MAKÜ-Uyg. Bil. Derg., 3(1), 47-64, 2019

Mehmet Akif Ersoy Üniversitesi Uygulamalı Bilimler Dergisi
Journal of Applied Sciences of Mehmet Akif Ersoy University

Low Velocity Impact Behaviour of Damaged Composite Plates Repaired by Composite Patches

Umut CALISKAN[1*], Recep EKICI[2], Mustafa Kemal APALAK[3]

[1]Asst. Prof., Erciyes University, Department of Mechanical Engineering, Orcid id: 0000-0002-8043-2799

[2]Assoc. Prof. Dr., Erciyes University, Department of Mechanical Engineering, Orcid id: 0000-0002-4420-8431

[3]Prof. Dr., Erciyes University, Department of Mechanical Engineering, Orcid id: 0000-0002-3263-5735

Geliş Tarihi/Received: 21.11.2018
Kabul Tarihi/Accepted: 22.01.2019

Doi: dx.doi.org/10.31200/makuubd.486219
Araştırma Makalesi/Research Article

ABSTRACT

Adhesive bonding technique is used in many engineering applications. Repairing with fiber composite patches using adhesive bonding technique are widely used for repairing cracks or other defects. Patch application to damaged materials with adhesive bonding is used to extend the service life of the material. In this study, patches were bonded damaged fiber-reinforced laminated composite plates and the dynamic load resistance was investigated numerically. Damaged composite plates and fiber reinforced composite patches are bonded with adhesive. Non-linear finite element analyses were performed in the ABAQUS finite element software. A cohesive zone model based on fracture mechanics was used as the adhesive material model. Low velocity impact behavior of damaged plates repaired by composite patches was also investigated for different patch material such as aluminum and fiber reinforced composite. Impact analyses performed on different impact energy with constant impactor weight were investigated in terms of contact force variations, kinetic energy variations and impact damage. Damaged plates without patch were perforated and damaged. Composite patches absorb impact energy and prevent the perforation.

Keywords: Composite Patch, Low Velocity Impact, Adhesive, Non-Linear Finite Element Method.

Kompozit Yamalar ile Tamir Edilen Hasarlı Kompozit Plakaların Düşük Hızlı Darbe Davranışı

ÖZET

* Sorumlu yazar/Corresponding author
E-mail/e-ileti: ucaliskan@erciyes.edu.tr

Yapıştırıcı ile birleştirme tekniği birçok mühendislik uygulamalarında kullanılmaktadır. Yapıştırma tekniği ile kullanılan fiber takviyeli kompozit yamalar ile tamir, çatlakların ve diğer hasarların tamirinde geniş çapta kullanılmaktadır. Yapıştırma tekniği ile hasarlı malzemelere yapıştırılan yama uygulamaları, malzemelerin kullanım ömürlerini uzatmak için kullanılmaktadır. Bu çalışmada, yamalar hasara uğramış fiber takviyeli kompozit plakalara yapıştırılmış ve dinamik yük dayanım kabiliyeti nümerik olarak araştırılmıştır. Yamalar ve hasarlı kompozit plakalar yapıştırıcı kullanılarak birleştirilmiştir. Lineer olmayan sonlu elemanlar analizleri ABAQUS sonlu elemanlar yazılımı kullanılarak yapılmıştır. Kırılma mekaniği temelli kohezif bölge modeli yapıştırıcı malzemesinin modellenmesinde kullanılmıştır. Yamalar kullanılarak tamir edilen hasarlı plakaların düşük hızlı darbe davranışı kompozit ve alüminyum yama malzemesi kullanılarak farklı yama malzemeleri içinde araştırılmıştır. Darbe analizleri, sabit kütleli vurucu ile farklı darbe enerjilerinde yapılırken temas kuvveti değişimi, kinetik enerji değişimi ve darbe hasarı açısından da araştırılmıştır. Yamasız hasarlı plaka delinerek hasara uğramıştır. Kompozit yamalar darbe enerjisini sönümlemekte ve delinmeyi önlemekte başarılı bir davranış sergilemiştir.

Anahtar kelimeler: Kompozit Yama, Düşük Hızlı Darbe, Yapıştırıcı, Lineer Olmayan Sonlu Elemanlar Metodu.

2. INTRODUCTION

The materials and their properties in the structures which is required high technology change continuously, new material types develop and using areas increase. The composite materials are this type material class. The other important subject is that the occurring damages at the composite and metal materials repair. The repair technique of the composite patch with bonding adhesive are used with the purpose of repairing materials and increasing working life of the materials. The damages in different size occur at the nose cone of the air crafts, cockpit glasses, the outside of the aero foils, horizontal and vertical stabilization because of extrinsic factors such as birds, hail, lightning, impact vehicles on the ground (Çalışkan et al, 2017).

The damage in different size occur again at the car bumper and hood cause of the crashing other cars and objects. Different repair technique and patch are used to prevent damage progression, increasing static and fatigue strength again, increasing the working life (Figure 1). The determining other issues are that choosing the suitable patch for the damaged materials, measuring the strength of the damaged materials after applying the patch. The researches about composite materials increase and they are used by basis and auxiliary material in the most of the recent applications (Çalışkan et al, 2017, Maamar et al., 2015, Pandey and Kumar, 2010, Kwon and Hall, 2015, Coelho et al., 2017, Deng et al., 2017). Impact response of material may depend on its application area and aim. In order to avoid the unstable responses of material due to any external effect, the optimal response of the material is expected. Materials deform elastically and plastically under an impact load in a short period. Impact mechanism develops strongly with surface conditions, and becomes more apparent on the metal surface whereas the damage may initiate inside the composite materials, such as along interfaces between the layers rather than on the surface of the composite material. Therefore, the prediction of the initiation and propagation of the damages in the composite materials needs various damage models to be considered (Çalışkan et al, 2017).

