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Modeling of flexural- and shear-critical reinforced concrete specimens under drop weight impact

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ABSTRACT

Drop weight testing of two reinforced concrete specimens was conducted and the laboratory results were used to validate the development of a finite element model. The laboratory specimens were constructed with and without shear stirrups to observe the failure of flexural- and shear-critical members, respectively. Both specimens were tested under a single impact and under the same input energy. Testing data was collected pertaining to the force at the impacting hammer, support reactions, and mid-span displacement. Similar results were achieved for both studies with the experimental data able to confirm the accuracy of the numerical modeling.

1. INTRODUCTION

Concrete beams have commonly been tested under low velocity impact using a drop weight apparatus. These tests are performed by dropping a mass of specific weight on the beam at velocities which are commonly been in the range of 1 to 6 m/s. Impact energy is therefore determined by the mass of the weight and the height at which it is dropped. Traditional reinforced concrete (RC) specimens have concentrated on flexural beam members, with shear to flexural capacity ratios (V_u/P_u) between 0.30 to 10. Where, V_u and P_u refer to the nominal shear and flexural capacities of a simply-supported beam under static point load as determined by Eqs. (22.5.5.1) and (22.5.10.5.3) and Sections 22.2 and 22.3 of the ACI 318-14, respectively.

Previous research on flexural members has been studied extensively. The investigations as done by Tachibana *et al.* (2010) and Kishi and Mikami (2012) were to determine practical design codes for flexural RC beams under impact. In these studies, testing was done on twenty-one and thirty-six flexural specimens, respectively. It was determined that the calculated static flexural capacity plays an essential part in the performance under impact, as similar failure patterns were observed from all

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researchers. Specimens were dominated by vertical flexural type cracking and increased amounts of local damage in the form of concrete crushing and fragmentation due to increase in impact energy. Additionally, it was observed that members with (V_u/P_u) values near 1.50 would fail in mixed modes of flexure and shear with increased shear failure mechanisms with higher impact velocities.

However, there exist relative few studies focusing on the testing of shear-deficient RC beams with values of with (V_u/P_u) below or near 1.0. Studies include those as performed by Kishi *et al.* (2002a, 2002b), Bhatti *et al.* (2009), and Saatci and Vecchio (2009). It has been observed that shear-deficient members fail in mixed modes of vertical and shear cracking failure, dependent on the value of (V_u/P_u), with beams with ratios of roughly 0.6 failing in obvious modes of shear and beams nearing unity having the possibility of failing in mixed modes of flexural and shear failure under low-velocity impact. Kishi *et al.* (2002a) noted shear failure to be defined by large diagonal cracking and deformation of the main rebar, stating that "with the development of severe diagonal shear cracks, that only the main rebar [was] resisting impact force."

2. LABORATORY TESTING

Two beams were constructed for testing of flexural- and shear-critical conditions. Fabrication drawings of both beams are provided in Fig. 1. Both specimens were 220 x 400 mm in cross section and had lengths of 3120 mm. The clear span length for testing was equal to 2300 mm. The longitudinal reinforcement for the members included two 20 mm diameter rebars at both the top and bottom, which were provided at a clear cover of 40 mm. For shear reinforcement, 10 mm diameter stirrups were used. In order to prevent severe shear failure of the specimen near the left and right supports, a stirrup spacing of 50 mm on center spacing was used starting at a clear distance of 40 mm from the left and right edge of the beam and extending to an inside distance of 590 mm.

Concrete strength as determined from cylinder tests during the day of impact was equal to 21 MPa. Both beam specimens were let to cure approximately 365 days prior to impact. Yield strength of the conventional steel reinforcement was equal to 464 and 656 MPa for the stirrups and longitudinal rebar, respectively. Shear and flexural capacities were calculated per the ACI 318-14 following equations 22.5.5.1 and 22.5.10.5.3 of Sections 22.2 and 22.3.

