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Low velocity impact behavior of shear deficient RC beam strengthened with CFRP strips

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Abstract. Many methods are developed for strengthening of reinforced concrete structural members against the effects of shear. One of the commonly used methods in recent years is turned out to be bonding of fiber reinforced polymers (FRP). Impact loading is one of the important external effects on the reinforced concrete structural members during service period among the others. The determination of magnitude, the excitation time, deformations and stress due to impact loadings are complicated and rarely known. In recent year impact behavior of reinforced concrete members have been researched with experimental studies by using drop-weight method and numerical simulations are done by using finite element method. However the studies on the strengthening of structural members against impact loading are very seldom in the literature. For this reason, in this study impact behavior of shear deficient reinforced concrete beams that are strengthened with carbon fiber reinforced polymers (CFRP) strips are investigated experimentally. Compressive strength of concrete, CFRP strips spacing and impact velocities are taken as the variables in this experimental study. The acceleration due to impact loading is measured from the specimens, while velocities and displacements are calculated from these measured accelerations. RC beams are modeled with ANSYS software. Experimental result and simulations result are compared. Experimental result showed that impact behaviors of shear deficient RC beams are positively affected from the strengthening with CFRP strip. The decrease in the spacing of CFRP strips reduced the acceleration, velocity and displacement values measured from the test specimens.

Keywords: shear deficient rc beam; impact behavior; cfrp strip; strengthening

1. Introduction

Reinforced concrete is the most widely used construction material in the world, therefore sometimes elements that are made from reinforced concrete need retrofitting and strengthening due to different reasons. Some of them cited as the change in structure usage purpose, increase at loadings due to increase in needs, corrosion damages due to environmental effects, mistakes that are made during project and manufacturing phases. Due to these reasons or similar ones,

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strengthening of reinforced concrete beams is used.

Strengthening techniques of reinforced concrete beams such as concrete jacketing, confinement with steel strips and many similar methods are investigated by the researcher up to now. But all of these techniques had many disadvantages such as increase in the weight of the member, affecting from corrosion and fire. In addition, they cannot applied all of the members and require significant workmanship. For these reasons, carbon fiber reinforced polymers (CFRP) is started to be used and became popular and widespread. CFRP is used widely due to lighter weight, resistant to corrosion and environmental conditions, ease of application to different and every type of surfaces and very high tension strength.

There are many analytical and experimental studies about the strengthening of reinforced concrete beams by using CFRP against static loadings and dynamic cyclic loads such as earthquake or wind loads at literature. But authors encountered very limited amount of study about low velocity impact behavior of concrete beams. There are studies at literature that investigate the impact behaviors of concrete, when the additive materials such polypropylene or steel fibers are added to concrete (Arslan 1995, Badr *et al*. 2006, Marar *et al*. 2001, Nataraja *et al*. 2005, Valipour *et al*. 2009). These studies showed that additives are affected the impact strength of the concrete positively, but these fibers made handling of the concrete different, increased the cost of it. In addition when the volume of the concrete increased, the homogeneous distribution of additives became difficult. As a result the properties of the concrete differ according to distribution. But there are limited amount of studies at literature about the RC beams strengthened with CFRP against the impact and blast loading. The researches on the retrofitting of RC structural members focused on the strengthening against the effects of shear or flexure (Muszynski 1998, Erki and Meier 1999, Bhatti *et al*. 2009, Kishi and Bhatti 2010, Kishi *et al*. 2002a). The authors did not encountered a comprehensive study in which impact behavior of shear deficient RC beams strengthened with CFRP strips are investigated in the literature. For these reasons, an experimental study conducted with the strengthened RC beams against shear under low velocity impact loading by using CFRP strips. Due to its nature impact loading is significantly complex type of loading. For this reason the behavior of concrete beams strengthened with CFRP strips under impact loading is also a complex and crucial subject, and it should be investigated. Although impact loads are not permanent and application properties (time, magnitude) are not known fully like the static loads, but instant magnitude can be larger than the other loading types (Krauthammer 1998, Nagaraj *et al*. 1993, Goldsmith 1960, Murtiadi 1999).

There is no established standards or methods for impact testing up to nowadays' studies (Kishi *et al*. 2002b, Ong *et al*. 1999, Mindess and Cheng 1993, Barr and Baghli 1988). But ASTM E 23 regulations improved the test setup performance significantly and gave good starting points for the limits of impacts experiments (Siewert *et al*. 1999). When the experimental impact studies at literature are investigated, they are categorized in to two main segments. One of them depends on the investigation on specimens under impact loads that are applied by test equipments. These types of studies are concentrated on mostly steel materials. The other studies use equipment with mechanisms that drop masses from height. This method is used mostly for the concrete impact testing (Banthia 1987, Bull and Edgren 2004). An impact tester that drops constant weight from a height is used for testing strengthened beams.

This system is designed by the authors. A constant weight hammer is dropped from selected heights with low velocity and measured accelerations are investigated after the impact of free falling hammer.

Specimens with normal and high compression strength concrete are strengthened with widely used carbon fiber reinforced polymers (CFRP) in this experimental study. Different behaviors under impact loading are investigated. Totally sixteen rectangular cross sectioned reinforced concrete beam specimens are tested. RC beams strengthened with CFRP strips are casted without shear rebar. The compression strength of concrete, input impact energy and the wrapping space of CFRP strips are taken as variables in experimental program. Two series of test specimen with concrete compressive strengths of 20 MPa and 30 MPa are produced. The constant weight hammer (5.25 kg) is dropped from two different heights of 500 mm and 750 mm to change input impact energy. CFRP strips having a constant width of 25 mm are bonded to beams with the spacing of 50 mm, 75 mm and 100 mm. Each of different test series have a reference test specimen without any retrofitting and this control specimen are compared with other RC beams that are strengtened with CFRP. Velocity and displacement values are calculated by using measured acceleration from the test specimens. The effect of parameters of experimental study and the strengthening technique with CFRP on the accelerations, velocities and displacements of test specimens are examined. ANSYS Explicit STR finite element software is used for making simulation of the impact test at computer simulation environment. Results of the FEM are compared with experimental results for obtaining consistent finite element model. As a results success of the FEM is investigated for the simulation of real experimental results, and the level of consistency of the results are determined.

2. Experimental program

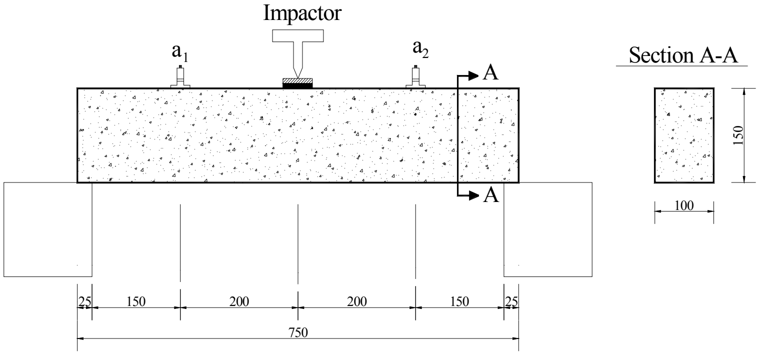
2.1 Test specimens and materials

In this study, sixteen simply supported rectangular RC beams without shear rebar are casted and tested under impact loading. The four of them are chosen as reference specimen and the remaining ones are strengthened with CFRP strips. The compressive strength of concrete, input impact energy and wrapping spacing of CFRP strips are taken as variables. Sixteen RC beams are divided into four groups. Four series of impact test with two different compressive strength (20 MPa and 30 MPa), two different drop heights (500 mm and 750 mm) and three different wrapping spacing of CFRP strips (50 mm, 75 mm and 100 mm) are carried out. Each experimental series are conducted by using four RC beams. One of the RC beams is taken a reference without any retrofitting and three of them are strengthened by externally bonded CFRP strips with three different wrapping spacing. Properties of RC beam specimens are given in Table 1. The dimensions of all RC beams are 750 × 150 × 100 mm (length × depth × width). Reinforcement details of all specimens are the same. All specimens had two ϕ6 mm diameter longitudinal tension and compression reinforcements at bottom and top side, respectively. The dimensions of test specimens and details of rebars are given in Fig. 1. Three ϕ4 shear rebar are placed to prevent dislocations of the compression and tension bars during concrete casting. Properties of rebar that are used for casting of test specimen are the same. As a result of axial tensile test applied to five specimen, average yield strength, ultimate strength and young's modulus are determined as f_{sy} = 238 MPa, f_{su} = 392 MPa and $E_s = 2{,}08 \times 10^5$ MPa, respectively.

