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Investigation of lateral impact behavior of RC columns

Özgür Anil[*1], R. Tuğrul Erdem[2a] and Merve Nilay Tokgöz[1b]

[1]*Department of Civil Engineering, Gazi University, Ankara, Turkey*
[2]*Department of Civil Engineering, Celal Bayar University, Manisa, Turkey*

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Abstract. Reinforced concrete (RC) columns which are the main vertical structural members are exposed to several static and dynamic effects such as earthquake and wind. However, impact loading that is sudden impulsive dynamic one is the most effective loading type acting on the RC columns. Impact load is a kind of impulsive dynamic load which is ignored in the design process of RC columns like other structural members. The behavior of reinforced concrete columns under impact loading is an area of research that is still not well understood; however, work in this area continues to be motivated by a broad range of applications. Examples include reinforced concrete structures designed to resist accidental loading scenarios such as falling rock impact; vehicle or ship collisions with buildings, bridges, or offshore facilities; and structures that are used in high-threat or high-hazard applications, such as military fortification structures or nuclear facilities. In this study, free weight falling test setup is developed to investigate the behavior effects on RC columns under impact loading. For this purpose, eight RC column test specimens with 1/3 scale are manufactured. While drop height and mass of the striker are constant, application point of impact loading, stirrup spacing and concrete compression strength are the experimental variables. The time-history of the impact force, the accelerations of two points and the displacement of columns were measured. The crack patterns of RC columns are also observed. In the light of experimental results, low-velocity impact behavior of RC columns were determined and interpreted. Besides, the finite element models of RC columns are generated using ABAQUS software. It is found out that proposed finite element model could be used for evaluation of dynamic responses of RC columns subjected to low-velocity impact load.

Keywords: ABAQUS; dynamic analysis; impact effect; RC columns; weight falling drop test

1. Introduction

Concrete composed of cement, aggregate and water is a construction material that tensile strength is very low. Steel reinforcing bars are used to overcome this problem and improve ductility of concrete material. Because of functional advantages, RC structural members are widely used in building industry around the world. Behavior of these members under different loading conditions is a significant interest area of researchers. RC columns are designed by considering the effects of both vertical static and dynamic loads such as earthquake and wind. Impact load is a kind of impulsive dynamic load which is ignored in the design process of RC columns like other structural members. Examples include RC structures designed to resist impact loading scenarios such as falling rock impact; vehicle or ship collisions with buildings, bridges, or offshore facilities; and structures that are used in high-threat or hazard applications, such as military structures or nuclear facilities. As a result, considerable work has been undertaken in an effort to develop impact-resistant design procedures and to improve the performance of reinforced concrete structures subjected to impact loads. However, there are very limited amount of studies on their effects in comparison to the studies which are under the effect of static and dynamic loads. The major reason for such inadequate study is the fact that the analyses and design of structures exposed to dynamic impact loading are generally very complex, and these analyses become more complicated when working with inelastic materials, such as reinforced concrete.

There aren't any existing standards or methods for impact testing up to nowadays' studies. When the experimental impact studies at literature are investigated, they are categorized into two main segments. One of them depends on the investigation on specimens under impact loads that are applied by test equipment. These types of studies are concentrated on mostly steel materials. The other studies use equipment with mechanisms that drop masses from a height. This method is used mostly for the concrete impact testing (Chakradhara *et al*. 2010, Kantar and Anıl 2012, Nasr *et al*. 2013, Erdem 2014, Yousuf *et al*. 2014).

Experimental and numerical studies about impact loading on structural members have been performed in the literature less than the other type of loading such as dynamic and static load (Yi *et al*. 2015, Fujikake *et al*. 2006). Erdem *et al*. (2014), studied the impact behavior of RC beam test members by both experimentally and numerically. In addition, they performed non-linear

∗Corresponding author, Professor
E-mail: oanil@gazi.edu.tr
[a]Associate Professor
E-mail: tugrul.erdem@cbu.edu.tr
[b]Ms.c. Student
E-mail: tokgozmervenilay@gmail.com

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analyses to confirm the test results. Astarlioglu and Krauthammer (2014) have studied the responses of a normal-strength concrete column and ultra-high performance fiber reinforced concrete column under blast loads. Boundary conditions and compressive axial load due to gravity are taken into consideration in the analysis. Comparison of the column behaviors have been made in time-history domain and load-impulse domain.

In the study of Yang and Qi (2013), optimization of empty and foam-filled thin-walled square columns under oblique impact loading is performed. Dynamic finite element analysis techniques are validated by theoretical solutions and experimental data in the literature are used to simulate the crash responses. It is concluded that the optimal designs are generally different under various load angles for either empty or foam-filled column. Thai and Kim (2014) have investigated the damage and failure analysis of RC walls under missile impact loading by finite elements analysis. Longitudinal rebar and shear bar spacing are the variables in dynamic analysis to find out the optimal design of RC walls under impact effect.

In their study, Alam and Fawzia (2015) have numerically studied the strengthened steel columns by CFRP under transverse impact effect. They presented the behavior and failure modes of the members by finite elements analysis. The results of the study reveal that the strengthening technique improves the impact resistance capacity by reducing lateral displacement. Astarlioglu *et al*. (2013) have investigated the dynamic response of RC columns subjected to axial and blast-induced transverse loads by utilizing advanced single degree of freedom (sdof) model. Level of axial force and longitudinal reinforcement ratio are the main variables of the study. The results of sdof analysis are validated by the results of finite elements analysis software. It is indicated that the level of axial compressive load is effective on behavior of RC columns under transverse blast-induced loads.

