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# **Experimental-numerical study on minimizing impact induced damage in laminated composites under low velocity impact**

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## **Abstract**

In this study, an experimentally validated numerical analysis was performed toward optimization of stacking sequence in multidirectional laminated composites subjected to low velocity impact. For this purpose, an optimization program was developed by integrating Finite Element Method (FEM) and Multi Objective Genetic Algorithm (MOGA) using modeFRONTIER. In this regard, three objective functions were defined; one, based on Hashin failure theory and two others based on interlaminar shear and tensile stresses. These objective functions were aimed to be optimized through tailoring ply angles with special focus on minimizing impact induced damage. The obtained results indicated that the proposed optimization method is an effective tool for optimizing stacking sequence of laminated fiber reinforced composite materials.

**Keywords:** Composite materials; Optimization; Impact induced damage; Finite Element Analysis (FEA).

## 1. Introduction

Fiber reinforced polymers (FRP) are extensively used in various engineering fields, especially in aerospace, military and automotive industries due to their high specific strength and stiffness, good fatigue performance, great corrosion resistance, etc. However, different damage mechanisms such as: matrix cracking, fiber breakage and fiber/matrix debonding affect load bearing capacities and operational life of these materials [1-6]. Hence, it is very important to investigate composite materials behavior and corresponding failure modes under various loading conditions. One of the most critical loading conditions is impact event which is a sophisticated phenomenon since it involves a very complex stress distribution in the material, e.g., inter-laminar shear stress inside the laminate, compression at the top, tension at the bottom and contact stress just behind the projectile [7,8]. Furthermore, impact loading causes barely visible impact damage (BVID) which can't be easily detected and significantly reduces strength and stiffness of composite materials. In recent years, a wide variety of experimental, numerical and analytical studies have been conducted to investigate impact induced damage in composite materials [7-

Abisset et al. [7] conducted scaled indentation experiments on quasi-isotropic composite plates and evaluated damage evolution by means of non-destructive methods such as X-ray computed tomography and ultrasonic scanning. The results revealed similar damage patterns for the scaled plates. It was shown that geometrical parameters, stacking sequences and the ply block thickness are the most important factors influencing the damage patterns. The degree of geometric nonlinearity was also found to be important, mainly affecting the delamination amount and corresponding critical load. Lopes et al. [8] followed their previous experimental work to investigate the scaling effect in more detail using finite element method. They simulated progressive failure behavior of matrix, fibers and interfaces between the plies by means of physically based constitutive material models. The comparison between the numerical and experimental results indicated a high reliability of FEM in predicting the impact dynamics, impact footprint, locus and size of various damage mechanisms such as delamination, fiber damage and matrix cracking, as well as the energy amount dissipated by delamination, intra-ply damage and friction.

Xu et al. [9] performed a numerical/experimental study on scaling effects in CFRP composites subjected to low velocity impact. According to their results, the elastic response of the composite plates obeys a scaling law, while damage does not scale in accordance with that predicted by simple scaling laws. Assessment of the damaged specimens showed that for specified scaled impact energy, fiber damage was greater in the larger samples in the form

of large cracks in the warp and weft directions. However, only small levels of delamination were shown in these specimens because of the highly toughened epoxy resin. It was also demonstrated that the fracture energy associated with fiber failure scales with the square of scale size,  $n^2$ , while the initial impact energy scales as  $n^3$ .

