First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Impact Load Response of Concrete Beams Strengthened with Composites

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ABSTRACT: Strengthening of concrete structures using composites under quasi-static loadings has been thoroughly studied in recent decade. However, there is perceived gap in the knowledge regarding response and performance of composite strengthened concrete structures subjected to dynamic impact loadings. This paper investigates the response of as-built and carbon fiber reinforced polymers (CFRP)-strengthened concrete beams subjected to a free fall drop hammer impact loading. The free fall impacting drop hammer height varied from 0.6 m to 4 m. Three-dimensional complex nonlinear finite element analysis (FEA) models of as-built and CFRP-strengthened concrete beams were developed. An experimental study on six as-built reinforced concrete beams reported in the literature was used to validate the accuracy of the proposed FEA models. The developed FEA results revealed that the U-shaped CFRP-strengthening was able to contain the dominant flexural cracks in the beam and changed the flexural failure mode to local concrete crushing at the impact location. FEA results also showed that the optimum amount of CFRP energy absorption capacity depends on the amount of tensile steel bars.

INTRODUCTION

Recent global terrorism activities and threats imposed eminent danger to the public infrastructure, and thus the demands for blast and impact resistance design of structures have increased ever before. Shock wave propagation is a common feature both in blast and impact loadings causing transient dynamic load. Many researchers have studied behaviors of as-built and fiber reinforced polymer (FRP)-strengthened reinforced concrete structures under the static loading where as little is known about as-built and FRP-retrofitted RC structures subjected to dynamic impact load. The followings are scattered investigations on as-built and retrofitted beams subjected to impact loadings.

Fujikake et al. (2009) investigated the behavior of reinforced concrete beams subjected to impact loading. Their study revealed that the amount of longitudinal compression reinforcement controlled the scale of the local damage that occurred nearby the impact location. They observed that local failures were reduced as the amount of longitudinal compression reinforcement increased. Saatci and Vecchio (2009) experimentally investigated the effect of shear mechanism on the impact response of reinforced concrete beam. The authors concluded that besides cross-sectional properties, the beams' mass and geometry such as span length are critical factors to accurately predict the impact resistance. Erki and Meier (1999) studied impact loading of reinforced concrete beams externally strengthened with CFRP laminates and steel plates. The authors reported that both retrofitting materials improved the impact resistance of the concrete beams. They also recommended anchoring the laminates at the member ends to prevent laminate debonding. Tang and Saadatmanesh (2005) investigated impact response of reinforced concrete beams strengthened with fiber reinforced polymer laminates. They observed that composite laminates improved the impact resistance, flexural strength, residual stiffness of the beams.

The present paper investigates the use of CFRP sheets to strengthen and prevent the collapse of reinforced concrete beams when subjected to drop hammer impact load. The proposed CFRP retrofit technique targets to contain both the developed shear and flexural cracks. The retrofitting also maintains structural integrity of the concrete beam by preventing concrete fallout. In the present study, simulation of overhead drop hammer impact test on as-built and CFRP-retrofitted concrete beams were performed using explicit nonlinear finite element software program LS-DYNA at the Ohio Supercomputer Center. A parametric study on the height of drop hammer was performed to quantify structural impact force demands, CFRP energy absorption capacity, and the concrete beam damage. Detailed finite element analysis procedures and results are presented in the following sections.

FINITE ELEMENT ANALYSIS MODELING OF AS-BUILT AND CFRP-STRENGTHNED CONCRETE BEAMS

Nonlinear finite element software program ANSYS was employed as a preprocessor to create the mesh and geometry of the reinforced concrete beams (ANSYS 2009). LS-PrePost software program was used to define all material models (LS-PREPOST 2007, LS-DYNA 2007).

Element types

A three-dimensional eight-node brick element, Solid164 was used in ANSYS to model the concrete, the impacting drop hammer, and the steel plates at the support locations. The element has three displacement, velocity, and acceleration degrees of freedom per node in x, y and z directions. In the analysis, the element was used as reduced one point integration with viscous hourglass control for faster element formulation. Solid164 element supports material and geometric nonlinearities in the explicit dynamic analysis.

Reinforcement bars were modeled using a three-dimensional spar element, Link160. The geometry of the element is defined with one-node at each element end and additional orientation node at element center. Link160 element has three degrees of freedom at each node for displacement, velocity and acceleration in x, y and z directions. Link160 element supports material and geometric nonlinearities and is compatible with Solid164 brick element.

