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Impact behaviour of concrete beams

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Scientific paper - Preliminary note

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Impact behaviour of concrete beams

The determination of behaviour of structural members under load has become increasingly prominent with current advances in technology. The effect of impact on solids should not be ignored. The impact behaviour of non-reinforced concrete beams is investigated in this study both experimentally and using the finite element analysis. Members are tested in laboratory, and the ABAQUS software is used in the analysis. Accelerations, velocities, displacements, impact forces, and energy absorption capacities, have been obtained in the scope of these analyses.

Key words:
ABAQUS, concrete beams, finite elements, impact load, impact testing

Prethodno priopćenje

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Otpornost betonskih elemenata na udarno opterećenje

Određivanje ponašanja konstrukcijskih elemenata pod opterećenjem postaje sve značajnije zbog današnjih tehnoloških dostignuća. Utjecaj udara na kruta tijela ne smije se zanemarivati. U radu je prikazano istraživanje reakcija nearmiranih betonskih elemenata na udarno opterećenje i to kako eksperimentalnim putem tako i primjenom analize konačnih elemenata. Elementi su ispitani u laboratoriju, a za potrebe proračuna primjenjen je računalni program ABAQUS. U okviru provedenih analiza dobivene su vrijednosti ubrzanja, brzina, pomaka, udarnih sila i apsorpcije energije.

Ključne riječi:
ABAQUS, betonske grede, konačni elementi, udarno opterećenje, ispitivanje na udar

Vorherige Mitteilung

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Verhalten von Betonbalken unter Anprallbelastung

Die Bestimmung des Verhaltens von Strukturelementen unter verschiedenen Lasten ist aufgrund der heutigen technologischen Fortschritte von zunehmender Bedeutung. Der Einfluss von Lasten beim Anprall von Festkörpern darf dabei nicht überschaut werden. In dieser Arbeit wird das Verhalten nichtarmierter Betonbalken unter Anpralllasten durch experimentelle Versuche und durch auf der Finite-Elemente-Methode beruhende Analysen untersucht. Dementsprechend sind die Laborversuche und die im Software-Programm ABAQUS durchgeführten Berechnungen beschrieben. Im Rahmen der vollendeten Analysen sind Werte der Beschleunigung, Geschwindigkeit, Verschiebung, Anprallkräfte und Energieabsorption ermittelt worden.

Schlüsselwörter:
Abaqus, Betonbalken, finite Elemente, Anprallbelastung, Anpralluntersuchung

1. Introduction

Developments in the area of engineering change according to the variety of materials. It is important to know the properties of materials in civil engineering. Behaviour of construction materials under various loading cases has been a major area of interest. The knowledge of advantages, deficiencies and deformations of materials is essential for scientists and engineers.

Concrete is a composite material that is widely used in the construction of structures, bridges and roads. It is composed of cement, aggregate, sand, water and chemical additives if necessary. While the compression strength of concrete is high, its tensile strength is very low. Concrete elements assume the desired shape and are resistant to high temperatures.

Structures are exposed to static and dynamic loads. While static loadings are permanent, dynamic loads occur suddenly. The impact load occurs at the moment of strike between objects. It is the change of stress that is due to dynamic effects on mechanical properties of specimens. There are several impact incidents such as vehicle strikes on structures, explosions in military establishments, projectile and missile strikes, crane accidents while carrying specimens, and rock falls affecting structures located at roadsides. Various experimental and numerical studies [1-13] have been performed to investigate the impact effect on specimens.

Impact tests are based on the investigation of specimens subjected to impact load, by means of several devices. Testing devices are used to determine the impact behaviour of structural elements in experimental studies. While a standard for test methods is not available, ASTM E 23 provides information about testing devices and limits in impact tests [14]. Impact resistance of specimens can be determined by means of such devices.

In this study, 6 different concrete beam specimens are produced to investigate the impact effect. In the experimental part of the study, these specimens are tested using testing apparatus and necessary devices such as accelerometers, dynamic force sensor, connection cables, data logger, and optic photocells. In the finite elements part, the ABAQUS program is used for dynamic analyses [15]. The acceleration-time, velocity-time, displacement-time, impact force-time, and energy absorption values, are obtained for both results. Finally, the results are compared and suggestions are proposed.

