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Lateral Impact Effect on Circular RC Columns

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Abstract

Reinforced concrete (RC) columns are the vertical carrier elements in a structural system. Generally, RC columns are divided into two parts due to their section geometry and confinement reinforcement. Columns are designed according to the dead, live and horizontal wind and seismic loads. However, effect of impact loading that is a kind of sudden impulsive dynamic one is ignored in the design process. Carbon fibre reinforced polymer (cfrp) is an effective way to repair and to strengthen the RC columns in a fast way. So, use of cfrp in the existing structural members especially with low concrete quality has been increasing lately in terms of ease of application. Main objective of this study is numerically investigating the impact behaviour of circular sectioned RC columns before and after strengthening by cfrp technique. In line with this purpose, Abaqus finite elements software that is commonly used in such problems has been utilized. Acceleration, impact load and displacement values of the RC columns as well as stress distributions are obtained after non-linear incremental numerical analysis. So, it is considered that the proposed finite element model could be useful for the researchers performing impact analysis. Besides, it is thought that the current study will make a contribution to the literature in the research area of dynamic reactions of RC columns under impact effect.

***Keywords*:** circular column, impact loading, numerical analysis, strengthening

Dairesel Kesitli Betonarme Kolonlarda Yanal Çarpma Etkisi

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Özet

Betonarme kolonlar, taşıyıcı sistemdeki düşey taşıyıcı elemanlardır. Genel olarak betonarme kolonlar, kesit geometrileri ve sargı donatıları nedeniyle iki kısma ayrılırlar. Kolonlar sabit, hareketli ve yatay rüzgâr ve deprem yükleri dikkate alınarak tasarlanırlar. Ancak, tasarım sürecinde bir tür ani dinamik yük olan darbe yüklemesinin etkisi göz ardı edilmektedir. Karbon fiber takviyeli polimer (cfrp), betonarme kolonları hızlı bir şekilde onarmak ve güçlendirmek için etkili bir yoldur. Bu nedenle, özellikle beton kalitesi düşük olan mevcut yapısal elemanlarda cfrp kullanımı, uygulama kolaylığı açısından son zamanlarda giderek artmaktadır. Bu çalışmanın temel amacı, dairesel kesitli betonarme kolonların cfrp tekniği ile güçlendirme öncesi ve sonrası çarpma davranışını nümerik olarak incelemektir. Bu amaç doğrultusunda, bu tür problemlerde yaygın olarak kullanılan Abaqus sonlu elemanlar yazılımından yararlanılmıştır. Doğrusal olmayan artımsal nümerik analizden sonra, betonarme kolonların ivme, çarpma yükü ve yer değiştirme değerleri ile gerilme dağılımları da elde edilmiştir. Böylelikle, önerilen sonlu eleman modelinin çarpma analizi yapan araştırmacılar için yararlı olabileceği düşünülmektedir. Bununla birlikte, bu çalışmanın çarpma etkisi altındaki betonarme kolonların dinamik tepkilerinin araştırılması alanında, literatüre katkı sağlayacağı düşünülmektedir.

***Anahtar Kelimeler*:** dairesel kolon, çarpma yüklemesi, nümerik analiz, güçlendirme

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1. **Introduction**

Concrete in which aggregate is bonded together by water and cement is the most common structural material in the construction technology. Although concrete gains compressive strength by time, its tensile strength is very low and usually ignored in the calculations. For this reason, steel bars are situated in the tensile zones of the RC structural elements. RC buildings occupy an important place in the structure industry all around the world. In the frame buildings, columns are the vertical structural members carrying the loads that are transferred from beams and the columns from the upper floors.

As the formwork of rectangular columns is easier to work due to the straight sides of the section, circular columns are not used as much as rectangular ones. However, circular columns occupy a smaller area and they are more pleasing in terms of aesthetic. In circular sectioned RC columns, longitudinal steel bars are confined by spiral reinforcements. These spiral reinforcements hold the longitudinal bars in their forms when the concrete is being placed and apply lateral pressure to support the strength of core concrete. In addition, circular columns have the same inertia moment in both axes. So, the spirals hinder the buckling of longitudinal reinforcements and sudden crashing of concrete.