In the study of Bao and Li (2010), researchers have analyzed the residual strength of blast damaged RC columns. Finite elements analysis is verified by experimental results. Ratios of reinforcement, column aspect and axial load are investigated in 12 columns. Finally, the parameters are incorporated into a proposed formula to estimate the residual axial capacity ratio. Wu *et al*. (2011) have studied the effects of explosive mass ratio on blast damaged composite columns. Test results are compared with the analytical results to validate the finite element model. Relationship between residual axial capacity and structural parameters as material strength, column details and blast conditions is investigated. In the end, two empirical equations are derived to predict the residual capacity index based on the explosive mass ratio.

In this study, 8 RC columns with 1/3 geometric scale are produced to investigate impact behavior under lateral loading. Special free weight drop test setup that is designed by the authors is used in the experimental part of the study. Steel hammer with 9 kg mass is applied on test specimens from 1000 mm height. Concrete compression strength, stirrup spacing and application point of impact loading are taken as the variables. Impact behaviors of the test specimens are determined by acceleration-time, displacement-time and impact load-displacement graphs. Besides, energy absorption capacities of specimens are calculated according to the area under the curve of the load-displacement graphs.

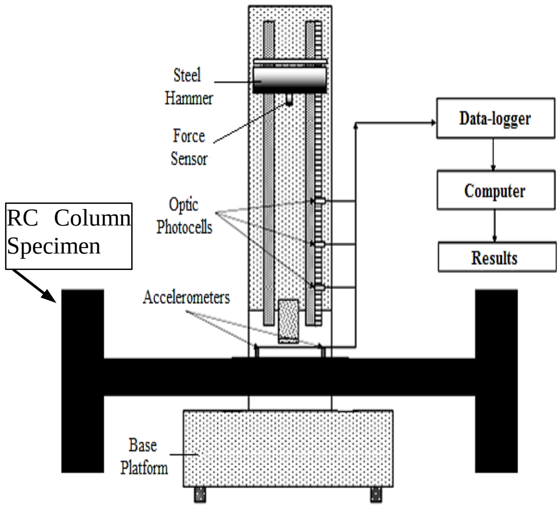


Fig. 1 Working mechanism of the test setup

It is aimed to investigate and interpret the effects of some variables on impact behavior of reinforced concrete columns. In this study, it is aimed to investigate variables such as column shear reinforcement ratio and place of load application point, which are thought to have significant effects on the behavior under the dynamic impulsive loads caused by impact or explosion in reinforced concrete columns. It is thought that the experimental findings obtained will contribute to literature. As can be seen from the literature summary given above, no study has been found to examine the behavior of the dynamic loads caused by impact or explosion in square cross-section reinforced concrete columns effect. Particularly, a study in which effects of confinement effect created by shear reinforcement and effects of impact loading applied to columns are not included in the literature. The location of the dynamic loading due to crushing or blasting on the vertical support elements may be in the symmetry axis of the building element or in the support zone according to crushing devices dimensions or distance of blast center to the column. It is thought that the study of the effects of such variables on the behavior of the columns will be an important contribution to the literature.

In addition to experimental study, non-linear dynamic analyses are performed by ABAQUS, 2010 finite elements analysis software to validate the acceleration, displacement, impact load and energy capacity values which are obtained from experimental part of the study. Besides, stress distributions of specimens are also obtained.

2. Experimental study

2.1 Test setup and equipment

A special weight dropping testing setup, which is designed by the authors, with necessary measurement devices are used in the experimental part of the study as presented in Fig. 1. The test setup is based on the free falling movement of a steel hammer with a definite mass to apply impact loading on test specimens. Potential energy is changed into kinetic one at impact moment.

Accelerometers, dynamic load cell, data-logger, LVDT, connection cables and optic photocells are the measurement equipment in the tests. Acceleration values are measured by symmetrically placed accelerometers. ICP type piezoelectric accelerometers are fixed on the test specimens by brass apparatuses. These accelerometers are able to measure any vibrations under dynamic effects. Besides, negative environmental conditions don’t affect their signal quality.

Impact loading is measured by dynamic load cell which moves with the steel hammer. Load cell properly measures the dynamic loads values under impact effect. Even big signals with small waves in short time spans can be measured by this sensor. Optic photocells on the test setup measure the drop time due to the movement of the hammer. Drop times are obtained in milliseconds by using optic photocells.

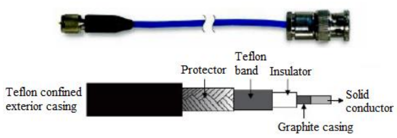
Linear variable differential transformers (LVDT) change the mechanical movement of an object into electrical signals. LVDT are fixed to test specimen to prevent moving during impact loading. Measured values are transferred to data-logger by low noise coaxial connection cables. Data-logger is able to collect measurement data very fast. The results are collected by data-logger and transferred to the software in the computer. Calibration of the measurement devices are performed by the software in the computer. Measurement devices used for test are given in Fig. 2.

2.2 Materials and test specimens

Seismic and wind load effects are commonly investigated by researchers in the literature. However, there are few studies about impact effects on structural members due to difficult and costly test conditions.

In the scope of this study, eight test specimens are manufactured in laboratory conditions. Behaviour of these members under impact loading is observed in the experimental program. Concrete compression strength, stirrup spacing and application point of impact loading are the experimental variables.

