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Dynamic response of reinforced concrete beams subjected to low-velocity impact loads using nonlinear finite element analysis

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ABSTRACT

The development of a nonlinear finite element method (FEM) for examining how reinforced concrete (RC) beams react to dynamic forces under the action of low-velocity impacting loads is presented in this article. The model was employed to analyze the stress distributions along with the time histories of impacting load and beam deflection, which were presented graphically. Comparisons with experimental data from previously conducted studies have been performed to verify the precision of the studied model. The findings demonstrated that the developed model was acceptable. Furthermore, the study performed a detailed parametric analysis, focusing on various factors such as replacing conventional steel bars with FRP bars, increasing concrete compressive strength, changing the impact location, using different diameters of reinforcing bars, and changing the depth of the concrete beam. According to the findings, using FRP bars resulted in 36% less peak load due to the uplift pressure caused by the FRP bars' high strength, while the maximum observed deflection of the beam reinforced with FRP bars decreased by approximately 9%. When the position of the impacting force was applied at one-third of the span of the beam, deflection was decreased by 12% when compared to the RC beam has been impacted at its midspan. In addition, the depth of the beams had a significant impact on the impacting load. These presented findings of the study may contribute to a better understanding of how a structure made of concrete responds to impacting loading.

Keywords: Concrete Beams; Dynamic Behavior; FRP bar; Drop-Weight; Impact Load; Finite Element

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1. Introduction

Reinforced concrete is regarded as among the most extensively used building materials in the contemporary construction. It can be obtained by mixing sand, aggregates, cement, and in some cases other materials such as polymers and fibers with water. It became a common material after the Portland cement invention in the 19th century; however, the limited tension capacity of the concrete initially prevented it from being widely used material in building construction. To take control of the low tensile strength of concrete, steel rebars are added in certain places to concrete, which will produce a composite material called reinforced concrete (RC). The versatility of reinforced concrete makes it an ideal material for construction projects of varying scale and complexity. In addition, the use of reinforced concrete has many advantages, such as improved durability, fire resistance, and earthquake resistance.

Despite its many advantages, the use of reinforced concrete also presents challenges, as an example, susceptibility of steel rebar to corrosion. If not properly maintained, it can lead to potential structural failure. Continuous research and development is therefore required to ensure that using reinforced concrete material in the construction sectors is both effective and secure.

However, even reinforced concrete can be subjected to sudden and severe impacting loads that can lead to catastrophic failure of the material. Understanding how (RC) beams respond to impacting loads is critical to ensuring the safety and resilience of these structures.

The Finite Element Method (FEM) is a common method to solve differential equations numerically arising in mathematical modeling and engineering. By decomposing structures into smaller elements, FEA accurately models stresses, strains, and deformations, providing valuable insight into design performance and safety. Its effectiveness lies in its ability to optimize designs, minimize material use, and reduce costs while maintaining structural integrity. Many studies have used finite element analysis (FEA) for structural analysis to gain insight into the behavior and performance of complex structures. These studies demonstrate the effectiveness of FEA in providing valuable insights into the behavior and performance of complex structures, allowing for more efficient and safe design [1]–[3].

Experimental investigations into the response beams made of reinforced concrete (RC) and placed under impacting loading have attracted the interest of numerous researchers [4]–[11]. Moreover, the impacting loading behavior of RC beams has been extensively studied through numerical investigations [12]–[19].

Yongjae Yu et al. [20], conducted both an experimental and a numerical study on 15 RC beams with five variables. The test results showed limitations of previous studies, the experimental results were used to suggest empirical formula. Parametric studies proved the reliability of both results of experimental and the recently proposed empirical formula.

The utilization of bars made of Polymer reinforced with fibers (FRP) for strengthening structures has the potential to mitigate damage caused by corrosion of steel reinforcements. However, there are no studies reported in open literature on the field of impacting resistance of either critical in flexure or critical in shear concrete beams that have been reinforced with Basalt FRP (BFRP) bars. Zhijie Huang et al. [21], implemented experimental study to examine the impacting behavior of six Basalt-Polymer reinforced by fibers (BFRP) bars RC beams under both impacting and quasi static loads. Based on the findings, when subjected to impacting loads, the beams that are critical in flexure experience a transition in breakdown mode from flexural dominated (under the effect of quasi static loads) to a combination of shear and flexural failure mode.

In contrast, the shear-critical beams continue to fail primarily due to diagonal shear even under impacting loading but exhibit more critical diagonal cracks and severe spalling and on the both sides of the beams. It is important to acknowledge that utilizing concrete with high strength type does not always result in improving impacting performance as it may become more brittle as its strength increases.

Furthermore, a numerical based models were created and already calibrated by using LS DYNA for simulating the impacting behavior of the beams under testing. The results of the numerical analysis indicated that augmenting the reinforcing ratio in tension can modify the mode of failure to be flexure shear combined instead of flexure governed, this ultimately leads to a reduction in the maximum deflection at the midspan. The study also noticed that the impacting resistance performance of the BFRP bars RC beams was comparable to that of conventional steel (RC) beams.

The impact performance of (RC) beams was analyzed and a method was suggested by Thong M. Pham et al. [22] for determining the shearing force and bending moment diagrams. The study confirmed the assumption of linear “inertia force” distribution along the beam up to the peak impacting force. The position of plastic hinges was found to significantly affect beam behavior, and a procedure was proposed to predict stationary points. A flow chart was provided for designing concrete beams subjected to impacting loads.

Yu et al. [23] studied the RC beams response under impacting loads by analyzing the combined effect of mass and impact velocity. Using LS-DYNA for FE analysis, the failure in flexure of RC beams tested by the other investigations, and various combinations of applied force or impacting velocity were considered as parameters. The research validated that the RC beams response is dependent on the pairing of mass and impact velocity, suggesting that the structural concrete design subjected to impacting loading and empirical equations should taking into account this combination.

Liu Jin et al. [24] presented a simulation method (3D meso-scale) to investigate the (RC) beams response under impacting loads. The study revealed that the proposed method demonstrates the capability to accurately depicting the collapsing mechanism of RC beam and its crack development. Also, stirrups influence the local damage of the concrete and has only a small effect on beam deflection at the mid span. In addition, decreasing of the hammer weight led to reducing the impacting force duration and decreases concrete damage. Furthermore, reducing the length value of the span makes the duration decrease and the maximum impact force increase.

In a study by J.S. Cheng and H.M. Wen [25], employed a dynamic fundamental model for RC to study how impacting velocity affects the behavior and failure of (RC) beams. The investigation also proposed an analytical equation to describe the critical state at which failure modes shift in RC beams subjected to impacting loading. The recorded results were consistent with experimental observations, and the research identified that the varying rate of strain sensitivities of concrete and rebar steels contribute to the shift of failure modes from bending to shear with an increase in impact velocity.

Thong M. Pham and Hao Hong [26] investigated the response of beams made of reinforced concrete that subjected to impacting with slow velocity, examining the effect of factors such as concrete strength, projectile weight and impact velocity using LS-Dyna models. The findings indicate that while the boundary conditions are minimally affected the impacting force, the displacement and damage sustained by longer beams are considerably impacted. When predicting the impacting load using an equivalent model of a single degree of freedom, the structural stiffness must account for the development of plastic hinges and their stationary position. The simply-supported beams' negative bending moment needs to be considered in design, and residual displacement exhibits a greater sensitivity to boundary conditions than other parameters. Changing concrete strength affects beam failure mode but not impact force or displacement.

