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# Numerical Assessment of the Impact Behavior of CFRP strengthened RC beams using different concrete models

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**ABSTRACT**

In the current paper, a numerical study was carried out using the finite element (FE) approach in order to simulate the impact behavior of reinforced concrete (RC) beams strengthened using carbon fiber reinforced polymer (CFRP) sheets attached to the tensile face of the RC beam. A three-dimensional finite element model was constructed and carried out using ABAQUS/Explicit software. Different material models were employed to simulate the nonlinear behavior of concrete to better understand the response of reinforced concrete structures subjected to impact loads. The examined concrete models were; Drucker-Prager, concrete damage plasticity, and Cap/Plasticity. Numerical results were verified alongside experimental ones available in the literature. The general behavior of the finite element models in terms of time-deflection at the beam mid-span, time-load, and failure mode showed good coherence with those obtained experimentally. Moreover, results showed that the concrete damage plasticity model exhibited more realistic results, that were asymptotic to experimental results, than other models.

## 1. Introduction

Blast and impact resistance design of structures has recently become one of the highest priorities for researchers and engineers as a result of increased terrorism activities and threats posing a significant hazard to civil infrastructure. The carbon fiber-reinforced polymer (CFRP) has proven to be an effective material for strengthening or retrofitting existing structures including beams, columns, and slabs. Because of the superior properties of CFRP materials, this application has increased in popularity around the world. The performance of FRP-strengthened beams under static loads has been extensively investigated in the literature[1-3]. However, there has been little research concerning the behavior of CFRP strengthened beams subjected to impact loading. The impact performance of CFRP-reinforced concrete (RC) beams is particularly interesting. Erki and Meier [4] investigated the behavior of eight RC beams, with various layers of externally bonded (EB) CFRP sheets, under impact loads. Results revealed that the application of the CFRP strengthening scheme improved the flexural capacity of the tested beams and reduced the mid-span deflection. Another experimental research on RC beams strengthened using CFRP laminates under high loading rates was investigated by White et al. [5]. The beams gained strength and stiffness 5% more than the control beam. Tang and Saadatmanesh [6] developed another method for applying the impact load. The CFRP sheet was externally applied to both top and bottom surfaces of the beam. Both bending capacity and stiffness of tested beams were significantly improved due to the applied strengthening scheme. In addition, Experimental results obtained by Soleimani, et al.[7] had proven the efficiency of strengthening RC beams using EB glass-fiber-reinforced polymers (GFRP) sheets in resisting quasi-static and impact loading regimes.

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## 2. The experimental program used for verification

An experimental study, performed by Pham TM and Hao [8], was used to verify and validate the numerical model built in the current study. The tested specimens were 150 mm in width and 250 mm in height with a total span of 2200 mm in length. Figure 1 presents the reinforcement details. The reinforcement was deformed steel bars for main reinforcement and mild steel bars for stirrups with nominal tensile strengths of 500 and 250 MPa, respectively. At 28 days, the beams attained a compressive strength equal to 46 MPa. As indicated in Figure 1, the beam was strengthened using the FRP layer attached to the beam soffit. Epoxy adhesive, with a tensile strength equal to 54 MPa, a tensile modulus equal to 2.8 GPa, and a 3.4 % tensile elongation, was used to bond FRP to the concrete substrate (West System, 2015)[9]. The used CFRP was 0.45 mm thick and 75 mm wide with a fiber density of 340 g/m$^2$. The FRP tensile strength, elastic modulus, and the average maximum strain, determined according to ASTM D3039 (1996)[10], were found to be 1548 MPa, 89 GPa, and 1.74 % respectively. As described in Pham and Hao (2016)[11], the load was applied by dropping a steel cylinder of 203.5 kg weight onto the center of the beam top surface. The impact velocity was 6.28 m/s and resulted from a dropping height of 2 m. Pin and roller supports were used producing a clear span of 1900 mm. Two samples were chosen for simulation and verification in this study. An un-strengthened sample (control beam (RB)) and a strengthened sample (NL1B) with CFRP sheet going longitudinally were used.

