Impact Analysis of Fabric Reinforced Plates

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Many studies are concerning with impact properties of composite materials because their large usage in aero-spatial, automotive, marine and sport industry. As the use of composites is continuously increasing the need for more valuable materials becomes essential in designing and producing such materials for a growing market. It is well known that thermoplastic matrix composites show better impact resistance than the thermoset matrix materials but their forming technology is more expensive. This study was designed to analyse the impact behaviour of fabric reinforced thermoset polymer matrix composites with an emphasis on structure of reinforcement. The matrix is an epoxy resin (Epiphen RE4020 – DE 4020, Bostik) while the used fabrics are of carbon fibres, aramid, fibres and glass fibres. Low velocity tests were performed on materials, according to ISO N-6603, and the results were inspected by tomography.

Keywords: epoxy resin, fabrics, impact tests

Despite their excellent mechanical properties the thermoset matrix composite materials are less used in applications that could involve impacts due to their limited resistance. This behaviour is generated, on one hand, by the intrinsic properties of polymer, and, on the other hand by the rigidity of fibre-matrix interphase. The visco-elastic properties of thermoset polymers are different from the ones of thermoplastic polymers. For instance during mechanical tests thermosets and thermoplastics shows different behaviours (the first are breaking and the others are yielding). Of course these behaviours are observable at low speed loading but they manifest also when the loading is fast (as in the case of impact tests)[1, 2]. The brittleness of thermoset polymer is producing strong shear effects which are determining the reinforcement fracture while in the thermoplastics the energy is disipated due to the viscoelastic/viscoplastic behaviour and the reinforcement is less affected. Still, for aerospace applications the thermosets are more attractive due to their thermal stability while the thermoplastics are avoided because the disadvantages induced by local increases of temperature (even for high temperatures processable polymers) [3-7]. An excellent description of parameters that are influencing the impact damages is made in [8].

Many studies are concerning the ways to improve the impact resistance of composite materials and structures with thermoset matrix and in this regard several solutions have been purposed: toughening the matrix [9-11], hybridising the reinforcement [12-16], making more elastic the reinforcement-matrix interphase [17], etc. Other studies are excellent experimental [18-23] or theoretical approaches [24-30] but generally the studies are oriented toward post impact analysis of materials and of their properties [31-35].

Of course the impact resistance of composites is one of great interest as far as the trend is to replace the metals in – almost – all their applications. The testing methods are standardized and the results are easily interpretable based on the actual knowledge but the composites are not the same and different results may occur. It is well known the fact that besides properties of matrix, properties of fibres and quality of interphase one very important aspect concerning the composites properties is the forming technique. The material inspection before and after testing remains a very important approach to understand materials behaviour besides its necessity regarding regular and normal analysis required by regulations.

It is obvious that the effects of impact are producing damages on any material but especially on reinforced composites because of their inhomogeneous structure. It is expected, for instance, that due to their different densities fibres and matrix to dissipate differently the energy with consequences regarding the interphase loading and, depending on interface quality, to different types of damages. The fibres properties are of great importance in explaining the impact behaviour of materials and especially in explaining the impact damages. The more complex is the material structure the more complex are the explanations for impact effects and for produced damages. In the case of fibres reinforced composites the failure theory is imparting the failure mechanisms into two categories – matrix failure and fibre failure. The first is appearing when the elastic constants of fibres are higher than the ones of matrix and, of course, the second one when the elastic constants of matrix are higher. In the case of fabric reinforced composites the situation is more complex due the fact that by its structure the fabric is introducing a fibre weakness because of reciprocal passing above and under of warp and fill yarns. When a load is applied on the warp direction the not only the warp yarns will be affected but also the fill yarns. The effects of impact, in this case, will be more complex than the ones in the case of uni-directional fibres reinforced composites.