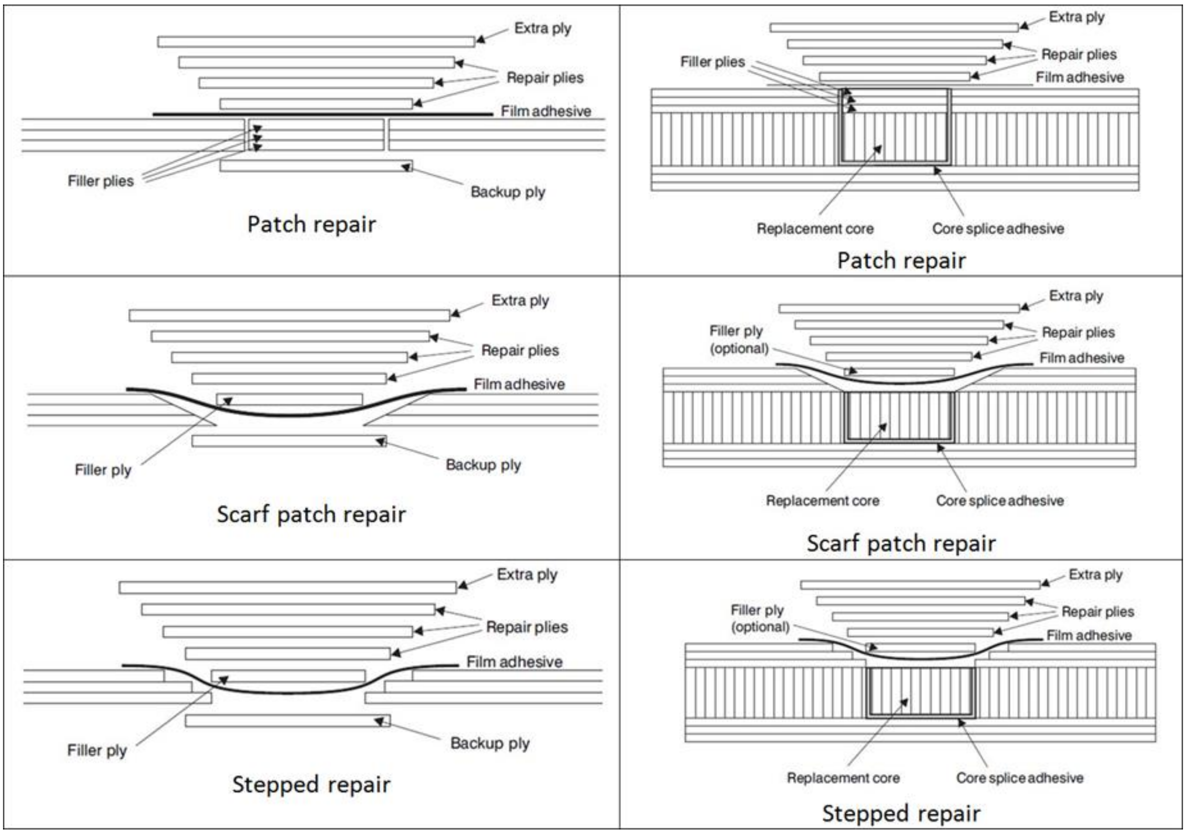


Figure 1. Different repair technique for laminated and sandwich composites

Maamar et al. (Maamar et al., 2015) studied the effect of the characterization of composite patch with two woven glass fiber and carbon composite materials. They studied the tensile strength behavior of composite patch experimentally. Samples with two different series were mechanized with different types of notches after cutting the tensile specimens with a numerical controlled machine. Two different set of specimens were drilled with diameters of 2, 4, and 6 mm in central hole. The hydrothermal aging was used to other series during 180 days. The temperature was 70°C and relative humidity was 95% in the hydrothermal conditions. A group of composite specimens was repaired with a composite patch which the material was the same of the specimen material. All the specimens subjected to the tensile test. After the hygrothermal aging, the glass fiber presented a percentage of lost of tensile strength about 44%, while the carbon fiber presented 24%. Increasing in drilled diameter, the tensile load decreased quickly specially at the diameter 6 mm as function of the hygrothermal aging. The glass fiber composite presented a more decrease in the tensile strength in comparison of the carbon fiber.

Pandey and Kumar (Pandey and Kumar, 2010) studied the interface behavior of fiber-reinforced composite patch with adhesively-bonded cracked aluminum alloy numerically. An elasto-plastic bilinear material model was used to model the adhesive material to characterize the deboned behavior. Two different patch geometries were selected according to literature information. Geometric and material nonlinearities were considered for square and octagonal patches. Shear stresses increased between the substrate and the patch. Parametric analysis on adhesive thickness and patch thickness were performed to predict their influence on damage tolerance of repaired structures. Their results showed that the peel and shear stresses were predominant and the peak shear stress occured at the edge of the patch in the adhesive. Different stress and strain-based failure criteria were considered in this study to predict the strength.

2. Kwon and Hall (Kwon and Hall, 2015) studied the effect of composite patches with thick stiffened plates. An analytical model was improved to predict the reduction in the mode I strain energy release rates resulting from the single-sided composite patches. They also computed the mode I strain energy release rates with and without composite patches using finite element analyses, and they compared results to the analytical model prediction. Stiffener parameters and plate thickness had a significant effect on composite patching. This information was true for both the tensile and bending load. When applying a tensile load, several important relations were found. First, a single-sided patch was more effective when applied to the opposite side rather than the same side of the plate as the stiffening members.

Coelho et al. (Coelho et al., 2017) studied the impact performance of repaired by overlap composite patches. They used single and double-patch specimens to experiment. In order to evaluate the impact fatigue strength, both configurations were submitted to multi-impacts, until the full perforation occurs. Their results show that higher maximum loads exhibited in the double-patch geometry.

Deng et al. (Deng et al., 2017) investigated buckling strengths and failure mechanisms of patches repaired carbon-fiber reinforced laminates subjected to compression without lateral restrains. They used for both symmetric and asymmetric patch. They used solid and cohesive elements for composite and adhesive layers, respectively. 3D strain failure criteria and an energy-based crack model was applied to model the softening behavior in composites with mesh dependency elimination. Patch was simulated by the cohesive zone model with a trapezoidal traction–separation law. They used geometric imperfection for the nonlinear analysis by the first-order linear buckling configuration.

The aim of this study is to investigate numerically low speed impact behavior of repairing damaged composite plates with composite patches and the effect of the patch material was also investigated in this study. The other important subject about in this study, the repair technich of the composite patch with bonding adhesive are used with the purpose of repairing materials and increasing working life of the materials. The damages in different size occur at the nose cone of the air crafts, cockpit glasses, the outside of the aerofoils, horizontal and vertical stabilizator because of extrinsic factors such as birds, hail, lightning, impact vehicles on the ground. The damage in different size occur again at the car bumper and hood cause of the crashing other cars and objects. Different repair technich and patch are used to prevent damage progression, increasing static and fatigue strength again, increasing the working life. The determining other issues are that choosing the suitable patch for the damaged materials, measuring the strength of the damaged materials after appliying the patch. When other studies in the literature are investigated, using of patches showed a lack of impact strength of damaged composites. First of all, these behaviors were intestigated using numerical method.

