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Numerical simulation of low-velocity impact test on PALF/Epoxy bio-composite laminates

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Abstract. Natural fiber-reinforced composites are highly demanded as it reduces the dependency on petroleum-based materials. The present work is focused on investigating the performance of PALF/Epoxy composite laminates under low-velocity impact through finite element analysis. The study presented to understand energy absorption, force-time response, force-displacement response, and damage characteristics of PALF/Epoxy composites. The composites with varying PALF fiber content (30, 40, and 50 % volume fraction) are modeled and simulated using LS-Dyna. Drop weight impact simulations of these composites are performed at different energy levels (3, 5, 10, 15, 20 J). The Impact simulations showed that the peak force of impact and displacement increases as the impact energy level increases. For 20 J of impact energy, a rise in fiber content from 30 to 40% and 40 to 50% volume fraction improved the energy absorption by 30.7 and 10.1 % respectively. PALF/Epoxy (30 % volume fraction) composites exhibited the peak force of 0.7678, 0.8666, and 0.9113 kN with a maximum displacement of 6.09, 14.74, 38.42 mm at 3, 10, and 20 J impact energy levels respectively. The impact study results designate that energy absorption of the specified composites is enhanced with increased loading of PALF content. H and Cross kind-shaped damage were witnessed for the first layer of PALF/Epoxy composites laminates.

Keywords: pineapple leaf fiber (PALF), epoxy, low-velocity impact, LS-Dyna, finite element analysis (FEA)

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1. Introduction

Natural fibres are widely used as reinforcement in composites. Manufacturers are interested in them because of attributes such as ease of processing, good specific stiffness, non-abrasiveness, biodegradability, and low cost. Synthetic fibres such as glass, carbon, and kevlar are made from petrochemicals-based synthetic materials. Those synthetic fibers are not environment-friendly and harmful to operating human beings. So the petroleum crisis and environmental sustainability make significant importance to natural fiber composite in the automotive, paper, and packaging industry. It has a very wide range of properties to become engineering application materials [1]. Low-velocity impact on the materials is of high concern as they are not visible and can be left undetected [2] With the rise in the practical applications of composite materials considering their lightweight, strength, and stiffness focus is on their properties. As natural fiber-reinforced polymer composites are susceptible to biodegradation at high humidity and temperature, variation in mechanical properties, dimensional instability, and poor impact performance is observed compared to synthetic fibers [3]. Thus Hybrid composites are also highly preferred because of the damage tolerance capability [4].

Mathivanan et al. [2] tested E-glass epoxy composite for low-velocity impact, it is studied that the perforation of the energy absorbed by the material is responsible for the damage. The force-displacement curve shows the absorbed energy with the change in impact velocity. The first threshold is when the material is damaged and the second is when the lamina fails. It has been observed that as the cross-ply fibers have better fiber interlock making them compact the impact energy absorbed is high compared to UD composites [3]. Hybridization has mostly increased energy absorption. Ahmed et al. [4] have studied the low-velocity impact behavior of hybridized fiber with jute. The load–energy-time plot study indicated pure jute composite has better absorption of impact energy compared to the hybrid and the post-impact tests showed that delamination is the major cause of the damage in hybrid. Mahesh et al. [5] numerically investigated the effect of thickness and impactor shape (Hemi, Flat and conical) on the LVI behavior of jute fiber reinforced epoxy bio-composite. The laminate impacted with a conical-shaped impactor absorbs the most energy, but with a flat-shaped impactor, it suffers more severe damage. To investigate the LVI response of Sisal/Epoxy composites, a finite element (FE) technique was used by Mahesh and Nilabh [6]. They discovered that when the impact velocity and laminate thickness rise, so does the energy absorption. Mahesh et al. [7] studied the effect of the stacking sequence of Jute(J)/Rubber(R) composites on LVI behavior at different energy levels using a conical shape impactor. Results depicted JRJ and JRJRJ provide better energy absorption and damage resistance respectively compared to other sequences. Failure pattern is also different in these flexible composites compared to stiff composites.

Militello et al. [8] conducted low-velocity impact tests on various Sisal/green epoxy composites by varying fiber volume fraction and lay-up. The result shows that angle-ply laminates exhibit superior impact performance. Sheikh Md Fadzullah et al. [9] developed pineapple leaf fiber reinforced polylactic acid bio-composites and tested them for drop weight impact test. Severe damage was observed for 3251D PLA-based bio-composites compared to 6100D PLA-based. The impact behavior of jute/methacrylate soybean oil (MSO) composites was studied using different thicknesses, fibre orientations, and weave patterns by Dhakal et al. [10]. Due to its larger areal weight and higher yarn per 10 cm compared to other specimens, the woven W2 sample exhibits the greatest impact resistance among the bio-composites investigated. Mahesh, Harausampath et al. [11] studied the effect of the content of nano-silica on the ballistic impact behavior of jute reinforced polyethylene glycol (PEG) composites. The ballistic results indicate that energy absorption of the proposed composites is enhanced with the increased loading of nano-silica particles. C.S. Hassan et al. [12] simulated the crash performance of Oil Palm Empty Fruit Bunch (OPEFB) fiber reinforced epoxy composite bumper beam according to Federal Motor Vehicle Safety Standards (FMVSS) 581 regulation. These composites exhibit comparable specific energy absorption with 56 % reduced mass compared to aluminum. Yahaya et al. [13] perform a ballistic test on Kenaf/Kevlar epoxy composites by varying the volume fraction of Kenaf fiber from 5.40 to 14.99 %. Hybrid composites show superior performance compare to dedicated composites.