Another aspect is regarding the forming technique namely the fact that producing a laminate is a matter of bonding together the pre-pregs. In the case of thermoplastics the situation is clear – if the process requirements are reached the polymer will melt between and in-between plies and the material quality is ensured. In the case of thermosets the situation is different because bonding requires adhesives and they are introducing supplementary problems due to the interphase adhesive-matrix. The situation is avoidable in the case of epoxy resins

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(which are excellent adhesives) if the fibres are prepared for a certain polymer (the one that will be used to form the composite matrix).

Designing a composite is a matter of balance between required properties, technical possibilities and prices. As it is well known trying to increase a certain property of composite leads to depreciations in other properties for instance increasing the elasticity of fibres-matrix interphase will determine a decrease on mechanical strength of material. In the case of fibres reinforced thermoset polymer the main failure mechanism is the one with matrix failure but – depending on fibres properties and orientations – this is followed by fibres breaking (due to the shear mechanisms if the shear modulus of fibres is low), fibres debonding (when the fibres shear modulus is high) or even yielding (when on the loading direction there are not long fibres). To design a thermoset composite properties sometimes requires to modify the matrix properties – generally by adding some powders inside – for small dimensions of immersed particles and for not very high concentrations it is accepted that mechanical properties of polymer are not decreased but improved (as in the case of CNT, for example). In the case of impact such modified polymer should better resist because its density is increased, the absorbed energy will be higher and the damages reduced.

When such polymer is used to form a fabric reinforced composite the situation become more complex from the microscopic point of view the micro-mechanic approach being necessary to explain the macroscopic results.

Experimental part

Materials and methods

Present study is based on the idea of controlling (by design) the properties of a fabric reinforced epoxy composite by means of using various types of fibres, various fibres orientations together with a comparative study regarding the effect of modified matrix.

Eight composites had been formed using a modified wet lay-up method with fabrics as reinforcement layers and epoxy resin (Epiphen RE402 – DE4020) as matrix for four of them and modified epoxy resin for other four. Each material is reinforced with 17 layers of fabrics which are symmetrically distributed referred to the middle layer. Table 1. contains the main characteristics of the fabrics. The hybrid fabric is modified from a carbon-aramid fabric with a yarn structure of 2:1 (carbon : aramid) on the warp and 1:2 (carbon : aramid) on the fill and on the fill direction each second yarn of aramid fibres was replaced with a glass fibres yarn in which a tinned cooper 0.2 mm diameter wire was inserted. This hybrid fabric was used as medial reinforcement layer and it was cut along the fill yarn. All the materials were formed by imbuing each layer of fabric with pre-polymer mixture and then it was placed into a mould. To apply this technique all the fabrics were prepared to ensure better interphase quality and stability during cutting and moulding manoeuvres. The preparation required many steps and finalized with a polymer thin deposition by spraying on the fabrics surfaces.

The reinforcements distributions (R) are in table 2. and C is denoting the carbon fibres fabric, K the aramid fibres fabric, G glass fibres fabric and, H the hybrid fabric. Each symbol is followed by a value representing the orientation of the warp yarns in the respective layer relatively to the longest edge of formed material. As all the composite plates were formed on rectangular moulds such as all of them have the dimensions of an A4 format the fill yarns of the middle layer are perpendicular on the longest edge of formed material and, as consequence, for all the reinforcement layer excepting the medial one the warp yarns of fabrics are parallel to longest edge of composite.

With these reinforcements two types of materials have been formed and cross-sectional microscopic images of them are in figure 1. A first type with epoxy resin as matrix and a second one with modified epoxy resin. The modified epoxy resin is, in fact, divided into two categories one used for external layers (1 to 5 and 13 to 17) and one used for internal layers (6 to 12). For the external layers the epoxy resin was modified by adding 10% weight ratio (wr) of starch, 10% wr of carbon black and 10% wr of aramid powder. For inner layers the epoxy resin was modified by adding 10% wr of starch, 10% wr of carbon black and 10% wr ferrite. The amount of starch was added to avoid the aggregation of the other substances and it was mixed with the resin (RE 4020) before mixing the others. The other two substances were prior mixed together and then they were mixed with the resin-starch mixture. After mixture homogenization (15 minutes stirring at 300 rot/min) the right amount of hardener (DE 4020) and the stirring continued for other 10 minutes. The liquid mixture was used to imbue the fabrics before they were placed into the mould. All the materials were extracted from moulds and thermally cured according to resin technical specifications.