2. Experimental study

In the experimental part of the study, concrete beam specimens are produced in the laboratory. Afterwards, these specimens are tested using the test devices and testing apparatus designed to investigate the impact effect. The results are collected in the data logger and transferred to the computer.

2.1. Testing apparatus and test devices

Since there is no standard for testing apparatus, the apparatus has been defined based on the analysis of studies presented in literature. The studies have revealed that the free falling testing apparatus is the best one for investigating crack patterns, damage situations, and deformation of specimens. This apparatus is based on the free falling movement of a steel hammer whose mass is changeable. The hammer drops to the centre of the test specimens, and the eccentricity of the hammer is set to zero to avoid secondary effects.

The main concept of the testing apparatus involves changing the potential energy to kinetic one at the moment of impact. The energy loss during the free falling movement equals to the energy gained by the test specimen. The apparatus is capable of dropping different masses from 2500 mm of height. The base platform measures 1000 x 1000 x 200 mm and is made of steel. The platform is designed as a thick structure capable of absorbing the movement at the moment of impact. There is 200 mm distance between slides of the apparatus. Optic photocells placed on the apparatus measure the drop time from the beginning of the hammer movement. Symmetrical holes are made on the base platform to provide support conditions for different distances. The testing apparatus is shown in Figure 1. There are four accelerometers, one dynamic force sensor placed at the edge part of the hammer, connecting cables, data logger, optic photocells, and a computer.

Figure 1. Testing apparatus

2.2. Preparation of concrete specimens for testing

Sizes of the test specimens vary from 100 x 100 x 710 mm to 200 x 200 x 710 mm. Moulds for the specimens have been prepared in laboratory using plywood. Then, they are placed into the curing pool for 28 days. Names of the test specimens are given in Table 1.

Tablica 1. Dimensions of the test specimens

Test specimen	Width [mm]	Height [mm]	Length [mm]
CS1	100	100	710
CS2	100	150	710
CS3	100	200	710
CS4	150	150	710
CS5	150	200	710
CS6	200	200	710

First of all, material ratios are decided for one cubic metre of concrete production. The necessary amounts are then calculated according to the volume capacity of specimen moulds. Material ratios per one cubic metre of concrete are given in Table 2.

Table 2. Materials for 1 m³ of concrete

Material	Quantity [kg]	Ratio [%]
Cement (42,5 R)	390	16,3
Gravel (5-15 mm)	910	38,2
Sand (0-5 mm)	870	36,5
Water	215	9,0

Twelve test specimens are first produced to define the drop height and mass of the hammer. Six of them are used in pre-tests. After mould lubrication operation, concrete is poured to cubic moulds as seen in Figure 2.

Figure 2. Test specimens and cubic moulds

The cubic specimens (dimension: 150 x 150 x 150 mm) are tested in the press machine after the 28-day curing period to define the concrete compression strength values. One cubic specimen in the press machine is shown in Figure 3.

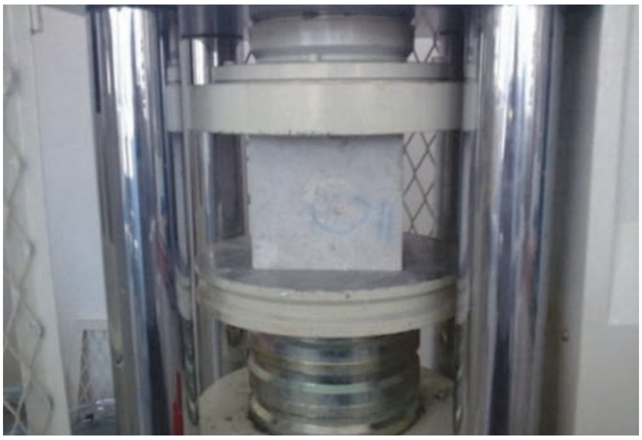

Figure 3. Compressive strength of concrete testing machine

Compression strength results are determined and given for each cubic specimen, together with an average value, as shown in Table 3.