Chambers et al. [10] experimentally studied impact induced damage in CFRP composites using fiber optic sensors. Based on their results, by means of a panel containing an array of closely located sensors, impact consequences can be accurately detected. Zhang et al. [11] investigated damage development and dynamic mechanical response of cross-ply composite laminates under low velocity impact condition. Based on continuum damage mechanics, they numerically investigated force-displacement, force-time and energy-time history curves along with the damage propagation behaviors of delamination and matrix cracking. Comparison between the numerical and experimental results demonstrated acceptable accordance, indicating high efficiency of the proposed FE model. Shi et al. [12] modeled intra- and inter-laminar cracking mechanisms in carbon/epoxy composite plates subjected to impact loading. The impact force and energy predicted by FE model were in a good agreement with experimental findings. Wisnom et al. [13] numerically evaluated discrete transverse cracks in polymer composites by means of cohesive zone interface elements. Through combining stress-based and fracture mechanics approaches, they could accurately predict initiation and propagation of different damage modes. Olsson et al. [14] analytically investigated dynamic impact event in composite plates. Using dynamic solution, they developed a delamination threshold load by considering inertial effects in delaminated sub-laminates.

Rahul et al. [15] applied FEM and genetic algorithm for minimizing cost and weight of the laminated composites. They used delamination and matrix cracking as failure criteria for optimization process, without investigating fiber breakage. Khedmati et al. [16] investigated stacking sequence optimization of composite panels under slamming impact loading for minimizing central deflection of the panels. Lopez et al. [17] studied optimization of hybrid laminated composites under *buckling loading*. They used maximum stress, Tsai-Wu and Puck failure criteria for optimization task. Kalantari et al. [18] investigated optimization of unidirectional hybrid composites under *bending loading* with the aim of minimizing the weight and the cost of the composite plates subjected to the constraint of a predetermined minimum flexural strength. Jacob et al. [19] studied multi-objective optimization of composite *pressure vessels* based on Tsai-Wu failure criterion for minimizing mass and maximizing the axial and hoop strength. Burn et al. [20] used bio-inspired design approach for strength improvement of composite T-joints under *bending loading* by means of modeFRONTIER software. Their optimization problem had only a single objective of minimizing the peak

interlaminar tensile strength, as the most important factor for delamination. According to the above mentioned literature, there are only a few studies in the field of composites optimization for “*impact loading*” conditions [14, 15], and in these studies different objective functions and design variables have been examined for optimization of composite materials. To the best of the authors’ knowledge, Hashin failure theory hasn’t been used so far as an objective function or the design constraint of the optimization process. Hashin criterion is a comprehensive criterion that considers different failure modes of: fiber tension, fiber compression, matrix tension and matrix compression. However, the theory doesn’t consider delamination damage mode. Hence, in this research, beside Hashin criterion, two other objective functions were defined to take into account all probable damage modes of laminated composites. Indeed, Hashin criterion was applied to account for matrix cracking and fiber breakage damage mechanisms, while interlaminar shear and tensile stresses were employed to consider delamination damage mode. Then these objective functions were aimed to be minimized by tailoring ply angles through integration of finite element method and genetic algorithm. For this purpose, an optimization program was developed based on finite element method and genetic algorithm using modeFRONTIER software. The main goal of the present study is to optimize stacking sequence of carbon/epoxy composites subjected to low velocity impact with the special focus on minimizing impact induced damage.

## **2. Experimental set-up**

The specimens used in this work are IM7/8552 composite plates made up of epoxy resin reinforced by carbon fibers with nominal volume fraction of 57.7%. The impact tests were performed based on ASTM D7136 standard [21]. For this purpose, composites plates were prepared in a rectangular shape with the dimensions of 150 mm \* 100 mm \* 1 mm. The plates comprise eight plies with nominal cured ply thickness of 0.125 mm, oriented by various stacking sequences in the form of  $[\theta_1/ \theta_2/ \theta_3/ \theta_4]_s$ , where  $\theta_i$  is the ply angle determined by optimization program. The layup orientations were considered symmetric to avoid mechanical coupling between extensional and bending loadings. The specimens were restrained using four clamps and the tests were conducted by using a hemispherical steel impactor with a diameter of 16 mm and a hardness of 62 HRC. The experimental set-up is shown in Figure 1.