Impact effect is not taken into consideration in the seismic codes. So, the studies about impact loading on structural members have been increased in recent years [1-5]. However, responses of structural members that are imposed upon impact loading is not completely explained due to several variables. Different test setups have been developed to investigate the impact effect on various materials by researchers [6-9]. Vehicle or ship collisions on bridges or offshore structures, projectile or missile attacks on military facilities, rock falls on the buildings located on mountain slopes, sudden explosions, aircraft impacts, accidental forklift events in factories are some examples of impact events [10].

As a result of major earthquakes, various strengthening techniques have been offered by engineers. Cfrp is one of the composite materials used to strengthen the columns. Because, seismic behaviour of the building becomes stabilised after column strengthening that is significant for the building stability. In recent years, cfrp sheets have been widely used to strengthen the existing columns with low concrete quality or inadequacy of longitudinal and transverse reinforcements. Although carbon fibre products are more expensive than other conventional building materials, they offer several advantages such as easy and rapid installation, lightweight, corrosion resistance, high load carrying capacity, stiffness and strength.

In this recent study, impact behaviour of the circular RC column before and after cfrp strengthening operation is numerically investigated. For this purpose, Abaqus software is used in the solutions [11]. The software is capable of performing various static and dynamic analyses due to its advanced material library. Therefore, several advanced studies have been generated by using Abaqus [12-19]. Explicit module of the software is used in dynamic problems. Finally, it is evaluated that the outcomes of this study could fill the deficiency in explicit dynamic analysis that focuses on impact effects.

2. Properties of the Column

While length of the RC column is 3000 mm, diameter value is taken to be 400 mm in the numerical analysis. Section details of the circular column are presented in Figure 1. Distance between spiral reinforcements is symbolised by “s” letter in the figure.

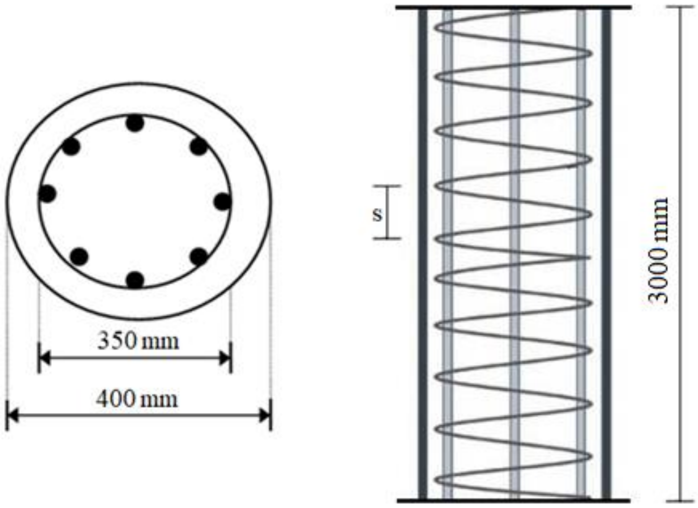

Figure 1. Details of the circular column

Totally, 8 longitudinal steel bars with 14 mm diameter are used in the column section. On the other hand, diameter of the spiral reinforcement is 8 mm. Length of the confinement regions at both ends of the column are 500 mm and spiral spacing is 150 mm in these regions. However, length of the middle region of the column is 2000 mm with a spiral spacing of 200 mm as explained in Table 1.

Table 1. Reinforcement properties

Type	Details
Longitudinal	8Ø14
Spiral	Ø8/200/150 mm

3. Numerical Analysis

Explicit feature of the Abaqus software yielding appropriate analysis outputs for explicit dynamic analysis is used in the solutions. Different material models can also be defined in this module. Basically, the equations are solved by explicit analysis that states the conservation of mass, momentum, and energy in each direction. These equations are explicitly solved for each time step and element of the model according to input values which are obtained at the end of the previous time step.