From the formed plates squared plates of 190 mm were extracted for impact tests which had been performed on an Instron 8874. The impact drop weight tests had been done according to ISO 6603-1 and ISO 6603-2 for 45 J and 90 J impact energy and 20 mm hemispheric impactor. The sample were extracted on a high pressure water jet machine and in fig. 1 there are visible effects of matrix

Table 1
IMPORTANT PARAMETERS OF FABRICS

Fabric	Density [g/m^2]	Warp yarn/fill yarn	Thickness [mm]
Carbon fibres	160	4/4	0,260
Aramid Fibres	173	6,7/6,7	0,173
Glass Fibres	390	6/6	0,190
Hybrid	270	4,5/4,5	0,330

Table 2
REINFORCEMENT STRUCTURE OF MATERIALS

R1	**C0**	**C0**	**C0**	**K0**	**K0**	**K0**	**G0**	**G0**	**H90**	**G0**	**G0**	**K0**	**K0**	**K0**	**C0**	**C0**	**C0**
R2	**K0**	**K0**	**K0**	**G0**	**G0**	**G0**	**C0**	**C0**	**H90**	**C0**	**C0**	**G0**	**G0**	**G0**	**K0**	**K0**	**K0**
R3	**G0**	**G0**	**G0**	**C0**	**C0**	**C0**	**K0**	**K0**	**H90**	**K0**	**K0**	**C0**	**C0**	**C0**	**G0**	**G0**	**G0**
R4	**G0**	**G0**	**G0**	**K0**	**K0**	**K0**	**C0**	**C0**	**H90**	**C0**	**C0**	**K0**	**K0**	**K0**	**G0**	**G0**	**G0**

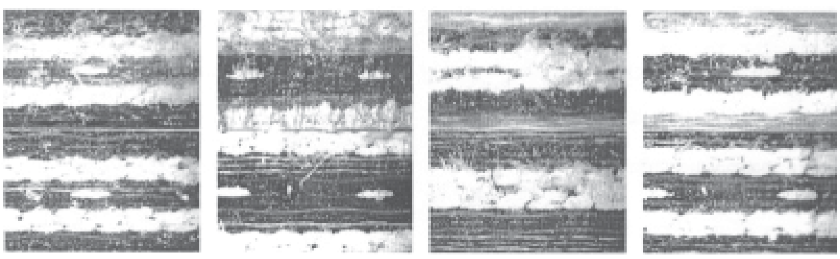

Fig. 1. Cross-sectional images of materials. Epoxy matrix (up) and modified epoxy matrix (down)

