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Research Article

Effect of Fibre Orientation and Loading Direction on The Compressive Response of E-Glass/Epoxy Laminated Composites Used in Modern Helicopter Blades

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ABSTRACT

In this investigation, the dynamic compression tests of glass fibre reinforced polymer was studied experimentally and numerically under varying the fibres orientation and the loading conditions to obtain the dynamic behavior. The composites consist of uni-directional E-glass fibres reinforced epoxy polymer composites used as an inner surface in modern helicopter blade application. Specimens with a cylindrical shape are impacted at a constant strain rate under in-plane and out-of-plane, subjected to the Split Hopkinson Pressure Bar (SHPB) and LS-DYNA® programs. The numerical results are in good agreement with experimental results. The results show that the out-of-plane stress values for different fibre orientation are close to each other, but the in-plane stress value is far lower for the fibres direction of 45^{00}. This study can give ideas about fibre orientation selection for dynamic effects during the helicopter blade production phase. Not only simple tests but also practical ideas make this study stand out. Considering results, 90^{0} fibre direction in helicopter blades seems more advantageous against dynamic effects.

Introduction

Several rotor blades combination creates a helicopter rotor system and a control system that generates the aerodynamic lift and thrust forces in forwarding flight. Since helicopters are capable of vertical landing and takeoff, they are exposed to foreign matter damage in different terrain conditions. As the blades rotate very fast and due to the turbulence it creates, the most exposed part to the foreign material damage is the surface of the blades. Historically, the blade surface was made with clothes initial, and then metallic materials were used in production. Helicopter rotor blade surface was moved into the third revolutionary change to the all-composite structure. There has been growing application in composite materials for lighter and more efficient helicopter blades instead of metallic materials. The main characteristics of composite structures superior to metal structures are low crack propagation rate and the nature of failures for rotor blades [1]. Examples of this trend are placed in recent aircraft as Airbus company helicopter models, in which the extensive use of composite parts. For instance, AS 532 Cougar helicopter rotor blades have hybrid composite parts whose outer surface is carbon fibre and the inner surface is glass fibre epoxy plates [2]. The utilization of laminated composite materials in many mechanical and aerospace engineering structures has increased due to, among other factors, their specific stiffness and strength [3]. Although composite materials have many advantages, they have a low resistance of high-speed impact compared to metallic structures. Thus, it is mandatory to accurately describe damage under dynamic loading and the effect of strain rate on the response of these materials for safety design. The Split Hopkinson Pressure Bar (SHPB) have widely used to describe the dynamic properties of materials at different strain rates [4-7]. The effect of different strain rates on dynamic behavior in composite laminates were studied using the Split Hopkinson Bar [8-11]. Hosur et al. [12] investigated the dynamic behavior of uni-directional carbon/epoxy composite laminates under SHPB compression tests related to various strain rates. The dynamic results were compared with static compression tests, and they found that the stiffness and hardness values obtained from dynamic tests are higher than the values obtained in static tests. The dynamic compressive action of uni-directional glass/epoxy composite at different off-axis angles in the transverse and longitudinal methods direction was studied by Kumar et al. [13]. Dynamic behavior of glass fibre reinforced polymers obtained for in-plane and out-of-plane compression tests were studied using SHPB varying the fibres direction and the loading types by Tarfaoui et al. [14,15]. For in-plane tests, they revealed that the dynamic strength of the material is dependent on fibre orientation and impact pressure. The material is also highly sensitive to fibre orientation at the same impact pressure for out-of-plane tests. The dynamic compressive behavior of $[0/90^0]_{26}$ glass/epoxy laminates in-plane and out-of-plane directions was studied using (SHPB) by Arbaoui et al. [16,17]. They emphasized that the in-plane loading condition is weaker than the out-of plane loading condition and the strain rate is the factor determining the dynamic properties. As can be seen from the available literature, there are studies in which glass fibre composites [18-22] but, there are few studies focused on production and practice related to the high-speed impact of modern helicopter blades using SHPB) device and LS-DYNA® program. This paper concerns the in-plane and out-of-plane dynamic impact of glass fibre laminated composites. Compression tests were performed at 10 psi impact pressure to catch desired speed (10 *m/s*) following the machine pressure-velocity chart. In-plane-loading, parallel to the layers plane and out-of-plane loading, according to the thickness, was selected due to the high-speed rotation behavior of the blades. All of the tests were carried out according to the fibres direction of 90^0 and 45^0. Dynamic stress and time results were presented as graphics for good comparisons. These results will play a helpful role in developing carbon/glass hybrid composite models for efficient design optimization related to helicopter blades.

