Proceedings of the 7th International Conference on Civil Structural and Transportation Engineering (ICCSTE'22)
Niagara Falls, Canada – June 05-07, 2022
Paper No. 146
DOI: 10.11159/iccste22.146

Parametric Investigation on the Performance of RC Slabs Subjected to Accidental Impact Loadings

Shamsoon Fareed[1], Asad-ur-Rehman Khan[1]
[1]Department of Civil Engineering, NED University of Engineering & Technology
University Road-75270, Karachi, Pakistan
sfareed@neduet.edu.pk; asadkhan@neduet.edu.pk

Abstract **-** Due to the loading intensities generated as a result of vehicular impacts, heavy drop weights, collision of ships and aircraft, debris impact loading form as a result of Tsunami and flood and impact forces generated due to the missiles, bullets and explosive loadings etc. may cause a reinforced concrete slab to withstand forces for a very short duration of time but having magnitudes and intensities much higher than the static loading rates. Several studies have already been carried out which focuses on investigating the response of slabs to accidental impacts having initial contact velocities of up to 1000m/s. The focus of these studies mainly aims in predicting the threshold value for the thickness of the reinforced concrete slabs under high-velocity projectiles impacts to restrict the level of penetration required in the nuclear and military structures. However, for the case of reinforced concrete slabs as a part of civil and non-protective structures, the loading intensities produced due to accidental and abnormal impact activities are mainly caused due to velocities of up to 10 m/s. Therefore, this investigation aims in studying the response of the reinforced concrete slabs subjected to low-velocity impact loading. Following a critical review of already published experimental studies and the empirical equations used in industry to predict the response of such slabs, a detailed parametric investigation on the response of the reinforced concrete slabs under low-velocity impacts has been carried out using a non-linear explicit dynamic technique using finite element software ABAQUS. The parametric investigation focuses on studying the influence of the velocity and thickness of the slab on the behaviour of the reinforced concrete slabs subjected to low-velocity impact loads. It was found that these parameters significantly influence the behaviour of the reinforced concrete slabs which are not explicitly considered in the empirical equations used by the industry, which in turn, as a result, does not always provide safe predictions for the case of the low-velocity impact loadings.

Keywords**:** Reinforced concrete slabs, low-velocity impacts, high-rate loading, non-linear finite element analysis, empirical equations

1. Introduction

The reinforced concrete (RC) slabs during its construction phase and design life may be subjected to loads having intensities much higher than the static loading rates. These loading rates based on the purpose and location of the structure may be generated due to the vehicular impacts, an accidental drop of heavy objects, aircraft collision, impact from debris produced due to Tsunami or flood, and impact generated due to the missiles and explosive loadings etc. Due to these actions, the reinforced concrete slabs may be subjected to velocities of up to 1000 m/s [1]. However, for the case of civil and non-protective structures, the loading intensities produced are mainly caused due to impact velocities of up to 10 m/s [2].

Based on the velocity of impacting objects, the loading intensities generated due to the above abnormal activities can be classified as high or low-velocity impacts. Several experimental [1-15] studies have been conducted to study the response of the RC slabs under high loading rates, however, the focus of most of these studies was to investigate the influence of the high-velocity projectiles penetrating the RC slabs to ensure a certain level of resilience required in the nuclear and military structures. As a result, the focus of these studies was to examine the required thickness to prevent penetration, perforation and scabbing. Furthermore, based on the high-velocity impact test results number of empirical equations has been derived.

This study initially focuses on the critical review of already published experimental studies of both high and low-velocity impacts. Following the critical review of the influencing parameter, a detailed parametric investigation has been carried out numerically using non-linear finite element (FE) analysis commercial package ABAQUS [16].