Table 3. Compression strength values for cubic specimens

Cubic specimen	Compression strength [MPa]	Average value [MPa]
Specimen 1	38,5	38,1
Specimen 2	37,9	
Specimen 3	37,5	
Specimen 4	38,8	
Specimen 5	37,6	
Specimen 6	38,3	

Some preparations must be made before the testing. Test specimens are painted so as to make cracks more visible. The places of four accelerometers on each specimen are marked. Holes are made and steel dowels 6 mm in diameter are placed into these holes as shown in Figure 4. Brass devices are used to measure acceleration without any loss. Finally, accelerometers are symmetrically placed into these brass devices. Thus, acceleration values are determined from 150 mm and 250 mm distances of the impact point.

Figure 4. Prepared test specimens

The steel plate and neoprene rubber layer are used in tests. They are placed in the centre of the specimens, and are braced using plastic clamp bands. When the hammer enters into direct contact with the test specimen, the point load is applied and a hole appears at top surface of the specimen. The steel plate and rubber layer are used to uniformly distribute the impact load across the specimen surface during the testing. The CS5 test specimen in the apparatus is presented in Figure 5. Support conditions are provided by steel connecting devices. The drop height is 1000 mm, and the mass of the hammer amounts to 8 kg for all specimens.

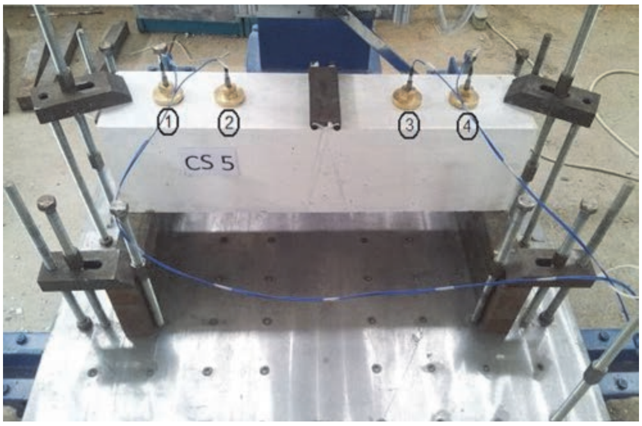

Figure 5. CS5 specimen prepared for testing

3. Finite elements analysis

The acceleration, velocity, displacement, impact force, and stress distribution values were obtained using the finite elements analysis. The ABAQUS program, which is widely used by researchers for dynamic analyses, was used in these analyses. The testing apparatus, test specimens, steel plate, and rubber layer, were first modelled in the program. The drop height of 1000 mm and the hammer mass of 8 kg were adopted in the analyses as well. Support conditions were defined so as to be similar to those registered during the experimental study. Linear models were used in the analysis since non-linear material models would extend the analysis time. Material properties are given in Table 4.

Table 4. Material properties

Property	Material		
	Concrete	Steel hammer and plate	Rubber layer
Weight per unit of volume [kg/m³]	2400	7850	1230
Modulus of elasticity [MPa]	32000	200000	22
Poisson's ratio	0,20	0,30	0,45
Shear modulus [MPa]	13333,33	76923,08	7,59

Since the problem is a free falling movement, only the gravity force was applied to the system. Rebound numbers were taken to be the same as those registered during the testing. Time increments were determined from the beginning to the end of the movement. The models were repeatedly analysed during very short time intervals. The distribution of accelerometers, steel plate, and rubber layer along the test specimens is presented in Figure 6.

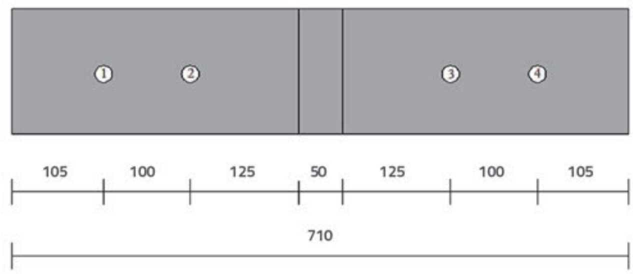

Figure 6. Top view of test specimens (dimensions in mm)

The models are separated into small pieces in the finite elements method. In this way, complex geometries can be investigated, and more accurate analyses can be performed. C3D10M (10-node modified tetrahedron) type specimens, which are appropriate for impact problems, are used in the analyses.