Experimental Procedure

Material and Specimens

Helicopter blades are sandwich structures with carbon fibre plate outside, glass fibre plate underneath and Nomex honeycomb core. Figure 1 represents this structure.

Figure 1. A real cross section from the helicopter blade.(outer surface; Carbon laminate, inner surface; glass laminate, core; Nomex honey comb)

The first part exposed to the impact is the outer carbon and glass fibre layers. Since the impact behavior of the glass fibre layer was discussed in this study, test samples were obtained by preparing glass fibre layers. Panels of 500*mm* × 500*mm* were made by infusion process (see Figure2), with 36 unidirectional layers, stacking sequence of $[0/45]_{36}$ and $[0/90]_{36}$.

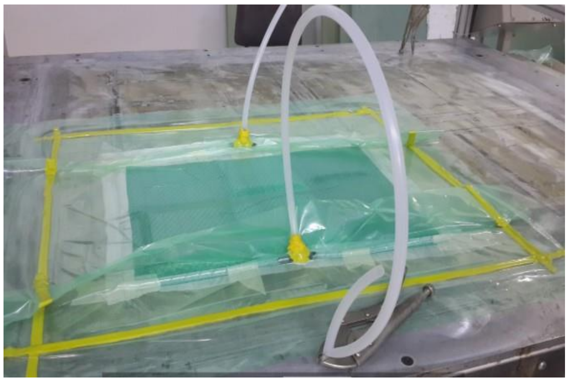

Figure 2. Production of composite layers

The thickness of the samples was applied for10.0 mm. The areal density is 600 g/m^2 for two type of samples. A bicomponent Araldite LY 564 epoxy resin with an Aradur 3487 BD hardener was used as a thermoset polymeric matrix. The mixing ratio of the epoxy to the hardener was 3:1 by weight. The resin was infused under the vacuum as 1 bar after packaging materials. Curing was applied on a heating table at 50^0C for 30 min preheating and cured at 100 ^0C for 2 hours. After, samples were left for cooling at room temperature. Each layer creates orthotropic mechanical properties in the three orthogonal directions. For dynamic experiments, the cylindrical specimens were cut with a diameter of 6.0 *mm* for out-of-plane and in-plane loading testing (see Figure3).

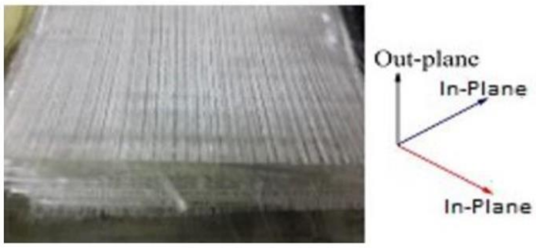

Figure 3. fibre layers and plane construction representation

The aspect ratio of the cylinder specimens was selected to satisfy dynamic equilibrium requirements in SHPB testing under plane loadings. The cylindrical samples were cut slowly using vertical CNC machine without using water (see Figure 4). The accuracy of the measurements was checked at each stage.

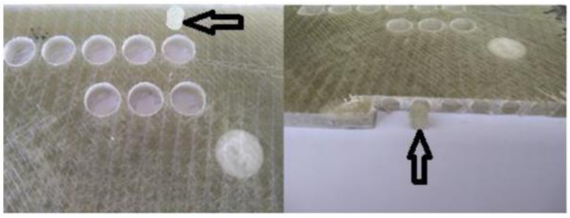

Figure 4. Cutting samples in the out-of-plane (a) and in-plane direction (b)

Experimental Details For Tensile Tests

The glass fibre reinforced polymer layers were produced using the vacuum infusion method. Uni-directional E-glass fibres and Aradut epoxy resin were used to produce the four-laminates. The composite laminates were about 1,5 mm in thickness. They were cut into samples having sizes of tensile test standards by using a water jet cutting machine (see Figure 5). LS-DYNA® parameters were determined with tensile testing of the glass fibre reinforced polymer specimens according to ASTM D3039 and ASTM D638 standards.