CFRP sheets were modeled using a four-node membrane element, Shell163. The element has three degrees of freedom at each node for displacement, velocity and acceleration in x, y and z directions, compatible with Solid164 brick element. CFRP layers were modeled using equal spacing integration points with options to define fiber orientation for each layer. Beytschko-Tsay element formulation was used for membrane Shell163 element.

Material models

LS-DYNA material model 159 was used to characterize the concrete behavior. The model has a smooth intersection between the shear yield surface and hardening cap. The initial damage surface coincides with the yield surface. The rate effects are modeled with visco-plasticity. An element loses its strength and stiffness once the damage accumulation would be equal to unity. The model is mesh insensitive and maintains constant fracture energy regardless of the element size.

LS-DYNA material model 3 (MAT_PLASTIC_KINEMATIC) was employed to model the steel bars. It has the options to integrate rate effects and kinematic or isotropic hardening rules. Failure strain value of 0.16 was used to erode failed elements. Perfect bond assumption between the steel bars and concrete was forced by coinciding Link160 and Soid164 element nodes so that the two materials share the same nodes.

LS-DYNA material model 22 (MAT_COMPOSITE_DAMAGE) was used to model the CFRP sheets. The model is orthotropic material with brittle type failure options. Maximum tensile strength in the fiber direction was used as the failure criterion for the CFRP layered sheet. Perfect bond assumption between the CFRP sheets and the concrete was implemented by connecting adjacent nodes of Shell163 and Solid164 element to share the same nodes.

Mesh generation and boundary conditions

The concrete beams were meshed with element sizes ranging from 22.5 to 25 mm following a preliminary analysis to optimize the mesh density for accuracy and for flexibility to enforce the perfect bond assumption between concrete, steel bars and CFRP sheets. The concrete beams had simply supported boundary condition and steel plates were added at the support locations for even stress distributions.

Nonlinear finite element analysis computation

LS-DYNA single precision software program on Glenn (IBM 1350) Linux Cluster at Ohio Supercomputer Center was used to perform nonlinear explicit finite element analysis of as-built and CFRP-strengthened concrete beams subjected to drop hammer impact load. The simulation time run duration was 0.05 second using 16 processors. LS-DYNA outputs were written for every $1xE10^{-6}$ second and total CPU time to complete each run was 2.1 hours. The value of 0.1 percent damping ratio was used to minimize computational time and to stabilize drop hammer during rebound.

FINITE ELEMENT ANALYSIS RESULTS OF VALIDATED MODELS

Fujikake et al. (2009) conducted experimental study on the impact response of reinforced concrete beams. The beam specimens labeled as S1322, S1616 and S2222 each with 600 mm and 1200 mm hammer drop heights were selected to validate the proposed finite element study. The concrete compressive strength of S1322, S1616 and S2222 beams were 42 MPa with 10 mm maximum aggregate size. The steel bars were D13, D16, D22 and D10 and had yield strength of 397 MPa, 426 MPa, 418 MPa and 295 MPa, respectively. D10 steel bars were used as stirrups. Beams S2222 and S1616 had 2-D22 and 2-D16 compression and tensile steel bars, respectively, where as the beam S1322 had 2-D13 compression steel bars and 2-D22 tensile steel bars. The geometry, reinforcement details and CFRP layout are presented in Figure 1.

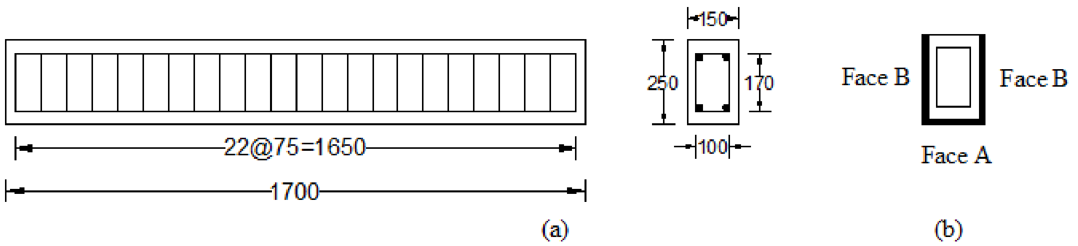

Figure 1. FEA validated models of beams (a) geometry and reinforcement details; (b) CFRP reinforcement layout (mm).