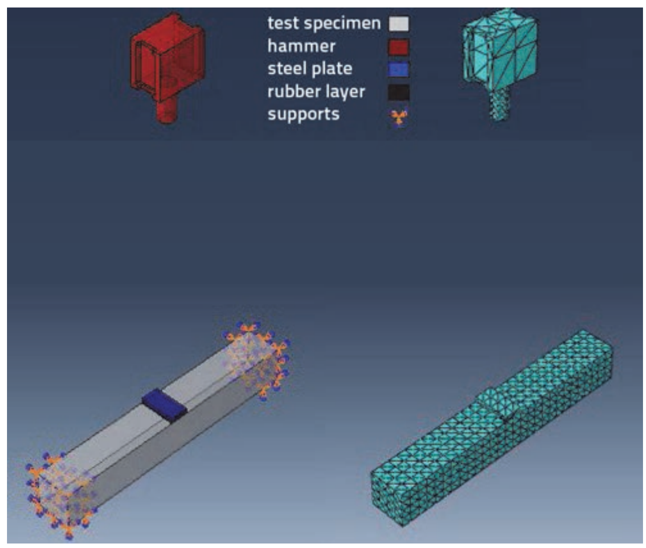

Figure 7. Finite elements model of CS1 test specimen

The size of the finite element is important for the time of analysis. More reliable results are obtained for small sizes. However, this would greatly extend the time of analysis. For this reason, the mesh design was made to decide the most suitable finite element size. The results are consistent between the sizes of 1 cm and 3 cm. So, the distances between meshes were taken to be 2.5 cm. Element numbers that are used in the steel plate and rubber layer are equal for the test specimens of equal width. Since the contact

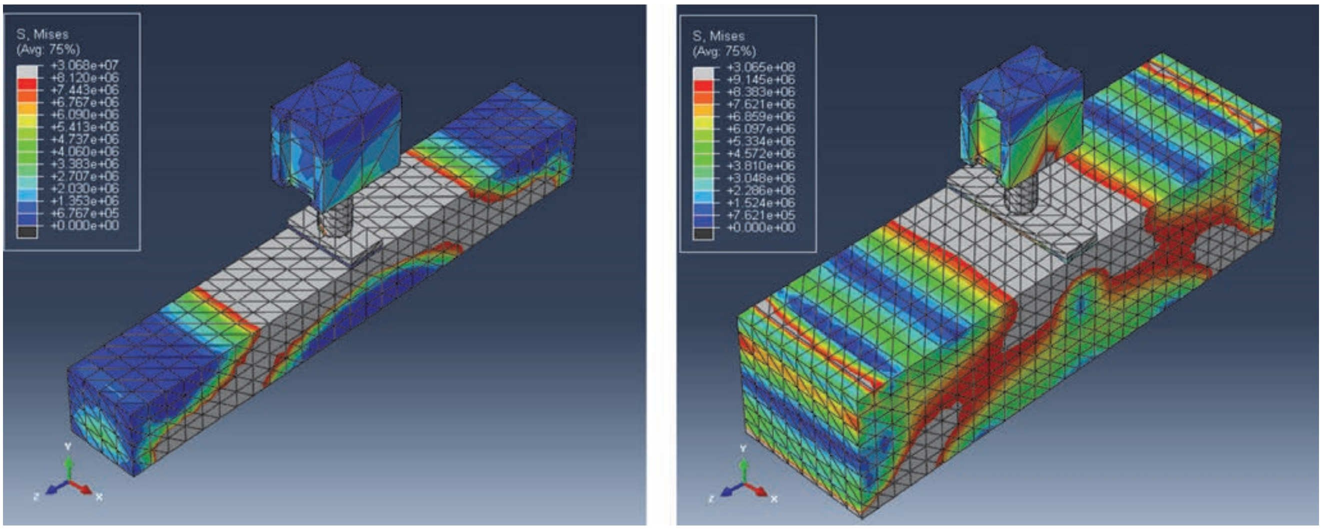

Figure 8. Stress distributions due to impact load

surface of the hammer is significant for the problem, the mesh size was taken to be 2.5 cm at the contact surface. The value of 5 cm was adopted for the remaining part of the hammer. The support lengths are 50 mm for each side of the test specimens. The finite elements model of the CS1 test specimen is shown in Figure 7.