Table 1 Specimen Properties

ID	**Transverse Reinforcement Ratio (%)**	P_u **(kN)**	V_u **(kN)**	**Capacity Ratio** (V_u/P_u)
SM_RC	NA	159	120	0.76
FM_RC	0.71%	159	841	5.30

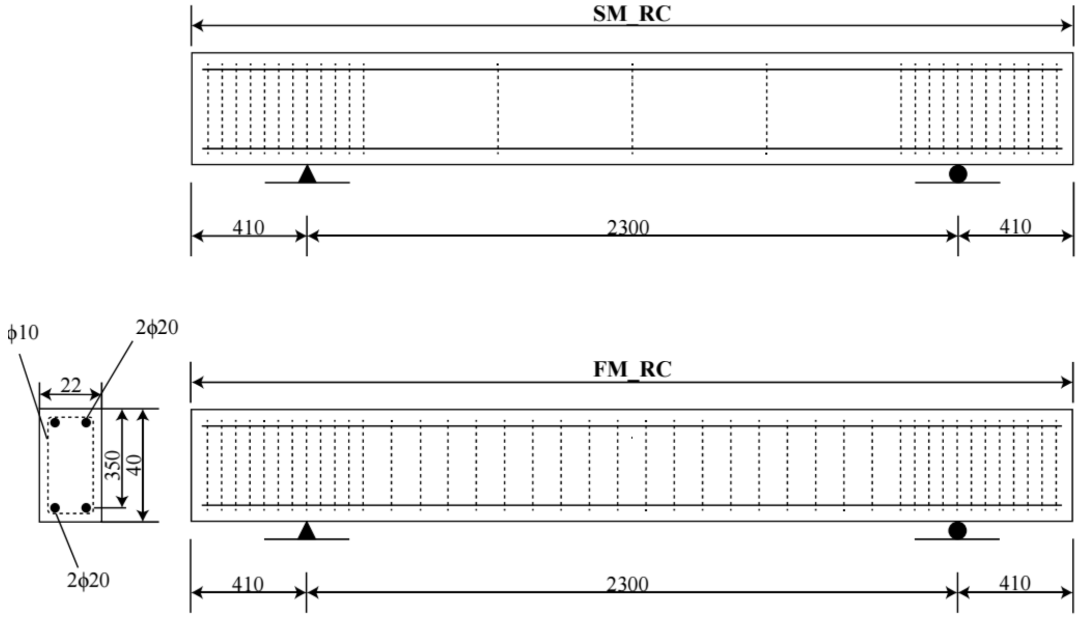


Fig. 1 Construction of SM_RC and FM_RC specimens (Unit: mm)

A three-point bending configuration was used for the impact testing of all specimens. In order to prevent uplift of the beam away from the support system at the time impact, two threaded bars were run into the support with a cross bar at the top of the beam to secure the beam into place. Additionally, both supports were instrumented with load cells for measuring the reaction forces at impact.

The drop hammer weight consisted of a series of removable plates attached to a flat 220 mm diameter circular impacting surface. Total mass of the hammer was equal to 420 kg and could be raised to the required height along two twin guide rails using a hydraulic lift system. Located between the impacting area and removable plates, the hammer was instrumented with a load cell. Collection of data was triggered by a laser which was also used to determine the velocity at the time of impact. The laser was located directly above the beam surface so that as the drop weight was in transit would trigger the laser immediately before impact. The drop height for this test was equal to 3.5 meters for both specimens

3. MODELING

Modeling was done using the LS-Dyna software. The following material models were used for the steel and concrete, “003 Plastic Kinematic” and “159 CSCM”, respectively. Steel stirrups and rebar were embedded in the concrete material using the “Lagrange in Solid” keyword. In order to avoid deformation in the testing set-up, a rigid material was used for defining both the support system and hammer drop weight. Mesh size for solid elements was equal to 20 mm. Additionally, beam elements used for steel reinforcement were equal to 20 mm. View of the model is shown below. Results of both experimental and modeling are provided in the following section.

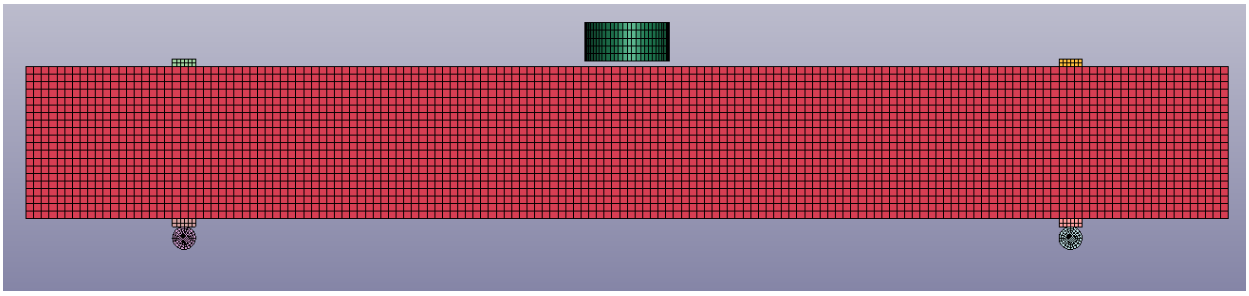


Fig. 2 Modeling of drop weight testing in LS-Dyna

4. RESULTS

Results for both laboratory testing and modeling are provided in the figures below. Fig. 3 shows testing the shear, SM_RC, and flexural, FM_RC, specimen after impact. Clear signs of shear failure are observed for the shear specimen with diagonal cracking occurring at the tensile fiber and oriented towards the impacting location. Additional shear failure also occurs at the support, most notably at the left reaction point. When compared to the flexural specimen, beam FM_RC had mixed modes of failure as illustrated in both vertical and diagonal cracking. Additionally, more intense localized failure was present for SM_RC as illustrated in additional spalling at the point of impact.

