Optimizing impact strength of laminate hybrid interply composites made of epoxy reinforced by continuous carbon and natural fibers

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Abstract. In this work, low velocity impact resistance of laminated hybrid interply composites, made of epoxy matrix which is reinforced by continuous synthetic carbon and natural fibers, has been studied experimentally. Natural fibers included Ramie and Hemp which were used as reinforcement in composite plies according to various stacking sequences. The effect of fiber orientation was taken into account by varying the relative direction of fibers in plies. Optimal configuration of a hybrid interply composite was assessed as function of the desired impact strength and cost of fabrication. It was found that carbon-Ramie composite for which the impacted face is reinforced with carbon fibers achieves the best cost-effectiveness.

1 Introduction

Composites are natural or synthetic materials that result from a mixture of basic materials. This combination enhances specific properties of the composite to achieve better performance than obtained with each constituent on its own. New materials can then be engineered with desired properties at the macroscopic scale to meet the strict requirements of particular applications.

A composite material consists in general of two primary parts: a matrix and reinforcement. The matrix gives the part its final shape and can be made from a polymeric resin such as epoxy that cures and transforms to a plastic. The reinforcement can be a fiber material that is embedded in the matrix. The matrix provides protection for the fibers from contact and environmental actions and allows for more effective distribution of the applied load into the fibers. The fibers are set up to get appropriate stiffness and strength in order to resist satisfactorily the transmitted loads. In addition to resistance to stresses, other properties can be sought in composites such as thermal stability or impact strength.

Many factors participate in shaping the composite mechanical properties. These include the material of the fibers, the volume fraction of fibers, the orientation of fibers, the material of the matrix and the bonding condition of fibers to matrix. Carbon fiber is widely used in practice because its properties go beyond those of many other known fibers. It is among the highest specific strength and highest specific modulus synthetic fibers [1]. However, it is very expensive. Epoxy is used in applications requiring high strength and extended durability. This resin has high strength to weight ratio and is very commonly used with carbon fibers. Epoxy is often applied in pre-impregnating fibers by performing infusion into them. Because it is expensive too, its use is restricted in practice to outstanding applications.

To reduce the cost of composites, many techniques have been introduced. These encompass various lay-up methods and special arrangements made of hybrid fibers. Beginning with a lamina or ply which is in general a curved layer of unidirectional fibers, stacking is performed at various orientations to obtain a laminate. The laminate can have different thicknesses and consist of various materials. The orientation of the principal material axes can vary from ply to ply according to selected orientation angles. These angles are conventially measured in a counter clockwise course.

Composite laminates made of plies containing two or more different types of materials are called hybrid interply composites. Stacking different interply types of fibers according to a specified order has been recognized to yield enhanced and cost effective composites. The configuration of the laminate, for a given layup, can be summarized by the stacking sequence obtained by adding the exact location of the various plies composing the layup. Composites made from the same material but with different stacking sequences may exhibit quite different characteristics. Optimization of the stacking sequence is then performed to find the most effective configuration with regards to the objectives of design.

Composites have been shown to suffer some limitations regarding their response to impact loading. Early research work has been dedicated to the analysis of composites behavior subjected to impact events [2]. Recent detailed review literature on this subject can be found in [3]. Under impact, continuous fiber reinforced composites do not undergo plastic deformations as do habitually metals. If the impact energy is low, the material exhibits only elastic deformations in the vicinity

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of the impact zone. However, if the impact energy is relatively high, damage of material including matrix cracking, delamination, fiber breaking, and fiber/matrix debonding may appear.

The absorbed energy during impact depends on many parameters such as the fiber-matrix link, fiber resistance and fiber orientation. A common test used to study the impact behavior of composites is the drop-weight test. In this test, a bar is mounted on a rigid stand and is hit with a rigid body having a known mass and falling from a certain height that can be varied to provide a desired impact velocity. During the impact, the force diagram can be recorded. This diagram shows in general two stages. The first is associated to the initiation of breakage and lasts until a critical load is attained. The second corresponds to the spreading of breakage occurring after this maximum load is reached. Depending on the material microstructure, this second regime can vary from an abrupt fragile mechanism to a progressively energy absorbing mechanism. Both of these impact stages participate to the impact resistance of the composite.

The mechanical properties of the composite constituents influence largely its impact response. For composite materials reinforced with continuous fibers, detailed experimental studies have enabled to identify several failure mechanisms. Failure modes that engage fracture of the matrix or interphase region result in low absorbing energy, while failure modes that involve fiber fracture yield greater energy absorption. The energy absorbing capability of the composite is then governed essentially by the fiber/matrix interphase region.