Xiwu Zhou et al. [27] Investigated the impacting properties of RC beams before and after replacement of steel bars with stainless steel ones of equal strength. The results showed that replacing small amounts of steel with stainless steel improved the beam's stiffness, elastic resilience, and reduced damage. However, increasing the reinforcement ratio resulted in more severe shear failures and worsened impact resistance.

Li, Chen, and Hao [28] analyzed the accuracy of impact force measurements and profiles in RC beams under drop weight impact. They found that the drop weight's mass distribution caused deviation from the real contacting force on the beam. They recommended keeping the dropped down weight mass ratio below 20 for accurate load cell recordings.

Pham et al. [29] conducted experimental study is to investigate the impacting response of concrete beams strengthened with basalt polymer reinforced with fibers (BFRP) and adding rubberized materials. To this end, twelve (RC) beams with varying rubber material contents of(30%, 15%, and 0%) were subjected to loads of impact type, while different schemes of wrapping were employed to assess the most efficient strengthening methods for both traditional and rubberized concrete beams with regards to their impact resistance performance. The results of the study demonstrate that rubberized concrete beams exhibit a higher imparted energy per unit weight (10-18%) compared to regular concrete, and that they also localize damage at the point of impact, resulting in a slower stress wave velocity. Even though the concrete containing 30%, 15%, and 0% rubber content exhibited strength in compression of 14.7 MPa, 25.4 MPa, and 50.3 MPa, respectively, the beams having rubberized material experience less displacement when subjected to the same impact as reference beams. Moreover, the rubberized concrete beams exhibit the lower critical impacting force compared to reference beams having the same impacting conditions. Additionally, using the wraps of U-shaped BFRP concentrated in the impacting area has showed comparable achievement to that with wraps BFRP uniformly distributed at the entire beam. The proposed scheme of strengthening provides a more cost-effective solution to improve the impacting resistance of concrete made structures.

Li et al. [30] simplified the impacting force profile of dropped down weight impact on RC beams by identifying six distinctive points represented by empirical equations, based on analytical parametric study results.

Pham et al. [31] implemented a study to compare the impacting responses of (RC) beams with hollow sections having rectangular sections (HCB) and rectangular solid section (SCB) shapes, both experimentally and numerically. The study found that the peak impacting force was smaller for the HCB, but it experienced greater lateral displacement compared to the SCB under the same impact condition.

Tran et al. [32] implemented an experimental study to investigate the impacting response of geopolymer concrete ambient curing (GPC) beams strengthened with various types of fibers, BFRP bars, and stirrups. The researchers concluded that the utilization of BFRP bars and stirrups resulted in an enhanced impact response of the GPC beams.

This research will attempt to examine virtually number of factors that would be saves both time and cost. Appropriate modelling techniques were used for simulation of the non-linear material properties, and impactor-concrete interaction relations. A parametric study was conducted using the verified model, focusing on the effects of using FRP bars instead of conventional steel bars, using higher strength for the concrete, the effect of the impactor location, the effect of the depth dimension of the concrete beam, and using various diameter of the reinforcement bars.

2. Data collection

The data used in this work was a result of the experiment carried out by Fujikake et al [33]. The experimental beam was designed with cross section values of 250 mm x150 mm and a span of 1700 mm, as shown in Figure 1. The simply supported beam consisted of ø10 mm stirrups with a intervals of 75 mm and a yield strength of 295 MPa. While the longitudinal reinforcements consisted of ø16 mm with a yielding strength of 426 MPa.

The beam was subjected to a mass value of 400.00 kg dropped down weight with low-velocity. The mass has been dropped freely onto the beam from 1.2 m height. The drop weight's striking head was equipped with a hemispherical tip having a 90 mm radius.

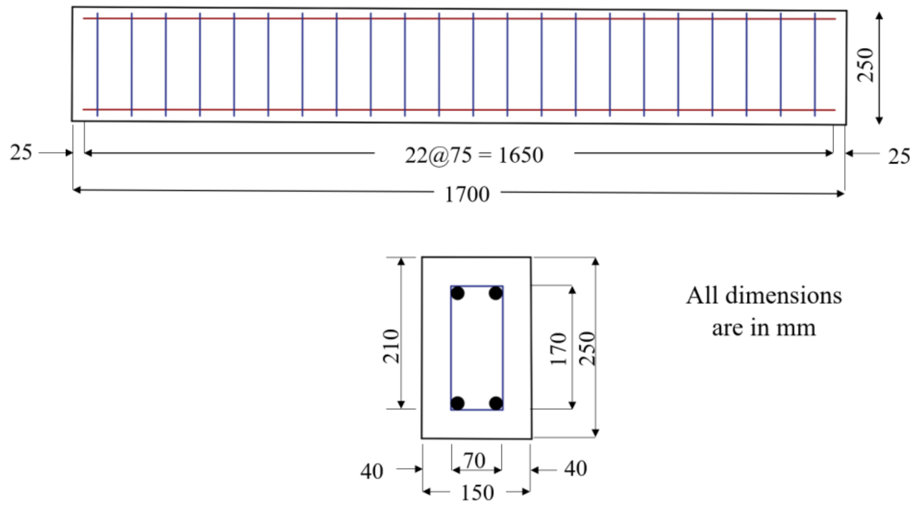

Figure 1. Details of the reference reinforced concrete beam

3. Numerical element finite modeling

Finite elements models were constructed to study the behavior of the previously described experimental beams. These beams were used to aid the development of finite element analyses and for comparison with parametric studies to detect the contributions of some factors to the dynamic capacity.

3.1. Model description

Finite elements analysis of the beam was performed using the software ABAQUS/CAE 2022 [34]. The model consisted of two primary components: a concrete body modeled with a solid element, and steel reinforcement modeled with a rebar element. And to simulate the impacting load, a dynamic explicit analysis was performed with a time step that closely matched the experimental interaction time. The finite element (FE) analysis utilized a homogeneous material to represent the concrete block in the tested beam. Eight-node solid (brick) elements were chosen to model the block and identified as C3D8R elements in ABAQUS due to their exceptional accuracy in following the constitutive law integration. These elements were ideal for conducting nonlinear static and dynamic analyses along with the capability to account for rotation in large-displacement and finite strain analysis. The use of C3D8R elements with reduced integration ensured the most reliable and precise simulation of the tested beam, providing the necessary insights into its behavior and response under various conditions.

For the reinforcement bars and stirrups, two-node three-dimensional linear truss elements (T3D2) were utilized. In order to represent the impacting loading, a hemispherical tip with a 90 mm radius was created. To simplify the model, four-node bilinear quadrilateral rigid element (R3D4) was implemented for the impactor modelling. A moderately fine mesh was employed to create the model, allowing for responses that closely match the results of experimental work. The mesh pattern of the model made of FE for the tested beam, including the reinforcement bars represented as embedded elements, is depicted in Figure 2.

