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Finite Element Analysis of Low Velocity Impact on Carbon Fibers/Carbon Nanotubes Reinforced Polymer Composites

Farzad Pashmforoush 

Department of Mechanical Engineering, Faculty of Engineering, University of Maragheh
Maragheh, P.O. Box 55136-553, Iran, Email: f.pashmforoush@maragheh.ac.ir

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Corresponding author: Farzad Pashmforoush (f.pashmforoush@maragheh.ac.ir)

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Abstract. An effort is made to gain insight on the effect of carbon nanotubes (CNTs) on the impact response of carbon fiber reinforced composites (CFRs) under low velocity impact. Certain amount of CNTs could lead improvements in mechanical properties of composites. In the present investigation, ABAQUS/Explicit finite element code (FEM) is employed to investigate various damages modes of nano composites including matrix cracking, fiber damage and delamination by employing Hashin's criterion and cohesive zone modeling. The obtained results for 0, 0.5, 1, 2 and 4% CNTs demonstrate that by including CNTs in composite plates, damage could be reduced. However, adding further CNTs causes sudden reduction of impact tolerance capability of the composite plates, particularly, damage due to delamination.

Keywords: Nano-composites, Impact behavior, Finite element analysis, Damage mechanisms, Carbon nanotubes.

1. Introduction

Nowadays, carbon fiber reinforced composites (CFRs) are widely used in various engineering fields where high specific strength and stiffness are mainly required. These characteristics are crucial for applications in aeronautics and military industries [1-5]. However, low resistance of composite materials in transverse impact necessitates analyzing of their damage mechanics to ensure safe implementation during service life. Composites, unlike metals, are damaged in several ways including fiber breakage, matrix cracking, fiber/matrix debonding and delamination. Damage reduces stiffness and load carrying capability of composites, and it propagates by service load and eventually could lead to catastrophic failure.

Gaining insight on damage in composites is a difficult task due to the various damage mechanisms involved as well as difficulties in conducting experimental tests. For these reasons, simulation of damage and damage modeling is an important aim [6-12]. Significant work is done to model composite impact. Wang *et al.* [13] conducted an experimental and numerical effort to study damage and failure of a laminated composite under low velocity impact. Hashin's damage criterion together with cohesive zone modeling were used in FEM code. The drop weight test and the non-damage inspection (NDI) were performed experimentally. Singh and Mahajan [14] developed an elastic-plastic damage model for three dimensional FRC composite under low velocity impact using ABAQUS/Explicit code and user subroutine VUMAT. Riccio *et al.* [15] conducted a FEM simulation for impact induced damage in composites considering the global-local technique to refine mesh around impact zone to increase the accuracy of the results. Cohesive elements and Hashin's criteria were employed in their research. Donadon *et al.* [16] employed a 3D failure model based on Continuum Damage Mechanics (CDM) for low velocity impact test using LS-DYNA explicit finite element code. Damage modeling usually achieved using CDM [17-19]. Shi *et al.* [20] employed the stress based criteria for damage initiation and fracture mechanics technique to model damage evolution. The FEM model was implemented in ABAQUS/Explicit with a user-defined subroutine (VUMAT) and NDT X-ray radiography is used to observe the damage and failure after low velocity



impact. Wan et al. [21] studied low-velocity impact behavior of glass fabric cloth reinforced epoxy composite panels embedded with wire nets. The impact tests were carried out with various incident velocities, and the perforation thresholds of the designed specimens were analyzed. The damage pattern obtained by FE simulations was in good agreement with those of experimental tests. Qian et al. [22] employed virtual crack closure technique to investigate dynamic fracture behavior under mixed mode loading condition. The obtained results showed that FE simulation could successfully analyze the dynamic crack propagation without any convergence problem. He et al. [23] studied the low velocity impact behavior of hybrid corrugated core sandwich structures. They investigated the influence of core thickness, impact energy and impact site on the absorbed energy, impact load and failure mechanisms. The obtained results indicated good agreement between the numerical and experimental data in terms of impact energy and failure modes.

Carbon nanotubes (CNTs) possess great mechanical properties such as extremely high Young modulus, high thermal and electrical conductivity. CNTs are mainly an additive component to enhance the mechanical properties of the base material. Recently, Tarfaoui *et al.* [24] investigated the effect of adding CNTs in a CFR composite, to ascertain their effect on various types of damage developed during the open-hole tensile test. The experimental results were compared with the FEM results. Hashin's Damage criterion was chosen for detecting damage initiation and a model by Matzenmiller *et al.* [25] was employed for damage evolution. Various volume fractions of CNTs (0, 0.5, 1, 2 and 4%) were analyzed. The obtained results showed considerable increase in mechanical properties in case of up to 2% CNTs; while, beyond 2% CNTs, the material properties showed significant degradation. CNTs affect the mechanical properties of the base material [26-29] and based on the matrix type, many different composites can be produced. Qian *et al.* [30] confirmed that by adding 2% of CNTs in a matrix, 36% to 42% increase in young modulus and 25% increase in tensile strength can be achieved. Similar results were obtained by Schadler *et al.* [31] and Zhu *et al.* [32].

CNTs can also be considered as an ingredient to enhance energy absorption of composite materials. On a survey by Sun *et al.* [33], they concluded that some nano-composites with special matrixes could achieve considerable improvement in impact energy absorption. In a study by Wang *et al.* [34], impact strength of polymer nano-composite was significantly improved by adding amino-functionalized MWCNTs. Similar results were obtained by Cooper *et al.* [35] by adding SWCNTs. Furthermore, the results by Kireitsey *et al.* [36] indicated that the impact toughness of nanotube-reinforced polymer composites is a function of Young modules of nanotubes.