“[Insert Figure 1]”

### 3. Finite element simulation

#### 3.1. Material model

The composite plates were regarded as homogenous materials with orthotropic linear elastic behavior before damage initiation. The material constitutive model prior to damage initiation was defined as follows:

$$\boldsymbol{\sigma} = \mathbf{C}_0 \boldsymbol{\varepsilon} \quad (1)$$

where:

$$\mathbf{C}_0 = \begin{bmatrix} E_1(1-v_{23}v_{32})\Gamma & E_1(v_{21}+v_{23}v_{31})\Gamma & E_1(v_{31}+v_{21}v_{32})\Gamma & 0 & 0 & 0 \\ E_1(v_{21}+v_{23}v_{31})\Gamma & E_2(1-v_{13}v_{31})\Gamma & E_2(v_{32}+v_{12}v_{31})\Gamma & 0 & 0 & 0 \\ E_1(v_{31}+v_{21}v_{32})\Gamma & E_2(v_{32}+v_{12}v_{31})\Gamma & E_3(1-v_{12}v_{21})\Gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{12} \end{bmatrix} \quad (2)$$

where,  $E_i$  is Young's modulus in  $i$  direction,  $v_{ij}$  is Poisson's ratio and  $G_{ij}$  is shear modulus in  $i$ - $j$  plane.  $\Gamma$  is a constant defined as:

$$\Gamma = \frac{1}{1-v_{12}v_{21}-v_{23}v_{32}-v_{13}v_{31}-2v_{21}v_{32}v_{13}} \quad (3)$$

The damage initiation criterion was specified based on 3D Hashin failure theory and the damage evolution law was determined based on the fracture energy dissipation concepts. The 3D Hashin criterion was implemented via user defined subroutine VUMAT. This criterion considers four damage modes, namely, fiber compression, fiber tension, matrix compression and matrix tension modes according to Eqs. (4)-(7) as follows [22]:

- Fiber compression mode ( $\sigma_{11} < 0$ ):

$$d_{fc} = \left( \frac{\sigma_{11}}{X_c} \right)^2 \quad (4)$$

- Fiber tension mode ( $\sigma_{11} \geq 0$ ):

$$d_{ft} = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 \quad (5)$$

- Matrix compression mode ( $\sigma_{22} + \sigma_{33} < 0$ ):

$$d_{mc} = \left[\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right] \left(\frac{\sigma_{22} + \sigma_{33}}{Y_c}\right) + \left(\frac{\sigma_{22} + \sigma_{33}}{2S_{23}}\right)^2 + \left(\frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2}\right) + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2}\right) \quad (6)$$

- Matrix tension mode ( $\sigma_{22} + \sigma_{33} \geq 0$ ):

$$d_{mt} = \left(\frac{\sigma_{22} + \sigma_{33}}{Y_t}\right)^2 + \left(\frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2}\right) + \left(\frac{\sigma_{12}^2 + \sigma_{13}^2}{S_{12}^2}\right) \quad (7)$$

Where,  $\sigma_{ij}$  are stress tensor components,  $X_t$  and  $X_c$  are longitudinal tensile and compressive strengths,  $Y_t$  and  $Y_c$  are transverse tensile and compressive strengths,  $S_{12}$ ,  $S_{13}$  and  $S_{23}$  are in-plane and out-of-plane shear strengths, respectively.  $d_{fc}$  and  $d_{ft}$  are damage indexes corresponding to fiber damage and  $d_{mc}$  and  $d_{mt}$  are damage indexes corresponding to matrix damage under compression and tension, respectively.