After the finite elements analyses were performed for each test specimen, appropriate stress distributions were obtained. Stress values are given in Pa (N/m^2). Maximum stress values were registered around the impact point. Stress distributions when full impact loading is applied on CS1 and CS6 specimens are given in Figure 8.

4. Results

Test and analysis results for test specimens of different section are given in this part of the study. The acceleration-time, velocity-time, displacement-time, impact force-time, and impact force-displacement graphs, were prepared for test specimens. While velocity values were obtained by integrating accelerations, displacement values were determined by integrating velocities. A band is taken for the first drop movement in acceleration-time graphs for integration operations. Minimum and maximum acceleration values of the selected bands are used to calculate velocity and displacement values. Comparison results for the CS4 test specimen are given in Figures 9 through 14.

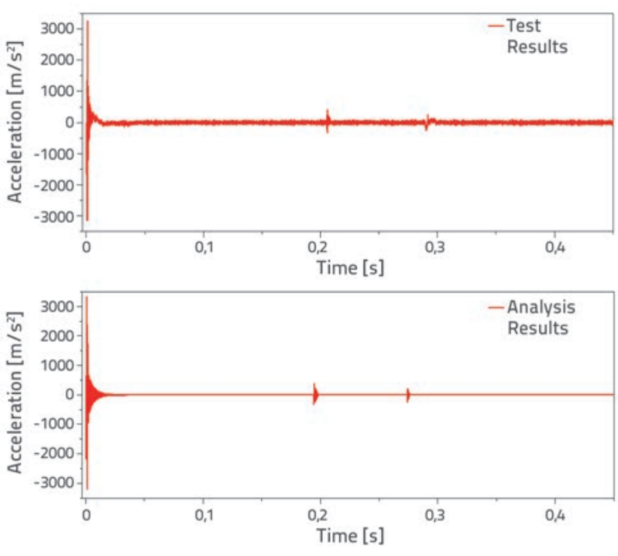

Figure 9. Acceleration-time graphs at 150 mm away from impact point

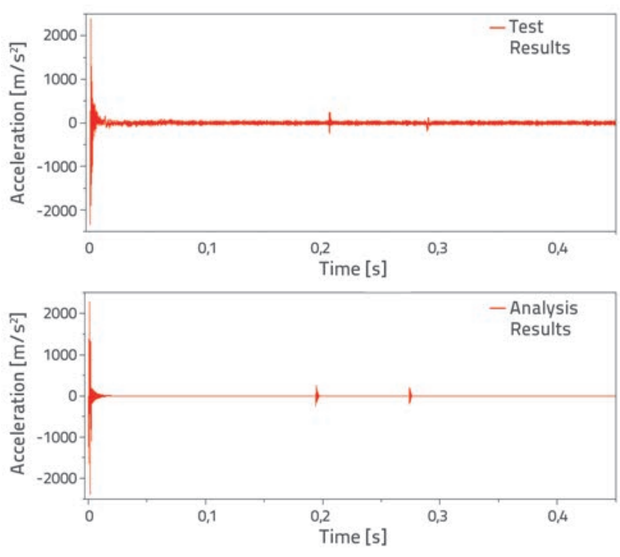

Figure 10. Acceleration-time graphs for 250 mm away from impact point

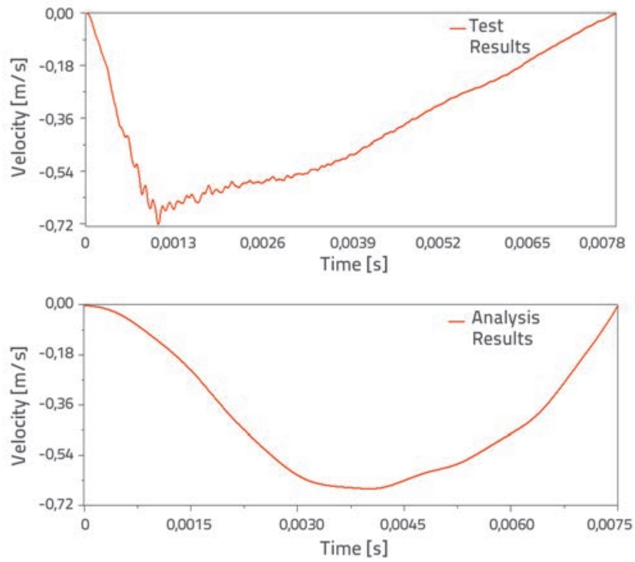

Figure 11. Velocity-time graphs

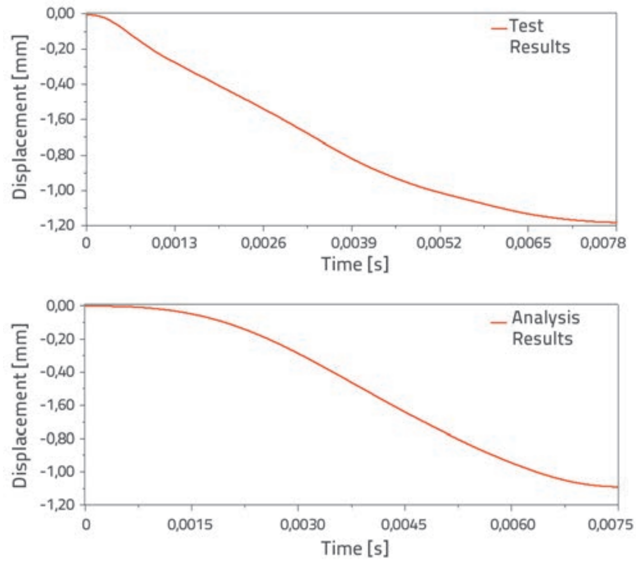

Figure 12. Displacement-time graphs

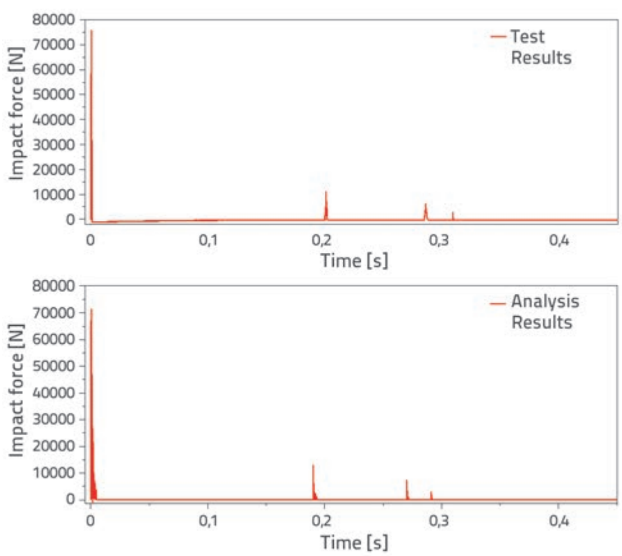

Figure 13. Impact force-time graphs

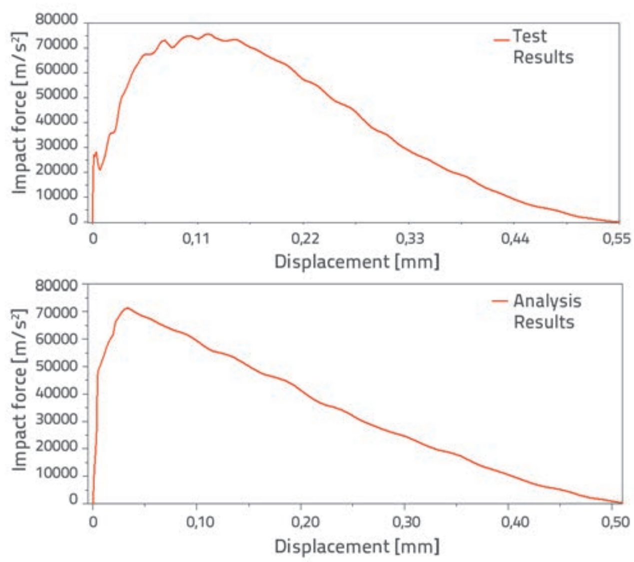

Figure 14. Impact force-displacement graphs

Acceleration values for all specimens subjected to testing and finite elements analyses, with average and standard deviation values, are given in Table 5. The values were determined by accelerometers during the testing. The results were also obtained for the same positions after the finite elements analysis.