Due to high costs of test setups, limits of test devices and difficult workmanship in laboratory when producing test specimens, numerical analyses are generated to investigate the impact behaviour of structural members. Besides, the authors have verified experimental values by numerical analysis results in their previous studies [20-22]. So, numerical analysis is a significant option to obtain reliable results when correct finite element models, material characteristics and analysis parameters are defined in the software.

First of all, RC columns with and without cfrp and the striker which implements impact loading on the columns are modelled in the software by considering the section dimensions and reinforcement configuration. C3D10M (10 node modified tetrahedron) members that are suggested for impact simulations are made use of in the modelling phase as presented in Figure 2. Afterwards, support regions are defined according to the boundary conditions in the axial, vertical and horizontal directions. Three dimensional finite element models of the circular columns are shown in Figure 3.

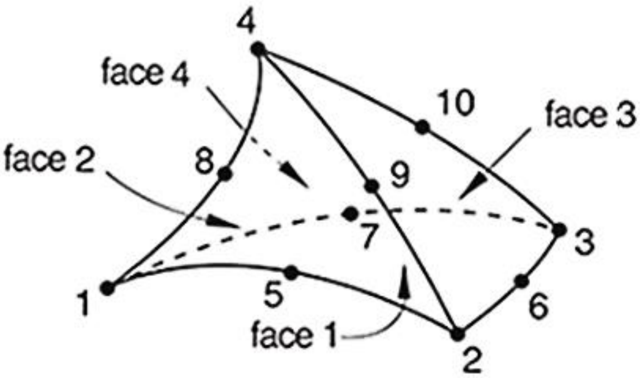

Figure 2. C3D10M elements

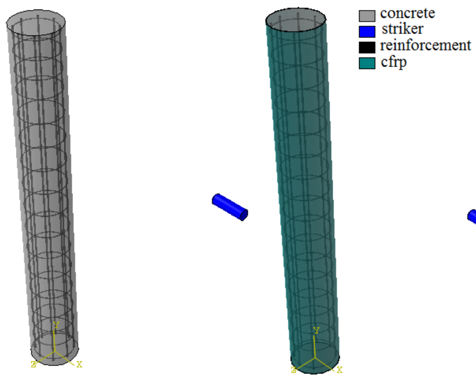

Figure 3. Numerical models

Material characteristics must be defined in the correct way to determine accurate analysis results. For this purpose, concrete damage plasticity model of the software that enables to identify the stress-strain relation of concrete in both compression and tension is utilized as given in Figure 4. Non-linearity of concrete is represented by this model which is a continuum, plasticity-based, damage one.