(a) ICP accelerometer



(b) Low noise coaxial cable

(c) Data-logger

(d) Differential transformer

Fig. 2 Test equipment

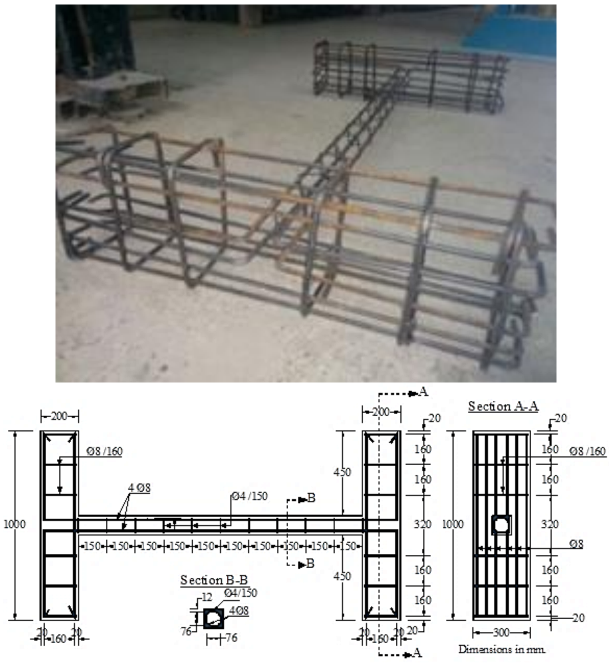


Fig. 3 Dimensions and reinforcement details of test specimens

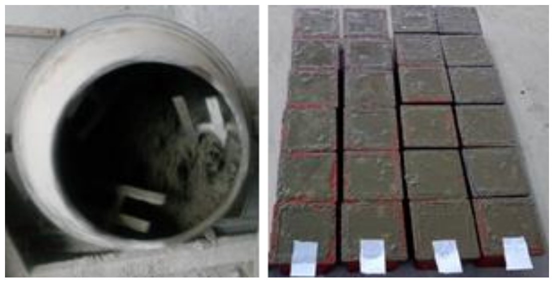


Fig. 4 Concrete production and cubic samples of specimens

Reinforcements of the RC columns are carefully constituted for each test specimen. S420 type reinforcement and two different stirrup spacing are used manufacturing process of the test specimens. RC column longitudinal reinforcement ratio is equal for each specimen. Sizes and reinforcement details using all of the test specimens are shown in Fig. 3.

Moulds of the test specimens are prepared in the laboratory by using plywood material. Lubrication of the moulds is performed before placing the reinforcement. Afterwards, material amounts for concrete production is determined. 10 MPa and 20 MPa compression strength concrete classes are targeted. The material ratios are given in Table 1 for two type concrete mixing. Concrete mixing machine is used for concrete production. Concrete is poured into the moulds of the RC column test specimens and fixe cubic concrete samples moulds are also prepared to determine the concrete compression strength values as shown in Fig. 4. After curing process has been completed for RC column test specimen and cubic samples, the specimens are categorized and prepared for tests. Properties of the RC column test specimens are given in Table 2

Before placing the test specimens in the testing setup, position of accelerometers are determined on the RC

Table 1 Material ratios for 1 m^3 concrete for low and normal strength

Material Type	Low Strength Concrete		Normal Strength Concrete	
	Amount (kg)	Ratio (%)	Amount (kg)	Ratio (%)
Cement (32.5 R)	210	8.77	325	13.57
Gravel (5-15 mm)	990	41.34	890	37.16
Sand (0-5 mm)	1050	43.84	990	41.34
Water	145	6.05	190	7.93

Table 2 Properties of test specimens

Specimen name	Average compression strength (MPa)	Stirrup spacing (mm)	Application point of impact loading
CS1	13.1	150	Middle of column
CS2	12.8	300	Middle of column
CS3	13.0	150	500 mm distance from column end
CS4	12.6	300	500 mm distance from column end
CS5	25.3	150	Middle of column
CS6	26.3	300	Middle of column
CS7	25.8	150	500 mm distance from column end
CS8	25.1	300	500 mm distance from column end

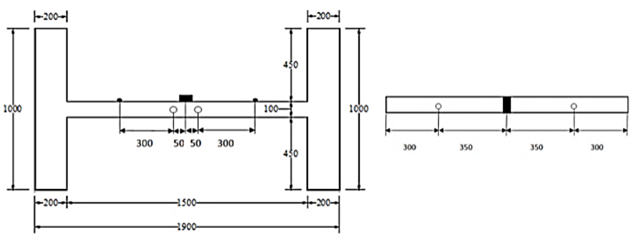


Fig. 5 Acceleration and displacement measurement sensors layout (Dimensions in mm.)

column specimens. Accelerometers are fixed by connection brass apparatuses to obtain measurement results without any loss. They are symmetrically placed from 350 mm distance from center of the test specimens. Displacement sensors are also located from 50 mm distance to symmetrical axis of column specimens. Positions of measurement devices on the test specimens are shown in Fig. 5. High strength steel plate with 10 mm thickness and neoprene rubber are also located to impact loading point. They are placed on the center of test specimens where impact loading is applied. By this way, impact loading is uniformly distributed and local crushing is prevented on the test specimens. A prepared test specimen in the testing setup is given in Fig. 6.

3. Experimental results

After test preparations are completed, all specimens are tested using with 9 kg hammer mass from 1000 mm height applying same amount impact energy (9.81×9.0×1.0=88.29 Joule) Time-varying acceleration, displacement and impact


Fig. 6 Test setup and instrumentations


Fig. 7 Crack distribution of CS2 specimen

load values are obtained for the first drop, first damage and failure damage situations. General behaviours of column specimens under sudden lateral impact loading are determined.