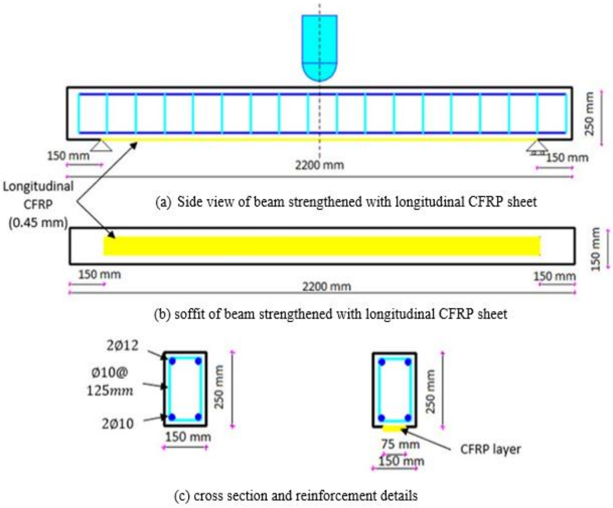


Fig. 1. Details of CFRP strengthened RC beam specimens[8].

## 3. Numerical modeling

The reinforced concrete beams analyzed in this research were modeled using solid elements (C3D8R) available in the ABAQUS / Explicit element library with three degrees of freedom (8-nodes). The numerical parameters for the concrete parameters in Table 1 were determined based on SIMULIA[12] recommendations to explain the Concrete Damaged Plasticity (CDP) model. To represent the internal reinforcement, a two-node linear displacement (B31) beam element was chosen (main reinforcement and stirrups). The impactor was modeled by a discrete rigid body at which the mass was applied to its reference point. The discrete rigid body was chosen to prevent any deformation from happening during the experiment[13, 14]. Shell elements (S4R) were used for the simulation of the CFRP. The mechanical parameters of CFRP developed in this study are given in Table 2 [8, 15, 16]. Embedded region coupling was employed to describe the connection between longitudinal and transverse reinforcements in concrete. The user can define one region as the host and another as embedded as a result of this relationship. In this model, the embedded region was represented by reinforcements, while the host region was represented by the concrete beam [17]. The contact region between CFRP and the concrete beam was modeled using a cohesive element (COH3D8)[18].

Consequently, many forms of material behavior have also been investigated to a better understanding of visco-elastic, visco-plastic, and post-cracking in reinforced concrete structures subjected to impact loads. Concrete damage plasticity modeling is based on the fact that tensile cracking and compression tend to crush concrete. Concrete compression hardening and Concrete tension stiffening are the two primary sub-options within this category. The same concept was used to develop Drucker-Prager and Cap/Plasticity modeling, but they contain additional features such as identifying the yield surface parameters and the advantage of cap yield, which may lead to better outcomes for high-velocity impact loading.

The interaction between the impactor and the tested beams was established using the contact pair option in ABAQUS / Explicit. The master and slave surfaces must be defined in order to use the ABAQUS / Explicit contact pair algorithm. As a result, the impactor was chosen as the master surface, while the impacted member (RC beam) was chosen as the slave surface [18, 19]. To avoid the scattering of results, a coupling restriction was applied. This coupling restriction is created by placing a reference point (RP) at the center of each support. A hammer for impact was used to apply the loading at the mid-span of the beam, with a surface-to-surface constraint. The degrees of freedom of U1, U2, and U3 were set to zero because the beams were simply supported. In the software ABAQUS program [17], Figure 2 shows the organization of reinforcing bars, RC beams, supports, and hammers.