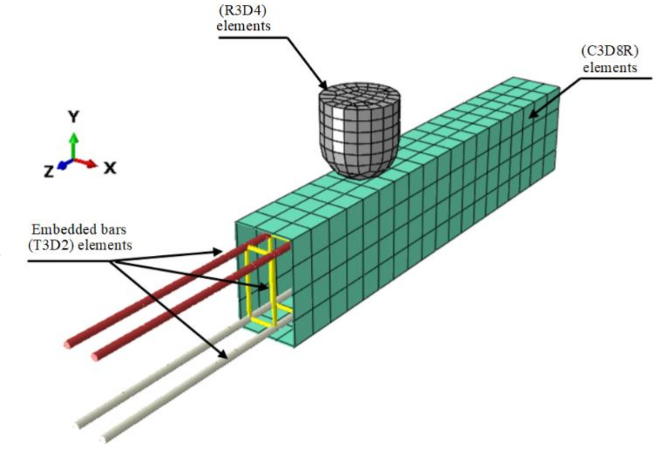

Fig. 2. Details of the finite element mesh utilized for concrete beam modeling

3.2. Material models

To model the behavior of concrete, the Concrete Damage Plasticity Model (CDP) was used, which is capable of handling static and dynamic loads. Both compression and tension stress-strain relationships must be specified as inputs for the ABAQUS software to characterize the behavior of concrete materials in this model. Consequently, the inelastic hardening equation proposed by Saenz [35] is employed to compute the uniaxial stress and strain for modeling the compressive behavior of concrete. On the other hand, the stress-strain relationship in tension was based on the formula suggested by Hsu and Mo [36].
Also, the ABAQUS CDP model considers the effect of damage on material stiffness, which enables a more accurate simulation of the characteristics of unloading stiffness that decrease progressively with an increase in damage during all the strain stages. To account for the loss in stiffness during unloading of concrete, the damage parameters dt and dc must be defined, with values ranging from 0 to 1, where 0 represents material not damaged, and 1 signifies complete loss of the strength [37].
Besides the stress-strain relationships in compression and tension, this model necessitates the definition of five parameters, which are listed in Table 1.These parameters include the flow potential eccentricity, the angle of dilation, K, the ratio of the invariant of second stress along the tension meridian and the compression meridian, the ratio between the initial yield stress in compression (fb_o) and the initial yield stress under uniaxial compression (fc_o), and the viscosity that defines the visco-plastic normalization.

Table 1. Plasticity concrete properties

Angle of dilation	fb_0/fc_0	Eccentricity	Viscosity	K
40	1.16	0.1	0.00005	0.667

For simulating the performance of the steel reinforcement (including steel stirrups and bars), the elastic properties of steel were specified by defining ratio of Poisson and the elasticity modulus, whereas its plastic response was defined using a yield strength of 426 MPa.

3.3. Interactions

To establish the mutual influence between the concrete beams and the reinforcement steel bars, the constrain option in ABAQUS was employed with the (embedded region) type. While, to represent the tangential interaction between the impactor and the upper face of the concrete beam, a contact model employing penalty contact with 0.5 friction coefficient was utilized. Furthermore, a contact attribute called "hard" contact simulation was conducted to model the typical interaction between the concrete beam and the impactor.

3.4. Boundary conditions and mesh size

To ensure that the model replicates the experimental behavior accurately, it is necessary to apply appropriate boundary conditions to the model. For precise impacting loading of the beam, it is crucial to take into account that the Reference Point (RP) which was created in the center of gravity of the impactor is defined specifically for the loading impactor which drops freely. The beam is supported at both ends by rollers. The tangential interaction between the rollers and the lower face of the concrete beam was a penalty contact with 0.05 friction coefficient for stability purpose. The “normal behavior” was chosen as “hard" contact to simulate the normal mutual influence between the rollers and the RC beam. The rollers displacements U1, U2, and U3 being considered zero.

3.5. Load

To simulate the free dropping of the 400 kg impactor, the velocity of the impactor of the instance of first impact was determined and entered into Abaqus through the Predefined Field. The mass of the concrete beam and the impactor were assigned at the center of gravity of the parts. It is vital that the inertia of the oscillating parts is defined. For this purpose, the mass and rotary inertia were verified and employed.

4. Model verification

Validation of the FE models in ABAQUS Standard involved comparing the predicted behavior with test results obtained from concrete beam specimens. This comparison was carried out by examining the simulation results of the FE models, specifically the impacting load and deflection versus time curves, and comparing them with the experimental curves. Figures 3 and 4 present a comparison between the numerical and experimental results for the reinforced concrete beam. The percentage difference is computed by taking the experimental values as the reference point. A positive percentage difference indicates a higher numerical impacting load than the experimental values. For both beams, there was good agreement between the experimental and numerical values. The pattern of the experimental and the analysis was identical in the peak and close to other in other regions of solicitations. The percentage of difference of the area under the curves of Abaqus relative to the experimental was a decrease by 6% only. Moreover, the ABAQUS model exhibits a maximum deflection of 37.38 mm, which indicates a difference of only 2.6% from the experimental result of 36.44 mm. To further explore the damage prediction model of the control specimen. The contours depicted in Figure 5 present the predicted extent of tensile damage in the concrete using ABAQUS. It is important to recognize that this type of damage is closely tied to the cracking strain and, as such, the contours provide a good representation of the pattern of cracks as well as the gradual deterioration of the concrete. It can be noted that the concrete experiences cracking initiation at the impacted area and near the supports, where the tensile damage exceeds zero.

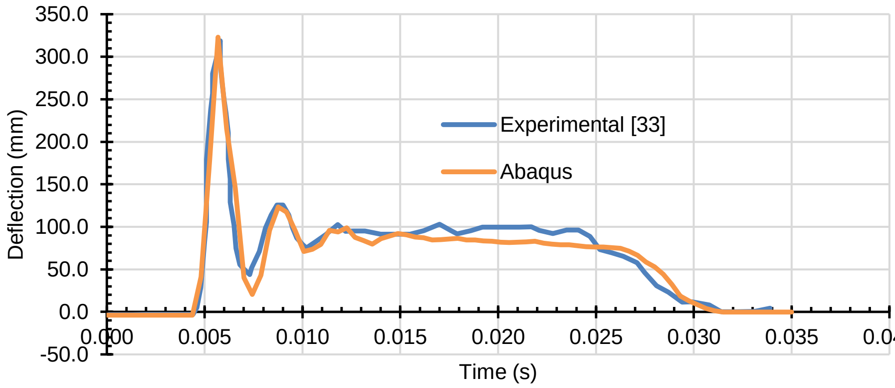

Figure 3. Comparing numerical and experimental time history of the impacting load