Crack and damage development of test specimens are observed during tests. While cracks occur in the first damage drop, some concrete spalling from test specimens and reinforcement rises to the surface when failure damage drop is reached. First damage and failure damage situations of CS2 test specimen are presented in Fig. 7 for example. From the figure it is observed nearly all specimens covered by inclined shear cracks due to impact loading. Furthermore, specimens with 300 mm transverse reinforcement spacing covered by wide and many shear cracks. In contrary to that on the specimens with 150 mm transverse reinforcement spacing generally hair line cracks were observed. Moreover spalling of concrete cover was observed only in the specimens with 300 mm transverse reinforcement spacing. Such observations illustrated the significance of transverse reinforcement spacing on the response of columns to the impact loading. Another important variable examined in the experimental study is the location of the impact load applied to reinforced concrete columns. When the impact load is applied to the axis of symmetry of the reinforced concrete columns, the damage distribution in the test specimens is more uniformly gathered at the lower and upper end supports of the column. Thus, the number of shear cracks and the widths of the cracks are smaller. However, if the impact load applied to reinforced concrete columns approaches one end of the column, the number of shear cracks and widths formed in the region is higher than symmetrical loading. The damage is concentrated at the end of the column where the load is located, causing this area of the test specimen to suffer more damage, especially during the failure drop phase.

The increase in the concrete compressive strength of the

Table 3 Drop times and numbers of test specimens

Specimen name	Drop time (msec)	Drop numbers	
		First damage	Failure damage
CS1	516	3	10
CS2	513	2	7
CS3	517	3	12
CS4	521	2	9
CS5	518	6	15
CS6	520	4	11
CS7	519	7	17
CS8	515	4	13

Table 4 Acceleration and displacement values of test specimens

Specimen name		First Drop		First Damage		Failure Damage	
		Acceler. (g)	Displ. (mm)	Acceler. (g)	Displ. (mm)	Acceler. (g)	Displ. (mm)
CS1	Min	-469.84	-3.93	-448.33	-3.99	-427.83	-4.34
	Max	326.13	1.26	338.56	1.40	323.45	1.53
CS2	Min	-593.50	-7.07	-423.20	-9.73	-584.86	-9.52
	Max	398.14	0.84	425.69	0.31	451.82	1.98
CS3	Min	-437.16	-6.63	-492.52	-7.44	-473.83	-8.26
	Max	433.34	1.85	401.76	2.53	412.44	3.24
CS4	Min	-456.60	-7.03	-622.00	-9.44	-568.7	-10.66
	Max	429.66	2.71	441.7	3.80	466.24	1.54
CS5	Min	-362.06	-7.18	-695.01	-9.77	-455.25	-11.03
	Max	362.18	0.50	367.08	0.67	370.58	0.89
CS6	Min	-855.72	-7.14	-537.44	-9.84	-418.68	-8.72
	Max	404.90	0.84	445.63	0.01	454.82	1.77
CS7	Min	-578.68	-5.73	-593.03	-7.24	-620.08	-8.09
	Max	397.10	2.47	411.78	3.87	488.55	4.30
CS8	Min	-937.23	-11.71	-798.77	-11.05	-976.15	-11.33
	Max	451.55	2.23	498.88	3.63	546.51	3.91

reinforced concrete column test specimens decreased the number of cracks and crack widths. In the case of increased concrete strength, the number of shear cracks in both the first drop and failure drop stages of the test specimens decreased. The spalling in the concrete cover was only observed in the test specimens with low concrete strength. In the experiments, the largest damage occurred in the CS4 test specimen where the concrete strength is low, the shear reinforcement is spacing 300 mm, and the load is applied close to the end part of the reinforced concrete column. Following CS4 test element, the greatest damage was observed in the CS2, CS3 and CS1 test elements. The shear reinforcement spacing must be decreased to prevent the brittle shear fracture mode that may occur in the test specimens, and the concrete compression strength must be high. If the impact load is closer to the midpoint of the column, the shear damage is reduced. This is one of the important experimental results obtained.

Due to drop height and mass of the hammer are constant, drop durations measurement are almost similar. This result shat that, minimizing friction effects in tests are achieved. Drop durations are counted by optic photocells in the test setup. By this way, drop time in milliseconds and

Table 5 Impact loads and energy capacities of test specimens

Spec. Name	First Drop		First Damage		Failure Damage	
	Impact load (kN)	Energy Capacity (joule)	Impact load (kN)	Energy Capacity (joule)	Impact load (kN)	Energy Capacity (joule)
CS1	16.47	14.63	21.29	16.51	19.63	15.74
CS2	22.02	19.08	23.34	31.87	22.54	30.06
CS3	16.63	13.55	18.42	18.76	16.37	20.93
CS4	23.89	20.50	27.36	34.35	26.44	38.95
CS5	22.79	20.54	14.30	20.20	16.57	25.27
CS6	20.95	19.61	22.11	29.51	20.57	26.83
CS7	22.34	19.78	24.68	25.35	22.93	28.32
CS8	17.64	26.13	18.90	28.91	16.29	25.41

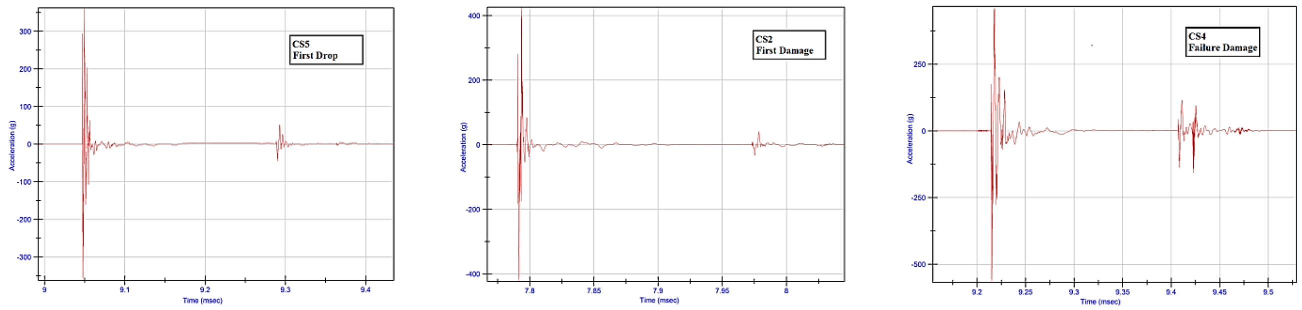
drop number values according to damage situations are determined as given in Table 3. It's observed that less rigid specimens reach failure damage situation earlier.