2. Critical Review of the Published Experimental Studies

Fig. 1 shows the relationship between the penetration depth (x_{exp}) and velocity of the impactor at the time of contact for the impact test data [1-15]. In general, it was observed that with the increase in the velocity of the impacting object the penetration depth exhibited by the specimens also increases. It was further observed that no definite relationship can be predicted due to the scattered nature of the test data. The scatter in the test data may be attributed due to different cross-sectional dimensions, concrete strength, amount of steel and contact face of the impacting object used in each test setup for the impact test data [1-15]. Furthermore, it is important to note that for the case of low-velocity impacts (i.e. up to 10m/s), the penetration exhibited by reinforced concrete slabs during impact tests (see Fig. 1) varied between 0.7mm to 46.3mm, whereas, for the case of high velocity impacts the penetration exhibited by reinforced concrete slabs varied between 0.6mm to 200mm. Based on that observation it can be concluded that the velocity is not only the parameter that influences the behaviour of reinforced concrete slabs under impact load as for the case of low and high-velocity impacts similar penetration depth were exhibited, for example, slabs when impacted with a velocity of 3m/s and 27m/s and 5.4m/s and 91.1m/s (see Fig. 1). It is important to note that the empirical equations used to predict the penetration depth exhibited by slabs under impact consider velocity as the main parameter and the relationship between penetration depth and velocity in most of these equations are directly proportional. However, as observed from Fig. 1, this is not always the case.

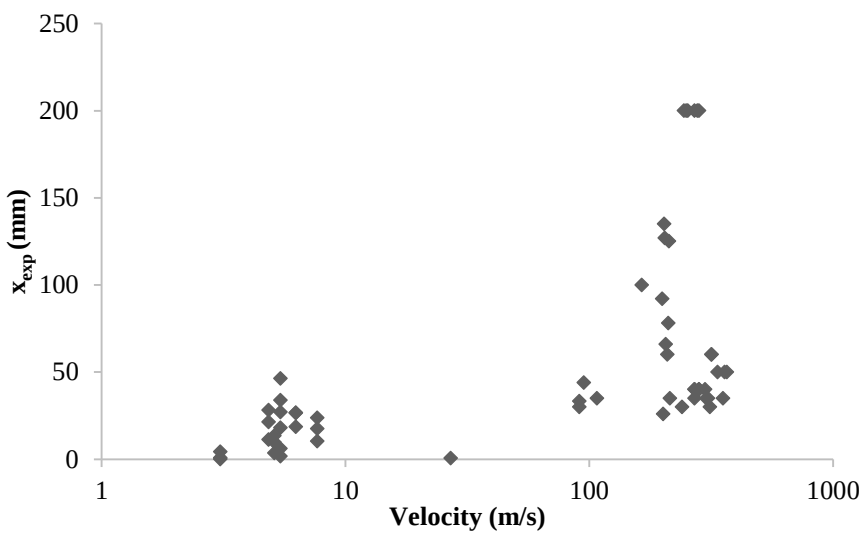

Fig. 1: Test data describing the relationship between the penetration depth (x_{exp}) and velocity of the impactor at time of contact.

Fig. 2 shows the comparison between the ratio of penetration depth observed experimentally (x_{exp}) and predicted (x_{pre}) using different empirical formulae concerning x_{exp} for the tests data. In general, it was observed that most of the test data for the penetration depth observed experimentally (x_{exp}) varied between 0mm to 50mm and for that x_{exp} the empirical equations used for predicting the penetration depth are found to be safe and, in most cases, overly conservative. It was also observed that for the x_{exp} in the range of 50mm to 100mm, the prediction of empirical equations was found to be less conservative as the ratio of penetration depth observed experimentally (x_{exp}) and predicted (x_{pre}) varied between 0.5 to 1. However, as the x_{exp} exceeds the 100mm threshold, the penetration predictions by most of the empirical equations are unsafe as shown in Fig. 2.

