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Influence of brittle shear damage on accuracy of the two-step method in prediction of structural response to blast loads

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ABSTRACT

A two-step numerical approach, which substantially reduces the modelling and computational effort in analysing structural responses to blast loads, was recently proposed. The method solves the responses of the equivalent SDOF system of a structural component during the blast loading phase to obtain the structural displacement and velocity at the end of the blast loading duration. Using these displacements and velocities as initial conditions, a detailed FE model is developed to solve the free-vibration response of the structure. It has been demonstrated that this approach yields very good predictions of structural displacement and longitudinal reinforcement stress at the mid span of RC beams. The accuracy in predicting the stresses in hoop reinforcements near the supports however varies from case to case. One possible reason for this inconsistency in predicting the stresses in hoop reinforcements near the supports is because of the brittle shear damage occurring near the structure supports during the loading phase, which is not considered in the second step free-vibration analysis in the proposed two-step method. To further improve the accuracy of the two-step method, in this paper, the influence of possible brittle shear damage during the blast loading phase is estimated, which will be included in the second step free-vibration analysis to improve the prediction accuracy of the two-step method. Pressure–Impulse diagrams for generic RC beams are generated for straightforward evaluation of the initial damage and the width of the initial damage zone at the end of the blast loading phase for inclusion in the second-step analysis. It is demonstrated that including damage caused by blast loads in the loading phase in the second step free-vibration analysis improves the prediction accuracy of the beam responses to blast loadings.

1. Introduction

During their service life, some structures are under potential threats from unexpected dynamic loadings such as those generated from accidental gas explosion in residential buildings, industrial accidents and terrorist bomb attacks. For these reasons, more and more attention have been paid to the structure protection against blast loadings. Historically, experimental and theoretical methods were the primary approaches to analyse structural responses to blast loads. Experimental study [1–4] can provide useful information for reproducing the structural performance under blast loading scenario and locating the blast induced damage, however, evaluating the structural response through blasting tests is always very expensive and often not possible owing to cost and safety concerns.

Theoretical approaches do not involve safety issue and do not involve high cost as a blasting test. The theoretical methods like Mindlin elastic plate theory and Timoshenko beam model can be used to predict responses of structural components to blast loads, but the complexity of the blast induced structural dynamic response often involves the non-linear inelastic material properties, effect of high strain rates, uncertainties of blast load calculations and the time-dependent deformations, thus the theoretical analyses often could not capture the complex blast loading and structural conditions in a real situation. To simplify the analyses, the equivalent single degree of freedom (SDOF) approach proposed in 1960s [5] is widely adopted in the study of blast induced structural response because the structural response can be straightforwardly calculated. The drawback of the SDOF approach is that the prediction accuracy depends on the reliability of the assumed structural deformation shape and the damage criteria, which are often difficult to be accurately determined, especially when the primary structural response involves both shear and flexural

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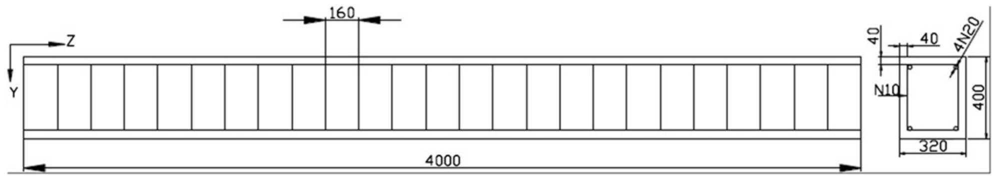

Fig. 1. Example beam under blast load.

modes, and when the structure suffers brittle failure. Moreover, the SDOF approach cannot be used to calculate the localized response and damage of structural members to blast loads.

