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Numerical prediction of concrete slab response to blast loading

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Abstract

In this paper, a dynamic plastic damage model for concrete material has been employed to estimate responses of both an ordinary reinforced concrete slab and a high strength steel fibre concrete slab subjected to blast loading. In the concrete material model, the strength envelope is a damage-based modified piece-wise Drucker–Prager model; the strain rate effect on tension and compression are considered separately; the damage variable is based on Mazars' damage model, which is a combination of tensile and compressive damage. The equation of state (EOS) is also a combination of the porous and solid EOS of concrete with different forms for tension and compression states. The interaction between the blast wave and the concrete slab is considered in the 3D simulation. In the first stage, the initial detonation and blast wave propagation is modelled in a 2D simulation before the blast wave reaches the concrete slab, then the results obtained from the 2D calculation are remapped to a 3D model. The calculated blast load is compared with that obtained from TM5-1300. The numerical results of the concrete slab response are compared with the explosive tests carried out in the Weapons System Division, Defence Science and Technology Organisation, Department of Defence, Australia. Repetitive applications of blast loading on slabs are also simulated and the results compared with test data.

Keywords: Blast loading; Damage; Steel fibre reinforced concrete; Numerical simulation; Material model

1. Introduction

Some structures during their service life might be subjected to explosive loads. For example, industrial explosion accidents are a cause of such events. Also some important infrastructure such as government buildings, embassy buildings, and bridges might be targets for a terrorist bombing attack. Understanding structural response to explosive loads is essential to protect critical infrastructure against explosions. Both ordinary reinforced concrete (RC) and high strength steel fibre reinforced concrete (SFRC) are extensively used as construction materials. SFRC material has been proven to be more effective in resisting blast loading [1,2]. Slabs are common structural members. It is of interest to understand the behaviour of both RC and SFRC slabs under blast loading.

Evaluating the performance of concrete structures to explosive loading through full-scale tests is often beyond affordability. A simplified single degree of freedom (SDOF) system is normally adopted to predict the dynamic response of a structural member subjected to blast loads [3,4]. A SDOF model has been proven to yield satisfactory overall structural response. However, it cannot predict the localised damage of a structural member. With the rapid development of computer technology and the advancement of numerical techniques, more detailed modelling than SDOF for more reliable predictions through computer simulation of structural response to blast loading has become viable [5,6]. A wave propagation code, or hydrocode, is the most popular method used to simulate this kind of problem. Usually, a hydrocode treats stresses and strains separately in volumetric and deviatoric portions. For the volumetric portion, the equation of state (EOS) is always used to determine the relationship between the hydrostatic pressure, the local density and the local energy. The deviatoric portion is governed by a strength surface, which is often related to the first stress invariant I_1 and the second

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invariant of the stress deviator tensor J_2. Sometimes the effect of the third deviatoric stress invariant J_3 is also used.

In numerical simulation, the dynamic material model for concrete plays a vital role for reliable prediction of concrete structural response to blast loads. As is well known, concrete has very different tensile and compressive strengths, and the material strength is sensitive to the pressure and strain rate. A general strength criterion for concrete is defined as a function of the stress state valid for concrete under general three-dimensional (3D) stress states. Based on static tests, many static strength criteria have been proposed in the past [7–11], such as Mohr–Coulomb Criterion, Drucker–Prager Criterion, Willam–Warnke five parameter Criterion, Ottosen Criterion and Hsieh–Ting–-Chen Criterion. Many researchers have also carried out dynamic experimental tests on concrete materials. It has been found that both the tensile and compressive strength of concrete is highly dependent on the strain rate, i.e., the strain rate effect. Usually, the concrete strength increases with strain rate. The strain rate effect was found to be non-linear and different for tensile strength and compressive strength [12–16]. This implies that the dynamic strength criterion of concrete is strain rate sensitive and is not proportionally amplified from the static criterion. However, in most of the concrete material models, the difference of the strain rate effects on tension and compression is usually neglected, instead, both the tensile and compressive strength are modified by using the same dynamic increase factor (DIF) [17].