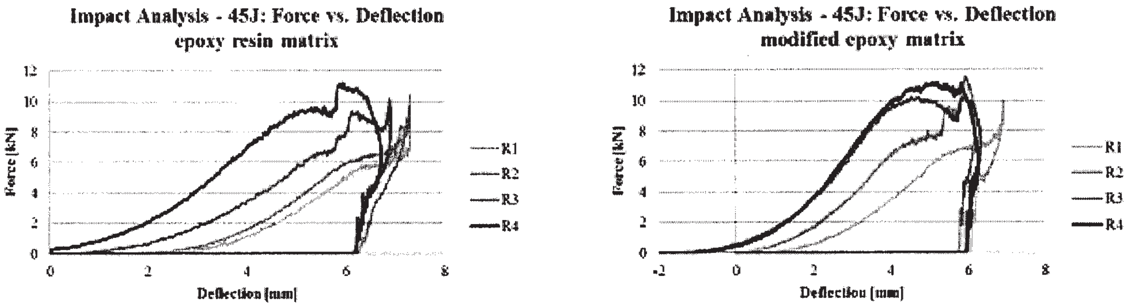

Fig. 2. Impact force vs. sample deflection during impact tests at 45J

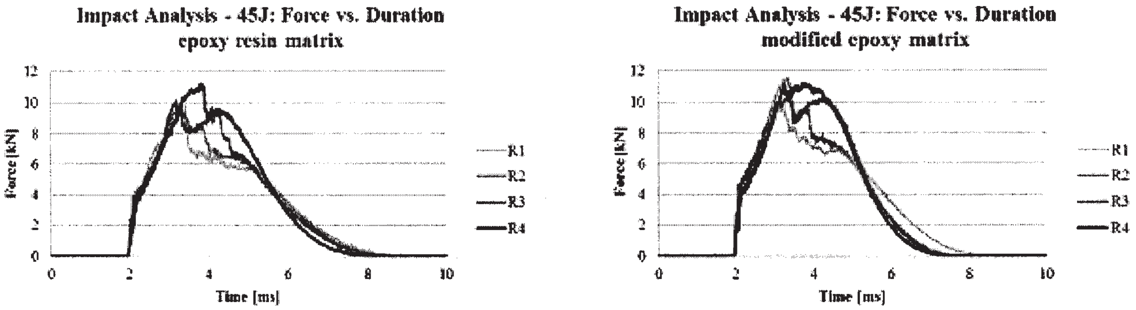

Fig. 3. Impact force vs. impact duration for impact tests at 45J

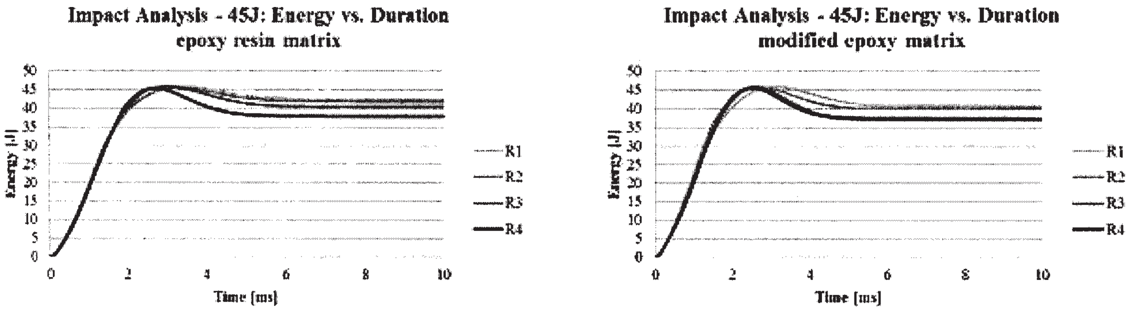

Fig. 4. Energy vs. duration during 45J impact tests

modification namely more precise cutting of aramid fibres that have aspect of a mat in the case of epoxy matrix.

Results and discussions

During the tests velocity, force, deformation and energy had been recorded as well as the impact duration by means of dedicated software and data acquisition systems. After tests all the samples were visually inspected and impacted plates were analysed by means of tomographic analysis to identify the damage mechanisms. Also the absorbed energy was evaluated according to [14] to ensure more comparison criteria. The results of 45J impact tests are presented in figures 2-4 and it is easily to notice that the materials with R1 and R2 reinforcements, on one hand, and materials with R3 and R4 reinforcements, on the other hand, have almost the same behaviour (the same profile of analysed curves) both in the case of epoxy resin matrix and modified epoxy matrix and that means that a very important aspect regarding impact behaviour is connected to number and position of glass fibres fabric layers in reinforcement.

