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# Numerical Modeling of Time-Displacement Response ofRC Slab Subjected to Impact Loading.

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***Abstract:****In this paper, the time-displacement response of Reinforced Concrete (RC) slab subjected to impact loading was investigated through the Finite Element (FE) modeling in which the Concrete Damage Plasticity (CDP) model was employed. The main parameters of the current study were the thickness of the slab (100, 150, 200, and 250 mm), the area of tension reinforcement, and the area of compression reinforcement. Results showed that the slab thickness and the tension reinforcement area significantly influenced the time-displacement response of the RC slab under impact loading. On the other hand, the compression reinforcement area showed almost no significant effect on the time-displacement response.*

***Keywords:****Drop-weight impact; free-falling low-velocity impact; non-linear analysis; concrete slabs; damage; concrete damage plasticity.*

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## I. Introduction

Tremendous studies have been carried out to investigate Reinforced Concrete (RC) structural elements subjected to static loading which can be simulated experimentally with loading rate less than about 0.1 strain/s. However, mechanical properties of RC structural elements will surely vary when exceeding such certain thresholds rate. Such variation may be attributed to the higher lack of tensile strength leading to intrinsic brittleness, lower ductility and consequently remarkable deterioration under repeated loads with different rates. Applying excessive loading rate can reflect the influence of sever loading conditions such as: projectile/drop impact, dynamic loads, earthquakes, tsunami and blast loading [1], [2].

Weights dropped freely over structural elements can be considered as a low-velocity impact loadingwhich includes:landing of aircraft, sudden impact of ship on offshores, RC deck slab bridges subjected to vehicle crashes. Several researches have been conducted experimentally on impact loading with small mass-up to collapse beyond either some times of shocks or with high-velocity rate (about 300~400 m/s) particularly in nuclear military fields. In these investigations it have been found that the very short time can hardly give sufficient ability of the RC member to globally react. Although local collapsing of slabs or beams can be occurred in the form of cone dislocation, insignificant flexural cracks may be formed.However, intrinsic suddenpremature failure,with absence of stresses cracks (shear-flexural), can be observed when using high-velocity impact case (about 1000m/s).

Several experimental and numerical studies[3]–[11]have been carried out investigating the behavior of concrete members under impact loading showing that RC slabs are more susceptible to impact loads due to their slenderness. Thai et al. [12] numerically investigated the punching resistant capacity of pre-stressed RC slabs under impact loading. Failure and damage were considered through the simulation of the nonlinear behavior of materials. Results revealed that the punching resistance significantly affected by the erosion value rather than the damping ratio. Moreover, the authors recommended using T-headed bars due to their significant effectiveness in enhancing the punching resistant capacity under impact loading and reducing the penetration depth.

A numerical study analyzing the behavior of RC slabs when subjected to impact loading was performed and reported in [13]. Two different concrete constitutive models available in the Abaqus/Explicit package, namely Brittle Cracking model and Concrete Damage Plasticity model (CDP) were employed in the study. The results showed that the Concrete Cracking constitutive model was not recommend simulating the impact behavior of RC slabs. On the other hand, the CDP model showed reasonable and acceptable results simulating the overall impact behavior, especially the stress/strain behavior, energy, and deformation. The main shortage of the CDP model that it cannot model spalling and scabbing of concrete as it does not provide a failure criterion.

Pereira et al. [14] simulated the response of concrete under ballistic impact providing an enhancement to the effective-rate-dependent damage model proposed by the authors and reported in [15]. The proposed model significantly simulated the behavior of concrete plates subjected to impact loading and showed good prediction of failure modes as a function of the projectile velocity and plate thickness.

Othman and Marzouk[16] performed a numerical study simulating the behavior of Ultra-High Performance FiberReinforcedConcrete (UHP-FRC) when subjected to impact loading. Results showed that the CDP constitutive model has the ability to predict the dynamic response of UHP-FRC under impact loading. The parameters of the CDP were identified through a sensitivity analysis due to the lack of experimental data regarding UHP-FRC. Moreover, the numerical results revealed that the plastic volumetric change, represented by the dilation angle, of UHP-FRC was smaller than that of conventional concrete.

Oucif et al. [17] implemented a numerical model, simulating the behavior of RC panel subjected to impact, in which the Johnson-Holmquist damage model was employed modeling the concrete behavior. The effect of steel reinforcement on the impact resistance was neglected in this study and the panel was treated as plain concrete as also recommended by polka Genikomsou and Polak[18]. Results showed that the damage model used was able to predict the impact behavior of plain concrete.