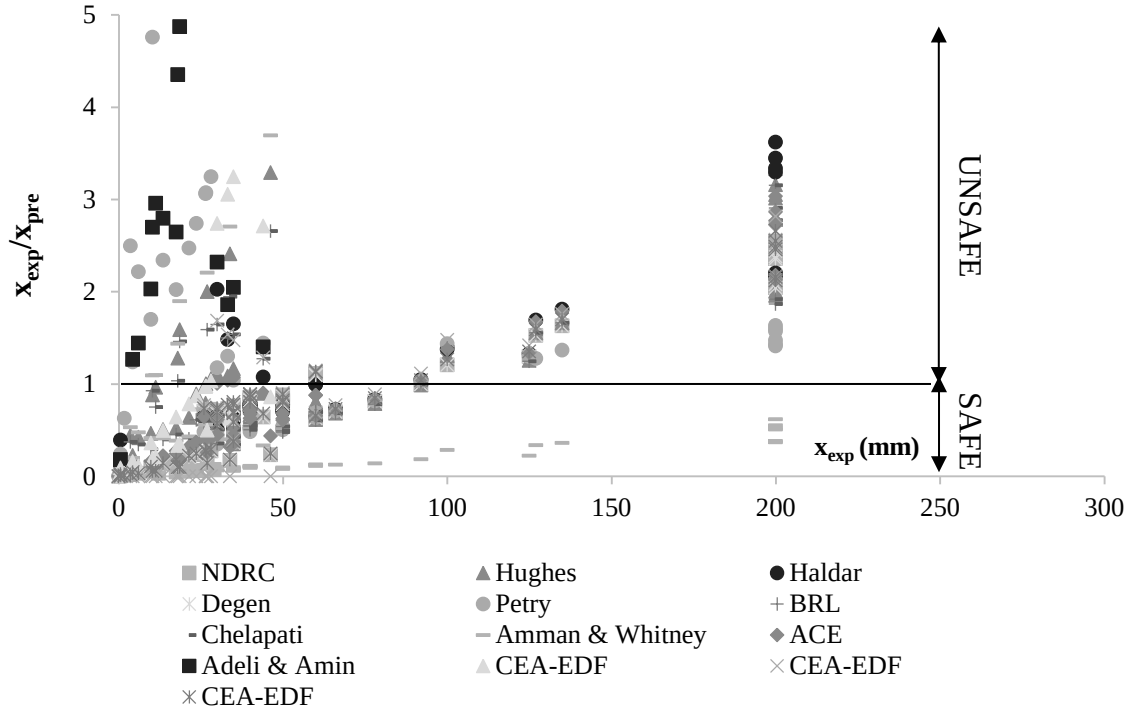

Fig. 2: Comparison of the ratio of penetration depth observed experimentally (x_{exp}) and predicted (x_{pre}) using empirical formulae concerning x_{exp}.

Based on the comparisons of the impact test results and the prediction of the empirical equations, it can be concluded that the behaviour exhibited by the reinforced concrete slabs for the case of low and high-velocity impacts differ significantly. Furthermore, it was also observed that no direct relationship can be formed between the penetration exhibited by the reinforced concrete slabs and the velocity of an impacting object as similar penetration depths were exhibited. It was also observed that for the case of low-velocity impacts the empirical equations are unable to accurately predict the response of the reinforced concrete slab. Therefore, this study focuses on investigating numerically the parameters influencing the behaviour of the reinforced concrete slabs under low-velocity impacts.

3. Non-Linear Dynamic FE Analysis

To examine the behaviour of the RC slabs under low-velocity impacts, FE analyses were conducted using the commercial FE package ABAQUS [16]. Firstly, test results of the available study [6] were used as a benchmark for the validation of the FE analysis, which was followed by a detailed parametric investigation influencing the behaviour of the RC slabs under impact loadings.

3.1. Validation of FE analysis

A study conducted by Chen and May [6] was used to validate the FE analysis. The study [6] details the impact tests conducted on RC slabs. For the validation purpose, 760 mm x 760 mm RC slab was used which were tested using 98.7 kg mass with an initial impact velocity of 6.5 m/s. Details of the impactor shape and dimensions, reinforced concrete slab details and test setup used in the experimental study are provided in detail elsewhere [6]. To save computational cost, due to the symmetric geometry of the test setup, only a quarter model of the full-scale test setup [6] was used. The FE analyses were conducted using the explicit dynamic technique.

Fig. 3 gives the relationship between the impact force and time exhibited by the RC slabs during the impact test and predicted numerically. In general, it was observed that when the contact occurred between the impact mass and the RC slab, the contact force exhibited increases significantly within a short duration of time and reaches its maximum magnitude within 1ms. After the peak impact force has been attained, the reduction in the impact force occurred as the separation initiated between the slab and the impacting object. It was also observed that before the contact was completely over between the slab and the impacting object, the second contact was also exhibited. As a result, the contact force started to increase again until it reached one-third of the peak contact force and, thereafter, remain constant for a short duration of time until it ultimately reaches zero as the contact between the slab and the impactor was completely over.