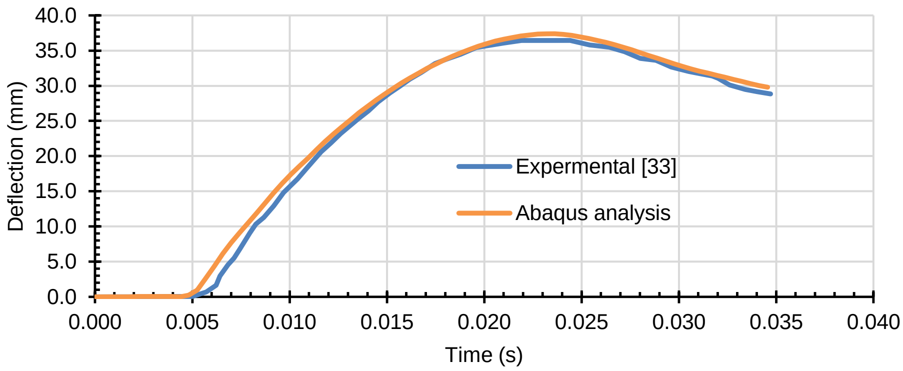

Figure 4. Comparing numerical and experimental deflection time history

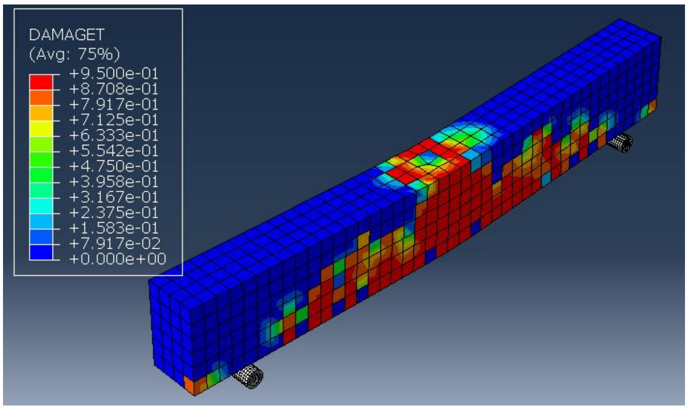

Figure 5. Crack pattern of the reference beam at impacting loading

5. Finite element parametric analysis

A validated numerical model was employed to perform a parametric analysis aimed at examining the effects of various influential factors on the dynamic capacity of beams made of reinforced concrete under impact loading. These parameters include the following:

1. The effect of using FRP bars as tension reinforcement.
2. The contribution of increasing the concrete compressive strength.
3. The influence of applying the impactor at one-third of the span of the RC beam.
4. The contribution of the depth of the beam.
5. The influence of altering the diameter of the reinforcement bars.

5.1. The effect of using FRP bars as the reinforcement bars

Further numerical models were developed to analyze the impact force and deflection results in relation to the CFRP reinforcement bars. The model has been adjusted by replacing the steel reinforcing bars in tension and compression with FRP bars with the same diameter. Regarding the independent behavior, FRP is generally considered a brittle material, exhibiting linear characteristics before being crushed and experiencing sudden rupture. Therefore, to accurately model the behavior of FRP reinforcement, it was assumed to exhibit a linear response until the point of failure. The FRP reinforcements were selected with a tensile strength of 3100 N/mm^2 and modulus of elasticity of 148000 N/mm^2.

Figures 6 and 7 depict the time histories of impacting load and deflection. After comparing the beam model reinforced with FRP reinforcement bars to the control model with steel bars, it was observed that the beam strengthened by FRP have less stiffness owing to the relatively low elasticity modulus of the FRP material, and in a result, the peak impacting load induced by the dropping impactor was less than that when steel reinforcement is used. Furthermore, the vibration time was less for the case of FRP reinforcement which indicates more energy absorption rate. It was noticed that the largest deflection at the beam with FRP reinforcement is 33.79 mm compared to 36.44 mm in the case of steel reinforcement as shown in Figure 7. This can be attributed to the increase upward force induced by the FRP reinforcement due to the higher yielding point compared to the steel reinforcement. Figure 8 illustrates that the cracks are in wider vicinity than the reference beam. This is due to the high yielding point of the FRP which prevented the early formation of a plastic hinge area and led to the formation of more smooth curvature along the beam axis.

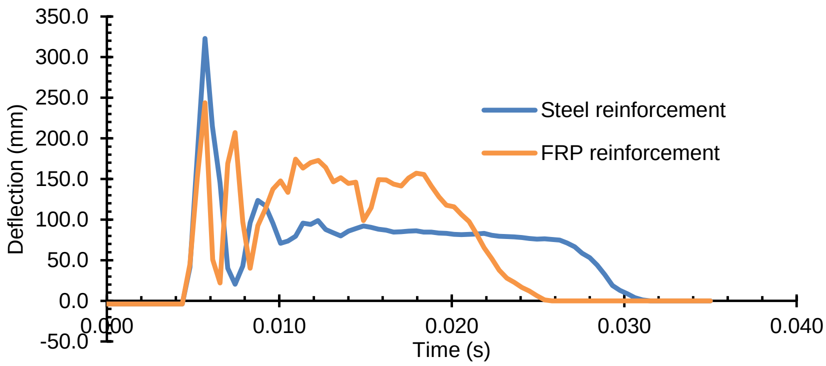

Figure 6. Effect of FRP reinforcing bars on impact force-time history

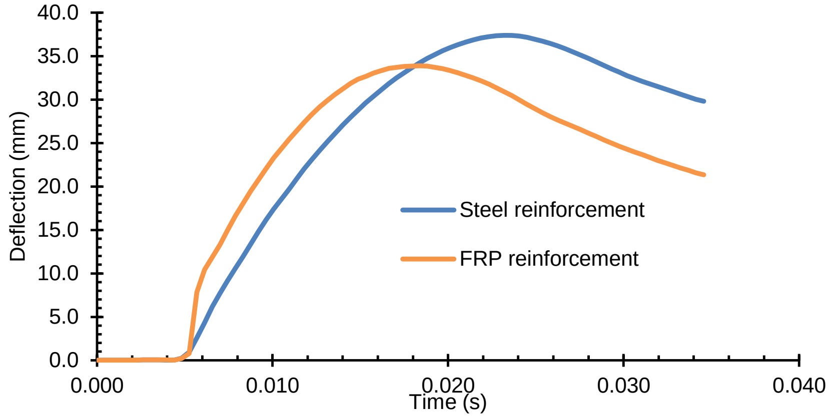

Figure 7. Effect of FRP reinforcing bars on deflection-time history

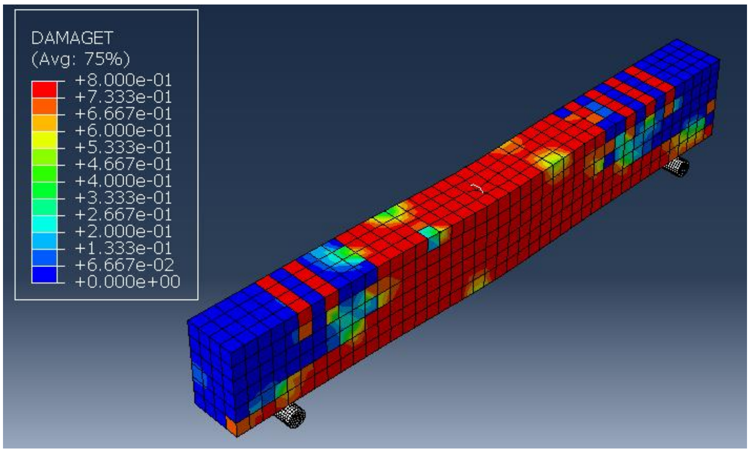

Figure 8. The pattern of cracks in the RC beam with FRP reinforcement bars

5.2. The contribution of increasing the concrete compressive strength

Typically, the compressive strength of concrete is a critical parameter that influences the behavior of concrete beams. To evaluate its impact on the impacting achievement of concrete beams, a compressive strength of 65.7 MPa was taken into account. In Figure 9 and 10, the impacting load and deflection-time histories for this model are presented. These Figures indicate that the peak impact force was 337.66 kN when 65.7 MPa concrete is used compared to 322.97 kN for the 42 MPa concrete beam. The difference in the impacting load is due to the rigidity role incurred by higher modulus of elasticity for the case of the 65.7 MPa concrete. In comparison to the reference specimen, the maximum deflection was lower at around 7% compared to the reference. Figure 11 depicts the pattern of impact damage occurred in the concrete beam, as obtained from the numerical simulation. In comparison to the reference beam, the cracking and damage are identical. Additionally, values below 0.7 indicate the presence of micro-cracks, which are very small and not visible near the supports.