Some material models have also been proposed to calculate the concrete structural response to dynamic loads [17–21]. In 1993, Johnson and Holmquist developed a brittle damage model for concrete [17]. This famous Johnson–Holmquist brittle damage model was first developed to model brittle materials such as glass and ceramics. It was then extended to model concrete material. In their concrete model, the strength of the material depends on the intact strength, fractured strength, strain rate and damage. They used the typical porous model for EOS, and the accumulated damage was modelled in terms of the equivalent plastic strain and the plastic volumetric strain. The strain rate effect was considered by using a DIF, however, the suggested DIF was much lower than what was found from some test results by other researchers, such as [12]. The strength criterion used was a modified Drucker–Prager Criterion. The shape in the deviatoric plane is circular. Based on the Johnson–Holmquist model, the RHT model [5] was developed in 1999. In that model the strain rate effect and the damage variable are similar to those in the Johnson–Holmquist model. The EOS is Herrman's P-α porous model. The main difference is the construction of the yield and failure surfaces. In the yield meridian plane, a cap is added; in the deviatoric plane, it has different tensile and compressive meridians, which means the stress deviator tensor J_3 is taken into consideration. In 2000, Gebbeken and Ruppert developed a high-dynamic material model for concrete [21], which is also derived on the basis of Johnson–Holmquist model. In their model, the EOS is a porous model similar to that in the Johnson–Holmquist model; the yield surface has different tensile and compressive meridians and a shape function has been adopted to define octahedral stresses in the deviatoric plane; the strain rate effect and the damage was more comprehensively modelled. The suggested DIF is extended to a very high strain rate, i.e., 10^6/s. However, comparison of the suggested DIF with the experimental tests [14] shows that the suggested DIF underestimates the strain rate effect in the high strain rate range. The damage during the compaction process of the concrete was added as the extra damage portion. In their paper [21], they mentioned that it is not necessary to add a cap in the meridian plane because some numerical problems may occur and besides, a closed cap on the hydrostatic pressure is non-physical according to the theory of plasticity. All these three models employ the same DIF for both tensile strength and compressive strength. Recently, Leppänen [22] improved the RHT model by using a different DIF for tension and a bi-linear crack softening law. The parametric study has shown that cracking and scabbing of concrete in a penetration problem is mainly influenced by the tensile strength, fracture energy and the strain rate in tension. All the above-mentioned models treat stresses and strains separately in volumetric and deviatoric portions. In 2002, Gatuingt and Pijaudier-Cabot [23] developed a damage visco-plastic model for concrete to consider the interaction between the spherical and deviatoric response. The constitutive relation for concrete is based on viscoplasticity combined with the rate-dependant continuum damage. The damage is modelled with Mazars' damage model, which is a combination of compression damage and tension damage. In the latter model, many parameters need to be determined, for example, 9 parameters are needed to determine the damage variable.

For all these models, the material parameters for concrete are very difficult to determine because the experimental test in the extreme condition is not easy to perform and it is not easy to obtain accurate results because of the limitations of the measurement method. Therefore, the strength model for the deviatoric portion is mainly based on the combination of static test results and the strain rate effect of concrete [5,17]; and the parameters to determine the EOS are mainly based on static experimental results and some assumptions on porous materials [17]. Recently, Gebbeken at al. [24] used data from detonation experiments and flyer-plate-impact tests to study the EOS properties of concrete.

Similar to those Johnson–Holmquist based models discussed above, the authors [20] developed a simple plastic damage material model and incorporated the model to a hydrocode AUTODYN. The objective of developing that model is to allow users to construct a reasonable material model from limited parameters that are easily determined or available. In the model, the strength criterion is a damage-based modified Drucker–Prager model, the effect of J_3 is not considered. It was found that