DOI: https://doi.org/10.14256/JCE.1557.2016

Građevinar 6/2017

Primljen / Received: 7.1.2016.
Ispravljen / Corrected: 2.10.2016.
Prihvaćen / Accepted: 1.3.2017.
Dostupno online / Available online: 10.7.2017.

Non-linear analysis of reinforced concrete slabs under impact effect

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Professional paper

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Non-linear analysis of reinforced concrete slabs under impact effect

Most of the existing structures are designed to resist static loads only. Various researchers indicate that sudden loads affecting structural members should also be considered in the design phase. Surfaces of many structures are covered with concrete slab members that are under the effect of sudden loads such as accidental drops, rock falls, or military attacks. A non-linear analysis of RC slabs is performed in this study using the Abaqus software. Impact parameters such as accelerations, velocities, displacements, impact forces, and energy capacities, are determined for each slab.

Key words:

impact parameters, non-linear analysis, sudden loads, support conditionss

Stručni rad

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Nelinearna analiza ab ploča opterećenih udarnim opterećenjem

Većina postojećih konstrukcija projektirana je tako da se odupre samo statičkim opterećenjima. Brojni istraživači ukazuju da u projektnoj fazi treba razmotriti i iznenadna opterećenja. Površine mnogih građevina izvedene su ab pločama koje su pod utjecajem iznenadnih opterećenja poput iznenadnih padova različitih elemenata, odrona kamenja ili vojnih djelovanja. Nelinearna analiza ab ploča u radu je provedena primjenom računalnog programa ABAQUS. Određeni su i detaljno analizirani parametri udara kao što su ubrzanja, brzine, pomaci, udarne sile i energetski kapaciteti za svaku ploču.

Ključne riječi:

parametri udara, nelinearna analiza, iznenadna opterećenja, uvjeti oslanjanja

Fachbericht

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Nicht lineare Analyse von Stahlbetonplatten belastet durch Stoßbelastung

Die meisten bestehenden Konstruktionen sind projektiert, um statischen Belastungen standzuhalten. Zahlreiche Forscher weisen darauf hin, dass in der Projektierungsphase auch plötzliche Belastungen berücksichtigt werden müssen. Die Oberflächen vieler Gebäude sind aus Stahlbetonplatten ausgeführt, die unter dem Einfluss überraschender Belastungen wie plötzliches Herunterfallen unterschiedlicher Elemente, Steinschlag oder Militäraktionen stehen. Die nicht lineare Analyse von Stahlbetonplatten in Benutzung wurde durch die Anwendung des Computerprogramms ABAQUS durchgeführt. Für jede Platte wurden die Parameter des Aufpralls wie Beschleunigung, Geschwindigkeit, Verschiebungen, die Stoßkräfte und die Energiekapazität bestimmt und detailliert analysiert.

Schlüsselwörter:

Stoßparameter, nicht lineare Analyse, plötzliche Belastung, Bedingungen der Anlehnung

1. Introduction

RC structures constitute the majority of the existing structure stock due to developments in this field. The design of these structures is performed under the effect of several static and dynamic loading conditions. Structural members may collapse when they are exposed to sudden loads such as impact and blast loads during their service life. As it is much more complicated to perform the analysis for sudden loads, not many studies have so far been published about this subject. Thus, it it becoming increasingly important to understand the behaviour of structural members under these loads as RC flat slab structures are widely used in construction projects owing to economic and functional advantages. RC slabs are widely used in the structures to separate floors from each other. They are usually horizontal members that transfer loads to beams, columns, and shear walls. Areas of usage of the most structures are covered by RC slabs. Since these members are slender, they are susceptible to collapse under sudden loads. It is therefore important to decide on the thickness and reinforcement configuration of RC slabs in the design phase.
Structural members, and slabs in particular, are directly susceptible to sudden loads, which may be due to several reasons. The impact load is a significant sudden dynamic load and its intensity may be significantly higher compared to other loads. Rockfalls, accidental events, especially in factories, vehicle collisions, explosions, projectile, missile or aircraft impacts, terrorist attacks and ice impacts, can all be considered as typical examples of sudden loads. These effects could completely destroy structures in a very short time span. The impact effect changes mechanical properties of structural members due to dynamic effects. Stress values change because of these effects at the strike moment. Damage expands beyond the impact point during such crushing events. For this reason, extensive damage and losses may be observed. Various experimental [1-9] and numerical studies [10-21] have recently been developed by many scientists to facilitate better understanding of these complex impact-related situations.
The resistance of structural members to impacts has been determined in literature through several experimental studies based on the use of testing apparatuses and essential test devices [22, 23]. However, experimental studies can be impractical and require expensive devices to observe crack pattern and failure of test members. On the other hand, similar results can be obtained through non-linear finite elements analyses when correct numerical models and analysis steps are defined [24-29].
Although there are some difficulties in individual phases of the analysis, non-linear dynamic solution results have proven to be increasingly accurate and reliable thanks to advances in modern computer technology. The results of non-linear analyses performed by various researches have been dependent on development of appropriate models in the scope of their solutions. For this reason, complex three dimensional finite elements analysis has in recent times come forward as an option relying on technological developments.
In this study, RC slab members are modelled for three different thicknesses and two support conditions by means of the Abaqus finite elements analysis software [30]. This software is used to explicitly investigate dynamic behaviour under impact load. The analyses have been completed for each model. In this way, the behaviour of thick slabs - which are otherwise difficult to test in laboratory conditions due to heavy loads - can be investigated by finite elements analyses.
As many researchers avoid numerical impact analyses due to several difficulties in the modelling of necessary parts, in defining contact surfaces and properties for each material, exploring proper mesh sizes, and performing time-consuming calculations, this paper may fill a gap in explicit dynamic analyses focusing on the effect of sudden loads.
This study also addresses the reliability of dynamic solutions, i.e. their capacity to present correct results. After necessary analysis steps are performed, impact parameters such as acceleration, velocity, displacement, impact force and energy capacity values are obtained. Stress distributions are also observed according to support conditions. Finally, the results are compared and appropriate suggestions are proposed.