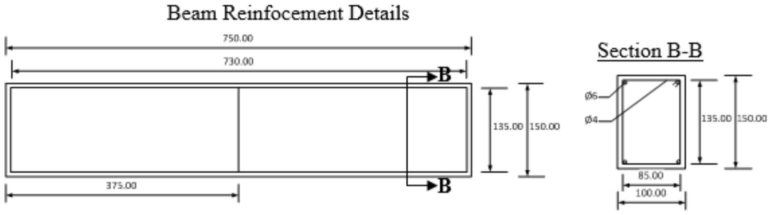
In experimental program, two series of test specimen with concrete compressive strengths of 20 MPa and 30 MPa are produced. The percentages of the materials by weight that are used in the production of concrete of the test specimens are given in Table 2. Concrete compression strength of the specimens is determined from the axial compression test of five standard cylindrical samples with 150 × 300 mm dimensions that are manufactured from the same concrete with test

Table 1 Properties of test specimens

Spec No.	Concrete Compression Strength f_c (MPa)	Drop height (mm)	CFRP strip properties	
			Width (mm)	Spacing (mm)
1	30	500	Reference	
2			25	50
3			25	75
4			25	100
5	20		Reference	
6			25	50
7			25	75
8			25	100
9	30	750	Reference	
10			25	50
11			25	75
12			25	100
13	20		Reference	
14			25	50
15			25	75
16			25	100



(a) Geometric dimensions of specimens



(b) Reinforcement details of specimens

Fig. 1 Dimensions and reinforcement details of test specimens

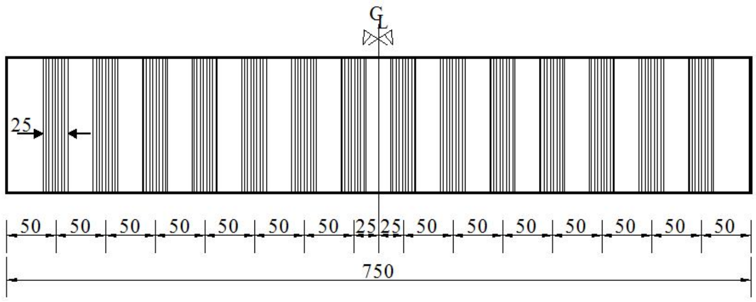
Table 2 Concrete mix properties

30 MPa strength concrete		
Materials	Weight (kg)	Weight percentage (%)
Cement	50	20,8
Gravel (7-15 mm)	90	37,5
Sand (0-7 mm)	70	29,2
Water	27,5	12,5
20 MPa strength concrete		
Materials	Weight (kg)	Weight percentage (%)
Cement	50	20,6
Gravel (7-15 mm)	85	35,1
Sand (0-7 mm)	75	31,0
Water	32	13,2

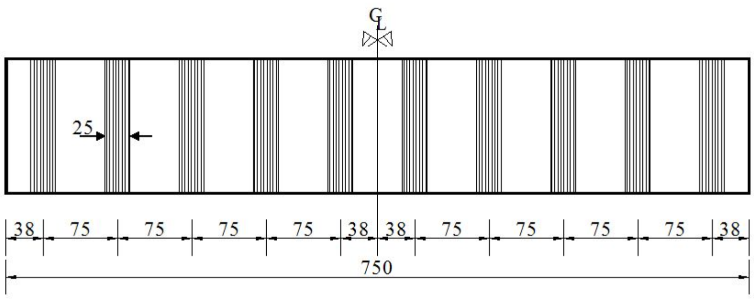
specimens. Cylindrical samples are cured under same cure conditions with test specimens. They put inside a water tank after the day of casting and seven days later they are transferred to laboratory floor for resting 20 days. Samples of specimens with the same strength series are tested at the same day. Two types of aggregates are used with the diameters from 1 to 7 mm and 7 to 15 mm. KPC 32.5 Portland cement is used for concrete production. The targeted concrete compressive strength for test specimens is provided. The average compressive strength is determined as 30.27 MPa for the first and third series, 20.43 MPa for the second and fourth series.

RC beams are externally wrapped by CFRP strips having a constant width of 25 mm with the spacing of 50 mm, 75 mm and 100 mm. In the experimental study, the CFRP strip spacings are selected based on the recommendations of ACI 440 Committe Report, 2004. In this report, which is widely used for the application of CFRP strips, it is recommended that the CFRP strip spacing should not be greater than $d/4 + w_f$. Consequently, CFRP strip spacing is calculated as 60.625 mm by the summation of one quarter of the effective beam depth and CFRP strip width. Therefore, one of the CFRP strip spacings is selected smaller than 60.625 mm and two of the CFRP strip spacings are selected greater than 60.625 mm to observe the variation of impact behavior in case of different spacings than the spacings proposed by ACI 440 Committe Report, 2004. The layouts of CFRP strips are given in Fig. 2. Two component epoxy (Sikadur 330) is used for bonding CFRP strips with unidirectional fibers (Sikawrap 230-C) to RC Beams. Mechanical properties of CFRP and the epoxy given by manufacturer are shown in Table 3. RC beam side faces at which CFRP strips are bonded roughened with mechanical grinder up to aggregates are exposed.

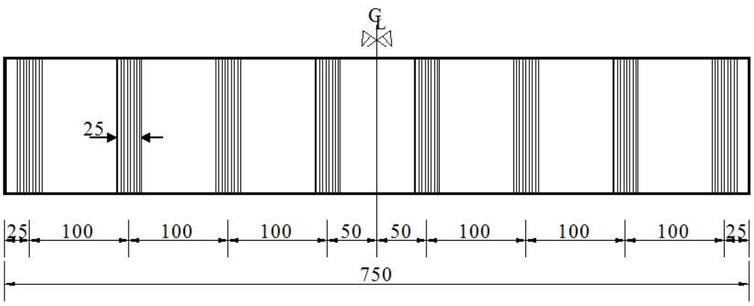
Then these surfaces are cleaned with water soaked sponges, and are dried with compressed air. Two part epoxy is mixed up a point at which mixture took a uniform single color, then 0.5 mm thick epoxy is applied on to the surfaces, approximately. A special hand tool with 0.5 mm teeth is used for applying epoxy on to concrete surface. After that CFRP strips are laid on to epoxy by hand carefully without changing the directions of the fibers. Only single layer of CFRP is used for strengthening of specimens. These CFRP strips are soaked with epoxy for preventing any air bubbles between the beam surface and CFRP. Finally another 0.5 mm thick epoxy is applied on to CFRP strips for protecting the direction of the fibers. The explained strengthening technique is applied to all off the specimens identically.