2. FINITE ELEMENT MODEL

ABAQUS/Explicit (version 6.14) (ABAQUS/User’s manual,) was used to exhibit the low velocity impact behavior of damaged composite plates. The impact behavior was investigated for different composite patch materials as metal and fiber reinforced composite under three impact energy levels of 10, 30 and 60 J. Notched composite plate was in dimension of 125x125 mm and its thickness was taken as 2 mm. Notch geometry was in dimension of 1x1x25 mm and adhesive thickness was 0.25 mm.

Two different types patch material were used as Al 6061 T6 and glass fiber/epoxy composite. Composite patch geometry was in dimension of 25x25 mm and thickness of 1 mm. Damaged composite plate with notched was shown in Figure 2. The stress and strain curve of metal patch of Al 6061 T6 was shown in Figure 3.

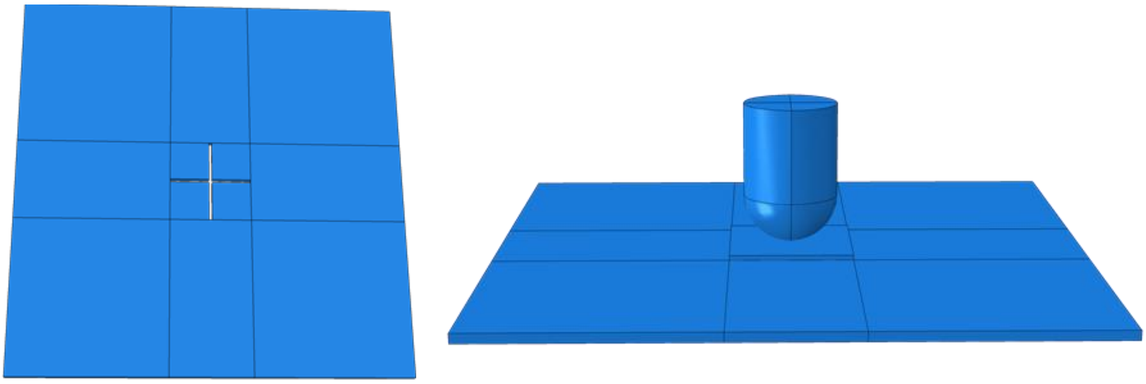


Figure 2. Finite element model

The material and geometric nonlinearities were considered for the finite element analysis. The Johnson-Cook material model was used to model metal patch. The Johnson-Cook material model consider a specific case of the ductile damage initiation criterion for metals in ABAQUS/Explicit code. The Johnson-Cook dynamic failure model parameters were given in Table 1 for Al 6061 T6 (Manes et al., 2014).

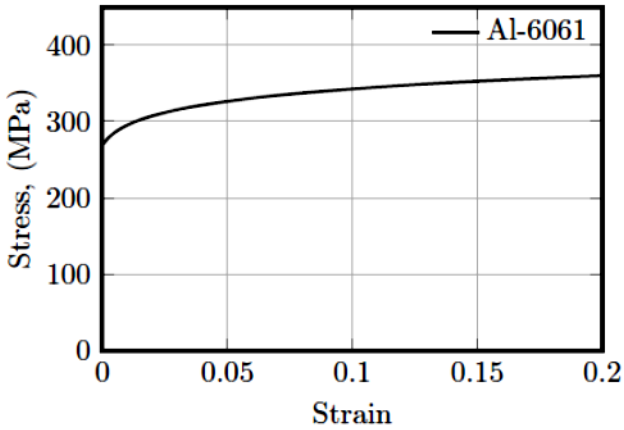


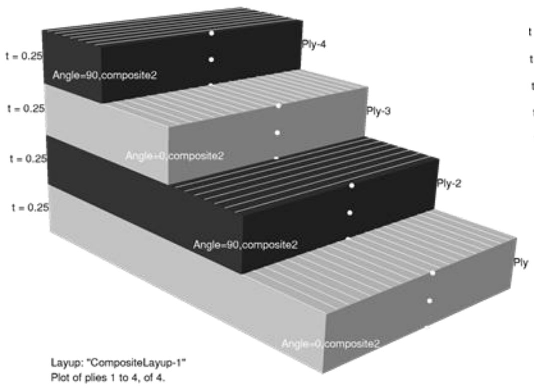
Figure 3. Stress-Strain curve of Al 6061 – T6

The impactor was modeled as a rigid body behavior and spherical tip geometry. The impactor diameter was 20 mm and mass was 5 kg. The motions in all directions of nodes where they are around of the damaged plate were prevent. A continuum shell element (8-node hexahedron, SC8R) was used to model damaged composite plates and patches. The GENERAL CONTACT ALGORITHM was used as the mechanical contact between the impactor and plate in Abaqus/Explicit code. Four layers (fiber angle of 0^{o}, unidirectional) were used to model composite laminate of patch. Composite plate was modeled as eight layer and fiber angle of 0/90^o (Figure 4). The material damage initiation capability for fiber-reinforced composite materials requires that the behavior of the undamaged material is linearly elastic, is based on Hashin's theory and can be used in combination with the damage evolution model described in “Damage evolution and element removal for fiber-reinforced composites” in the Abaqus/Explicit code.

Table 1. Constants for Johnson-Cook dynamic failure model of Aluminum Al 6061 T6

Aluminum 6061 T6	Johnson-Cook Model
ρ (kg/m 3)	2700
E (GPa)	70
v	0.33
C_p (J/kgK)	910
α (K^{-1})	2.30x10^{-5}
$\dot{\varepsilon}$ (s^{-1})	597.2
A (MPa)	270
B (MPa)	154.3
C	0.1301
n	0.2215
m	1.34
T_f(K)	925
d_1	-0.77
d_2	1.45
d_3	0.47
d_4	0.0
d_5	1.6

Ply orientations of fiber composite plate and patch was shown in Figure 4. Damage initiation refers to the onset of degradation at a material point.



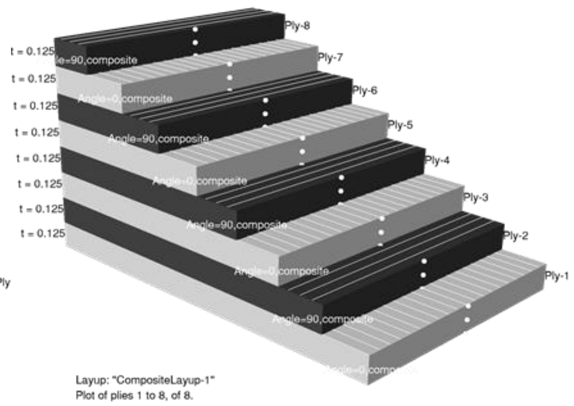


Figure 4. Ply orientations of fiber composite plate and patch.