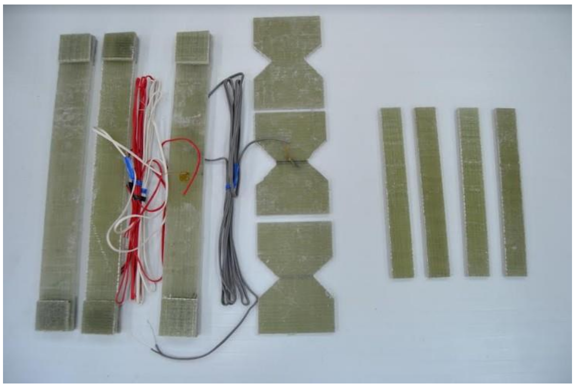

Figure 5. Sizes of tensile test specimens

Dynamic Compressions

The prepared samples were subjected to uniaxial high strain rates in compression using the SHPB technique. Developed according to the recommendations of Gallina and coworkers [23], the SHPB apparatus (see Figure 6) is suitable for tests at strain rates in the range of 10^2 to 10^4 s^{-1}.

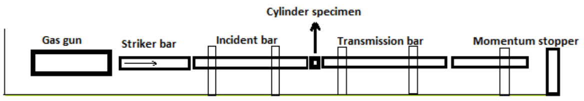

Figure 6. Split Hopkinson pressure bar system setup

To provide the hypothesis of one-dimensional wave propagation, the length of the striker bar used in the SHPB apparatus is 300.0 mm and transmission bars are 2.0 m with a length/diameter ratio of 100 for both the incoming and transmitting rods [24].

High strength steel was chosen for the bar material to match the impedance resistance with the composite samples [25]. To validate the results obtained from the experiment, at least three SHPB samples were tested for each parameter listed in Table 1.

Sample Number	fibre Orientation, out-of-plane/in-plane impact and test number (respectively)
A10	90° fibre orientation, out-of-plane loading, LS-DYNA®
A1	90° fibre orientation, out-of-plane loading experiment
A20	90° fibre orientation, in-plane loading, Ls Dyna
A2	90° fibre orientation, in-plane loading experiment
B10	45° fibre orientation, out-of-plane loading, Ls Dyna
B1	45° fibre orientation, out-of-plane loading experiment
B20	45° fibre orientation, in-plane loading,LS-DYNA®
B2	45° fibre orientation, in-plane loading experiment

TABLE 1. Sample numbers, fibre Orientation, out-of-plane/in-plane impact and test number. (Note:Since the B10 LS-DYNA® results are the same as the A10 LS-DYNA® results, only A10 is presented in the comparison charts.)

Petroleum jelly was rubbed into the sample and bar interior surfaces to reduce interfacial friction.19.0 mm diameter maraging steel bars were used for all tests. Considering the velocity effects on the sample and data scattering, the sample strength was 6 *GPa* and the yield strength in the bar was 2.4 *GPa* at most, which was adapted to the experimental design.

The maximum sample diameters d_s and bar diameters d_b can be estimated. 2.4 *GPa* bar strength is an ultra high strength steel featıre. Accordingly, equation 1 gives the sample diameter approximately 6 mm. After determining the sample diameter, the second priority dimension is the sample thickness. The aspect-to diameter ratio is 1.0 for the brittle materials used in the SHPB experiments, and slight failure strain in the specimen limit the achievable strain rate [26]. Both end faces of the sample should be flat and parallel. Figure 7 shows an example of a composite cylindrical specimen.

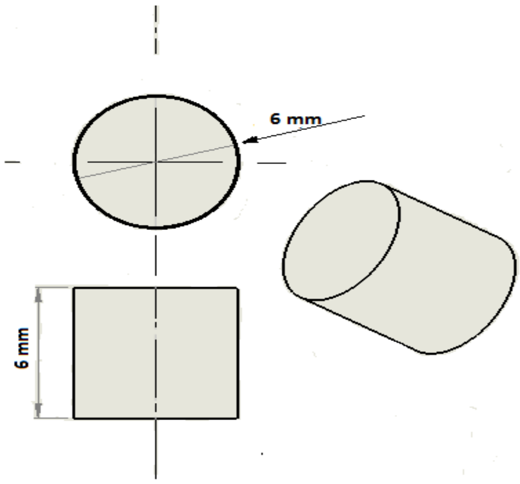

Figure 7. Geometry of a hard specimen prepared for SHPB

While inspecting the damaged helicopter blades, the impact relates to the out- of-plane and the in-plane. Because, according to the working principle, foreign materials moved by turbulence or blade rotating at a speed of about 265 RPM during contact with the branches of a tree or stone hit the composite structure just behind the leading edge. Due to the shape of the raindrop, a parallel collision occurs on the layers immediately after contact with the surface (see Figure 8).