(a) Beam 2, 6, 10 and 14 (CFRP strip width w_f = 25 mm, spacing s_f = 50 mm)



(b) Beam 3, 7, 11 and 15 (CFRP strip width w_f = 25 mm, spacing s_f = 75 mm)



(c) Beam 4, 8, 12 and 16 (CFRP strip width w_f = 25 mm, spacing s_f = 100 mm)

(Dimensions in mm)

Fig. 2 Strengthening details of specimens

While applying the procedure, the attention paid on keeping temperature of the laboratories around 20°C ± 2. After CFRP strips are bonded, seven day curing time is passed for reaching the full strength of epoxy. After that specimens are tested. The success of bonding of CFRP to concrete surface is strongly dependent on the proper application of the procedure and surface preparation. Keeping the direction of fibers of CFRP strips and soaking the epoxy into CFRP, while avoiding air bubbles are the key factors for the success of bonding. Strengthening procedure should be done with great care for determining the impact behavior of strengthened specimen with CFRP strips completely (Anıl and Belgin 2008, 2010, Anıl *et al*. 2010, Baran and Anıl 2010). Specimens are strengthened with CFRP strips and are prepared for testing after completing their

Table 3 Properties of CFRP Sikawrap 230-C (unidirectional) and resin Sikadur 330

Properties of CFRP	Remarks of CFRP
Thickness (mm)	0,12
Tensile strength (MPa)	4100
Elastic modulus (MPa)	231000
Ultimate tensile strain (%)	1,7 %
Properties of resin	Remarks of resin
Tensile strength (MPa)	30
Elastic modulus (MPa)	3800

(a) Accelerometer mounting detail of specimens (b) Impact loading point detail (Steel plate and rubber)

Fig. 3 Preparation of test details for specimens

curing time. Then sensor placing that are used for measuring impact loading effects of dropping hammer are determined and special brass apparatus are fixed onto these places by using studs (see Fig. 3). In addition a specially manufactured steel plate with its silicone bearing is mounted with two steel studs on to region at which impact loading is applied with hammer (see Fig. 3). So loading is applied linearly all along the cross section. All of these apparatus are mounted onto same locations, therefore identical loading is applied and measurements are taken.

2.2 Test setup and instrumentations

Due to the fact that specimens are made up of reinforced concrete, free falling impact hammer test system is chosen for applying impact force. Geometric shape of the specimens, the material of the hammer and the shape of the hammer tip, the mechanical properties of the both specimens and strengthening materials are taken into account during preparation of the test methods. The factors that are affected on the behaviors of the reinforced concrete beam strengthened with CFRP are determined by making literature survey (Tang 2002). These factors can be cited as fallows; impact energy and initial velocity of the hammer, strain due to impact load, the type and weight of the composite material, the size of the bonding area of the composite, concrete compression strength, beam span, the bonding quality of the CFRP on to concrete surface. All of the above parameters cannot be investigated with a single study. Therefore some of them are kept constant during the experimental study.

The equipments in the literature that are used for dropping hammer are designed such that they allow to drop hammers with different weight from adjustable heights. By the help of investigated studies the dimensions of the equipment are determined. The most significant parameter that is effective on the result of impact test is the eccentricity. By the help of pre drop tests, eccentricity is minimized. During these tests, the weight of the base of test equipment is increased, and as a result, eccentricity is became zero. The detail of the designed equipment is shown in Fig. 4. The base is manufactured from square 1000 mm by 1000 mm steel plate that weight about 1000 kg. Due to the fact that specimen sizes can change, the platform of the test equipment is manufactured as large as possible. Experimental setup has the capability of dropping variable weights from 2500 mm. Existing hammer weight can be increased by adding extra weights for the different experimental purposes. The weight of the hammer is 5.25 kg and same hammer is used for all experiments. The other effective parameter on the test result is known as friction, and friction is reduced by using special materials. Hammer is guided with hard chrome coated grinded rods and cestamide rollers are used between the hammer and the rods during free fall.

Hammer first hit to a steel plate that is supported with a rubber cushion. The purpose of using steel plate is to distribute the load linearly and uniformly to the cross section of the specimen. For minimizing the internal forces, hard rubber is used between the specimen and steel plate. The

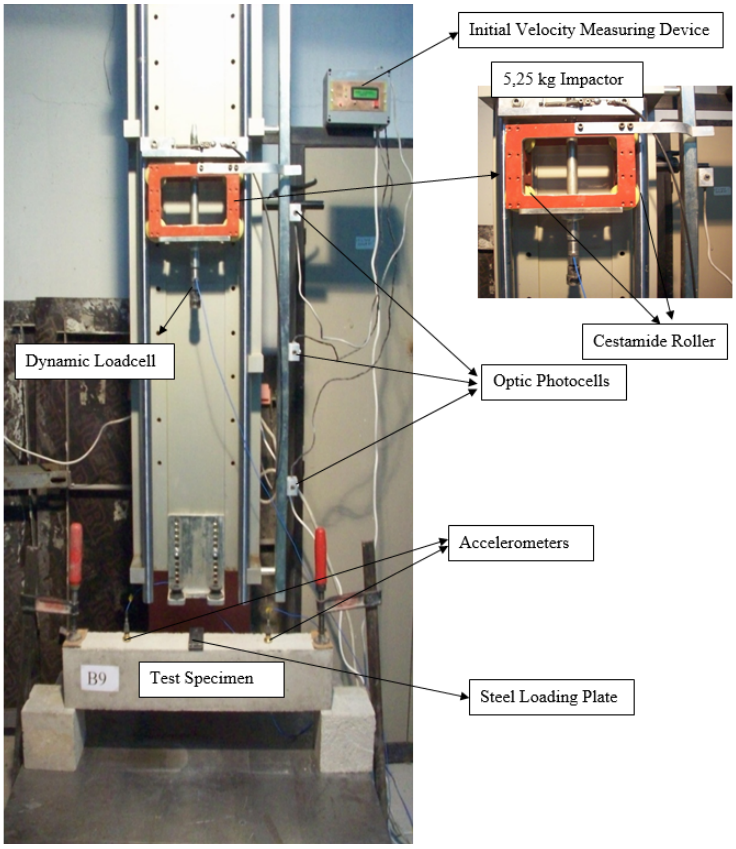


Fig. 4 Test setup and instrumentation

dimension of the steel plate and rubber are $50 \times 150 \times 15$ mm. Steel plate with rubber is fixed to specimen by using steel dowels (Fig. 3(b)). An instrument is placed along with the setup for measuring the terminal velocity of the hammer. Instrument uses optical photocells for measuring the drop time and from the time velocity can be calculated.

Two accelerometers are mounted on symmetry axis of the specimen, and 200 mm apart from the center of symmetry. Right and left side of the specimen and difference between them are measured with these two accelerometers. Accelerometers are mounted on brass apparatus that are mounted on to specimen by using steel dowels (Fig. 3(a)). The data from accelerometers are transmitted to a data logger that is connected to computer and then analyzed with software. ICP type accelerometers with model number 353B02, manufactured by PCB Group were utilized for acceleration measurements of the test specimens. A 003A20 model special cable, manufactured by PCB Group, was used for transmission of measurements acquired from the accelerometers to data logger without data loss. These are low noise, coaxial cables that are suitable for operation at high temperatures and for transmission of high or low impedance voltage signals with ICP sensors.

The diameters of the cables are 2 mm and operation temperature range is between −90 and +260°C. Impedance of the cable is 50 ohm. N1 9233-USB-9162 model data logger manufactured by National Instruments Company was used for collection of measurements and transmission to the computer at the laboratory. This data logger is a four channel dynamic signal acquisition unit and is composed of IEPE sensors which can acquire measurements with high accuracy. The data logging device is composed of two independent modules. The first module is the data logger to which the measurement devices are also connected. The second is the signal transmission module, which transmits the signal from the first module to computer. Data transferred to computer from data logger is stored after conversion to the required type via Labview Signal Express 3.5 software, developed by National Instrument Company. Calibrations of the measurement devices are performed using this software as well. Diadem 10.1 software, also developed by National Instruments, was used for necessary editing operations during data processing.

