U.P.B. Sci. Bull., Series D, Vol. 78, Iss. 1, 2016 ISSN 1454-2358

LOW ENERGY IMPACT AND POST IMPACT BEHAVIOR OF EPOXY MATRIX-WOVEN FLAX FABRIC COMPOSITES

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Predicting the residual properties after impact of polymeric composites is an important issue in determining their ability to post impact loading. Epoxy matrix-woven flax fabric composite plates were impacted with falling mass from increasing heights until visible damage was induced. The progressive damage due to increased impact energy levels was studied. The mechanical properties degradation of the impacted composite plates was studied through three-point bending experiments of composite beams sectioned from the composite plates and subsequently accurately predicted by applying two different models developed by the first author.

Keywords: flax fabric, impact behavior, analytical modeling, mechanical testing

1. Introduction

The ever increasing need for the development of components with less weight in combination with the need for increased strength to mechanical and other loads and wear prompted the development of polymer matrix composite materials with low density without simultaneously degraded properties [1]. Nowadays, as a result of environmental and economic concerns, there has been a growing scientific and economic interest in polymer matrix-natural fibers reinforced composite materials [2, 3]. Natural fibers offer various advantages compared to conventional synthetic fibers and their processing requires low energy consumption and production cost [4-6].

Flax fibers are today one of the most important natural fibers used as reinforcement in manufacturing of semi-green composites, as well as of full green composites when a biodegradable polymer is used as matrix material [7]. Due to their environmental benefits and attractive performance (recyclability, specific modulus, etc.) over synthetic fibers, their use to reinforce polymeric matrices has been significantly developed for various applications (construction, transport etc.) in recent years. One of the first applications of flax as reinforcement was at an aircraft on the Second World War [8, 9]. Noteworthy are the attempts today to use flax-based biocomposites into PSA Peugeot Citroën car models and Boeing aircrafts [10]. Boeing produced a sidewall panel for a 737 aircraft made with a

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flax-thermoset composite. Using a vacuum bag process, the part was produced at full scale. In addition, many suppliers of composite materials are using nowadays flax as reinforcement in polymer matrices for specific applications such as sporting goods and other consumer products, providing a combination of sustainability, processing and performance.

In service conditions, low-energy impact loadings and related damages are unavoidable and often undetectable by human eye inspections. Impact damage in structures made of composite materials is of major concern, since such damage can be introduced during the life of the structure and its mechanical properties can be dramatically reduced as a result. Various research programs have been conducted in order to obtain a better understanding of the behavior of composite materials under impact [11-13]. Many efforts have also been made in order to predict the damage and the residual properties after impact [14, 15]. However, there is still a very limited scientific literature on the impact response of natural fibers (woven) composites [16].

In the present investigation, epoxy matrix-woven flax fabric composite plates were fabricated using a simple open molding hand lay-up manufacturing process. The material to be examined is made up of four plies (layers), each ply consisting of fabrics of the same thickness, all uniformly parallel and continuous across the material. The plates were subsequently impacted with falling mass from increasing heights until visible damage was induced.

The progressive damage due to increased impact energy levels was studied, as well as the variation of the maximum impact load and absorbed energy/impact energy ration as a function of impact energy were calculated. The mechanical properties degradation of the composite was measured through 3-point bending tests of composite beams sectioned from the composite plates. Finally, it is worth to mentioning that all experimental results were accurately predicted by applying two different predictive models developed by the first author.

2. Materials and methods

Four ply laminates, all in the same direction, of woven bi-directional flax fibers, were prepared using a simple open molding, hand lay-up, manufacturing process. The fabric used as reinforcement in the composite consisted of elementary fibers with a diameter of about 15 μm. The mechanical properties of flax fibers are tabulated in Table 1 [17].

Table 1

Mechanical properties of flax fibers

Property	Elementary Flax fiber
Modulus (GPa)	60-80
Strength (MPa)	500-1500
Elongation at break (%)	2-3
Density (g/cm^2)	1.4-1.5

RENLAM© CY 219 epoxy resin, cured with the Ren© HY 5161, supplied by HUNTSMAN, was used as matrix material of the composite. The pre-polymer, before the manufacturing process begins, was heated up to 50°C in order to have its viscosity decreased. Proper amounts of curing agent were, subsequently, added and the mixture, after being stirred thoroughly, was put in a vacuum chamber for degassing. The physical properties of epoxy resin, hardener and the resin/hardener mixture are tabulated in Table 2.