The Hashin's theory was used to model as the damage initiation criteria for fiber-reinforced composites in Abaqus. This theory considers four different damage initiation mechanisms: fiber tension, fiber compression, matrix tension, and matrix compression and mechanical properties for the composite plates E-glass/epoxy are given in Table 2 (Singh et al., 2015).

Table 2. Elastic and strength properties for composite patch

Longitudinal modulus, E_{11}	40 (GPa)
Transverse modulus, $E_{22} = E_{33}$	10 (GPa)
Shear modulus, $G_{22} = G_{33}$	3.15 (GPa)
Shear modulus, G_{23}	4.32 (GPa)
Volume fraction of fiber, V_f	0.54
Poisson's ratio, $\mu_{12} = \mu_{13}$	0.3
Poisson's ratio, μ_{23}	0.21
Density	1780 (kg/m^3)
Longitudinal tensile strength, X_T	988 (MPa)
Transverse tensile strength, $Y_T = Z_T$	44 (MPa)
Longitudinal compressive strength, X_C	1432 (MPa)
Transverse compressive strength, $Y_C = Z_C$	285 (MPa)
In-plane shear strength $S_{12} = S_{13}$	60.6 (MPa)
Interlaminar shear strength, S_{23}	22 (MPa)

The initiation criteria have the following general forms:

Fiber tension ($\widehat{\sigma_{11}} \geq 0$) (Hashin, 1980)

$$F_f^t = (\frac{\widehat{\sigma_{11}}}{X^T})^2 + \alpha \left(\frac{\widehat{\tau_{12}}}{S^L}\right)^2 \tag{1}$$

Fiber compression ($\widehat{\sigma_{11}} < 0$) (Hashin, 1980)

$$F_f^c = (\frac{\widehat{\sigma_{11}}}{X^C})^2 \tag{2}$$

Matrix tension ($\widehat{\sigma_{22}} \geq 0$) (Hashin, 1980)

$$F_m^t = (\frac{\widehat{\sigma_{22}}}{Y^T})^2 + \alpha \left(\frac{\widehat{\tau_{12}}}{S^L}\right)^2 \tag{3}$$

Matrix compression ($\widehat{\sigma_{22}} < 0$) (Hashin, 1980)

$$F_m^c = (\frac{\widehat{\sigma_{22}}}{2S^T})^2 + \left[(\frac{Y^C}{2S^T})^2 - 1\right]\frac{\widehat{\sigma_{22}}}{Y^C} + \left(\frac{\widehat{\tau_{12}}}{S^L}\right)^2 \tag{4}$$

$\widehat{\sigma_{11}}, \widehat{\sigma_{22}}, \widehat{\tau_{12}}$ are components of the effective stress tensor, $\hat{\sigma}$, that is used to evaluate the initiation criteria and which is computed from (Hashin, 1980):

$$\hat{\sigma} = M\sigma \tag{5}$$

Where σ is the true stress and is the damage operator (Hashin, 1980):

$$M = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix} \tag{6}$$

d_f, d_m, and d_s are internal (damage) variables that characterize fiber, matrix, and shear damage, which are derived from damage variables, d_f^t, d_f^c, and, d_m^c corresponding to the four modes previously discussed, as follows (Hashin, 1980):

$$d_f = \begin{cases} d_f^t & if\ \widehat{\sigma_{11}} \geq 0 \\ d_f^c & if\ \widehat{\sigma_{11}} < 0 \end{cases} \tag{7}$$

$$d_m = \begin{cases} d_m^t & if\ \widehat{\sigma_{22}} \geq 0 \\ d_m^c & if\ \widehat{\sigma_{22}} < 0 \end{cases} \tag{8}$$

$$d_s = 1 - (1 - d_f^t)(1 - d_f^c)(1 - d_m^t)\ (1 - d_m^c) \tag{9}$$

The adhesive layer and interfacial adhesive failure between the composite plate and patch was modelled the cohesive zone approach. The cohesive parameters of the epoxy adhesive were given in Table 3 (Campilho et al., 2013). The cohesive response of the adhesive layer modelled a three-dimensional cohesive element (COH3D8). The nominal traction stress vector t, with the components: tn^0, ts^0 and tt^0, which represent the normal and the two shear tractions, respectively. G_n and G_s are the areas under the CZM laws in tension and shear. The cohesive thickness was taken as 0.2 mm for the adhesive layer.

Table 3. Cohesive parameters of adhesive Araldite 2015 used in CZM

Property	Araldite 2015
E (GPa)	1.85
G (GPa)	0.56
t_n^0 (MPa)	21.63
t_s^0 (MPa)	17.9
G_n^0 (N/mm)	0.43
G_s^0 (N/mm)	4.70

3. RESULTS

Impact analyses were performed for impact energies of 10, 30 and 60 J, respectively. The impactor was spheral tip geometry of 20 mm in diameter, and 5 kg of a mass. The mechanical design parameter of patch material was investigated to improve the impact energy absorption capability of the structure and avoid damage. The temporal variations of the contact force and kinetic energy were determined for three impact energy levels of 10, 30 and 60 J, respectively. Two different types of composite patch material were used for repairing notched composite plate. Impact analyses were also performed for without patch for three energy levels. These three situations were compared in terms of contact force histories, kinetic energy levels, stress distributions and Hashin damage initiation criterion on the notched composite plate. Figure 5 shows the effect of patch material on the temporal variations of the contact force and kinetic energy histories for three impact energy levels, respectively. GF patch means glass fiber composite patch in Figure 5. The peak contact forces are measured as about 2, 4.2 and 5 kN under the impact energy level of 10 J notched composite plate without patch, with metal patch and composite patch, respectively, and the corresponding peak contact times are 5, 5.1 and 8 ms for same specimens, respectively. The impact analyses are completed in the total contact times of 9, 11 and 15 ms. The peak contact forces are measured as 3.2, 8 and 13 kN under the impact energy level of 30 J notched composite plate without patch, without patch, with metal patch and with composite patch, respectively, and the corresponding peak contact times are nearly similar for all specimens in about 4 ms. The impact analyses are completed in the total contact times of 12, 7 and 7.1 ms. The peak contact forces are measured as 3.5, 8.2 and 14.3 kN under the impact energy level of 60 J notched composite plate without patch, with metal patch and with composite patch, respectively, and the corresponding peak contact times are nearly similar for all specimens in about 3 ms.

