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Experimental and finite element analysis of doubly reinforced concrete slabs subjected to blast loads

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ABSTRACT

This paper presents research on the response and behavior of both high strength concrete (107 MPa) and normal strength concrete (27.6 MPa) slabs doubly reinforced with high strength low alloy vanadium (HSLA-V) reinforcement (VR) and conventional steel reinforcing bars (NR) subjected to explosive loads. Four types of reinforced concrete (RC) slabs namely High Strength Concrete (HSC) with HSLA-V Steel Reinforcing bars (HSC-VR), High Strength Concrete with Conventional Steel Reinforcing bars (HSC-NR), Normal Strength Concrete (NSC) with HSLA-V Steel Reinforcing bars (NSC-VR), and Normal Strength Concrete with Conventional Steel Reinforcing bars (NSC-NR) have been studied and compared both experimentally and numerically. The slabs were subjected to blast loads using a shock tube capable of generating both positive and negative phase pressures. Data collected during the dynamic experiments consisted of reflected pressure obtained from several pressure gages arranged along the perimeter of the test article and mid-span deflections captured from an accelerometer, a laser device, and high speed video. The numerical analysis was performed with the commercial program LS-DYNA using two material models. The concrete material models considered were Winfrith Concrete Model (WCM) and Concrete Damage Model Release 3 (CDMR3). Results from the numerical simulation are compared with the experimental values to determine material parameters and other finite element model related constraints. Mesh sensitivity and crack propagation studies were also conducted. From this study it was observed that CDMR3 and WCM can be used over a wider range of concrete compressive strengths. The advantages and disadvantages of using high strength materials are discussed.

1. Introduction

Blast and impact events on structures such as the Oklahoma City bombing in 1995 and the September 11, 2001 attacks, have led researchers to probe into the aspects of making buildings and other socio economically vital structures strong enough to withstand extreme loadings. Furthermore, it becomes important to understand the response of reinforced concrete as a structural material when subjected to large stresses and strain rates through explosive loadings. The study of the dynamic nonlinear responses of individual structural components like beams, slabs, and columns of an entire building system has recently become an important topic. Advances in finite element modeling and analysis have further enhanced interest in studying the behavior and response of these individual components towards dynamic loadings by providing more reliable predictions.

Experimental and numerical analysis can be performed on steel reinforced concrete elements. However, blast experimental efforts require specialized equipment, labor, and could be fairly expensive. Numerical analysis of the dynamic behavior of steel reinforced concrete when subjected to the extreme loadings can be studied using the non-linear finite element software such as ABAQUS® and LS-DYNA®. LS-DYNA® has a number of features that make it suitable for blast load simulations and has been used in this study.

2. Objective

The objective of this research was to numerically and experimentally study the composite response and behavior of both high strength concrete 107 MPa and normal strength concrete 27.6 MPa slabs doubly reinforced with high strength low alloy vanadium (HSLA-V) reinforcement and conventional steel reinforcing bars (NR) when subjected to explosive loads. Four types of reinforced

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concrete (RC) slabs namely High Strength Concrete (HSC) with HSLA-V Steel Reinforcing bars (HSC-VR), High Strength Concrete with Conventional Steel Reinforcing bars (HSC-NR), Normal Strength Concrete (NSC) with HSLA-V Steel Reinforcing bars (NSC-VR), and Normal Strength Concrete with Conventional Steel Reinforcing bars (NSC-NR) have been studied and compared both experimentally and numerically. The slab construction and experimental work was performed at the U.S. Army Corps of Engineers – Engineer Research and Development Center (USACE-ERDC) in Vicksburg, MS. The 1652 mm × 857 mm × 101.6 mm slabs, reinforced longitudinally on the front and back face (referred to as double mat), were subjected to dynamic air blast loads using the Blast Load Simulator (BLS) located in Vicksburg. Pressure gages at multiple locations around the perimeter of the test article documented the reflected pressure, an accelerometer and a laser device were used to characterize the mid-span deflection, and still photos and high speed video were used to document the final damage patterns. Results from the experimental study are used to determine the characteristics that improved the performance of the slabs subjected to blast loads the most.

Numerical analysis of the dynamic behavior of steel RC slabs subjected to the extreme loadings associated with explosive events can be studied using the non-linear finite element software such as LS-DYNA [1]. The explicit finite element analysis discussed in this document was conducted using LS-DYNA and two concrete material models, the Winfrith Concrete Model (WCM) [2] and Concrete Damage Model Release 3 (CDMR3) [3,4]. Results from the numerical simulation are compared with the experimental values to determine the primary numerical features, the strengths and weaknesses of the models studied, to identify other constraints related to finite element models, and to identify important material parameters and their effect on the slab response. Mesh sensitivity studies were performed using a 25.4 mm and 12.7 mm mesh size. A 6.35 mm mesh size was used for crack propagation studies to qualitatively compare crack development in the RC slab. The results indicate that the mesh size plays a significant role in the predictions. Results presented include a comparison of experimental and numerical results including deformation histories, crack propagation and damage patterns. Conclusions are drawn from the numerical and experimental program regarding the efficacies of using conventional and high strength concrete and steel materials.