Table 1. Material parameters of concrete [17]

| parameter | Value | Description |
|---|---|---|
| $\Psi$ | 30 | Dilation angle |
| $\epsilon$ | 0.1 | Eccentricity |
| $fb_0/fc_0$ | 1.16 | The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress. |
| $k$ | 0.667 | Kc, the ratio of the second stress invariant on the tensile meridian |
| $\mu$ | 0.0001 | Viscosity Parameter |

Table 2. Properties of CFRP sheets[15]

| Property | Description | Unit | Value |
|---|---|---|---|
| $\rho$ | Density | $kg/m^3$ | 1600 |
| $E_1$ | Modulus of elasticity in the fiber direction | GPa | 89 |
| $E_2$ | Modulus of elasticity in the transverse direction | GPa | 17 |
| $G_{12}$ | shear modulus | GPa | 6 |
| $\sigma_{1t}$ | Tensile strength (Longitudinal) | MPa | 1548 |
| $\sigma_{1c}$ | Compressive strength (Longitudinal) | MPa | 1200 |
| $\sigma_{2t}$ | Tensile strength (Transverse) | MPa | 50 |
| $\sigma_{2c}$ | Compressive strength (Transverse) | MPa | 250 |
| $\tau_{12}$ | shear strength | MPa | 70 |

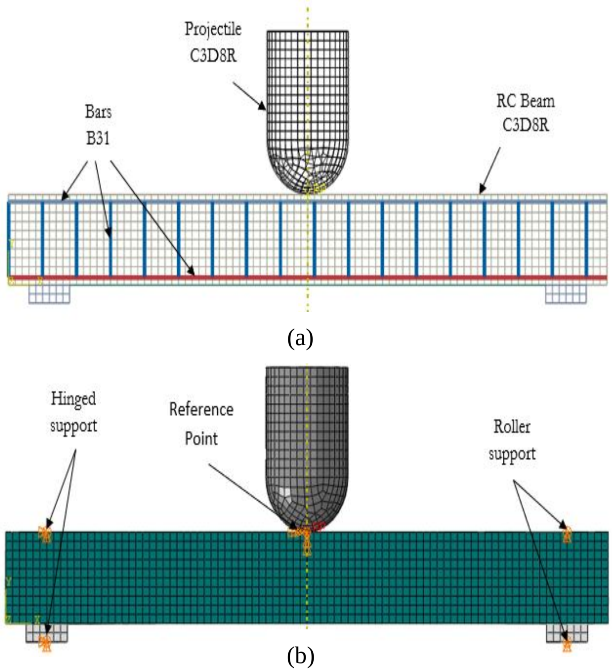


Fig. 2. Details of FE model: a) Two – dimensional finite element model; b) Loads and boundary conditions applied to the FE model.

## 4. Verification of nonlinear finite element and experimental work of Pham TM and Hao[8].

### *4.1. Results of impact force and reaction forces*

Table 3 compares both experimental carried out by Pham and Hao [8] and FE results. According to Table 3, the difference in peak impact force for experimental, concrete damage plasticity, Drucker-Prager, and cap/plasticity the decreasing percentage values for RB beams were 2.3 %, 5.5%, and 8.6%, respectively, whereas for NL1B beams the Increasing percentage values were 8.7 %, 25.1 %, and 9.8 %. Figures 3 and 4 represent the time histories for impact force-time histories and reaction force-time histories, respectively, for all impacted beams. The response of all beams showed a similar time history pattern, as can be seen in Figures 3 and 4.