Carbon fibers have been found to have large elastic energy absorbing capability. These fibers have then been used to enhance impact resistance of composites. However, they are expensive and a recent tendency has been observed towards performing partial substitution of these noble fibers with more cost-effective fibers. In this context, natural fibers appear to be very attracting due to their large availability in nature and their simple processing. In addition, they are environmental friendly which is nowadays a fact of prime concern. Among these fibers, Ramie fiber [4] and Hemp fiber [5] have been recognized to have interesting mechanical properties.

The objective of this work is to analyze the effect on the impact strength and cost resulting from substituting carbon fibers by Ramie or Hemp fibers. A symmetric plane laminate made from stacking four laminas is considered. Experimental tests have been conducted with different staking sequences. The obtained impact strength and calculated cost are used to elaborate a decision making chart enabling the designer to identify the best natural fiber to use and the optimal stacking configuration with regards to cost and impact resistance.

2 Materials and methods

2.1 Hybrid interply laminates

In order to limit degradation affecting stiffness or load carrying capability of composites during service life, adequate impact resistance is needed. The behavior under impact loading of composite structures varies considerably; however damage induced by impact events can be roughly classified according to the actual velocity of impact. There are principally three regimes of impacts [6]. Low velocity impact (LVI) is associated to impact occurring with a speed which is below $10\,\mathrm{m/s}$.

Considering LVI regime, composites are designed to absorb the impact energy with restricted degree of damage. This has been achieved in the past by using simple composites such laminates made of carbon fiber reinforced epoxy [7]. However, the actual concern for environmental sustainability and cost reduction emphasized attention in using natural fibers as an alternative reinforcement. Natural fibers are abundant in large quantities, they are cost effective, biodegradable, and offer acceptable mechanical properties compared to synthetic fibers. But, unlike these lasts they can exhibit more sensitivity to environmental conditions as well as higher variability in properties. In order to overcome these problems, natural fibers are not used alone. Combining them with synthetic fibers has been found to be more beneficial [8]. The combination through hybrid composites which are reinforced by both synthetic and natural fibers enables to balance more effectively the requirements regarding the desirable properties and cost.

In this work, the natural fibers Ramie and Hemp are considered in order to assess their behavior under impacts in a hybrid interply composite laminate. These materials were selected on the basis of their physical, chemical and mechanical characteristics. Hybrid composite laminates were prepared by using these two different types of natural fibers mixed with one carbon fiber in a matrix made of thermosetting polymer epoxy resin. Properties of fibers reinforcements are given in Table 1. The matrix used is Epoxy LY-556 with Hardener HY-951. It has a density of $1.15\,\mathrm{g/cm^3}$ and costs $750\,\mathrm{INR/kg}$.

Table 1. Properties of fiber reinforcements used in the fabrication of hybrid composites.

Fiber material	**Density** $\mathrm{g/cm^3}$	**Cost** $\mathrm{INR/kg}$
Hemp	1.37	390
Ramie	1.51	424
Carbon	1.80	4030

Table 1 shows that densities of the natural fibers are close each one to the other; this is because of their high content of cellulose. They are also lighter than carbon fiber. Table 1 shows also that the cost of natural fibers is one order lower than that of carbon fiber.

Table 2 gives the main mechanical properties of Ramie and Hemp fibers as well as those of carbon fiber and epoxy resin. Table 2 shows that the tensile strength and modulus of natural fibers are comparable and that they are lower than those of carbon fiber.

Table 2. Mechanical properties of natural fibers, carbon fiber and epoxy resin [3,9-10].

Fiber/ matrix	Ramie	Hemp	Carbon	Epoxy
Diameter (μm)	20−80	17−23	7.1	-
Tensile strength (MPa)	398−937	310−750	4480	100
Tensile modulus (MPa)	61-128	30−60	231	6
Elongation (%)	3.6−7.8	2−4	1.8	-

The composites structure considered in this work is that of hybrid interply composites laminates. They are made from epoxy reinforced with continuous reinforcing carbon fibers mixed with Hemp or Ramie fibers. As stacking influences impact resistance, various stacking sequences were analyzed. They correspond to the symbol $[0/\theta]_s$ with different values of angle θ to take into account the effect of plies fiber orientation.

2.2 Manufacturing method of laminates

The composite laminates were prepared with help of the vacuum assisted resin infusion molding process. They have all 10% volume fraction of fibers and thickness of 2mm. The different fiber laminates were located with different orientations (0°, 45°and 90° respectively). Fabrication of composites laminates was performed by mixing properly a mixture of 10:1 epoxy and hardener ratio with the help of mechanical stirring process for 10minutes. The desiccator was used for removal of the gas entrapped in the solution during mixing and the final prepared mixture was poured into the laminates mould. The pre-curing process and post-curing process of the fabricated laminates were done at 120°C and 160°C for three to six hours respectively. Finally, the laminates were cut according to ASTM D256 standard for testing.