The yield strength of HLSA-V steel reinforcement is 572 MPa and the failure strain is slightly higher than that of conventional reinforcing bar. The introduction of vanadium into the chemical composition of a steel reinforcement bar has the advantages of increased strengths without compromising on ductility or formability and has good fracture toughness and weldability.

3. Literature survey and material models

Several material concrete models are available in LS-DYNA; such as, the Winfrith Concrete Model [2], Holmquist Johnson Concrete Model [5], Continuous Surface Cap Model for Concrete [6] and the Karagozian and Case Concrete Damage Model Release 3 [3,7]. Based on two previous studies [8,9] on concrete material models, the Concrete Damage Model Release 3 (CDRM3) and Winfrith Concrete Model (WCM) have been chosen for use in this study.

Several research studies have addressed the issue of the behavior of RC slabs subjected to explosive loading. Ågårdh et al. studied the behavior of RC slabs subjected to blast loading using finite elements [10,11] and used the Winfirth model to compare with experimental studies on fiber reinforced slabs. They have reported a good comparison of peak displacement results for low charge weights and noted that the strain rate effect of the material model was not significant due to the large standoff distance. Xu et al. [12] used the Pseudo-Tensor concrete material model [13] with a principal strain based erosion criterion to study concrete spallation in reinforced concrete slabs under various blast loading and structural conditions. They obtained numerical relationships between critical charge-standoff and three different damage criteria. Tanapornraweekit et al. [14] performed an experiment on an RC slab subjected to 5000 kg of TNT explosive and compared numerical simulation results using CDMR3. The maximum deflection obtained from LS-DYNA was seventeen percent less than experimental values. Zhou et al. [15] used a plastic damage model to study the dynamic behavior of both RC slabs and steel fiber concrete slabs and compared the results with explosive tests. They derived critical charge weight-standoff distance curves for four different damage levels. Schenker et al. [16] performed full scale field tests on concrete slabs in order to validate the model using a hydrocode based program. They also studied the effectiveness of using aluminum foam as a blast energy dissipater but the results were inconclusive. Hao et al. [17] studied the influence of concrete strength ratio, slab thickness, steel reinforcement ratio on RC slabs subjected to the blast loading using LS-DYNA and the Johnson–Holmquist model and compared it with a single experimental study of an open air near field explosion of 5 kg TNT on an RC slab. Sangi et al. [18] compared the experimental and numerical behavior of the reinforced concrete slabs with WCM and CDMR3, when subjected to drop weights. They observed that the damage pattern and the impact force histories obtained from the WCM were in agreement with the experimental values. Morales et al. [19] have presented a new setup and tested four RC panels subjected to each open air blast loading and have performed numerical analysis using the Winfrith Concrete Model and Brittle Damage model for concrete. The authors concluded that reasonably good simulation results can be achieved using simplified material models. Thiagarajan et al. [20] performed a preliminary study on the numerical simulation of high strength steel and high strength and normal strength concrete slabs and compared it with experimental results. In that study the CDMR3 showed a poor response for high strength concrete parameters that were generated internally by LS-DYNA. The work presented here extends the study to compare and contrast the behavior for four different slab combinations and also has material parameters for the CDMR3 that have been input manually based on concrete mixes developed by Neeley et al. [21] for a similar high strength concrete mix. A brief comparison of the two material models used in this study is presented below.

1. CDMR3 is a three invariant model that uses three shear failure surfaces and includes damage and strain-rate effects, while the Winfrith model is a smeared crack model (sometimes known as pseudo crack) and smeared rebar model that is implemented in the 8 node single integration point continuum element.
2. In CDMR3 the equation of state is required to define the pressure–volumetric strain curve, while the Winfrith model will automatically use a scaled curve if it is omitted from the input.
3. Both models are capable of material strain rate effects with the strain rate being defined by a load curve in CDMR3, while the Winfrith model uses the CEB [22] strain rate enhancement and enhances the elastic, shear and bulk moduli as well as the strength in tension and compression.
4. In CDMR3 model the most significant user improvement provided by Release III is a model parameter generation capability, based solely on the unconfined compression strength of the concrete, while the Winfrith model does not generate parameters from uniaxial confined strength alone.
5. CDMR3 model is not capable of crack generation, while Winfrith model has a crack generation capability with up to three