Delamination is the main damage mode of laminated composites, especially under low velocity impact event. Literatures on modeling of delamination are mainly divided to either virtual crack closure technique (VCCT) or cohesive zone models (CZMs) [37-39]. CZM is largely adopted for various materials due to its simplicity and versatility. Bedon *et al.* [40] used CZM to study the failure mechanisms of notched connections for timber-concrete composite beams. The FE results were compared with push-out experimental data taken from literature. It was shown that the FE model could successfully capture the behavior of the notched connections, including the failure mechanisms and collapse load. In another study by the same author [41], CZM was employed to model the adhesive connections in the case of brittle adherents such as glass. The comparison of FE results with those of experimental tests indicated the good performance of CZM in prediction of damage initiation and propagation in the adhesive joint specimens.

In the present research, the effect of adding CNTs to a CFR composite was investigated using ABAQUS/Explicit finite element code and the various damage modes developed during transverse low velocity impact were analyzed. For this purpose, Hashin's damage initiation criterion was employed for predicting fiber and matrix damage and cohesive surface element was used for predicting delamination. The results demonstrated the beneficial effect of adding CNTs until a certain point in which it degrades impact performance of the composite plate. To the best of author's knowledge, there is no any investigation concerning the effect of CNTs on low velocity impact of composite materials so far. There are, however, studies mainly devoted to modeling and characterization of CNTs based composite [42-45].

2. Damage Modeling

2.1. Damage initiation criteria

Damage modeling usually encompasses two phases: damage initiation and damage evolution. In the present study, Hashin's criterion is implemented to identify fiber and matrix failure initiation. This is three dimensional failure criteria of unidirectional fiber composites based on quadratic stress polynomials and are expressed in terms of the transversely isotropic invariants of the applied stress state. One of the main advantages of these failure criteria is district failure mode for both matrix and fibers, making it ideal for investigate damage sources in composites [46]. This criterion involves four damage modes, namely, fiber tension, fiber compression, matrix tension and matrix compression modes according to the following Eqs. (1)-(4):

- Fiber tensile failure: ($\hat{\sigma}_{11} \geq 0$):

$$F_f = \left(\frac{\hat{\sigma}_{11}}{X^T} \right)^2 + \alpha \left(\frac{\hat{\sigma}_{12}}{S_{12}} \right)^2 = 1 \quad (1)$$

- Fiber compressive failure ($\hat{\sigma}_{11} < 0$):

$$F_{fc} = \left(\frac{\hat{\sigma}_{11}}{X^c} \right)^2 = 1 \quad (2)$$

- Matrix tensile failure ($\hat{\sigma}_{22} \geq 0$):

$$F_{mt} = \left(\frac{\hat{\sigma}_{22}}{Y^T} \right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}} \right)^2 = 1 \quad (3)$$

- Matrix compressive failure ($\hat{\sigma}_{22} < 0$):

$$F_{mc} = \left(\frac{\hat{\sigma}_{22}}{2S_{23}} \right)^2 + \left[\left(\frac{Y^c}{2S_{23}} \right)^2 - 1 \right] \frac{\hat{\sigma}_{22}}{Y^c} + \left(\frac{\hat{\sigma}_{12}}{S_{12}} \right)^2 = 1 \quad (4)$$

where, σ_{ij} is effective stress, X^T and X^c are tensile and compressive strength of composite laminate in fiber direction, Y^T and Y^c are tensile and compressive strength in transverse direction, S_{12} and S_{23} are longitudinal and transverse shear strength of the composite, respectively. The coefficient α is for shear stress contribution on the fiber tensile failure.

2.2. Damage of fiber-reinforced composites

Whenever, damage occurred in a substance, the load carrying capability of the material is reduced. To introduce the damage in a model, damage operator is used. This operator maps the continuum stress in the substance without damage to the one with damage as follows:

$$\hat{\sigma} = \frac{\sigma}{1-d} \quad (5)$$

where, $\hat{\sigma}$ is the effective or real stress and σ is the stress in a substance without damage and d is the damage variable defined by Eq. (6):

$$d = \frac{A - A^{ef}}{A} \quad (6)$$

where, A is the total cross-sectional area and A^{ef} is the real load carrying area in a damaged substance.

In damage modeling, it is assumed that the material stiffness is degraded as the damage evolves and eventually leads to the material complete failure.

2.3. Damage evolution

The equivalent stress-displacement relations can be used for defining the behavior of damage as the damage displacement increases. Equivalent stress and displacement for each of the damage mode must be calculated using the Eqs. (7)-(10):

- Fiber tension:

$$\begin{aligned} \delta_{eq}^{ft} &= L^c \sqrt{\langle \varepsilon_{11} \rangle^2 + \alpha \varepsilon_{12}^2}, \\ \sigma_{eq}^{ft} &= \frac{\langle \sigma_{11} \rangle \langle \varepsilon_{11} \rangle + \alpha \tau_{12} \varepsilon_{12}}{\delta_{eq}^{ft} / L^c} \end{aligned} \quad (7)$$

- Fiber compression:

$$\begin{aligned} \delta_{eq}^{fc} &= L^c \langle -\varepsilon_{11} \rangle, \\ \sigma_{eq}^{fc} &= \frac{\langle -\sigma_{11} \rangle \langle -\varepsilon_{11} \rangle}{\delta_{eq}^{fc} / L^c} \end{aligned} \quad (8)$$