Table 2

Matrix RENLAM© CY 219, Hardener Ren© HY 5161 and Resin/Hardener mixture HUNTSMAN physical properties

Property	Unit	RENLAM CY 219	Ren© HY 5161	Mixture
Appearance Color	visual	Clear liquid Amber	Clear liquid Amber	Yellowish
Viscosity at 25°C	mPa·s	10,000- 12,000	30- 70	1,000- 1,200
Density	$g \cdot cm^{-3}$	1.1	1.0	1.1

The composite laminates were made by first stacking sheets of reinforcements and by resin impregnating each ply by hand spray. The prepreg was then placed in the mold and compression molded at room temperature for 30 min using a pressure of 40bar. After completing the manufacturing process, the polymerization process consisted of curing in an oven at 50 °C for 24 hours. In this way complete polymerization of the matrix material was obtained and, consequently, the properties of the final product were not exhibiting any storage-dependence. Lastly, the materials were removed from the molds and from each panel of material impact plates were mechanically machined. Neat epoxy resin plates of the same dimensions were subsequently fabricated.

For the mechanical characterization of the un-impacted plates, three beam specimens were machined from each batch. In addition, five specimens of the same dimensions were sawn from each impacted plate for the three-point bending testing after impact. More precisely, in order to study the spread of damage zone and its effect on the residual bending modulus and flexural strength, four strips were taken symmetrically from both sides of the panels, and the fifth one was obtained from the central plate area, thus containing the main impact damage (see Fig. 1).

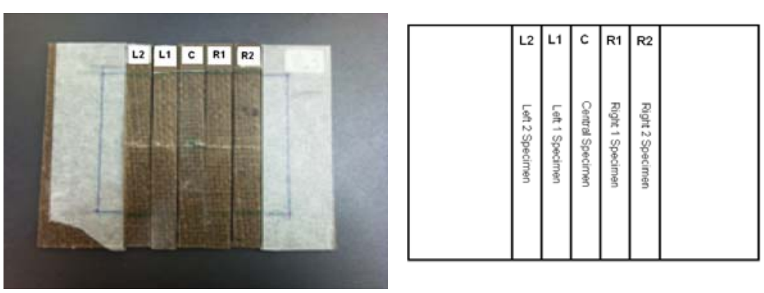

Fig. 1. Position of composite beams sectioned from the impacted composite plate, where L2, L1, C, R1, R2 refer to Left 2, Left 1, Central, Right 1and Right 2 beam respectively

Low energy impact tests were carried out at room temperature on composite plates as well as on neat epoxy resin plates. The impact energies studied were 1.25 J, 1.88 J, 2.51 J, 3.13 J, 3.76 J (see Table 3). The tests were conducted using a guided drop weight tester according to ASTM D5628-96 (see Figure 2, 3). Keeping constant the falling mass, the resulted impact velocities were 1.06 m/s, 1.43 m/s, 1.74 m/s, 2.06 m/s and 2.17 m/s respectively. The impactor was manually left to fall from different pre-determined drop heights.

Table 3

Correlation of impact height-impact energy

Height of impact (cm)	Dynamic Energy (Joule)
0	0
10	1.25
15	1.88
20	2.51
25	3.13
30	3.76

Fig. 2. The guided drop weight tester

Fig. 3. The guided drop weight tester base

In the instrumented falling weight impact test used in the present work, dart was fitted with a force transducer to measure the force throughout the impact test while impact and rebound velocities were accurately measured by means of photocells. The collected data were then processed with a Lab-view data acquisition system to provide a wealth of information from each specimen tested.

The quasi-static experimental characterization of the composite and of the neat epoxy resin was carried out according to ASTM D790-99. The 3pb flexural tests were conducted at a Universal testing machine INSTRON 4301 (see Figure 4).