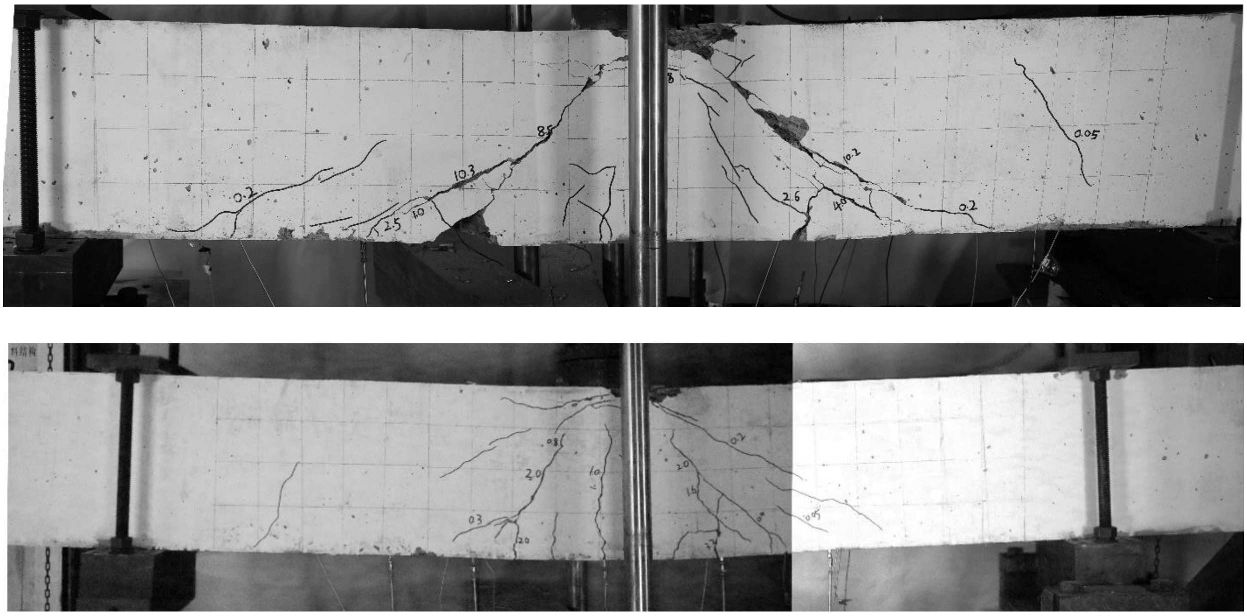


Fig. 3 Member SM_RC (top) and FM_RC (bottom) after drop