- Matrix Tension:

$$\begin{aligned} \delta_{eq}^{mt} &= L^c \sqrt{\langle \varepsilon_{22} \rangle^2 + \varepsilon_{12}^2}, \\ \sigma_{eq}^{mt} &= \frac{\langle \sigma_{22} \rangle \langle \varepsilon_{22} \rangle + \tau_{12} \varepsilon_{12}}{\delta_{eq}^{mt} / L^c} \end{aligned} \quad (9)$$

- Matrix compression:

$$\begin{aligned}\delta_{eq}^{mc} &= L^c \sqrt{\langle -\varepsilon_{22} \rangle^2 + \varepsilon_{12}^2}, \\ \sigma_{eq}^{mc} &= \frac{\langle -\sigma_{22} \rangle \langle -\varepsilon_{22} \rangle + \tau_{12} \varepsilon_{12}}{\delta_{eq}^{mc} / L^c}\end{aligned}\quad (10)$$

where, L^c is the characteristic length to alleviate mesh dependency of the results. $\langle \rangle$ is the Macaulay bracket operator defined as follows:

$$\langle x \rangle = (x + |x|) / 2 \quad (11)$$

Each time, after the initiation of damage, the damage for each mode is computed based on the damage displacement relationship as follows:

$$d = \frac{\delta_{eq}^f (\delta_{eq} - \delta_{eq}^0)}{\delta_{eq} (\delta_{eq}^f - \delta_{eq}^0)} \quad (12)$$

in which, δ_{eq}^0 is the initial displacement where the damage is taking place for the first time, and δ_{eq}^f is the ultimate displacement where the material totally fail.

2.4. Delamination modeling

Delamination is a type of damage in laminated composites where adjacent plies lose their bond and hence start to evolve. Cohesive zone modeling [47-50] is a method to model the adhesion between two plies, the damage due to loss of cohesiveness and the final failure. In the present work, cohesive surface is implemented among plies of the composite. In the cohesive surface, the cohesive layer thickness is assumed to be really thin as it normally occurred in laminated composites.

3. Impact Modeling

3.1. FEM modeling

To model the impact, commercial software ABAQUS/Explicit is used. Fig. 1 illustrates the modeling of the composite plate, mass drop and the base plate. According to the ASTM D7136 standard, the energy of drop mass should be 6.7 J/mm of composite thickness, for which, our composite must withstand the energy of about 16 J. Hence, the initial velocity of colliding mass is set to 4 m/s and it's mass to 2 kg. The dimension of the composite plates is chosen as 100 mm x 100 mm to comply with the low velocity impact test ASTM D7136 standard. The composite plate is made of 8 plies, each with 0.313 mm thickness with stacking sequence of [(45/-45/90/0)]_s. Each ply is modeled separately and bonded by cohesive surface. The minimum element size is 0.5 mm and the element type is SC8R (continuum shell). This element has 3 degree of freedoms, 8 nodes, hexahedron with finite membrane strain. Formulation of continuum shell elements is as the same as the conventional shell element, except that, it is applied on the 3D model rather than a surface [51]. A 3D model is constructed and continuum shell element is assigned. Thickness of shell element is computed automatically by ABAQUS according to 3D model local thickness. In computational phase, however, instead of 3D element, a shell finite element formulation is utilized which considerably reduces computational burden. The thickness of these elements is determined based on the 3D model thickness. Mesh for each ply contains 2128 nodes and 1008 elements and total number of nodes and elements are 17024 and 8064, respectively. The mesh pattern was made using ABAQUS internal meshing tools. In order to increase the efficiency of the FE model, a finer mesh was used in the impact zone, while a coarser mesh was employed in the area away from the impact region. Mesh of collision surface is refined while the other parts are coarsely meshed to reduce the computational time. As shown in Fig.1, underneath of the composite plate, there is a base which is a hollow square block. The base and drop mass is modeled as rigid bodies. To reduce computational burden, the collision is simulated using on quarter model. The base is modeled as rigid and has been fixed throughout the simulation. The plate is located on the base and a contact interaction is defined between plate and base. Except symmetric boundary conditions on internal faces of plate, no further boundary condition is applied.

3.2. Mechanical properties

In this study, carbon fiber and carbon nanotube reinforced composites are produced based on the parameters and data presented by [24]. A laminated composite consists of 8 plies of CFR keeping together by epoxy matrix. CNTs are blended in the matrix and reinforced by 5HS carbon fibers. To consider the effects of CNTs, 5 specimens with 0%, 0.5%, 1%, 2% and 4% CNTs are fabricated and used in the impact test. Mechanical properties of laminated composite as obtained by [24] are listed in Table 1. In this table, E, ν and G are Young modulus, Poisson ratio and Shear modulus, in different directions in Cartesian coordinate, respectively. Parameters required for Hashin's damage initiation criteria are shown in Table 2. Following the initiation of the damage, evolution of damage takes place as discussed in section 2.3. The parameters for the damage evolution are provided in Table 3. Parameters pertained to the cohesive zone modeling, as discussed in section 2.4 are provided in Table 4.