The global damage indexes for fiber and matrix ( $d_f$  and  $d_m$ ) are defined as:

$$\begin{aligned} d_f &= 1 - (1 - d_{ft})(1 - d_{fc}) \\ d_m &= 1 - (1 - d_{mt})(1 - d_{mc}) \end{aligned} \quad (8)$$

After damage initiation, the material constitutive model is given by:

$$\boldsymbol{\sigma} = \mathbf{C}_d \boldsymbol{\varepsilon} \quad (9)$$

Where,  $\mathbf{C}_d$  is the damaged stiffness matrix defined as:

$$\mathbf{C}^d = \begin{bmatrix} C_{11}^d & C_{12}^d & C_{13}^d & 0 & 0 & 0 \\ C_{12}^d & C_{22}^d & C_{23}^d & 0 & 0 & 0 \\ C_{13}^d & C_{23}^d & C_{33}^d & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}^d & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}^d & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}^d \end{bmatrix} \quad (10)$$

where:

$$\begin{aligned} C_{11}^d &= (1-d_f) E_1 (1-\nu_{23}\nu_{32}) \Gamma \\ C_{12}^d &= (1-d_f)(1-d_m) E_1 (\nu_{21} + \nu_{31}\nu_{23}) \Gamma \\ C_{13}^d &= (1-d_f)(1-d_m) C_{13} \\ C_{22}^d &= (1-d_f)(1-d_m) E_2 (1-\nu_{13}\nu_{31}) \Gamma \\ C_{23}^d &= (1-d_f)(1-d_m) E_2 (\nu_{32} + \nu_{12}\nu_{31}) \Gamma \\ C_{33}^d &= (1-d_f)(1-d_m) E_3 (1-\nu_{12}\nu_{21}) \Gamma \\ C_{44}^d &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc}) G_{12} \\ C_{55}^d &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc}) G_{23} \\ C_{66}^d &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc}) G_{13} \end{aligned} \quad (11)$$

Where,  $C_{ij}^d$  and  $C_{ij}$  denote damaged and undamaged tensor coefficients, respectively.  $s_{mt}$  and  $s_{mc}$  are constant coefficients corresponding to shear stiffness loss due to matrix failure under tension and compression, respectively [23].

Material properties of IM7/8552 composite are summarized in Table 1 [24].

**Table 1.** Material properties of IM7/8552 [24].

$E_1$ (GPa)	161	$\nu_{23}$	0.436
$E_2$ (GPa)	11.4	$X_t$ (MPa)	2806
$E_3$ (GPa)	11.4	$X_c$ (MPa)	1690
$G_{12}$ (GPa)	5.17	$Y_t$ (MPa)	60



$G_{13}$ (GPa)	5.17	$Y_c$ (MPa)	185
$G_{23}$ (GPa)	3.98	$S_{12}$ (MPa)	90
$\nu_{12}$	0.32	$S_{13}$ (MPa)	90
$\nu_{13}$	0.32	$S_{23}$ (MPa)	90

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### 3.2 FE model

Finite element simulation of the impact event was carried out using general purpose finite element package ABAQUS/Explicit. Due to the symmetry of the problem, only quarter of the specimen was modeled to reduce the computational cost, by properly defining symmetry planes as shown in Figure 2. In order to increase the efficiency of the FE model, a finer mesh was applied in the impact region, while a coarser mesh was utilized in the area away from the impact zone. The optimum element size was determined by performing preliminary convergence studies based on the trial and error method. The impactor was modeled as a rigid body and initially positioned to be in contact with the top surface of the composite plate, just right in the center of the specimen with initial velocity of 1.414 m/s in the direction perpendicular to the plate, giving an impact energy of 5 J. The contact between the specimen and impactor was modeled using general contact algorithm available in ABAQUS/Explicit by defining an element set contacting both external and internal faces of the specimen, to ensure that the impactor interacts with interior elements after failure of exterior elements. The contact formulation was defined based on penalty method with friction coefficient of 0.3 between the specimen and the impactor [5].

