AFRP RETROFIT OF REINFORCED CONCRETE COLUMNS AGAINST IMPACT LOADING

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ABSTRACT

Structures can be exposed to impact loads as a result of an explosion, falling objects, projectiles and vehicle collisions. Within the increasing threat of these impact sources, it is very important to protect the columns that are the vital members of the structural systems to ensure structural and personal safety. This study focuses on the performance of axially loaded reinforced concrete members subjected to impact loading. A dropped-weight test set-up developed to perform impact tests on reinforced concrete members. The test set-up was used to perform low elevation impact tests on reinforced concrete (RC) columns that targets to simulate vehicular impact against ground floor columns of low-rise buildings. Since, there is limited information about the transverse impact performances of RC columns; the main objective of this research is to assess the vulnerability of RC columns under transverse impact loads and to enhance their performances by using Aramid Fiber Reinforced Polymer (AFRP) sheets. The scope is limited to 300 mm square columns with 3 m height in low to medium rise buildings which were found to be more vulnerable to lateral impacts according to previous research conducted by the authors, (Gurbuz *et al*. 2010, 2011). This research provides fundamental knowledge on the behavior of RC columns under low elevation impact loading and also generates new information on impact strengthening of vulnerable concrete columns by AFRP sheets.

KEYWORDS

Aramid, drop weight, FRP, impact, reinforced concrete columns, strengthening, structural dynamics.

INTRODUCTION

Structures should provide adequate safety for the loads that they could be exposed to during their lifetime. In addition, when the structure is subjected to abrupt dynamic loads such as explosive or impulsive loads, the damage to the structure should be limited to provide life safety of occupants.

This research focuses on vehicle crash against RC columns which results in a low elevation lateral impact loading. A large number of RC beam tests have been performed to investigate RC member response against mid span impact tests, (Chen and May 2009; Fujikake *et al*. 2009; Kishi *et*. *al*. 2001, 2002; Saatci and Vecchio 2009; Tang and Saadatmanesh 2005; Abbas *et al*. 2010; Remennikov and Kaewunruen 2006). However, the former impact tests conducted by falling weight impacting at the mid height of the specimen, lack of presenting the real dynamic response of RC columns subjected vehicular impacts; since low elevation impact tests of axially loaded RC columns have not been explored extensively by the earlier researchers. Based on the limited research findings, the behavior of RC members with mid span impacts significantly differs from that of axially loaded members with low elevation impacts, (Thilakarathna *et al*. 2010). This has provided a motivation for the current experimental research, low elevation impact tests conducted on axially loaded RC columns in the Structural and Earthquake Engineering Laboratory in Istanbul Technical University (ITU). Drop weight tests were performed to gain a better understanding of impact behavior of axially loaded RC columns and a retrofit method, which utilizes AFRP sheets, against impact loading is studied.

Although, the composite materials became popular in retrofitting applications in the field of structural engineering, most of the research primarily focused on strengthening/retrofitting applications either for static or seismic loading. The current knowledge on FRP strengthening against impact is very limited, (Tang and Saadatmanesh 2003; Gurbuz *et al*. 2011). Therefore, the effectiveness of external AFRP confinement on impact performance enhancement of structural members with axial load was investigated in this research. The experimental findings will also contribute to collaboration of numerical modelling approaches such as the model by Gurbuz et al., 2010.

TEST PREPARATION

Test Specimens

There are many factors affecting the behavior of RC members under impact loading such as the dimensions and span of members, cross-section properties (steel ratio, stirrups, concrete cover), material properties (concrete, steel, FRP) and stiffness of the impact surface, (Bhatti *et al*. 2009, 2011; Fujikake *et al*. 2009; Ho 2004; Kishi and Mikami 2002; Kishi *et al*. 2002, 2006; Saatci and Vecchio 2009; Remennikov and Kaewunruen 2006). The only testing parameter in this experimental study was the strengthening effect. Two identical testing specimens were tested, one of which was strengthened and the other not. The two test specimens were designed to represent typical ground level columns of low-rise buildings. The cross-sectional dimensions of specimens were 300x300 mm and their lengths are 3200 mm. Figure 1 shows a typical test specimen, its dimensions and reinforcement layout. Four 18 mm diameter bars (4Φ18, A_s=10.18 cm^2) were used as longitudinal reinforcement spanning the specimen. They were placed symmetrically, resulting in a reinforcing ratio 0.01, ($\rho=A_s/bd$, ρ=0.01, b: width, d: depth of the specimen). Square transverse links were 8 mm in diameter (Φ8) and spaced at 150 mm along the member length (Φ8/150). The clear concrete cover was 25 mm on all sides. The members were designed so that their span at the test set-up is 3000 mm.

