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STRUCTURAL BEHAVIOR OF UHPC EPOXY COMPOSITE PLATE SUBJECTED TO VELOCITY IMPACT LOADING

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Abstract

This article aims to investigate the structural behavior of Ultra High Performance Epoxy Composite Plate subjected to velocity impact loading. Two types of material were utilized for the composite plate: epoxy, and UHPC. UHPC plate plays as a front layer to strengthen the energy absorption and protect the epoxy layer. The material model used to simulate the epoxy plate was verified by experimental results to prove its accuracy and efficiency. Impact loading was implemented in the Abaqus model by an impactor nose which has 25 mm diameter. The projectile was assumed at the velocity of 120 m/s. The damage propagated due to the increment of the impact energy was estimated by the Johnson-Holmsquist concrete (JHC) material model in Abaqus. Maximum deflection, the kinetic energy versus internal energy were also investigated in the current article. Based on the obtained result, the Epoxy material combined with UHPC material was proved to be a potential application in impact resistance design.

Keywords: ultra high performance concrete (UHPC); epoxy, composite plate; carbon-fiber; impact.

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1. Introduction

The composite structures under impact action and energy absorption have recently received much attention. Due to the application of these structures increasing rapidly with strict technical requirements, the idea of utilizing new materials with various layers is bonded to strengthen the loading capacity of the composite structure. Epoxy Composite layers are significantly important in the field of high energy absorbance to replace steel armor layers subjected to impact loading. This field relates to the applications of the structures which possess high specific strength and superior damage tolerance. Considering impact loading, the damage performance of composite laminate under impact loading is an important research topic that deserves investigation. A few studies of composite laminate under impact loading were carried out. Ulven et al. conducted a few tests to investigate the relation between the geometry of the projectile and the damage state of the composite panels made from carbon/epoxy material under the ballistic impact [1]. The parametric studies including perforation mechanism and damage state were implemented in the study. Using the simulation method, Huang and Lee investigated the performance of Curvature Carbon Epoxy panels under the velocity impact [2]. The obtained results are positive, however, the quasi-static analysis used in the study seems to be not enough to capture the behavior of the composite structure under dynamic load. In general, a dynamic explicit analysis in simulation combined with advanced material models is necessary. Aslan et al. conducted the tests to study the effect of dimension on the impact response of epoxy laminated composite plates under the velocity impact. They concluded that the response of composite structures almost depends on their in-plane dimensions [3]. Asaee et al. conducted the tests to study the performance of various combinations of hybrid laminates subjected to velocity impact loading using an impact testing

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machine. The parameters including target size, projectile diameter, and test temperature were considered in these studies. The results of these studies showed that the impact resistance of the composite structure is proportional to the thickness of the layers [4].

Ultra-High Performance Concrete (UHPC) is one of the advanced construction materials. UHPC has superior properties like high strength in tension/compression, high durability [5–9]. Moreover, UHPC has been demonstrated to show greater energy absorption and dissipation than conventional concrete [10–12]. These characteristics make UHPC structures become potential designs subjected to the blast and impact. The main objective of the article is to study the impact resistance of the epoxy laminate strengthened by the UHPC layer. The obtained results from this study demonstrated the effectiveness of the composite laminate combined from different materials to resist impact loading.

2. Material model

Concrete is considered as a complicated material due to its behavior. Particularly under dynamic load, concrete material's properties can be changed by high strain rate and overloading [13]. A proper model in the simulation must not only capture the elastic and plastic behavior of concrete material but also the changes under dynamic load. The Finite Element Method (FEM) has become a crucial tool in structural engineering. The outstanding performance of the simulation model enables researchers to capture accurately the complicated behavior of the structure under dynamic load-like impact. There are several models that can be utilized to simulate concrete material, such as Concrete Damaged Plasticity [14], Concrete Smeared Cracking [15], Drucker Prager [16], and the Johnson-Holmsquist concrete (JHC) model [17]. Among them, the Johnson-Holmsquist concrete (JHC) model is particularly noteworthy [18]. The JHC material model is suitable for material with brittle properties under impact loading, which generates large strains and high pressures. The concepts form the JHC: pressure depends on yield surface and damaged state. The relation between the pressure and volume is implemented by the equation of state with the nonlinear behavior.