“[Insert Figure 2]”

## 4. Optimization procedure

The optimization program was developed by integration of FEM model and genetic algorithm in modeFRONTIER software. The main goal of the optimization procedure was to find out the optimum stacking sequences that lead to the least impact induced damage in composite plates. For this purpose, the ply angles were considered as input variables ranging between  $0^\circ$  and  $\pm 90^\circ$  with a  $15^\circ$  step for practical manufacturing. The objective functions were

defined based on the damage indexes of Hashin failure criterion as well as the interlaminar shear and tensile stress components of  $\sigma_{13}$  and  $\sigma_{33}$  as follows:

$$Obj_1 : \min[\sqrt{(d_{fc})^2 + (d_{ft})^2 + (d_{mc})^2 + (d_{mt})^2}] \quad (12)$$

$$Obj_2 : \min[\sigma_{13}] \quad (13)$$

$$Obj_3 : \min[\sigma_{33}] \quad (14)$$

It should be mentioned that the average of the parameters was calculated to evaluate the damage amount in the whole specimen.

The optimization problem has only one constraint that limits the stacking sequences to be symmetric in order to avoid mechanical coupling. The MOGA-II (multi objective genetic algorithm) was used as the optimization solver.

The optimization workflow is illustrated in Figure 3.

“[Insert Figure 3]”

## 5. Results and Discussions

Experimentally measured load-displacement curves were compared with the FE predictions in Figure 4, for the  $[0/90/90/0]_s$  configuration. As shown in this figure, both experimental and numerical results exhibit similar trends, especially in the initial region of the curves, where there is a linear relationship between the load and displacement. However, the load measured by experimental tests is more oscillatory. In the second stage of the impact test, the load suddenly drops and then oscillates around an approximately a constant value. In the final stage, the load gradually decreases until settles to zero. In order to evaluate the performance of the FE model quantitatively, the peak load and maximum displacement predicted by FEM were compared with those of experimental recordings. The peak loads obtained by FE model and experimental tests are 1.687 KN and 1.552 KN, respectively and the maximum displacements recorded by the FE model and experimental tests are 7.41 mm and 7.82 mm, respectively. The results

indicate good correlation between numerical and experimental findings, however, the maximum load predicted by the FEM is a little higher than that recorded by the experimental tests, and the maximum displacement obtained by the FEM is a little lower than that obtained experimentally. This discrepancy can be attributed to the fact that delamination was not directly simulated, which resulted in over-prediction of FE model stiffness and consequently caused higher peak load and lower maximum displacement. It should be mentioned that the effect of delamination was accounted by considering inter-laminar tensile and shear stresses,  $\sigma_{33}$  and  $\sigma_{13}$ .

**“[Insert Figure 4]”**

After validation of the FE model, the optimization program was run by integrating the FEM and genetic algorithm. The aim of the optimization process was to find out the optimum layup orientation that leads to minimum impact induced damage. As mentioned in section 4, the objective was to minimize Hashin failure indexes (Eq. (12)) as well as inter-laminar tensile and shear stresses of  $\sigma_{33}$  and  $\sigma_{13}$ , as the most influential stress components in delamination (Eqs. (13) and (14)). The optimization process was carried out as follows: First, 10 layup orientations were defined as starting set of input variables. Then, FE simulations were performed in ABQUS/Explicit based on these orientations. The outputs of FE simulations (i.e.,  $\sigma_{13}$  and  $\sigma_{33}$  stress components and Hashin damage indexes) were then passed to modeFRONTIER optimization solver (MOGA-II in this study). By evaluating the FE results, the optimization algorithm updated the input variables (i.e. ply angles) in accordance with the objective functions defined by Eqs. (12)-(14). The new updated ply angles were again passed to the FE model and this process was iterated 100 times, fully automatically using modeFRONTIER software. In this regard, 1000 simulations were performed. The optimization results are shown in Figure 5 by means of a 3D bubble chart. In this figure, the mean of  $\sigma_{13}$  and  $\sigma_{33}$  are depicted in x-axis and y-axis, while the Hashin damage factor is illustrated based on the bubble size, the larger the bubble size, the greater the damage factor. The optimum solution lies in the bottom left of the chart (indicating lower  $\sigma_{13}$  and  $\sigma_{33}$ ) with a smaller bubble size (indicating lower damage factor).