Acceleration values are measured from two points of the test specimens. Since these points are symmetrical each other, measured values are very close. Displacements are also measured by two LVDT devices. The values are transferred to data-logger for each drop movement of steel hammer. Maximum measured acceleration and displacement values according to damage situations are presented in Table 4. The results reveal that location of impact load, reinforcement configuration and compression strength of concrete have important effects on the results. It's also observed displacement values increase as the test specimens approach to failure damage. Dynamic load cell connected to steel hammer measures impact load for each drop. On the other hand, energy absorption capacities of test specimens are also calculated according to damage situations. The results are given in Table 5. The dynamic impact loading and maximum displacement distributions applied to the test specimens are combined for the same time interval. The impact load-displacement graphs are plotted during the time the impactor is in contact with the reinforced concrete column test specimen and during the period of maximum reaction. The energy values consumed by the column test elements as a result of the impact test were obtained by calculating the area under these graph lines. Examples of acceleration-time, displacement-time, load-time, load-displacement graphs of the test specimens are shown Fig. 8 (a)-(d).

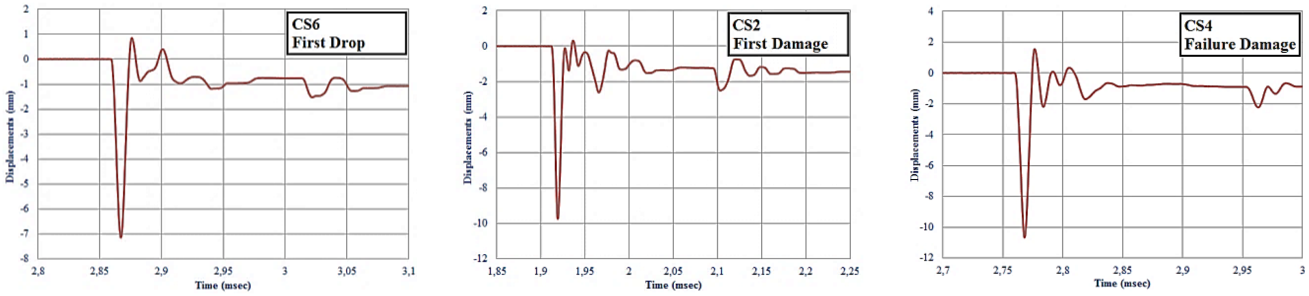
4. Finite elements analysis

Explicit module of ABAQUS analysis software is used for analyses to determine the behaviour of column specimens under lateral impact loading. This module is proper for incremental dynamic analysis characteristics and many material models can also be created in the module. In addition, element type, mesh size, boundary conditions, contact surfaces and time steps for reasonable analysis time are significant parameters which directly affect the results.

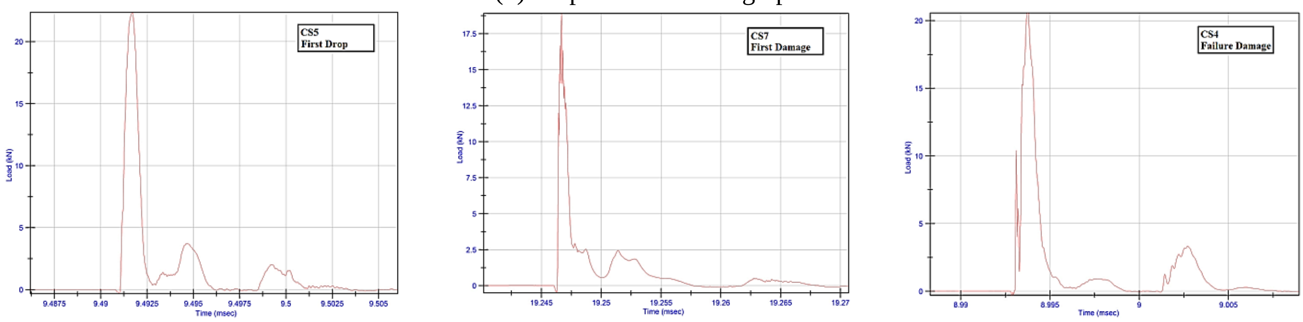
First of all, finite elements models of testing setup, hammer, test specimens, longitudinal and transverse