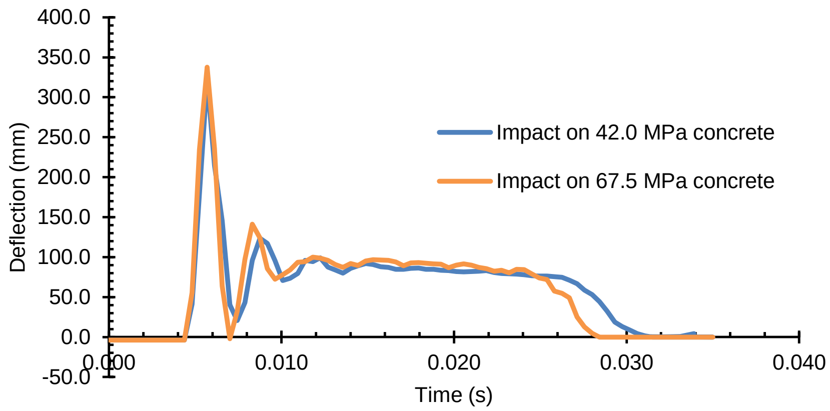

Figure 9. The impact force-time history as affected by the compressive strength of the concrete

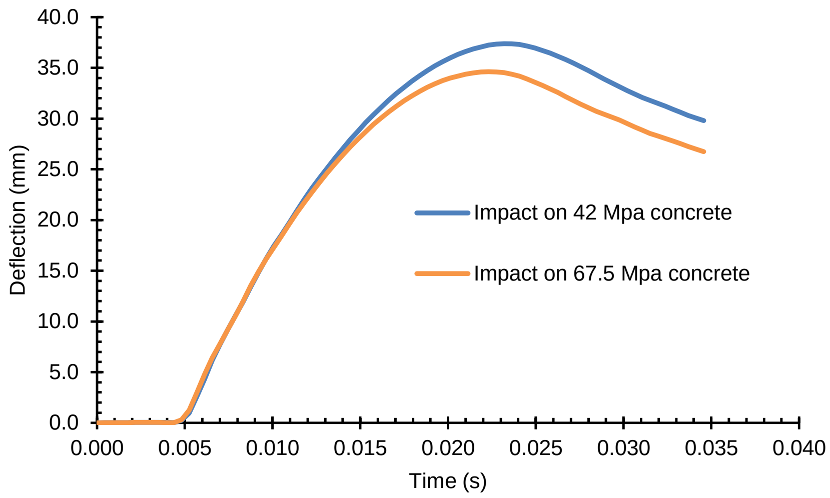

Figure 10. The deflection-time history as affected by the of the concrete strength in comp.

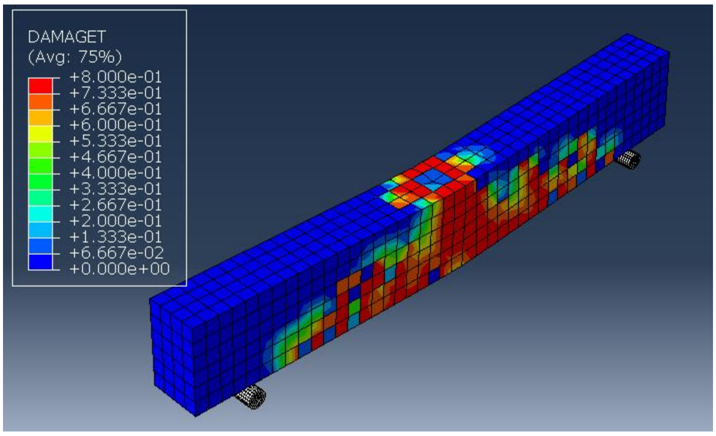

Figure 11. The pattern of cracks in the RC beam with high strength concrete

5.3. 5.3. The effect of applying the impactor at one-third of the span of the beam

For all previous models, the midspan of the beam was used as a location of the applied dropped weight. However, in this model, the parameter analysis takes into account the effect of the drop weight's location while keeping the drop weight velocity constant. The weight was applied at one-third of the span of the concrete beam to explore the effect of this parameter on its dynamic behavior.

Figures 12 and 13 illustrate the effects of the drop weight's location for the same impact weight. These Figures reveal a reduction in deflection at the maximum impacting load of around 12%, while a decrease in the impacting load was observed at about 34% during the impact instant compared to the reference model.

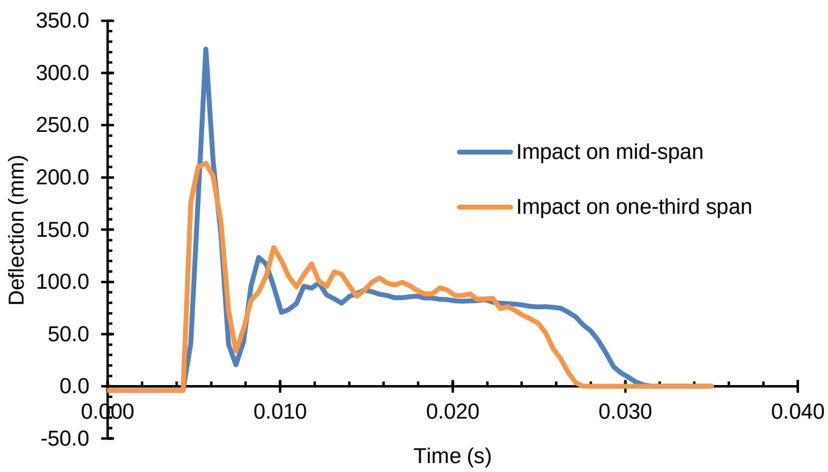

Figure 12. Effect of the location of impacting weight on impacting force-time history

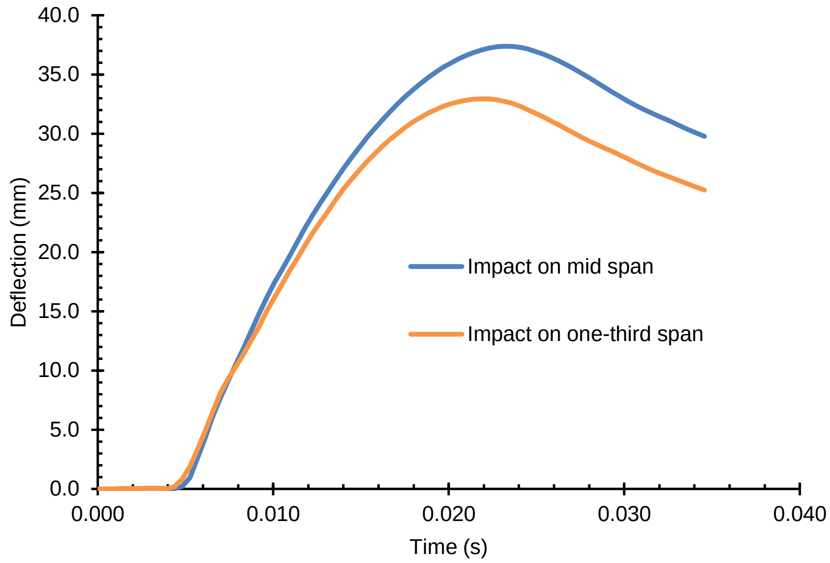

Figure 13. Effect of the location of impacting weight on the deflection-time history

With regards to Figure 14, altering the position of the dropped down weight away from the midspan of the beam has an impact on the pattern of damage. It is observable that when the impact is concentric, the concrete experiences cracks that are more concentrated at the midspan. On the other hand, when the impact is eccentric, the damaged area is significantly larger than that of the concentric impact.