Dynamic impact loading was generated by freely dropping hammer mass of 400 kg on the top face of the beam at mid span location. Impacting speed of the hammer mass was calculated at a height 10 mm away from the top face the beam using the equation of motion. The calculated speed was assigned as an initial speed of the drop hammer in FEA. This approach was utilized to minimize the significant number and size of LS-DYNA output files written for such small time step of $1xE10^{-6}$ second when the hammer was dropped from a height ranging between 0.6 m to 4 m measured from the top of the beam. A time shift in abscissa of time history plots was applied to reflect the aforementioned approach. The striking head of the hammer had semi-spherical head with 90 mm radius as shown in Figure 2.

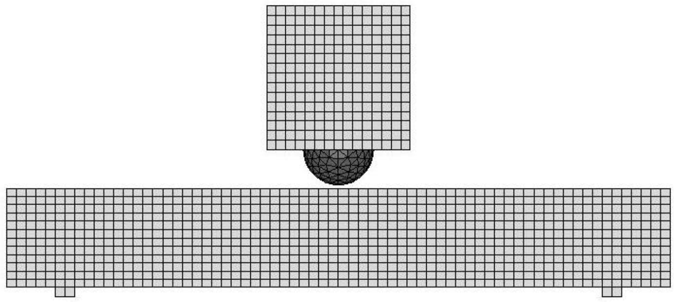

Figure 2. FEA mesh of reinforced concrete beam and impacting hammer.

Experimentally measured contact impact forces between the reinforced concrete beams and the drop hammer were used to validate the accuracy of the proposed finite element models. Figure 3 shows comparison of experiment and FEA results of dynamic impact force versus time history of S1322, S1616 and S222 beams for 600 mm and 1200 mm drop heights. The dynamic impact time history plots are characterized by high amplitude pulse followed by transient relatively low amplitude waveforms. In comparing the finite element analysis and experimental results, the peak dynamic impact forces varied by 5%, 6.5% and 8.71% when the drop hammer was 600 mm and by 2.64%, 3.68% and 3.12% when the drop hammer changed to 1200 mm for S1322, S1666 and S2222 beams, respectively. The FE results showed more pronounced drops after the peak, due to the hammer rebound. Finite element simulation and experimental results were in good agreement with respect to the behavior and the peak response.

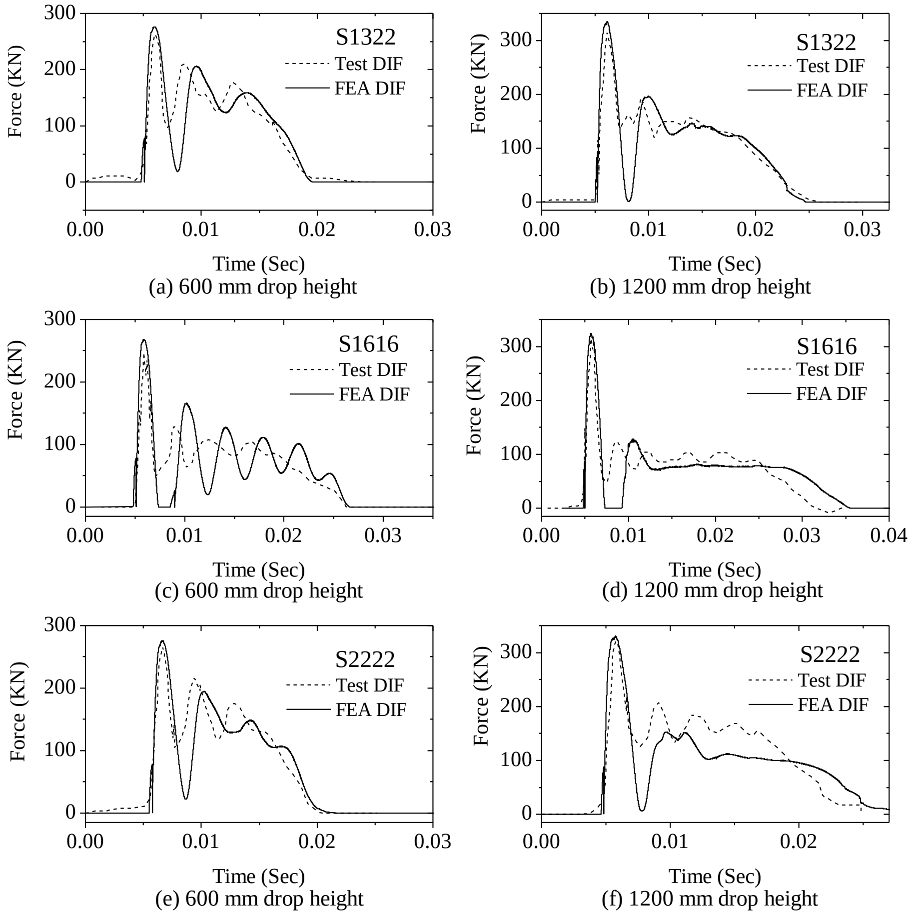

Figure 3. Dynamic impact force versus time history of the reinforced concrete beams