Generally, the composite concrete material can significantly affect the major behavior of stiff mode into the ductile one with the presence of steel bars or use new generation of concrete [19-22]. Also, a comperhensive research have been carried out for the concrete structures influenced by ambient conditions [23-26].

Experimental investigations can be considered as impractical and expensive methodology predicting the behavior of RC elements when subjected to impact loading. For this, numerical analysis have become popular technique that provides a detailed simulation to the response of RC element under impact loading. On the other hand, numerical analysis may present some difficulties such as the selection of an appropriate material constitutive model, definition of the contact surfaces between different materials, and choice of a proper mesh size.

From the analysis of the available literature, numerous numerical studies were performed investigating the impact behavior of RC slabs. Most of performed studies focused on the selection of the appropriate material constitutive model and the determination of its parameters. There is a lack and uncertainty regarding different parameters (such as amount of steel reinforcement, slab thickness, slab inertia, etc.) that may influence the impact behavior. For this, the aim of the current research is to conduct a numerical investigating on the impact behavior of beam-less RC slab.

## II. Numerical/finite element modeling

### *2.1.Specimen's details*

In the current study, the specimen used was a flat slab previously used in the experimental program carried out and reported in[11], see Fig. 1.

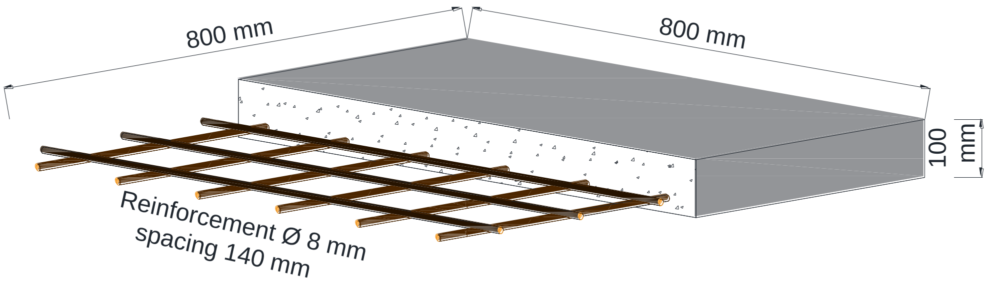


**Fig. 1.**Slab specimens used in the study by Kumar et al. [11].

### *2.2 Finite Element Model set-up*

Reinforced concrete is well known for its non-linear behavior, which originates fromthe non-linear stress-strain relationship of plain concrete.In the current study, the Concrete Damage Plasticity (CDP) available in ABAQUSpackagewas selected due to the general capability it provides for modelling concrete as quasi-brittle material. CDPmodel represents the inelastic behavior of concrete through the concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity. In order to calibrate the CDP model, a sensitivity analysis was carried out and the different model's parameters were determined. The stress-strain relationship for concrete used in this study is presented in Fig. 2.

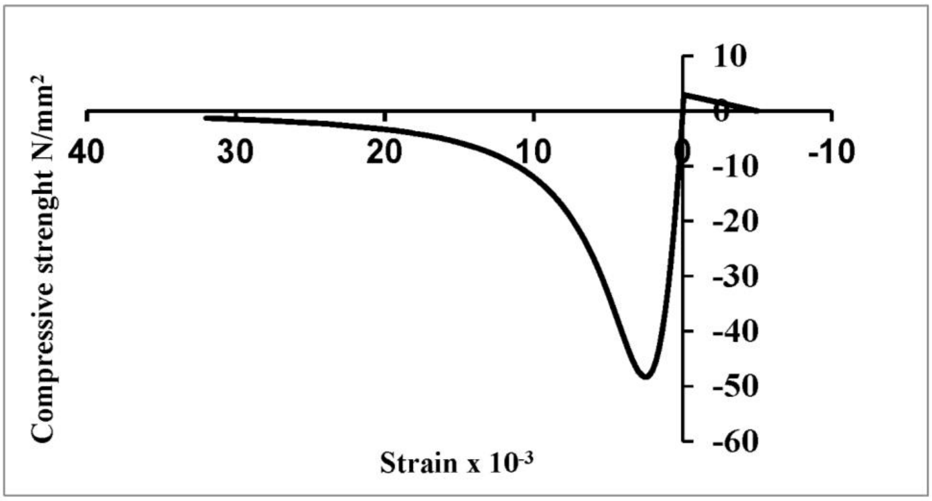


**Fig. 2.**Stress-strain relation for concrete.

The uniaxial material behavior of the reinforcing steel was modeled using a bilinear stress-strain relation. Therefore, the reinforcing steel material model only requires the yield strength, the modulus of elasticity as well as the ultimate strength and the corresponding ultimate strain. Elastic-perfectly plastic material property for steel reinforcement was used to model RC member as shown in Fig. 3.

