. At present, a few material models are available for the analysis of concrete structures under dynamic loading, including the Soil and Crushable/Non-crushable Foam Model [16], the Soil Concrete Model [17], the Brittle Damage Model [18], the Johnson and Holmquist Concrete Model [19], and the Gebbeken and Ruppert Concrete Model [20]. These models take into account the pressure hardening, strain hardening and strain rate dependency of concrete material, while some of them are limited to a certain class of problems due to their highly restrictive assumptions [21]. In this study, the Karagozian & Case Concrete Model-Release III [22,23] in LS-DYNA, which has been found to be able to describe the concrete response satisfactorily [21], is selected for the current finite element analysis.

2.1. Concrete material model

In the present finite element model, the Karagozian & Case Concrete Model-Release III (MAT72 R3) [22,23] in LS-DYNA is used for simulating the concrete. This model was first released in 1994 [22,24] based on the Pseudo-TENSOR Model (MAT16). It is a three-invariant model, in which three shear failure surfaces were used with damage and strain-rate effects included [17]. Different dynamic increase factors (DIFs) can be applied for concrete in tension and compression to simulate the desired rate effect in this model. It maintained the decoupling of the volumetric and deviatoric responses, with an equation of state relating the current pressure to the current and previous most compressive volumetric strain, and a failure surface limiting the second invariant of the deviatoric stress tensor [24]. In addition, it presented a significant overhaul of MAT16, including (1) adding a third independent failure surface based on a Willam–Warnke three-invariant formulation; (2) introducing a radial stress path for the strain rate enhancement algorithm; (3) adding a fracture energy dependent strain in tension; and (4) fixing several shortcomings in the original model [25]. The second release was extended to include shear dilation, and the strain-rate effect algorithm was modified to allow for implementation of different DIFs in tension and compression [25]. In this third release, an automatic input capability was added to generate the parameters for generic concrete material, and the strategy used in fitting the strain softening was modified [24]. Compared with other constitutive models used for concrete-like materials, MAT72 R3 is found to be relatively simple and numerically robust. It can reproduce key concrete behaviours which are critical to blast and impact analyses, and it is also easy to be calibrated using laboratory data [25].

The model uses three independent strength surfaces, i.e. initial yield surface, maximum failure surface and residual surface, which can be expressed as [25]

$$F_i(p) = a_{0i} + \frac{p}{a_{1i} + a_{2i} \cdot p} \tag{1}$$

where F_i is the ith failure surface, a_{0i}, a_{1i} and a_{2i} are the parameters defining the three-parameter failure surfaces, and $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$ is the pressure, in which σ_1, σ_2 and σ_3 are the principal stresses.

For hardening, the plasticity surface is interpolated between the yield and maximum surfaces based on the value of the damage parameter; for softening, a similar interpolation is performed between the maximum and residual surfaces.