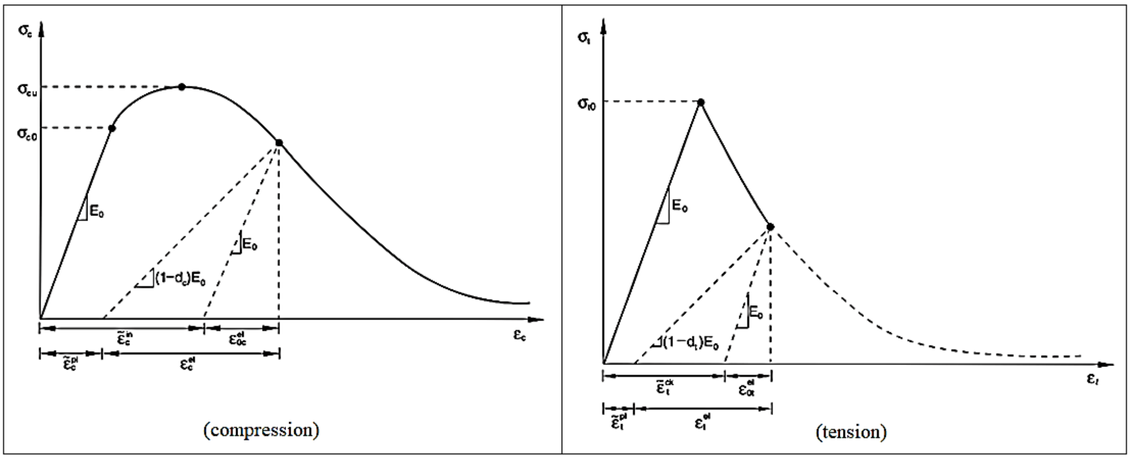

Figure 4. The model of concrete

There are compression and tension regions in concrete model. In the compression part, the output suits linear to the the value of the initial yield, (σ_{c0}) under uniaxial compression. On the other side, the behaviour of concrete changes in the plastic region because of the stress hardening followed by strain softening within the ultimate stress (σ_{cu}). In the tension part, stress-strain relationship behaves linear until reaching the failure stress (σ_{t0}) that corresponds to first micro crack occurrence in concrete under uniaxial tension. Finally, the softening stress-strain response generates the form of micro cracks after failure stress.

Main plasticity variables of the model are the dilation angle (ψ), the flow potential eccentricity (e), the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (σ_{b0}/σ_{c0}), the coefficient specifying the shape of the deviatoric cross-section (K_c), and the viscosity parameter (μ) which are utilized to indicate the function of yield surface. Furthermore, Poisson's ratio, density, compressive and tensile strength, modulus of elasticity of the material are also identified in Abaqus. Final strain value of concrete (ε_{cu}) is taken as 0.003 by Mander's model for concrete without confinement. Elastic modulus and tensile strength of concrete are computed in accordance with the compressive strength value by (Eq. 1) and (Eq.7) [23,24]. Concrete properties are summarized in Table 2.

$$E_c = 4700\sqrt{f_c} \tag{1}$$

$$f_t = 0.623\sqrt{f_c} \tag{2}$$

Table 2. Properties of concrete

Characteristic	Value
Poisson's ratio	0.20
Density (kg/m³)	2400
Elastic modulus (MPa)	14862.70
Compressive strength (MPa)	10
Tensile strength (MPa)	1.97
$\boldsymbol{\psi}$	30
$\boldsymbol{e}$	0.10
$\boldsymbol{\sigma_{b0}/\sigma_{c0}}$	1.16
$\boldsymbol{K_c}$	0.6667
$\boldsymbol{\mu}$	0.0001

To prevent local crushing in the analysis, a loading plate from steel material is placed in the point where impact loading is implemented by the striker. The characteristic of tie contact in Abaqus is used to ensure the adherence between the column and the steel bars. While the elasto-plastic material model is utilized for the reinforcement, the linear elastic model is used for the steel loading plate. Material characteristics of steel are shown in Table 3.

Table 3. Characteristics of steel material

Characteristic	Reinforcement	Loading plate
Poisson's ratio	0.30	0.30
Density (kg/m³)	7850	7850
Elastic modulus (MPa)	200000	200000
Shear modulus (MPa)	76923	76923
Bulk modulus (MPa)	166670	166670
Yield strength (MPa)	420	-

Strengthened RC column is externally wrapped by cfrp material. Material characteristics of cfrp are defined for the strengthened column before generating numerical analysis in the software. The values are presented in Table 4. In addition, the interface between concrete and cfrp is provided by the cohesive zone model in the software.

Table 4. Characteristics of cfrp

Property	Value
Thickness (mm)	0.12
Poisson's ratio	0.30
Weight (gr/m^2)	220
Elastic modulus (MPa)	231000
Tensile strength (MPa)	4100
Ultimate tensile strain (%)	1.7

The numerical models are divided into smaller parts to acquire more accurate outputs. However, analysis time extends when very small pieces are utilized in the analysis. For this reason, mesh convergence analysis is performed between 2 and 5 cm values and finite element size is taken to be 2.5 cm in the numerical analysis. To exhibit an example, geometry of the RC column without cfrp after mesh design is given in Figure 5.

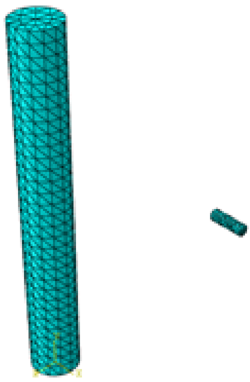

Figure 5. Mesh operation

Time steps and increments are other important analysis parameters in the software. Time steps are defined for the whole movement of the steel striker. Time increments are defined as 2×10^{-8} sec from the start of the contact between the striker and the column. Surface to surface contact property is identified. So, surface of the striker that implements the impact loading is determined as master. On the other side, surface of the column which is exposed to sudden impact effect is defined as slave. In addition, to simulate the possible friction losses, friction coefficient is assumed as 0.02 in the analysis.