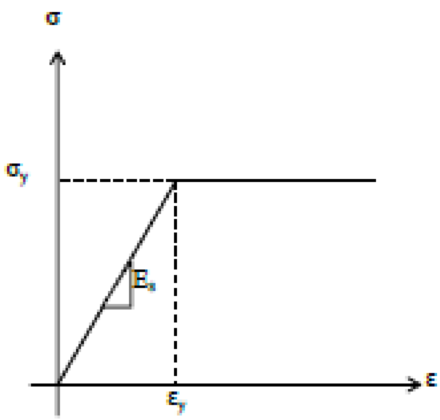


**Fig. 3.**Stress-strain relation for steel reinforcement.

***2.3 Model built-up and numerical parameters***

In the present study eight node continuum solid element (C3D8R) wasemployed for modellingthe concrete portion of the RC slab, and two nodetruss element (T3D2) was used for modelling the reinforcement, while the impact hammer wasmodeled using a rigid element.

For the present analysis of slab, surface-to-surface contact (Explicit) algorithm based on a penalty formulation was used to model the interface between the concrete slab and the impactor. The interaction between support plate and slab was also been modeled by surface-to-surface contact (Explicit) contact method. Friction between the two surfaces was neglected. Acceleration due to gravity also included in the analysis. On the other hand, the embedded technique was used to create a bond between the steel reinforcement and concrete.Fig. 4shows the details of FE model for the slabtested in the study.

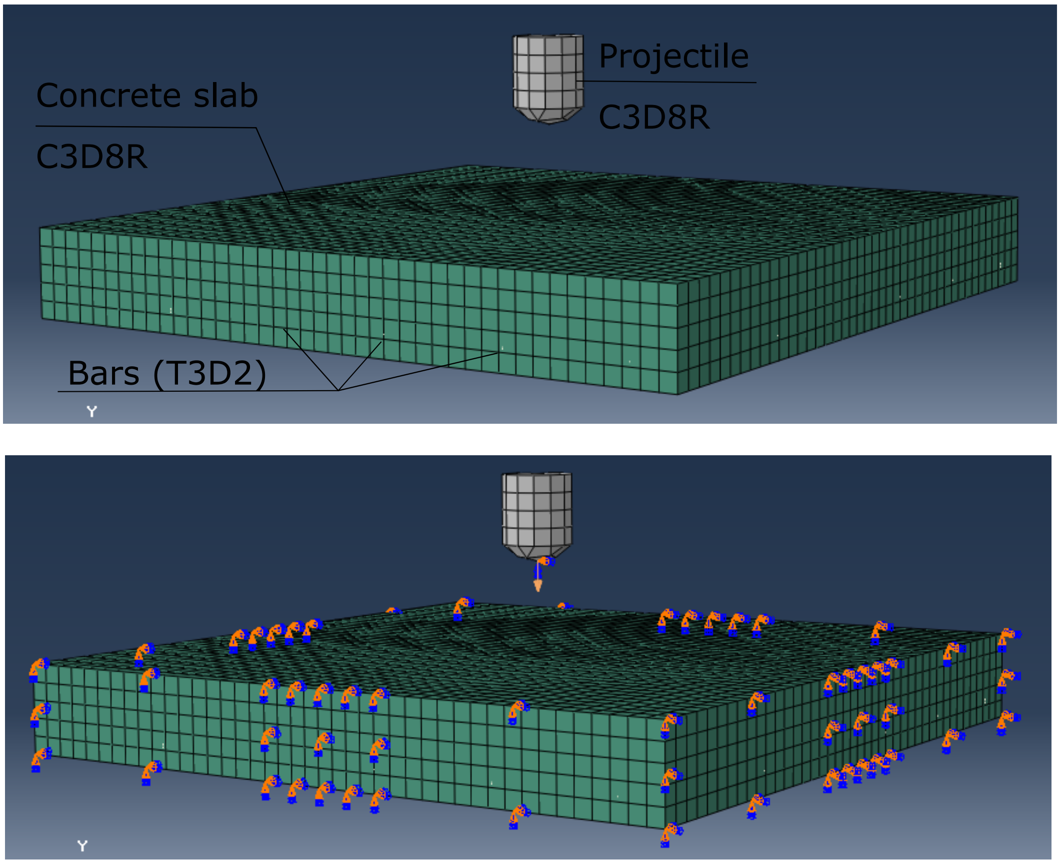


**Fig. 4.**Details of FE model; a) Elements and meshing, and b) Boundary conditions and predefined load.

The impact load was applied, simulating tests carried out by Kumar et al. [11], by releasing a 248.5 kg impact hammer from a height equal 500 mm from the top surface of the slab, resulting in an impact speed of 3.13 m/s.