2. Properties of the slabs

Dimensions of the RC slabs are 100 x 100 x 8 cm, 100 x 100 x 12 cm, and 100 x 100 x 15 cm. Reinforcement diameters, numbers and spaces are taken as constant for each member. On the other hand, two different support conditions are considered in the analyses. Geometrical properties of the RC slabs with support types are given in Table 1.
Support conditions are also taken into consideration in the study. Fixed support types are used in non-linear analyses. Two and three dimensional views of fixed support conditions of four and two opposite sides are presented in Figure 1.a and 1.b.

Table 1. Geometrical properties of RC slabs

Mark of RC slabs	Width [cm]	Length [cm]	Thickness [cm]	Support type
RS1	100	100	8	All sides
RS2	100	100	12	All sides
RS3	100	100	15	All sides
RS4	100	100	8	Opposite sides
RS5	100	100	12	Opposite sides
RS6	100	100	15	Opposite sides

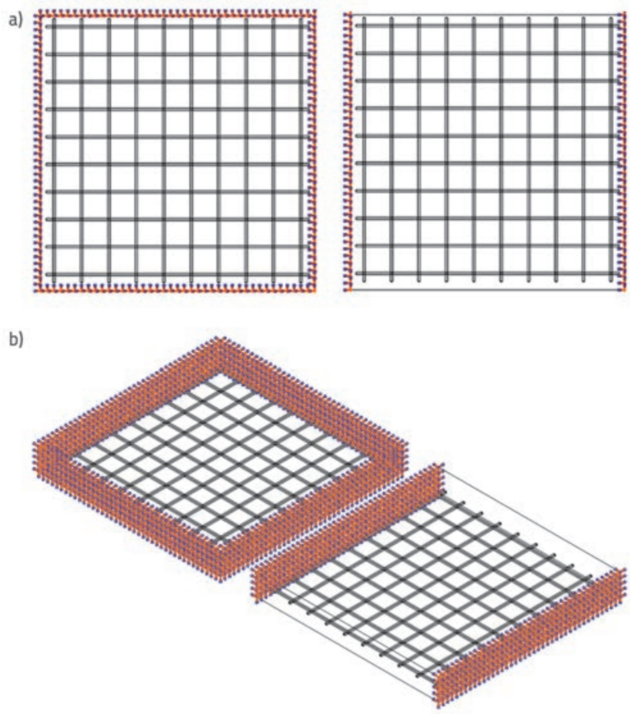

Figure 1. Fixed support conditions: a) Top view of support conditions; b) Three dimensional view of support conditions