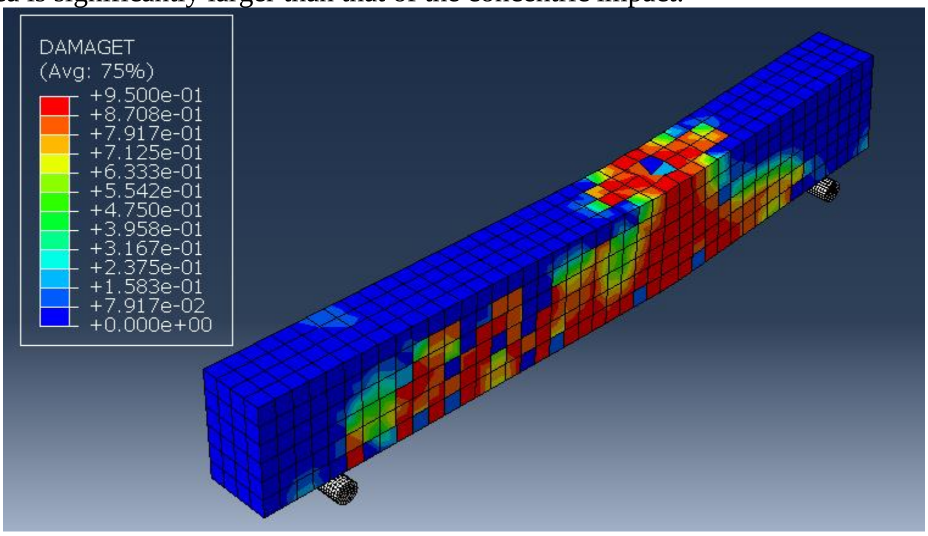

Figure 14. The pattern of cracks in the RC beam subjected to eccentric impacting loading

5.4. The contribution of the depth of the beam

In this section, an examination will be conducted to study how a reinforced concrete beam depth affects its dynamic behavior. To evaluate the effectiveness and contribution of the beam depth, two values, specifically 200 mm and 300 mm, have been selected. Additionally, a control beam has been utilized as a reference.

Figures 15 and 16 display time history for the impacting mass and the deflection for beam depths of 200 mm and 300 mm, in comparison to the reference beam. The findings indicate that increasing the depth of the beam to 300 mm enhances its stiffness, causing it to attract approximately 13% more impact force. Conversely, it is noticed that at the instant of impact, the deflection at the midspan of a beam is lower when it has a higher depth magnitude, which is about 24% lower than the control beam. For the studied beam having a depth of 200 mm, a 27% reduction in impact force was observed compared to the control model which can be related to higher cracks formation due to lower rigidity of the 200 mm beam and as a result, lower cracked moment of inertia which leads to more ductility and more energy dissipation.

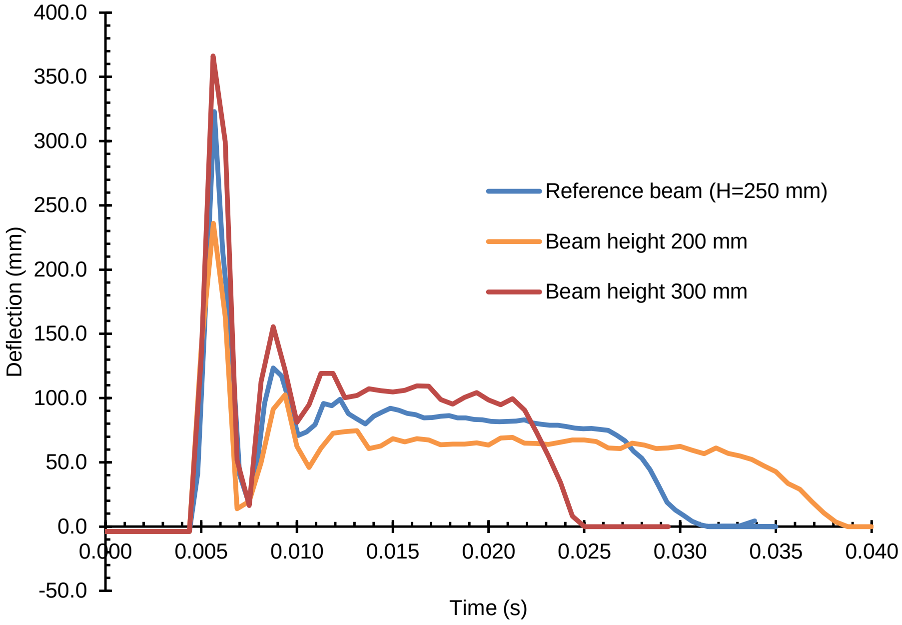

Figure 15. Effect of the beam depth on impacting force-time history

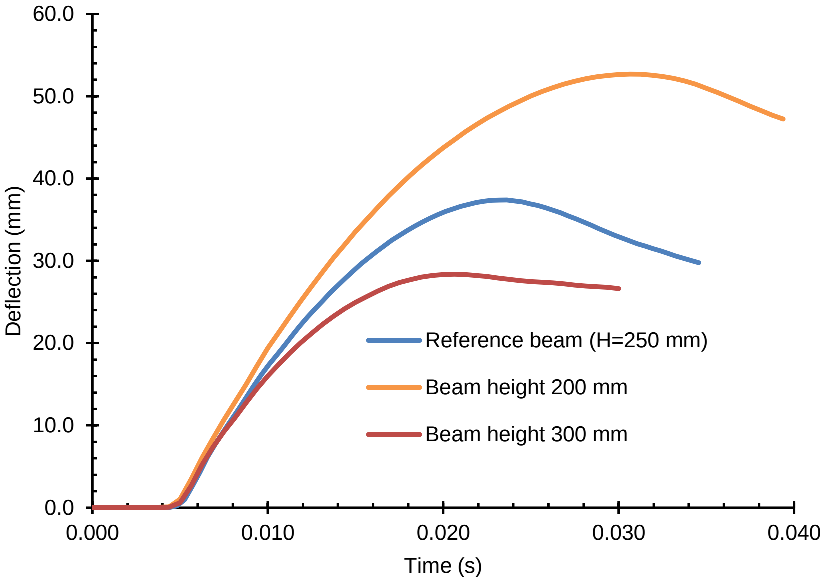

Figure 16. Effect of the beam depth on deflection-time history

Based on Figures 17 and 18, it can be observed that the increasing damage in the concrete body is attributed to the decreasing depth of the concrete beam subjected to impacting loading. This can be seen in the comparison between the two Figures, where the concrete beam with a depth of 200 mm experiences more severe tensile damage than the 300 mm concrete beam depth.

