

IMPACT LOADING ON RC CANTILEVER BEAM

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Abstract

Structural elements are designed to resist several static and dynamic load combinations. On the other hand, impact loading is not considered in the design of these elements. However, failure modes may occur under sudden impact effects. In this study, it is aimed to investigate the impact behaviour of a reinforced concrete cantilever beam. For this purpose, a reinforced concrete beam-column connection is modelled in Abaqus software. As impact loading could be applied in different ways, three types of the striker geometries are utilized in the numerical simulations. After performing non-linear finite elements analysis, the numerical outputs such as accelerations, impact loads and displacements are obtained from the software. These values are exhibited by time dependent graphs. In addition, stress distributions as well as damage patterns are visually presented for each case. Finally, analysis results are evaluated and interpreted as to what extent the suggested numerical procedure could be utilized in such simulations.

Key words: Abaqus, beam-column connection, impact, non-linear analysis

Introduction. As component materials such as concrete and steel bars become together, a composite material named reinforced concrete (rc) occurs. This composite material is widely used in construction works all around the world. The advantages of rc could be regarded as high strength, durability, stiffness, fire resistance, low maintenance and cost effectiveness. So, rc structures constitute the large part of the building stock. The main structural elements of the rc structures

are the columns and beams which are the vertical and horizontal members in the structural system.

Structural elements are subjected to static and dynamic load combinations in the design phase. So, rc structures are affected by dead and live loads as well as seismic and wind loads. However, impact loading that changes the behaviour of the structural members in a very short span of time is not taken into consideration. Some examples of impact loading could be counted as blasts, missile strikes, rock falls and vehicle crashes as well as the collision of masses due to the landslide and flood [1, 2]. So, there is a lack of studies about impact responses of the elements in the literature.

Impact loads may cause significant deformations and damages to the structural system. There is not a specific chapter about the effect of impact loading on the structural elements in the current design codes. Experimental studies are performed due to the regulations that are defined in ASTM E 23 [3]. Impact test setups are designed by researchers by following the impact limits in this standard [4–7]. The changes in the structural elements are followed by measurement devices such as accelerometer, load cell, lvdt, and strain gauge. All experimental data are transferred to an electronic device called data logger to interpret the experimental impact behaviour of test specimens.

Numerical studies have gathered momentum with the developments in the computer technology in recent years [8–11]. As it is not easy to design impact test setups and provide costly measurement devices, researchers perform numerical simulations to investigate the impact behaviour of structural elements produced from various materials. Besides, maximum limits of the test devices narrow the course of the experimental studies. On the other hand, impact analysis is a non-linear dynamic solution and strict attention must be paid to the analysis steps in the computer environment.

There are several examples of impact incidents. So, impact loading could be implemented in different ways [12–14]. In this study, three different striker geometries are considered in the numerical simulations. Impact loading is applied to the rc cantilever beam. For this purpose, a beam-column connection is modelled in Abaqus finite elements analysis software [15]. Since Abaqus is capable of performing non-linear incremental analysis accurately, it is widely used by researchers for such simulations [16–18]. In addition, the software has a great variety of material characteristics in its library. The authors aim to address the reliability of the analysis outputs of this study and it is thought that the analysis variables on the impact behaviour of rc cantilever beam will be a significant contribution to the literature.

Properties of the beam-column connection. In the first part of the numerical analysis, the finite element models are constituted in the software. While the section dimensions of the column are 40×40 cm, beam sizes are 25×50 cm. In addition, the length values are taken to be 200 and 150 cm for the column and