When comparing the response of slab both exhibited experimentally and predicted numerically, in general, good agreement was found. For the initial period before the maximum contact, a force was attained excellent agreement was observed, however, divergence was observed in predicting the maximum impact force as FE predicted a slightly higher impact force compared to that exhibited experimentally. It was also observed that the FE predictions during the unloading phase of first contact differ from experimental results as FE predicted a lower magnitude of contact force before the start of the second contact between the slab and the impacting object. However, a similar response both in terms of contact time and magnitude of the contact force was observed from the start of the second contact.

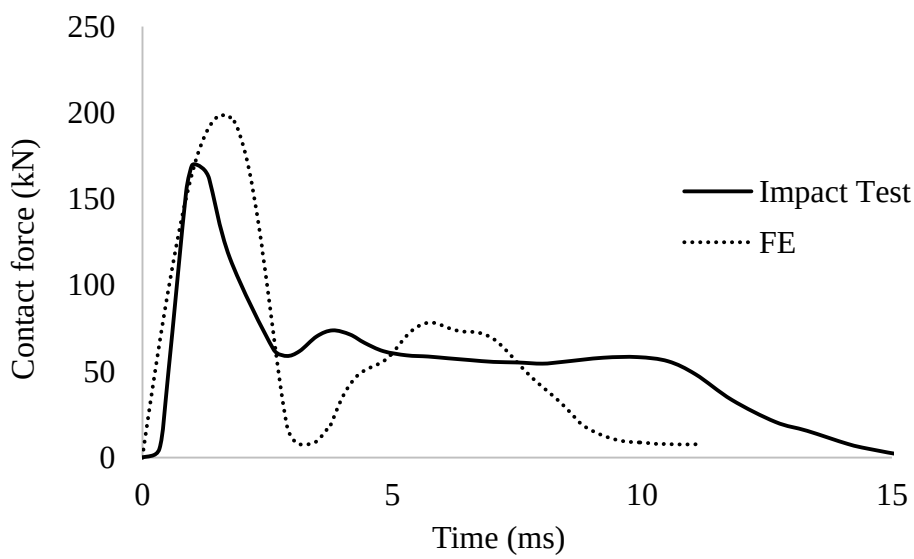

Fig. 3: Impact force-time history relationship exhibited experimentally and predicted numerically.

3.2. Parametric Investigation

As already discussed, that the behaviour of the RC slabs under high-rate loading is influenced by several parameters which include the velocity of an impacting object, cross-section dimensions of the slab, concrete compressive strength etc. Furthermore, it was also observed that several investigations have been carried out to study the behaviour of the reinforced concrete slabs under high-velocity impacts, however, very limited published studies have been found for the case of reinforced concrete slabs subjected to low-velocity impacts. Therefore, the study presented herein focuses on a detailed parametric investigation of the influence of parameters on the response of the RC slab subjected to low-velocity impacts. The parameters considered in this study are (i) the velocity of an impacting object and (ii) the thickness of the slab.

Influence of velocity

To investigate the influence of the velocity of an impacting object on the response of the RC slabs under low-velocity impacts, three case studies as described below were conducted. For this purpose, the same FE model as described invalidation was used with three different impact velocities.

(a) Case study – V1: impact velocity of 6.5m/s as used in the experimental study.
(b) Case study – V2: impact velocity of 4.0 m/s
(c) Case study – V3: impact velocity of 10.0 m/s