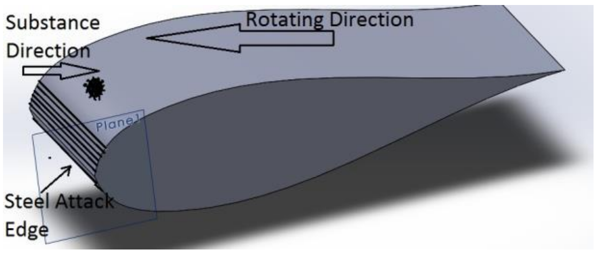

Figure 8. Illustration of impact processing to blade

In Fig 9, the Turkish Air Force Blade Repair Center photos illustrate real foreign material damage on the blade surface during flight.

Figure 9. Damaged main rotor blade: Turkish Airforce Blade Repair Center

It shows that in-plane impacts are an issue to be emphasized for both carbon and glass fibre plates in addition to out-off plane impacts. The basis of the study was inspired by real damages on blades.

$$d_s = \sqrt{\frac{0.3 \times 2.4}{6}} d_B = 0.346 \times 19 = 6.57\ mm$$

Numerical Model

Mat_Composite_Failure_Solid_Model

The simplified failure model of glassfibre reinforced polymersamples was conducted to obtain an impact curve under the impact loading. material mode $MAT59$ (MAT_COMPOSITE_FAILURE_SOLID_MODEL) was selected for model the SHPB testing. In $MAT59$, material parameters (Table 2) are obtained from static tests using the same composite plate samples.

E_a	E_b	E_c	G_{ab}	G_{bc}	G_{ba}	V_{ba}	V_{bc}	V_{ca}
25.3 GPa	25.3 GPa	1.51 GPa	4.7 GPa	3.8 GPa	3.8 GPa	0.2	0.12	0.12
XX_T	YY_C	S_{BA}	XX_C	YY_T	S_{CB}	S_{CA}	ZZ_T	ZZ_C
610 MPa	412 MPa	100 MPa	412 MPa	610 MPa	93 MPa	93 MPa	366 MPa	247 MPa

TABLE 2. Material parameters for glass fibre reinforced polymer laminates

Impact Demage Simulation

The material type and size used in the computational model were the same as reported in the experimental studies without bar length. Simulations were modelled for glass fibre reinforced polymer cubic test samples by SHPB bars. SHPB bars have been reduce by 1:20 to get results in a shorter time. In addition, the density of the bars has been increased at the same rate. The results of these analysis were substantially similar to the SHPB test results. The impact simulation curves of out-of-plane specimens are more convergent than the curves of in plane test results.

Results And Discussion

An engineering stress-time curve was obtained so that the strain rate did not change. The specimen was broken into pieces at a strain rate of about 1000 $s^{-1}$and a velocity of the striker bar of about 10.0 *m/s*. Each type of specimen with the same test condition has been tested more than three times to verify the reliability of the results. The stress-time curves at constant strain rates have been obtained for different fibre orientations, as shown in Fig 10-13 (out-off-plane, in-plane direction).