3. Experimental results and discussions

3.1 Observed behavior and failure modes of specimens

The changes of acceleration and applied impact loading depending on time are measured from each specimen with the intent of examination and comparison of the behaviors of the specimens under the effect of impact loading. The velocity-time and displacement-time graphs are calculated by taking the integral of acceleration-time graphs that are measured from the specimens. Acceleration values of the specimens are measured by dropping constant weight hammer (5.25 kg) onto the specimens ten times, from two different heights of 500 and 750 mm; and their velocity and displacement values are calculated. After ten drops, the crack widths and maximum mid-point displacement values of the specimens are measured, as well. Some examples selected from the acceleration-time and impact load-time graphs that are received from the specimens are shown in Fig. 5. The changes of the maximum acceleration values that are measured from the four series of specimens that are tested within the scope of this experimental study, with respect to the number of drops, are given in Fig. 6, for the right and left sides of the beams, and selected crack distribution photographs of the specimens are given in Fig. 7. The experimental results that are obtained from the specimens are summarized in Table 4.

The variables analyzed in the scope of this experimental study are concrete compressive strength, applied impact energy, and spacing of CFRP strips for strengthening. When the results that are obtained from the specimens are analyzed, it is ascertained that the increase in the concrete compressive strength raised the acceleration values that are measured from the specimens. The increase in the acceleration values increased the velocity and displacement values, as well. The increase in the concrete compressive strength increased the specimens' ability to make deformation, and consequently, their capacity of energy absorption. The increase in concrete compressive capacity decreased the voids ratio of the concrete, and increased its hardness. The waves that are occurred as a result of the collision in solid medium moved much faster and reached the accelerometer with a slighter loss. For these reasons, it is thought that higher acceleration, velocity and displacement values are measured from the specimens with higher concrete compressive strength. The impact energy is the second variable that is analyzed in the scope of this study. When the specimens are undergone to a impact loading with larger energy through the effect of the constant weight dropped from a higher height, the energy that is transmitted to the specimens increased as well, and therefore, greater acceleration values are measured. As a result of the increase in the acceleration values, also the velocity and displacement values increased.

The last variable analyzed in the experimental study is the spacing of CFRP strips that are applied to beams for strengthening. When the experimental results are investigated, the acceleration values that are measured from the specimens are increased, in parallel to increase in the spacing of CFRP strip. The CFRP strips reduced the ductility level of the specimens and increased their stiffness.

The CFRP strips eliminated the deficiency of shear reinforcement by wrapping the specimens and increased their capacities and caused a decrease in the measured acceleration values. The specimens with 50 mm spacing of CFRP strips had lower acceleration values than that of the ones with 75 mm spacing; whilst the specimens with 75 mm spacing had lower acceleration values than that of the ones with 100 mm spacing. The measured acceleration values and consequently the velocity and the displacement values are reduced in parallel to the decrease in the spacing of CFRP strip. This behavior is observed to be identical for all specimens. Acceleration values increased as a result of the increase in the spacing of CFRP strips for all specimens with changing concrete compressive strength and impact energy. The test specimens with 100 mm CFRP strip spacing showed similar behaviors with that of the reference specimens. This result shows that 100 mm CFRP strip spacing is inadequate for strengthening of shear deficient RC beams.

The specimens with 75 and 50 mm CFRP strip spacing showed more successful impact behaviors, and their acceleration, velocity and displacement values remained in lower limit values. The most successful behavior in the experimental series is obtained from the specimens that are strengthened with 50 mm spaced CFRP strips.

When the crack distributions of the specimens that are given in Fig. 7 are analyzed, the spacing of CFRP strip is observed to affect the specimens' crack width and mid-point displacement values. The measured mid-point displacement and maximum crack width values reduced, in parallel to the decrease in the spacing of CFRP strip that are used for strengthening of the specimens. The maximum mid-point displacement value and maximum crack width values that are measured from the specimens after the completion of the consecutive ten drops are given in Table 5. The increase in the concrete compressive strength is caused to a decrease in the crack width and the mid-point displacement values, as expected. The crack width and maximum mid-point displacement values increased in parallel to the increase in the drop height. The mid-point displacement and crack widths that are measured from the specimens with 50 mm CFRP strip spacing had the lowest

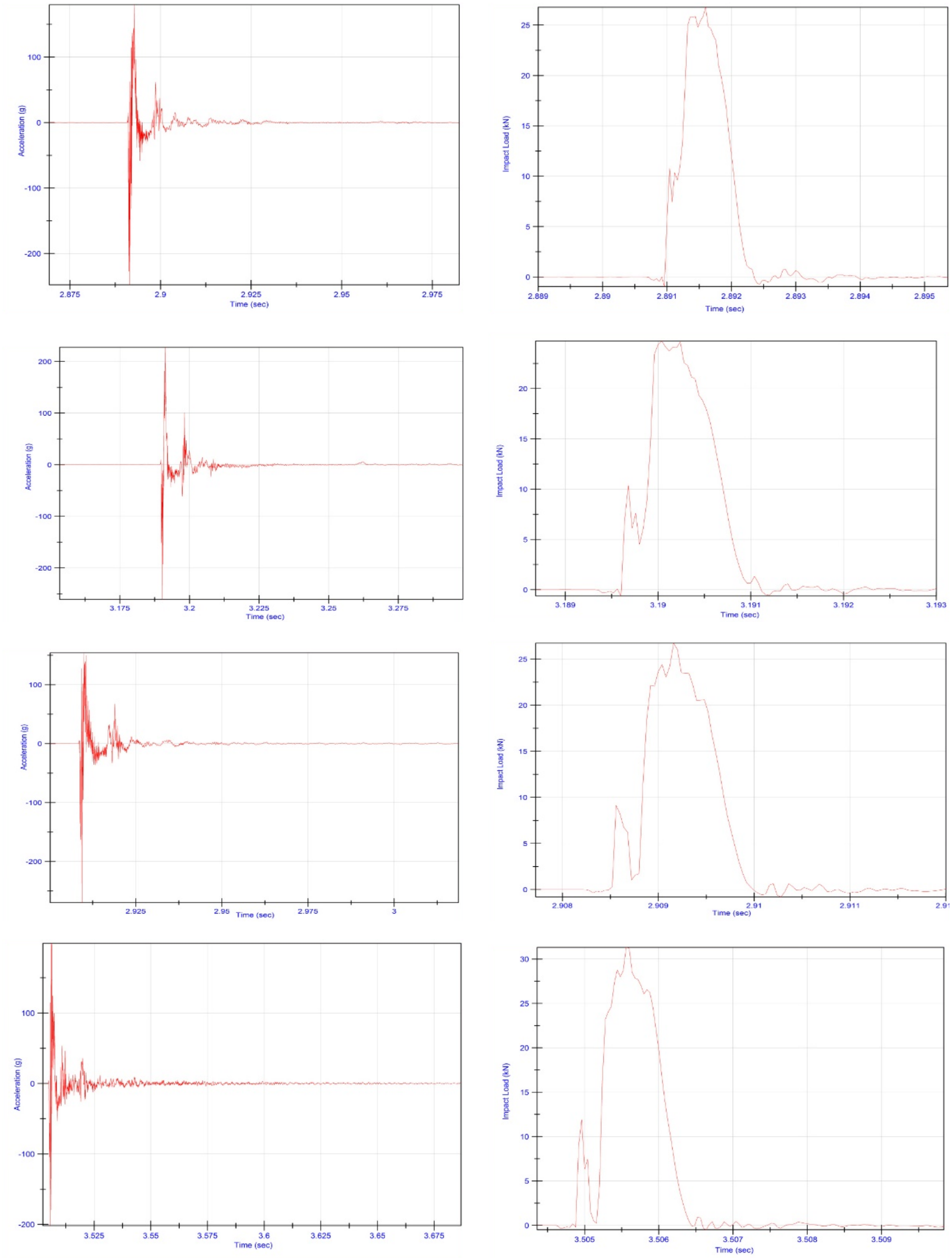
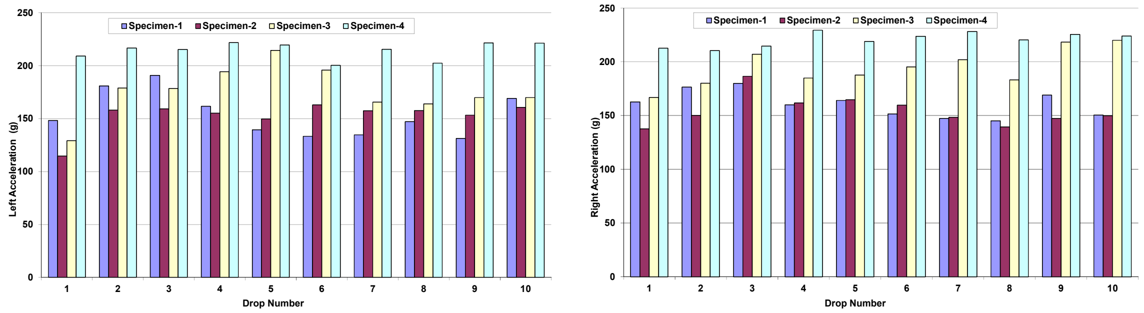
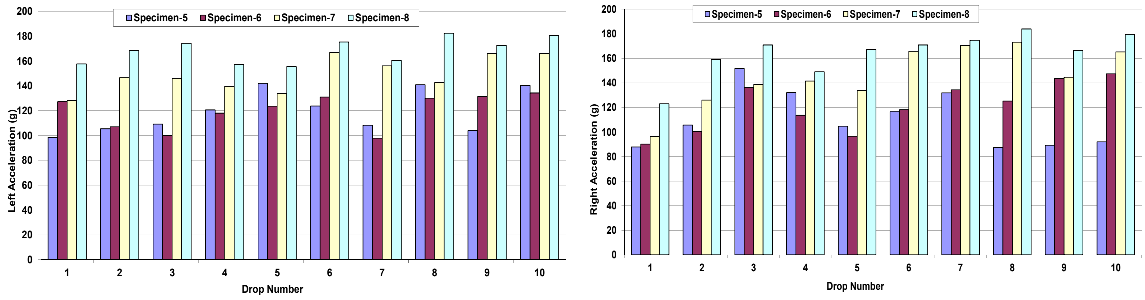