2.3 Experimental procedure

The impact testing was performed by using Izod impact machine. It has a pendulum of 1.83kg at an initial height of 595mm. For each type of composite laminates, three samples were tested and average value was reported. Plate samples of laminates have been prepared according to simple or hybrid interply arrangement, with each ply reinforced by homogeneous continuous unidirectional fibers that are made of carbon, Ramie or Hemp. A total of nine different types of laminates were prepared. The orientation angle between the plies was varied in the set {-90,-45,0,45,90}, resulting in a total number of 49 samples. They were all tested in the same environmental conditions under low velocity impact regime.

Figure 1 shows a hybrid interply stacking sequence consisting of four symmetric plies. The unidirectional fibers of the impacted face have the orientation 0 in the axes xy, while the second ply fibers are orientated by angle θ.

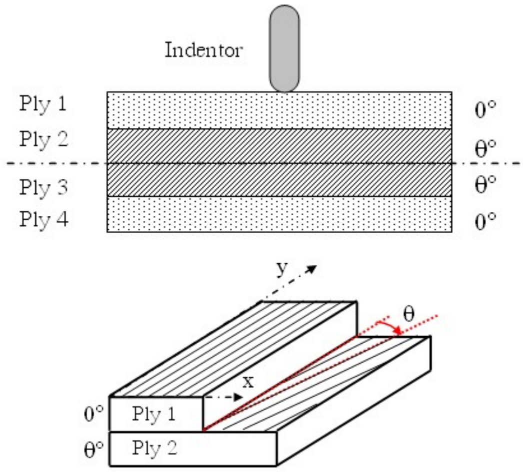

Fig. 1. Hybrid composite laminate having four plies and the stacking sequence $[0/\theta]_s$ where θ is the orientation angle.

3 Results and discussion

Each sample having a certain staking sequence and orientation angle between plies was tested and its impact strength recorded. As design against impact is a compromise between the desired impact resistance and cost, this last was calculated for each composite sample by taking into account the cost of epoxy and that associated of reinforcing fibers.

Cost effectiveness for each stacking sequence of hybrid interply composites was then analyzed by considering the obtained impact strength of the plate and the relative orientation angle used in the plies. For this purpose, interpolations giving the impact strength as function of the engaged cost were derived.

Figure 2 gives the obtained interpolation curves for the stacking sequences $[\text{Carbon}-\text{Hemp}]_s$ (continuous line) and $[\text{Hemp}-\text{Carbon}]_s$ (dash-dotted). Figure 3 gives those of the stacking sequences $[\text{Carbon}-\text{Ramie}]_s$ (continuous line) and $[\text{Ramie}-\text{Carbon}]_s$ (dash-dotted), while Figure 4 gives those of the stacking sequences $[\text{Hemp}-\text{Ramie}]_s$ (continuous line) and $[\text{Ramie}-\text{Hemp}]_s$ (dash-dotted). In these figures the five orientation angles are indicated in color, while circles indicate the available experimental results used in interpolations.

From Figures 2 to 4, one can see that the orientation angle $\theta=0$ provides almost in all cases the most advantageous results. Figures 2 and 3 show that the stacking sequences with carbon fibers are more advantageous than those without carbon fibers. The results associated to this last case are erratic and do not provide a monotonous interpolation of impact resistance as function of Hemp fibers mass content. This might be due to extreme variability affecting composites made from natural reinforcing fibers alone.

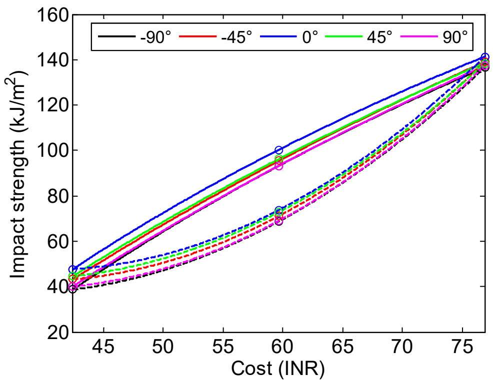

Fig. 2. Curves giving impact strength versus cost for the stacking sequences $[\text{Carbon}-\text{Hemp}]_s$ and $[\text{Hemp}-\text{Carbon}]_s$.