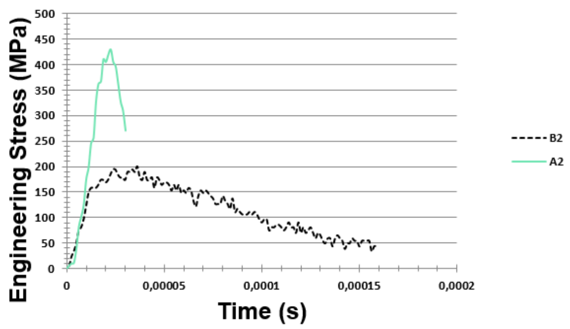

Figure 10. The stress-time curves of the specimen under in-plane loading

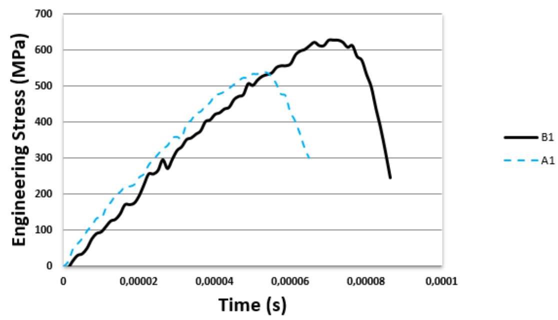

Figure 11. The stress-time curves of the specimen under out-of-plane loading

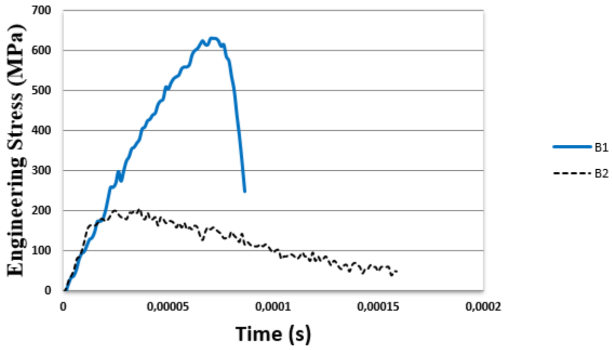

Figure 12. The stress-time curves of the specimen under out-of-plane loading and in-plane loading.

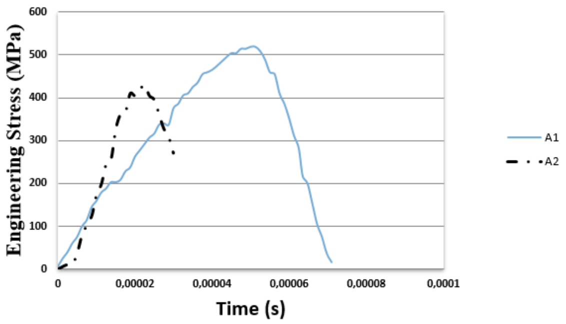

Figure 13. The stress-time curves of the specimen under out-of-plane loading and in-plane loading

All results of glass fibre samples agree well; it could be considered correct and used to be studied. The appropriateness of the results is seen and interpreted from the comparative charts presented (see Figure 14).

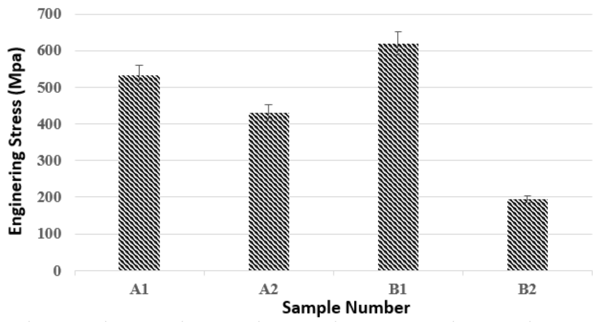

Figure 14. A comparison of all test results with the standard deviation.

A2 reached approximately the twice stress value compared to B2.Considering that the materials hit the propeller surface horizontally in general, the 90^0 fibre array is considered an advantage.

For in-plane tests, impact pressure and fibre orientation largely determine the dynamic strength of the material. A1 and B1 reached a similar stress value compared to in-plane loading. It was observed that the fibre arrangement does not significantly affect the impacts applied to the surface in a vertical direction. When evaluating the effect of vertical impacts on the blades, it is concluded that fibre orientation may not be compared. B1 reached more than twice the stress value compared to B2 (see Figure 12). A1 reached a more significant stress value than A2 (see Figure 13). The difference between A1 and A2 is far smaller than between B1 and B2. The slope of the curves steepens with in-plane loading for A. In addition, the peak stress of composites was obtained for B with out-of-plane loading. As in this study, Tarfaoui et al. [5] presented that the dynamic strength of materials mostly depends on fibre orientation for in-plane tests. It can be seen that A2 and B2 comparison in Figure 10. Arbaoui et al. [16,17] emphasized that the dynamic properties of $[0/90^0]_{36}$ glass/epoxy laminates are strain-rate sensitive, and the out-of-plane loading condition is when the material is more resistant than the in-plane loading condition.