On Glass, Kenaf, and hybrid Glass/Kenaf reinforced epoxy composites, low-velocity impact tests were performed at three distinct levels of energies (3, 6, and 9 J) by Majid et al. [14]. To improve impact resistance, chopped strand mat of glass fiber should replace with woven glass fiber. Mahesh et al. [15] compared the LVI performance of are Jute-Epoxy (JE) and Jute-Rubber-Jute (JRJ) composites. For impact speeds of 2.5, 5, 7.5, and 10 m/s, JRJ composites absorb about 54, 51.2, 58.1, and 61.78 % more energy than JE laminate. So it is prominent material for structural protective claddings. Flax fiber reinforced PP composite was studied by Dutta et al. [16] and observed that at initiation the energy absorption is low compared to the propagation phase the results indicate that the amount of energy absorption is lower in the initiation phase when compared to the propagation phase. Thus the numerical model proposed is effective to study the low-velocity impact behavior of natural fiber composites. The peak load sustained by the composite indicates the change in orientation and volume fraction can help increase the load capacity.

Panciroli et al. [17] compared the impact resistance of flax/epoxy with glass/epoxy composites. Numerical simulations were performed to get more insights into the mechanism and evolution of damage during the impact. Deng et al. [18] studied the damage behavior of sandwich panels made up of honeycomb core and CFRP factsheets. The effect of the structural factors and impact energy were studied when these panels were loaded with localized low-velocity impact. Patil et al. [19] investigated the effect of impact energy on LVI and Compressive After Impact (CAI) properties of Hemp/epoxy and Jute/epoxy composite. Jute/epoxy composites exhibited higher impact energy absorption and CAI strength compared to Hemp/epoxy. Nayak et al. [20] reviewed the impact characteristics of nanofiller synthetic and natural fiber reinforced polymer nanocomposites.

Most of the research reported in the referred literature is to study the low-velocity drop weight impact performance of bio-composites using different natural fiber as Jute, Kenaf, Oil Palm, and Sisal fiber. In this article, an attempt has been made to investigate the performance of PALF/Epoxy bio-composite laminate under low-velocity impact loading. The effect of PALF fiber content and different energy levels of impact are studied through finite element analysis using LS-Dyna for its performance under LVI.

2. Materials and methods

Materials. The three configurations of PALF reinforced epoxy composites laminates of stacking sequence [0/90, ±45, 0/90, 0/90, ±45, 0/90] with six layers each of 0.5 mm are considered. Each configuration is designated as 30PE, 40PE, and 50PE based on the content of PALF fiber as 30, 40, and 50% of volume fraction respectively. The mechanical elastic and strength properties of the proposed PALF/Epoxy composite laminate are necessary for impact simulation. These properties are evaluated by micromechanical modeling principles through the material designer of ANSYS 19.2. The constituent properties for this are referred from the literature[21,22]. The evaluated mechanical properties of PALF/Epoxy are summarized in Table 1.

Modelling and Simulation. ANSYS LS-Dyna 2020 is used to simulate the low-velocity impact response of the PALF/Epoxy composite laminate of three configurations. LS-Dyna software package contains a huge library of material constitutive models. The composite enhanced damage material model (MAT054) is commonly adopted for modelling composite structures under impact loading owing to its robustness and simplicity [23-26,27].

MAT054 is an orthotropic material model with optional brittle failure for composites following either the suggestions of Chang and Chang [28] or Tsai and Wu[29]. The composite plate of size 150 × 100 mm is modeled with 8-node brick elements with a single integration point. A biased meshing scheme is adopted with a minimum element size of 0.5 mm and the total number of elements is 403,200 elements. The model plate i.e. laminate is made up of six laminae of stacking sequence [0/90, ± 45, 0/90, 0/90, ± 45, 0/90], each lamina possesses a thickness of 0.5 mm. The impact ball is modeled as a rigid hemispherical solid with a diameter of 12.7 mm. The ball is having a mass of 1.3 kg and is defined to move in a perpendicular direction with an initial velocity (2.21, 2.88, 3.87, 4.72, 5.55 m/s) as per the requirement of energy level (3, 5, 10, 15, 20 J). The meshing of PALF/Epoxy laminated composite with impactor is shown in Fig. 1. Fixed boundary conditions on edge of the laminated plate are applied and solved to get impact properties as the energy absorbed, reaction force, and deformation.

Table 1 Elastic and strength properties of PALF/Epoxy used in the impact simulation study

Elastic and Strength Properties	Unit	Configuration		
		30PE	40PE	50PE
Young's Modulus along X direction (E_1)	MPa	16115	18517	20492
Young's Modulus along Y direction (E_2)	MPa	16115	18517	20492
Young's Modulus along Z direction (E_3)	MPa	10323	11968	13473
Shear Modulus in XY (G_{12})	MPa	5663.6	6734.4	7617.6
Shear Modulus in YZ (G_{23})	MPa	2565.8	2947.4	3322.6
Shear Modulus in XZ (G_{31})	MPa	2565.8	2947.4	3322.6
Poisson's Ratio in XY (μ_{12})	-	0.2246	0.2192	0.2164
Poisson's Ratio in YZ (μ_{23})	-	0.3447	0.3202	0.3006
Poisson's Ratio in XZ (μ_{31})	-	0.3447	0.3202	0.3006
Density	g/cm^3	1.3233	1.3503	1.3710
Longitudinal Tensile Strength (X_t)	MPa	144.193	182.594	220.995
Transverse Tensile Strength (Y_t)	MPa	40.20	46.16	54.18
Longitudinal Compressive Strength (X_c)	MPa	144.193	182.594	220.995
Transverse Compressive Strength (Y_c)	MPa	40.20	46.16	54.18
In Plane Shear Strength (S)	MPa	32.16	36.93	43.34

Fig.1. Meshed model of PALF/Epoxy composite laminate with hemispherical impactor

The impactor's initial impact velocity (V_I) is defined as the speed at which the impactor begins to move toward the target from a specific height. As the impactor strikes the plate, either it rebounds or penetrates where the velocity will reduce which is called residual velocity (V_R).