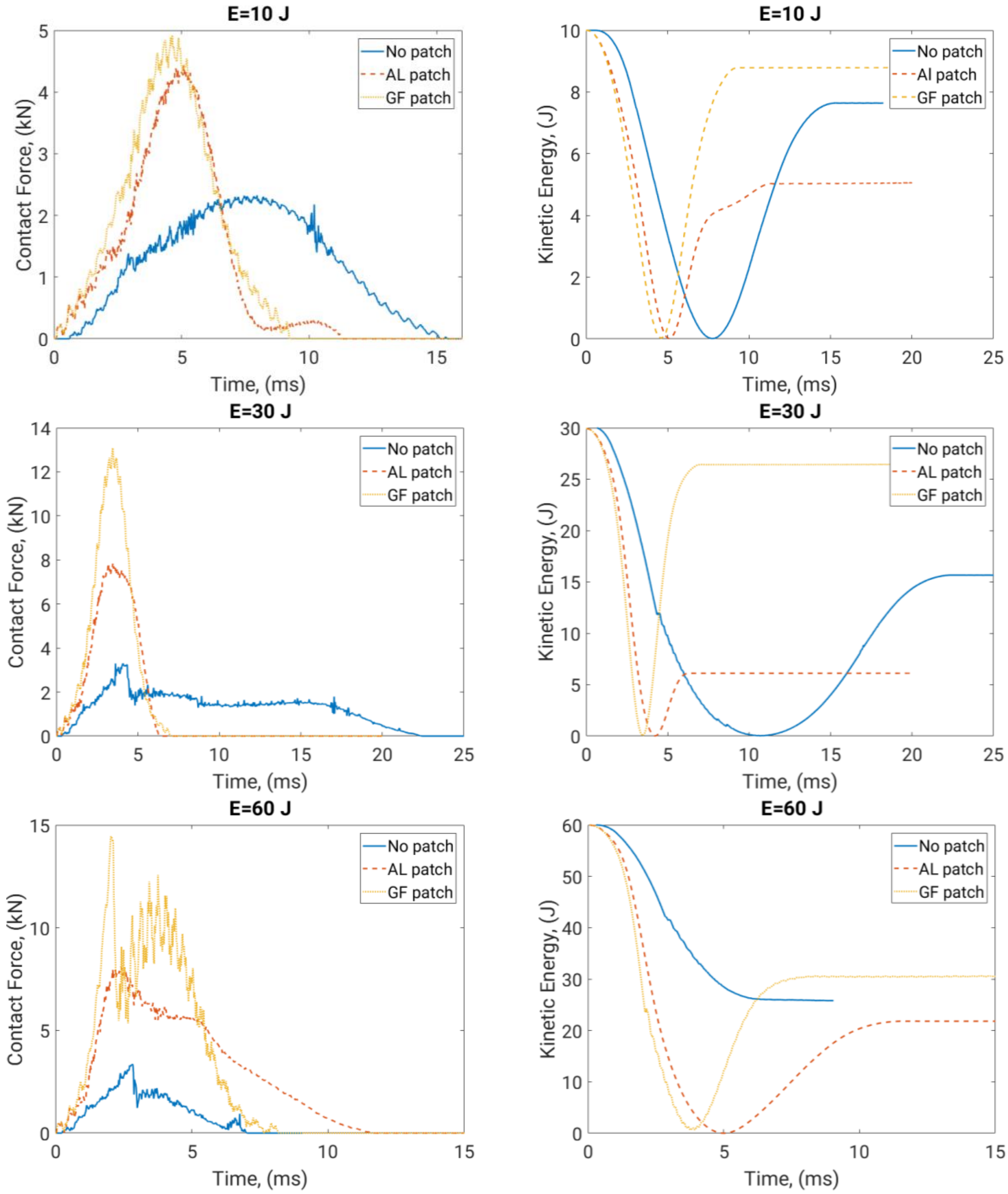


Figure 5. Effect of the composite patch material on the variations of contact force for the impact energies of 10, 30 and 60 J

The impact analyses are completed in total contact times of 7, 12, 8.2 ms. As the impact energy is increased, the peak contact force levels are increased. The notched composite plate without patch is perforated in the impact energy of 60 J. The minimum peak contact force appeared in notched composite plate without patch and the maximum peak contact force was appeared in notched composite plate with composite patch.