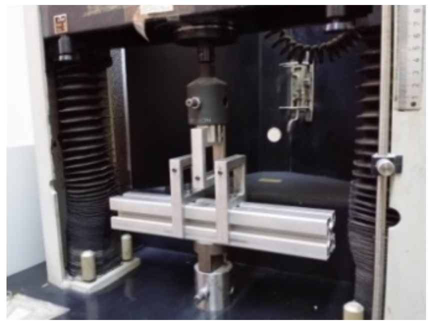

Fig. 4. INSTRON 4301 Universal Testing Machine

3. Modeling

In the present work, the mechanical properties degradation of the impacted plates was accurately predicted by applying two analytical models; namely: the Residual Strength after Impact Model, (RSIM) and the Residual Property Model, (RPM), developed by the first author.

As described in a previous publication [18], the RSIM fundamental assumption is that the flexural stiffness degradation is related to the residual strength after impact as described by Equation 1.

$$\frac{\sigma_r}{\sigma_0} = \frac{D_{ij,r}}{D_{ij,0}} \tag{1}$$

where σ_r represents the residual after impact flexural strength of the impacted material, σ_0 is the strength of the un-impacted material, $D_{ij,r}$ is the flexural stiffness of the impacted material and $D_{ij,0}$ is the flexural stiffness of the un-impacted material.

According to the analysis presented by Papanicolaou et al. in [18], the final form of the model is given by Equation 2.

$$log\left(\frac{\sigma_r}{\sigma_0}\right) = log\left(\frac{d}{U^{\alpha}}\right) \Rightarrow log\left(\frac{\sigma_r}{\sigma_0}\right) = log(d) - \alpha log(U) \tag{2}$$

where σ_r is the residual after impact strength of the material, σ_o is the strength of the un-impacted material, α is the energy absorption coefficient, d is a constant that depends on the properties of the material and the conditions of the experiment and U is the impact energy applied.

The second model applied in the present work, was the RPM model. The RPM model is a semi-empirical model developed by George C. Papanicolaou and can be applied for the prediction of the residual properties of materials after any type of damage, irrespectively of the type of the material and the cause of damage. The basic assumption of the RPM is that the mechanical properties degradation of a material, due to a source of damage, follows an exponential decay law [19]. The final expression used for the prediction of the residual property value after impact is given by Equation (3).

$$\frac{P_r}{P_0} = s + (1 - s)e^{-s\frac{\Delta U}{U_0}} \quad (3)$$

where P_r is the current residual property value after damage of the material considered, P_0 is the value of the same property for the un-impacted material, U_0 is the impact energy threshold (i.e. the minimum impact energy needed for the degradation to occur) and ΔU is the impact energy U-U_0 increment, where U is the impact energy applied.

4. Results and Discussion

Impact damage in woven composites can take many forms, such as fiber pull-out, fracture in regions of tensile stresses, debonding and microbuckling of fibers under compressive stresses. All these forms of damage are reflected on the impact load - time diagram through small/large oscillations appearing in the curve. However, it is difficult to separate the effect of each damage type on the residual properties of the woven laminate. The applied energy is calculated by integrating the force applied to the specimen along the deflection. The fracture energy is the energy stored in the plate when a sudden drop in the force is observed. The sudden drop in the force, with almost no change in the energy, is typical to the brittle failure. The load-time history can be divided into two distinct regions - a region of fracture initiation and a region of fracture propagation. In the initiation region, as the load increases, elastic strain energy is accumulated in the specimen during the contact with the impactor. In this region, no gross failure takes place but failure mechanisms on a microscale are possible. When a critical load is reached at the end of the initiation phase, the composite specimen may fail. At this point, the fracture propagates either in a catastrophic brittle manner or in a progressive manner continuing to absorb energy at smaller loads. The total impact energy is the sum of the initiation energy and propagation energy.

In the present work, low energy impact tests were carried out on epoxy matrix-woven flax fabric composite plates, using flax fibers as impact-resistant reinforcement, as well as on neat epoxy resin plates for comparison. The impact behavior of the mentioned materials was studied for increasing impact energy levels. Concerning neat epoxy resin plates, impact behavior and damage tolerance were studied up to impact energy 2.5 J, as for higher energy levels almost all the plates were fractured. For the composite plates non-perforating impact occurred during the impact tests.

