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Parallel blast simulation of nonlinear dynamics for concrete retrofitted with steel plate using multi-solver coupling

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ABSTRACT

The blast damage behaviors for concrete panels retrofitted with steel plates exposed to blast loading are investigated. In order to enhance the reliability of the simulation results, the equation of state, strength, and failure model of materials are implemented in an explicit analysis program, AUTODYN. In particular, the implemented formulation includes the rate-dependent plasticity and damage softening; the non-linear strain and strain-rate hardening and non-linear strain softening. Furthermore, simplified and idealized 2D axis-symmetry, 3D, and parallel 3D simulations are compared in order to achieve accurate and efficient computation running times using multi-solver coupling method. Comparing the 2D axis-symmetry and 3D models, 2D model is stiffer and has a smaller deflection than the 3D models by geometries of retrofit material. The result of 3D numerical simulation becomes mesh size dependent, because of the explosive characteristics and mechanical properties of concrete. The parallel 3D simulation shows good scalability up to 15 processors and can be simulated at very high speed-up, while still consuming a reasonable amount of run times. Also, the retrofitted concrete panels are compared to the non-retrofitted concrete panel; maximum deflection and maximum deflection ratio are reduced by 1 mm, 3 mm, and 5 mm thick steel plates, scabbing can be prevented by retrofitted with steel plates. The simulation result shows good agreement with the experimental result. Finally, discussion on the numerical results with respect to code criteria and damage localization in retrofitted concrete panels is presented.

1. Introduction

The blast resistance of different types of civilian and military facilities to protect against accidental explosions and terrorist attacks is an important security issue. For example, the blast occurred at the basement of World Trade Centre in 1993 had a charge weight of 816.5 kg TNT and the Oklahoma bombing in 1995 had a charge weight of 1814 kg at a stand-off of 4.5 m [1]. Due to the blast load propagating through the atmosphere and an impulsive loading with the huge magnitude of pressure in a very short duration, the strain-rate dependency and local damage effect of concrete structures must be considered in blast analysis [2,3].

Compared to the other construction materials, concrete is generally known to have a relatively high blast resistance capacity. However, to improve resistance against extreme blast loads, some existing protective concrete structures require retrofitting during their service life. These retrofitted structures use steel or fiber reinforced polymer plates to enhance the energy absorbing capacity of concrete structures and to limit structural damage [4–6]. To understand the behavior of concrete structures under blast loading, full scale blast tests are required. However, these tests are limited due to security restrictions and a lack of the considerable resources required. Therefore, numerical modeling and simulation have recently been proven to be valuable explicit programs in simulating the behavior of such structures under blast loading [7–9].

In this paper, the retrofit materials of concrete structures are applied to the 1 mm, 3 mm, and 5 mm thick steel plates to increase the stiffness and improve the ductility of the concrete panels. To enhance the accuracy of the numerical analysis, the equation of state (EOS), strain-rate dependent strength and failure model of explosive, concrete, and steel are implemented in AUTODYN [10]. Also, the effects of the maximum deflection and deflection ratio from the numerical blast analysis on retrofitted concrete panels were evaluated. For the accuracy and reliability of numerical analysis results, retrofitted structure under blast loading is described using the multi-solver coupling method. The method needs to solve for air and blast surrounding the charge while at the

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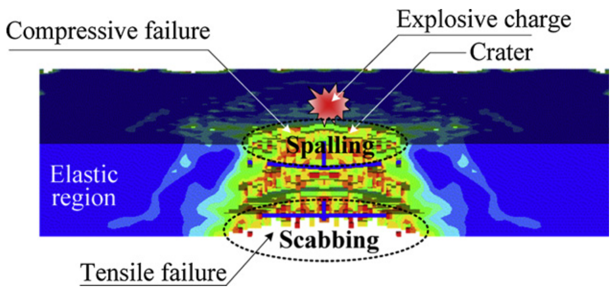

Fig. 1. Local damage caused by close-in explosion on a concrete panel.