Table 3. Comparison between experimental results[8], and FE results.

| Sample | | RB | NL1B |
|---|---|---|---|
| Peak Impact force (kN) | EXP | 453 | 470 |
| | Concrete damage | 442.36 | 510.85 |
| | Drucker Prager | 428 | 587.96 |
| | Cap plasticity | 414.18 | 516.17 |
| Maximum Displacement (mm) | EXP | 52.3 | 41.1 |
| | Concrete damage | 51.4 | 38 |
| | Drucker Prager | 22.13 | 17.66 |
| | Cap plasticity | 38.56 | 27.95 |
| Residual Displacement (mm) | EXP | 41.6 | 31.2 |
| | Concrete damage | 49.5 | 33.4 |
| | Drucker Prager | 20.78 | 16.2 |
| | Cap plasticity | 36.49 | 25.6 |
| Duration (ms) | EXP | 39 | 38 |
| | Concrete damage | 32 | 30 |
| | Drucker Prager | 28 | 25 |
| | Cap plasticity | 30 | 27 |

The first peak in the impact force's time history shown in figure 3 had an isosceles triangle geometry, a large amplitude (about 450 kN), and a short time period (about 5 ms). After 10 ms following the initial peak, a triangular-shaped second peak was present for the experimental specimen, and then followed by many triangular-shaped peaks along with the following 30 ms. These small peaks were not well observed for numerical specimens.

Meanwhile, the reaction forces-time history reveals an interesting phenomenon. Figure 4 shows that the existence of a negative reaction force followed by the positive ones. This behavior has also been reported in previous research [20, 21] due to the application of a high-loading rate [22]. Furthermore, Kishi and Mikami [21] experimented and discovered a similar behavior in which the negative reaction was created first, followed by the positive reaction. This intriguing observation has yet to be given a clear explanation. The addressed behaviour could be explained using the theory of stress wave propagation. As shown in Figure 4, the second peak significantly differs from the first peak for the strengthened beam for all types of concrete models used in this analysis, being the CDP the most relevant to the experimental curve. For example, at the second peak, Beam ML1B's positive reaction force has reached its maximum value. The FRP sheets were activated as a result of the first peak deformation thus enhanced the beam load-carrying capacities, the stiffness, and the maximum reaction force of the strengthened beam at the second peak. After the longitudinal FRP strips were activated, the beams became stiffer, resulting in higher load (reaction forces). Figure 4 shows that the reaction forces began as negatives, then climbed to their maximum positive value achieving the equilibrium, then returning to negatives due to the existence of free vibrations.

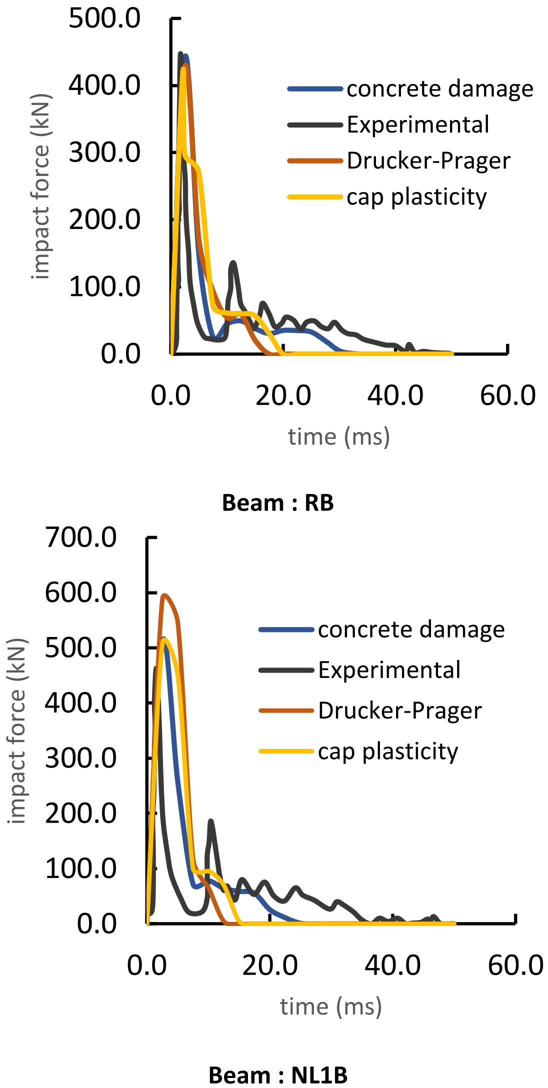


Fig. 3. FE versus experimental impact force-time histories[8]: Beam RB, and Beam NL1B.