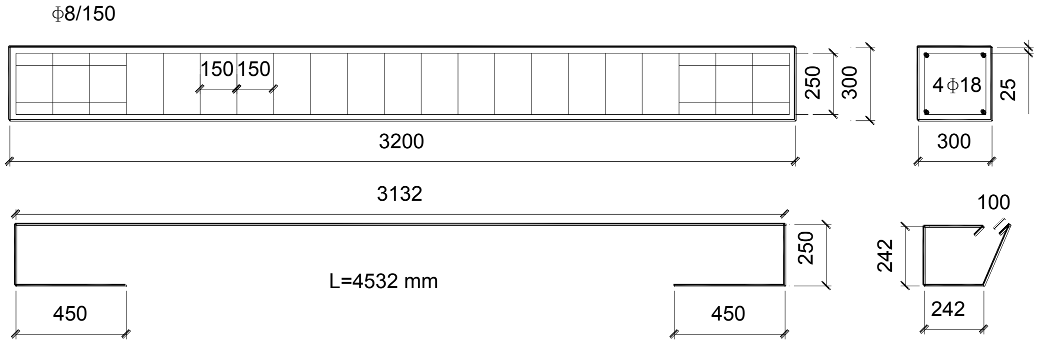

Figure 1 Geometry and reinforcement details of the specimens (all dimensions are in mm)

Strengthening

AFRP sheets were used as a retrofitting material in this research. One column specimen was wrapped externally with AFRP sheets in the transverse direction using two layers. Aramid based FRP sheets are particularly preferred in impact and blast retrofits due to their higher tensile strength and stiffness beside other fiber types, (Crawford *et al*. 1997).

At first, corners of the square column were grinded with 30 mm diameter. Then the surface preparation took place for proper bonding between the aramid fiber sheets and concrete surface. Concrete surfaces were mechanically scarified with a grinding wheel and dust was removed. Properly cleaned and dried surfaces were achieved to obtain full contact. Primer was applied with a roller on the concrete surfaces to penetrate the pores and improve the adhesion. The retrofitting system included two components as fibers and polymer. Two-component epoxy resin (epoxy and hardener), which was mixed by a ratio of 3:1 (epoxy/hardener) was used as a matrix material. It bonded the aramid fibers to concrete surfaces. Epoxy resin was applied over the whole surface of the RC column and the aramid fiber sheets were totally saturated to achieve perfect bond with the concrete surface. Constant pressure was exerted by moving the roller in both ways in the direction of the aramid fibers until they were fully saturated. Finally, the air was also removed by this application. Then these steps were then repeated for the second layer of AFRP sheets. Second coat of epoxy-resin was applied a using a roller, working in the direction of the fiber.

Materials

All the specimens were cast from the same concrete batch. Three cylinders were tested at the 28th day and the average compressive strength of concrete was determined as 28.1 MPa. The average compressive strength was increased to 30.7 MPa at the time of impact testing. Moreover, splitting tension test (Brazilian test) with three cylinder samples (150x100 mm) was also conducted at the end of the impact tests in order to determine the tensile strength of the concrete. The average tensile strength was 2.8 MPa.

Two types of steel bars with 18 mm (longitudinal reinforcement) and 8 mm (transverse links) diameters were used in the test specimens. Special care was taken to get all the reinforcement of the column specimens from the same batch. Three bar samples were tested for each diameter. The average yield stresses of Φ18 and Φ8 bars were 465 MPa and 513 MPa, respectively.