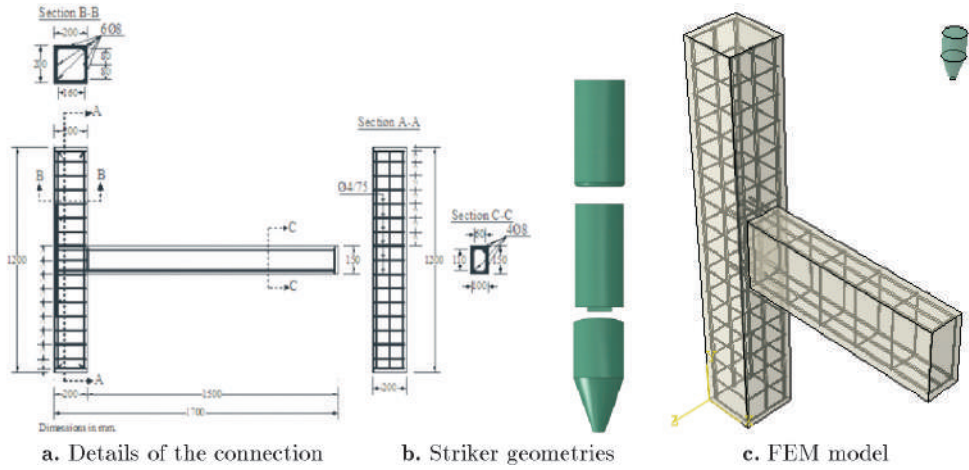


Fig. 1. Beam-column connection and strikers

beam, respectively. A total of 8 steel rebars having 14 mm dimensions are used in the column section. These longitudinal rebars are confined by 6 mm stirrups with 20 cm intervals. Three rebars with 12 mm dimensions are utilized for each top and bottom parts of the beam section. Dimension of the stirrups is 6 mm and placed with 30 mm intervals. Reinforcement configuration and dimensions of the beam-column connection is presented in Fig. 1a.

A typical beam-column connection is generated in the software. While one end of the beam is fixed to the column, the other end of the beam is free. In addition, fixed support properties are assigned for both ends of the column. Support regions of the connection are defined with the boundary conditions in the horizontal, vertical, and axial directions. There are three different striker geometries that are utilized in the software. As impact loading could be applied in different ways, it is aimed to obtain the differences between striker types. The considered striker geometries are hemi-spherical, flat, and angular, respectively. The details of the striker types are shown in Fig. 1b. Finite elements model of the rc beam-column connection under the effect of hemi-spherical striker is exhibited in Fig. 1c.

Numerical analysis. The striker that applied impact loading is modelled as well as the beam-column connection and longitudinal and transverse reinforcement in the software. In line with this purpose, C3D10M (ten node modified tetrahedron) elements which generate the most accurate results in impact simulations are utilized. The material characteristics are assigned to the related geometries by using the advanced material models in the library of the software in the next step of the numerical analysis. To define the complex behaviour of concrete, the concrete damage plasticity (cdp) model is utilized. In this model, stress-strain relationship of concrete is defined in both tension and compressive

regions. Cdp model is a continuum, plasticity-based, damage model representing the non-linearity of concrete successfully.

There are two main parts such as compression and tension in the cdp model. MANDER's stress-strain model for unconfined concrete is utilized to represent the behaviour of concrete in compression [19]. In this part, a linear response is established to the value of initial yield (σ_{c0}). However, the change is observed in the plastic region. The response is specified by the stress hardening followed by strain softening beyond the value of the ultimate stress (σ_{cu}). In the tension part of the cdp model, a linear elastic relationship is characterized until reaching the level of failure stress (σ_{t0}). First micro cracks occur in concrete at this point. After failure stress, the softening stress-strain path starts. Thus, the formation of the micro-cracks is generated due to the response of the softening stress-strain behaviour.

The degradation of the elastic stiffness is defined by two damage variables as d_c and d_t in cdp model. The values of these variables change between 0 and 1 such as $d_c < 1$ and $0 < d_t$. Undamaged material is exhibited by zero. However, total loss of strength is represented by one. So, the stress-strain relationship is under compression and tension load effects are established by the equations below. The initial elastic stiffness of the material, the equivalent plastic strain in compression and tension are symbolized by E_0 , $\tilde{\varepsilon}_c^{pl}$ and $\tilde{\varepsilon}_t^{pl}$ in these equations, respectively.

$$(1) \quad \sigma_c = (1 - d_c)E_0(\varepsilon_c - \tilde{\varepsilon}_c^{pl})$$

$$(2) \quad \sigma_t = (1 - d_t)E_0(\varepsilon_t - \tilde{\varepsilon}_t^{pl}).$$

To present the damage variables d_c and d_t in a better way, Eqs (1, 2) are simplified. The equivalent plastic strains are $\tilde{\varepsilon}_t^{pl} = b_t \left(\varepsilon_t - \frac{\sigma_t}{E_0} \right)$ and $\tilde{\varepsilon}_c^{pl} = b_c \left(\varepsilon_c - \frac{\sigma_c}{E_0} \right)$, respectively. So, the values of b_t and b_c parameters are practiced as 0.1 and 0.7 in the software [20]. The damage variables are given in Eqs (3, 4).

$$(3) \quad d_t = 1 - \frac{\sigma_t/E_0}{\tilde{\varepsilon}_t^{pl} \left(\frac{1}{b_t} - 1 \right) + \sigma_t/E_0}$$

$$(4) \quad d_c = 1 - \frac{\sigma_c/E_0}{\tilde{\varepsilon}_c^{pl} \left(\frac{1}{b_c} - 1 \right) + \sigma_c/E_0}.$$

