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Performance of highway bridges subjected to blast loads

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ABSTRACT

Since the collapse of the WTC towers in September 2001, concern about the protection of buildings and infrastructures against blast loads has increased significantly. Comprehensive experimental and numerical studies of blast loading effects on buildings have been carried out in recent years, whereas for bridge engineers, blast-resistant design is still a new area which requires separate and systematic investigation. The objective of this paper is to simulate the performance of three modern types of reinforced concrete bridges under various blast loads, including a slab-on-girder bridge, a box-girder bridge and a long-span cable-stayed bridge. To solve the computational constraints in performing numerical analysis on a personal computer, a Multi-Euler domain method based on the fully-coupled Lagrange and Euler models is adopted and further developed for long–span bridge application. This study investigates various detonation scenarios in terms of the explosive weight and location, and their interactions with bridge structures. Both the localized damage mechanism and the global structural response of three bridges are examined. By studying the blast-resistance of each bridge under different explosion threats, the most critical scenarios are identified respectively. Studies of bridge protection against potential attacks by using Carbon Fibre Reinforced Polymer (CFRP) strengthening are also discussed. Numerical results in this study provide bridge owners and engineers with thorough and important information on the structural performance of highway bridges under blast loads, helping them in choosing effective protection strategies for possible potential explosion events.

1. Introduction

1.1. Background

Over the past 60 years, more than 550 terrorist attacks on bridges and related infrastructure systems have been recorded [1]. Since highway bridges are important components of national transportation lifelines, catastrophic bridge failures can have large economic and socio-economic consequences. Especially, to fulfill the transportation and resource supplement purposes, more long-span bridges have been constructed in recent years, such as cable-stayed bridges, suspension bridges and cross-sea box-girder bridges. Therefore, there is a need to protect highway bridges against intentional and accidental explosions. In the past, both official and non-governmental design guidelines were proposed for military structures and buildings to resist weapons or blast effects [2,3]. Although some of the developments could be applied on bridges, specific information on blast-resistant bridge design is still limited. To begin addressing this concern, the Federal Highway Administration (FHWA) and the US Army Engineer Research and Development Center (ERDC) initiated a State Pooled Fund Program in 2006 that performed analytical studies and large-scale experimental blast tests on steel bridge towers subjected to blast loads [4]. Since then, many efforts have been expended on the field testing of bridge components and numerical simulations on full scale highway bridge under explosions. Hao and Tang [5] simulated the damage propagation of a large cable-stayed bridge under the explosion of 1000 kg of TNT, and investigated the effectiveness of FRP strengthening technique. Fujikura and Bruneau [6] investigated the blast resistance of reinforced concrete bridge piers by employing steel jacketing which has been widely used in seismic-resistant design. Son and Lee [7] evaluated the performance of the concrete-filled composite steel pylon subjected to blast loads by using a very sophisticated fully coupled finite element algorithm that considers the fluid–structure interaction. Yi et al. [8] proposed a novel hybrid blast load method and applied to the simulation of a three-span simply supported bridge under blast loads.

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Although the findings and suggestions for bridge blast-resistant design have been made in the above publications, there is still a great need to study all possible blasting threats to bridge structures, such as the in-deck detonation and explosions near piers that involve complex reflection and confinement effects. In the present study, three modern types of bridges are analyzed, including a reinforced concrete slab-on-girder bridge, a box-girder bridge and a long-span cable-stayed bridge. In order to obtain the detailed local and global damage patterns and predict an accurate overall response of the bridges under blast loads, a three-dimensional finite element model for each bridge is built using a commercial explicit finite element analysis package ANSYS AUTODYN [9]. To solve the limitations of CPU speed and element number on a personal computer, a Multi-Euler domain method is adopted and further developed for long-span bridge application [10]. In order to determine the most vulnerable case, several proposed detonation events are analyzed for each bridge in terms of explosive charge weights and locations, ranging from a hand-placed charge to a truck bomb case. Based on the simulation results and observations, the most critical cases for each type of bridge are identified. Studies of retrofitting the slab-on-girder bridge by using the Carbon Fibre Reinforced Polymer (CFRP) strengthening techniques are also presented.

1.2. Blast wave theory & analysis methods

Baker [11] stated that an explosion is a high-rate chemical phenomenon in which energy is released in a very fast and violent manner. The detonation process will generate high pressure within a period of tens to hundreds of milliseconds, loading different parts of the structure with varying arrival times. When an explosion occurs in a free field, a shock wave will be produced, together with high temperature up to 3000–4000 °C. The peak overpressure then starts to decay within a very short duration which is referred to as the positive phase. Fig. 1 presents an idealized pressure time-history profile of both the incident and reflected pressures. When a shock wave strikes a solid surface, the wave will be reflected resulting in the reflected pressure. Eventually, the process stops and the pressure returns to the ambient level over a longer duration.