MBrace® Composite strengthening system was used for retrofitting of the RC column specimen. The method mainly consisted of primer, two component epoxy resin and unidirectional AFRP sheets. Manufacturer's specification for aramid fibers Mbrace Fiber AF 120/3200 are listed in Table 1.

Table 1 Properties of Aramid fiber

Fiber Areal Weight	Fabric Thickness	Fiber Strength	Fiber Stiffness	Elongation
280 g/m^2	0.194 mm	3200 MPa (Kevlar 49)	120 GPa (Kevlar 49)	0.024

Test Set-up

Loading situation seen in vehicle crash was simulated by the impact testing set-up. The column was tested with axial compression and width of the impact loading zone was 30 cm, which represented the contact zone height of a vehicle. Additionally impact was applied 1 m away from the column east end support, considering the average vehicle height from the ground. The impact tests performed by drop weight test set-up. The freely falling weight dropped from a predefined height and impact was applied to the selected location of the member. The members were placed horizontally and the impactor was dropped freely from different heights.

An existing test set-up in ITU Structural and Earthquake Engineering Laboratory was modified to be used for drop weight impact tests, as shown in Figure 2. In the existing test set-up, the steel construction was designed to provide desired support conditions at both ends of the column. The west support point, where the axial load was applied by hydraulic jack and cylinders (60 t capacity), was designed to allow axial translations and rotations. A load cell (100 t capacity) was used to measure the axial load and the axial load was tried to keep constant during the tests. The load cell and the cylinder were clamped to prevent bouncing after the impact. Under the effect of drop weight the specimen could shift laterally or lift up. Therefore column ends were clamped by high strength steel rollers (70 mm in diameter) prevent uplifting and lateral movements. These rollers were placed at the top and the bottom surfaces of both column ends. Thus the supports allowed for some rotation and lateral contraction caused by the axial load application. The steel profiles supporting the whole specimen from the two end points were fixed to prestressed strong floor (120 cm thickness) by 32 mm high strength steel rods. The steel supports were designed to be stiff enough to support the loading without significant deformation.

Figure 2 Test set-up

The drop weight test apparatus (steel frame towers and the impactor) was added afterwards to the existing test set-up. The specimens were placed horizontally in the set-up and the impactor was dropped to the 2/3th length of the column (2 m away from the west support of the specimen). Impact load was induced by a freely dropping impactor from a specific height. Impactor can be dropped from a maximum height of 6.0 meters due to the constraints of the test set-up. The impactor was raised and carried by the crane. It could be moved up and down to a designated height by the crane. When the impactor reached the predefined height, it was released resulting free fall of the weight.

Instrumentation

In impact experiments the major difficulty is to measure and record correct test data in a short duration, which is about 0.010 to 0.100 seconds (10-100 milliseconds). Therefore special care must be given to choose proper sensors to make accurate measurements and high-speed data acquisition (DAQ) system to collect and save the data during the tests. A high speed dynamic acquisition (DAQ) system was used in the present tests to collect data at a 5 kHz sampling rate that means signals from each sensors were read and recorded at a rate of 5000 times per second. Thirteen channels of instrumentation (7 potentiometers, 5 accelerometers, 1 load cell) were provided to examine the impact response of the column by the collected sensor data. DEWE43 and SIRIUS dynamic data loggers manufactured by DEWESoft Company were used for data acquisition during the impact test series.

The specimens and the test set-up were instrumented to measure accelerations, displacements and axial forces. The output from the impact tests of the reinforced concrete columns consisting of deflection time histories at seven locations, as shown in Figure 3 were collected. Resistive linear position transducers (potentiometer) were placed underneath the column along its length to collect the displacements during the test. LPM 100 model potentiometers produced by Opkon were used during the tests. They are capable of measuring displacements up to 100 mm precisely and were connected to allow some rotation to avoid any potential damage to the sensors. Seven potentiometers were attached to measure the distribution of deflection along the length. They were placed in between the two supports with 50 cm spacing from each other.