Kinetic energies, the initial kinetic energy (KE_I) of the impactors striking the target, and residual kinetic energy (KE_R) of the impactor are calculated by using Eq. (1) and (2). The mass of the impactor is m.

$$KE_I = \frac{1}{2}\, m\, V_I^2 \tag{1}$$

$$KE_R = \frac{1}{2}\, m\, V_R^2 \tag{2}$$

The difference between the initial kinetic energy and the residual kinetic energy computed by equation (3) is the energy absorbed (E_a) by the laminate

$$E_a = KE_I - KE_R \tag{3}$$

3. Results and Discussion

Energy Absorption. The PALF/Epoxy bio-composites are impacted by a rigid hemispherical shape impactor with a velocity of 2.21, 2.88, 3.87, 4.72, and 5.55 m/s which results in the level of impact energy of 3, 5, 10, 15, 20 J respectively. As the impactor strike a composite plate it reduces the impact energy by decimation in form of damage. This quantification of dissipation of energy is termed energy absorption. The residual velocity and absorbed energy of 30PE, 40PE, and 50PE PALF/Epoxy composites at altered impact velocities and impact energy are presented in Table 2.

Table 2 Residual velocity and energy absorbed of PALF/Epoxy composites at a different impact energy level

Composition	Impact Velocity (m/s)	Residual Velocity (m/s)	Velocity Drop (m/s)	Impact Energy (J)	Absorbed Energy (J)	Energy Absorption Ratio (%)
30PE	2.21	1.538	0.672	3	1.38	46.01
	2.88	1.727	1.153	5	2.98	59.50
	3.87	1.134	2.736	10	7.75	77.51
	4.72	-1.261	5.981	15	10.72	71.50
	5.55	-3.355	8.905	20	9.86	49.32
40PE	2.21	1.582	0.628	3	1.33	44.32
	2.88	1.853	1.027	5	2.76	55.17
	3.87	1.134	2.736	10	6.35	63.49
	4.72	-1.261	5.981	15	12.21	81.37
	5.55	-2.418	7.968	20	12.89	64.45
50PE	2.21	1.591	0.619	3	1.30	43.41
	2.88	1.841	1.039	5	2.80	56.10
	3.87	2.211	1.659	10	5.56	55.61
	4.72	1.675	3.045	15	10.91	72.77
	5.55	-1.826	7.376	20	14.19	70.96

Figure 2 shows the variance in energy absorption of PLAF/Epoxy composites at various levels of impact energy. It is observed that for 20 J of impact energy, a rise in the content of fiber from 30 to 40 and 40 to 50 improved the energy absorption by 30.7 and 10.1 % respectively. Maximum energy absorption for 30PE, 40PE, and 50PE is observed at 15, 20, and 20 J respectively. This is because higher fiber content restricts damage to laminate at a low level of impact energy.

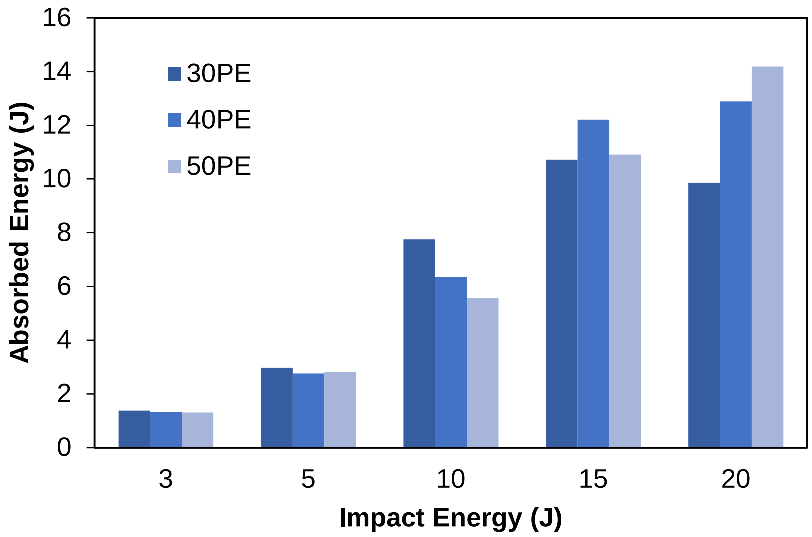

Fig. 2. Variation of absorbed energy of PALF/Epoxy composites with different impact energy