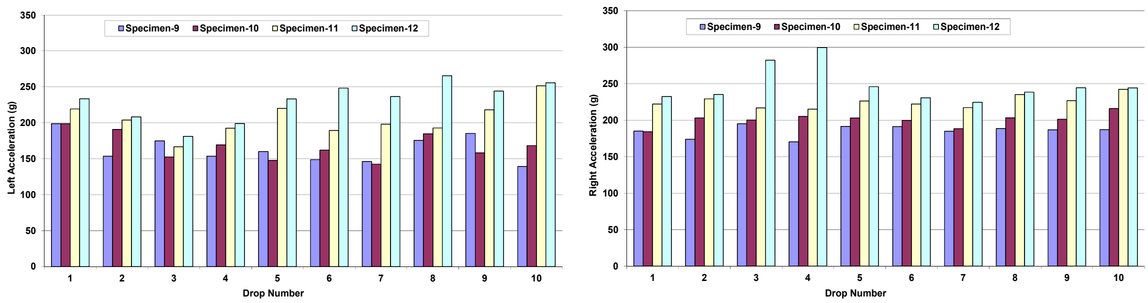
Fig. 5 Measured acceleration-time and impact force-time graph examples



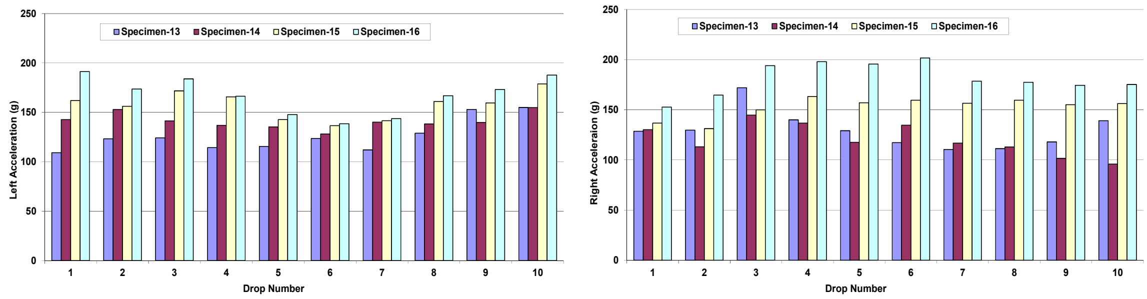
(a) Maximum acceleration chancing with drop number for Specimen 1, 2, 3 and 4



(b) Maximum acceleration chancing with drop number for Specimen 5, 6, 7 and 8



(c) Maximum acceleration chancing with drop number for Specimen 9, 10, 11 and 12



(d) Maximum acceleration chancing with drop number for Specimen 13, 14, 15 and 16

Fig. 6 Maximum acceleration measurement of specimens

Table 4 Experimental results

Spec. No.	Left				Right				Impact load (kN)
	Max. acce. (g)	Min. acce. (g)	Max. velocity (m/sec)	Max. displa. (mm)	Max. acce. (g)	Min. acce. (g)	Max. velocity (m/sec)	Max. displa. (mm)	
1	190,757	-261,020	0,399	1,565	179,918	-220,080	0,507	2,063	26,78
2	163,006	-184,780	0,367	1,467	186,480	-165,150	0,388	1,559	27,29
3	214,464	-195,630	0,415	1,711	219,991	-198,950	0,454	1,915	24,91
4	221,871	-142,010	0,479	2,492	229,350	-160,210	0,553	2,782	25,24
5	142,048	-285,950	0,246	0,930	151,731	-222,310	0,354	1,116	26,72
6	134,230	-247,220	0,288	1,263	147,349	-230,640	0,333	0,874	25,78
7	166,754	-208,880	0,337	1,433	173,163	-208,430	0,411	1,394	23,42
8	182,302	-210,450	0,395	1,304	183,898	-261,820	0,429	1,455	26,18
9	198,870	-272,190	0,406	1,812	195,250	-240,840	0,519	2,329	31,30
10	198,781	-230,780	0,419	1,319	216,040	-275,690	0,462	1,850	30,83
11	251,570	-225,290	0,516	2,818	242,489	-222,660	0,656	3,667	33,09
12	265,616	-213,460	0,598	2,915	299,688	-254,780	0,752	3,747	32,64
13	154,952	-260,140	0,289	1,113	171,984	-234,810	0,345	1,378	30,30
14	154,800	-227,900	0,321	1,110	144,602	-212,850	0,352	1,133	28,29
15	178,790	-287,770	0,323	1,288	163,238	-240,010	0,378	1,903	29,66
16	191,300	-326,810	0,407	1,945	201,664	-244,590	0,426	2,323	31,71

values; and the values that are measured from specimens with 100 mm CFRP strip spacing are close to that of the reference test specimens. When the distribution of cracks that are observed from the specimens are analyzed, it is seen that the crack with the maximum width occurred at the steel plate region, where loading is applied and is situated at the mid-point of the beam. The other cracks that are observed are at more capillary levels; and CFRP strips limit the cracks at the specimens that are strengthened with CFRP strips having 50 mm and 75 mm spacing.