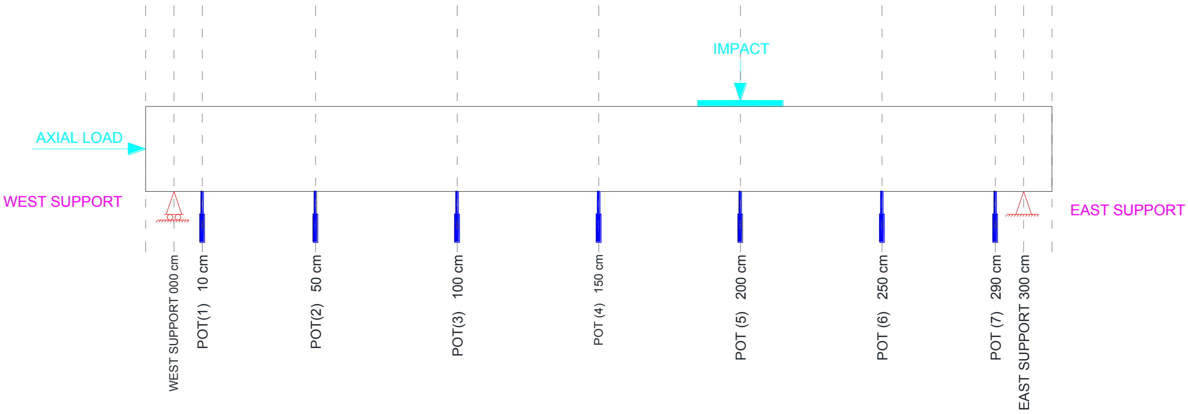

Figure 3 Potentiometer locations from west support

A compression load cell was placed at the east support to measure the axial load. The CLP-100CMP Model load cell, manufactured by Tokyo Sokki Kenkyujo Co. Ltd., with a 1000 kN maximum load capacity was used in the tests.

IMPACT TESTS

Two full-scale RC columns comprising an unretrofitted (control specimen) and a retrofitted column specimen were tested. All the tests were conducted on axially loaded RC members and the impact load was applied by drop weight. The axial load was identical for the specimens, which represented the axial loads on typical frontal ground level columns of low-rise buildings (4-5 story buildings). The axial load level was kept constant at 375 kN which corresponds to approximately 12% of axial load capacity of the cross-section (N_u) or in other words the axial load ratio (n) is 0.12 (Equation 1) where N is the applied axial load, f'_c is the concrete compression strength, b and h are the width and depth of the specimen.

$$n = \frac{N}{bhf'_c} \qquad (1)$$

For obtain the responses from different levels of impacts, drop heights were increased gradually. The tested members have identification name. *Imp* denotes impact tests, *R* denotes reference specimens (unretrofitted) and *A* denotes the AFRP retrofitted specimens. The reinforcement details of specimens were planned carefully to avoid shear failure.

Reference Specimen (ImpR1)

The first impacted column, ImpR1 was a control specimen. ImpR1 was subjected to impact load of 585 kg dropped from 3.0 m (17000J). Deflection data at the locations of 10 cm, 100 cm, 200 cm, 250 cm and 290 cm from the west support were accurately collected from the performed test. Deformation versus time curves, recorded by each potentiometer along the specimen length are presented in Figure 4.

Deflection time histories are typical in shape and in period. They act as a half-sine waves with period of 60 ms. The loading point deflection readings (potentiometer at 200 cm, @200cm) indicated that the column deflected a maximum of 47.6 mm. The peak deflection of 47.6 mm occurs at about 20 ms after the impact, and then deflection rapidly drops at the failure and oscillates around 19 mm, which is the permanent deflection. In the time history curve of the potentiometer at 10 cm location (from the west support), negative deflections were recorded 6 ms after the induced impact, which shows the uplifting movement of the specimen. Due to the post vibration of the specimen, deflection at this point ends up with almost zero value deflection, which verifies successfully restrained movement of the end points.