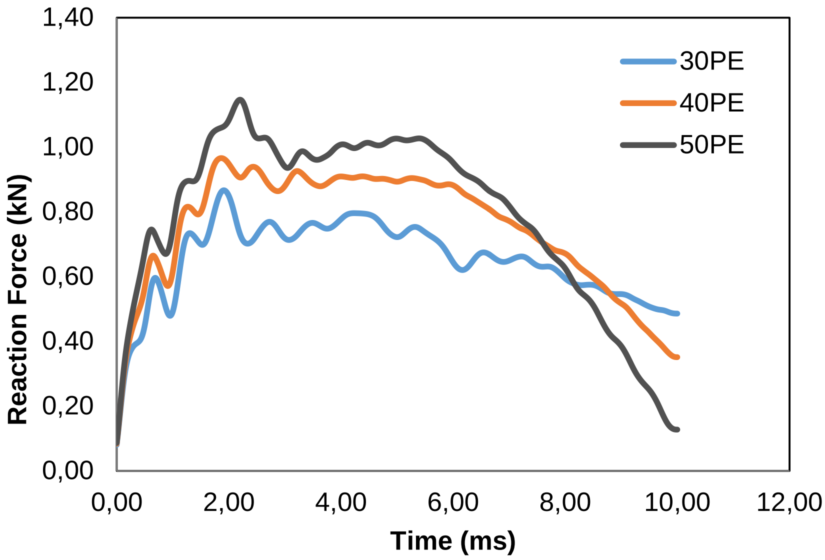

Fig. 3. Variation of the reaction force of PALF/Epoxy composites at 10 J impact energy

Force-time Response. A variation of impacted force concerning time is the force-time response of PALF/Epoxy composite. The force-time response of 30, 40 and 50PE configurations are obtained at different impact energy level (3, 5, 10, 15, 20 J) i.e. changing velocity (2.21, 2.88, 3.87, 4.72, 5.55 m/s). Figure 3 depicts the force-time response of PALF/Epoxy composites at 10J impact energy. The force increases up to peak value for a time of 2 ms and then decreases it represents the maximum resistance force (Pmax). The value of Pmax shows the ability of composite material to resist impact loading [6]. Curve before and after peak force indicates fracture initiation and fracture propagation region respectively. Forces increase initially and drop before reaching a value of Pmax is called critical force (Pcrc), this is a change in the stiffness of the composite due to damage evolution. The maximum reaction force of 0.867, 0.966, and 1.15 kN is observed for 30, 40, and 50PE composite respectively. The improvement of about 11.41 % and 19.04 % in resistance to impact is seen when the volume fraction of fiber rises from 0.3 to 0.4 and 0.4 to 0.5 respectively[7]. The deviation of peak force of PALF/Epoxy bio-composites with altered impact energy levels is depicted in Fig. 4. When impact energy is raised from 3 to 10 J and 10 to 20 J, the improvement in peak force is 12.9 and 5.2 % respectively for 30PE composites.

At all energy levels, an increase in the content of fiber raises the peak force of the reaction. For 50PE composites peak force of 1.1942 kN was observed at 15 J impact energy and then it drops to 1.1071 kN when impacted with 20 J energy. It shows the saturation of impact resistance force beyond 15J energy.

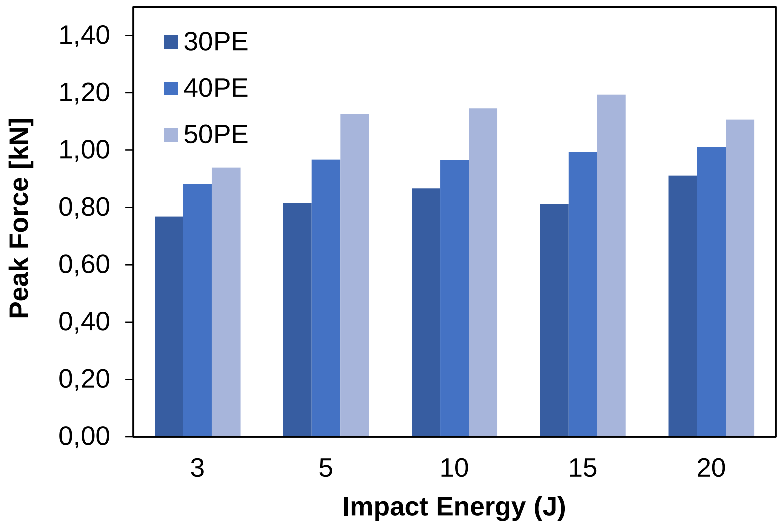

Fig. 4. Peak forces of PALF/Epoxy composites as a function of impact energy

Force-displacement Response. Figure 5 depicts the variation of reaction force against displacement of 30PE, 40PE, and 50PE composites. In all compositions of PLAF/Epoxy composites, curves attempted to form a closed loop in which it reached peak force and tried to return to the initial point. For 50PE composition shows higher area under the curve, indicating energy transformations of the impactor to plate. At low impact energy, the curve has close movement toward the initial point but at higher impact energy curve moves away from the initial point [30].

