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Finite element study on the impact responses of concrete masonry unit walls strengthened with fiber-reinforced polymer composite materials

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ABSTRACT

Research on the impact behaviour of concrete masonry unit (CMU) walls strengthened with fiber-reinforced polymer (FRP) composites is considerably limited. In this study, the effectiveness of externally bonded (EB) FRP technique on the resistance of CMU walls under high-velocity impact force was therefore investigated numerically. Finite element (FE) models were developed using LS-DYNA. The Concrete Damage Rel3 model and Enhanced Composite Damage material models were used for concrete and composite materials, respectively. Furthermore, the Add Erosion and Smooth Particle Hydrodynamics options were included to accurately represent impact behaviour. The FE models were validated using literature results. Applications of various EB FRP composites to CMU walls were investigated with the parameters of fiber types, fiber direction, fiber layer, and impactor velocity. The numerical results show that the EB FRP strengthening technique is significantly effective to improve the impact resistance of CMU walls by preventing an impactor from perforating the CMU walls.

1. Introduction

There are many existing structures which do not meet current code requirements or are structurally deficient. In addition, structures sometimes need to be upgraded to improve resistance against additional loads. For these structures, strengthening is generally more recommendable than reconstruction from the standpoint of cost and time. Therefore, research has been extensively conducted to develop a reliable strengthening technique. Strengthening methods using steel materials attracted interest of engineers. However, fiber-reinforced polymer (FRP) composites are generally considered to be more effective and efficient as strengthening materials due to their well-known advantages such as corrosion resistance and high strength-to-weight ratio than steel.

There is a representative strengthening technique using FRP composites. That is externally bonded (EB) FRP method. The EB FRP strengthening method has proved to be reliable to improve performance of both masonry structures and reinforced concrete (RC) subjected to static loading [1–3]. Bui and Limam [2] tested four-full scale concrete masonry unit (CMU) walls to investigate the behaviour of masonry walls strengthened with EB FRP strips subject to out-of-plane loading. The load-carrying capacity of the FRP-strengthened masonry walls was significantly increased up to 250% in comparison with non-strengthened ones.

The efficacy of EB FRP technique on fatigue resistance has been assessed [4,5]. Aidoo et al. [4] investigated the fatigue behaviour of large scale RC T-beams strengthened with EB CFRP composites. It has been reported that the fatigue life of a RC beam can be improved since EB CFRP materials resist some of stresses mainly carried by steel reinforcement.

The performance of CMU walls strengthened with EB FRP composites under blast loading was investigated [6,7]. Various strengthening materials, such as EB glass FRP (GFRP) composite, sprayed-on polyuria, and hot-dipped galvanized A-36 steel, were used as retrofit materials [6]. It was reported that EB FRP strengthening technique was successful since EB GFRP laminates hindered debris from entering the structure. In addition, a buried arch having been damaged by blast loading was strengthened with EB CFRP strips [8]. It was concluded that EB CFRP strips were effective to strengthen a blast-loaded arch.

The effectiveness of EB FRP method on improving impact resistance should be also appraised since there are many structures exposed to the risk of damages caused by drop weight, vehicle collision, debris, and/or terror attacks. Before applying FRP composites to structures, the impact behaviour of FRP itself is of interest to designers. Therefore, at a material level, FRP laminates subject to high- and low-velocity impact force were investigated [9–11].

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Notation

The following symbols are used in this paper:

C	function defined by load curve;
E	internal energy per initial volume;
E_1 and E_2	axial and transverse modulus of elasticity, respectively;
G_{12}	shear modulus;
p	pressure;
T	function defined by load curve;
α	weighing factor for nonlinear shear stress;
γ	ratio of specific heats;
ε_1, ε_2, and ε_{12}	axial, transverse, and shear strain, respectively;
ε_v	volumetric strain given by the natural logarithm of the relative volume;
σ_1 and σ_2	axial and transverse stress, respectively;
τ_{12}	shear stress; and
ν_{12} and ν_{21}	major and minor Poisson's ratio, respectively.

At a structural level, the impact behaviour of RC structures strengthened with FRP composites was studied [12–14]. The performance of non-strengthened masonry walls under low-velocity impact force was also investigated [15,16]. Gilbert et al. [15] examined 21full-scale non-strengthened masonry walls subject to low-velocity impact loading. As proved in this study, masonry walls are substantially vulnerable to impact force due to the brittle nature of masonry unit components. Therefore, masonry walls need to be strengthened to avoid brittle failure. Some studies on the responses of CMU walls strengthened with EB FRP composites under low-velocity impact loading were conducted [17,18]. Cheng and McComb [17] tested nine full-scale CMU walls to investigate the effectiveness of EB FRP composites against low-velocity impact loading. It was found that the impact resistance of CMU walls strengthened with EB FRP composites was considerably improved in comparison with the non-strengthened CMU wall.