FINITE ELEMENT ANALYSIS RESULTS OF CFRP-STRENGTHENED REINFORCED CONCRETE BEAMS

A U-shaped CFRP retrofit technique was applied along the span length to improve the shear and flexural capacities of the beams. The U-shaped retrofit type was selected to meet practical application of CFRP around the exposed beam faces. Tyfo®SCH-41 which is a unidirectional FRP composite with 0° carbon fiber orientation with respect to the longitudinal axis of the beam was applied on face A for flexural strengthening (see Figure 1(b)). Tyfo®SCH-41 sheet is 1 mm thick and has a tensile strength of 986 MPa in the fiber direction, tensile modulus of 95.8 GPa, and rupture strain of 1%. Tyfo®BCC sheet with 0.86 mm thickness and ±45° carbon fiber orientation was applied on face B for shear strengthening (see Fig 1(b)). Tyfo®BCC has a modulus of elasticity of 47.9 GPa, tensile strength of 661 MPa in the fiber direction, and rupture strain of 1.4 %. The U-shaped CFRP retrofit consisted of four layers of Tyfo®SCH-41 and Tyfo®BCC CFRP wraps with 0°/0°/0°/0° and +45°/-45°/+45°/-45° fiber orientations, respectively. Tyfo®SCH-41 and Tyfo®BCC are manufactured by Fyfe Company LLC (For additional details refer to www.fyfeco.com). The U-shaped CFRP retrofit improved the performance of the beams subjected to overhead impact loading by absorbing a portion of the total energy that otherwise would cause an increase in the internal energy of the beam and subsequent increased in damage. Figure 4 illustrates drop height variation versus percentage of the total energy absorbed by the CFRP strengthening. As shown in the figure, the energy absorption capacity of the CFRP did not vary linearly with the drop height. The maximum amount of energy absorbed by the CFRP were 19.89% and 18.34% at drop height of 0.9 m for S1322 and S1616 specimens, respectively and 29.10% at drop height of 1.5 m for S2222 beam. As dropping height increased beyond these elevations for each beam series, the effectiveness of CFRP energy absorption capacity decreased. Tensile steel reinforcement ratios were 2.46% for S1322 and S2222 and 1.26% for S1616 beams. In the CFRP-strengthened beams, the CFRP sheets absorbed 10% more energy in S1616 beam as compared to S1322 and S2222 beams. This indicates that the optimum level of CFRP energy absorption capacity depends on the amount of tensile steel bars and the capacity of CFRP energy absorption saturates at certain optimum level. Beyond this optimum level, the effective shear and flexural strength gains from the external CFRP retrofitting scheme diminish regardless of the magnitude of peak dynamic impact load.

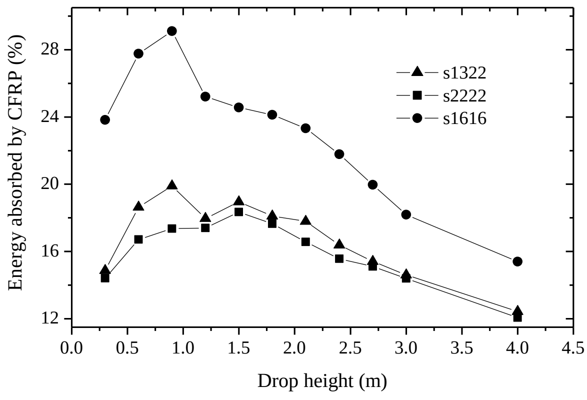

Figure 4. Drop height versus percentage of energy absorbed by the CFRP.

Failure modes

The U-shaped CFRP reinforcement strengthening changed the behavior and the failure mode of the beams. Fujikake et al. (2009) reported that overall failure mode of as-built reinforced concrete beams S1322, S1666 and S2222 were flexure. This was also observed in FEA results as shown by the crack patterns of the same beams as shown in Figure 5. Flexural cracks at the center of the beam governed the failure mode of as-built S1322, S1666 and S2222 RC beams. Eroded elements represent elements that are eminently cracked and no longer have the capacity to carry any load. Minor inclined shear cracks were also observed.