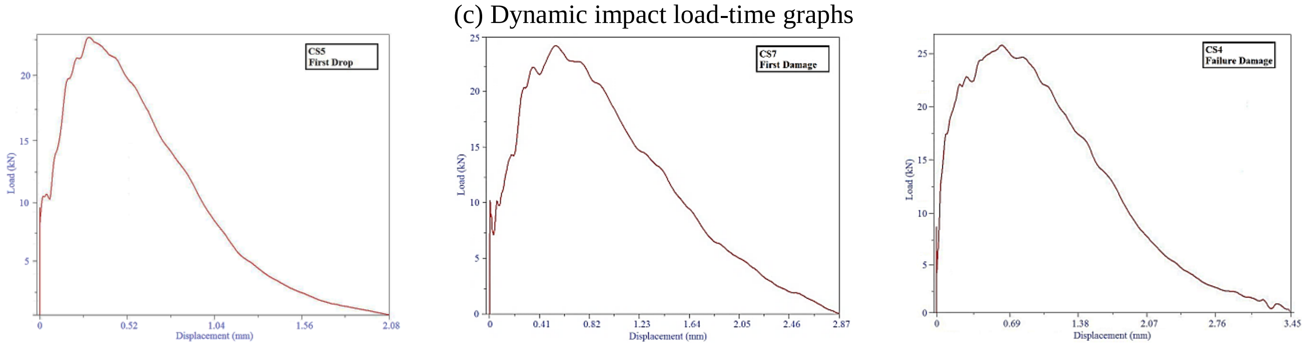
(a) Acceleration-time graphs



(b) Displacement-time graphs



(c) Dynamic impact load-time graphs



(d) Dynamic impact load -displacement graphs

Fig. 8 Examples of experimental graphs of test specimens

reinforcements and steel plate with neoprene rubber are created in the software. C3D10M (10-node modified tetrahedron) element type which is suitable for impact solutions is utilized for all models. Finite elements model of CS1 and CS3 specimens for two load conditions are presented in Fig. 9 for examples.

The supports of test specimens are assigned with the boundary conditions in horizontal, vertical and axial directions. On the other hand, steel hammer only moves vertically. Mesh size of the finite elements is important in terms of accurate analysis. Finite elements models of complex geometries are divided into small pieces. For this purpose, a few trials have been made to determine to proper mesh size. Finally, mesh size is decided as 20 mm for all geometries. Examples of finite elements models after defining support conditions and mesh properties are given in Fig. 10.

Because the solution requires incremental dynamic analysis, time steps and increments are determined from the beginning to the end of the drop movement of the steel hammer. The dynamic analyses are repeated for both time spans and increments until reaching the final values. While time increment is decided as 2×10^{-8} sec for 5000 time steps when the contact occurs between the hammer and the test specimen. Two different node and element numbers are used due to change in stirrup spacing. Node and element

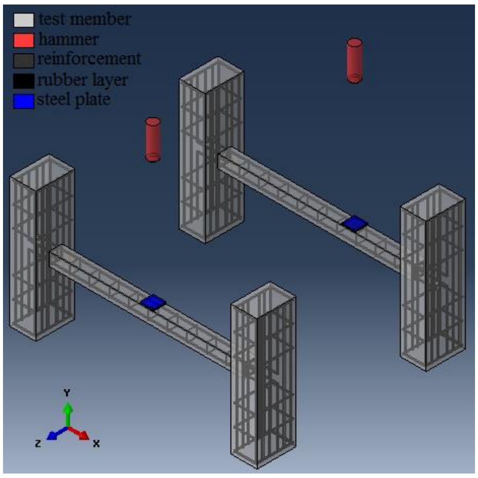


Fig. 9 Examples of finite elements models

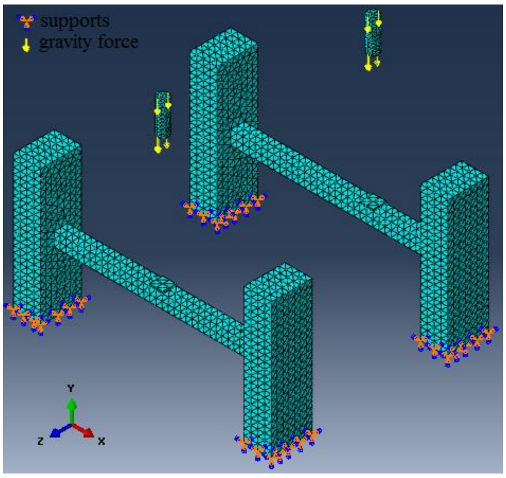


Fig. 10 Examples of finite element mesh example of specimens

Table 6 Node and element numbers

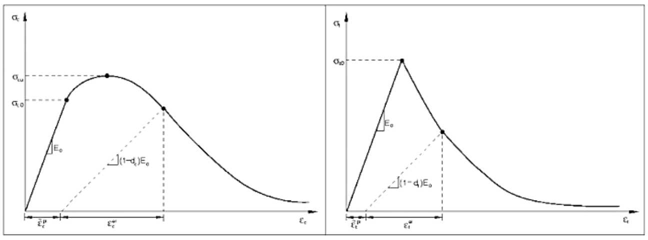
Specimen Name	Stirrup spac. (mm)	Node Number			Element Number		
		Test Spec.	Ham.	Steel plate and rubber	Test Spec.	Ham.	Steel plate and rubber
CS1,CS3, CS5,CS7	150	75104	1054	125	54349	581	48
CS2,CS4, CS6,CS8	300	66853			42942		

numbers in analyses are summarized in Table 6.

Since there are no external forces in free falling movement, only gravity force is applied to the system in the solutions. Connection between geometries is provided by interaction property of the software. Surface to surface contact is considered between steel hammer and test specimen. While the surface of the hammer which applies the impact loading is selected as master, surface of the test specimen is slave in the software. By this way, both surfaces are not allowed to penetrate each other. Because friction effects can't be set to zero in the experimental program, coefficient of friction is taken as 0.2 in the solutions.

Table 7 Material properties for reinforcement, steel hammer, plate and rubber

Property	Material		
	Reinfor.	Steel hammer and plate	Rubber layer
Weight per unit of volume (kg/m^3)	7850	7850	1230
Young's Modulus (MPa)	200000	200000	22
Poisson's ratio	0.30	0.30	0.45
Bulk modulus (MPa)	166670	166670	73.33
Shear modulus (MPa)	76923	76923	7.59
Yield strength (MPa)	420	-----	-----
Ultimate strength (MPa)	500	-----	-----



(a) for compression (b) for tension

Fig. 11 Material models for concrete

Steel plate and neoprene rubber layer are placed on the middle of the test specimens same as the experimental program. When hammer strikes test specimen directly, point loading and local crushing are observed. However, inner reaction of specimens is distributed. For this reason, steel plate and rubber tied together to reduce inner effects at impact moment and distribute the impact loading on test specimens.