The visual inspection is offering, together with the tomographic inspection, another perspective over the impact effects as it can be seen in figures 5-8. In the case of R1 materials the damages have the same aspect with imperforated materials and delamination between groups of layers of same fabric. The cracks in counter face are more developed in the case of epoxy resin matrix material. In figure 6 the analysis is regarding the R2 materials. The effects on the impact face are not so visible due to the

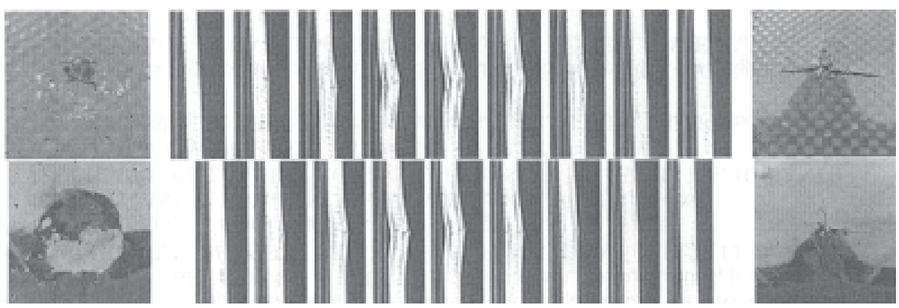
Fig. 5. Damages inspection for R1 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

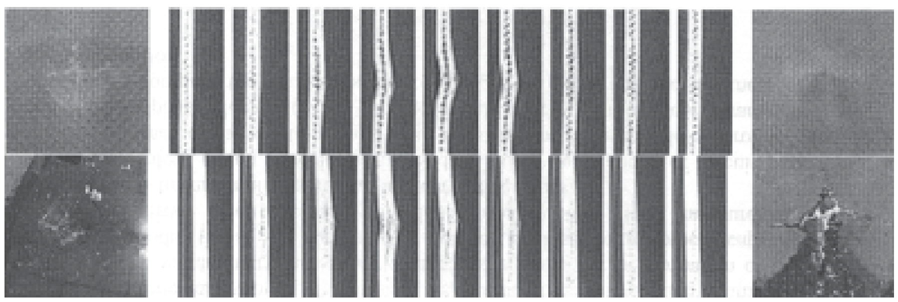
Fig. 6. Damages inspection for R2 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

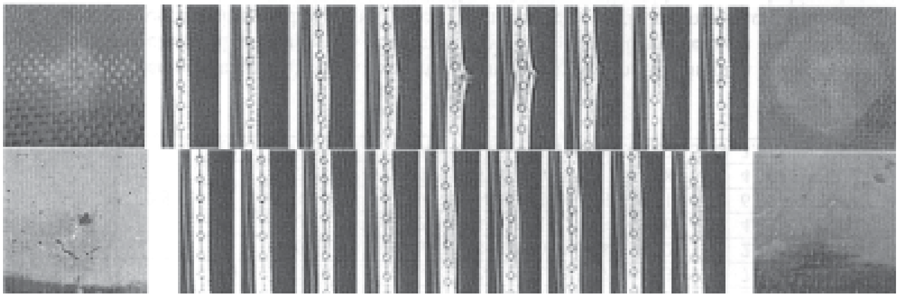

Fig. 7. Damages inspection for R3 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area.

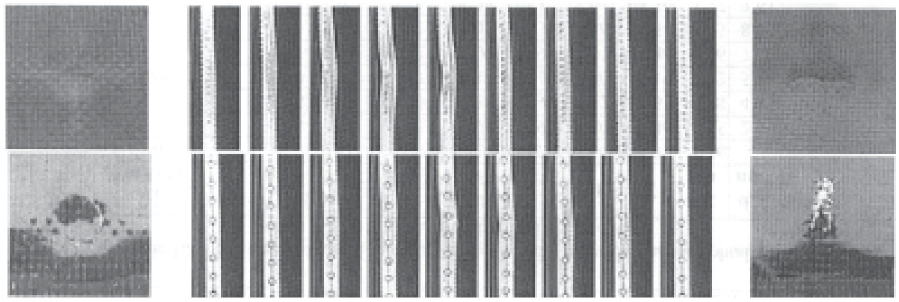

Fig. 8. Damages inspection for R4 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