Constant level of impact energy is applied on the columns owing to the constant values of the drop height and mass of the striker. By this way, effect of cfrp material on the low compressive strength column is comparatively determined. While drop height is 1500 mm, mass of the striker is 75 kg in the analysis. So, applied energy on the columns (75x9.81x1.5) is 1.103 kJoule.

Because it is not possible to place accelerometers at the impact point in the experimental studies, the acceleration values are obtained from 100 mm distances of the middle part of the column where impact loading is applied in the analysis. In addition, maximum displacement and impact load values are also obtained from the software. The results are comparatively shown in the following table.

Table 3. Analysis results

Property	Acceleration (m/s^2)		Displacement (mm)	Impact load (kN)
Column without cfrp	-3854	+4127	13.78	34.63
Column with cfrp	-4581	4906	3.46	36.28

Time histories of acceleration, displacement and impact load values are determined from the software. Examples of acceleration-time, impact load-time and displacement-time graphs are visually presented in the figures below.

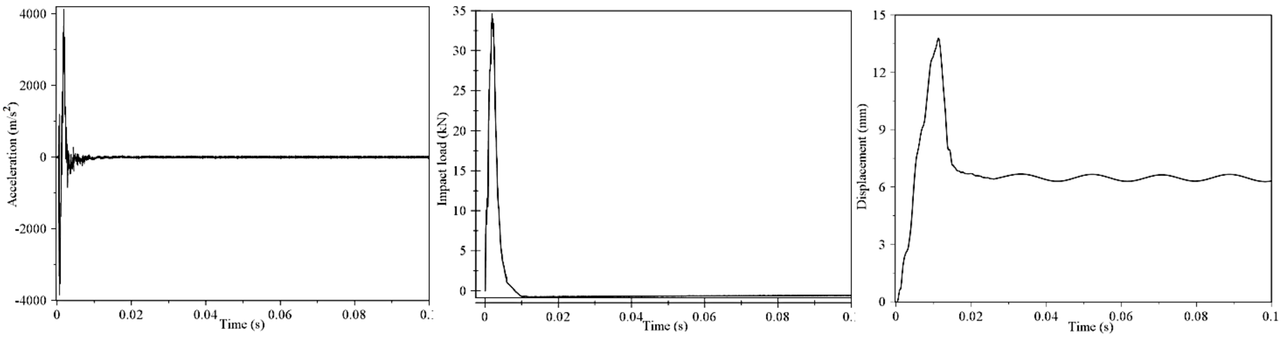

Figure 6. The graphs for the column without strengthening

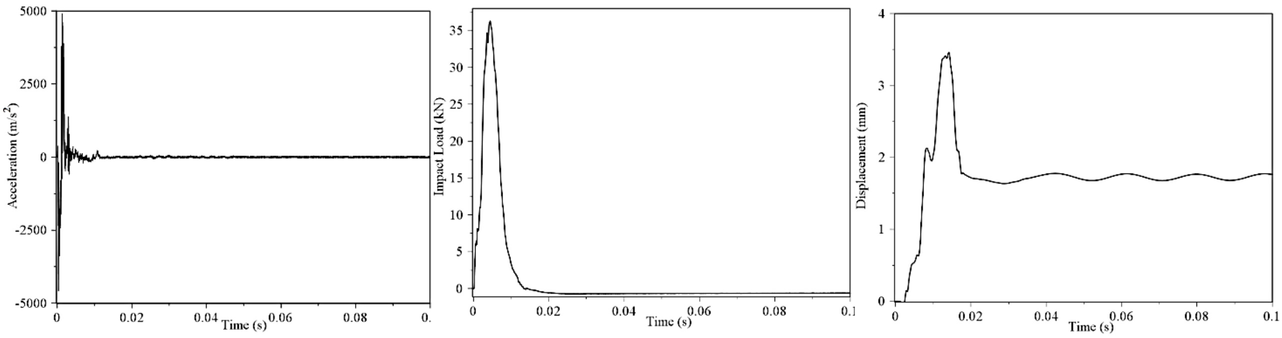

Figure 7. The graphs for the column with strengthening

After performing finite element simulations, Von-Mises stress distributions in Pa (N/m^2) unit form are determined as impact loading is completely applied on the columns. While the column without cfrp is shown on the left part, strengthened column is presented on the right part of the Figure 8. It is seen that maximum stresses are accumulated around impact point and expanded to the support regions.

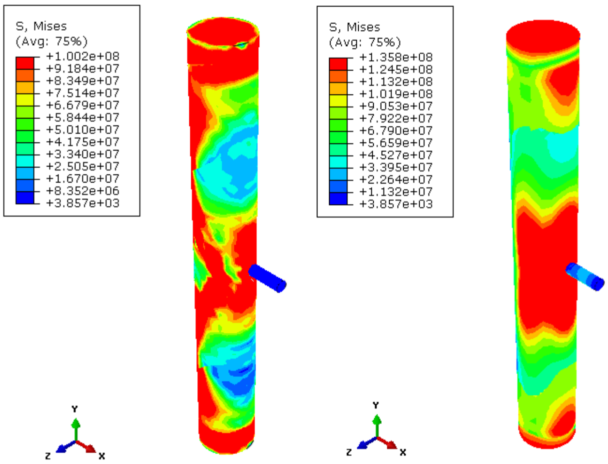

Figure 8. Stress distributions for the columns

4. Conclusion

Columns are the most important structural members in a RC frame building. Usually, rectangular columns are used in the structures. On the other hand, circular columns provide high strength and ductility in both directions. Although columns are designed according to static and dynamic load combinations, possible impact effects are ruled out in the design phase. However, columns may be exposing to sudden impact effects in their service period.