weight testing

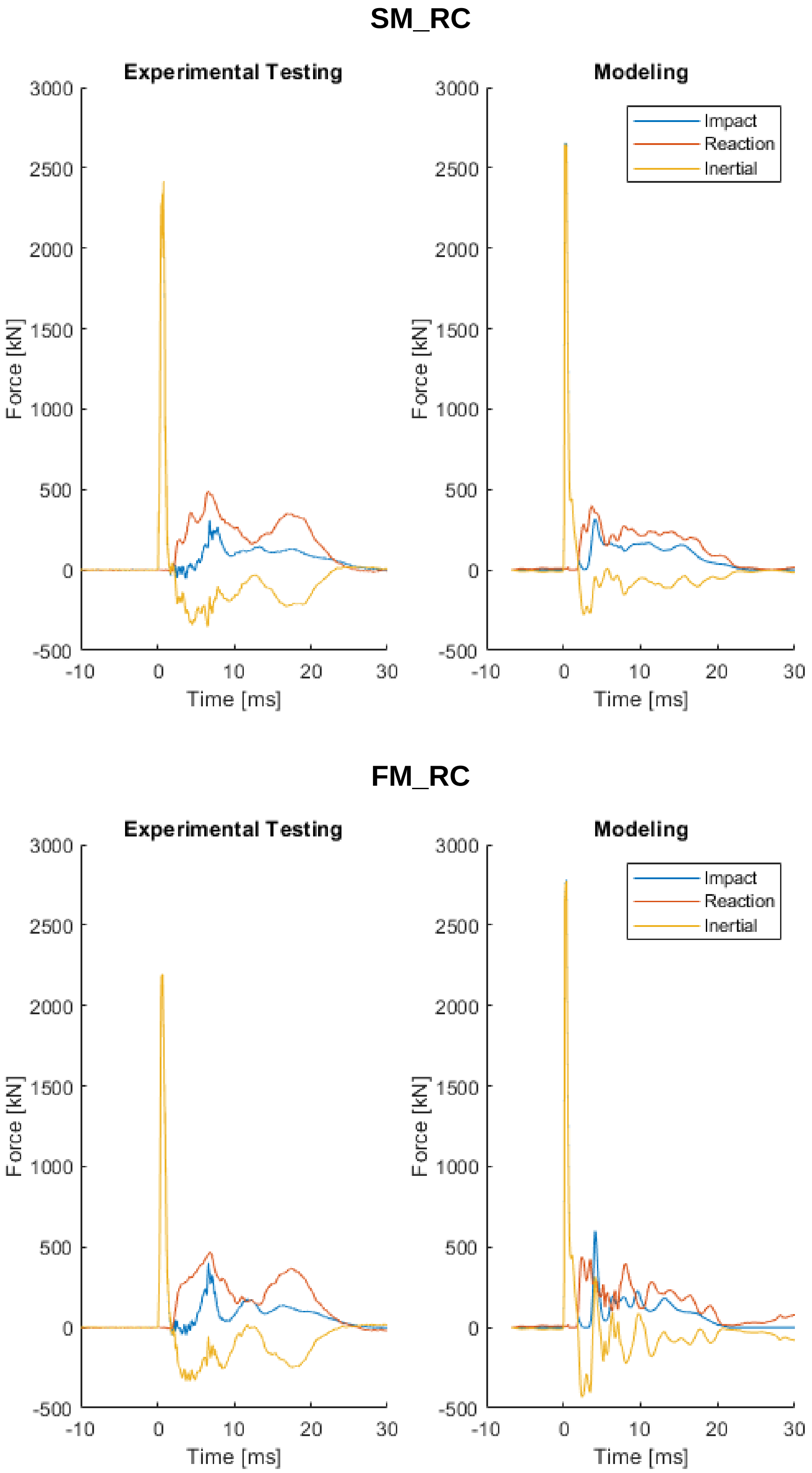
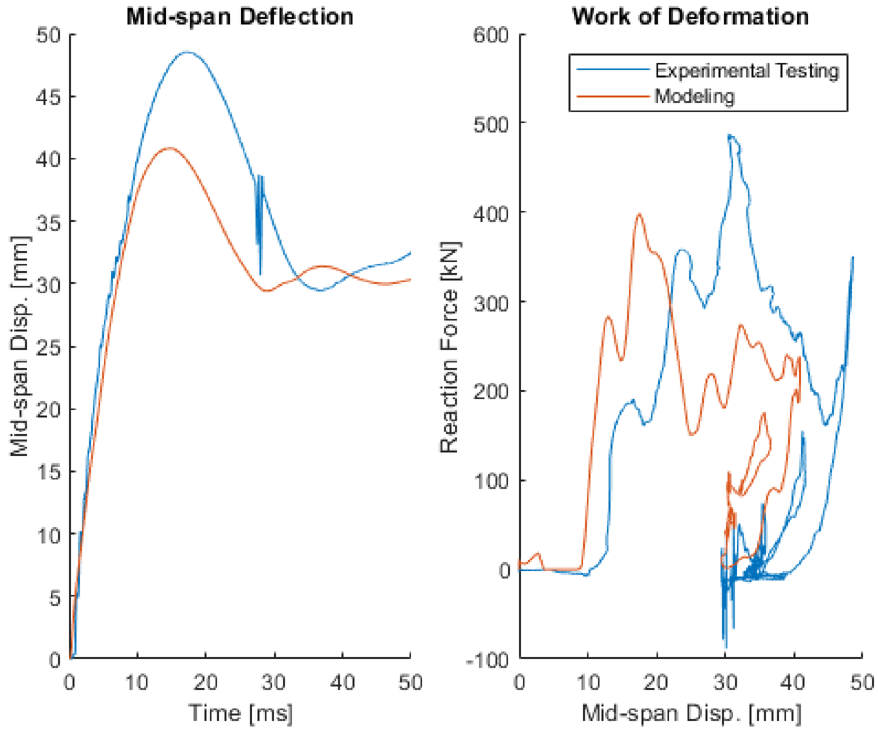