In order to capture a better-calibrated, numerical model with perfect constitutive numerical parameters, current FE model was re-executed several trials aiming to present the sensitivity of three main numerical parameters which were: mesh size ($l$), dilation angle ($\psi$) and viscosity parameter($\mu$).Numerical results obtained were checked against those obtained experimentally from the study carried out by Kumar et al. [11].

The model was meshed with size not less than that of concrete coarse aggregate used for casting experimental specimens as recommended by Genikomsou and Polak[18]. The used meshes were 10 mm, 20 mm and 25 mm dividing slab thickness into about 10 elements, 5 elements and 4 elements for each respectively, as shown in Fig. 5. The time-displacement curves for both experimental and numerically executed FE models are shown in Fig. 6. Time-displacement response of FE model with a mesh size of 20 mm showed a good agreement with that of experimental one compared to other mesh sizes, as already noted elsewhere [16].

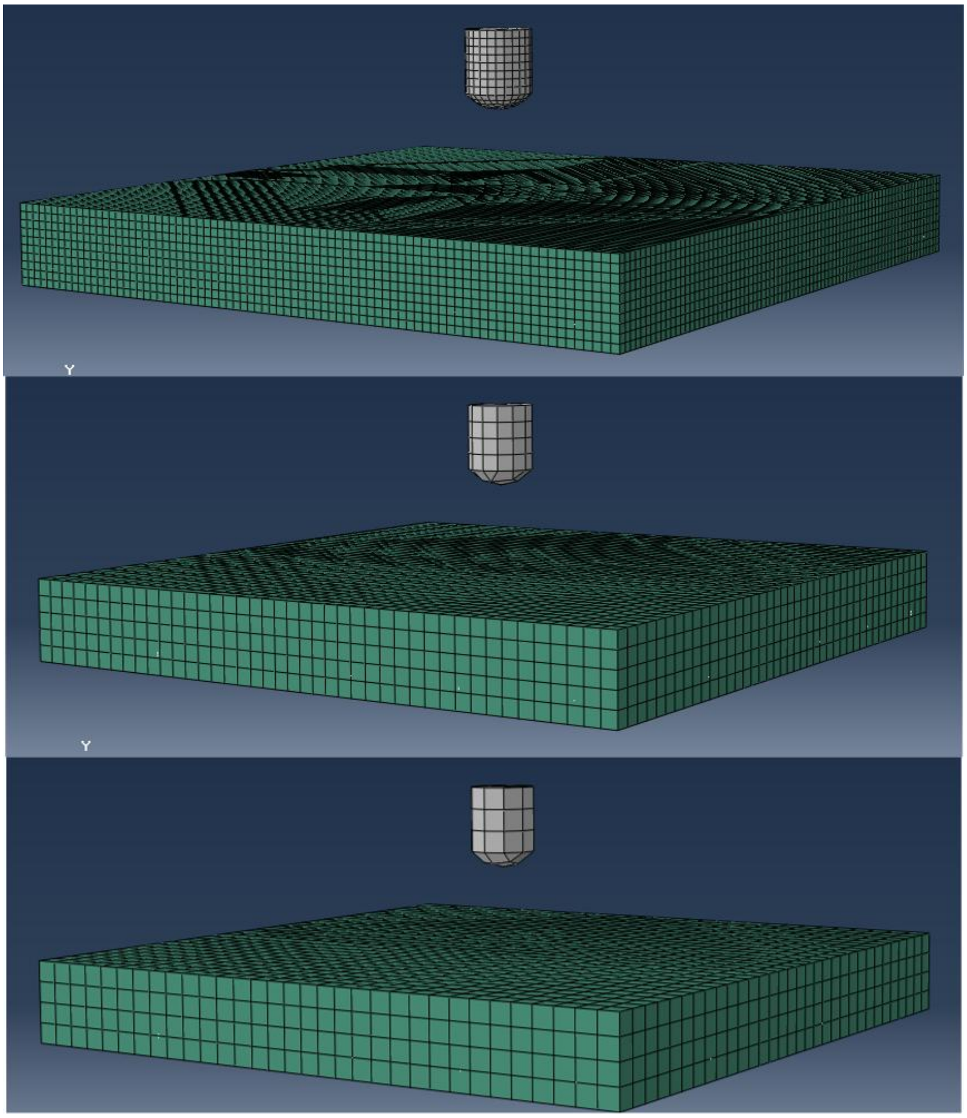

**Fig. 5.**Different mesh sizes used in the study; a) 10 mm, b) 20 mm, and c) 25 mm.

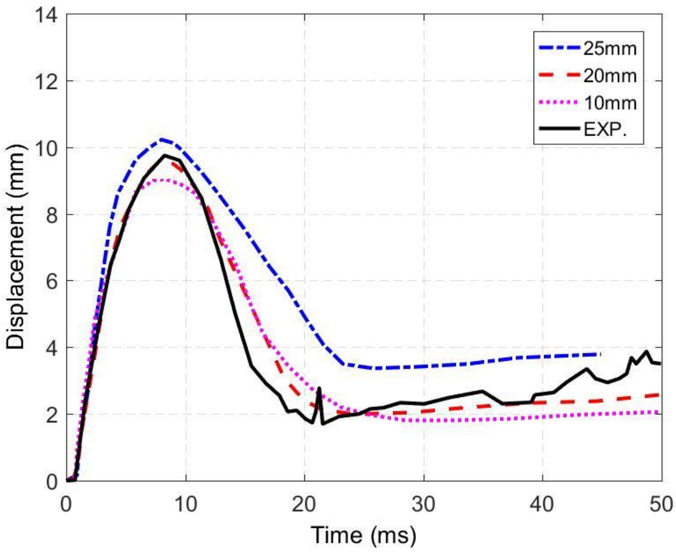