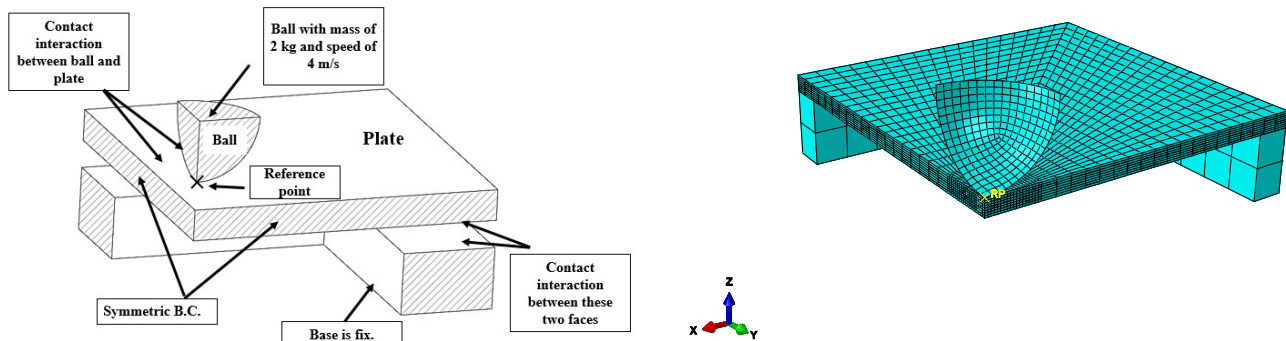


Fig. 1. Configuration of low velocity impact test model. The plate is 100 x 100 mm, with 8 plies each with thickness of 0.313 mm and stacking sequence of [(45/-45/90/0)]_s.

Table 1. Mechanical orthotropic properties of composite plies [24].

CNTs content	0%	0.5%	1%	2%	4%
E_{11} (GPa)	59.11	59.138	59.16	59.219	59.33
E_{22} (GPa)	59	59	59	59	58.55
E_{33} (GPa)	7.6	7.623	7.6	7.67	7.81
ν_{12}	0.089	0.089	0.0892	0.0892	0.0892
ν_{13}	0.27	0.27	0.27	0.274	0.275
ν_{23}	0.28	0.28	0.277	0.279	0.28
G_{12} (GPa)	8.25	8.257	8.27	8.285	8.316
G_{23} (GPa)	3.97	3.99	4.017	4.04	4.105
G_{13} (GPa)	0.27	0.27	0.27	0.274	0.275

Table 2. Parameters of Hashin's damage initiation criteria [24].

X^T (KJ/m ²)	X^C (KJ/m ²)	Y^T (KJ/m ²)	Y^C (KJ/m ²)	S^T (KJ/m ²)	S^C (KJ/m ²)	Evo
2490	1500	700	800	100	100	0.5

Table 3. Fiber and matrix critical fracture energy as proposed by [24].

G_f^f (KJ/m ²)	G_f^m (KJ/m ²)	G_m^f (KJ/m ²)	G_m^m (KJ/m ²)
100	100	5	5

Table 4. Cohesive zone modeling parameters with respect to CNT content [24].

CNT percentage (%)	Elastic (N/mm ³ × 10 ⁶)	Quads (MPa)	Damage evolution (N/m)
	$K_n; k_s; k_t$	$t_1^0; t_2^0; t_3^0$	$G_{I0}; G_{II0}; G_{III0}$
0	1	10-14-14	0.1-0.1-0.1
0.5	1	10-15-15	0.1-0.1-0.1
1	1	13-17-17	0.1-0.1-0.1
2	1	9-14-14	0.1-0.1-0.1
4	1	3-7-7	0.1-0.1-0.1

3.3. Experimental set-up

The experimental tests were conducted according to ASTM D7136 standard. For this purpose, the composites plates were prepared in rectangular shape with the dimensions of 100 mm x 100 mm. The plates were made up of 8 plies with thickness of 0.313 mm and stacking sequence of [(45/-45/90/0)]_s. The layup orientation was considered to be symmetric to avoid mechanical coupling between bending and extensional loadings. The impact tests were carried out by a hemispherical steel impactor with mass of 2 kg and a hardness of 62 HRC.

4. Results and Discussion

4.1. Impact damages of composite

Here, the results of impact and accompanying damages are illustrated for a composite plate with 2% CNTs content. The computation process takes more than 2 hours in 4 cores CPU 2.7 GHz with stable time increment of 5.93 E-8 and total number of increments of 349327. Maximum deformation (7.7 mm) is occurred at 5.9 ms after impact initiation as shown in Fig. 2a. Contour of delamination damage at the end of impact is shown in Fig. 2b. Considerable delamination has taken place around area of the impact. Figs. 3a, b and c show the contour of Hashin's fiber tension, matrix compression and tension damage variable, respectively at the end of the impact. Again, the damages in the area of impact and around it are obvious and considerable.

4.2. Effect of CNTs content on the impact response of composite plates

In this section, the impact event is simulated for the 0, 0.5, 1, 2, 4% CNTs contents fiber reinforced composite plate.

The mechanical properties associated with each CNTs contents are used in FEM analysis and the results for different type of damage and the impact force versus time are gathered and compared.

Fig.4 shows the force-displacement curve of the drop mass versus time for various contents of CNTs. These figures demonstrate the effect of CNTs content on force-displacement curve. For clarification purpose, only two contents of CNTs are drawn on each graph. Last graph belongs to the highest content of CNTs. As the plots demonstrate, the content of CNTs has considerable effect on the force and displacement of the composite. For CNTs contents of 0, 0.5, 1, 2%, the maximum deformation is almost the same, while, for CNTs content of 4%, the maximum deformation is literally higher than others. The maximum force for CNTs content of 0, 0.5, 1, 2%, are almost same and is above 450 N, however, for CNT content of 4%, the maximum force is lower than 400 N.