The other plasticity materials of the cdp 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 determining the shape of the deviatoric cross-section (K_c), and the viscosity parameter (μ). These parameters are also used in concrete modelling to define the yield surface function, the potential flow and the viscosity of concrete. According to

Mander's concrete model, the value of ultimate concrete strain value (ε_{cu}) is considered 0.003 in the software. In addition, the value of ultimate strain in tension (ε_{tu}) is taken as $\varepsilon_{tu} = 10\varepsilon_{cr}$, and (ε_{cr}) is the strain at ultimate tensile strength. Tensile behaviour is assumed to be linearly increasing until (ε_{cr}) and decreasing until (ε_{tu}). Furthermore, Eqs (5, 6) are considered to define the tensile strength and elastic modulus according to the value of compressive strength. Concrete material has a Poisson's ratio of 0.20, a density of 2400 kg/m³, an elastic modulus of 17585.79 MPa, a compressive strength of 14 MPa, and a tensile strength of 2.33 MPa. In addition, the values of ψ , e , σ_{b0}/σ_{c0} , K_c , and μ parameters are 30, 0.10, 1.16, 0.6667 and 0.0001, respectively.

$$(5) \quad E_c = 4700\sqrt{f_c}$$

$$(6) \quad f_t = 0.623\sqrt{f_c}.$$

Material characteristics of the steel striker as well as the longitudinal and transverse reinforcement are also defined in the software. While elastoplastic material without hardening is used to model the reinforcement, linear elastic model is utilized for striker. So, the values of Poisson's ratio, density, elastic modulus, shear modulus, bulk modulus, and yield strength for the steel material are considered 0.30, 7850 kg/m³, 200000 MPa, 76923 MPa, 166670 MPa, and 420 MPa, respectively. The reinforcements are embedded in beam-column connection. Thus, tie contact property of the software is used to provide the adherence between the beam-column connection and the reinforcement.

In the mesh convergence analysis, the numerical analysis is performed between 15 and 30 mm finite element sizes for the striker having hemi-spherical geometry. It is seen that extended computational time is required for the smaller mesh sizes than 15 mm. Besides, a negligible difference is established in the analysis outputs for the values between 15 and 20 mm. So, mesh size is considered 20 mm in the numerical analysis.

The numerical analysis is generated for the first drop of the striker. While mass of the hammer is 100 kg, drop height of the striker is taken as 2000 mm. Thus, a constant level of impact energy is applied on the cantilever beam. The striker is allowed to move vertically and only gravity force is defined to the hammer. Steel hammer moves vertically, and it is not affected by any external forces in the experimental program. The connection between the striker and the beam is ensured by surface-to-surface contact property of the software. While the surface of the striker implementing the impact loading is selected as master, and the surface of the cantilever beam is defined as slave in the numerical simulation.

Results. In the solution of incremental dynamic analysis, time increments are utilized in the software. For this purpose, time intervals are defined from the beginning to the end of the drop movement. The value of the increments is considered 2×10^{-8} s from the contact moment of the striker and the cantilever

beam. The analysis is performed for each striker geometry and tip displacement, acceleration and impact load values are determined from the software. The numerical values are given in Table 1. Besides, time histories of the acceleration, displacement and impact load values are exhibited for the flat type striker having the most critical analysis outputs in Fig. 2.

Table 1
Analysis results

Striker type	Acceleration (m/s^2)		Displacement (mm)	Impact load (kN)
Hemi-spherical	−4618	5003	12.67	46.57
Flat	−6135	6604	14.52	48.81
Angular	−4246	4047	8.43	36.16

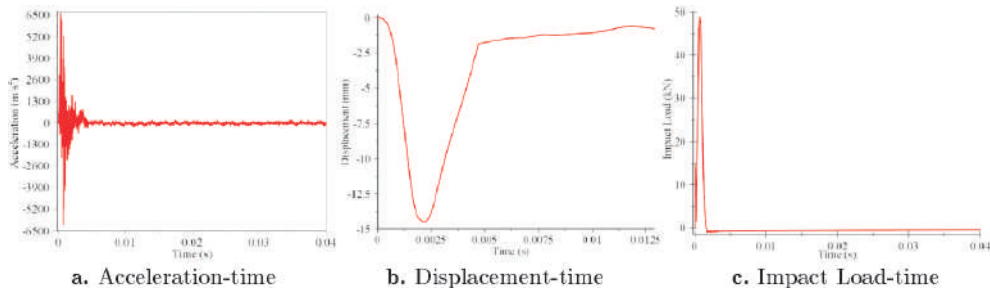


Fig. 2. The graphs for the flat type striker

Another important analysis output is determining the damage developments sudden impact loading. For this purpose, the Von Mises stress distributions and fracture patterns through damage function of the software are obtained. In this way, impact behaviour of the beam-column connection is numerically observed for all of the striker geometries. It is seen that both stress and crack distributions show parallelism under impact effect as shown in Fig. 3. Although impact loading is applied on the tip part of the cantilever beam, the beam-column connection has also been affected. Unit of the stress values is considered Pa (N/m^2) in Fig. 3.