After accelerations were measured by accelerometers, the velocity and displacement values were calculated after integration operations. The comparison of velocity values is given in Table 6.

Displacement values were calculated by integrating velocities. Test and analysis results are given in Table 7.

Impact force values were measured by the dynamic force sensor placed at the edge part of the steel hammer. The results are given in Table 8.

Energy absorption capacities of test specimens were calculated according to the area under the curve of the impact force-displacement graphs. The capacity values are given in Table 9.

Rebound movements were registered after the steel-hammer drops. Rebound numbers and the corresponding time periods according to the test and analysis results are given in Table 10. These values were determined using the dynamic force sensor that moved with the hammer.

Table 5. Acceleration values

Test specimen		Values at 150 mm			Values at 250 mm		
		Test [m/s²]	Analysis [m/s²]	Test / Analysis	Test [m/s²]	Analysis [m/s²]	Test / Analysis
CS1	min.	-2869	-2708	1,06	-2352	-2013	1,17
	maks.	2334	2403	0,97	1435	1856	0,77
CS2	min.	-3097	-2815	1,10	-1842	-2025	0,91
	maks.	2312	2422	0,95	2186	2018	1,08
CS3	min.	-2628	-2958	0,89	-2349	-2325	1,01
	maks.	3025	2743	1,10	2115	2284	0,93
CS4	min.	-3142	-3198	0,98	-2350	-2392	0,98
	maks.	3248	3323	0,98	2390	2288	1,04
CS5	min.	-3758	-3573	1,05	-2604	-2634	0,99
	maks.	2935	3337	0,98	2926	2774	1,05
CS6	min.	-3791	-3663	1,03	-3129	-2911	1,07
	maks.	3142	3395	0,93	3130	2996	1,07
Average				0,99	Average		1,01
Standard deviation				0,08	Standard deviation		0,10

Table 6. Velocity values

Test specimen	Values at 150 mm			Values at 250 mm		
	Test [m/s]	Analysis [m/s]	Test / Analysis	Test [m/s]	Analysis [m/s]	Test / Analysis
CS1	-1,25	-1,18	1,06	-1,18	-1,11	1,06
CS2	-0,93	-0,92	1,01	-0,83	-0,88	0,94
CS3	-0,84	-0,89	0,94	-0,68	-0,77	0,88
CS4	-0,72	-0,66	1,09	-0,65	-0,61	1,07
CS5	-0,68	-0,64	1,06	-0,63	-0,57	1,11
CS6	-0,47	-0,45	1,04	-0,43	-0,39	1,10
Average			1,03	Average		1,03
Standard deviation			0,05	Standard deviation		0,09

Table 7. Displacement values

Test specimen	Values at 150 mm			Values at 250 mm		
	Test [mm]	Analysis [mm]	Test / Analysis	Test [mm]	Analysis [mm]	Test / Analysis
CS1	-1,84	-1,64	1,12	-0,92	-0,86	1,07
CS2	-1,56	-1,50	1,04	-0,78	-0,81	0,96
CS3	-1,38	-1,44	0,96	-0,69	-0,75	0,92
CS4	-1,18	-1,09	1,08	-0,65	-0,60	1,08
CS5	-0,88	-0,79	1,11	-0,49	-0,43	1,13
CS6	-0,36	-0,32	1,13	-0,29	-0,26	1,12
Average			1,07	Average		1,05
Standard deviation			0,06	Standard deviation		0,09

Table 8. Impact force values

Test specimen	Test	Analysis	Test / Analysis
	Impact force [N]	Impact force [N]	
CS1	54424	50576	1,08
CS2	61979	56838	1,09
CS3	69759	66625	1,05
CS4	75704	71437	1,06
CS5	76428	78825	0,97
CS6	83878	81938	1,02
Average			1,04
Standard deviation			0,04

Table 9. Energy capacities of specimens

Test specimen	Test	Analysis	Test / Analysis
	Energy capacity [J]	Energy capacity [J]	
CS1	15,66	13,98	1,12
CS2	17,82	15,72	1,13
CS3	19,57	17,38	1,13
CS4	20,55	18,14	1,13
CS5	20,83	20,94	0,99
CS6	21,30	21,06	1,01
Average			1,09
Standard deviation			0,07