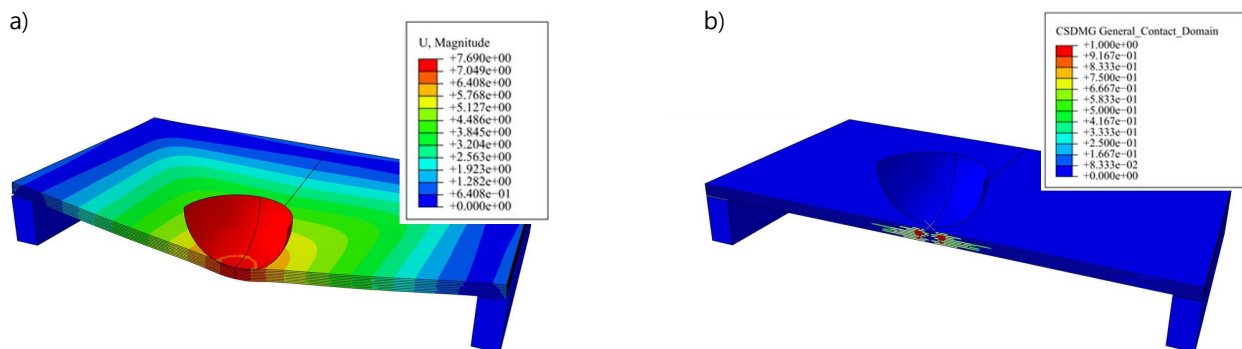


Fig. 2. Displacement (A) and delamination damage contours (B); A) Time: 3ms (Maximum deflection); B) End of impact at 8 ms.

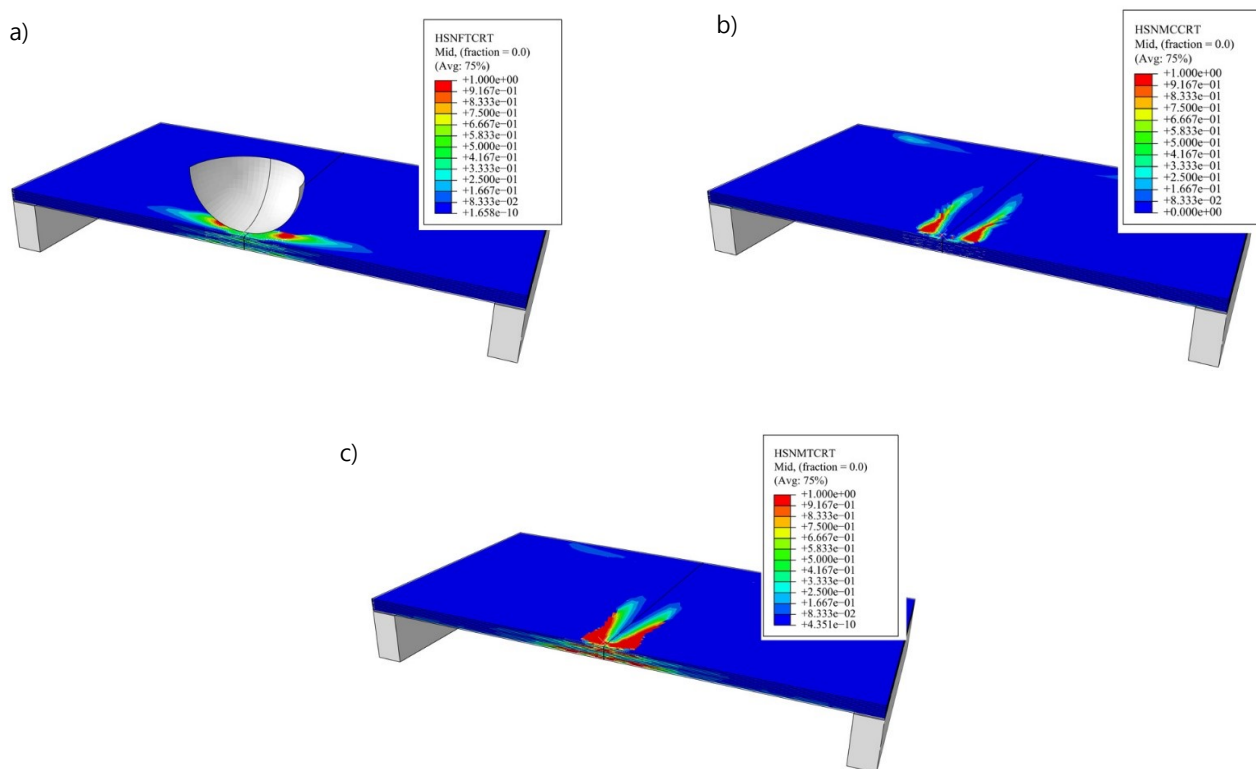


Fig. 3. Hashin's damage variables at the end of impact; A) Fiber tension; B) Matrix Compression; C) Matrix Tension (Fiber compression is not plotted due to lack of damage).

After the end of FE simulations for each particular CNTs contents, the velocity of drop mass is measured and the kinematic energy loss is calculated. For CNTs content of 0, 0.5, 1, 2 and 4%, the energy loss is 14.25, 13.45, 13.3, 13.52 and 65.65%, respectively. The obtained results indicate that the further increase in CNTs content could cause a lot of damage and kinematic energy transfer to the composite structure. This result is cautionary, because a little extra amount of CNTs causes sudden enormous loss of impact capability of the composite specimen. This result is not yet obtained by other researchers and is one of the import remarks of the present investigation.