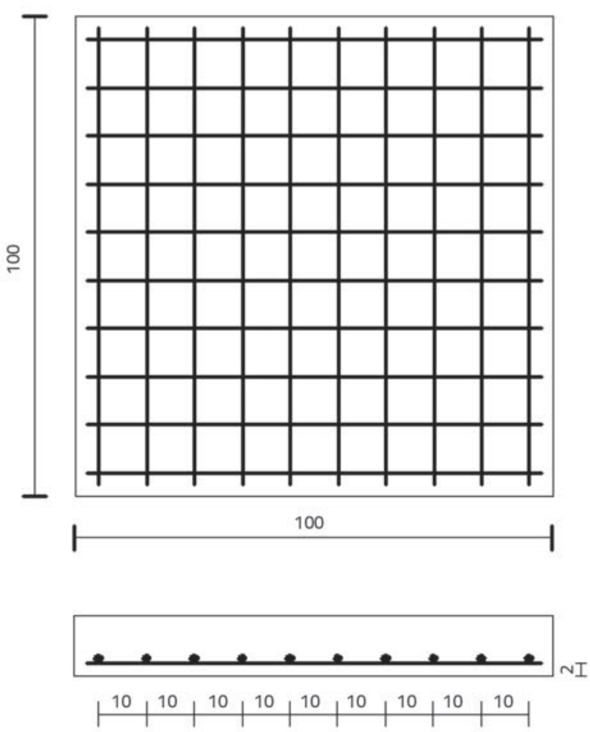

Figure 2. Top and side views of slab members, dimensions in cm

Material properties are assumed to be 30 MPa for concrete compression strength and 420 N/mm^2 for yield strength of the reinforcement. Reinforcing bars measure 8 mm in diameter and are spaced at 10 cm intervals. Ten reinforcing bars are placed in each direction of the RC slabs. Concrete covers are taken as 2 cm in the analyses. The plan and side views are shown in Figure 2 to present the reinforcement configuration.

3. Finite elements analysis

The analyses are performed using the Abaqus/Explicit software to investigate behaviour of RC slab members after exposure to sudden loading. The explicit module, appropriate for different types of material models, is responsible for successful completion of dynamic analyses. Once the models are created, the element types, material properties of related sections, proper step and mesh sizes, connection between surfaces of elements, correct boundary, and initial conditions are provided.
Time steps have an important effect on the results of impact analyses. For this purpose, both step and total time spans are checked consistently. Time steps are determined from beginning to the end of the drop movement of the steel striker. While the time increments have been defined as 0.060 seconds before the contact point, they have been set to 2x10^{-8} seconds when the contact between the striker and the slab has started. Since this is an incremental dynamic problem, the finite element models are analysed for very small time increments until proper results are obtained in terms of stress distribution, acceleration, impact force and displacement values.
The first step of the analysis is to divide the entire geometry so as to define the real model of the physical problem. Finite elements models should be separated into small pieces, known as meshing, so that the analyses can be performed correctly. Thus, complex geometries can be investigated and the results are more reliable. In this study, the models are divided geometrically to obtain proper solutions. C3D10M elements are utilized in the analyses. Three dimensional 10-node modified tetrahedron shaped elements are widely used to simulate the impact behaviour of structural members.
In impact problems, the vertical striker does not interact with the test member directly. A steel plate and a rubber layer are tied together and placed on the member. According to results obtained by experimental studies [3, 4], the striker applies point load onto the member. However, the inside reaction of the member is distributed. For this purpose, a steel plate with a rubber layer is used in analyses to reduce inside effects at impact moment, and distribute the impact load onto members.
Horizontal movement of the steel vertical striker is restrained. It can only move vertically. As the problem is related to the free falling movement, only gravity force is applied to the system. A rubber layer and a steel plate are located in the middle of the slab members. The connection between individual members has an important effect on results. The interaction between these members and the striker must be modelled properly so as to enable reliable determination of impact behaviour. So, while the striker surface is selected as master, the plate surface is slave. The contact between them is tangential. As there are frictions in

practice, the coefficient of friction is taken to be 0.2 for all contact surfaces.

First of all, three dimensional geometries of individual members are created by means of C3D10M (10-node modified tetrahedron) elements. The slab member with reinforcement, rubber layer and steel plate sections are combined. The steel striker is of different geometry. It is modelled as a cylinder shape that applies impact load in the midpoint of the slab member by falling from the height of 125 cm.

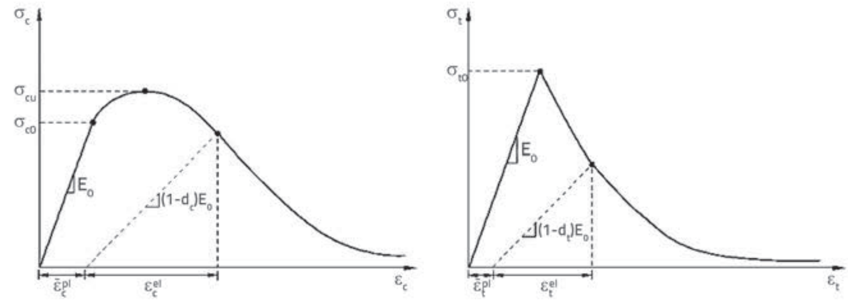

Figure 4. Stress-strain relationships for the concrete material

Secondly, the test setup has been established by combining these members to obtain a complex geometry. Fixed support types are assigned for two situations as four sided and two opposite sided. Three dimensional simulation models for RS2 and RS5 members are presented in Figure 3.