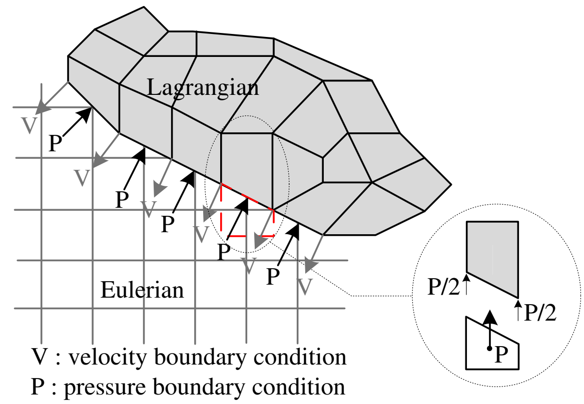

Fig. 3. Schematic of the Eulerian–Lagrangian coupling method.

same time should be able to solve the complex geometry of the structure response. In the present solver, an explosive can best be described using an Eulerian solver for the explosive detonation and blast while the structural response is generally best modeled using a Lagrangian solver. Numerical simulation of non-linear dynamic blast analysis using hydrocode can be simulated in 2D axis-symmetry, simulation running times are reasonable, but stiffer than the experiment results in this case [4]. In order to the true physics of the problem, 3D simulation can be approached as it resembles the actual situation. However, despite great advances in computation performance there are still limitations when computing 3D simulations for blast analysis. Run-times can be the order of days or weeks or even longer particularly when serial computing systems are used. Moreover, the numerical analysis for the behavior of concrete structure under irregular blast loading influences the results of numerical simulations by mesh geometries. This mesh size dependence is occurred due to gaps between the explosive energy and internal energy of structures and specific mechanical properties within the material model. Particularly, the fracture energy of the concrete material is greatly mesh dependent and the explosive characteristics such as amount of explosive and stand-off distance can also affect the mesh size dependence for blast analysis. These problems can be solved by using smaller mesh size which satisfies the consistent results [11,12]. However, if a smaller element size is used, it results the higher computational cost [13]. To resolve this problem, an approach to improve this situation is to adopt 3D parallelization. The numerical analysis is carried out using a simplified 2D axis-symmetric, 3D, and parallel 3D models and then compared with experimental results [4] and failure criteria of ASCE code [14].

2. Explosive blast loading

For detonation of cased bombs filled with high explosives, the surroundings will be subjected to blast load. Depending on the blast load and structure characteristics, the response behavior of the target structure will differ. In the case of blast loading at relatively large stand-off with uniform loading over the element, the response will be global, and for close-in blast loading and small stand-offs, the resulting damage is localized. The global damage of a concrete beam or slab can be generalized into membrane, flexural and shear failure. The local damage does not in general lead to structural failure, and a certain level of local damage is often allowed to occur. For contact bursts, blasts with short stand-offs or blast of large charges, a compressive stress wave is generated by the high-pressure pulse applied to the front face and causes localized cratering, so called spalling. The compressed stress wave travels through the thickness of the structural element and is reflected as a tensile wave when reaching the rear face. This tensile wave may cause failure in the rear face region, resulting in the scabbing of the concrete, meaning that a part of the concrete will separate from the structure and travel into the space behind with a velocity. If the front face crater and the scabbing zone are merged, perforation has occurred as shown in Fig. 1.

The formulas and parameters used for characterization of the blast load are in most cases empirically determined, but in some cases require additional theoretical and computational investigations. Due to a large amount of test data from explosive detonations, the blast load characteristics from such detonation can be estimated with great accuracy. The blast wave resulting from encased explosions or where the blast wave is reflected on other surfaces before arriving at the target can make the resulting blast load very complex and case-dependent. The pressure-time history of blast wave is divided into a positive and a negative phase. In the positive phase following the explosion, pressure at that position suddenly increases to a maximum overpressure and develops instantaneously and decays to atmospheric pressure. The maximum negative pressure has much lower amplitude than positive overpressure. The positive phase is more relevant in the research of blast wave effects on structures because of its high

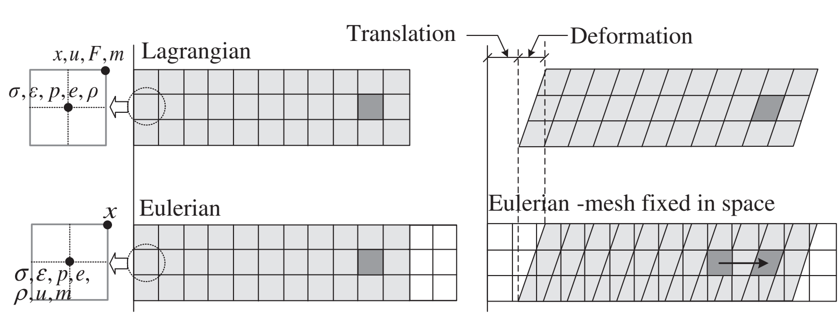

Fig. 2. Comparisons of the Eulerian and Lagrangian discretizations.