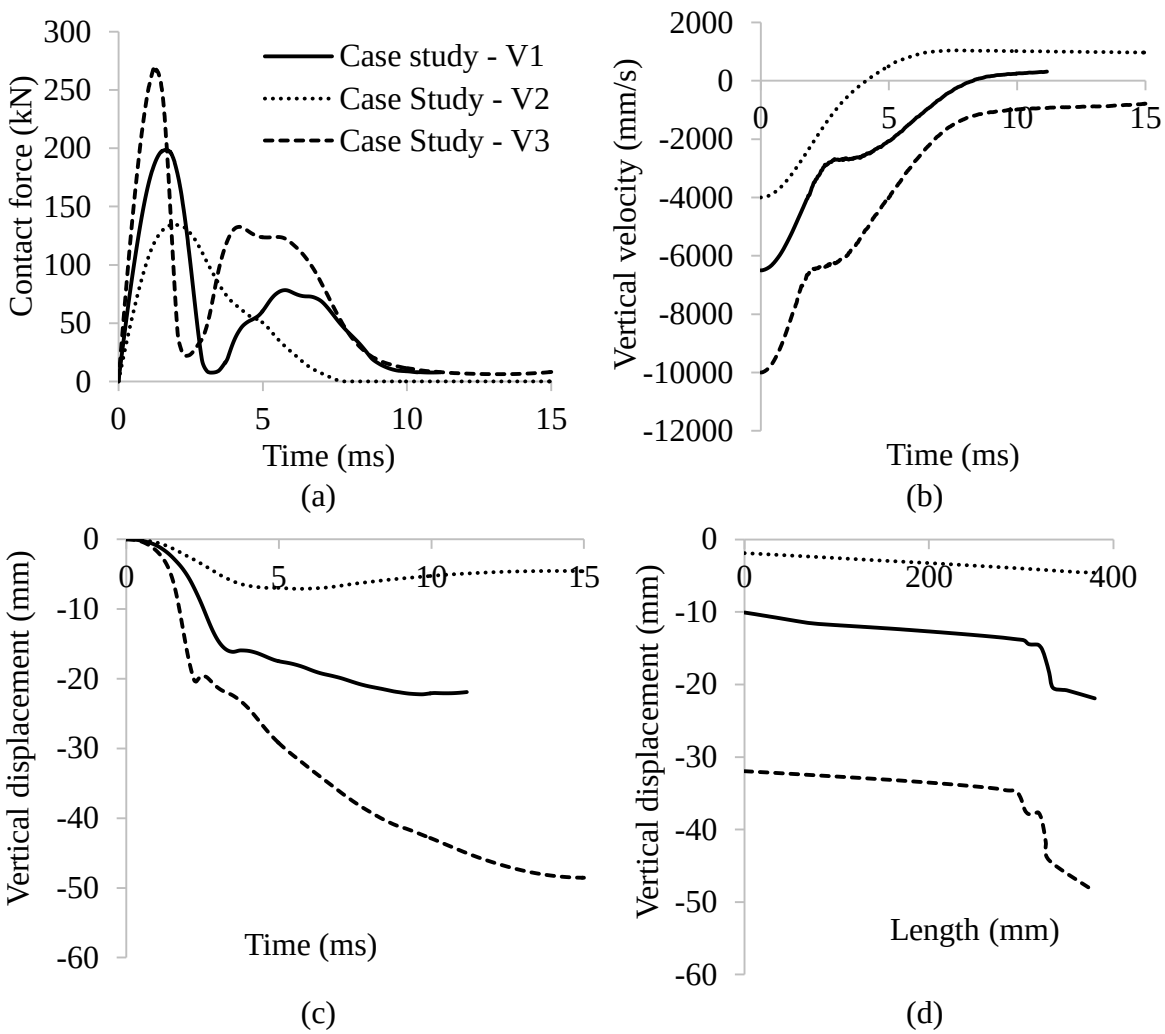

Fig. 4: Behaviour of the reinforced concrete slabs in terms of (a) contact force-time histories, (b) vertical velocity time histories, (c) vertical displacement time histories and (d) displacement profile along the length when subjected to impact loads having an initial impact velocity of 6.5m/s (Case study - V1), 4.0m/s (Case study - V2) and 10.0m/s (Case study -V3).

Fig. 4 (a-d) shows the behaviour of the reinforced concrete slabs in terms of contact force, vertical velocity and vertical displacement time histories and displacement profile along its length when subjected to impact loads having initial impact velocity of 6.5m/s (Case study V-1), 4.0m/s (Case study V-2) and 10.0m/s (Case study V-3) The displacement profile was measured at the top face of the RC slabs throughout the mid-point along its length. From 4 (a), in general, it can be seen that with increasing impact velocities the maximum contact force and duration of the also increases. Furthermore, it was also observed that for the case study V-2, when 4m/s impact velocity was used, the contact occurs only once, and soon after reaching the maximum magnitude, the contact force become zero indicating the end of the contact between the slab and the impactor [see Fig. 4 (a)]. However, in opposite to case study V-2, the contact force did not become zero after reaching its maximum magnitude, rather a second contact was formed during its rebounding phase for the case when velocities of 6.5m/s (Case study V-1) and 10.0m/s (Case study V-3) were used.