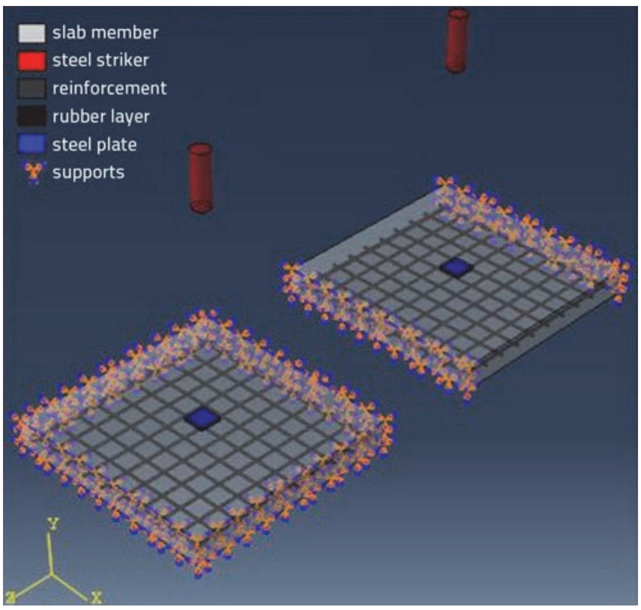

Figure 3. Simulation for each support condition

Rebound movements of the steel striker are restrained. So, the analyses are performed for each single drop of the striker. While the drop height is 125 cm, the mass of the striker is taken to be 10 kg in the analyses. The solutions continue until the RC slabs reach failure damage situation in which maximum displacements and stresses are observed. The analyses are repeated under the effect of the equal mass of the striker from the position of the first drop.

Afterwards, material properties are assigned to the related geometrical sections. Linear elastic material models are used for the steel striker, steel plate, rubber layer and reinforcement. Concrete damaged plasticity property of the software is used to define concrete. Stress-strain relationships for the concrete material in compression and tension are shown in Figure 4. Concrete is modelled with the compression strength of 30 MPa, density of 2400 kg/m^3, elasticity modulus of 32000 kg/m^3 and Poisson's ratio of 0.20. In addition, material characteristics of the steel striker, steel plate, rubber layer and reinforcement are given in Table 2. These material properties are assigned to sections before dynamic analyses are conducted.

Table 2. Material properties

Property	Material		
	Steel striker and plate	Rubber layer	Reinforcement
Weight per unit of volume [kg/m^3]	7850	1230	7850
Modulus of elasticity [MPa]	200000	22	200000
Poisson's Ratio	0.30	0.45	0.30
Shear modulus [MPa]	76923.08	7.59	76923.08
Bulk modulus [MPa]	166670	73.33	166670
Yield strength [MPa]	-	-	420
Ultimate strength [MPa]	-	-	500

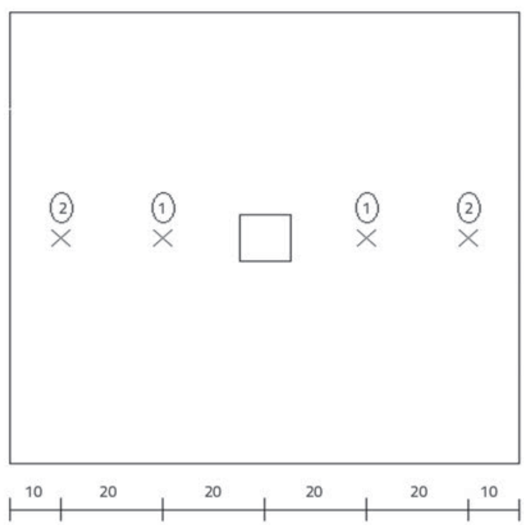

Figure 5. Section details, dimensions in cm

Acceleration values are obtained from four points on the RC slabs. Impact force values which occur after sudden loading are determined from the edge point of the steel strike after each drop movement. Rubber layer and steel plate are situated at the midpoint of the slab members. Geometrical positions of measurement points are shown in Figure 5. While the measurement points at 20 cm from the impact point are numbered as point 1, the measurement points at 40 cm from impact point are numbered as point 2.