The basic concept of the JHC model can be described follows:

$$\sigma^* = A(1-D) + BP^{*N})[1 + C\ln(\dot{\varepsilon}/\dot{\varepsilon}_0)] \tag{1}$$

where A, B, and C are the material constants; N is obtained by fitting the model to test value; $\dot{\varepsilon}, \dot{\varepsilon}_0$ defines the plastic strain rate and reference strain rate. The parameter D, from 0 to 1 is a scalar damage variable that express the damage state of a material. Damage variables are accumulated by the volumetric plastic strain $\Delta_{\mu pl}$ and equivalent plastic strain which $\Delta_{\varepsilon pl}$ by the equation:

$$D = \sum \frac{\Delta\varepsilon_p + \Delta\mu_p}{\varepsilon_p^f + \mu_p^f} \tag{2}$$

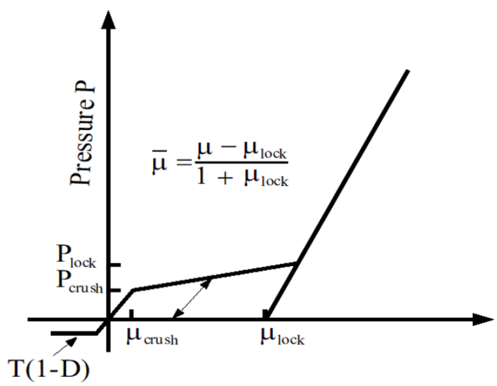


Figure 1. Hydrostatic pressure and volumetric strain of material in JHC model

where $\Delta\varepsilon_p, \Delta\mu_p$ define the increase of plastic strain and plastic volumetric strain, which can be defined follows:

$$\varepsilon_p^f + \mu_p^f = D_1(P^* + T^*)^{D_2} \tag{3}$$

where P^* and T^* define the normalized pressure and normalized tensile strength, respectively; The damage parameters D_1 and D_2 can be defined from the test data.

Fig. 1 shows the relation of hydrostatic pressure and volumetric strain in JHC model. P_{crush} and μ_{crush} denotes the pressure and volumetric strain increment; T presents the maximum tensile stress; $\mu = \rho/\rho_0 - 1$; ρ and ρ_0 determine the current density and the reference density; μ_{lock} is the locking volumetric strain and P_{lock} is the locking pressure.

Pressure and the volumetric strain can be defined follows:

$$P = K_1\overline{\mu} + K_2\overline{\mu}^2 + K_3\overline{\mu}^3 \tag{4}$$

where: K_1, K_2, K_3 are the material constants.

3. Results and discussion

3.1. Validation of simulation model

This section includes the validation of the FE model to assure that the selection model has been accurately implemented and is thereby further utilized to investigate the parametric studies. Two simulation models of the Epoxy laminate under low-velocity impact are performed. The simulation results are compared with the experiment of Chandekar et al. [19]. Expoxy fibers are oriented in two directions of 0° and 90°. The input parameters of the Epoxy material are listed in Table 1. The Epoxy laminate with the dimension of 152 mm × 152 mm is impacted by a steel projectile with a diameter of 12.7 mm. In the tests of Chandekar, the weight of the projectile is over 5 kg, which is depicted in Fig. 1(a). The proposed simulation model is compared with cases No. 2 and No. 4 in the test of Chandekar, in which, the drop height of the projectile is 0.1 m and 0.2 m, corresponding to the thickness of the Epoxy layer is 5.31 mm and 5.33 mm, respectively.

Table 1. Input parameters of Epoxy material [19]

Property	Warf (0°)	Weft (90°)
Young modulus $E_a; E_b; E_c$ (GPa)	38.3; 10.6; 10.6	10.6; 38.3; 10.6
Shear modulus $G_{ab}; G_{bc}; G_{ca}$ (GPa)	3.96; 2.45; 3.96	3.96; 3.96; 2.45
Poisson's ratio $Pr_{ab}; Pr_{bc}; Pr_{ca}$	0.0787; 0.0787; 0.0426	0.285; 0.4206; 0.0787
Density (kg/m^3)	11.74	11.74