Fig. 4 (b) shows the velocity-time histories of the impactor having an initial contact velocity of 6.5m/s, 4.0m/s and 10.0m/s. As can be seen that with increasing impact velocities of an impacting object, the velocity with which the impactor rebound decreases. It may be attributed to the fact that when the impactor impacted the slab, the energy stored in the impactor is transferred into two main parts (i) elastic energy and (ii) plastic energy. The plastic energy is used to cause the permanent deformation in the impact zone which in turn reduces the elastic energy which causes the impactor to rebound. Therefore, with the increase in the velocity of an impacting object the plastic deformation exhibited by the RC slab increases and as a result the impactor rebound with low residual velocity.

Fig. 4 (c) shows the vertical displacement time histories of the RC slab impacted with initial velocities of 6.5m/s, 4.0m/s and 10.0m/s. The vertical displacement was measured at the mid-point of the RC slab at its top face. As can be seen from Fig. 4 (c) that with increasing impact velocities of an impacting object, the localized damage exhibited by the slab at the impact zone also increases. It was also observed that for the case of low-velocity impact (Case study V-2), once the maximum damage caused to the slab has been attained it remains identical throughout the impact duration, however, for impacting velocities of 6.5m/s (Case study V-1) and 10.0m/s (Case study V-3) the damage caused to the slab in the impact area increases with the increase in the impact duration.

Fig. 4 (d) shows the deformed profile of the RC slab along its length due to impacting velocities of 6.5m/s (Case study V-1), 4.0m/s (Case study V-2) and 10.0m/s (Case study V-3). The displacement profile was measured at the top face of the RC slabs throughout the mid-point along its length. It was observed that the damage caused to the RC slab subjected to low-velocity impacts is both local and global. Furthermore, with increasing impact velocities of an impacting object, the damage exhibited by RC slabs, both, locally and globally also increases. It is important to observe that the global deformation exhibited by RC slabs remains the same away from the impacting area of the slab irrespective of the impacting velocity considered herein.

Influence of thickness of slabs

As already discussed, the empirical equations used by the industries to predict the penetration depth caused due to high magnitude impact generated forces mainly aims in avoiding perforation of impacting object through the slabs. As a result, with the increasing threat of perforation, the thickness of the slabs is increased. Therefore, a study has also been conducted to investigate the effect of the thickness of plain concrete slab on its impact behaviour. For his purpose slabs with three different thicknesses were investigated with the same FE model but without reinforcement. The slab was impacted with a mass of 98kg and an initial contact velocity of 6.5m/s. The details of the case studies considered are given below:

(a) Case study – T1: slab having a thickness of 78 mm (as used in the experimental study)
(b) Case study – T2: slab having a thickness of 117 mm (1.5 times as used in the experimental study)
(c) Case study – T3: slab having a thickness of 156 mm (2 times as used in the experimental study)

Fig. 5 shows the deformed shape of the slabs made with plain concrete having thicknesses of 78 mm (Case study –T1), 117 mm (Case study – T2) and 156 mm (Case study –T3). It was also observed that the maximum deformation

occurs at the impact zone which decreases significantly away from the impact zone irrespectively of the thickness of the plain concrete slab used. Furthermore, with the increasing thickness of the slab, the maximum deformation exhibited in the slab at the impacting area was found to decrease. This observation was in agreement with the already published studies investigation as already discussed above.