Sizes of the finite elements are significant with regard to analysis and solution time. Finite element models are separated into small pieces in the analysis. Although more sensitive results are obtained as the finite element size decreases, the result calculation time becomes longer. Therefore, a high performance computer is used to decide on the finite element size in the finite element mesh. The size operation is performed for RS1 as presented in Table 3. The analyses are repeated for different sizes from 20 cm distance of impact point for the first drop. It can be seen that the number of nodes and elements are highly affected by the sizes.

Table 3. Size operation for plate RS1

Output	**Element size** [cm]			
	4	**3**	**2**	**1.5**
Number of nodes	47043	89685	233551	442942
Number of elements	33006	63336	166244	316145
Maximum acceleration [m/s^2]	2075	3808	4485	4659
Maximum velocity [m/s]	-0.32	-0.53	- 0.69	- 0.70
Maximum displacement [m]	-0.29	-0.48	- 0.62	- 0.64
Maximum impact force [N]	48589	79213	92574	98143

As the sizes decrease from 4 cm to 1 cm, the number of nodes and elements increases considerably. However, the analysis results are less affected for the last two trials. As it is known that the analysis becomes more difficult to accomplish due to the increase in the number of nodes and members, the decision was made to set the mesh size value to 2 cm after completion of convergence analyses. The finite elements model of the problem for RS2 is presented in Figure 6.

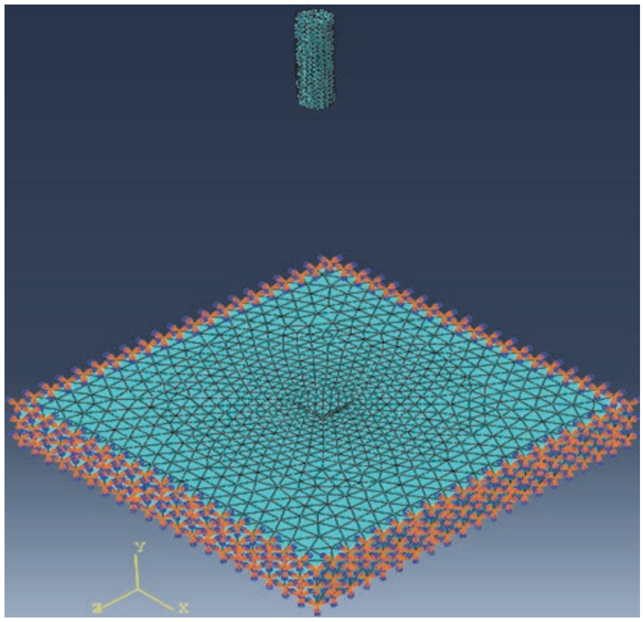

Figure 6. Finite elements model of the system

4. Results

After the finite elements models are created, material properties are assigned and support conditions are provided. Then the analyses are performed for each situation. While the drop height is 125 cm, the mass of the steel striker is taken to be 10 kg in the simulations. The analyses continue until the RC slabs reach failure

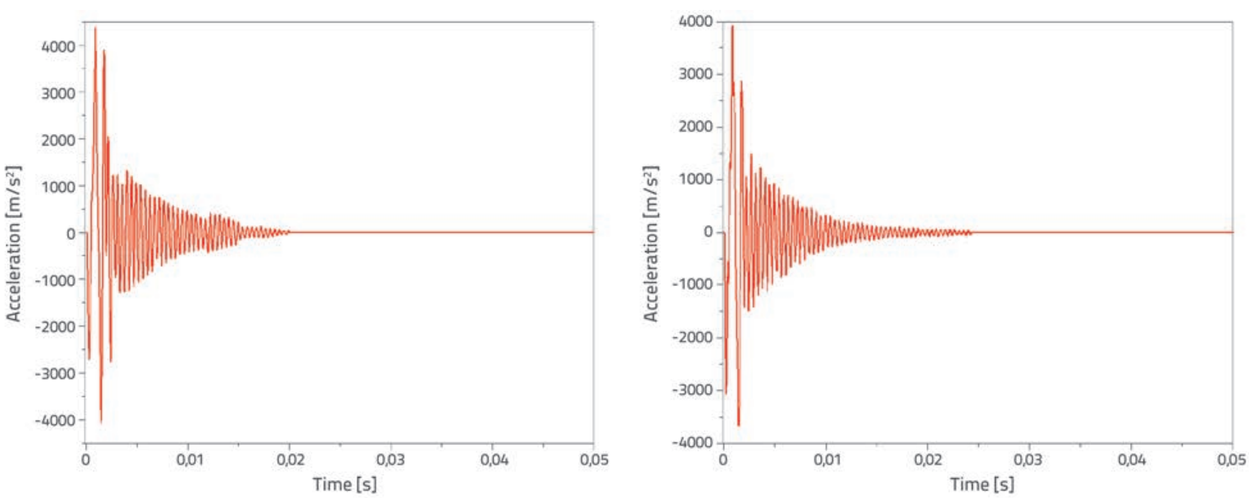

Figure 7. Acceleration-time graphs for plate RS2 from 20 cm and 40 cm of impact point for the first drop