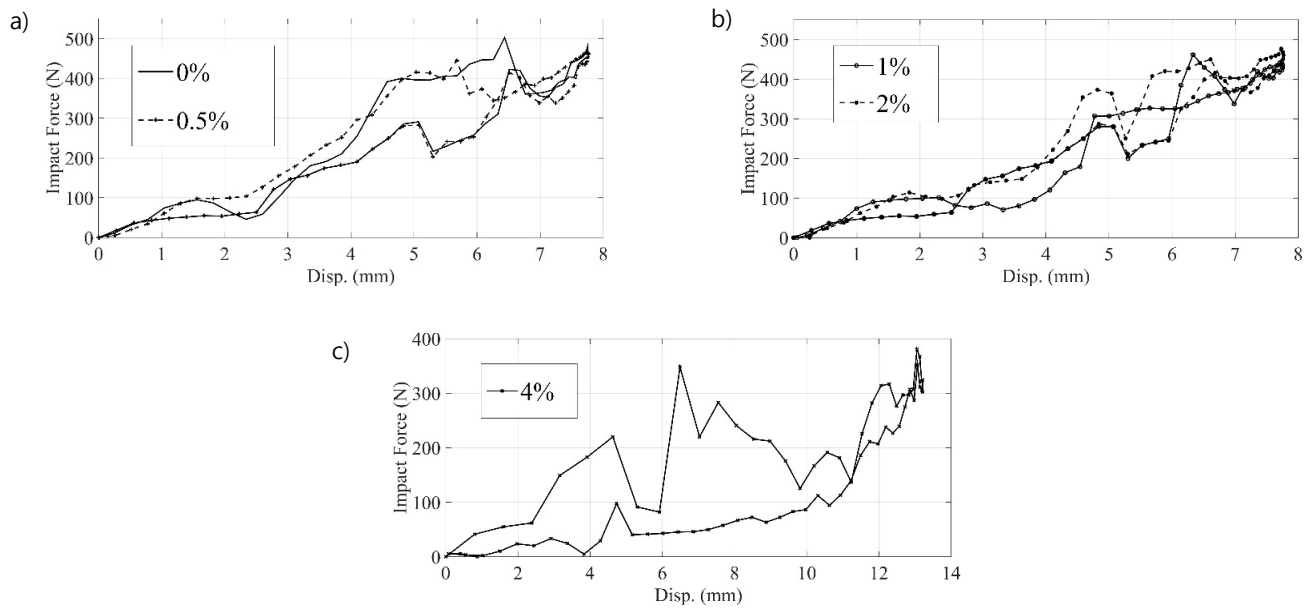


Fig. 4. Effect of CNTs content on force-displacement behavior during impact test: A) 0 and 5%; B) 1 and 2%; C) 4%.

For each plies of the composite, the damage and its contour are different. Here, the results of important damage variables for the composites with 2 and 4% CNTs are presented. Figs. 5-8 demonstrate delamination, fiber tension, and matrix compression and tension damage for 2 and 4% CNTs, for each of the plies in the composite plate at the end of simulation. These images are given for the sake of inspection of impact damage in each plies and the significance degree of each damage variable. Looking at Fig. 5, it can be noticed that a large magnitude of delamination takes place in the composite with 4% CNTs which means that the composite is highly susceptible to delamination with adding extra CNTs. This is mainly because of the reduction in quads as given in Table 4. More CNTs content, at this point, act like a defect and therefore reduces mechanical and fracture properties [52]. Main delamination occurred in lower plies of the composite. There is not any noticeable damage for fiber compression and so the results are not presented for the sake of space saving. Fig.6 shows fiber tension damage for each plies. Main damage occurred in the first ply at the center of the ply and the lower plies possess less damage. Similar results are obtained for compression damage as shown in Fig. 7. However, severe damage is happened for both upper and lower plies when the matrix damage is concerned. Almost the matrix of all plies is damaged, especially around the center of plies. Fig. 8 shows matrix tension damage which has mainly affected the first and the last plies.

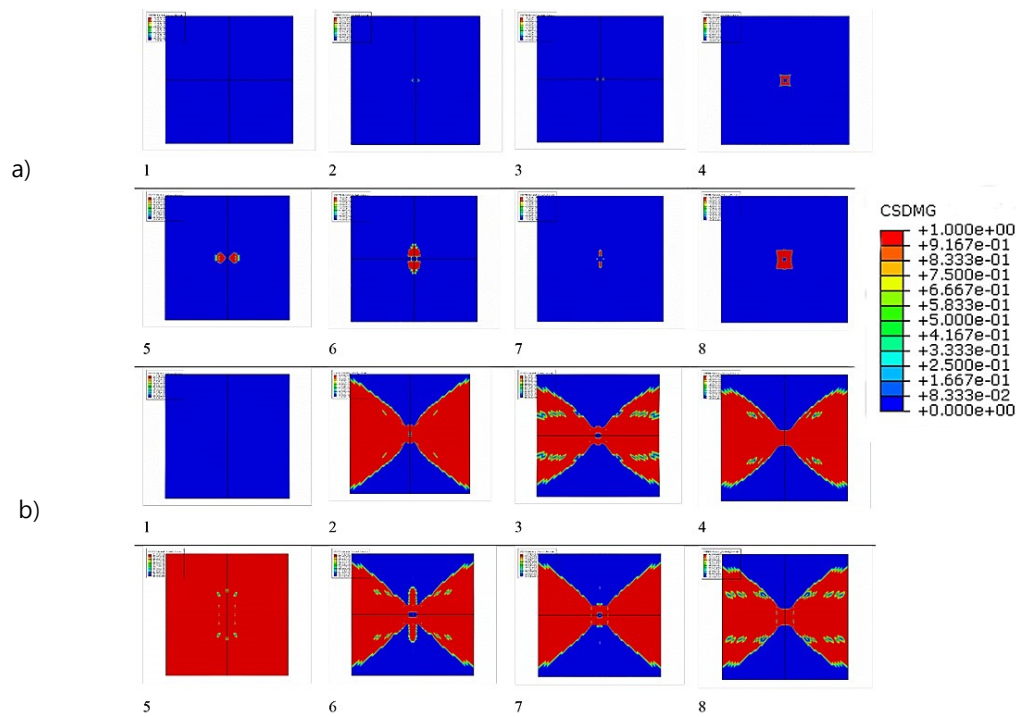


Fig. 5. Delamination in plies of composites for: A) 2% and B) 4% CNTs.