Experimental Results Comparison. We obtained that $[0/45^0]_{36}$ glass/epoxy laminates are more resistant in the case of out-of-plane loading as compared to the in-plane loading case than results of $[0/90^0]_{36}$ glass/epoxy laminates comparison case. A1 and B1 comparisons can be seen easily in figure 11. Composites contain weaker epoxy resin than fibres between fibre layers. The fibre material has minimal time to respond when loading by the in-plane dynamic method. However, all specimen types have already split into pieces with 10 m/s striker velocity, as shown in figure 15.

Figure 15. Disruption of the specimen under in-lane loading

Experimental and Numerical Results Comparison. The compression after impact simulations is applied with the LS-DYNA® program.

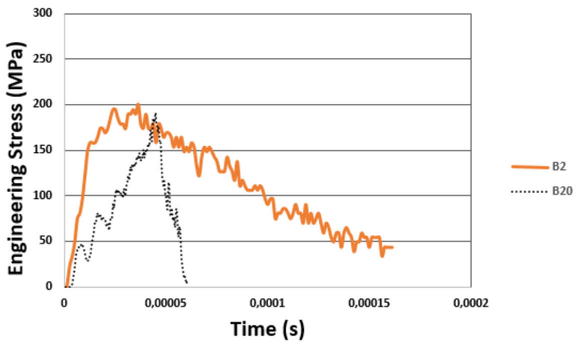

Figure 16. Comparison of stress and time with varying fibre orientation under in-plane loading conditions (Fibre

Orientation:45^0)

Comparisons of the stress and time values obtained from the tests and numerical simulations performed for all samples are presented on graphics (see Figure 17-18).

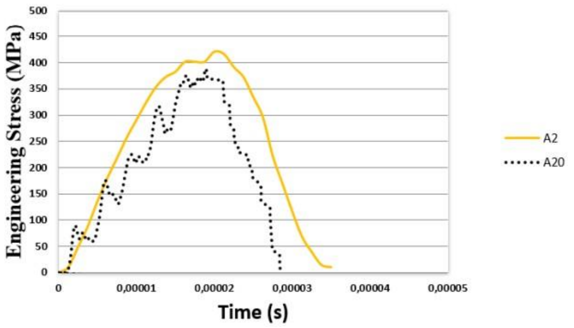

Figure 17. Comparison of stress and time with varying fibre orientation under in-plane loading conditions (Fibre Orientation:90^0)

Stress was obtained as 190.0 *MPa* for 45^0 fibre Orientation specimen and 185.0 *MPa* for the numerical model in LS-DYNA® under in-plane loading conditions as shown in Figure 17. The results show the difference rate between experimental and numerical results as 3%. Stress were obtained as 430.0 *MPa* for 90^0 fibre Orientation specimen and 375.0 *MPa* for the numerical model in LS-DYNA® under out of-plane loading conditions as shown in Figure 16. The results show the difference rate between experimental and numerical results as 12%. Stress was obtained as 520.0 *MPa* for the 90^0 fibre orientation specimen and 470.0 *MPa* for the numerical model in LS-DYNA®

under out-of-plane loading conditions, as shown in Figure 18.

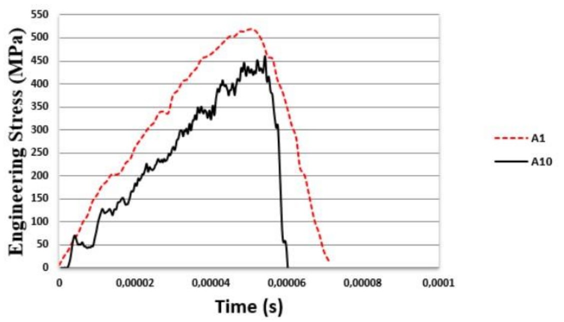

Figure 18. Comparison of stress and time with varying fibre orientation under out of-plane loading conditions (Fibre Orientation:90^0)

The results show the difference rate between experimental and numerical results as 9%. Also, graphic line slopes are very close to each other for out-of-plane loading conditions than in-plane loading.