**“[Insert Figure 5]”**

The best ten optimum solutions are summarized in Table 2. The results demonstrate mean of  $\sigma_{13}$  and  $\sigma_{33}$  stress components as well as mean of all damage indexes of Hashin failure model individually. Hence, it is straightforward to analyze different stacking sequences from the viewpoint of various failure modes such as: fiber breakage and matrix damage (under compression and tension) as well as delamination.

As seen in Table 2, the stacking sequences of  $[90/90/90/0]_s$  and  $[0/90/90/0]_s$  have the least values of fiber damage factor under compression; the stacking sequences of  $[45/-60/60/45]_s$  and  $[60/90/0/-45]_s$  have the least values of fiber damage factor under tension; the stacking sequences of  $[45/-60/0/90]_s$  and  $[45/-60/60/45]_s$  have the least values of matrix damage factor under compression and stacking sequences of  $[45/-45/45/-45]_s$  and  $[0/90/90/0]_s$  have the least values of matrix damage factor under tension. Considering all of the Hashin failure indexes (i.e. Eq. (12)), the stacking sequences of  $[45/-45/45/-45]_s$  and  $[30/-60/60/-30]_s$  exhibit the best performance. From the viewpoint of delamination damage mode (i.e. inter-laminar stress components of  $\sigma_{13}$  and  $\sigma_{33}$ ), the stacking sequences of  $[45/0/90/-45]_s$  and  $[60/90/0/-45]_s$  have the least values of  $\sigma_{13}$  and the stacking sequences of  $[90/90/90/90]_s$  and  $[0/90/90/0]_s$  have the least values of  $\sigma_{33}$ . Considering all of the objectives (Hashin damage factor,  $\sigma_{13}$  and  $\sigma_{33}$  stress tensors) altogether, the  $[60/90/0/-45]_s$  stacking sequence has the least value of the sum of three objectives, and subsequently was regarded as the best optimum layup orientation.

**Table 2.** Ten optimum stacking sequences.

No	Layup	$d_{fc}$	$d_{ft}$	$d_{mc}$	$d_{mt}$	Obj <sub>1</sub>	Obj <sub>2</sub> : $\sigma_{13}$ (0.1GPa)	Obj <sub>3</sub> : $\sigma_{33}$ (0.1GPa)
1	$[60/90/0/-45]_s$	0.0769	0.0929	0.1363	0.3708	0.4130	0.0901	0.1704
2	$[0/90/90/0]_s$	0.0693	0.1233	0.1413	0.3315	0.3871	0.1388	0.1598
3	$[45/-45/45/-45]_s$	0.0718	0.1212	0.1366	0.3231	0.3780	0.1384	0.2256
4	$[45/-45/-60/60]_s$	0.0814	0.1002	0.1354	0.3445	0.3920	0.1047	0.2661
5	$[45/-60/60/45]_s$	0.0994	0.0907	0.1209	0.3697	0.4116	0.1301	0.2370
6	$[90/90/90/90]_s$	0.0413	0.0978	0.2179	0.4953	0.5515	0.1436	0.1165
7	$[45/0/90/-45]_s$	0.0814	0.0937	0.1334	0.3894	0.4299	0.0887	0.3061
8	$[30/-60/60/-30]_s$	0.0876	0.0991	0.1245	0.3348	0.3809	0.1058	0.3384
9	$[30/-60/45/-45]_s$	0.0809	0.1049	0.1295	0.3426	0.3895	0.1261	0.3174