With the development of both the computer technology and numerical techniques, it is possible to simulate the structural response under blast loads with the help of some popular wave propagation or hydro codes. Xu et al. [6] employed a dynamic plastic damage model for concrete material to estimate the dynamic responses of an ordinary reinforced concrete slab and a high strength steel fibre concrete slab subjected to blast loading. Shi et al. [7] derived analytical formulae to construct pressure–impulse curves of RC columns based on numerical results. Hao et al. [8] conducted numerical simulations of progressive collapse of an RC frame structure under blast loads with the hydro code LS-DYNA [9]. Zhou et al. [10] used computer code AUTODYN to predict damage of high-strength concrete slabs to blast load. With experimental verifications, it has been proved that such computer based numerical simulations can provide acceptable predictions of the structural response to dynamic loading at a lower cost. However, it is also commonly acknowledged that even with modern computer power, the detailed simulation of a complex structure under short duration blast loading can still be an impossible mission. This is because such modelling requires very small element sizes and short integration time step to impart the blast energy into the structure in numerical simulations. As a result, it leads to huge finite element models and long computation hours. The high cost often prevents application of numerical simulations in blast response analysis and design in a normal consulting firm, especially when it involves modelling an entire structure.

Recently, an innovative two-step numerical technique that combines the SDOF method and computer hydro code has been proposed by Li and Hao [11]. This two-step approach is based on the assumption that the blast loading duration is very short so that the peak response and damage of the structure occurs in the free-vibration phase. To calculate the responses and damage in the free-vibration phase, it is not necessary to use very small elements and short integration time step, therefore the free-vibration response can be simulated efficiently. Whereas in the traditional direct numerical simulations, very small mesh size needs be used in order to impart the blast energy into the structure. This results in a large number of small elements. Small element size in turn makes the integration time step very small. These make the complete simulation including both the forced and free-vibration phase of the structural response to blast loads extremely time consuming. In the proposed two-step method, the structural “forced-response” during the blast loading phase is calculated approximately in the first step by using the traditional equivalent SDOF approach with an appropriate deformation assumption (elastic, plastic or shear deformation shape). The velocity and displacement response at the end of this step are calculated by solving the response of the equivalent SDOF system and they are then used as the initial conditions in the second-step free-vibration analysis to predict structural response and damage. Numerical simulation results demonstrated that compared to the direct numerical simulations,

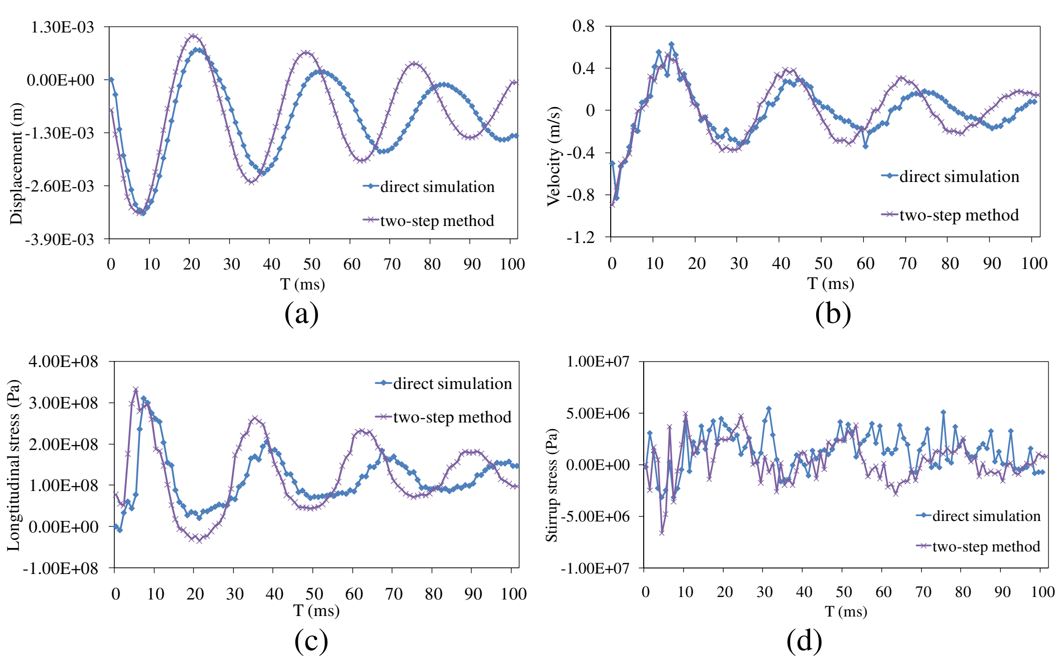

Fig. 2. Structural response to blast load of amplitude 1 MPa and duration 0.05T, (a) mid-span displacement, (b) mid-span velocity, (c) stress in longitudinal reinforcement at the mid-span, (d) stress in stirrup near the support.