3.2 Acceleration, velocity and displacement behaviors of specimens

Comparison of the measured maximum acceleration values of the specimens with respect to the number of drops are given in Fig. 8. How the acceleration values are affected by the variables analyzed within the scope of the experimental study are interpreted by using these graphs. The measured acceleration values of the specimens increased in parallel to the increase in the concrete compressive strength. The average maximum acceleration values that are measured from left and right sides of the Specimen 1, 2, 3, and 4 are 27% and 24% higher than that of Specimen 5, 6, 7 and 8, respectively. The same behavior is also observed from the 3rd and 4th series specimens. The average maximum acceleration values that are obtained from left and right sides of the Specimen 9, 10, 11, and 12 are 34% and 40% higher than that of Specimen 13, 14, 15 and 16, respectively.

The increase in the energy that is applied by the impact loading led to an increase in the measured acceleration values. The average maximum acceleration values that are obtained from

Fig. 7 Failure modes of specimens

Table 5 Maximum mid-point displacement and crack width of specimens

Spec. No.	Maximum mid-point displacement (mm)	Maximum crack width (mm)
1	2,21	1,61
2	1,93	1,15
3	2,09	1,23
4	2,18	2,22
5	2,51	1,93
6	2,2	1,37
7	2,36	1,51
8	2,47	1,63
9	2,98	2,89
10	2,43	2,18
11	2,58	2,53
12	2,76	3,04
13	3,26	3,42
14	2,87	2,29
15	3,04	2,77
16	3,19	3,28

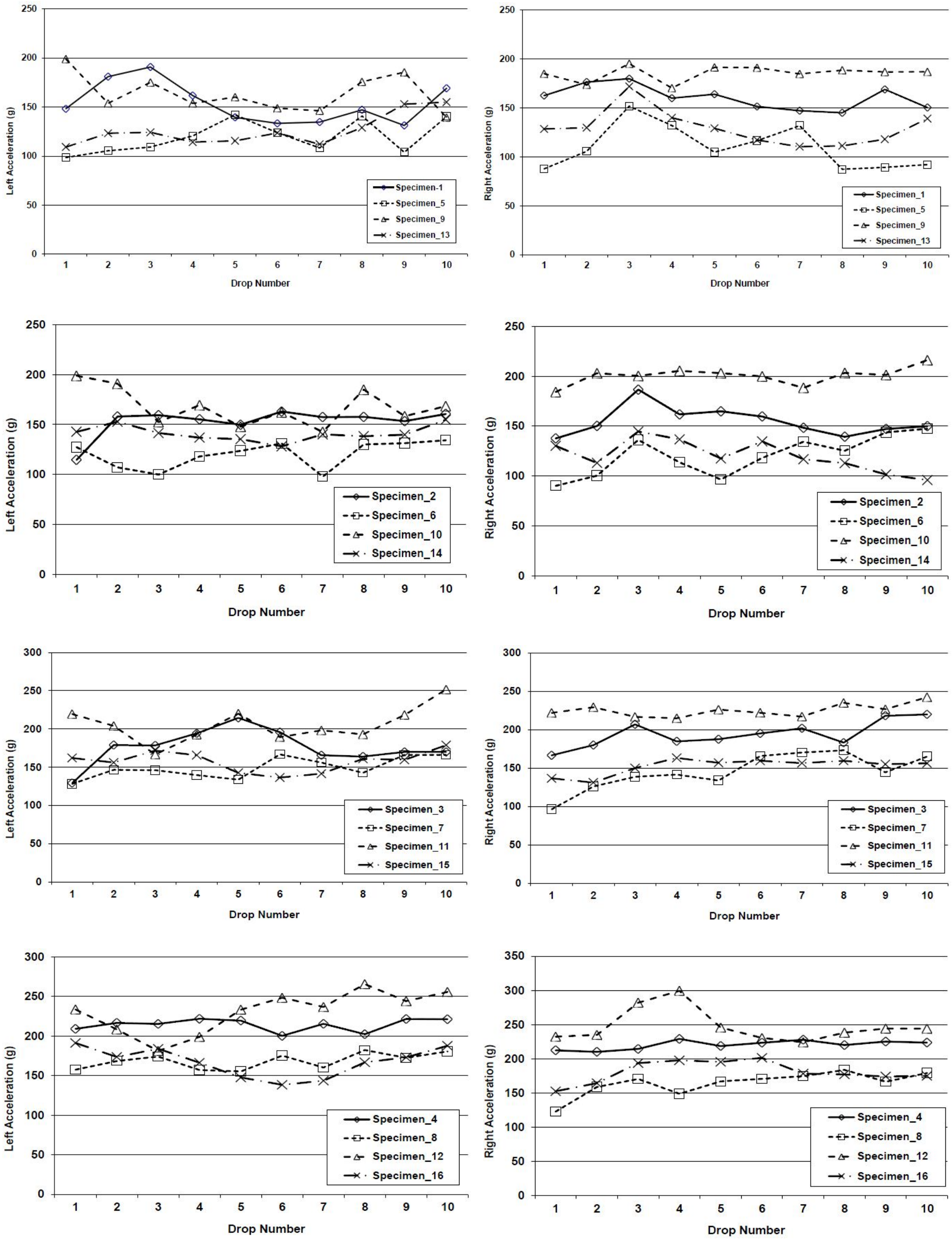


Fig. 8 Comparison of maximum acceleration of specimens with drop number

left and right sides of the Specimen 1, 2, 3, and 4 are 16% and 16% higher than that of Specimen 9, 10, 11 and 12, respectively. The same behavior is also observed from the 2nd and 4th series specimens. The average maximum acceleration values that are obtained from left and right sides of the Specimen 5, 6, 7, and 8 are 9% and 4% higher than that of Specimen 13, 14, 15 and 16, respectively. In consequence of the increase in the measured acceleration values from the test specimens, also the velocity and displacement values increased. The increase in the concrete compressive strength of the test specimens and drop heights led to an increase in the velocity and displacement values, as well.

The decrease in the spacing of CFRP strip that are used for strengthening led to a decrease in the measured acceleration, velocity and displacement values. The maximum acceleration value that are measured from left side of the Specimen 4 with 100 mm spaced CFRP strip is 3% greater than that of the Specimen 3 with 75 mm strip spacing. The maximum acceleration value of Specimen 3 is 32% greater than that of the Specimen 2 with 50 mm strip spacing. The same behavior is observed from the acceleration values that are measured from the left side of the second, third and fourth series of specimens. The difference between the maximum acceleration values that are measured from the specimens with 100 mm and 75 mm strip spacing is lower, while the difference between the specimens with 75 and 50 mm strip spacing is higher. The difference between average maximum acceleration values that are measured from the left sides of fourth series specimens with 100 mm CFRP spacing is 6% higher than that of 75 mm CFRP strip spacing, and the same difference is 24% for the test specimens with 75 and 50 mm strip spacing. The differences between average maximum acceleration values that are measured for the right sides of the specimens with 100 mm CFRP spacing is 14% higher than that of specimens with 75 mm strip spacing, and the same difference is 15% for the test specimens with 75 and 50 mm strip spacing.

4. Analytical study

4.1 Finite element modeling of experiment

The acceleration, velocity and displacement values that are obtained from the experiments are compared with the results of the numerical analysis that are obtained from the 3D models through the finite elements program ANSYS that is widely used software for engineering applications and academic studies. In ANSYS Explicit STR program, concrete, steel, CFRP and rubber are defined as elastic material. The main resason for the linear elatic material behavior assumption is having a shorter computation time. The analysis conducted in scope of this study is an incremental dynamic analysis. Therefore it should be repeated many times with small time increments. In addition to that, if the nonlinear material behavior was used, the material nonlinearity would significantly increase the number of repeated analyses and increase the computation time. Consequently, it is decided to observe the accuracy of the analytical study for the linear elastic material behavior. The density, elastic modulus and poisson ratio values that are entered into the software for all materials are given in Table 6.