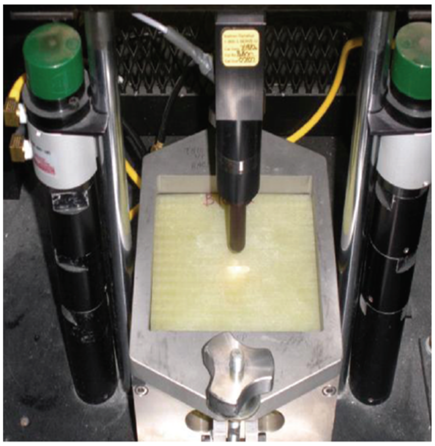
Table 2 lists the parameters for the experiment of Chandekar and the simulatio model. In order to reduce the computational time, only half of the Epoxy laminate and projectile is simulated. According to the observed data in Figs. 3(a), 3(b), and Table 2, it can be seen that the calculated results reveal a good agreement with the experimental data of Chandekar. The disparity of maximum impact load between Chandekar's test and simulation model is 11.2% and 8.7%, respectively. Due to the influence of parameters in the experimental process and simulation model, these values can be acceptable for dynamic analysis models.

Table 2. Impact load versus time in the test of Chandekar and simulation model

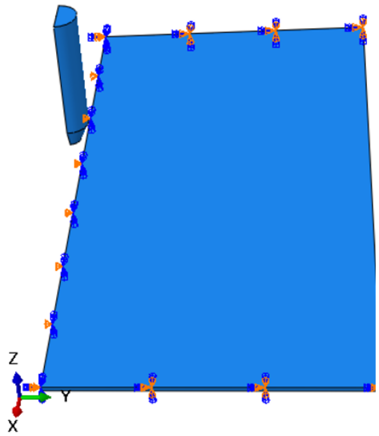
Case	Drop height (m)	Laminate thickness (mm)	Impact velocity (m/s)	Max. impact load (N) (1)	Max. impact load (N) (2)	Disparity (%)
1	0.1	5.11	1.36	2865.3	3186.5	11.2
2	0.2	5.33	1.92	4323.9	4702.7	8.7

Note: (1) - Chandekar's test; (2) - Simulation

Figs. 3(c) to 3(f) show the damage state of Epoxy laminate in the test and simulation. The damage index of laminate models is determined over the range $0 \leq D \leq 1$. Where the value of zero corresponds



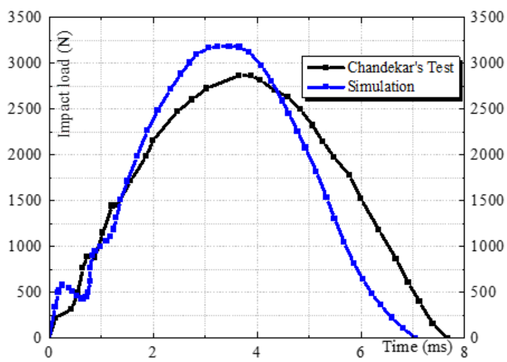
(a) Test of Chandekar



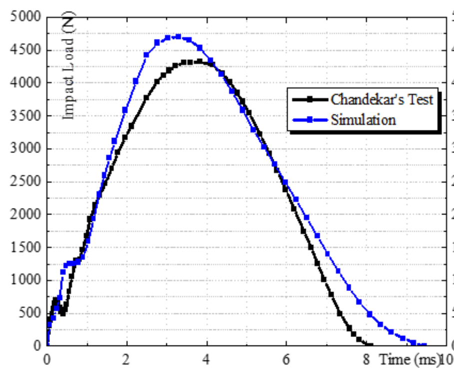
(b) Simulation model in Abaqus

Figure 2. Simulation model validation

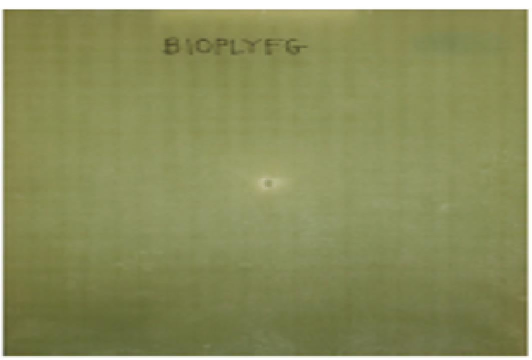
to the case of no damage, the value of 1 (red colour) defines the most serious damage of structure. Damage level increases with an increment in the large drop height, which results in a higher maximum impact load. In the semi-translucent Epoxy thin plate, the damage can be easily observed by the naked eye.