The FE simulation results for [60/90/0/-45]<sub>s</sub> orientation are illustrated in Figure 6, representing contour plot of Hashin damage indexes (i.e. matrix and fiber damage under tension and compression). For comparison, the contour plot of damage indexes for [0/-30/45/90]<sub>s</sub> orientation is shown in Figure 7. As shown in these figures, the damage severity is much more evident in stacking sequence of [0/-30/45/90]<sub>s</sub> in comparison to [60/90/0/-45]<sub>s</sub> orientation. The damage coefficients of  $d_{fc}$ ,  $d_{ft}$ ,  $d_{mc}$  and  $d_{mt}$  for [0/-30/45/90]<sub>s</sub> orientation are 0.0844, 0.0816, 0.1499 and 0.4596, respectively. For both layup orientations, the damage pattern shows that matrix damage under tension is the most prevailing failure mode, followed by matrix damage under compression, fiber damage under tension and fiber damage under compression, respectively.

“[Insert Figure 6]”

“[Insert Figure 7]”

The maximum damage diameter of these specimens was also calculated. In Figure 8, measurement of damage extent is illustrated based on the experimental impact tests. According to ASTM D7136 standard [20], eight points were located relative to the specimen center and the damage extent was determined based on the maximum distance between these points along the identified lines. Performing the measurements, it was calculated that the maximum damage diameter for [0/-30/45/90]<sub>s</sub> and [60/90/0/-45]<sub>s</sub> orientations are 13.42 mm and 11.07 mm, respectively.

“[Insert Figure 8]”

## 6. Conclusions

In this paper, an optimization program was developed to minimize impact induced damage in IM7/8552 composite plates. For this purpose, genetic algorithm and FEM were integrated by means of modeFRONTIER software. First, the accuracy of FE model was validated through comparing the load-displacement curve of the composite plates obtained by the experimental tests and the FE simulations. The comparison revealed good agreement between the numerical and experimental results, both quantitatively and qualitatively. After validation of the FE model, the optimization program was run in order to find out the optimum layup orientation that leads to minimum amount of damage. The damage amount was evaluated based on the values of Hashin damage indexes as well as the inter-laminar shear and tensile stresses, as the most important factors affecting delamination. The obtained results indicate that the stacking sequences of  $[90/90/90/0]_s$  and  $[0/90/90/0]_s$  have the least values of fiber damage factor under compression; the stacking sequences of  $[45/-60/60/45]_s$  and  $[60/90/0/-45]_s$  have the least values of fiber damage factor under tension; the stacking sequences of  $[45/-60/0/90]_s$  and  $[45/-60/60/45]_s$  have the least values of matrix damage factor under compression and stacking sequences of  $[45/-45/45/-45]_s$  and  $[0/90/90/0]_s$  have the least values of matrix damage factor under tension. Considering all of the Hashin failure indexes, the stacking sequences of  $[45/-45/45/-45]_s$  and  $[30/-60/60/-30]_s$  exhibit the best performance. From the viewpoint of delamination damage mode (i.e. inter-laminar stress components of  $\sigma_{13}$  and  $\sigma_{33}$ ), the stacking sequences of  $[45/0/90/-45]_s$  and  $[60/90/0/-45]_s$  have the least values of  $\sigma_{13}$  and the stacking sequences of  $[90/90/90/90]_s$  and  $[0/90/90/0]_s$  have the least values of  $\sigma_{33}$ . Considering all of the objectives altogether, the  $[60/90/0/-45]_s$  stacking sequence was regarded as the optimum layup orientation.

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## **References**

- [1] Sevkat E. Experimental and numerical approaches for estimating ballistic limit velocities of woven composite beams. *Int J Impact Eng* 2012; 45:16–27.
- [2] Kolor SSR, Ayatollahi MR and Tamin MN. Elastic-damage deformation response of fiber-reinforced polymer composite laminates with lamina interfaces. *J Reinf Plast Comp* 2017; 36(11): 832–849.