Concrete, rebars, CFRP, supports, steel plate, rubber and hammer are modeled through "Design Modeller" module that enables system geometries to be modeled within the structure of ANSYS Workbench. While concrete, hammer, supports, steel and rubber are modeled as solid elements, CFRP and rebars are modeled as surface element and line elements, respectively. All the

Table 6 Material properties of finite element model

Material type	Properties	Value	Unit
Concrete (30 MPa)	Density	2400	kg/m^3
	Elastic modulus	28534×10^6	MPa
	Poisson ratio	0,2	------
Concrete (20 MPa)	Density	2400	kg/m^3
	Elastic modulus	31800×10^6	MPa
	Poisson ratio	0,2	------
Steel	Density	7850	kg/m^3
	Elastic modulus	2×10^{11}	Pa
	Poisson ratio	0,3	------
CFRP	Density	230	kg/m^3
	Elastic modulus	23400×10^6	Pa
	Poisson ratio	0,4	-
Rubber	Density	1230	kg/m^3
	Elastic modulus	22×10^6	Pa
	Poisson ratio	0,45	------

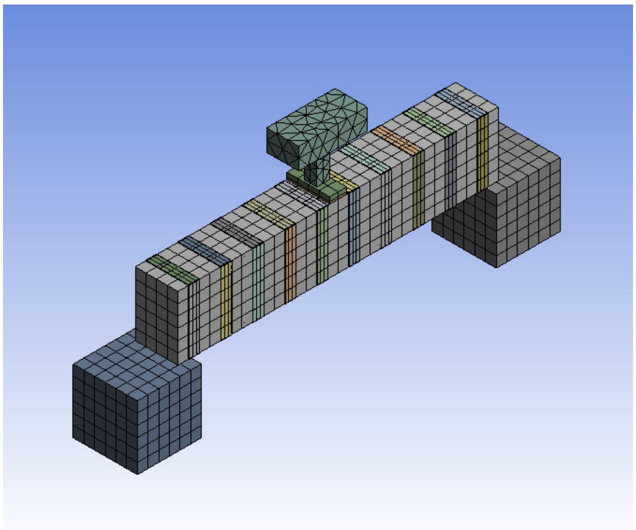


Fig. 9 Finite element mesh example of specimen

specimens are modeled in one to one scale. The hammer mass is formed in a geometry similar to the geometry that is used in the tests, in such a way that it weights as 5,250 kg. In the impact analysis that is made by ANSYS Explicit STR, the volume geometry of the RC beams and supports, and the volume geometry of the hammer are meshed with hexahedral and tetrahedral mesh elements, respectively. CFRP surface geometry is meshed with quadrilateral; and rebar geometry is meshed with beam (line) elements. An example that is selected from the finite element meshes of specimens is given in Fig. 9. In the analyses, a perfect adherence is considered to be available between the reinforced concrete beams and CFRP, but the contact parameters between them are ignored.

4.2 Comparison of experimental and finite element analysis results

The graphs, in which the experimental results and the values of finite element analysis are compared, are given for maximum acceleration, velocity and displacements in Fig. 10. When the results of experiment and numerical analysis are compared, the acceleration values that re obtained through ANSYS analyses are found to be higher. Comparison of experimental and finite element analysis results are given in Table 7. The acceleration values that are obtained from the beam of Specimen 1, 2 and 3 through ANSYS numerical analysis are greater than the ones measured from both right and left sides. Measured experimental acceleration values of Specimen 4's beam are found to be greater than that of the ones obtained from the analyses. ANSYS numerical analysis acceleration values in Specimen 1, 2 and 3's beams are 22%, 23% and 18% higher than the average of the acceleration values measured from right and left sides, respectively, while the average of the experimental measurements at Specimen 4's beam is 9% higher than that of the analyses. The acceleration values that are obtained from the beam of Specimen 5, 6 and 7 through ANSYS analyses are greater than the values obtained by experimental measurements. The acceleration values of Specimen 8's beam that is obtained by numerical analysis are in the range of the values that are measured from right and left sides. When compared to the average of the experimental result that is taken from the right and left, the acceleration values of Specimen 5, 6, 7 and 8's beams obtained in consequence of ANSYS numerical analysis are 42%, 24%, 25% and 10% higher, respectively. Conformity is observed between the experimental results and the results of analyses of Specimen 9, 10, 11 and 12. The numerical analysis acceleration value of Specimen 9's beam is 14% higher than the average of the measured values, and the average of the values measured in Specimen 10, 11 and 12's beams were 3%, 7% and 9% higher than the results of ANSYS analyses, respectively. The acceleration values from the analyses of Specimen 13, 14, 15 and 16's beams are 35%, 13%, 13% and 2% higher than the average of the measured values, respectively.

When the velocity values obtained from ANSYS analyses are compared with the velocities that are calculated according to the experimental data, the differences varied in the range of 10% to 55%. The displacement values obtained through ANSYS analyses are considerably lower than the average of the displacement values that are calculated for two points according to the experimental data.

The numerical analysis and experimental displacement results of the beams without CFRP strips are close to each other. The experimental displacement values of the beams with CFRP strips are 1,5 to 3.0 times higher than the displacement values that are obtained through ANSYS analyses. When the results of the experiments and analyses are compared, the acceleration and velocity data showed conformity to an acceptable extent. According to the numerical analysis and experiment results, the acceleration values showed conformity with averagely 16% difference, in the range of 2% and 42%. The velocity values showed conformity with averagely 28% difference, in the range of 10% and 55%.

When the displacement values are compared, significant differences are observed between the experimental results and analyses results. Although the displacement values obtained in the