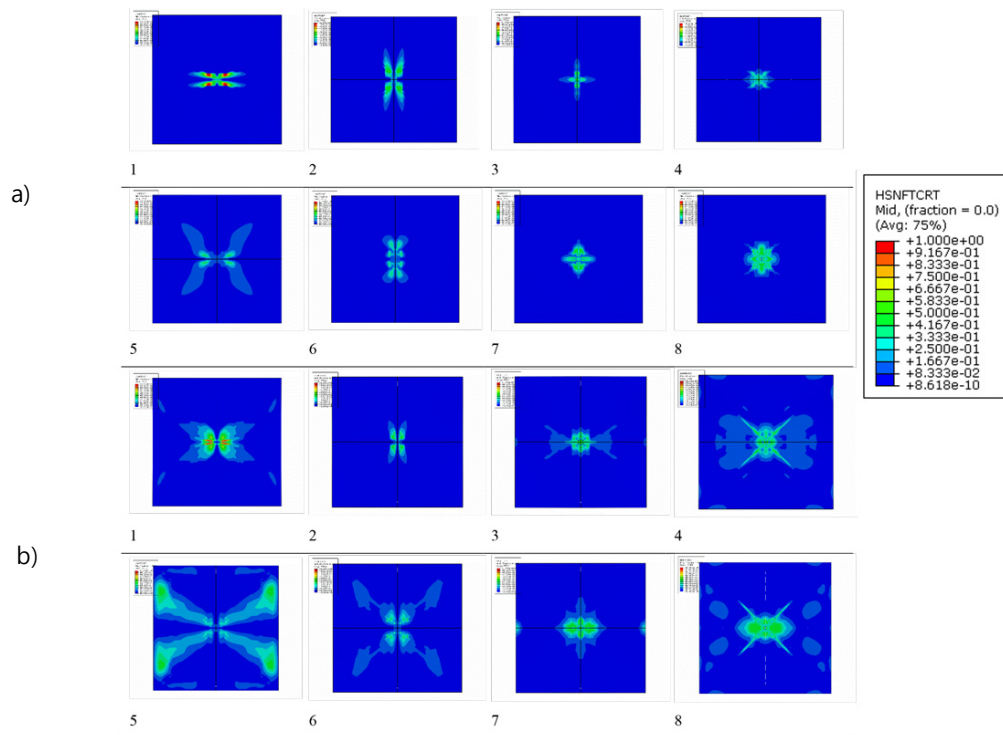


Fig. 6. Fiber tension damage for each ply; A) 2% and B) 4% CNTs.

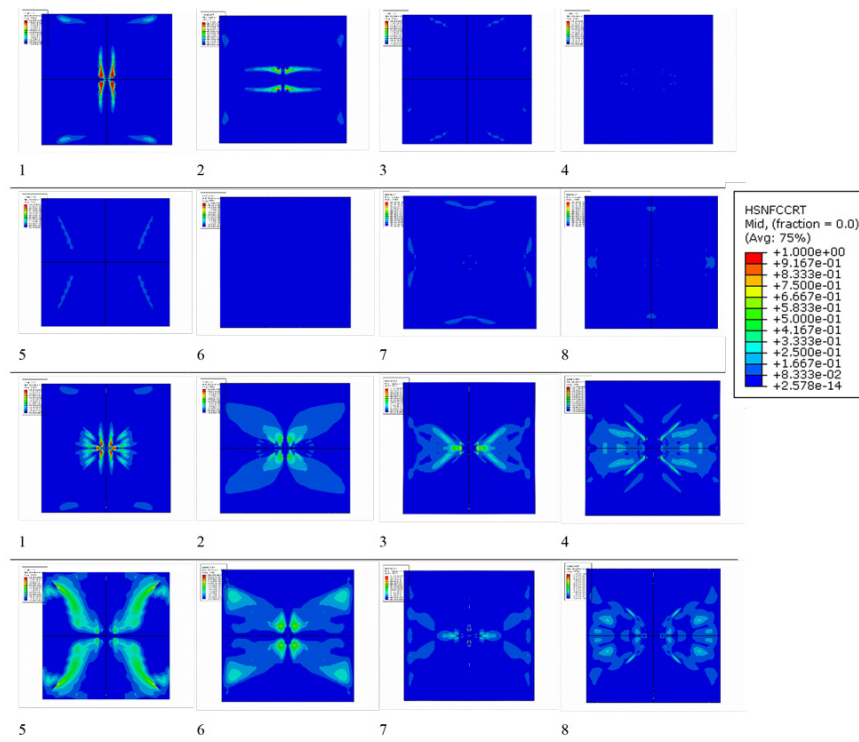


Fig. 7 Matrix compression damage for each ply; A) 2% and B) 4% CNTs.