- [3] Pashmforoush F, Fotouhi M and Ahmadi M. Damage Characterization of Glass/Epoxy Composite Under Three-Point Bending Test Using Acoustic Emission Technique. *J Mater Eng Perform* 2012; 21(7): 1380–1390.
- [4] Vu VD, Sheikh AH, Nguyen GD, et al. A kinematically enhanced constitutive model for elastic and inelastic analysis of unidirectional fibre reinforced composite materials. *Int J Mech Sci* 2017; 126: 171–185.
- [5] Sun XC, Wisnom MR and Hallett SR. Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 2 – Numerical simulation. *Compos Struct* 2016; 136: 727–742.
- [6] Xu Z, Yang F, Guan ZW, et al. An experimental and numerical study on scaling effects in the low velocity impact response of CFRP laminates. *Compos Struct* 2016; 154: 69–78.
- [7] Abisset E, Daghia F, Sun XC, et al. Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 1 – Experiments. *Compos Struct* 2016; 136: 712–726.
- [8] Chambers AR, Mowlem MC and Dokos L. Evaluating impact damage in CFRP using fibre optic sensors. *Compos Sci Technol* 2007; 67(6): 1235–1242.
- [9] Gower HL, Cronin DS and Plumtree A. Ballistic impact response of laminated composite panels. *Int J Impact Eng* 2008; 35(9):1000–1008.
- [10] Lopes CS, Camanho PP, Gürdal Z, et al. Low-velocity impact damage on dispersed stacking sequence laminates. Part II: Numerical simulations. *Compos Sci Technol* 2009; 69(7-8): 937–947.
- [11] Shi Y, Pinna C and Soutis C. Modelling impact damage in composite laminates: A simulation of intra- and inter-laminar cracking. *Compos Struct* 2014; 114: 10–19.
- [12] Wisnom MR. Modelling discrete failures in composites with interface elements. *Composites: Part A-APPL S* 2010; 41(7):795–805.
- [13] Olsson R, Donadon MV and Falzon BG. Delamination threshold load for dynamic impact on plates. *Int J Solids Struct* 2006; 43(10): 3124–3141.
- [14] Rahul, Sandeep G, Chakraborty D, et al. Multi-objective optimization of hybrid laminates subjected to transverse impact. *Compos Struct* 2006; 73(3): 360–369.
- [15] Khedmati MR, Sangtabi MR and Fakoori M. Stacking Sequence Optimisation of Composite Panels Subjected to Slamming Impact Loads using a Genetic Algorithm. *Lat Am J Solids Struct* 2013; 10(5): 1043–1060.
- [16] Lopez RF, Luersen MA and Cursi JES. Optimization of Hybrid Laminated Composites using a Genetic Algorithm. *J Braz Soc Mech Sci & Eng* 2009; 31(3): 269-278.

- [17] Kalantari M, Dong Ra and Davies I. Multi-objective robust optimization of unidirectional carbon/glass fibre reinforced hybrid composites under flexural loading. *Compos Struct* 2015; 138: 264–275.
- [18] Pelletier JL and Vel SS. Multi-objective optimization of fiber reinforced composite laminates for strength, stiffness and minimal mass. *Comput Struct* 2006; 84(29-30): 2065–2080.
- [19] Burns LA, Mouritz AP, Pook D, et al. Strength improvement to composite T-joints under bending through bio-inspired design. *Composites: Part A APPL S* 2012; 43:1971–1980.
- [20] ASTM standard D7136/D7136M:2003. Standard test method for measuring the damage resistance of a fiber-reinforced polymer matrix composite to a drop weight impact event.
- [21] Vo T, Guan ZW, Cantwell WJ, et al. Modelling of the low-impulse blast behaviour of fibre–metal laminates based on different aluminium alloys. *Compos Part B Eng* 2013; 44(1): 141–151.
- [22] ABAQUS. Theory Manual, Version 6.9, Hibbitt, Karlsson & Sorensen, Inc, 2009.
- [23] Su ZC, Tay TE, Ridha M, et al. Progressive damage modeling of open hole composite laminates under Compression. *Compos Struct* 2015; 122: 507–517.