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Improvement of Biocomposite Performance Under Low-Velocity Impact Test - A Review

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Abstract. The study of the impact energy and the composite behaviour plays a vital role in the efficient design of composite structures. Among the various categories of impact tests, it is essential to study low-velocity impact tests as the damage generated due to these loads is often not visible to the naked eye. The internal damages can reduce the strength of the composites and hence the impact behaviour must be addressed specifically for improving their applications in the transport industry. The main aim of this paper is to provide a comprehensive review of the work focusing on the assessment of biocomposites performance under low impact velocity, the different deformations, and damage mechanisms, as well the methods to improve the impact resistance.

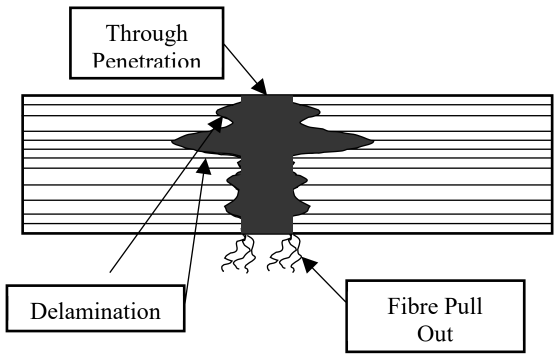
1. Introduction

Composites prepared by reinforcing biopolymers with natural fibers are referred to as green composites. Coir, flax, sisal, and hemp are examples of natural fibers, while starch, poly-lactic acid (PLA), and poly-hydroxy alkanoates (PHA) are examples of biopolymers used for the preparation of green composites. The development of the first green composites dates back to the late 1980s [1]. They are not only eco-friendly but also renewable, displaying low weight and good strength. For all the reasons mentioned above, these composites are gathering attention from the aerospace and automobile industries. Nevertheless, their limitations such as moisture absorption, propensity for improper interfacial adhesion between matrix and fibre, poor wettability, and poor compatibility of natural fibres with hydrophobic matrices hinder its widespread application. However, these limitations are reduced to an extent with the usage of physical and chemical treatments.

1.1 Impact Energy on Composite Materials

Impact strength can be defined as the resistance of the material to withstand the maximum impact load without fracturing or rupturing. The impact properties of polymeric composites depend upon the toughness of the material. The toughness of the material is the ability to absorb the energy and plastically deform without fracturing [2]. The overall toughness of the composites is highly dependent on the matrix and fibre interface, geometry and construction of the composites, testing conditions, and the nature of constituent materials. The interfacial properties depend on the type of polymer matrix, functionalization of fibres, and methods of fabrication. The natural fibre reinforced composites (NFRCs) with good interfacial properties can dissipate a large portion of the impact energy through failure modes such as fibre breakage and fibre pull-out. The materials with good toughness can be used in applications such as the automotive industry, construction, renewable energy equipment (e.g. windmill blades), and so on [2].

The issue of the impact energy can be characterized into two areas such as low-velocity impact and high-velocity impact. In this report, the former topic is the subject of the review. The events occurring in the range of 1 to 10 ms^{-1} can be termed as low-velocity impacts. These impacts can be simulated by using a falling weight or a swinging pendulum, generally a large mass. In this type of test, the contact period is such that the whole structure has time to respond to the loading [3]. Low-velocity events can cause barely visible impact damage in composite structures which is hard to inspect and may cause a catastrophic failure [4]. These low-velocity impacts can result in damages such as fibre breakage, matrix cracking, and delamination [5]. It is of importance to study this impact range as it is prone to occur during production or service activities and is considered dangerous for the composite laminates [6]. High-velocity impacts can occur by a small mass (e.g. runaway debris, small arms fire) and they are simulated by a gas gun in general [3]. In general, high-velocity impacts produce localized and deep damage and this type of failure is known as visible impact damage. These damages can be easily identified during maintenance inspections [5]. During high-velocity impacts, the dominant failure mode is the fibre breakage [7][8]. The comprehensive possibilities of the impact-induced damages under high velocity, medium velocity, and low-velocity impacts are shown in Fig.1a, Fig.1b and Fig.1c respectively [7]. Table 1 shows the different types of impact tests with different velocities [7].