Fig. 5 presents a comparison of the peak loads suffered the composite and the neat epoxy resin plates as a function of impact energy. The maximum peak load indicates the maximum load the material can bear before undergoing major damages. These data depend, significantly, on the amount of fibers in the composite and the plate thickness. Plate thickness has also a significant effect on the local indentation during impact. In an impact event, peak load and contact duration are important factors influencing impact characteristics. Stiffer materials show shorter contact durations and higher peak loads than their softer counterparts [20].

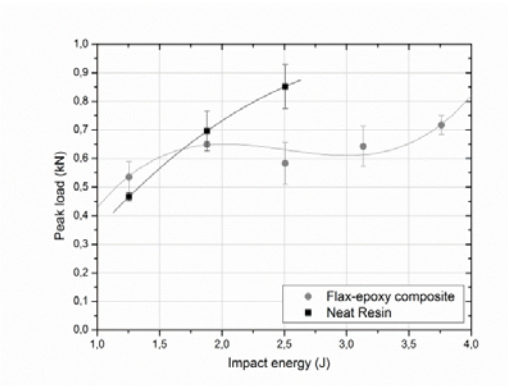

Fig. 5. Variation of the maximum impact load on the plates as a function of impact energy

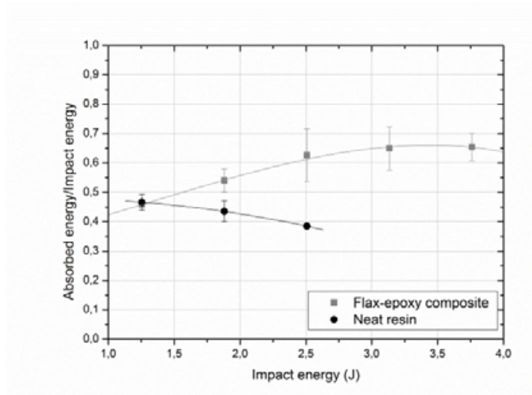

Fig. 6. Variation of the absorbed energy/impact energy as a function of impact energy

In the present study, a small variation in the peak load with impact energy, as concerned with the flax-epoxy composite plates, was observed. Regarding the absorbed energy/impact energy ratio, it increased with increasing impact energy (see Figure 6). This behavior was observed up to approximately 3.2 J, while for higher energy values many micro-cracks in the matrix material were developed as well as partial delaminations in the composite specimens took place. These damages were reflected as large oscillations in the impact load-contact time curve.

For a composite laminate material the degree of delamination between two adjacent plies and other secondary modes of failure such as matrix cracking and debonding result in a reduction of its residual post impact flexural properties [21]. An energy threshold, below which impact damage is inadequate to produce any material property degradation, does indeed exist. This impact energy threshold is variable depending on the stacking sequence of the laminate and it is likely to be very low (on the order of a few Joules) [22, 23]. Impact effects on woven fabric reinforced composites are affected by the weave architecture and the thickness of the textile used as reinforcement [24]. Moreover, during manufacturing process, defects and voids entrapped between and into the different layers of the laminates, can affect the bending as well as the after impact flexural properties [25].

Regarding the depth of indentation in the flax-epoxy composite plate, this seemed to increase with the increase of impact energy while there were no visible cracks or perforation on the front plate face for the applied impact energies. The damage on the opposite plate face (back face) started to be visible at impact energies higher than 2.5 J. These damages had the form of microcracks oriented ±45 degrees relative to the woven fibers direction. At higher energy levels these microcracks started to propagate from the center of the plate following a radial path. This cracking pattern is characteristic of woven composites when undergoing impact damage [26].

Concerning neat epoxy resin plates, the peak load was continuously increasing with the increase of impact energy while the ratio of absorbed/impact energy was decreasing. The neat resin is considered as a stiffer material as compared to the flax-epoxy composite, the contact duration was found shorter, the peak loads were higher and at impact energies higher than 2.5 J, the material fractured in a brittle mode.

Table 4 lists the bending characteristics of the un-impacted materials. As one can observe, the resin after reinforcing showed an increase in bending modulus and flexural strength while strain at maximum strength decreased.