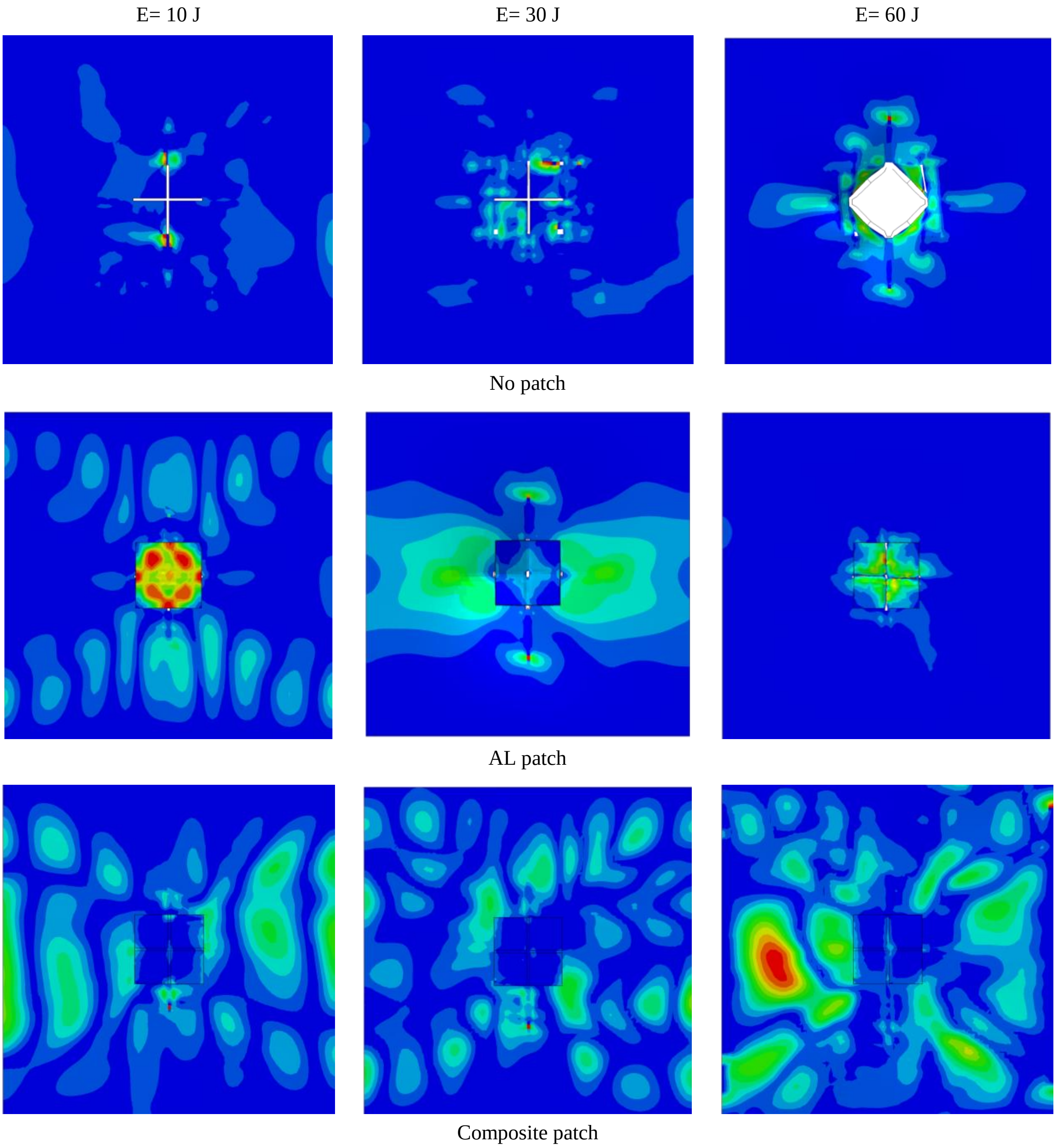


Figure 6. The effect of the patch material on the stress distribution for the impact energy levels of 10, 30 and 60 J

The notched composite plate without patch, with metal patch and with composite patch reduce impact energy of 10 J to kinetic energy levels of 7.8, 5 and 9 J, respectively; thus, the impact energies are dissipated by 22, 50 and 10 %, respectively. For the impact energy level of 30 J the models reduce to kinetic energy levels of 15, 7 and 26 J, respectively and the impact energies are dissipated by 50, 76.6 and 13.3%, respectively. They also reduce impact energy of 60 J to kinetic energy levels of perforated, 20 and 30 J, respectively; thus, the impact energies are dissipated by 100, 66.6 and 50%, respectively. The composite plate with metal patch deforms plastically, so the notched composite plate with metal patch could absorb more much impact energy. The notched composite plate without patch was perforated in the impact energy level of 60 J.

Figure 6 the effect of the patch material as metal and composite on the stress distribution for the impact energy levels of 10, 30 and 60 J. As the impact energy is increased, the stress levels increase naturally. Generally, high level stress regions appear in fiber direction for all specimens. Figure 7 shows effect of tensile and compression fiber, tensile and composite matrix Hashin damage initiation criterion on notched composite plate without patch for the impact energy levels of 10, 30 and 60 J. Tensile damage occurs in notch around, however compression damage occurs in fiber direction along specimen length. Compression damage is effective according to tensile damage. Matrix tensile damage level is maximum.

Figure 8 shows effect of tensile and compression fiber, tensile and composite matrix Hashin damage initiation criterion on notched composite plate with metal patch for the impact energy levels of 10, 30 and 60 J. Damage regions are decreased by using patch according to without patch composite plate. Compression damage also is effective than tensile damage and fiber and matrix compressive damage is opposite direction. Tensile damage occurs around notch regions. Figure 9 shows effect of tensile and compression fiber, tensile and composite matrix Hashin damage initiation criterion on notched composite plate with composite patch for the impact energy levels of 10, 30 and 60 J. Minimum damage levels occur in composite plate with composite patch. Using composite patch is very successful to prevent fiber and matrix damage. Fiber compression damage occurs in boundary condition regions.