The reason for this is that the depth of the concrete beam plays a critical role in determining its resistance to impacting loading. A deeper concrete beam has more inherent strength to withstand loads caused by the impact, reducing the likelihood of catastrophic damage. Conversely, a shallower concrete beam has a smaller cross-sectional area, which means that it is more susceptible to cracking and other forms of catastrophic damage.

Overall, the comparison of these Figures underscores the importance of considering the depth of concrete beams when designing structures that are expected to withstand impacting loading. By understanding how depth influences the behavior of concrete beams under these conditions, engineers can make informed decisions that improve the safety and durability of their designs.

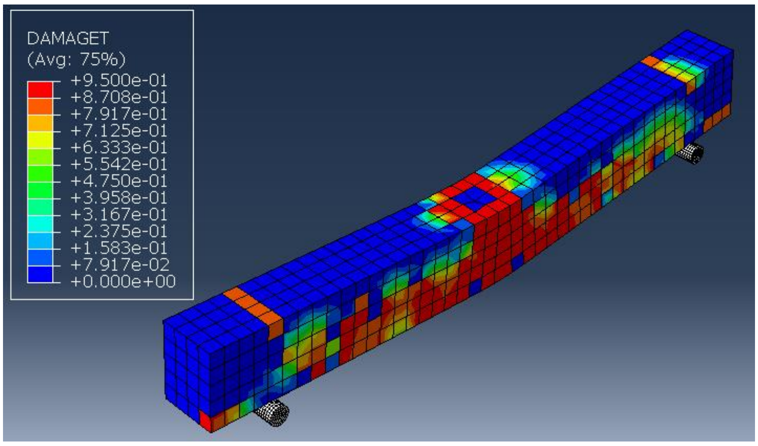

Figure 17. The pattern of cracks in the RC beam with 200 mm depth

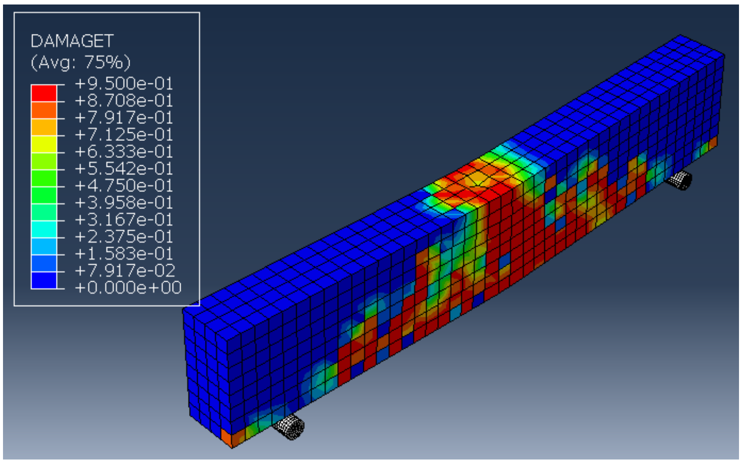

Figure 18. The pattern of cracks in the RC beam with 300 mm depth

5.5. The influence of altering the diameter of the reinforcement bars

To explore the impact of using various reinforcement diameters of on the dynamic response of beams made of RC, numerical simulations were conducted on four different diameters: 10 mm, 12 mm, 20 mm, and 25 mm. Figure 19 depicts the results of the numerical simulations for the time history of the impacting force. As presented in this Figure, an increase in the diameter of reinforcement results in a corresponding increasing the values of ultimate impacting load for the RC beams. When the tensile reinforcement is replaced with 20 mm diameter, the ultimate load values for RC beams decreased by 6% and has been increased by 3% for the 25 mm reinforcement, when contrasted with the control beam (with a diameter of 16 mm). Interestingly, the beam with reinforcement bars of 20 mm diameter experiences decreases in the peak load. This may be due to a phenomenon called "bar buckling," where the bars buckle under compressive stresses, leading to increased tensile cracking.

The remaining two curves illustrate the outcomes achieved by reducing the diameter of reinforcement to be 10 mm and 12 mm, compared to the diameter used in the experimental study. It can be noted that the ultimate load has been decreased by 15% when the diameter is 10 mm and 12 mm.

Similarly, as shown in Figure 20, the reinforcement contribution then decreased the deflection gradually from 40% to 59%, when the diameter increased from 16 mm to 20 mm and 25 mm, respectively. Whereas the deflection increased to 64.24 mm and 51.85 mm when 10 mm and 12 mm diameters were used, respectively.

The diameter value of the reinforcement bars has a significant impact on the crack pattern of the beams under impacting loading, as illustrated in Figures 21 to 24. According to these Figures, beams with reinforcement bars of 10 mm and 12 mm diameter experience more catastrophic failure compared to the beam with reinforcement bars of 25 mm diameter. This is because smaller diameter bars are less able to resist the tensile stresses induced by impacting loading, leading to more cracks and eventual failure.

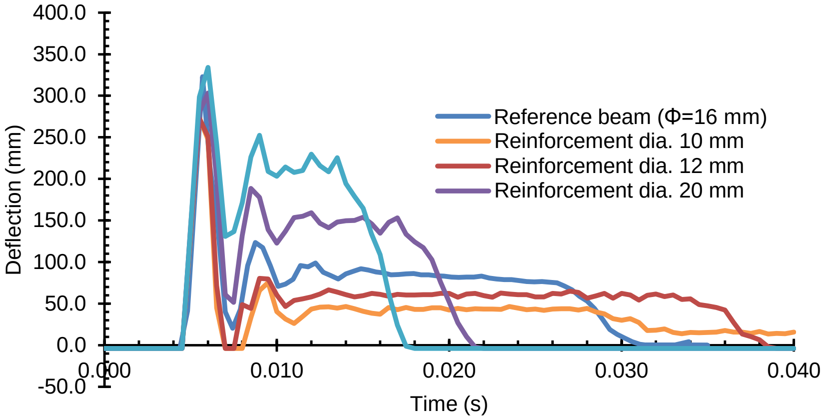

Figure 19. Effect of changing reinforcing diameter on the dynamic behavior of RC beams