Material properties are assigned to geometries. Linear elastic material models are used for hammer, longitudinal and transverse reinforcement, steel plate and rubber layer. While material model for properties of the reinforcement, hammer, steel plate and rubber layer are presented in Table 7.

Two concrete models are considered in the study. Properties of concrete materials are defined by using concrete damage plasticity model in the software. This model is one of the best models to represent the complex behaviour of concrete material. Stress-strain relationship is defined both in compression and tension as shown in Fig. 11. Density of concrete is 2400 kg/m^3 and Poisson's ratio is 0.2. Tensile strength is considered %10 of compression strength. Ultimate strain is taken as 0.003 mm/mm. While Young's Modulus is 24000 MPa and Shear Modulus is 9600 MPa for C10 concrete class, they are 28000 MPa and 11200 MPa, respectively for C20.

Material properties are assigned to related geometries. Drop height is 1000 mm and mass of the hammer is taken as 9 kg in the solutions similar to experimental program. Since the problem is a non-linear dynamic one, a high performance computer is used for analyses to obtain more sensitive results in a faster way. So, the analysis results are considered to be useful on the impact behaviour of lateral impact loading.

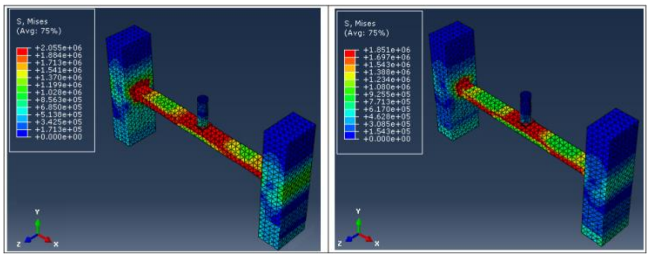


Fig. 12 Stress distributions for CS5 and CS1

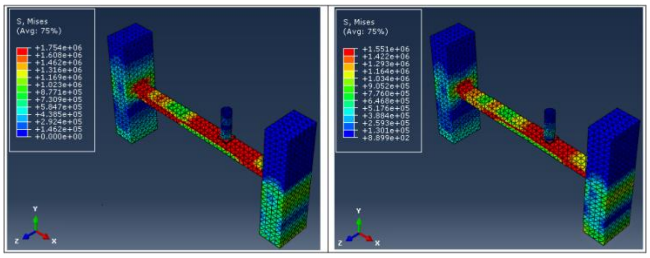


Fig. 13 Stress distributions for CS7 and CS8

The analyses are performed for the first drop moment of the hammer. Acceleration values are obtained from two symmetrical points on the test specimens. On the other hand, impact loads are determined from the applying impact loading on specimens. Von-Misses stress distributions that are parallel to crack development on specimens are also determined in the analyses. Some examples of stress distributions after impact load is transferred to specimens are presented in Figs. 12 and 13. In the incremental dynamic nonlinear analysis of the test specimens, the ABAQUS finite element software, which is also common in the literature, is used. Analyses were performed by using the finite element method with this software. ABAQUS analysis software does not perform analyses like very large deformations beyond plastic limits, piece snapping or disintegration analyses using Applied Element Method. In literature, Snapping or disintegration analyses were implemented by using spring element between all of the finite elements which were modelled continuum object. This type of analysis was made by using the Applied Element Method such as Ls-Dyna Software. For this reason, it is not possible to model damage cases like rupture and spalling of concrete in experiments with ABAQUS finite element software. However, the maximum Von-Misses strain distributions obtained with the ABAQUS finite element software largely match up with the damage and crack distribution occurring in the experiments. In regions where stress concentration is present, shear cracks and spalling of cover have occurred. There is a great similarity between the fracture and damage distribution in the experiments and the distribution of the stress contours obtained from numerical analysis. Fig. 12 and Fig. 13, it can be seen that the impact loading causes stresses at the impact point and the columns-support connection point. Experimental damage and shear crack propagation were concentrated in these regions and their widths increased. In addition, if the impact point approaches one of the points at which the column is supported, an increase in the stress intensity near the support point is observed, which is in

Table 8 Comparison of acceleration and displacement values of specimens

Spec. Name		Max. Acceleration (g) Test Results	Analysis Results	Test/ Analysis ratio	Max. Displacement (mm) Test Results	Analysis Results	Test/ Analysis ratio
CS1	Min	-469.84	-405.74	1.16	-3.93	-6.55	0.60
	Max	326.13	341.33	0.96			
CS2	Min	-593.5	-452.14	1.31	-7.07	-6.82	1.04
	Max	398.14	373.23	1.07			
CS3	Min	-437.16	-463.47	0.94	-6.63	-5.18	1.28
	Max	433.34	488.21	0.89			
CS4	Min	-456.6	-472.81	0.97	-7.03	-5.45	1.29
	Max	429.66	455.73	0.94			
CS5	Min	-362.06	-466.24	0.78	-7.18	-6.05	1.19
	Max	362.18	401.23	0.90			
CS6	Min	-855.72	-584.18	1.46	-7.14	-6.33	1.13
	Max	404.9	427.15	0.95			
CS7	Min	-578.68	-598.61	0.97	-5.73	-5.35	1.07
	Max	397.1	475.24	0.84			
CS8	Min	-937.23	-633.16	1.48	-11.71	-5.97	1.96
	Max	451.55	533.21	0.85			
Average				1.03	Average		1.19
Standard deviation				0.23	Standard deviation		0.33