4.3. Experimental comparison

The composite plates were made based on the mechanical specifications given by Ref [12] and were tested according to the procedure outlined by ASTM D7136 standard. As described in Sec. 3.1, the impact tests were conducted with a hemispherical steel impactor with mass of 4 kg and initial velocity of 4 m/s; leading to the total kinetic energy of 16 J (6.7 J/mm of plates thickness). Fig.9a shows one of the composite plates utilized in the low velocity impact. This image shows failure at the center and back part of the plate, where the drop mass collided to the plate. To illustrate the consistency of FEM and experimental results, matrix tension damage contour for the last ply is shown in Fig. 9b. Here, good correlation can be observed among experimental and numerical results and the impacted plate damage is oriented as predicted by FE simulation.

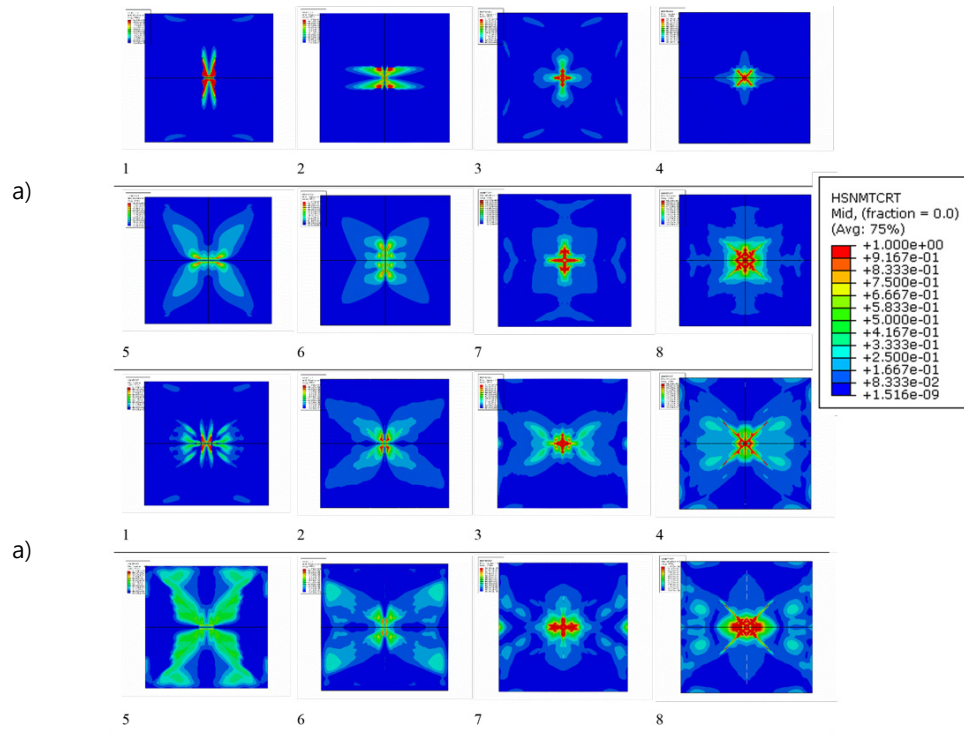


Fig. 8 Matrix tension damage for each ply of: A) 2% and B) 4% CNTs.

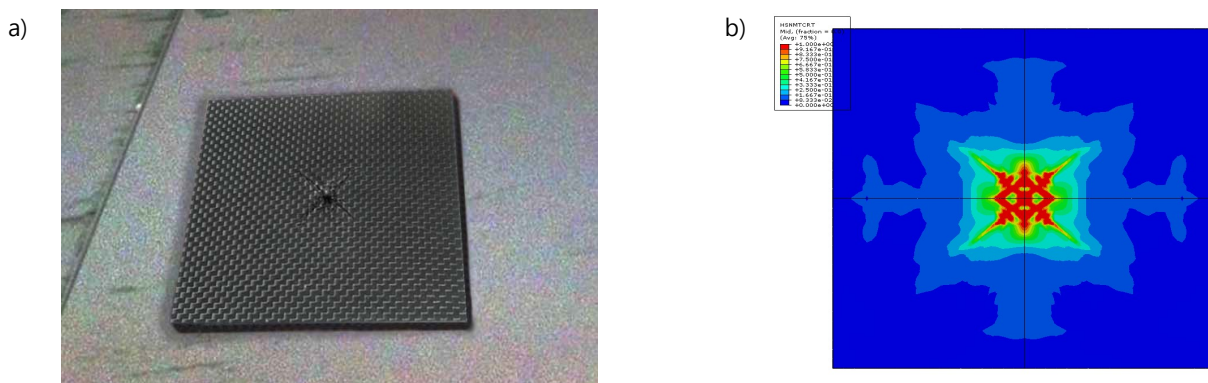


Fig. 9. Composite plate after impact; a) back part of plate; b) contour of matrix tension damage given by FEM simulation.

5. Conclusion

In this study, the low velocity impact of a carbon nanotube reinforced CFR composite was simulated by ABAQUS/Explicit FEM code and the experimental tests were carried out to compare the consistency of the numerical results. Main forms of damage including fiber, matrix failure and delamination were modeled using Hashin's criterion and cohesive zone modeling, respectively. As other researchers pointed out, adding low amount of CNTs leads to considerable mechanical improvement of a composite. Here, 0.5, 1, 2 and 4% CNTs inclusion was investigated by FEM code. The obtained results showed that CNTs more than 2% caused sudden decline of composite impact tolerance, which is mainly because of the plies' bond deterioration. For lower amount of CNTs, the impact capability of the composite plates improved slightly. However, the path of force-displacement graphs was affected considerably by adding CNTs but the maximums were not. Contours of different damage variables were provided to gain further insight.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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ORCID iD

Farzad Pashmforoush  <https://orcid.org/0000-0002-2219-5158>



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