Table 10. Rebound numbers and time periods for test specimens

Test specimen	Test / Analysis	1.rebound time [s]	2. rebound time [s]	3. rebound time [s]	4. rebound time [s]
CS1	Test	0,180	0,255	–	–
	Analysis	0,174	0,245	–	–
CS2	Test	0,180	0,255	–	–
	Analysis	0,173	0,245	–	–
CS3	Test	0,190	0,270	0,290	–
	Analysis	0,181	0,257	0,274	–
CS4	Test	0,200	0,285	0,310	–
	Analysis	0,190	0,270	0,291	–
CS5	Test	0,220	0,315	0,345	–
	Analysis	0,207	0,296	0,326	–
CS6	Test	0,235	0,340	0,380	0,400
	Analysis	0,220	0,320	0,357	0,378

5. Conclusions

In this study, six concrete test specimens, whose sizes varied between 100 x 100 x 710 and 200 x 200 x 710 mm, were tested under the impact of the designed testing apparatus and necessary test devices. The drop height and mass of the hammer were taken to be constant during the testing. The concrete production was realized in a single operation, during which the concrete was poured into the moulds. Tests were performed after the 28-day curing period. Four accelerometers, one dynamic force sensor, connection cables, one data logger, and a computer, were used, together with the testing apparatus. In addition, a steel plate and rubber layer were used in order to uniformly distribute the impact load across test specimens, and to reduce internal effects at the moment of impact. Drop times were expressed in milliseconds using optic photocells. The acceleration-time, velocity-time, displacement-time, impact force-time, and impact force-displacement graphs were created, and the absorbed-energy values were calculated.

In the finite elements analysis, the testing apparatus and test specimens are modelled by the ABAQUS finite elements program which is widely used for dynamic analyses. The analyses are performed once material properties and support conditions are defined. The drop height adopted is 1000 mm, while the mass of the hammer is 8 kg. The most appropriate finite element size and time steps are decided after the pre-analyses. The analyses are performed for the first drop and the resulting rebound movements. The values concerning the acceleration, velocity, displacement, impact force, and absorbed energy, are obtained, and the relationship between the test and analysis results is investigated. Furthermore, stress distributions of the specimens at the moment of impact are determined.

Acceleration values are symmetrically measured by four accelerometers situated at 150 mm and 250 mm away from the impact point. The velocity and displacement values are calculated after integration operations for the same points in which accelerations are obtained. Impact forces are also measured by the dynamic force sensor. Absorbed energy

values by test specimens are calculated using the impact force-displacement graphs.
Acceleration-time graphs are created based on the values measured with accelerometers. Acceleration values measured at 150 mm away from the impact point are greater than those measured at 250 mm. Acceleration values also increase with an increase in section size. The greatest values have been obtained at the CS6 test specimen. In addition, noise effects can be seen more clearly from the acceleration-time graphs of test results.
When the velocity and displacement values were investigated, it was established that higher values are obtained from the distance of 150 mm, just like in case of acceleration values. On the other hand, the values decrease with an increase in section size. The highest velocity and displacement values were obtained for the CS1 test specimen, and the lowest values were obtained for the CS6 test specimen. Due to noise effects and variations in the gravity force and data numbers, some differences between the test and analysis results were registered.
Impact forces were measured with the dynamic force sensor which was placed at the edge part of the hammer. Higher values were obtained as the section size increased. The highest impact force value was registered at the CS6 test specimen. Absorbed energy values were calculated according to the area under the curve of impact force-displacement graphs. The CS6 test specimen had the highest energy capacity when compared to other specimens.
Rebound movements after the drop were also registered for test specimens. Rebound numbers increase from the CS1 test specimen to the CS6 test specimen. Rebound periods are parallel to rebound numbers. Since the hammer moves higher as the section sizes increase, the biggest rebound periods were observed at the CS6 test specimen.
Diagrams were also created once the acceleration, velocity, displacement, impact force and absorbed energy values were obtained during the finite elements analyses. The average and standard deviation values were calculated to enable comparison between the test and analysis results. A good correspondence between the results was registered. Consequently, the analysis model can be used at the design phase to determine the impact behaviour of test specimens. Finally, this study can be further developed by investigating deformation propagation, different materials, and structural members.

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