**Fig. 6.**Identification of numerical and constitutive parameters: Meshing size

The dilation angle used in CDP modeling is to represent the vector direction of plastic strainincrement as well as increase of stress at shear-normal stress plane (*p-q*) response. The dilation angle herein varied from 20 degree to 40 degrees. Numerical results showed that the best prediction was given by $\psi$ = 35 degree while the lower or higher dilation angle value resulted in a slight underestimation or overestimation, respectively as depicted in Fig. 7.

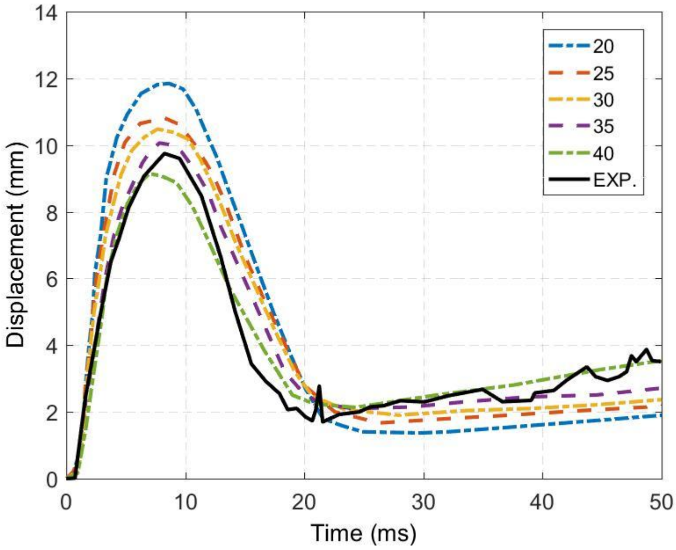


**Fig. 7.**Identification of numerical and constitutive parameters:Dilation angle ($\psi$)

For sensitivity analyses, the control FE model with 20 mm mesh size and 35 degree dilation angle was considered, while time relaxation parameter, viscosity ($\mu$), was selected to be: 0.005, 0.01, and 0.015. The time-displacementrelationships observed from the sensitivity analysis can be seen in Fig. 8.Numerical results illustrated that the most essential response wasgiven by μ= 0.01with 20 mm meshing size, while more lake of viscosity presented a prematuredivergence.

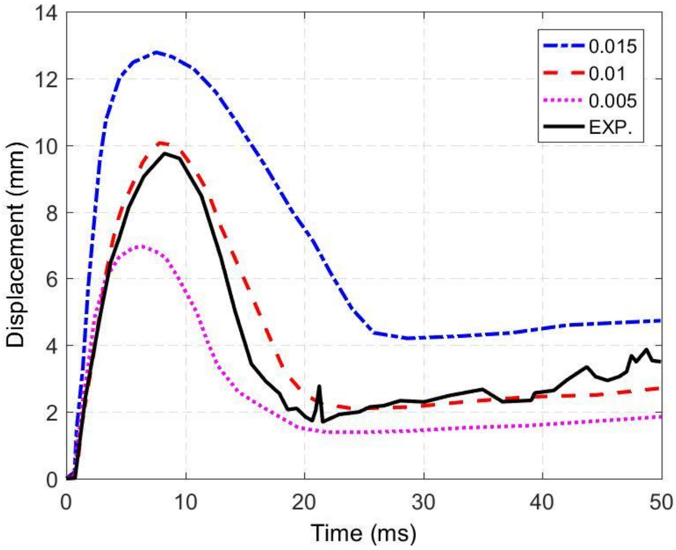


**Fig. 8.**Identification of numerical and constitutive parameters:Relaxation parameter($\mu$) (Viscosity)

Fig. 9 shows the crack pattern observed through the FE numerical analysis showing a good coherence when compared to that obtained experimentally in [11].