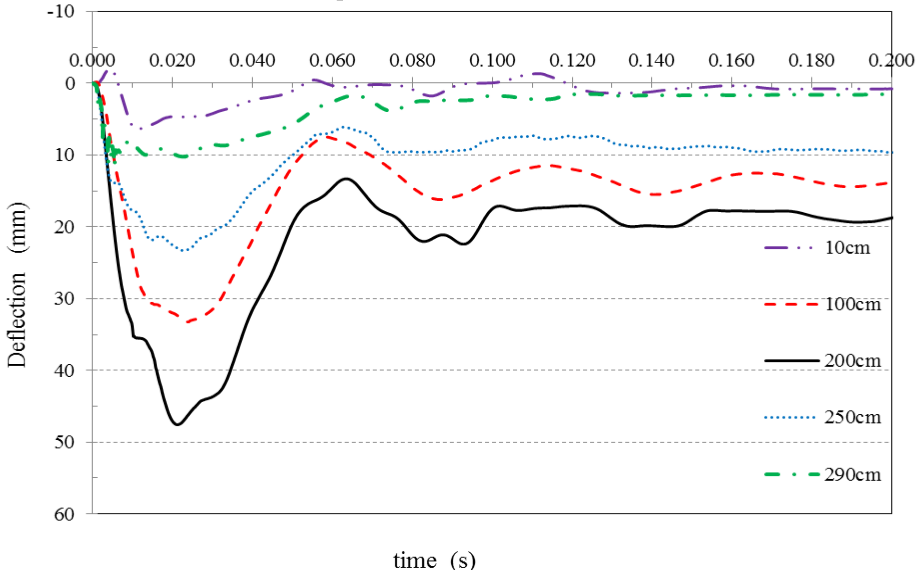

Figure 4 Deflection time history of ImpR1

Damage after the induced impact is presented in Figures 5-6. Concrete crushed and the concrete cover spalled at the top face just near the impactor and extended in the direction of the west support. This damage at the top concrete was due to the compression stresses caused by the impactor and the flexure effect. The concrete cover was extensively damaged that the top longitudinal reinforcement exposed, Figure 5.

Figure 5 Concrete cover disintegration and concrete crushing at the top next to the contact surface

Inclined shear cracks at both sides of the loading zone and minor flexural cracks just under impactor at the tensile zone indicated the formation of the shear-flexure type failure of the specimen (Figures 5-6) and no cracks were observed close to the support points. The shear-flexure failure was demonstrated by the widening of diagonal shear and vertical flexural cracks. The shear cracks started from the outer side of loading surface and extended towards the bottom face of the specimen. However the shear crack that extended towards the west support was more inclined (Figure 6a) while the crack that extended to the east support was steeper (Figure 6b). Damage was dominated by shear with little flexure involved. Visible excessive permanent damage and residual deflection associated with shear was observed after the impact.

a. steeper cracks close to east support b. inclined cracks close to the west support

Figure 6 Inclined shear cracks

Cracks were marked and the crack widths were measured after the impact test. The widths of the residual cracks are presented in the crack map of ImpR1, Figure 7. The maximum crack width was 3 mm and cracks were mostly close to the loading zone of the specimen. The inclined crack widths varied from 1.8 mm to 3.0 mm and travelled the full depth of the specimen diagonally.

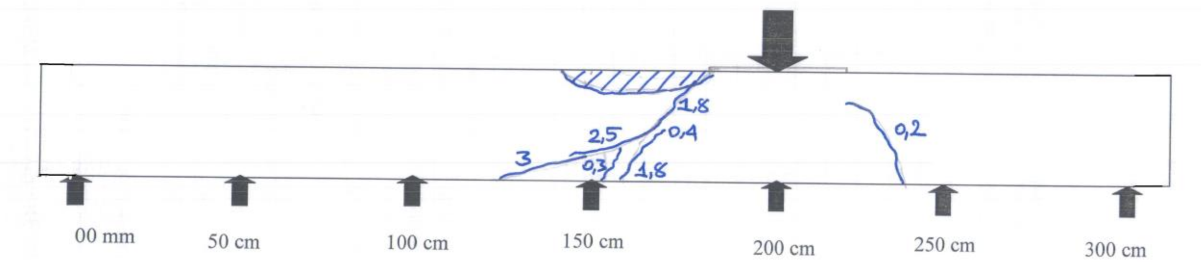

Figure 7 Crack map of ImpR1 (crack widths are in mm)

Aramid Retrofitted Specimen I (ImpA1)

ImpA1 was the retrofitted specimen that was externally confined with by 2 plies of unidirectional AFRP sheets in the transverse direction. By this application method, the shear capacity of the reference columns was aimed to be improved considering the dominant shear-flexure failure under impact.