Conclusions. The cantilever beam whose one end is supported to a vertical element and the other end is unsupported is widely used in rc constructions. The main purpose of using cantilever beams is to support balconies and roofs. In addition, cantilever beams allow overhanging structures without any extra supports. Cantilever beams that are widely used in constructions are analysed under the effect of vertical loads such as point load, distributed load and varying load. However, sudden impact loading is not considered in the design of cantilever beams.

Within the scope of this study, non-linear dynamic analysis of a cantilever beam under sudden impact loading is investigated. For this purpose, a beam-column connection is modelled in the software. As there are several impact sce-

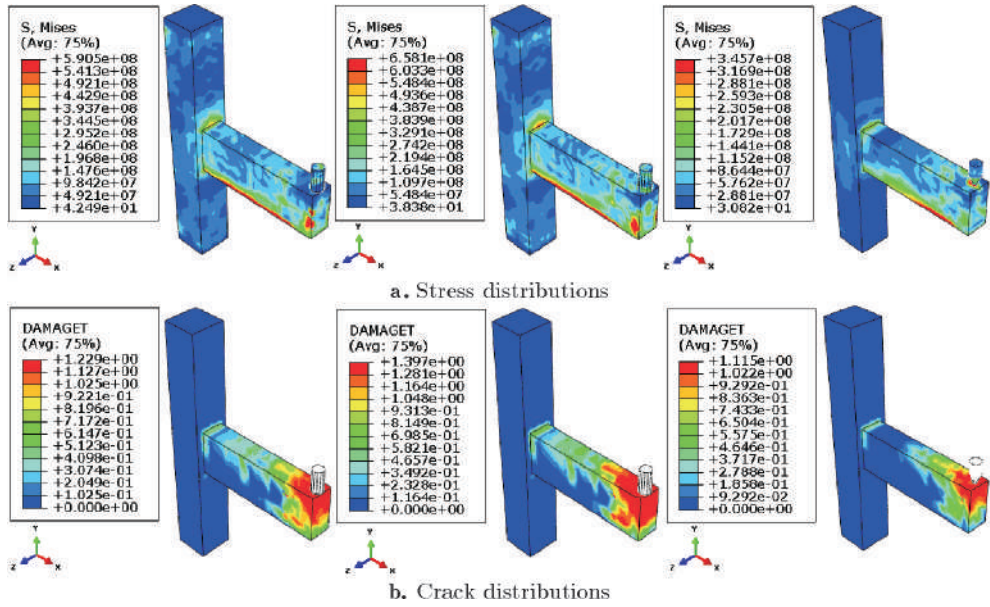


Fig. 3. Distributions for each striker type

narios that structural elements may experience, different striker geometries are considered in the numerical analysis. By this way, impact behaviour of the beam-column connection is assessed due to the change in the contact area between the striker and the cantilever beam. Analysis outputs such as accelerations, displacements and impact loads are determined as well as the stress and crack distributions for each case.

When the analysis outputs are evaluated under the same level of impact energy, it is seen that the numerical results alter due to the contact area of the striker types. Even though constant level of input energy is implemented on the cantilever beam, flat striker type is more efficient on transferring the impact load on the beam. Therefore, maximum accelerations, displacements and impact loads are obtained for this type of striker. On the other hand, minimum values are determined for the angular striker type whose contact area is the smallest one.

The damage developments on the beam-column connection are also observed for each case. Von Mises stress distributions and the fracture patterns are obtained when impact loading is fully transferred on the cantilever beam. Although there is not much difference between the hemi-spherical and flat striker types, the increase in the contact area between the striker and the beam has induced the distribution of damage to get around a larger area. Thus, minimum effects are observed for the angular striker type having the lowest contact area.

In the light of the examined parameters, it is considered that numerical analysis is a significant option when accurate analysis steps are constituted. Due to several reasons such as designing test setups, producing heavy test specimens,

meeting high costs, requiring workforce in the laboratory and complying with the limits of the test devices, computer simulations open a new window into impact behaviour of structural elements. As a result of the numerical analysis, it is thought that the findings of this study set light to future investigations in respect of impact analysis of different elements.

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