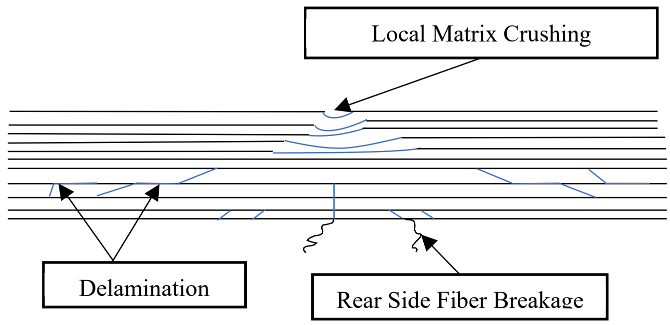


Fig. 1a Damage Induced Due to High-Velocity Impact   Fig. 1b Damage Induced Due to Medium Velocity Impact

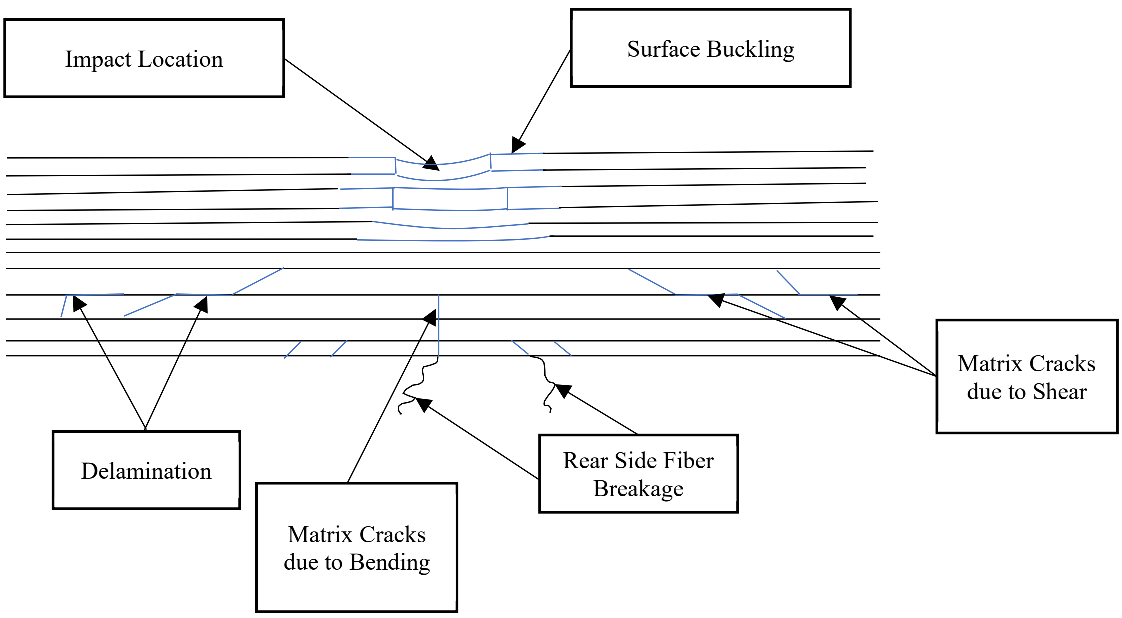


Fig. 1c Damage Induced Due to Low-Velocity Impact

Interfacial bonding between fibres and matrix is one of the important factors in determining the impact and fracture toughness properties of the NFRCs. Interfacial bonding is characterized by the property known as Interfacial Shear Strength [9]. Upon improving the interfacial bond strength, the failure mode of natural fibres will be changed from fibre pull-out mode to fibre fracture mode. The change in the failure mode of fibres will result in a more brittle composite and hence less energy will be needed for the composite material to fail. The enhancement in the interfacial adhesion allows greater stress transfer between the matrix and reinforcements and it will reduce the capacity of fibre debonding. It can also hinder the fibre pull-out which is the main source of dissipation of energy for the improvement of the composite toughness. Therefore, flexural and tensile strengths can be improved at the expense of ductility of the composite [2].