Table 4

Bending Properties of un-impacted neat resin and four layers woven flax-epoxy composite

Material	Bending Modulus (GPa)	Flexural Strength (MPa)	Strain at Flexural Strength (%)	Strain at break (%)
Neat resin	2,6	65,5	3,7	-
Flax-epoxy composite	5,5	100	2,7	2,7

The degradation of the mechanical properties of the composite and of neat epoxy resin after impact is shown in Figs. 7 and 8. As a general observation, we can mention the sigmoidal type of degradation of the properties of the materials tested with impact energy. Also, as expected, the central specimen which experiences the highest damage showed the highest reduction in modulus and strength while as the distance from the central damage increases, a lower decrease is observed. Finally, as it can be deduced from the properties variation shown in Figs. 7 and 8, there is a symmetrical expansion of the damage zone around the central point of impact.

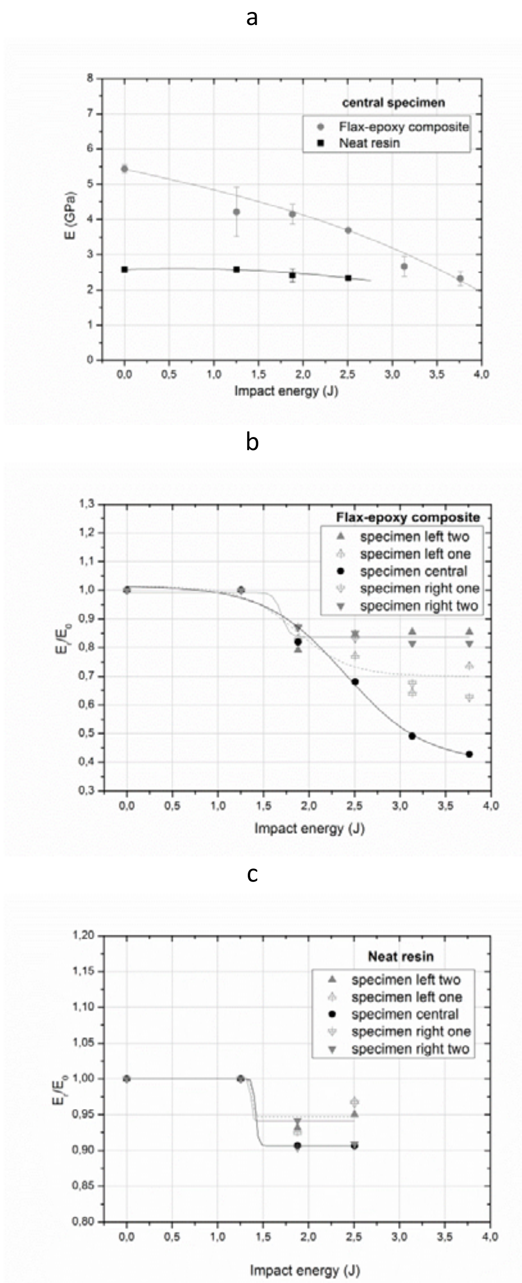

Fig. 7. Variation of bending modulus as a function of impact energy

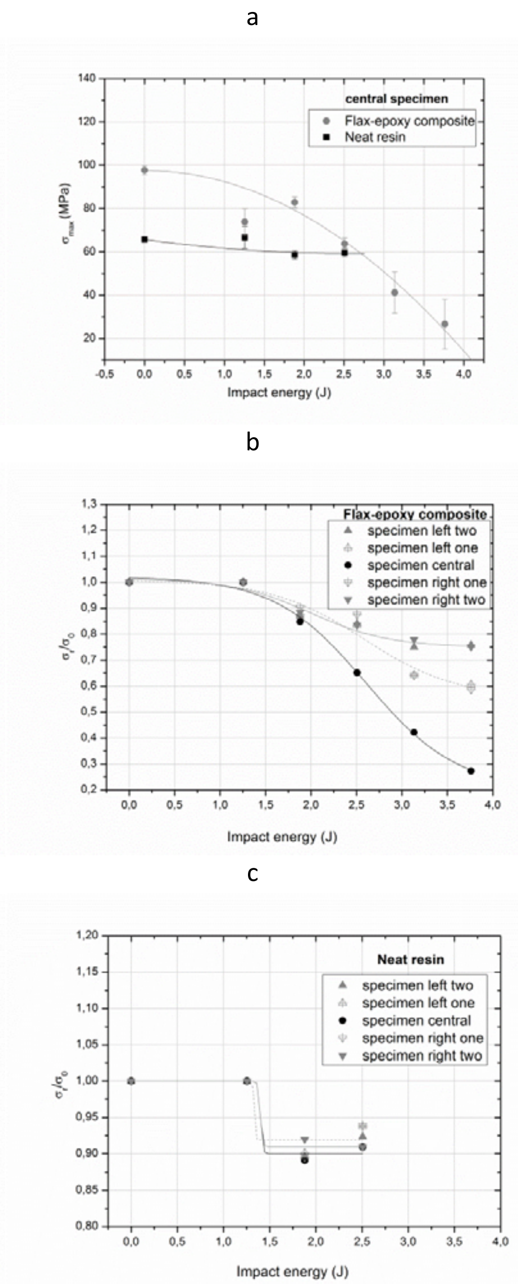

Fig. 8. Variation of flexural strength as a function of impact energy

In Fig. 9, a comparison between the experimental findings and respective RPM predictions of the post-impact residual bending modulus of the composite and neat epoxy resin as a function of the impact energy is made. Fig. 10 shows the experimental results as compared to the RSIM and the RPM model predictions of the post-impact residual flexural strength of the composite and the neat epoxy resin as a function of the impact energy. The predicted values in both models were very close to the respective experimental results.

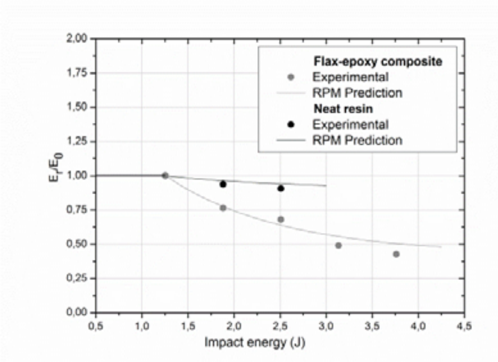

Fig. 9. RPM predictions and respective experimental results for the normalized after impact bending modulus