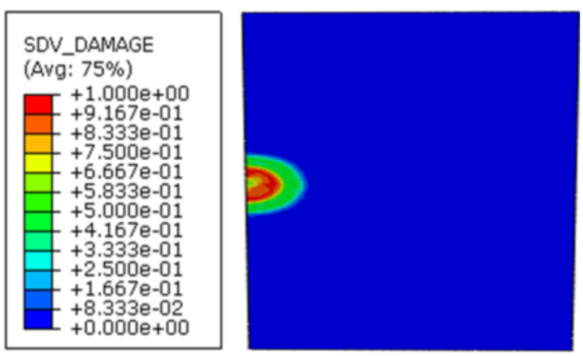
(a) Impact load - time curve in the test and simulation (case 1)



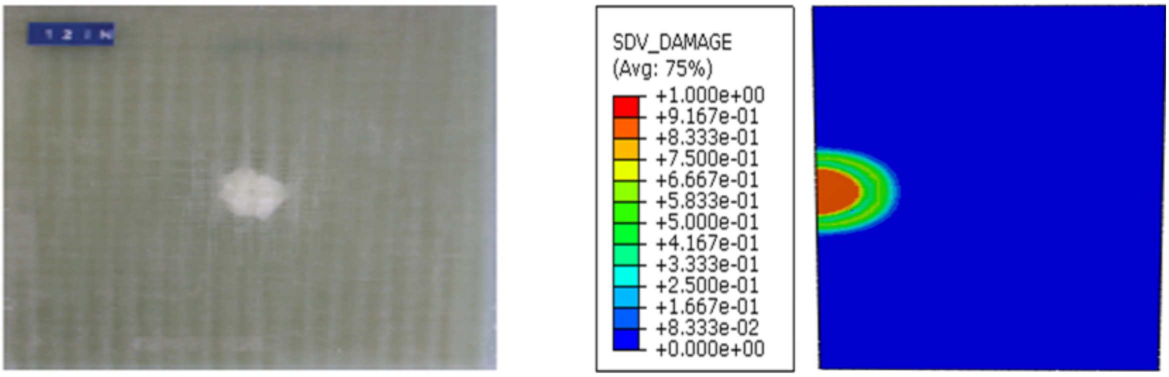
(b) Impact load - time curve in the test and simulation (case 2)



(c) Damage state of the plate in the test (case 1)



(d) Damage state of the plate in the simulation (case 1)



(e) Damage state of the plate in the test (case 2)

(f) Damage state of the plate in the simulation (case 2)

Figure 3. Results according to the test [19] and simulation

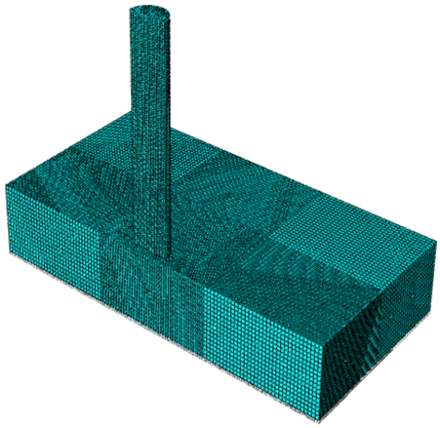
3.2. Extensive parametric study

In this section, an extensive parametric study is implemented to estimate the structural behavior of composite laminate subjected to a projectile. The composite plate contains UHPC thin plate and an Epoxy layer. The thickness of the UHPC plate is 60 mm while the Epoxy laminate has a thickness of 5 mm. The flat nose projectile has a length of 160 mm and 25 mm in diameter.