Table 3
ABSORBED ENERGY [J] DURING IMPACT TESTS

	R1		R2		R3		R4	
	EM	MM	EM	MM	EM	MM	EM	MM
Test 45J	12,471	14,33	15,269	6,618	14,867	1,134	1,0625	1,5385
Test 90J	51,676	55,388	58,919	61,59	57,106	39,8875	47,164	55,042

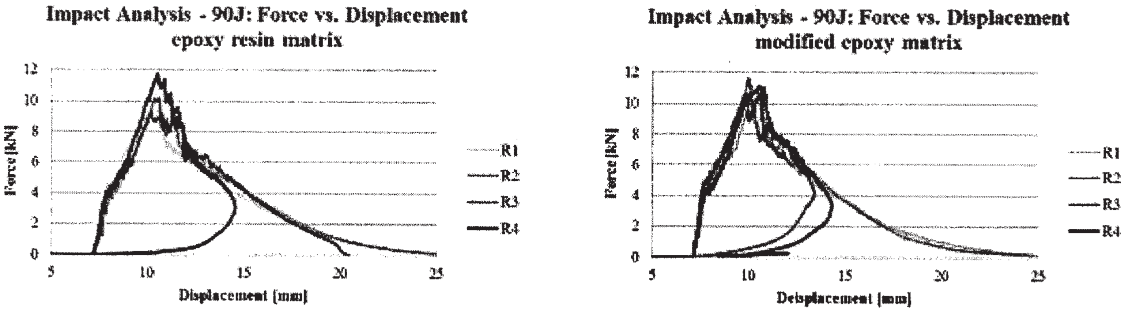

Fig. 9. Impact force vs. sample deflection during impact tests at 90J

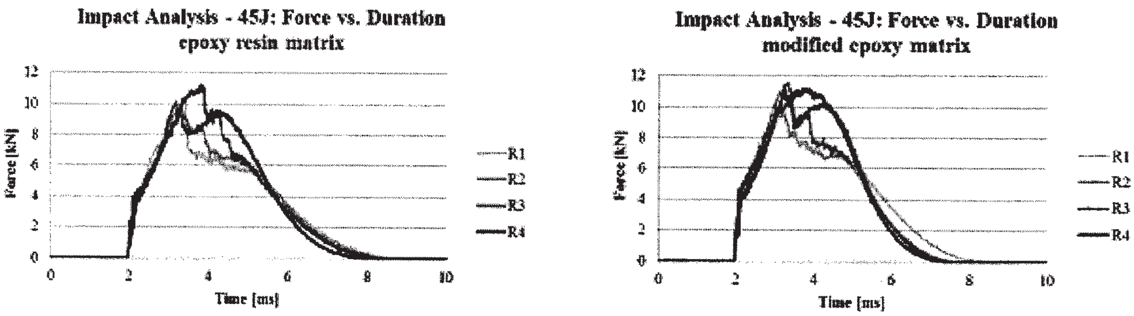

Fig. 10. Impact force vs. impact duration for impact tests at 90J

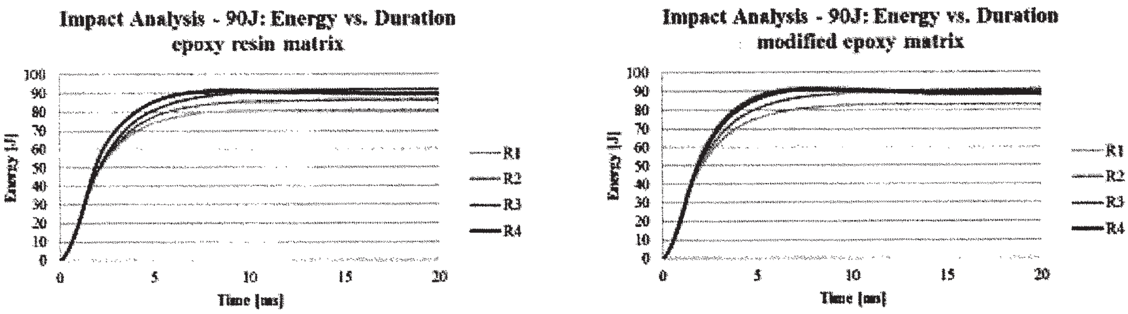

Fig. 11. Impact force vs. impact duration for impact tests at 90J

matrix in the case modified epoxy matrix material. The same type of damage is visible on the impact area counter face with initiated cracks along the yarns in warp and in fill of the fabric. The tomographic inspection does not indicate major differences between the behaviours of the two materials. Figure 7 concerns with R3 reinforcement materials and both materials are