Due to the major earthquakes, rapid and effective strengthening applications have been investigated in recent years. As conventional strengthening methods in RC buildings such as jacketing of the columns, adding shear walls and steel bracings require plenty of workmanship and time, cfrp wrapping in the exterior surfaces of the columns has been come forward as a significant strengthening technique in the existing structures.

In this study, a low strength circular RC column is designed in the first place. This column is subjected to sudden impact loading in the software. Afterwards, the column with the same section and reinforcement properties is externally wrapped by cfrp material. The strengthened column is also analysed under impact loading to evaluate the differences between both columns. Explicit dynamic analysis performed for each column and acceleration, displacement and impact load values are determined from the software as well as stress distributions.

When the analysis results are examined, it is seen that cfrp strengthening method is effective on the impact response of the RC column. While accelerations values have increased, displacement values are considerably limited for the strengthened column. As the same impact energy has been applied on both columns, there is not big difference between the impact load values. In addition, maximum stresses have distributed on a larger area for the column without cfrp.

As some problems such as design and limits of test setups, perfect support conditions, high costs, difficult workmanship and supply of measurement devices are encountered in the experimental impact studies, finite element simulations are performed by high technology computers to get an idea on impact responses of structural members. This study has revealed that the accurate finite element model may be used in the assessment of impact behaviour of circular columns with or without cfrp. So, the study is evaluated to be important in terms of investigating the impact responses of circular columns. Finally, this study could be developed by applying different levels of input energies on the columns with different section properties in both experimental and numerical studies.

5. References

[1] Demartino C, Wu J, Xiao Y (2017). Experimental and numerical study on the behavior of circular rc columns under impact loading. *Procedia Engineering*, 199, 2457-2462.

[2] Majeed MA, Yigit AS, Christoforou AP (2012). Elastoplastic contact/impact of rigidly supported composites. *Composites Part B: Engineering*, 43(3), 1244-1251.

[3] Viau C, Doudak G (2019) Behaviour and modelling of cross-laminated timber panels with boundary connections subjected to blast loads. *Engineering Structures*, 197, 109404.