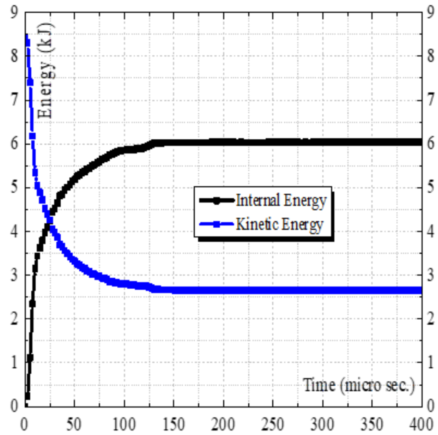
Table 3. Material parameters of UHPC [20]

Variable	Description	UHPC
ρ (Ton/mm^3)	Density	2.55e^{-9}
f_c (Mpa)	Compressive strength	156
G (MPa)	Shear Modulus	33200
A	Material Constant	0.79
B	Material Constant	1.6
N	Material Constant	0.61
D1	Damage constant	0.05
D2	Damage constant	1
μ_{lock}	Locking volumetric strain	0.1
P_{crush} (MPa)	Pressure arising in a uniaxial compression test	19
μ_{crush}	Volumetric strain in a compression test	0.0001
K_1 (MPa)	Equation of State Constant	8500
K_2 (MPa)	Equation of State Constant	17100
K_3 (MPa)	Equation of State Constant	20800

The UHPC laminate contains two layers of steel bars placed in vertical and horizontal directions. The steel bar has a diameter of 8 mm and the depth of the cover layer is 12 mm. Compared to the spacing of the reinforced steel bar, the diameter of the projectile is much smaller, so it does not affect the behavior of the composite laminate under impact loading [21]. The material behavior of UHPC and steel projectile are described by the JHC model and Johnson-Cook (JC) model. These models are available in ABAQUS [22, 23]. The C3D8R element with reduced integration and hourglass control in the simulation model are assigned for steel projectile, UHPC, and Epoxy plate. The velocity of the projectile is 120 ms/s as an initial condition in the simulation model. A 1.5 mm mesh is established at the center of the plate (impact region) whereas the rest has a mesh of 3 mm. Table 3 shows the input parameters for UHPC material [20]. Fig. 4(a) shows the full 3D simulation model of UHPC Epoxy laminate.



(a) 3D mesh simulation model



(b) Internal energy - Kinetic energy of the model

Figure 4. Simulation result

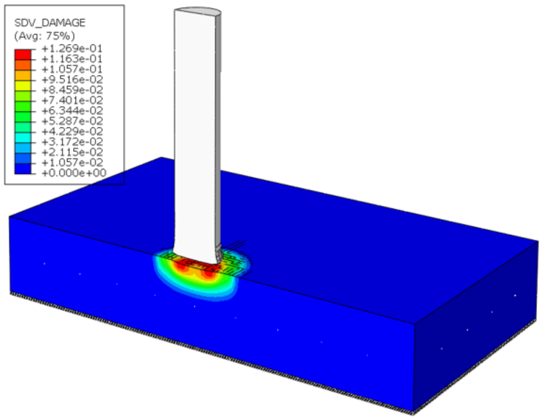
Epoxy adhesives are used to connect the UHPC plate and the epoxy laminate. Epoxy adhesives can be considered as one of the most efficient adhesives and therefore often utilized as structural, loading capacity and properties due to its advantages to adhere to many different types of surfaces [24]. Furthermore, high durability to resist fluid, thermal and chemical attack is another outstanding property of this adhesive. In Abaqus, the interaction between the UHPC plate and Epoxy laminate is applied by the surface-to-surface interaction, in which adhesive properties are shown in Table 4 [25].

Table 4. Properties of adhesive in simulation [25]

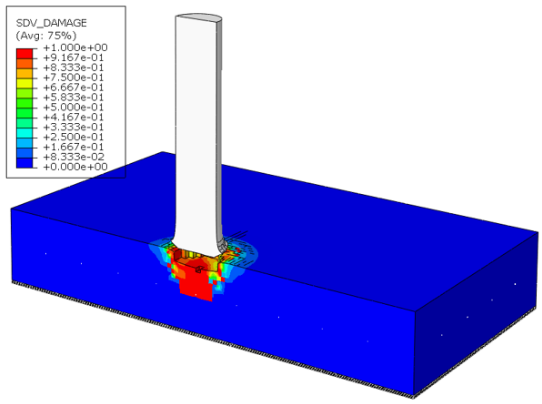
Variable	Description	Value
E (GPa)	Young's modulus	17.24
G (GPa)	Shear modulus	0.665
f_s (Mpa)	Shear strength	2.84
K (N/mm^3)	Stiffness coefficients	$K_{nn} = 172400, K_{ss} = K_{tt} = 6650$