However, research on the impact response of CMU walls strengthened with EB FRP composites is still limited. In particular, research on the efficacy of EB FRP composites on CMU walls under high-velocity impact loading is quite rare although experimental study [19] was undertaken to investigate the behaviour of non-strengthened CMU walls subject to high-velocity impact force. In addition, although another FRP-strengthening technique called near-surface-mounted (NSM) FRP method is reliable and generally considered to be more effective than EB FRP method under static loading [20–22], this is questionable in case of impact loading since impact damage is rather local than global. If an impactor hits an area somewhere between NSM FRP rods, the impactor can easily perforate CMU walls. Therefore, the effectiveness of FRP composites on CMU walls subject to high-velocity impact force was investigated in this study. FE analysis (FEA) has been implemented using commercially available three-dimensional explicit FE software, LS-DYNA [23]. First, CMU models under low-velocity impact force were verified using the test results [17]. Then, the validated CMU models were slightly modified to be compared with specimens under high-velocity impact force. The modified CMU models were in good agreement with the test results [19]. Using the validated CMU models, the efficacy of the two FRP strengthening methods was assessed. The results provided in this paper are useful for the comprehensive design of CMU walls strengthened with FRP composites under high-velocity impact loading.

2. Numerical modelling

2.1. Material model

Many material models are available in LS-DYNA. Appropriate material models were chosen for various materials including concrete, FRP composites, steel, and wood in the present study. Strain rate varying from $10^{-6}\,s^{-1}$ (quasi-static loading) to $10^{4}\,s^{-1}$ (blast loading) is an essential factor influencing the impact behaviour of CMU walls since the strength, modulus of elasticity, and strain of concrete can be affected by strain rate. In this study, the structural response of CMU walls under high-velocity impact force is a main interest. Therefore, the Concrete Damage Rel3 (Mat 72R3) model has been selected since the model reflects crucial parameters such as strain rate effect given by a user defined curve and damage function calculated as a function of effective plastic strain, pressure, and strain rate enhancement factor.

The Mat 72R3 model is also named Karagozian & Case (K&C) Model – Release 3 [24]. The K&C model is a plasticity model decoupling the volumetric and deviatoric parts of concrete response. To accurately represent material behaviour, the Equation of State (EOS) Tabulated Compaction was chosen for the pressure-volumetric response. The tabulated compaction model is linear in internal energy. Pressure is defined as follows:

$$p = C(\varepsilon_v) + \gamma T(\varepsilon_v)E \qquad (1)$$

where, p = pressure; C and T = functions defined by load curves; ε_v = volumetric strain given by the natural logarithm of the relative volume; γ = ratio of specific heats; and E = internal energy per initial volume. The pressure and volumetric strain response are depicted in Fig. 1. Tensile failure occurs when tension stress is larger than the pressure cutoff. As shown in Fig. 1, unloading occurs along the unloading bulk modulus to the pressure cutoff. Then, reloading follows the unloading path to the point where the unloading began and continues on the loading path.

The deviatoric response is defined by a movable surface found among three independent failure surfaces that correspond to the initial yield strength, maximum concrete strength, and residual concrete strength.

Strain rate effects in the K&C model are implemented using a radial rate enhancement procedure on the failure surface by using a logarithmic dynamic increase factor (DIF) curve to increase con-

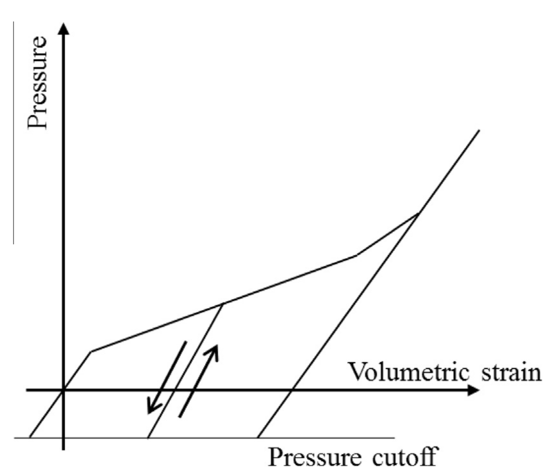

Fig. 1. Pressure and volumetric strain response.