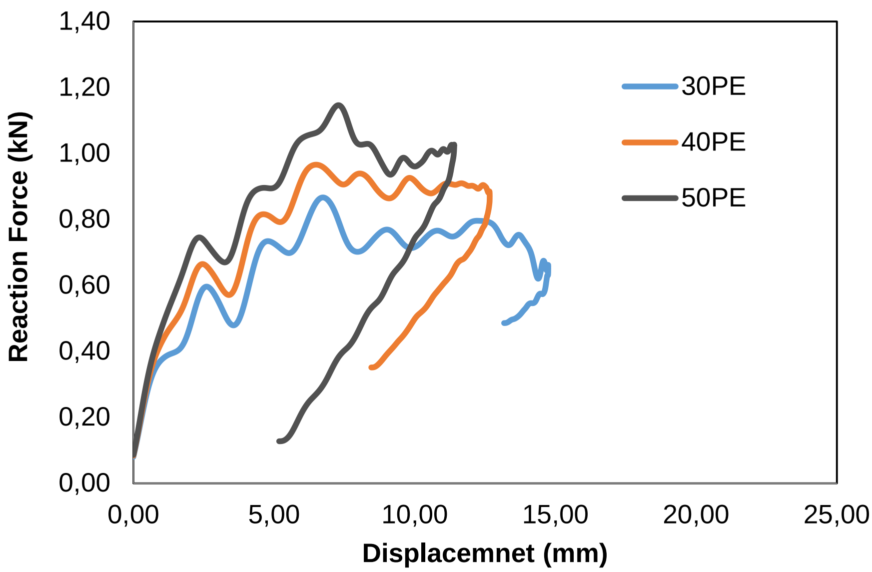

Fig. 5. Variation of reaction force against displacement of PALF/Epoxy composites at 10J impact energy

Figure 6 depicts the maximum displacement of 30PE, 40PE, and 50PE PALF/Epoxy composites with different levels of impact energy. The maximum displacement of 30PE, 40PE, and 50PE increases by 142.1, 133.1, and 130.4 %, respectively, when the impact energy is increased from 3 to 10 J. An increase in impact energy increases the maximum displacement but it is restricted by an increase in the content of fiber [14].

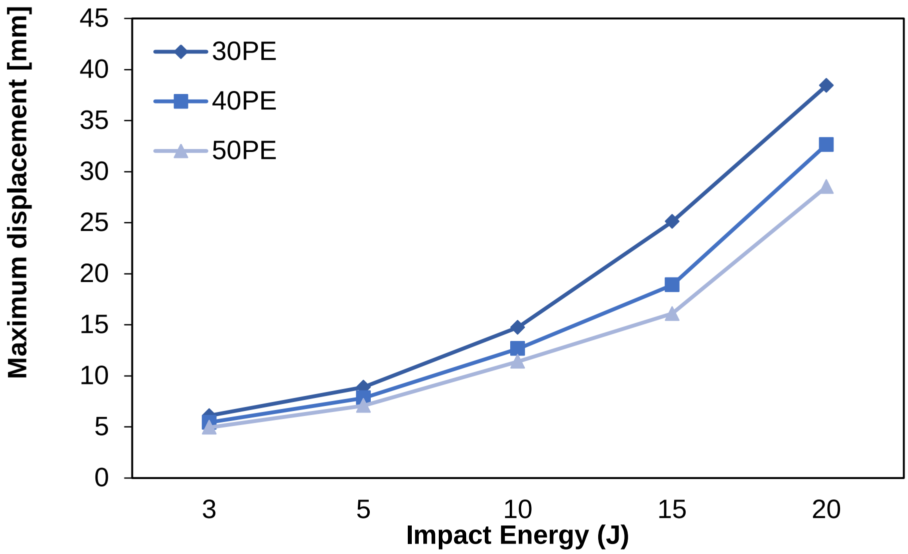

Fig. 6. Maximum displacements of PALF/Epoxy composites with impact energy

Damage Characterization. This section discusses damage caused in 30PE, 40PE, and 50PE PLAF/Epoxy composites at the impact of different impact energy levels. The damage counters were obtained under different failure modes of the first lamina of laminates viz. fibre failure under tensile and compression mode and matrix failure under tensile and compression mode. Figures 7 and 8 depict the contours of matrix damage on the first laminate under compressive and tensile mode respectively of 30PE, 40PE, and 50PE PALF/Epoxy composites at an impact energy of 3 to 20 J. The value 1 (counter colour blue) means the laminate is fully intact whereas the value 0 (counter colour red) means the laminate has failed. For 30 PE composites, an increase in impact energy level increase the damaged area of the matrix but the shape of damage for compressive and tensile mode is h-shaped and cross (+) shaped respectively. At 15 J impact energy level, the 30 PE composite is failed and the impactor penetrated through it but 40PE and 50PE sustained. The area of damage depicts that as the content of fibre increases from 30 % to 50 %, the intensity of damage is reduced in both failure modes.

Figures 9 and 10 depict the contours of fiber damage on the first laminate under compressive and tensile mode respectively of 30PE, 40PE, and 50PE PALF/Epoxy composites at the impact energy of 3 to 20 J. The shape of damage of fiber under compression and tensile mode is cross (+) but the intensity has a small deviation. This is because failure strain for PALF fibre under compression and tension mode is equal i.e.1.6 %. The 30PE PLAF/Epoxy composite sustained till 10J energy whereas 40PE and 50PE till 15J impact energy.