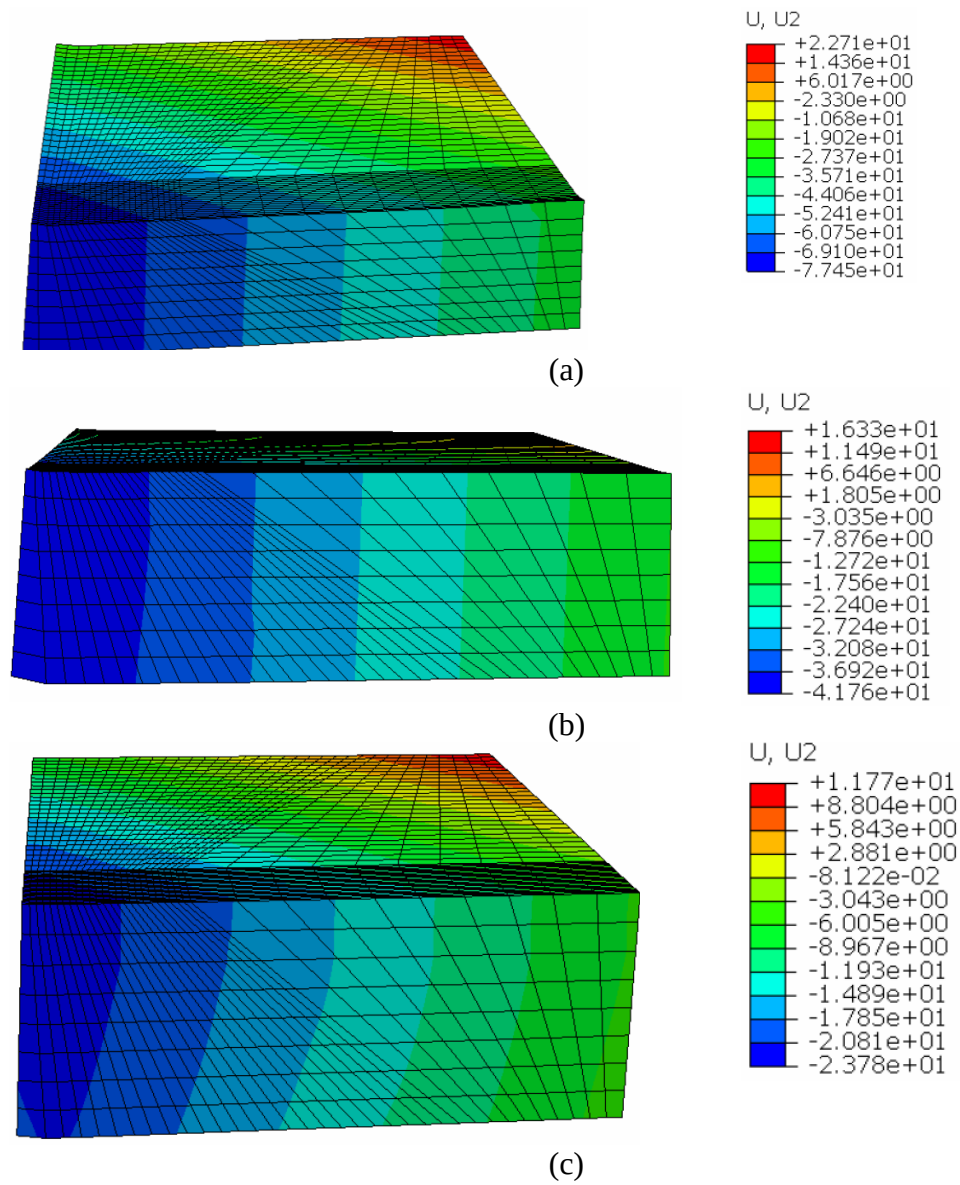

Fig. 5: Post impact deformed shape of the reinforced concrete slab having thicknesses of (a) t_{exp}(Case study – T1), (b) $1.5t_{exp}$(Case study – T2) and (c) $2t_{exp}$(Case study – T1).

4. Conclusion

In this investigation, the response of the reinforced concrete slabs subjected to low-velocity impact loading was investigated using non-linear finite element explicit dynamic technique with commercially available software ABAQUS. From the detailed parametric studies conducted herein, it was observed that the impacting velocities and thickness of the slab significantly influence the behaviour of the slabs under the impact loading which is not explicitly considered in the empirical equations used by the industry, which in turn, as a result, does not always provide safe predictions for the case of the low-velocity impact loadings.

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