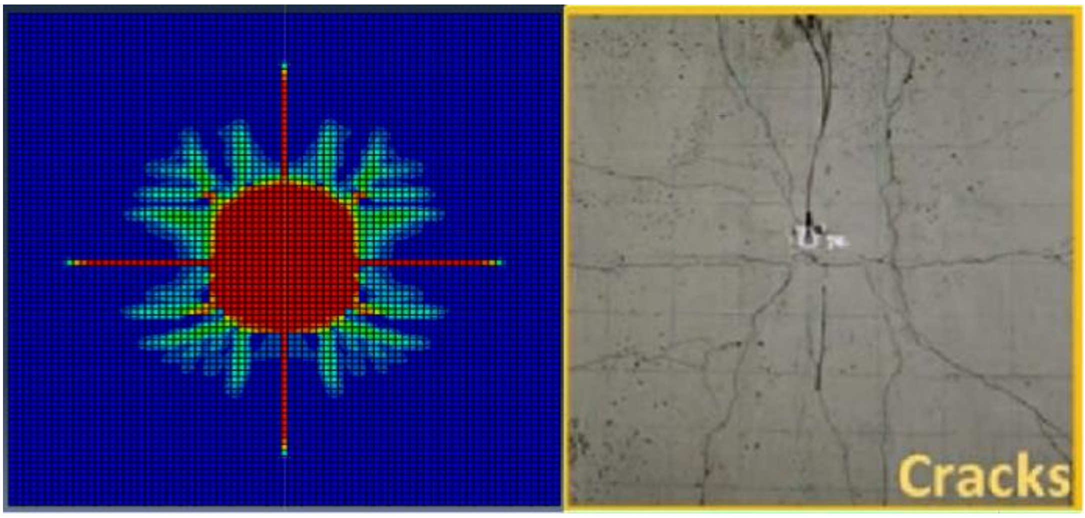


**Fig. 9.**Crack patterns observed through; a) FE model, and b) Experimental tests [11].

***2.4Numerical parametric study***

Parametric study was performed investigating the effect of slab thickness, tension reinforcement area, and the existence of compression reinforcement on the time-displacement response of flat slab under impact loading.

## III. Results and discussion

Fig. 10shows the time-displacement response of RC slabs having different thicknesses when only tension reinforcement was used. Results revealed that increasing the slab thickness decreased the peak deformation at the center of the RC slab. The displacement increased sharply for specimens of thickness 100 mm and 150 mm than those having 200mm and 250 mm thickness, this can be attributed to the higher stiffness provided by increasing the thickness. Increasing the thickness form 100 mm to 150mm resulted in a reduction in the peak displacement by 17%, this reduction was 37% and 56% for specimens with thickness equal to 200mm and 250mm, respectively.

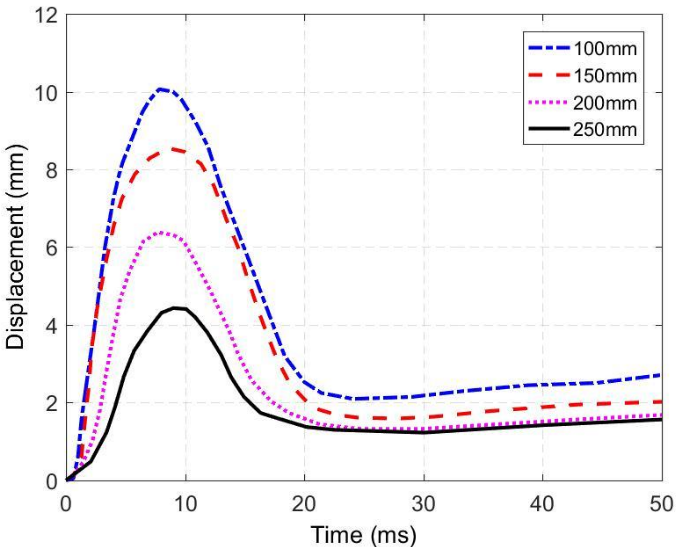


**Fig. 10.**Time-displacement response at different slab thicknesses using tension reinforcement only.

The effect of slab thickness on the time-displacement response due to impact loading, when using both tension and compression reinforcement, is presented in Fig. 11. However, lower peak displacement values were obtained, almost similar behaviors to those of specimens having only tension reinforcement were observed. Increasing the thickness form 100mm to 150mm resulted in a reduction the peak displacement by 21%, this reduction was 38% and 61% for specimens with thickness equal to 200mm and 250mm, respectively. For the same slab thickness, specimens having both tension and compression reinforcement showed peak displacement 9% lower than those having only tension reinforcement.