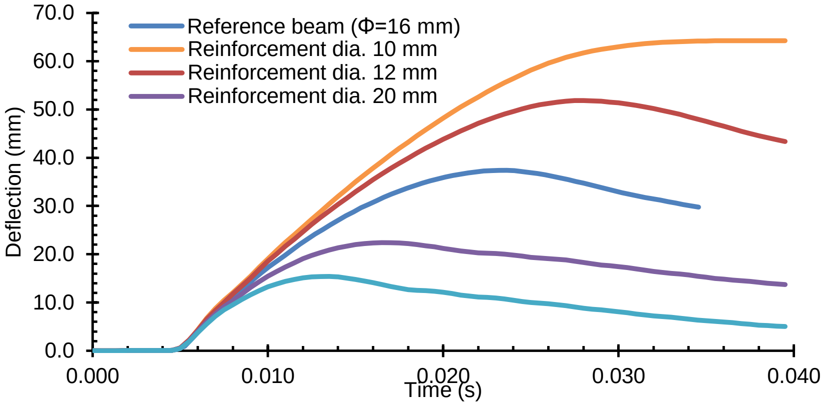

Figure 20. Effect of different reinforcing diameter on deflection-time history

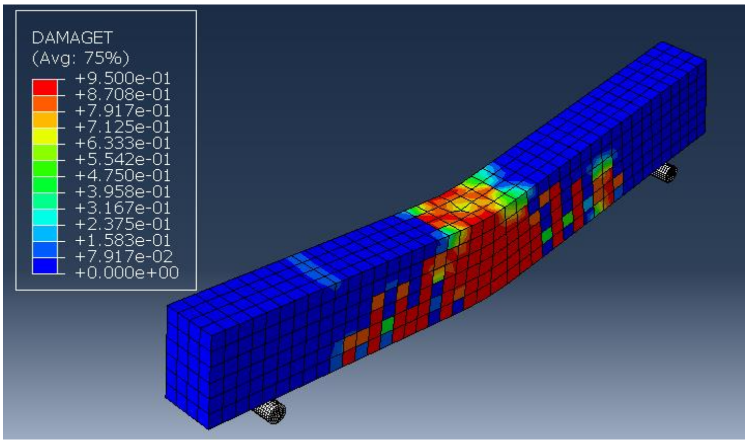

Figure 21. The pattern of cracks in the beam made of RC having rebars of 10 mm diameter

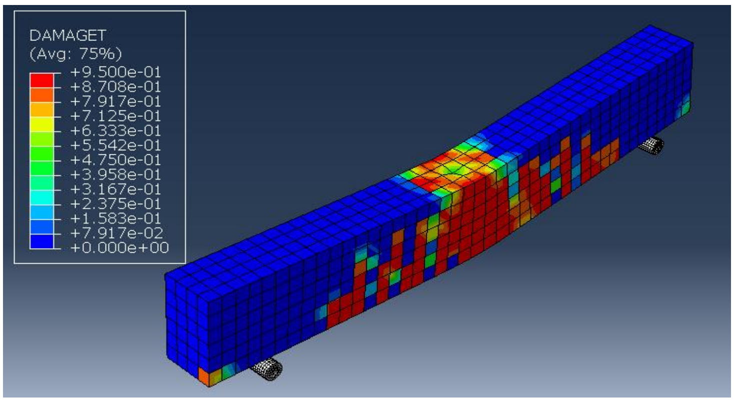

Figure 22. The pattern of cracks in the beam made of RC having rebars of 12 mm diameter

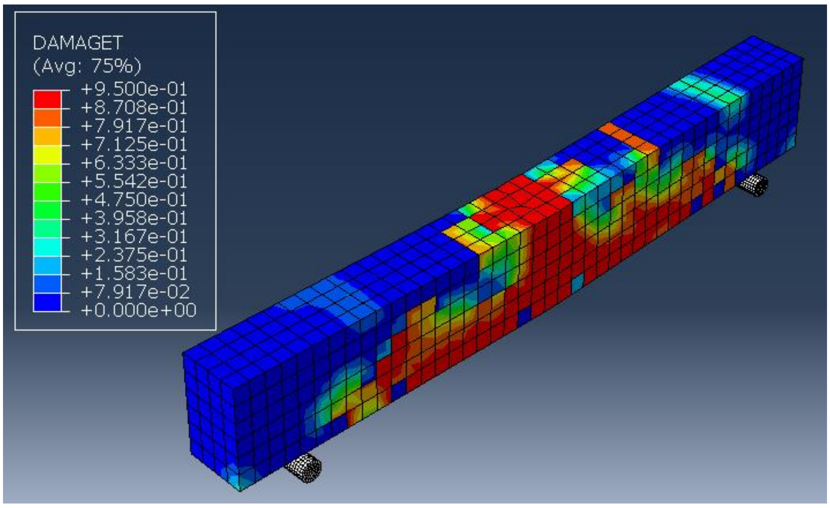

Figure 23. The pattern of cracks in the beam made of RC having rebars of 20 mm diameter

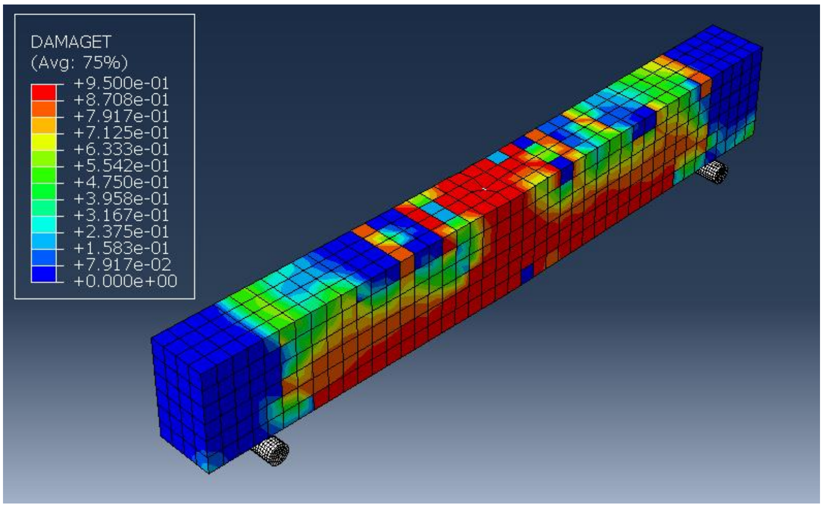

Figure 24. The pattern of cracks in the beam made of RC having rebars of 25 mm diameter

6. Conclusions

According to the findings obtained from the simulations as numerical, the conclusions as follow able to be detected:

1. The accuracy and reliability of analytical models to predict the response of (RC) elements have been demonstrated by the remarkable agreement obtained between trial findings and numerical simulations. The analytical models have proven to be an efficient tool for predicting the performance of RC elements, making it possible to explore multiple scenarios and design options with minimal effort. Furthermore, the utilization of Finite element Analysis (FEA) models has made the process faster and highly cost-operative.

2. Abaqus responded as expected to the concrete compressive strength increasing to 65.7 MPa with little change in in the overall performance of the vibrating pattern.

3. When comparing the impacting load of a beam reinforced with steel reinforcement bars in tension in Abaqus to a beam with FRP rebars, the latter was found to achieve 36% less peak load due to the uplift pressure incurred by the high strength of the FRP rebar. Similarly, the maximum deflection of the beam reinforced with FRP bars was observed to decrease by approximately 9%.

4. In the case of the impact position taken at one-third of the span of the beam, a reduction in deflection was observed, with a decrease of 12% compared to the beam impacted by the drop weight at the midspan. These findings indicate that the impact location has a notable impact on the deflection during the moment of impact.

5. According to the study, the depth of the beams had a notable impact on the impacting load. As the depth decreased from 250 mm to 200 mm, the impacting load decreased by up to 27%. Additionally, the deflection at the instant of impact increased by up by 29%. Conversely, when the depth increased from 250 mm to 300 mm, the impacting load increased by up to 13%, and the deflection decreased by up to 24%.

Declaration of competing interest

"The authors state that they do not have any financial or non-financial interests that may influence the content of this paper".

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