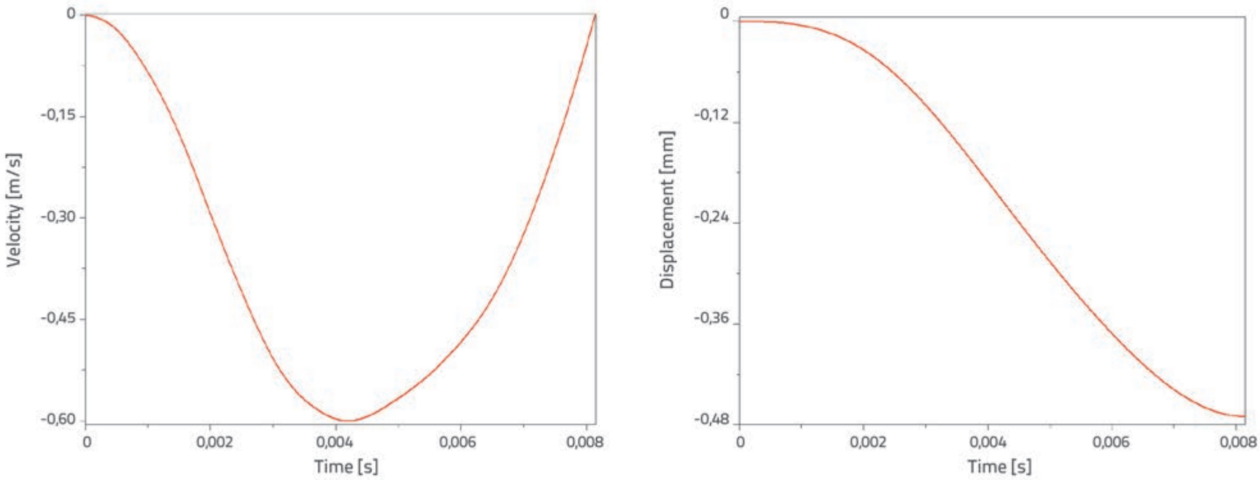

Figure 8. Velocity-time and displacement-time graphs for plate RS2 for the first drop

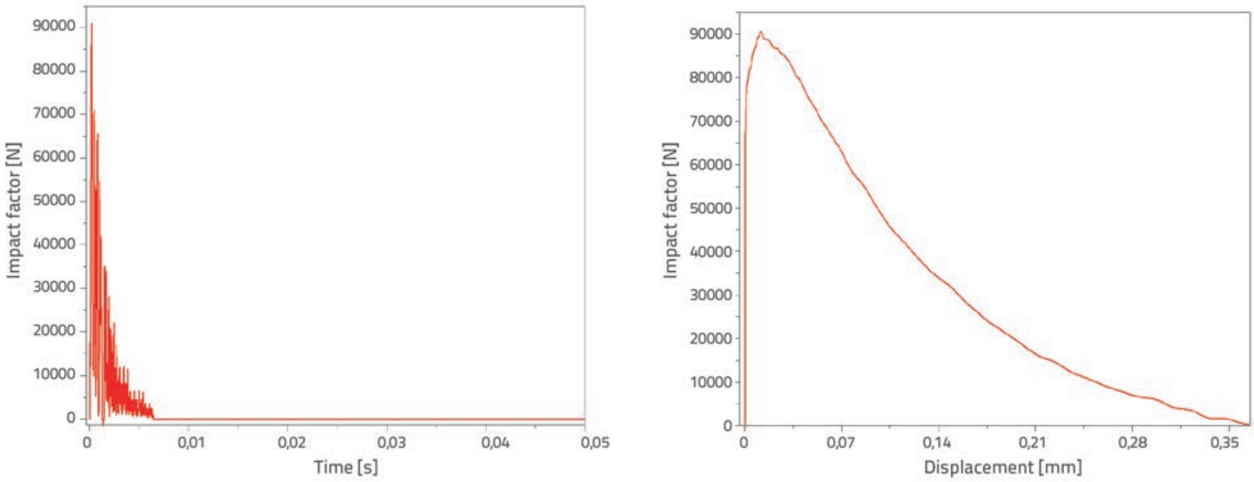

Figure 9. Impact force-time and impact force-displacement graphs for plate RS2 for the first drop

damage situation, which occurs after the final drop movement of the hammer. It is impossible to obtain new acceleration, impact force and displacement values once the slab has reached failure damage. The acceleration, velocity, displacement and impact force values are obtained for the first and final drop movements of the striker.