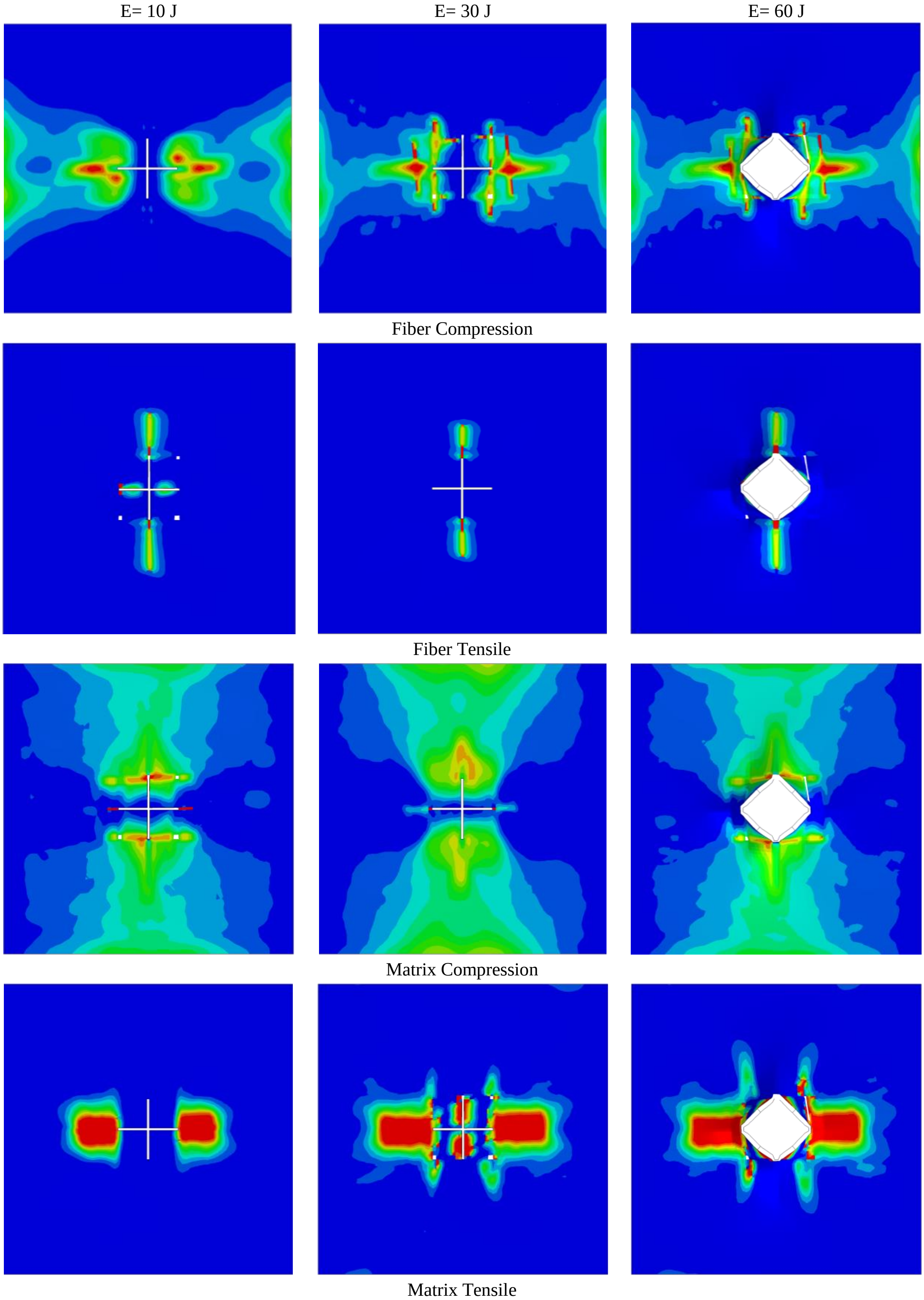


Figure 7. The effect of Hashin Damage Initiation Criterion on no patch composite plate for the impact energy levels of 10, 30 and 60 J

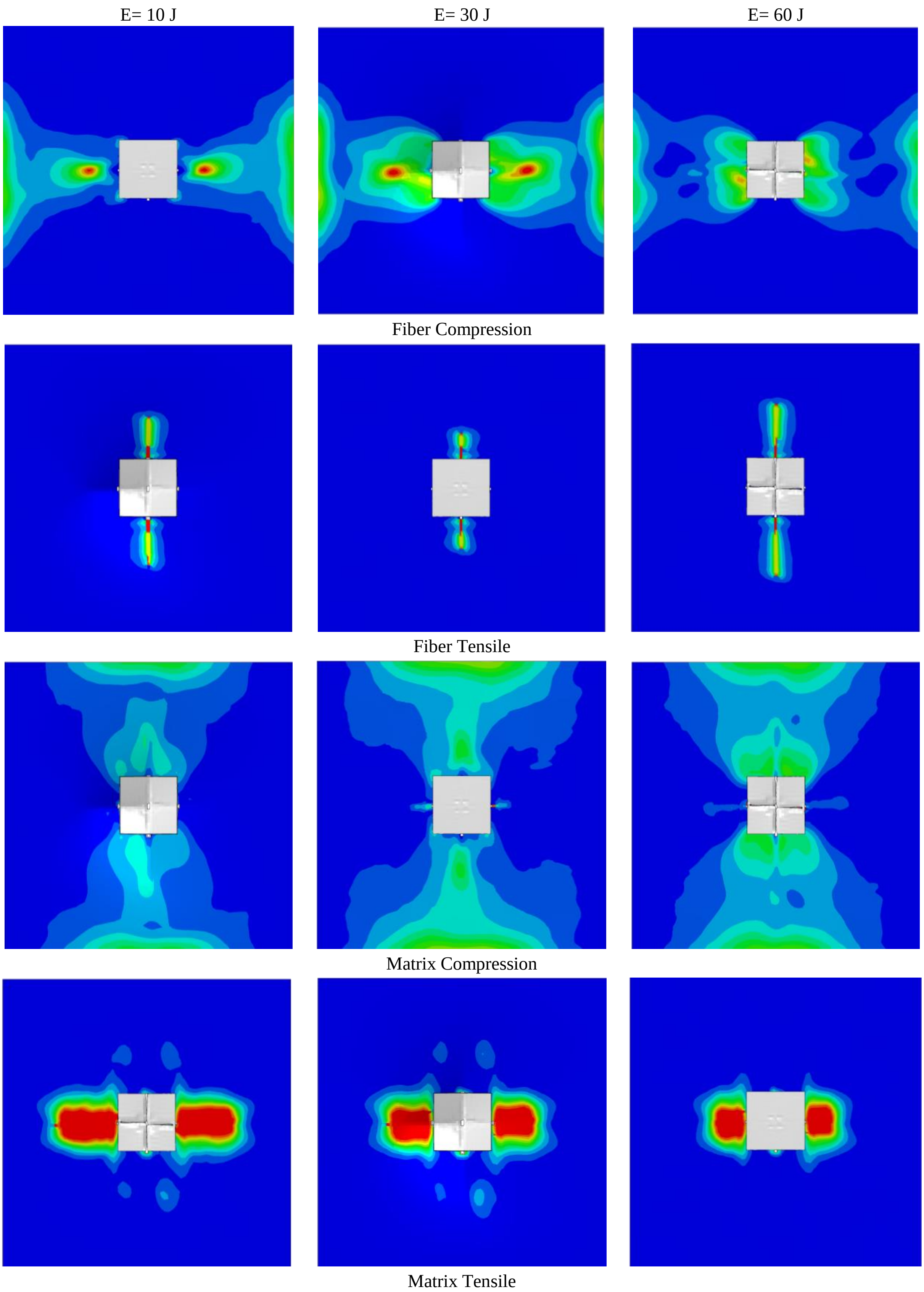


Figure 8. The effect of Hashin Damage Initiation Criterion on composite plate with metal patch for the impact energy levels of 10, 30 and 60 J