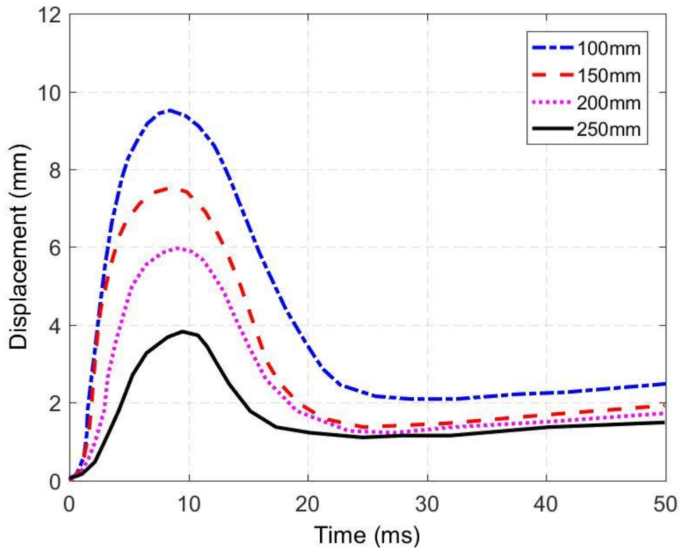


**Fig. 11.**Time-displacement response at different slab thicknesses using tension and compression reinforcement.

The effect of increasing tension reinforcement with no compression reinforcement, at different slab thicknesses, on the time-displacement response is presented in Fig. 12. For specimens having thickness equal to 100mm and 150mm, increasing the diameter of tensile reinforcing bars from 8 mm to 10 mm reduced the peak displacement by an average value of 19%, while increasing the diameter from 10 mm to 12 mm had no significant effect on the peak displacement as well as the total time-displacement behavior.

In the case of specimens with thickness equal to 200mm and 250mm, increasing the diameter of tensile reinforcing bars from 8 mm to 10 mm reduced the peak displacement by an average value of 11%.Similarly, increasing the diameter from 10 mm to 12 mm resulted in a reduction in the peak displacement by an average value of 11%.