Fig. 4(b) depicts the internal energy and the kinetic energy of the simulation model with the 120 m/s of impact velocity. The kinetic energy of the projectile is determined by its mass and velocity. At the first time corresponding to a velocity of 120 m/s, the maximum kinetic energy of the projectile is 8.4 kJ. After impacting the UHPC plate, the kinetic energy of the projectile decreases gradually. At the step time of contacting the Epoxy laminate, the kinetic energy of the projectile is 2.6 kJ. On the contrary, the internal energy of the simulation model increases from 0 to 6.1 kJ. It can be seen that the UHPC plate absorbs most of the energy of the impact while the epoxy layer absorbs the rest. The estimation of the energy enables the definition of the maximum impact values of composite laminate without perforation.

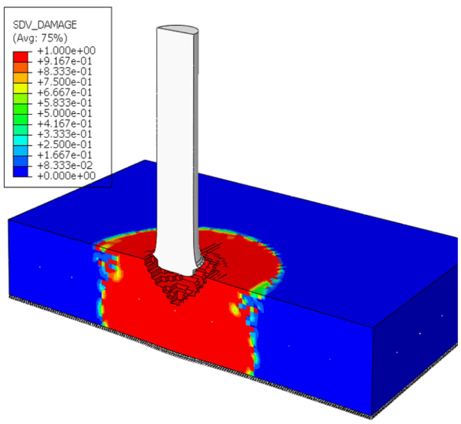
Fig. 5 shows the damage state of the UHPC Epoxy plate during the penetration of the projectile under the velocity of 120m/s. As shown in Eq. (2), damage assessment of material is accumulated by the volumetric plastic strain and equivalent plastic strain. The damage index in the simulation model is defined over the range $0 \leq D \leq 1$. Where the value of zero corresponds to the case of no damage, the value of 1 (red color) shows the most serious damage to the structure. It can be seen that the damage in the UHPC layer starts at the impact region and later on increases significantly with the propagation of the fracture around this region. At time $t = 8e^{-5}$ sec., the compressive wave passes through the UHPC layer. And the tensile wave propagates in the free region in the middle of the UHPC layer. The tensile wave leads to an increment in the damage state around the impact region. It can also be seen that the projectile penetrates the UHPC layer at $t = 3.6e^{-4}$ sec.



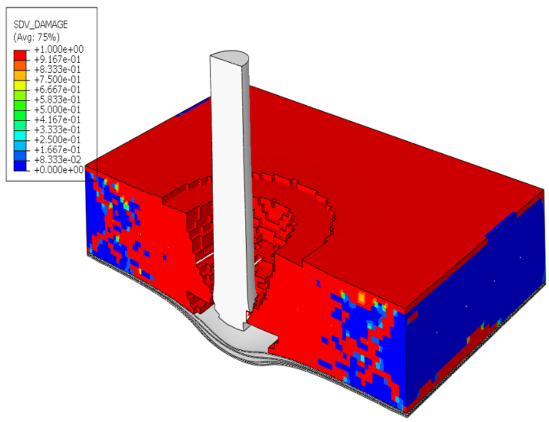
(a) $t = 8e^{-5}$ sec.



(b) $t = 1.5e^{-4}$ sec.



(c) $t = 2e^{-4}$ sec.



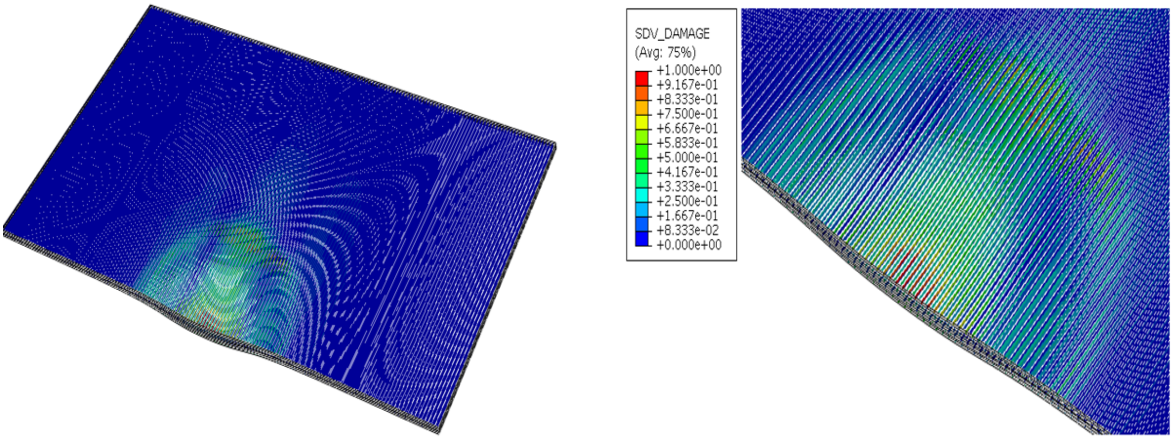
(d) $= 3.6e^{-4}$ sec.