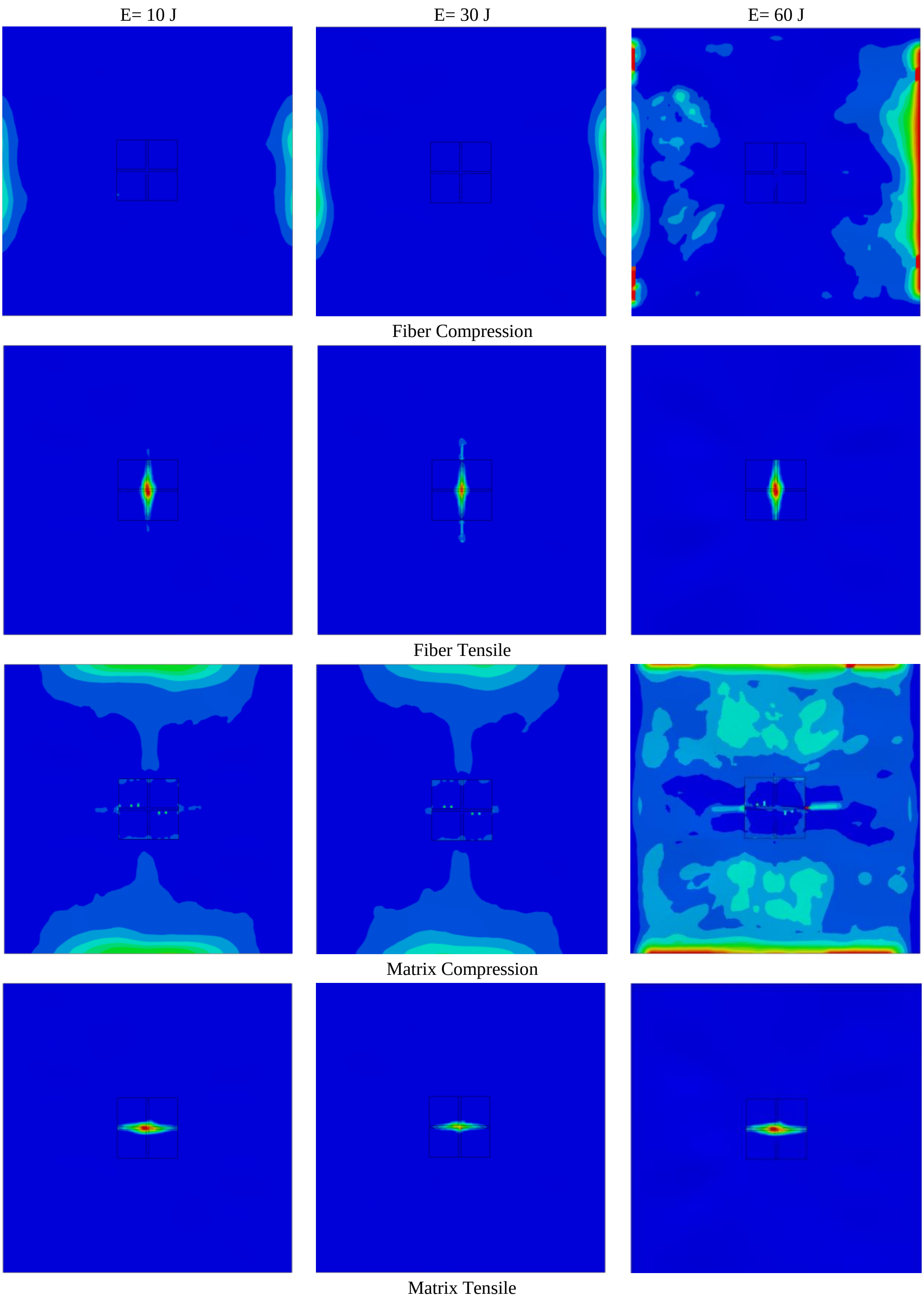


Figure 9. The effect of Hashin Damage Initiation Criterion on composite plate with composite patch for the impact energy levels of 10, 30 and 60 J

4. CONCLUSION

This study addresses the low velocity impact behavior of damaged composite plates with different patches as numerically. The temporal variations of contact force and kinetic energy of damged composite plates with patches were determined numerically for three energy levels. The cohesive zone model was impelemented for modelling the adhesive layer. As the impact energy is increased, the peak contact force levels are increased. The notched composite plate without patch is perforated in the impact energy of 60 J. The minimum peak contact force appeared in notched composite plate without patch and the maximum peak contact force was appeared in notched composite plate with composite patch. The composite plate with metal patch deforms plastically, so the notched composite plate with metal patch could absorb more much impact energy. The notched composite plate without patch was perforated in the impact energy level of 60 J. As the impact energy is increased, the stress levels increase naturally. Generally, high level stress regions appear in fiber direction for all specimens. Tensile damage occurs in notch around, however compression damage occurs in fiber direction along specimen length. Compression damage is effective according to tensile damage. Matrix tensile damage level is maximum. Damage regions are decreased by using patch according to without patch composite plate. Compression damage also is effective than tensile damage and fiber and matrix compressive damage is opposite direction. Tensile damage occurs around notch regions.

ACKNOWLEDGEMENT

This study was supported by The Scientific and Technological Research Council of Turkey (TUBİTAK) (216M519).

REFERENCES / KAYNAKLAR

ABAQUS/Explicit (Version 6.14). *User's manual, Finite Element Software*. Available from: http://www.simulia. com.

Andrew, J., Srinivasan, S. M. & Arockiarajan, A. (2018). The role of adhesively bonded super hybrid external patches on the impact and post-impact response of repaired glass/epoxy composite laminates. *Composite Structures*, 184, 848-859.

Campilho, R.D.S.G., Banea, M.D., Neto, J.A.B.P. & Silva, L.F.M. (2013). Modelling adhesive joints with cohesive zone models: effect of the cohesive law shape of the adhesive layer. *International Journal of Adhesion and Adhesives*, 56, 44-48.

Coelho, S. R. M., Reis, P. N. B., Ferreira, J. A. M. & Pereira, A. M. (2017). Effects of external patch configuration on repaired composite laminates subjected to multi-impacts. *Composite Structures*, 168, 259-265.

Çalışkan, U., Ekici, R. & Apalak M.K. (2017). Effect of composite patch geometry in notched plates under low velocity impact. *International Journal of Engineering Research and Development*, 9, 115-125.

Deng, J., Zhou, G., Bordas, S. P. A., Xiang, C. & Cai, D. (2017). Numerical evaluation of buckling behaviour induced by compression on patch-repaired composites. *Composite Structures*, 168, 582-596.

Hashin, Z. (1980). Failure criteria for unidirectional fiber composites. *Journal of Applied Mechanics*, 47, 329-334.

Kwon, Y. W. & Hall, B. L. (2015). Analyses of cracks in thick stiffened plates repaired with single-sided composite patch. *Composite Structures*, 119, 727-737.

Maamar, D. B., Zenasni, R., Olay, J.V. & Amado, A. A. (2015). Effect of hydrothermal aging and circular notch on tensile strength of woven composite materials repaired by a bonded composite patch. *International Journal of Composite Materials*, *5*(2), 25-29.

Manes, A., Serpellini, F., Pagani, M., Saponara, M. & Giglio, M. (2014). Perforation and penetration of aluminum target plates by armour piercing bullets. *International Journal of Impact Engineering*, 69, 39-54, 2014.

Pandey, P.C. & Kumar, S. (2010). Adhesively-bonded patch repair with composites. *Defence Science Journal*, 60, 320-329.

Singh, H., Namala, K. K. & Mahajan, P. (2015). A damage evolution study of E-glass/epoxy composite under low velocity impact. *Composites Part B*, 76, 235-248.