Conclusions

The glass/epoxy laminate composites in our research are reliable materials for the inclusive casings of the helicopter rotor blades. For this reason, considering the working principle of the blades, the focus is on out-of-plane and in-plane impact using SHPB. The epoxy mainly bears the loading when dynamic compression is applied in the in-plane direction. For tensile strength character, in-plane strength is much higher than out-of-plane strength contrast the compression strength character [27]. Tarfaoui et al. [28] highlighted that the glass/epoxy composites offer high strength properties in out-of-plane pressure dynamic load tests as we obtained. Details photos and research from the helicopter blade repair centre show that the damages occur in-plane direction due to the blades' structure and range of motion. Designers can increase the dynamic resistance strength of helicopter rotor blades with 90^0 degrees fibre orientation selection. Depending on the loading direction and fibre orientation, the material behaves as follows:

1. The composites are strain-rate sensitive materials. The strength limit and the slope of the stress–time curves steepen for 45^0 fibre orientation under in-plane dynamic compression.

2. Regardless of the application direction of the force and fibre orientation, all samples were split into pieces with 10 *m/s* striker velocity.

3. $\pm 90^0$ and $\pm 45^0$ fibre orientation stress value decreasing rate was obtained as 17% and 69%, respectively, while the stress value decreases by changing loading direction from out-of-plane to in-plane.

4. Out-of-plane and in-plane stress value decreasing rate was obtained as 16% and 55% respectively in the stress value decreases while the changing of fibre orientation from $\pm 90^0$ to $\pm 45^0$.

5. Considering that the materials which hit the propellers generally come horizontal to the surface because of the blade shape and flight principle, the $\pm 90^0$ fibre array is considered to be an advantage.

6. It was observed that the fibre arrangement does not have a significant effect on the impacts applied to the surface for out-of-plane direction.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared

There is no conflict of interest with any person / institution in the article prepared

Authors' Contributions

Çelik A: Study conception, testing, simulation, analysis, and interpretation of data, drafting of manuscript

Arman Y: Conceived the original idea, supervised the project, critical revision

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References

[1] L.L.Douglas and W.K. Stratton. Technical breakthrough for helicopter rotor blades, SAE Transac- tions,Composite Structure Vol. 84, Section 4: 750934–751187 (1975), pp. 3114-3130.

[2] W.B. Harlamert, R. Edinger, Development of an aircraft composite propeller, SAE Transactions, Vol. 88, Section 3: 790527–790858 (1979), pp. 2028-2033.

[3] R.M. Marat-Mendes, M.M. Freitas, Failure criteria for mixed mode delamination in glass fibre epoxy composites, Composite Structure 92 (2010) 2292–2298.

[4] Z. Song, Z. Wang, H. Ma, H. Xuan, Mechanical behavior and failure mode of woven carbon/epoxy laminatecomposites under dynamic compressive loading, Composite Part B 60 (2014) 531-536.

[5] M. Tarfaoui, S. Choukri, A. Neme, Dynamic response of symmetric and asymmetric Eglass/epoxy laminates at high strain rates. Key Engineering Materials 2010;446:73–82.

[6] A. Jadhav, E. Woldesenbet, S. Pang, High strain rate properties of balancedangle-plygraphite/epoxycomposites. Composite PartB 34 (2003)339-346.

[7] J. Arbaoui, M. Tarfaoui, C. Bouery, A. EL Malki Alaoui, Comparison study of mechanical prop- erties and damage kinetics of 2D and 3D woven composites under high-strain rate dynamic compressive loading. Int J Damage Mech 2016:1–22.

[8] S. Sassi, M. Tarfaoui, H.B. Yahia.An investigation of in-plane dynamic behavior of adhesively- bonded composite joints under dynamic compression at high strain rate, Composite Structures, Volume 191, 1 May 2018, Pages 168-179.

[9] A.M.A El-Habak. Mechanical behavior of woven glass fibre-reinforced composites under impact compression load. Composites 1991;22(2):129–34.

[10] J. Harding, Effect of strain rate and specimen geometry on the compressive strength of woven glass-reinforced epoxy laminates. Composites 1993;24(4):323–32.

[11] R. L. Sierakowski, G.E. Nevill. Dynamic compressive strength and failure of steel reinforced epoxy composites. Journal of Composite Materials 1971;5:362–77.

[12] M.V. Hosur, J. Alexander, U.K. Vaidya, S. Jeslani, A. Mayer, Studies on the o.-axis high strain rate compression loading of satin weave carbon/epoxy composites. Composite Structure 2004; 63: 75–85.