Table 9 Comparison of load and energy values of specimens

Spec. Name	Impact Load (kN) Test Results	Analysis Results	Test/ Analysis Ratio	Energy Capacity (Joule) Test Results	Analysis Results	Test/ Analysis Ratio
CS1	16.47	20.43	0.81	14.63	18.54	0.79
CS2	22.02	19.69	1.12	19.08	18.27	1.04
CS3	16.63	20.78	0.80	13.55	17.71	0.77
CS4	23.89	19.27	1.24	20.50	17.43	1.18
CS5	22.79	26.13	0.87	20.54	21.83	0.94
CS6	20.95	24.55	0.85	19.61	21.37	0.92
CS7	22.34	25.32	0.88	19.78	24.83	0.80
CS8	17.64	23.58	0.75	26.13	24.32	1.07
Average			0.92	Average		0.94
Standard deviation			0.17	Standard deviation		0.15

agreement with the damage and crack distribution in the experiments.

Maximum accelerations and displacements of test specimens for the first drop are determined after non-linear incremental dynamic analyses. The values are compared with test results and given in Table 8. Average and standard deviation values are also calculated to present the relationship between test and analysis results. Impact loads are also determined after the steel hammer applies the loading on test specimens for the first drop. Energy capacities are calculated by considering load and displacement values of test specimens. The results are given in Table 9.

The maximum acceleration, maximum displacement, impact loading and the amount of energy consumed by the test specimens were calculated by the incremental dynamic analysis performed with the ABAQUS finite element software. It is seen that maximum impact loading, the amount of energy consumed by the test specimens and maximum acceleration values are more consisted with experimental values. The maximum impact load, energy capacity and maximum acceleration values were found to be in great agreement with the experimental study results. The greatest difference between the results of the analysis and the experimental results is the maximum displacement values. The maximum displacement values calculated by finite element analysis are less than the displacement values measured in the experiments. This result shows that the numerical calculation model behaves more rigidly than the experimental members. Material models of concrete used in ABAQUS finite element software are material models developed for static and long term dynamic loads. It is considered that an adjustment should be made on the model for impact loading, which is an impulsive loading type. In addition, the author believes that the ABAQUS material models developed for crushing concrete under compression and for cracking under the tension effect of concrete need to be adjusted for impact loading.

5. Conclusions

RC columns are one of the most significant bearing specimens in structures. They are affected by different loads during their service lives. Due to the developments in science and engineering, behaviour of RC columns under sudden dynamic loads has been an important field of interest. Researchers have been working on these specimens under sudden loads by designing different test setups.

In this paper, experimental and numerical studies have been performed to understand the behaviour of RC columns under lateral impact loading. For this purpose, 8 RC columns are manufactured and tested under lateral impact loading using with free weight drop test setup. Two different concrete compression strength, stirrup spacing and application point of impact loading are parameters that are investigated into experimental study. Impact loading is applied on test specimens dropping by a 9 kg steel hammer from 1000 mm height. Test setup is specially designed by the authors to investigate the behaviour of RC specimens. Accelerometers, differential transformers, optic photocells, dynamic load cell, and a data-logger are used to obtain test results.

Acceleration values are obtained by two accelerometers on the test specimens. The results are presented for the maximum values of these accelerometers. Accelerations change due to rigidity of test specimens. Damage situations even inner cracks affect the acceleration values. Acceleration values become bigger as the concrete compression strength increases. When the application point of loading changes, bigger values are measured from the accelerometers which are close to the impact point.

Impact loads are obtained for each drop by dynamic load cell that is connected to hammer. Impact load values change according to damage situations of test specimens. The results of first drop are almost same for the specimens having the same stirrup configuration and concrete compression strength. Minimum impact load is obtained from CS1 test specimen.

Displacements are measured by differential transformers from two symmetrical points of the test specimens. Displacement values get bigger as the test specimens approach to failure damage situation. These values are affected by the application point of loading at the same time. Displacement values change due to the distance between impact point and differential transformers. Stirrup distances and concrete compression strength have also effect the results. Displacements get bigger according to damage development in test specimens.

Energy capacities of test specimens are determined by calculating the area under the curve of impact load-displacement graphs. Load and displacement values are considered for the same time intervals. Energy capacities usually increase from first drop to the failure drop movements. It’s observed that both impact load and displacement values are effective while calculating energy capacities. In this way, the biggest capacity is determined for the failure drop of CS4 test specimen.

Since friction losses are minimized, drop durations of test specimens are very close to each other. Stirrup configuration and concrete compression strength effect drop numbers more than application point of loading. However, test specimens reach failure damage earlier when the load is applied on the center point. While drop numbers of test specimens for first damage are almost equal, drop numbers for failure damage differ from each other. Minimum drop numbers are observed for CS2 test specimen with 10 MPa compression strength and 300 mm distances between stirrups. Increase in the drop numbers have also resulted in increase in displacement values of test specimens.

In the numerical part of the study, ABAQUS/Explicit software is used for dynamic simulations. Test setup with column specimens are created and analysed under lateral impact loading. The analyses are performed for the first drop movement. Thus, acceleration, impact load, displacement and energy capacities of specimens are compared for the first drop of test specimens. In addition stress distributions are obtained after applying impact loading on specimens. Support conditions, material properties, drop height, mass of the hammer and reinforcement configuration are same as the experimental program.

Average and standard deviation values are calculated to obtain the compatibility between test and analysis results. It is seen that the results are consistent with each other in terms of acceleration, displacement, impact load and energy capacity. In addition, stress distributions are determined for both loading conditions. Maximum stress values are obtained around impact point and expand to the supports in the analyses.

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