Firstly, the acceleration, velocity and displacement values are obtained from four symmetrical points of the RC slab, as presented in Figure 5. Afterwards, velocities and displacements are also calculated after integration operations to obtain the results. Impact force values are also determined after drop movements of the steel striker. The diagrams are presented between Figure 7 and Figure 9 for the first drop movement of the RC slab measuring 100 x 100 x 12 cm, whose four sides are supported. Non-linear dynamic analyses are performed for all RC slabs according to two support conditions. Impact parameters such as acceleration, velocity, displacement and impact force values are obtained from the software. The velocity and displacement values are calculated after integration operations for the related points where accelerations are obtained.

Impact force values are determined at the edge point of the steel striker. Finally, energy capacities are calculated according to the area under the curve of impact force-displacement graphs. The results are comparatively presented from Table 4 to Table 7 for the first and final drops.

Table 4. Acceleration values

Slab member		Values at 20 cm		Values at 40 cm	
		First drop [m/s²]	Final drop [m/s²]	First drop [m/s²]	Final drop [m/s²]
RS1	Min	-4328	-3403	-3557	-3084
	Max	4303	3633	3804	3106
RS2	Min	-4351	-3466	-3726	-3225
	Max	4485	3713	3984	3186
RS3	Min	-4795	-3622	-4218	-3207
	Max	4962	3983	4472	3365
RS4	Min	-4176	-3308	-3731	-2965
	Max	4285	3377	3473	2780
RS5	Min	-4317	-3426	-3853	-3006
	Max	4368	3581	3598	3122
RS6	Min	-4723	-3615	-4263	-3184
	Max	4608	3747	4054	3316

Table 5. Velocity values

Slab member	Values at 20 cm		Values at 40 cm	
	First drop [m/s]	Final drop [m/s]	First drop [m/s]	Final drop [m/s]
RS1	-0.69	-0.92	-0.58	-0.79
RS2	-0.60	-0.81	-0.51	-0.70
RS3	-0.47	-0.61	-0.39	-0.52
RS4	-0.75	-0.99	-0.63	-0.83
RS5	-0.64	-0.87	-0.54	-0.75
RS6	-0.50	-0.65	-0.42	-0.54

Table 6. Displacement values

Slab member	Values at 20 cm		Values at 40 cm	
	First drop [mm]	Final drop [mm]	First drop [mm]	Final drop [mm]
RS1	-0.62	-1.23	-0.49	-1.02
RS2	-0.47	-1.04	-0.37	-0.86
RS3	-0.36	-0.88	-0.28	-0.74
RS4	-0.66	-1.36	-0.54	-1.13
RS5	-0.51	-1.12	-0.43	-0.94
RS6	-0.40	-0.95	-0.33	-0.82

Stress values for RC slabs are obtained in Pa (N/m^2) unit form after the conduct of non-linear analyses. Although maximum stresses occur around the impact point, the values change according to support conditions, especially at the sides of the slabs.

Stress distributions according to two support types are shown in Figure 10 for the RC slab member measuring 100 x 100 x 12 cm. The results are presented for the first drop movement of the striker after complete application of the impact load on the RC slab. It can be seen that stress distribution is greatly affected by support conditions.

Table 7. Impact force and energy capacity values

Slab member	Impact force of first drop [N]	Impact force of final drop [N]	Max. energy capacity [J]
RS1	81065	58753	26.78
RS2	92574	73062	31.24
RS3	108234	81391	33.05
RS4	79867	54247	25.71
RS5	90321	70476	30.81
RS6	104649	77359	31.86

5. Conclusions and suggestions

RC slabs are widely used in structures as structural members. During their service life, these members are susceptible to sudden loading that may result from various causes. In this paper, non-linear dynamic analyses are performed to determine behaviour of RC slabs under impact load. For this purpose, 100 x 100 cm sized RC slabs, with three different thickness values and two support conditions, are modelled in Abaqus. The drop height and striker mass are adopted as constant values in the simulations. Impact parameters, such as acceleration, velocity, displacement, impact force, and energy capacity values, are obtained with stress distributions after the analysis.
Two symmetrical points, situated 20 cm and 40 cm away from the impact point where the steel striker drops, are defined on RC slab members to determine acceleration values. Afterwards, velocities