[13] P. Kumar, A. Garg, B.D. Argawal. Dynamic compressive behavior of unidirectional GFRP for various fibre orientations. Mater Lett 1986;4(2):111–6.

[14] M. Tarfaoui, Experimental investigation of dynamic compression and damage kinetics of glass/epoxy laminated composites under high strain rate compression. In Advances in Com- posite Materials; 2011. p. 359–82 [Chapter 16].

[15] M. Tarfaoui, S. Choukri, A. Neme, Damage kinetics of glass/epoxy composite materials under dynamic compression. Journal of Composite Materials 2009;43(10):1137–54.R. Sharma, P. Sircar, and R. B. Pachori, "Automated focal EEG signal detection based on third order cumulant function," Biomed. Signal Process. Control, vol. 58, p. 101856, 2020.

[16] J. Arbaoui, M. Tarfaoui, A. EL Malki Alaoui, Mechanical behavior and damage kinetics of woven E-glass/Vinylester laminate composites under high strain rate dynamic compressive load- ing: experimental and numerical investigation. International Journal of Impact Engineering 2016:44–54.

[17] J. Arbaoui, M. Tarfaoui, A. EL Malki Alaoui, Dynamical characterisation and damage mech- anisms of E-glass/Vinylester woven composites at high strain rates compression. Journals of Composite Materials 2015:1–11.

[18] P.S. Venkatanarayanan, A. Stanley, Intermediate velocity bullet impact response of lam- inated glass fibre reinforced hybrid (HEP) resin carbon nano composite, Aerospace Science & Technology. Sep2012, Vol. 21 Issue 1, p75-83. 9p. DOI: 10.1016/j.ast.2011.05.007.

[19] E. Rolfe, C. Kaboglu, R. Quinn, P.A. Hooper, H. Arora, J.P. Dear, High helocity impact and blast loading of composite sandwich sanels with novel carbon and glass construction in: Journal of Dynamic Behavior of Materials. 2018 4(3):359-372.

[20] R.S. Sikarwar, R. Velmurugan, Impact damage assessment of carbon fibre reinforced composite with different stacking sequence, Journal of Composite Materials Jan2020, Vol. 54 Issue 2, p193-203. 11p. DOI: 10.1177/0021998319859934.

[21] R.P.R. Subba, R.T. Sreekantha, K, Mogulanna, I. Srikanth, V. Madhu, R.K. Venkateswara, Ballis- tic impact studies on carbon and E-glass fibre based hybrid composite laminates in plasticity and Impact

Mechanics, Procedia Engineering. 2017 173:293-298 Language: English. DOI: 10.1016/j.proeng.2016.

[22] S.G. Vicente, L.S. Paradela, F. Gálvez, Analytical simulation of high-speed impact onto hybrid glass/carbon epoxy composites targets in International Symposium on Dynamic Response and Failure of Composite Materials, DRaF2014, Procedia Engineering. 2014 88:101-108 Language: English. DOI: 10.1016/j.proeng.2014.11.132.

[23] F. Gallina, R.S. Birch, M. Alves, Design of a split hopkinson pressure bar. 17th ABCM Int. Congr. Mech. Eng., São Paulo 2003.

[24] B.A. Gama, S.L. Lopatnikov, J.W. Gillespie, Hopkinson bar experimental technique: a critical review. Appl Mech Rev 2004;57:223. http://dx.doi.org/10.1115/1. 1704626.

[25] V.L. Reis, G.M. Cândido, M.V. Donadon, C.V. Opelt, M.C. Rezende,Effect of fibre orientation on the compressive response of plain weave carbon fibre/epoxy composites submitted to high strain rates, Composite Structure 203 (2018) 952–959.

[26] W. Chen, B. Song, Split hopkinson (kolsky) bar, Mechanical Engineering Series, USA, DOI 10.1007/978-1-4419-7982-7.

[27] H. Ku, H. Wang, N. Pattarachaiyakoop, M. Trada. A review on the tensile properties of natural fibre reinforced polymer composites. Composite Part B – Eng 2011;42(4):856–73.

[28] M. Tarfaoui, S. Choukri, A. Neme. Effect of fibre orientation on mechanical properties of the laminated polymer composites subjected to out-of-plane high strain rate compressive loadings, Composite Science and Technology 2007, 68(2): 477–485.