Figure 5. Damage state of UHPC layer during impact process

Table 5. Severe damage state of the UHPC Epoxy laminate after the impact

Impact velocity (m/s)	UHPC layer (%)	Epoxy layer (%)
120	38.3	8.5

Fig. 6(a) describes the damage state of Epoxy laminate after the impact. Many local damage points in the Epoxy laminate near the impact area can be observed. However, the Epoxy laminate is not completely damaged. The projectile penetrates the UHPC layer but can not pass the Epoxy laminate. A close-up view of the damage state in the Epoxy laminates exhibits the matrix cracking and fiber breakage phenomenon (Fig. 6(b)). This can be related to the energy absorption mechanisms. This result demonstrates the high impact loading resistance of Epoxy material. Table 5 summarizes the damage state of UHPC Epoxy laminate after the impact. The damage level of the UHPC layer and the Epoxy layer is 38.3% and 8.5%, respectively. The damage state of the UHPC layer is not only focused on the impact area but also propagated over the whole cross-section. On the contrary, the Epoxy layer has a considerably smaller damage state and it is mainly concentrated around the impact area. This result can be explained by the plasticity of the Epoxy material.



(a) In overall view

(b) In close-up view

Figure 6. Damage state of Epoxy laminate after impact

Fig. 7 depicts the velocity of the projectile during the impact after the first velocity of 120 m/s. The initial velocity of the projectile decreases gradually after penetrating the UHPC layer. At t = $3.6e^{-4}$ sec., the projectile penetrates completely through the UHPC layer. At that time, Epoxy laminate plays an important role as a barrier to dissipate the energy of the projectile. The velocity of the projectile reduces from 21.6 m/s to 0 (18%) revealing that Epoxy possesses high impact resistance.

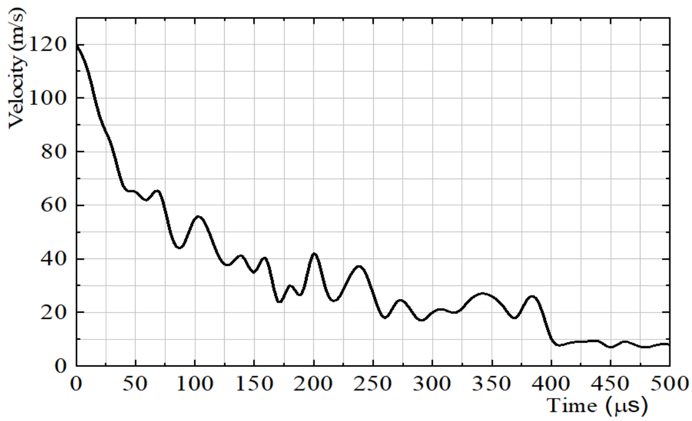


Figure 7. Velocity of projectile during impact process

4. Conclusions

In the present study, the structural behavior of composite laminated by UHPC and Epoxy was investigated numerically. The simulation model was validated by the experimental result of the Epoxy laminate under the low-velocity impact. From the results, the following conclusions can be drawn:

- The Epoxy laminate with a thickness of 5 mm reduces 20% the velocity of the projectile. Epoxy material is proved to be highly resistant to impact and is strongly recommended for impact-resistant designs.

- After the impact, compared to highly brittle material like UHPC, Epoxy material shows a smaller level of damage state, mainly distributing around the impact region.

- The results obtained from this study open a new direction to design laminated structures with greater impact resistance, where the Epoxy layer plays the role of backing material and the UHPC layer protects the Epoxy laminate from serve damage.

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