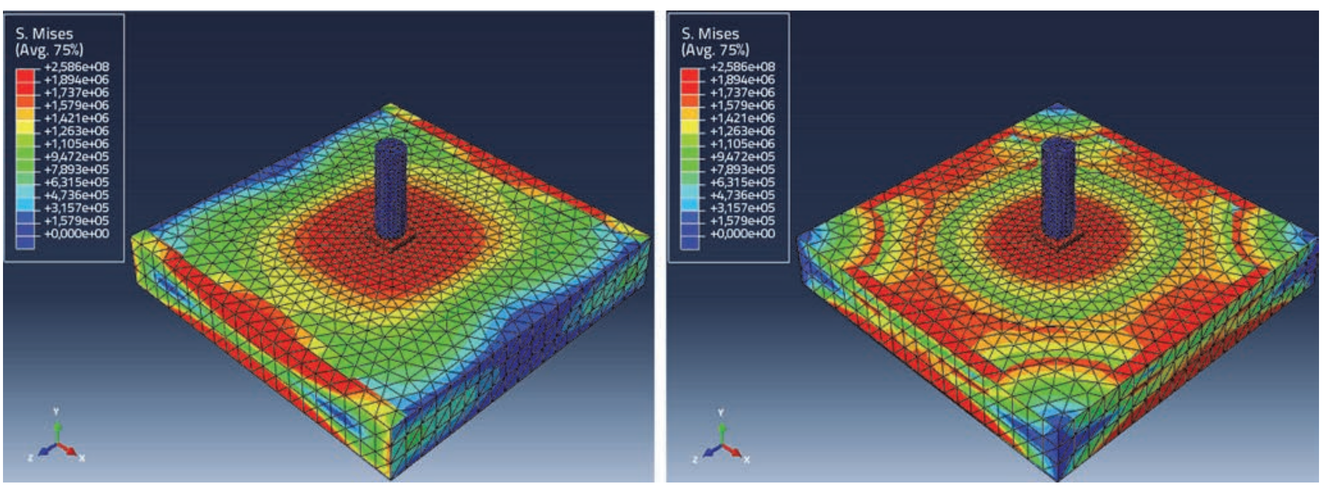

Figure 10. Stress distributions for plates RS2 and RS5

and displacements are calculated for the same points after integration relevant acceleration values. Impact forces are obtained for each drop movement of the steel striker. Energy capacity values are also calculated according to impact force-displacement graphs. A steel plate and a rubber layer are placed at the midpoint of the RC slabs to uniformly distribute impact load on slab members and reduce inner effects when sudden load is applied.

The finite element simulations are performed for three slab thicknesses and two different support types. Because of member rigidity, thicker RC slabs, supported at four sides, are less affected by sudden load compared to other slabs. The most rigid RC slab is RS3 measuring 15 cm in thickness, supported at all four sides. Therefore, compared to other slabs, RS3 was the last one to reach failure damage. On the other hand, RS4 member 8 cm in thickness, with two opposite supported sides, was the first one to reach failure damage.

Impact results are greatly influenced by the support rigidity and slab thickness values. Acceleration values increase with an increase in section size, and higher acceleration values are obtained for thicker RC slabs with all sides supported. While acceleration values decrease, the velocity and displacement values increase due to drop movements of the striker. Crack and damage properties of RC slabs are the main reasons for this situation. As the RC slabs approach the failure damage situation, accelerations decrease with an increase in velocity and displacement values. In addition, all values determined 20 cm away from the impact point are bigger, compared to values registered at 40 cm.

Impact force values are obtained at the edge point of the steel striker after each drop movement. These values exhibit the same behaviour as accelerations due to member rigidity. Impact forces also decrease as the RC slabs get close to failure damage situation. Energy capacity values of RC slabs are calculated according to the area under the curve of impact force-displacement graphs. The biggest energy value is obtained for the RS3 member having the maximum impact load value.

Maximum stress values occur at the central point of the slabs where the sudden loading is applied. The biggest values are observed for the RS4 slab member measuring 8 cm in thickness. Because of the increase in support rigidity, cracks and damage around the midpoint of the slabs expand to the supports for RS1, RS2 and RS3 members whose four sides are supported. On the other hand, the damage is generally localized around the impact point for the rest of the slab members whose opposite sides are supported. For this reason, these members reach the failure damage situation earlier.

Since it is almost impossible to ensure perfect test and support conditions in experimental studies, finite elements analyses with accurate models and materials have come forward as substantial alternatives. These analyses reduce workloads and provide information about behaviour of structural members under sudden loading conditions. Consequently, researchers will further improve these studies by investigating different structural members affected by sudden load using high performance computers.

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