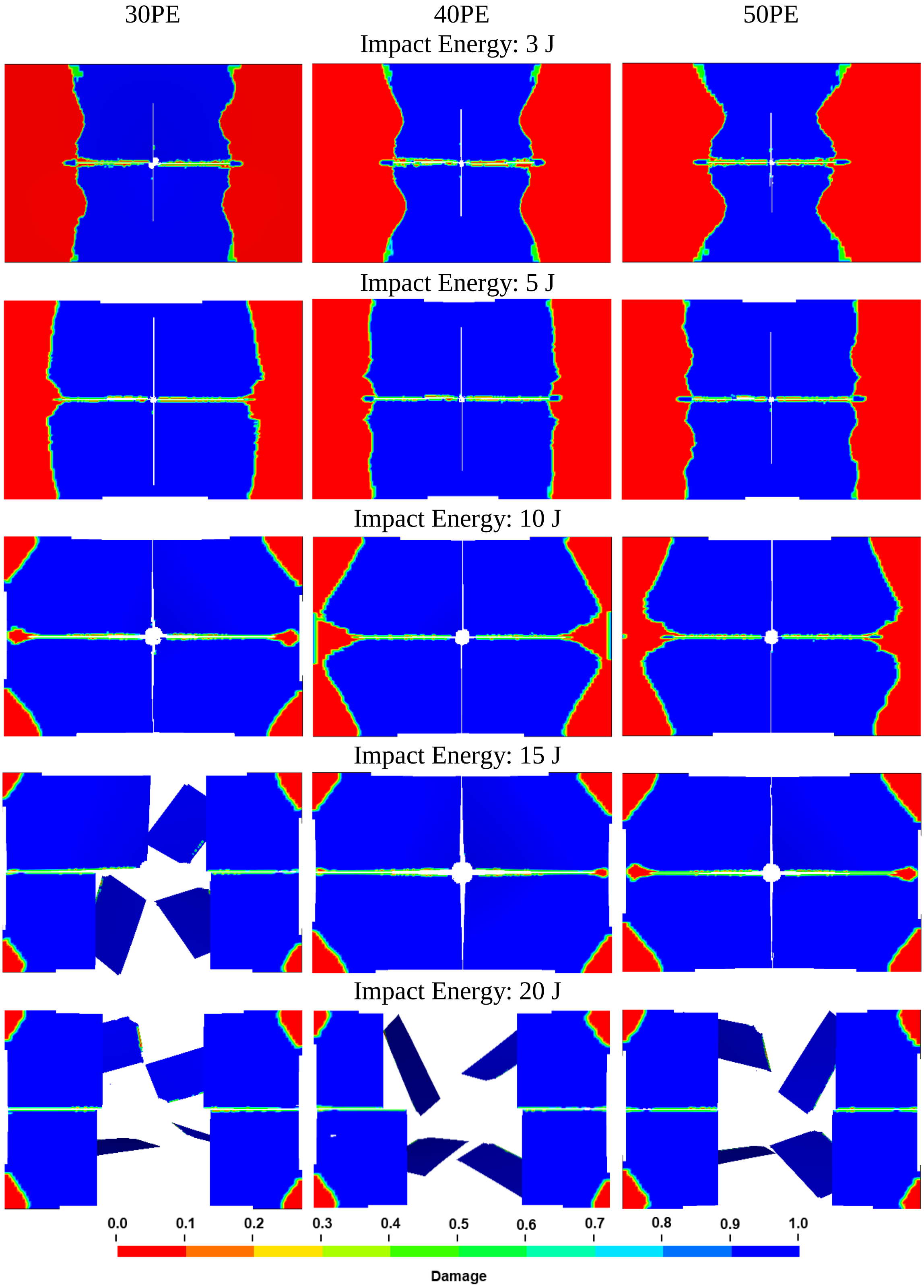

Fig. 7. Contours of matrix compressive damage on first laminate

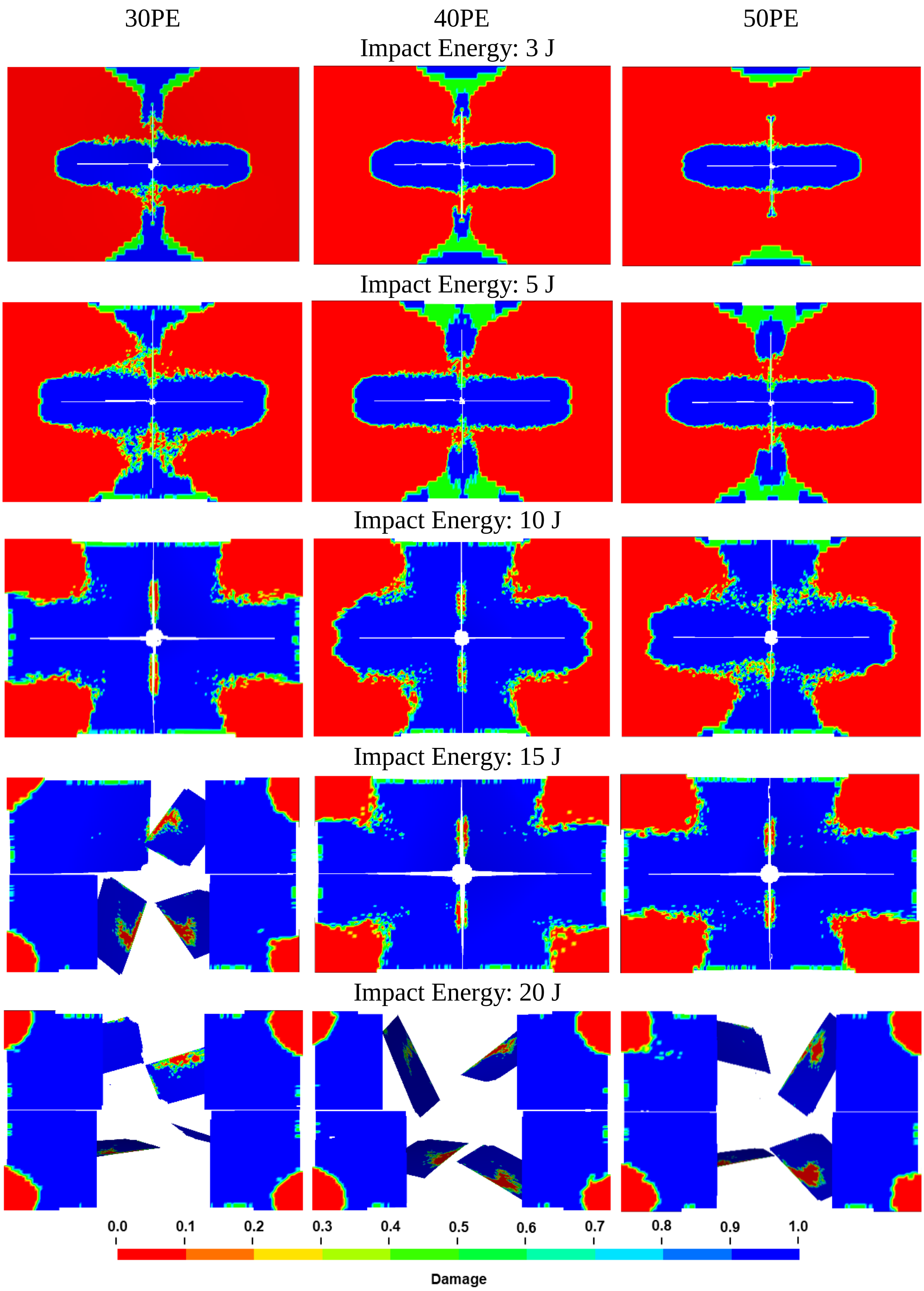

Fig. 8. Contours of matrix tensile damage on first laminate

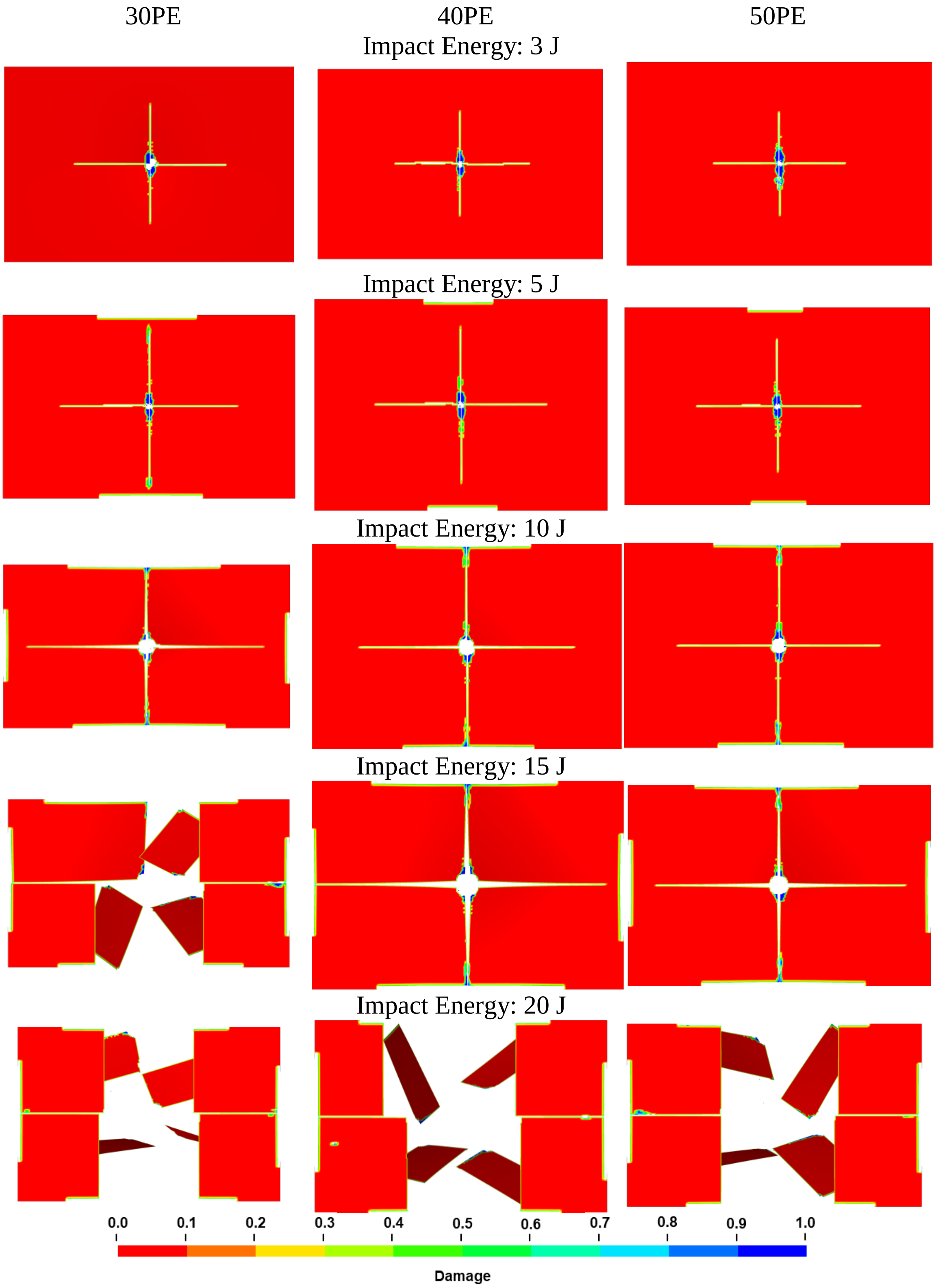

Fig. 9. Contours of fibre compressive damage on the first laminate

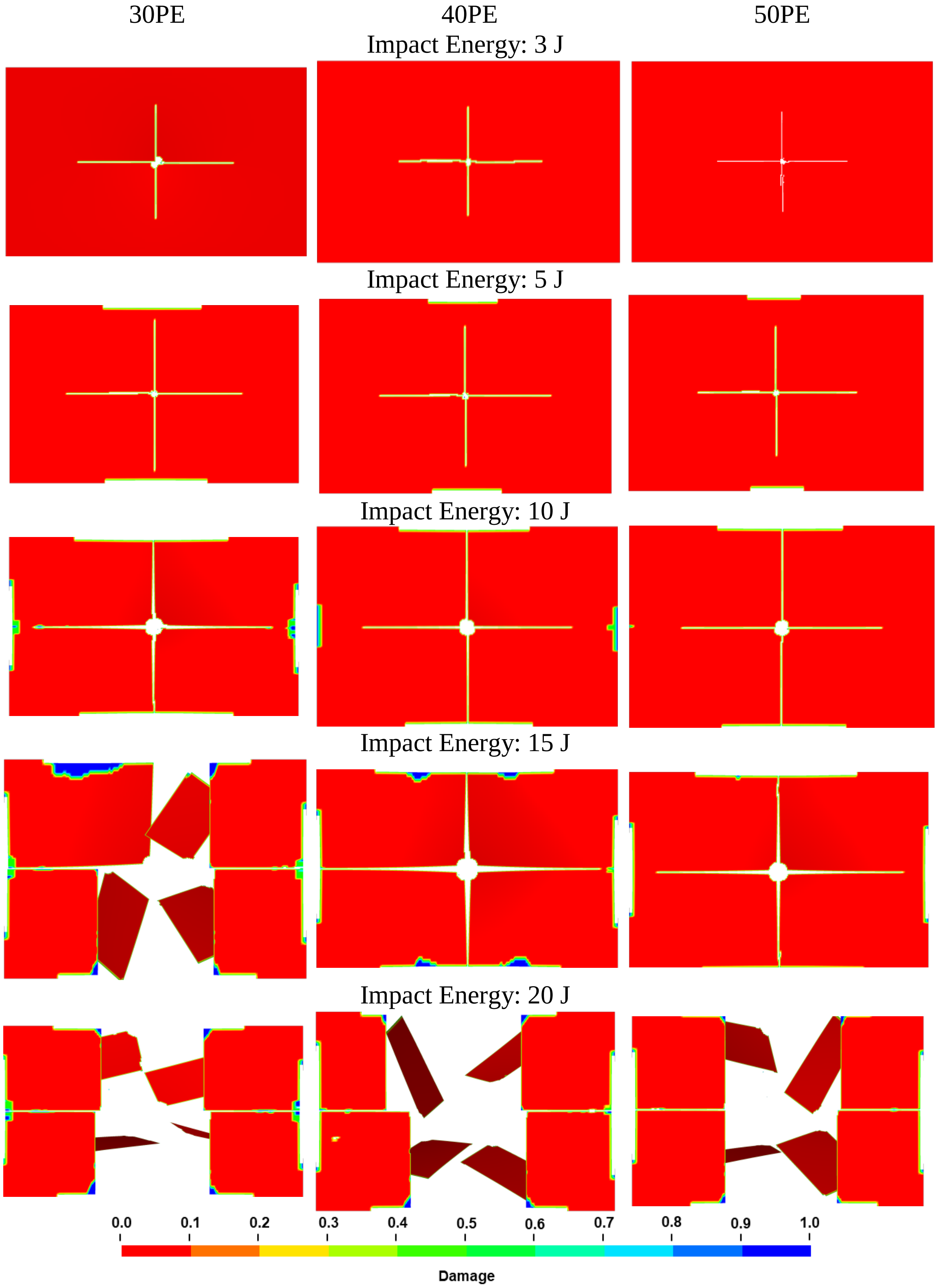

Fig. 10. Contours of fiber tensile damage on the first laminate

4. Conclusions

In the current research work, numerical simulation of PLAF/Epoxy composites under drop weight low-velocity impact has been carried out. The impact response of PLAF/Epoxy by varying impact energy levels has been simulated and the following conclusions are drawn,

- Energy absorption for 30PE, 40PE, and 50PE PLAF/Epoxy composites improved with an increase in impact energy up to 10J, 15J, and 15J respectively. After this impactor penetration was seen.
- Amongst all compositions, 50PE composites show the maximum energy absorption of 14.19 J when it is impacted with a 20 J energy level.
- For 30 PE composites, an increase in impact energy from 3 to 10 J and 10 to 20 J raises the maximum peak force by 12.9 and 5.2 % respectively.
- The peak of reaction force rises with an increase in the level of impact energy. For 50PE bio-composites maximum peak force of 1.1942 kN was observed at 15J impact energy.
- At 3 J impact energy; the maximum displacement of 30PE, 40PE and 50PE composites was 6.09, 5.43, and 4.94 mm. The increase in impact energy raises the maximum displacement of composites but it is restricted by a rise in fiber content.
- Damage characteristics of a matrix under tensile and compression mode are different i.e. cross (+) and h shaped but it is identical (cross-shaped) for fiber.

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