The retrofitted specimen was impacted twice using different drop heights. In the first impact, the drop weight was constant as 585 kg and height was 3.5 m (20000J). This impact, which was higher than the impact applied to reference specimen, did not cause damage as severe as the damage of the reference specimen. Therefore, the drop height was increased to 4.5 m in the second impact. By this way the impact energy was increased to 26000 J with the increased drop height.

1st Impact: 585 kg, 3.5 m (20000J)

Deflection time history of the ImpA1 specimen obtained by the potentiometers located at 10 cm, 100 cm, 200 cm (loading point), 250 cm and 290 cm from the west end of the specimen are given in Figure 8. The maximum deflection is 50.3 mm, which occurred at 20 ms after the induced impact. The total period of the deflection wave is about 60 ms and the permanent deflection value is 13 mm. It is interesting to note that while the maximum deflection is higher with respect to reference specimen due to increased impact energy, the residual displacement and damage are significantly less due to enhancement provided by AFRP retrofit.

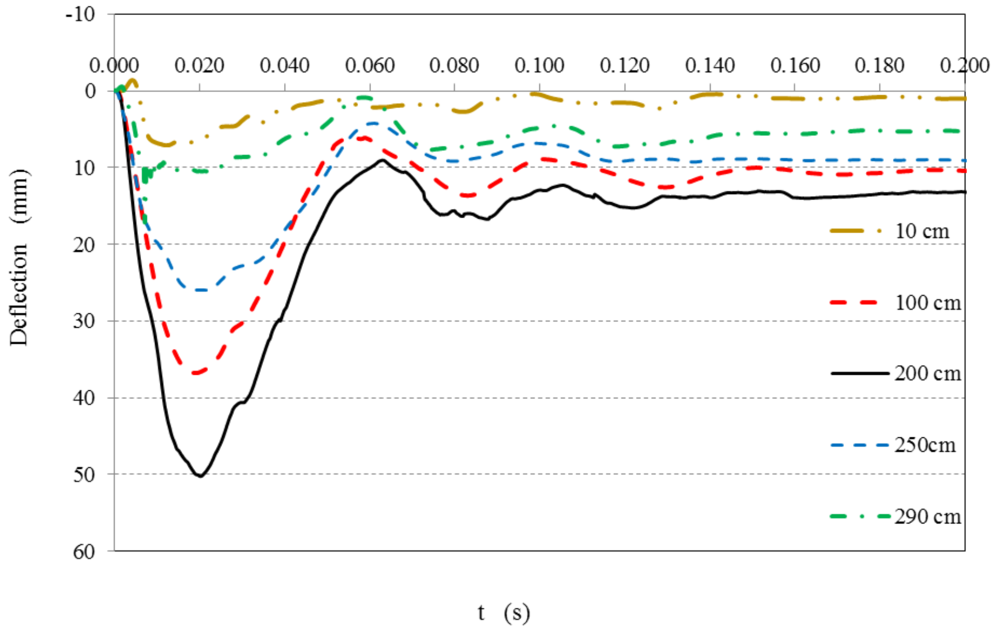

Figure 8 Deflection time history of ImpA1, after the first impact

After the first impact, the crack formation of ImpA1 between the distances 150 cm to 200 cm (under impact zone) from the west support is presented in Figure 9. Two vertical minor flexure cracks initiated at the outermost bottom tension zone. No visible damage/rupture was seen on the AFRP sheets. The formed damage was like a matrix cracking. Impact load is short in duration and causes high stress concentration at the loading region and forms cracks that expand along limited impacted area.