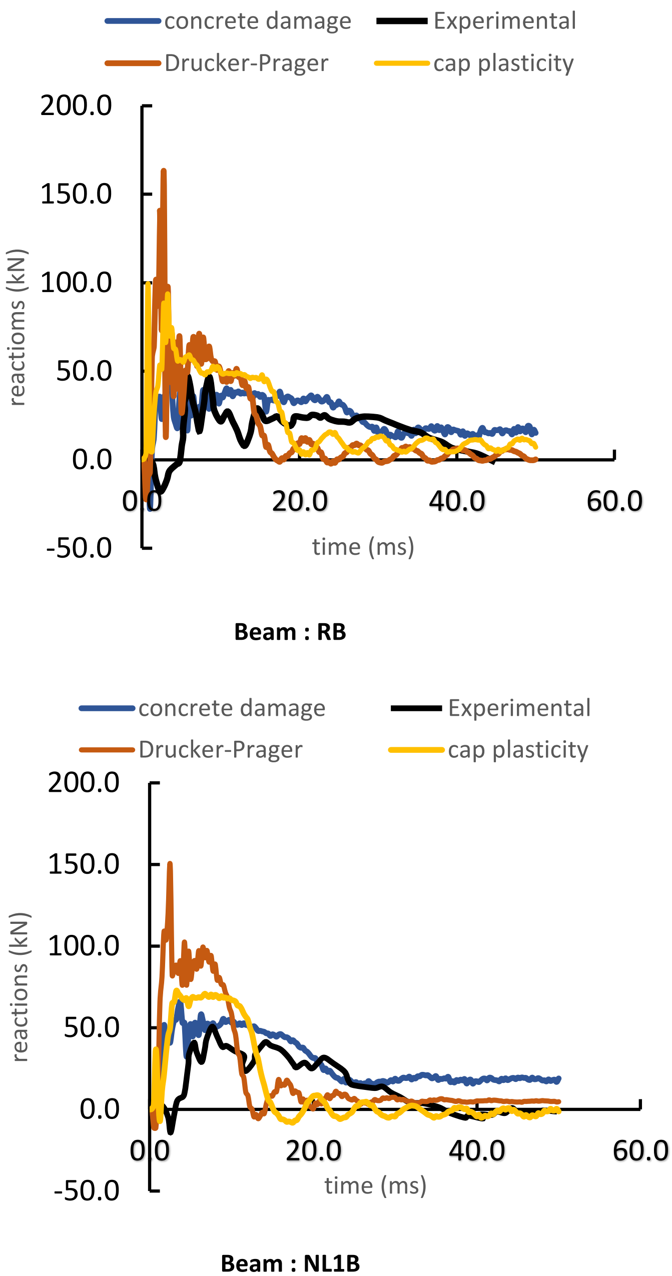


Fig. 4. FE versus experimental reactions-time histories[8]: Beam RB, and Beam NL1B.

### *4.2. Results of beams displacement*

Figure 5 presents the displacement-time response. In around 35 ms, all beams exhibited their maximum displacement, however a slight reduction was present in the experimental specimen, and then back to their residual deflection. Compared to experimental results, concrete damage plasticity, Drucker-Prager, and cap/plasticity for RB beam showed a lower maximum displacement by about (1.7%, 57.7% and 26.3%), respectively and the residual displacement increased for concrete damage plasticity by 19%, while it decreased for Drucker-Prager, and cap/plasticity by (50% and 12.3%), respectively. And for NL1B beam, the use of FRP sheets resulted in a significant reduction in the maximum mid-span displacement by (7.5%, 57% and 32%), respectively and the residual displacement increased for concrete damage plasticity by 7%, while it decreased for Drucker-Prager, and cap/plasticity by (48% and 18%), respectively.