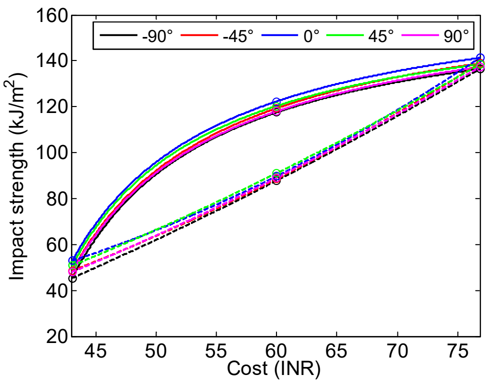

Fig. 3. Curves giving impact strength versus cost for the stacking sequences $[\text{Carbon}-\text{Ramie}]_s$ and $[\text{Ramie}-\text{Carbon}]_s$.

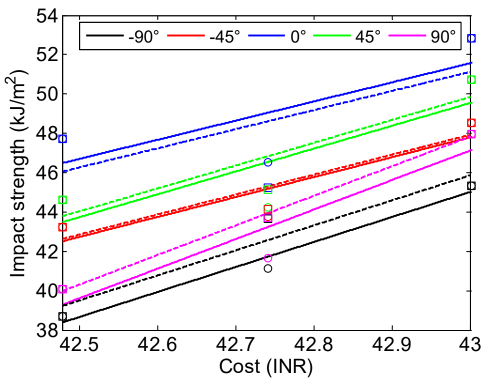

Fig. 4. Curves giving impact strength versus cost for the stacking sequences $[\text{Hemp}-\text{Ramie}]_s$ and $[\text{Ramie}-\text{Hemp}]_s$.

Figures 2 to 4 show that the most cost-effective stacking sequences are obtained for the fiber orientation in ply 2 that is parallel to that in ply 1, which indicates that the best orientation angle is equal to zero. Figures 2 and 3 show that the impact occurring on ply reinforced by carbon fibers gives systematically higher resistance than that happening on the ply reinforced with natural fibers. This may be explained by the fact that fiber/matrix interphase region has better resistance for carbon fibers. Due to variability of mechanical properties of natural fibers, the results of carbon free composites are close and show less sensitivity to orientation of impacted face.

Using Figures 2 and 3 enables to determine, for a given cost, the best stacking sequence. The staking sequence $[\text{Carbon}-\text{Ramie}]_s$ was found to be the most cost-effective. It is followed by the stacking sequence $[\text{Carbon}-\text{Hemp}]_s$.

4 conclusions

Optimization of impact resistance of laminate hybrid interply composites made of epoxy and reinforced with continuous carbon, Ramie or Hemp fibers was performed. Various samples were fabricated as laminates with four plies according to symmetric stacking sequences and with variable fiber orientation between the first ply and second ply. They were tested to measure strength against low velocity impact. Post processing of the obtained results and consideration of cost of the tested samples enabled to determine the most cost-effective stacking sequence. It was shown that the best results are obtained from hybridization of carbon fibers and Ramie fibers with the impacted face being that with carbon fibers.

It should be noted that other important aspects, such as the effect of ply thickness and number of plies have to be studied further in order to assess more straightforwardly the advantage of using natural fibers as alternative reinforcement in composites.

References

1. A.B. Srong, *Fundamentals of Composites Manufacturing* (Society of Manufacturing Engineers, Dearborn, 2008)
2. W.J. Cantwell, *Impact damage in carbon fibre composites* (PhD Thesis, University of London, 1985)
3. V. Mahesh, S. Joladarashi, S.M. Kulkarni, Defence Technology **17**, 1 (2021)
4. M. Sfiligoj Smole, S. Hribernik, K. Stana Kleinschek, T. Kreže, *Plant Fibres for Textile and Technical Applications* (IntechOpen, 2013)
5. T. Chernova, P. Mikshina, V. Salnikov, M. Ageeva, N. Ibragimova, O. Sautkina, T. Gorshkova, *Development of Hemp Fibers: The Key Components of Hemp Plastic Composites* (IntechOpen, 2018)
6. S.N.A Safri, M. Sultan, N. Yidris, F. Mustapha, The International J. of Eng. and Sci. **3**, 9 (2014)
7. M.A. Abtew, F. Boussu, P. Bruniaux, C. Loghin, I. Cristian, Comp. Struct. **223** (2019)
8. Z. Al-Hajaj, B. Lawrence Sy, H. Bougherara, R. Zdero, Comp. Struct. **208** (2018)
9. A. Shahzad, Hemp fiber and its composites-a review, J. of Comp. Mater. **46**, 8 (2012)
10. D. Mujiyono, D. Nurhadiyanto, A.F. Mukhammad, J. of Fund. and Appl. Sci. **9**, 7S (2017)