Fig. 4 Time history of dynamic forces for SM_RC (top) and FM_RC (bottom)

SM_RC



FM_RC

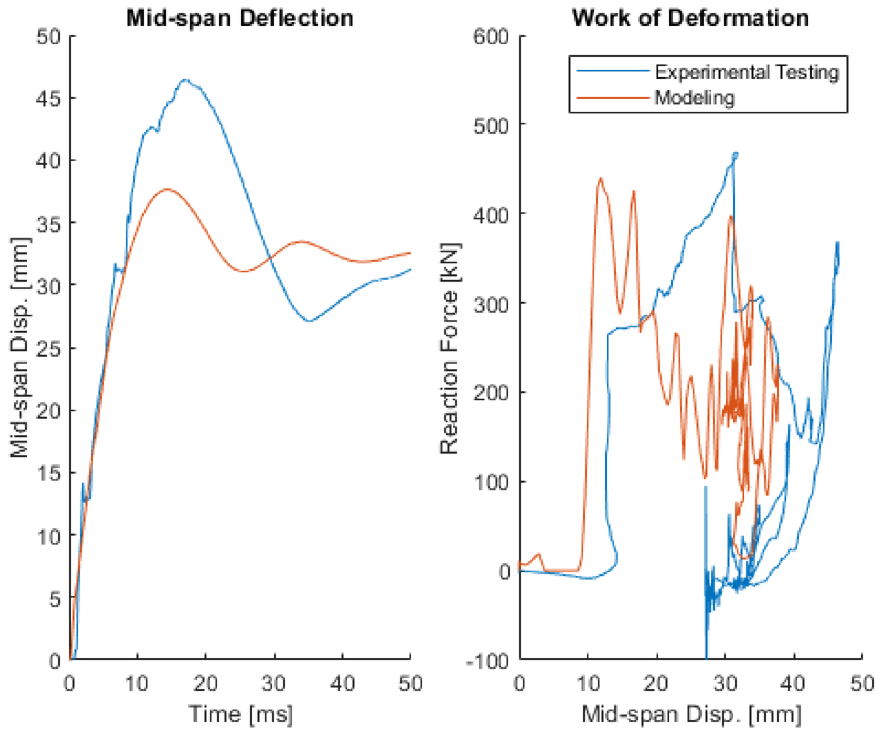


Fig. 5 Time history of Mid-span deflection and work of deformation for SM_RC (top) and FM_RC (bottom)

Fig. 4 provides the obtained time histories for dynamic forces for both the experimental and LS-Dyna model. Where the impact and reaction forces refer to the; forces measured at the point of impact and summation of the reaction forces at both supports, respectively. As the impact force is known to be a summation of the reaction and inertial forces, the inertial force as provided in the figure refers to the impact force minus the reaction force. The measured maximum impact force for both specimens was much higher than the reaction forces transferred to the beam, with peak values of 2411 and 2195 kN for specimen's SM_RC and FM_RC, respectively. Distributions of impact and reaction forces were similar for both cases with the impact showing a large initial peak before suddenly decreasing to zero before the occurrence of a second lower peak. The second rise of the impact force coincides with the initiation of the reaction forces which has some time delay due to the propagation of the impacting load through the specimen. Fig. 5 provides the time history of the mid-span deflection and work of deflection as obtained from the reactionary loads. Similar behavior was achieved for the LS-Dyna model.

Table 2 Maximum Recorded Values

	Experimental Testing			**Modeling**		
ID	**Maximum Impact Force (kN)**	**Maximum Reaction Force (kN)**	**Maximum Deflection (mm)**	**Maximum Impact Force (kN)**	**Maximum Reaction Force (kN)**	**Maximum Deflection (mm)**
SM_RC	2411	488	49	2646	392	41
FM_RC	2195	469	46	2750	440	38

5. CONCLUSION

Impact testing of shear- and flexural- critical beams resulted in distinct failure mechanism attributed to the presence of transverse reinforcement. This was observed in clear shear diagonal cracking and mixed modes of failure for the SM_RC and FM_RC, respectively. However, similar distributions of impact, reaction, and mid-span deflections were obtained for both specimens as illustrated within the peak obtained values. For both beams, impacting forces contained high inertial forces. In reference to the applicability of the use of LS-Dyna software, similar trends can be achieved when compared to the laboratory testing.

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