presenting delamination (even they are imperforated) with larger spreading in the case of epoxy resin matrix materials. Figure 8 shows the visual and tomographic inspection of R4 materials and is noticeable the delamination between the glass fibres fabric group and carbon fibres fabric group in the case of epoxy resin matrix material while in the case of modified epoxy matrix one there are not major modifications.

One important parameter on the impact analysis is the absorbed energy and its values for each material and for

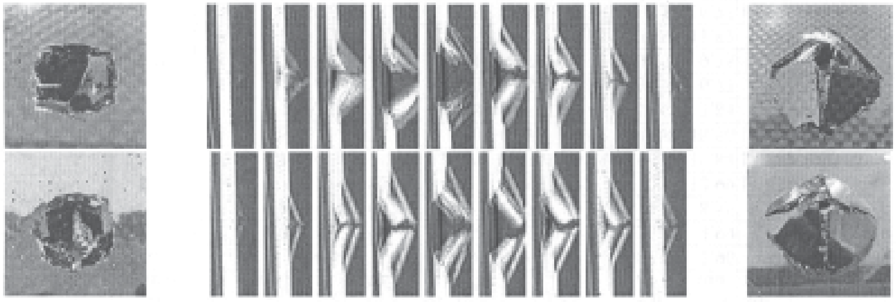

Fig. 12. Damages inspection for R1 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

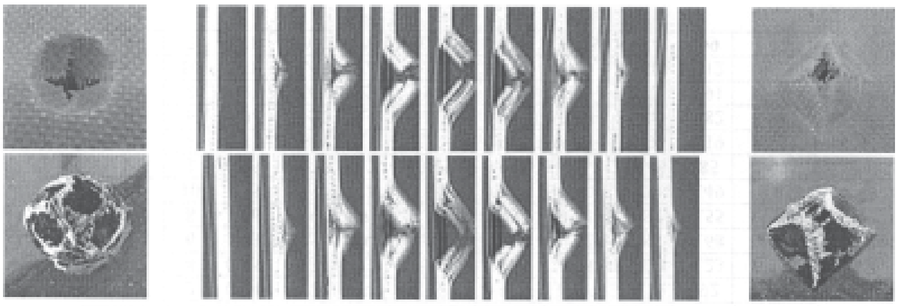

Fig. 13. Damages inspection for R2 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

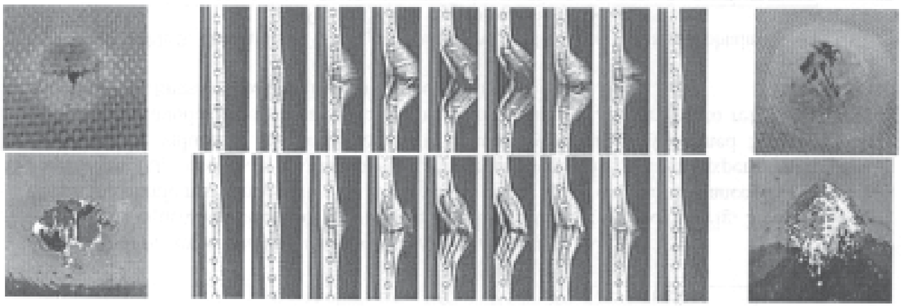

Fig. 14. Damages inspection for R3 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