Conventional structural nonlinear analysis for reinforced concrete structures under blast loads is based on simplified decoupled approaches, either employing empirical formulas or assuming a simplified triangular load pattern for estimation [12,13]. Generally, these decoupled methods are simple to use and efficient in estimating the global structural performance, since limited number of parameters is required, and many current design codes and standards are based on simplified SDOF techniques. However, it is obvious that these equivalent SDOF or MDOF models have limitations in evaluating visualized structural damage and dealing with complex internal explosion scenarios. With the rapid development of computer hardware and the maturity of computational mechanics over the last decades, it has become more effective and reliable to conduct detailed numerical simulations of blasting effects on structures on a personal computer.

The approach used in this study adopts a fully coupled Euler-Lagrange interaction model which is based on the explicit nonlinear finite element and finite volume methods [14]. Important effects of explosion such as the wave reflection, confinement effect and the negative explosion phase can be accurately modeled. This fully coupled model can be broadly divided into three parts: (a) the detonation of the high explosive, (b) the propagation of the blast wave, and (c) the interaction between the wave and the target. Currently, many commercial finite element softwares have incorporated this hydrocode. A hydrocode is defined as a computational mechanics tool that typically solves the behavior of both the solid and fluid materials under multi-situations in accordance with a series of equations of state (EOS), which give "the relationship between the density (or volume) and internal energy (or temperature) of the material associated with high pressure" [15]. ANSYS AUTODYN, as one of the most well-known explicit finite element packages that was developed for weapon-scale phenomena, has been widely used for blast and ballistic analysis because of its outstanding graphical interface and the advanced remapping techniques in modeling the coupled Euler-Lagrange interaction [9].

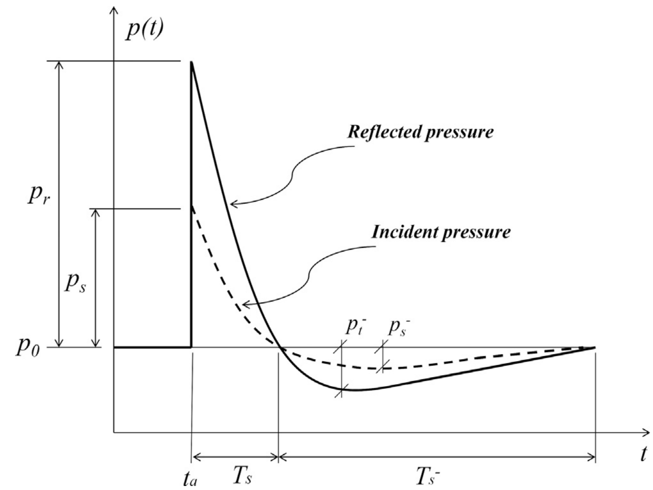

Fig. 1. Pressure-time comparison of free field and reflected blast loads.

In this approach, the structures are normally modeled by Lagrange elements while the high explosive materials and the ambient air are modeled by Euler elements. Lagrange methods are used to solve the structural deformation where the element mesh is fixed with the material. The Euler method is developed to solve the fluid dynamics so that the material in the Euler mesh can flow within the fixed grid to avoid the distortion problems found in the Lagrange mesh. By applying the principles of conservation of mass, momentum and energy, the material performance and the structural response can be obtained under extreme loading conditions.

In order to conduct blasting analysis of full scale structures for three highway bridges on a personal computer, a Multi-Euler domain method is adopted [10]. The essence of the method is that the original single air domain will be divided into several subsequent Euler domains, and will either be built or neglected in accord with the blast wave propagation. The iteration process will stop when one of the following two criteria is met: (a) the maximum pressure in the overall structure is smaller than 0.5 MPa or (b) the increasing Euler domains have reached the end of the structure. Using this method, the peak pressure can be controlled to a certain air range with fewer Euler elements, thus avoiding any waste of computer resources. The original Multi-Euler domain method is applicable for simple bridges with small dimensions where each subsequent air domain will be generated in one direction only. For complex long-span bridges, an updated Multi-Euler domain method is developed accordingly. This updated method builds the air domain in three-dimensions in accord with the spherical wave spread, so that the blast load effects on every bridge component can be simulated at the same time without any waste of computational resources. The detailed procedure of the Multi-Euler domain method is summarized in the flowchart shown in Fig. 2 [16].

2. Model development

2.1. Bridge configuration

As the most common types of bridge structures in highway systems, the reinforced concrete-steel composite slab-on-girder