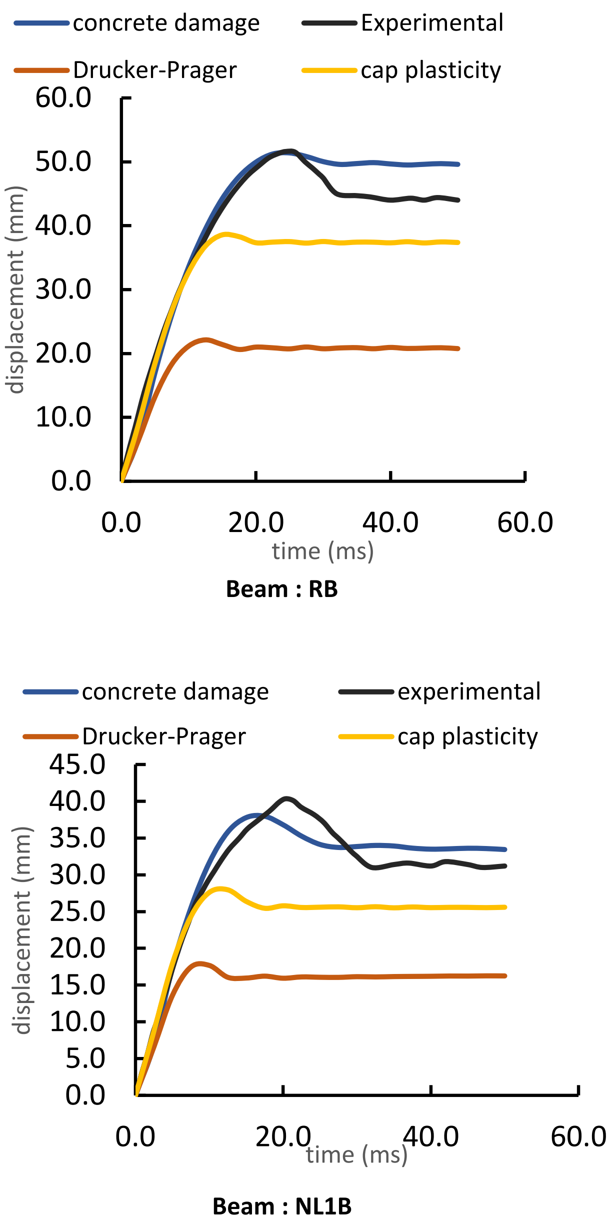


Fig. 5. FE versus experimental displacement-time histories[8]: Beam RB, and Beam NL1B.

## 5. Conclusions and recommendations

This paper numerically investigates the response of RC beams externally strengthened using CFRP sheets and subjected to impact load. The main object of the study is to compare different models to simulate the nonlinear behavior of reinforced concrete. The used models were concrete damage plasticity, Drucker-Prager, and Cap/Plasticity. Following the results obtained, the main conclusions can be drawn:

- The general behavior of the finite element models in terms of time-displacement at the beam mid-span, impact force-time histories, and reaction force-time histories showed good coherence with those obtained experimentally.
- The developed numerical model concrete damage plasticity showed a slight difference from the experimental results [8] of maximum displacement by about (1.7%) for RB beam and (7.5%) for NL1B beam, while when using Drucker-Prager and Cap/plasticity there are a large difference in maximum displacement by(57.7% and 26.3%) for RB beam and (57% and 32%) for NL1B beam.
- Simulation of concrete with Drucker-Prager and Cap/Plasticity resulted in a ductile behavior as they are plasticity-based models, while Concrete Damage Plasticity, which is a brittle-cracking model introduced a brittle behavior.
- Modeling in concrete using brittle behavior results is more realistic and asymptotic to experimental results than when using ductile behavior.

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