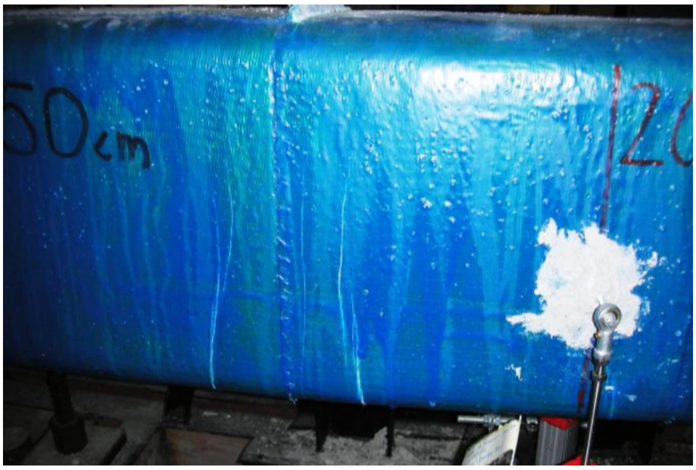

Figure 9 Cracks of ImpA1 after the first impact

Cracks were marked and the crack widths were measured after the first impact, which are presented in the crack map given in Figure 10. Minor vertical flexure cracks formed with a residual width of up to 0.8 mm.

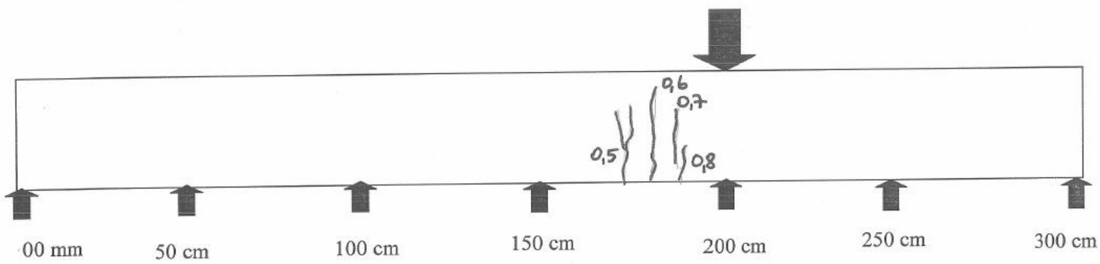

Figure 10 Crack map of ImpA1, after the first impact

2nd Impact: 585 kg, 4.5 m (26000J)

After the second impact, the previous vertical flexure cracks (marked as A) at bottom tension zone propagated further up (marked as B), as in Figure 11. Additionally, new vertical flexure cracks formed as a result of the second impact. AFRP sheets ruptured at the top surface next to the impact region, Figure 11. Aramid fibers ruptured at the top face due to the local effect of the impact loading.

a. Vertical cracks at the loading region b. Rupture of the Aramid fibers at the top surface

Figure 11 Damage of ImpA1, after the second impact

The general crack pattern of the impacted retrofitted specimen was characterized by vertical flexural cracks located around the impact zone. The width of the vertical flexural cracks formed on either side of the loading region had a range of 0.2-3.0 mm. The widths of the residual cracks after the second impact are presented in the crack map of ImpA1, Figure 12.

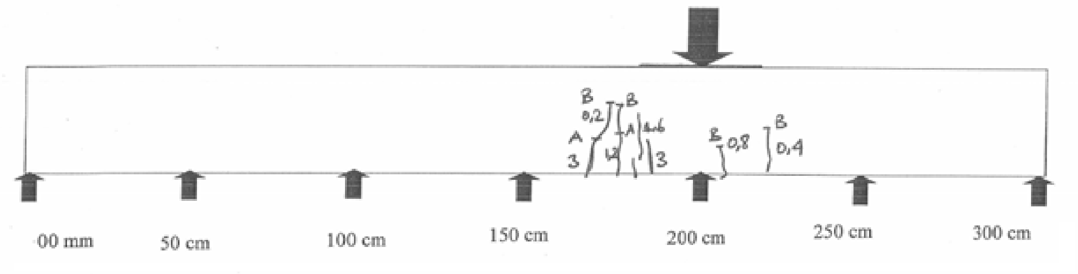

Figure 12 Crack Map of ImpA1, after the second impact (crack widths are in mm)