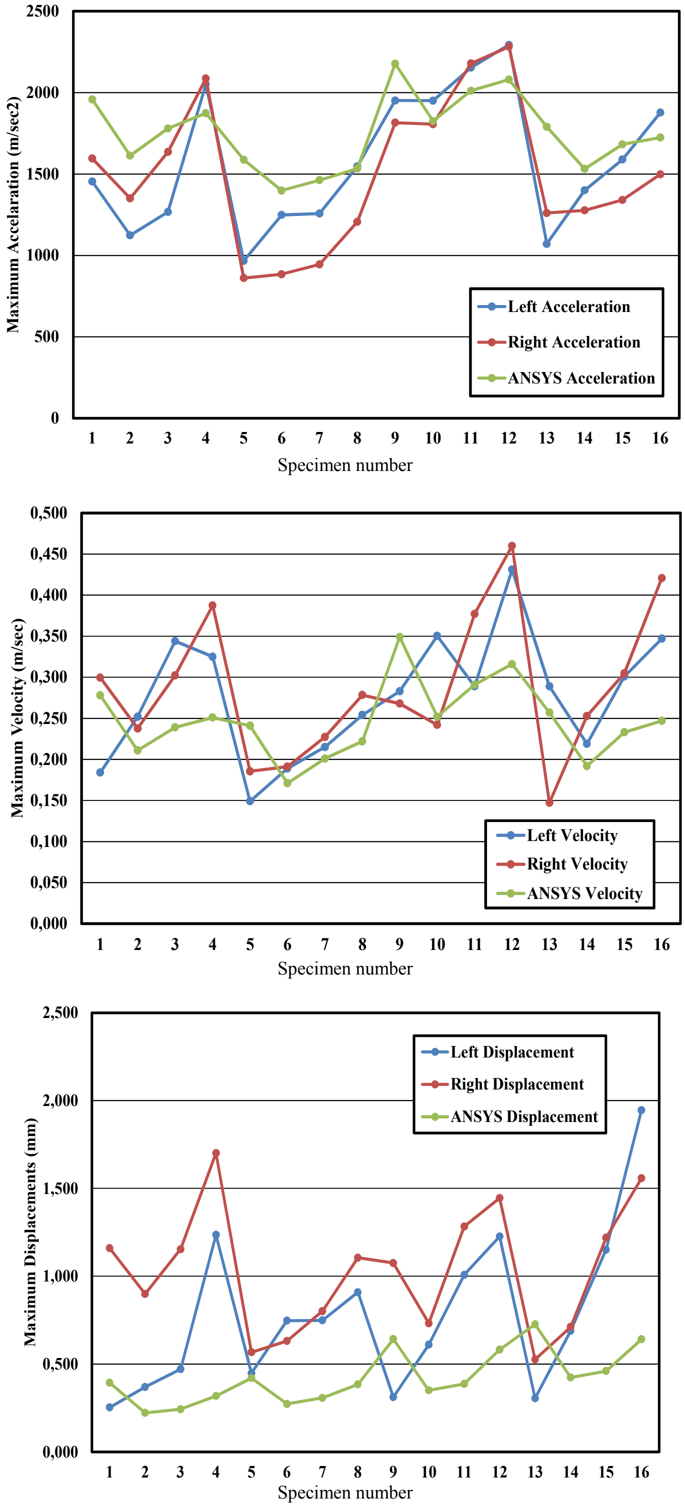


Fig. 10 Comparison of experimental and analytical results of specimens

Table 7 Comparison of experimental and finite element model results of specimens for first drop cycle

Spec. No.	Side of beam	Experimental results			Finite element analysis results		
		Max. Acce. (m/sec^2)	Velocity (m/sec)	Displa. (mm)	Max. Acce. (m/sec^2)	Velocity (m/sec)	Displa. (mm)
1	Left	1453,8	0,184	0,253	1958,3	0,278	0,393
	Right	1595,4	0,299	1,159			
2	Left	1123,9	0,252	0,369	1612,7	0,211	0,222
	Right	1350,6	0,238	0,899			
3	Left	1267,1	0,344	0,471	1779,9	0,239	0,243
	Right	1635,2	0,302	1,154			
4	Left	2051,5	0,325	1,235	1873,0	0,251	0,318
	Right	2085,9	0,387	1,701			
5	Left	966,8	0,149	0,448	1587,5	0,241	0,420
	Right	860,9	0,186	0,567			
6	Left	1248,5	0,189	0,747	1398,3	0,171	0,273
	Right	884,7	0,191	0,631			
7	Left	1257,2	0,215	0,749	1461,7	0,201	0,307
	Right	945,1	0,227	0,801			
8	Left	1546,3	0,254	0,909	1533,3	0,222	0,384
	Right	1206,3	0,278	1,105			
9	Left	1950,9	0,283	0,312	2177,0	0,349	0,642
	Right	1815,1	0,268	1,075			
10	Left	1950,1	0,350	0,610	1824,8	0,252	0,350
	Right	1806,1	0,242	0,732			
11	Left	2153,1	0,289	1,008	2010,6	0,291	0,387
	Right	2178,6	0,377	1,283			
12	Left	2292,4	0,431	1,226	2079,7	0,316	0,582
	Right	2281,5	0,460	1,445			
13	Left	1070,9	0,289	0,305	1789,9	0,257	0,726
	Right	1260,6	0,147	0,526			
14	Left	1399,8	0,219	0,689	1531,2	0,192	0,423
	Right	1277,0	0,253	0,711			
15	Left	1589,1	0,301	1,151	1682,2	0,233	0,460
	Right	1340,8	0,305	1,219			
16	Left	1876,7	0,347	1,945	1723,6	0,247	0,641
	Right	1498,1	0,421	1,558			

experimental study are higher than the values obtained through ANSYS impact analysis, the effect of the experiment variables on the displacements had similar tendencies. The increase in the spacing of CFRP strips, impact velocity, and the use of higher concrete strength led to the increase in displacements in both experimental and ANSYS analysis results.

5. Conclusions

The low-velocity impact behavior of shear deficient reinforced concrete beams that are strengthened with CFRP strips are examined within the scope of this study. The variables investigated in the study are input impact energy, concrete compressive strength, and wrapping spacing of CFRP strip that is used for strengthening against shear. Four series of specimens with concrete compressive strengths of 20 and 30 MPa; and 50, 75 and 100 mm spacing of CFRP strips at which hammer is dropped from two different heights of 500 mm and 750 mm, are tested within the scope of the experimental study. The results that are obtained from the study on totally 16 specimens, by producing 1 reference specimen for each series, are summarized below.

- In consequence of the increase in the drop height, which is one of the variables examined in the scope of the study, an increase is observed at the acceleration, velocity and displacement values that are measured from the specimens.
- As a result of the increase in concrete compressive strength, an increase in the acceleration, velocity and displacement values that are measured from the specimens are observed. The highest acceleration, velocity and displacement values are measured from the 3rd series of the specimens, which had a concrete compressive strength of 30 MPa and are tested from a drop height of 750 mm, within the scope of the experimental study.
- The wrapping spacing of the CFRP strips that are used for strengthening is the main variable of this experimental study, and it is observed to be extremely effective on the impact behavior of the reinforced concrete beams. Among the experimental series, reference specimen and the specimens with 100 mm CFRP strip spacing are showed similar behaviour and close to each other.
- CFRP strips that are applied to the specimens for strengthening increased the stiffnesses of the reinforced concrete beams, and reduced their ductility levels. Therefore, the accelerations measured from the specimens are reduced, in parallel to the decrease in the spacing of CFRP strips. Lower acceleration, velocity and displacement values are measured from the specimens that became rigid and with a reduced ductility.
- Acceleration, velocity and displacement values that are measured from the specimens increased in parallel to the increase in the spacing of CFRP strips. Therefore, acceleration, velocity and displacement values close to that of the values of reference specimens are measured from the specimens that are strengthened with CFRP strips having 100 mm spacing.
- The obtained results showed that the strengthening method with CFRP strips is highly effective in enhancing the impact behavior of the shear deficient reinforced concrete beams. The CFRP strips that are wrapped with low spacing led to decreases in the measured acceleration values and the velocity and displacement values also decrease parallel to acceleration. Thus, the specimens are enabled to reach higher acceleration values, by means of lower velocity and displacement values.
- The impact loading applied to the specimens reduced in consequence of the drops applied in the test. The impact loading measured to be the highest in the first drop reduced as a result of the increase in the damage that occurred in the specimens, and similar behaviors are observed in all specimens. The increases in the height of drop and compressive strength of concrete increased the impact loading.
- The maximum deformation occurred exactly at the mid-point of the reinforced concrete

beam, where the impact loading is applied. In general, the first crack in all specimens occurred at a capillary level as starting from the bottom surface of the beam, at the time of the first drop, when the largest loading is applied. The crack, which occurred at the time of the first drop, propagated in consequence of the increased number of the drops, and reached up to top surface of the beam in the experimental program.

- Some assumptions are made for saving the analysis time of the finite elements program ANSYS. Elastic material assumption is made for concrete. Authors thought that if nonlinear concrete models that represents the impact behaviour more realistically is used for modelling, closer results can be obtained to experimental ones. A perfect adherence is assumed to be achieved between the concrete and CFRP surfaces. Contact problems are non-linear problems. Experimental results are expected to be approached more, if CFRP-concrete contact points are modeled through the computer systems that permit the use of finer finite element meshes.
- When the results are examined, the effect of the variables such as concrete compressive strength, impact velocity and spacing of CFRP strip on the impact behaviors of the concrete beams are observed to have similar tendencies at experimentally and ANSYS analyses. Finite element models can give ideas to users for the designs of reinforced concrete structures under the effect of impact loading by means of the impact analyses that are performed through the finite elements program ANSYS Explicit STR. At this point, experimental results can be approached more, and more suitable models can be formed by means of developing nonlinear material models, detailed contact algorithms, and the increase in the number of analysis time steps.

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