[4] Li H, Chen W, Pham TM, Hao H (2021). Analytical and numerical studies on impact force profile of RC beam under drop weight impact. *International Journal of Impact Engineering*, 147, 103743.

[5] Xu X, Ma T, Ning J (2019). Failure mechanism of reinforced concrete subjected to projectile impact loading. *Engineering Failure Analysis*, 96, 468-483.

[6] Yılmaz T, Anil Ö, Erdem RT (2022). Experimental and numerical investigation of impact behavior of rc slab with different opening size and layout. *Structures*, 84, 818-832.

[7] Zhang X, Hao H, Li C (2016). Experimental investigation of the response of precast segmental columns subjected to impact loading. *International Journal of Impact Engineering*, 95, 105-124.

[8] Aghdamy S, Thambiratnam DP, Dhanasekar M (2016). Experimental investigation on lateral impact response of concrete-filled double-skin tube columns using horizontal-impact-testing system. *Experimental Mechanics*, 56, 1133-1153.
[9] Erdem RT (2014). Prediction of acceleration and impact force values of a reinforced concrete slab. *Computers and Concrete*, 14(5), 563-575.
[10] Anil Ö, Erdem RT, Tokgöz MN (2018). Investigation of lateral impact behavior of RC columns. *Computers and Concrete*, 22(1), 123-132.
[11] Abaqus User's Manual, Version 6.12 (2015). Simulia, Dassault Systèmes Simulia Corp.
[12] Sadighi M, Parnanen T, Alderliesten RC, Sayeaftabi M, Benedictus R (2012). Experimental and numerical investigation of metal type and thickness effects on the impact resistance of fiber metal laminates. *Applied Composite Materials*, 19, 545-559.
[13] Genikomsou AS, Polak MA (2015). Finite element analysis of punching shear of concrete slabs using damaged plasticity model in abaqus. *Engineering Structures*, 98, 38-48.
[14] Mars J, Jarraya A, Dammak F, Dhiab A (2015). Finite element implementation of an orthotropic plasticity model for sheet metal in low velocity impact simulations. *Thin-Walled Structures*, 89, 93-100.
[15] Makarem FS, Abed F (2013). Nonlinear finite element modeling of dynamic localizations in high strength steel columns under impact. *International Journal of Impact Engineering*, 52, 47-61.
[16] Liu ZG, Liu Y, Lu J (2012). Numerical simulation of the fluid–structure interaction for an elastic cylinder subjected to tubular fluid flow. *Computers & Fluids*, 68, 192-202.
[17] Liu PF, Liao BB, Jia LY, Peng XQ (2016). Finite element analysis of dynamic progressive failure of carbon fiber composite laminates under low velocity impact. *Composite Structures*, 149, 408-422.
[18] Raza A, Khan Q, Ahmad A (2019). Numerical investigation of load-carrying capacity of gfrp-reinforced rectangular concrete members using cdp model in abaqus. *Advances in Civil Engineering*, 2019, 1745341, 1-19.
[19] Kartheek T, Das TV, (2020). 3D modelling and analysis of encased steel-concrete composite column using abaqus. *Materialstoday:Proceedings*, 27(2), 1545-1554.
[20] Erdem RT (2021). Dynamic responses of reinforced concrete slabs under sudden impact loading. *Revista de la Construccion*, 20(2), 346-358.
[21] Erdem RT, Gücüyen E (2017). Non-linear analysis of reinforced concrete slabs under impact effect. *Gradevinar*, 69(6), 479–487.
[22] Erdem RT, Berberoğlu M, Gücüyen E (2023). Investigation of concrete slabs made with cement based mortars under impact loads, *Gradevinar*, 75(2), 117-127.
[23] Obaidat YT, Heyden S, Dahlblom O (2010). The effect of CFRP and CFRP/concrete interface models when modelling retrofitted RC beams with fem. *Composite Structures*, 92(6), 1391-1398.
[24] Li C, Hao H, Bi K (2017). Numerical study on the seismic performance of precast segmental concrete columns under cyclic loading. *Engineering Structures*, 148, 373-386.