By the end of the impact test, the aramid jacket was removed from the concrete surface in order to observe the failure/damage mechanism closely. The general crack pattern of the impacted area is presented in the autopsy photo given Figure 13. After the first impact, vertical flexure cracks formed on the AFRP as matrix cracks then the cracks were widened and spread into the concrete surface of the specimen during the second impact. These damages on concrete were flexural cracks formed on tension side of the region with no significant crushing on the top concrete. Since the concrete damage on the top compression zone was limited, the AFRP fibers ruptured due to the local impact effect of the drop weight. The failure mode of retrofitted RC specimen subjected to impact load can be categorized as flexural failure.

Figure 13 Autopsy of ImpA1, after the second impact

RESULTS AND DISCUSSION

Results from impact tests on RC columns before and after retrofitting with AFRP are compared. These results enable the evaluation of the effectiveness of AFRP retrofitting based on its ability to increase impact load carrying capacity as well as transforming the failure mode from shear to flexure.

Failure Mode

The failure mode of the reference specimen, which was designed to be flexure-critical under static loading conditions, differs significantly under impact loads from pure flexure to an undesirable brittle shear-flexure failure due to change of material properties under the higher loading rates, as it was also indicated by Saatci and Vecchio (2009). Similar results were drawn by Remennikov and Kaewunruen (2006) where they indicated that the impact performance of the column was limited by its shear strength.

Reference specimen reached the ultimate state by the formation of major diagonal shear cracks, significant spalling of concrete cover and minor flexural cracks located near the impact area. No cracks occurred near column supports in the tests. Since impact loading is a fast dynamic load, column could only respond during very short time duration by formation of cracks and permanent deflections over a local area.

The observed failure mode in the retrofitted specimen differs significantly compared to reference specimen. The shear strength of the specimen ImpA1 was increased by the application of AFRP retrofitting so that no shear damage was detected after the impulse. While at the first low impact test of the retrofitted column just minor flexural cracks were detected under the loading zone, as the impact level increased in the second stage these former cracks widened and the aramid fibers ruptured at the top face. The AFRP jacket was removed after the test and the observed vertical flexural cracks and minor concrete crushing at the top demonstrated clearly the flexural failure of the retrofitted specimen.

Effect of Retrofitting

ImpR1 was heavily damaged under the impact of 585 kg dropped from 3.0 m; however, ImpA1 had minor cracks under the impact of 585 kg dropped from 3.5 m, which had a higher impulse than that on the first specimen. Additionally, the retrofitted column ImpA1 could stand for a second impact of 585 kg dropped from 4.5 m. This finding clearly revealed that, strengthening with AFRP sheets increased the shear strength, and accordingly the performance of column specimens under impact loads as it was also indicated by Tang and Saadatmanesh (2003) and Ferrier and Hamelin (2005).

The residual deflection values of ImpR1 and ImpA1 (after first impact) are measured as 19 mm and 13 mm, respectively. The residual deformation in the ImpA1 was reduced since no shear deformation was formed in case of ImpA1. Moreover concrete crushing at the top loading surface was limited by the application of the AFRP retrofitting.

The stiffness of the specimen retrofitted by the AFRP jacket had not changed. The periods of the deflection waves were about 60 ms for both specimens.

CONCLUSIONS

Following conclusions can be formed from the results of the drop weight tests of axially loaded RC columns before and after AFRP retrofitting in shear.

* Reference specimen exhibited a shear-critical behavior under impact loads even though it was designed as flexure-critical under static loading conditions.
* The main observed damage of the reference specimen was shear failure with flexure.
* The damage caused by the impact loading was located around the loading zone and no damage was observed close to the column supports.
* The failure mode the column under impact loading was transferred from a brittle shear failure to a more ductile flexural failure by the application of the AFRP retrofitting.
* The impact capacity of the retrofitted columns under drop weight impact test, significantly increased and the residual deflection is decreased compared to the unretrofitted specimens.

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