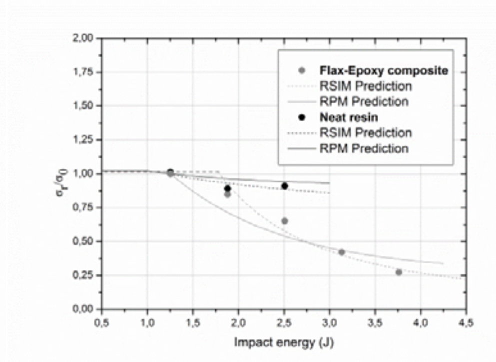

Fig. 10. RSIM, RPM predictions and respective experimental results for the normalized after impact flexural strength

5. Conclusions

Impact tests have been performed on woven flax-epoxy composite as well as on neat epoxy resin plates and related parameters such as maximum impact load, absorbed energy/impact energy ratio as a function of impact energy were calculated. Results proved that the eco-composite showed a higher impact resistance as compared to the neat epoxy resin.

The influence of the impact damage on the residual mechanical properties of the materials tested was studied through three-point bending experiments. In all of the cases, both the residual after impact bending modulus and strength showed higher values in the case of the composite as compared to the neat epoxy resin. The spread of the damage zone and its effect on the residual behavior was also studied. As expected, the central specimen which experiences the highest damage showed the highest reduction in modulus and strength while as the distance from the central damage increases, a lower decrease is observed. Finally, as it can be deduced from the properties variation with distance from the point of impact, there is a symmetrical expansion of the damage zone around the central point of impact.

Two analytical models, previously developed by the first author, were applied to predict the residual mechanical properties after low-energy impact of the woven flax-epoxy composites and the neat epoxy resin. The models predicted equally well the residual properties values and the results enable a better understanding of the influence of low-energy impact on the residual mechanical properties of the materials tested.

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