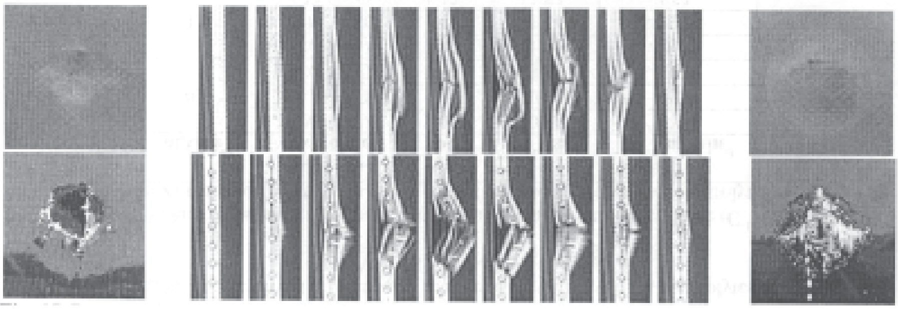

Fig. 15. Damages inspection for R4 materials (epoxy resin matrix – up, modified epoxy matrix – down). Left – impact area. Right – impact area counter face. Middle – tomographic inspection of impact area

both impact energy values are given in table 3. In the case of 45J tests just the R1 type reinforcement material presents a small increasing of absorbed energy and that means that on modified matrix material the effects are more important.

Regarding the 90J tests the analysed parameters are presented in figures 9 – 11. Analysing the curves it is easily to notice that the R3 materials have different behaviours depending on matrix while the other three reinforcements are acting in the same way regardless the matrix. The R3 reinforcement is perforated when the matrix in epoxy resin but is not perforated when the modified epoxy is used as matrix. From visual and tomographic inspection it may be noticed that the carbon fibres fabric layers are forming a subsystem which breaks each time meaning. This breaking mechanism is generated by the fracture of the matrix followed by fibres fracture due to shearing. Both R1 materials damaged areas are looking alike meaning the modification of matrix is not solving the carbon fibres behaviour even if the diameter of perforation is smaller in the case of modified matrix, as it can be seen in figure 12. For the R2 reinforcement the modified matrix is leading to better results (fig. 13) at 90J and another mechanism is visible – the fibres debonding as well as in the case of R3 and R4 materials but in the case of R2 are aramid fibres while in the case of the other two it is about glass fibres. Comparing the images in figure 14 it is observable that the material with modified epoxy has a better behaviour while for materials in fig. 15 the situation is inversed. In figure 15 the upper part there are consequences of all the three modes of delamination.

Conclusions

Layered materials had been formed using a technique that allows not only the alternation of layer but also the use of differently modified matrix at different levels. The materials were formed based on four types of fabrics one of them being used just medial layer in the sequence of 17 layers. Four types of reinforcement had been used to form composites and these four types are different only by the number of layers made of the same fabric and by the order of each type of fabric but they are all symmetrical referring to medial layer.

The samples were tested for impact at low speed by drop weight method at energy of 45J and 90J. The results showed that the best impact behaviour is reached for the materials with glass fibres fabric in external layers with small variations induced by type of matrix. The carbon fibres fabric layers are very strong bonded together and they are failing due to the matrix failure producing damages on the other layers because of their strength.

To achieve better results it is necessary to elasticize the interphase fabric-matrix to allow a better loading transfer. Modifying the matrix seems to be a good method to improve composites impact behaviour especially when the carbon fibres reinforcement layers are placed inside the materials.

Further studies have to take into account separation of carbon fabric layers and the use of modified epoxy as reinforcement for less number of layers. It is also of interest to increase the number of layers from each type of reinforcement fabric to analyse the impact properties of materials. In order to design the properties of a composite structure it is very important to take into account the impact properties and to know how each modification will affect these properties.

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