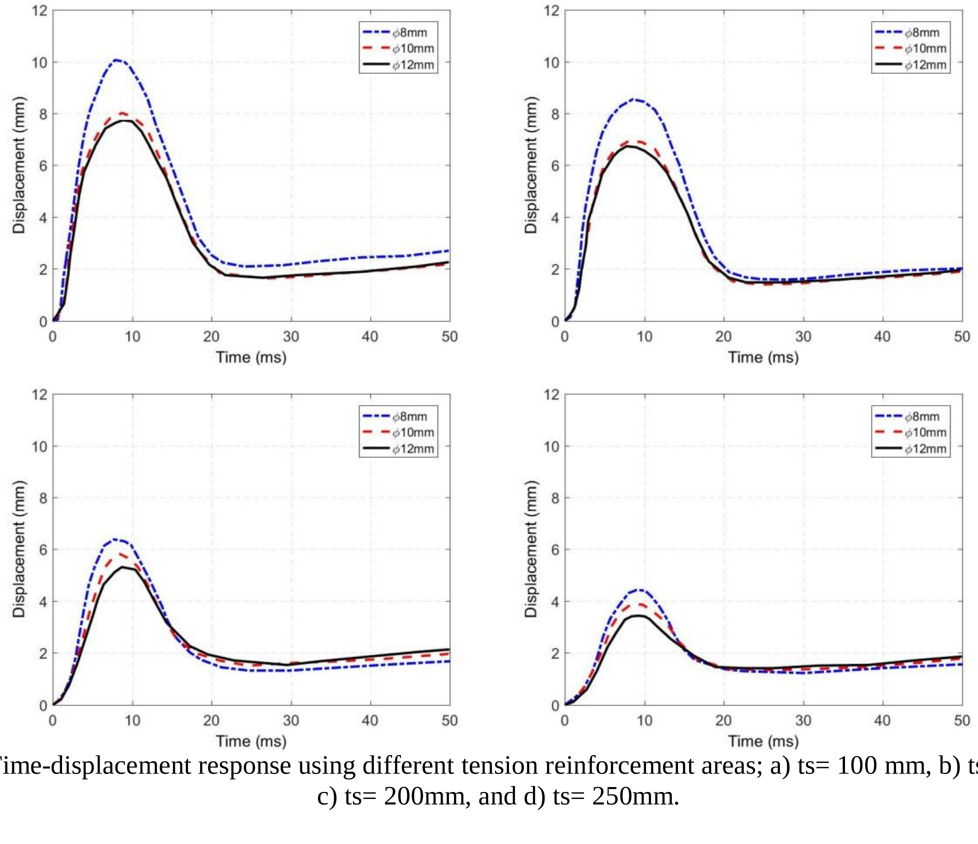


**Fig. 12.**Time-displacement response using different tension reinforcement areas; a) ts= 100 mm, b) ts= 150mm, c) ts= 200mm, and d) ts= 250mm.

Fig. 13shows the time-displacement response under impact loading when using different bar diameters of compression reinforcement while keeping the tension reinforcement constant. Results showed that, for all slab thicknesses tested, increasing the bar diameters of compression reinforcement had almost no significant effect on the time-displacement behavior.

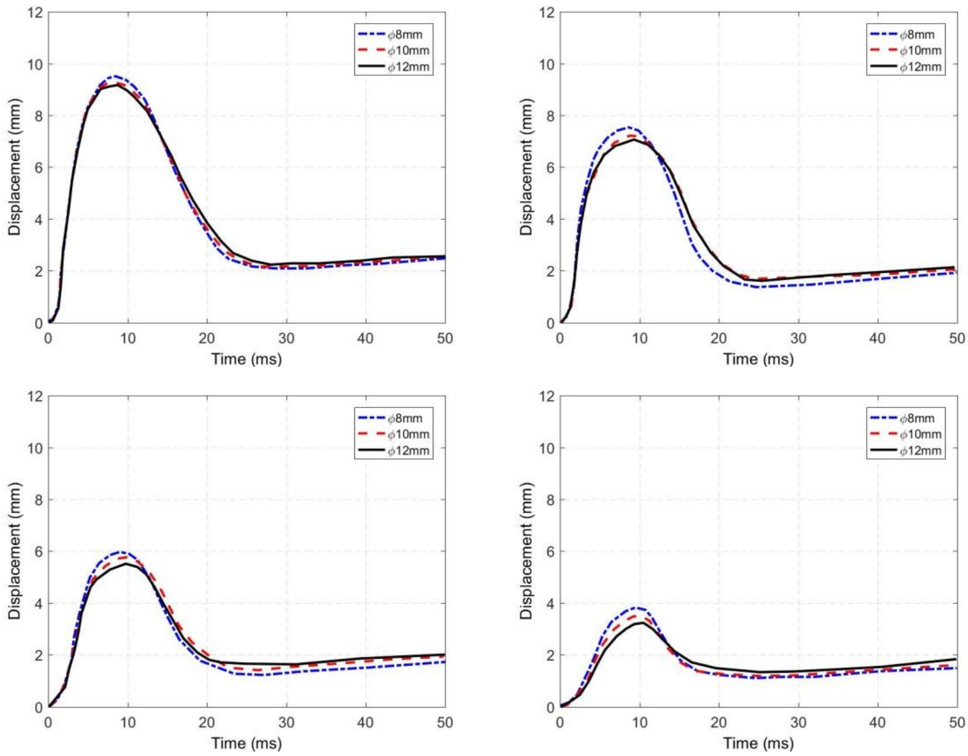


**Fig. 13.**Time-displacement response using different compression reinforcement areas; a) ts= 100 mm, b) ts= 150 mm, c) ts= 200 mm, and d) ts= 250 mm.

## IV. Conclusions

This paper presents a parametric study investigating the effect of slab thickness, the tension reinforcement area, and the compression reinforcement on the time-displacement response of RC slab subjected to impact loading. Based on the results obtained, the following conclusions were driven:

- The Concrete Damage Plasticity (CDP) model is able to simulate the behavior of RC slab under impact loading.
- Increasing the slab thickness decreased the peak deformation at the center of the RC slab.
- The use of compression reinforcement resulted in lower peak displacement values, however, almost similar behaviors to those of specimens having only tension reinforcement were observed.
- Increasing the diameter of tensile reinforcing bars reduced the peak displacement at the center of the RC slab.
- The use of compression reinforcement had almost no significant effect on the peak displacement as well as the overall time-displacement behavior.

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