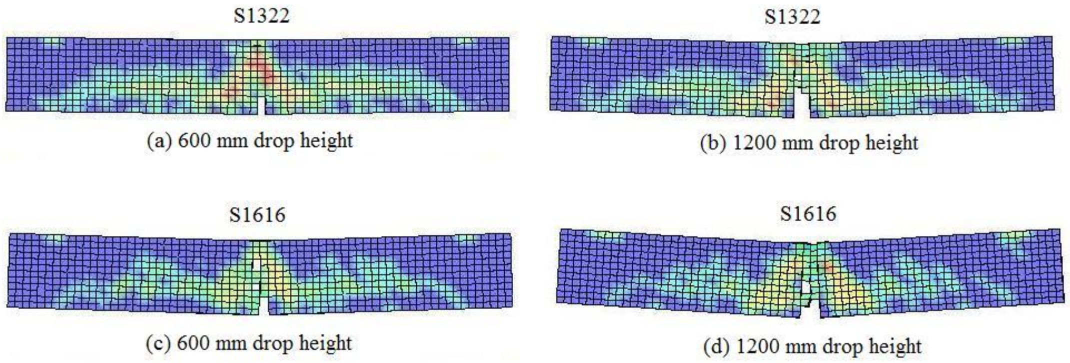

Figure 5. Crack patterns of as-built S1322 and S1616 RC beams.

For the failure mode of U-shaped CFRP-strengthened RC beams, the crushing of the concrete at the location of impact was observed. The damage was more pronounced for higher drop heights (Figure 6). The flexural cracks which were observed and governed the failure modes of as-built concrete beams were effectively contained with CFRP retrofitting. No CFRP rupture was observed.

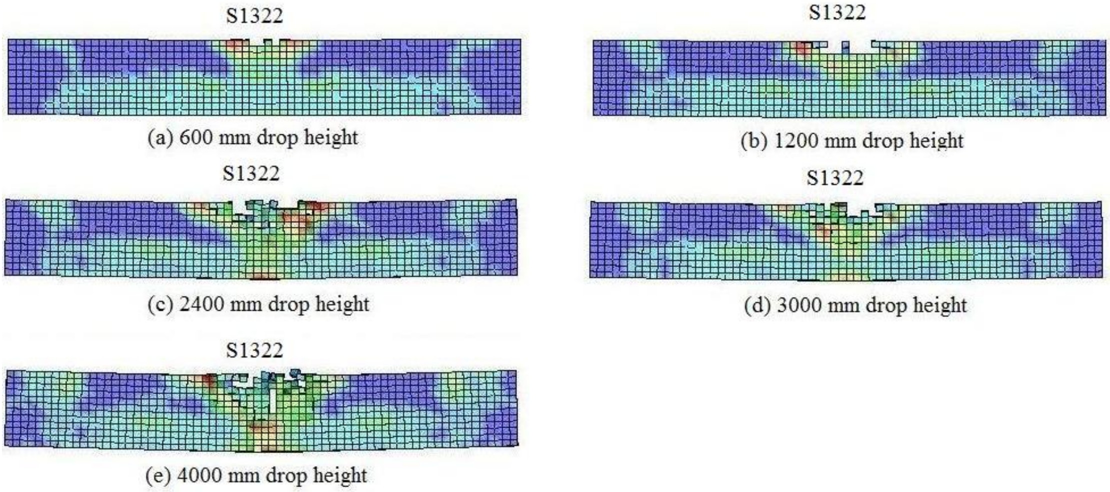

Figure 6. Crack patterns of CFRP-strengthened S1322 RC beam.

CONCLUSIONS

The present study has shown that U-shaped CFRP-strengthening is effective in improving the response of concrete beams under the impact loading. The U-shaped CFRP strengthening not only contained flexural cracks but also changed the overall failure mode of RC concrete beams from flexure to local crushing of the concrete at the impact location. From the finite element results it was observed that the CFRP energy absorption capacity did not vary linearly with the drop hammer height and the optimum amount of CFRP energy absorption capacity was governed by the amount of tensile steel bars.

ACKNOWLEDGMENTS

This work was supported in part by an allocation of computing time from the Ohio Supercomputer Center.

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