Table 1 Types of Impact Test with respect to Impact Velocity [7]

S No	Velocity Range (m/s)	Test Equipment	Applications
1	Low Velocity 0-11	Drop Hammer Pneumatic Accelerator	Dropped Items Vehicle Impact Crash
2	High Velocity > 11	Compressed Air Gun Gas Gun	Free Falling Bombs Fragments Owing to Explosion
3	Ballistic Impact > 500	Compressed Air Gun Gas Gun	Military
4	Hyper Velocity > Impact 2000	Powder Gun Two-Stage Light Gas Gun	Exposed to Meteoroid Impact

1.2 Process Variable Optimisation by Design of Experiments

Few researchers have studied the application of the design of experiments for the optimization of parameters for improving the impact properties of the biocomposites. Compression molding parameters such as temperature, pressure, and time were optimised for obtaining the enhanced impact properties of PLA reinforced flax composite. They also studied the individual and interaction effects of the parameters on the impact energy of the composite developed [10]. A study was performed to optimize the parameters for injection-molded biocomposites. The team had considered four variables such as temperature, holding pressure, screw speed, and fibre length [11]. Likewise, certain researchers [12], [13], [14], [15] had worked in the direction of optimising parameters to improve the impact properties of various biocomposites. Table 2 shows the optimised parameters of different processes for obtaining optimum impact properties.

Table 2 Optimised Processing Variables for Different Processes

Process	Fibre (%)	Temp (°C)	Pressure (bar)	Time (min)	Screw Speed (rpm)	Fibre Length (mm)	Ref
CM	-	200	30	3	-	-	[10]
Extruder	-	140	10	-	100	2	[11]
Extruder & IM	20	190	-	-	300	> 3mm	[12]
Extruder & IM	10	190	-	-	300	≥ 3 mm	[13]

CM- Compression Molding; IM- Injection Molding;

1.3 Main Factors Influencing the Impact Properties of Biocomposites

According to the literature available on the topic reported, the vital factors that influence the impact properties of the biocomposites are (i) Intrinsic properties of the constituents and the corresponding packing arrangements, length, loading, and orientation of the fibers; (ii) Type of physical and chemical treatment on natural fibers; (iii) Environmental conditions such as temperature and moisture; (iv) Material Properties of reinforcing fiber and matrix, which constitute the natural composite; (v) The type of hybridization of natural fiber with another natural or synthetic fibers; (vi) Type of nano reinforcements [2]. The main factors affecting the damage of NFRCs are shown in Fig. 2. NFRC exhibited a good correlation between the length of fibres, their weight fractions, their effect on fracture behaviour in the natural composites. When short fibres (4≤length≤10 mm) were used as reinforcements in high loading fractions (55≤ wt% <70) the composites exhibited decrement in the fracture toughness. In contrast, there was an improvement in the fracture toughness when they used reinforcements with the length of (10≤length≤25 mm). Fracture toughness was highest at 10 vol % for 4 mm fibre, 40 vol % for 7 mm fibre, and 50 vol % for 10 mm fibre [2]. The energy absorption capacity for long fibres was increased due to reasons such as fibre debonding, pull-out, and fracture mechanisms that occur at the matrix-fibre interface. It is considered that fibres when pulled out from the matrix dissipate the energy due to their friction and thereby play a role in fracture toughness. However, it is to be noted that the development of stress concentration zones due to the poor adhesion with the matrix can lead to the reduction in the impact strength of the composite.

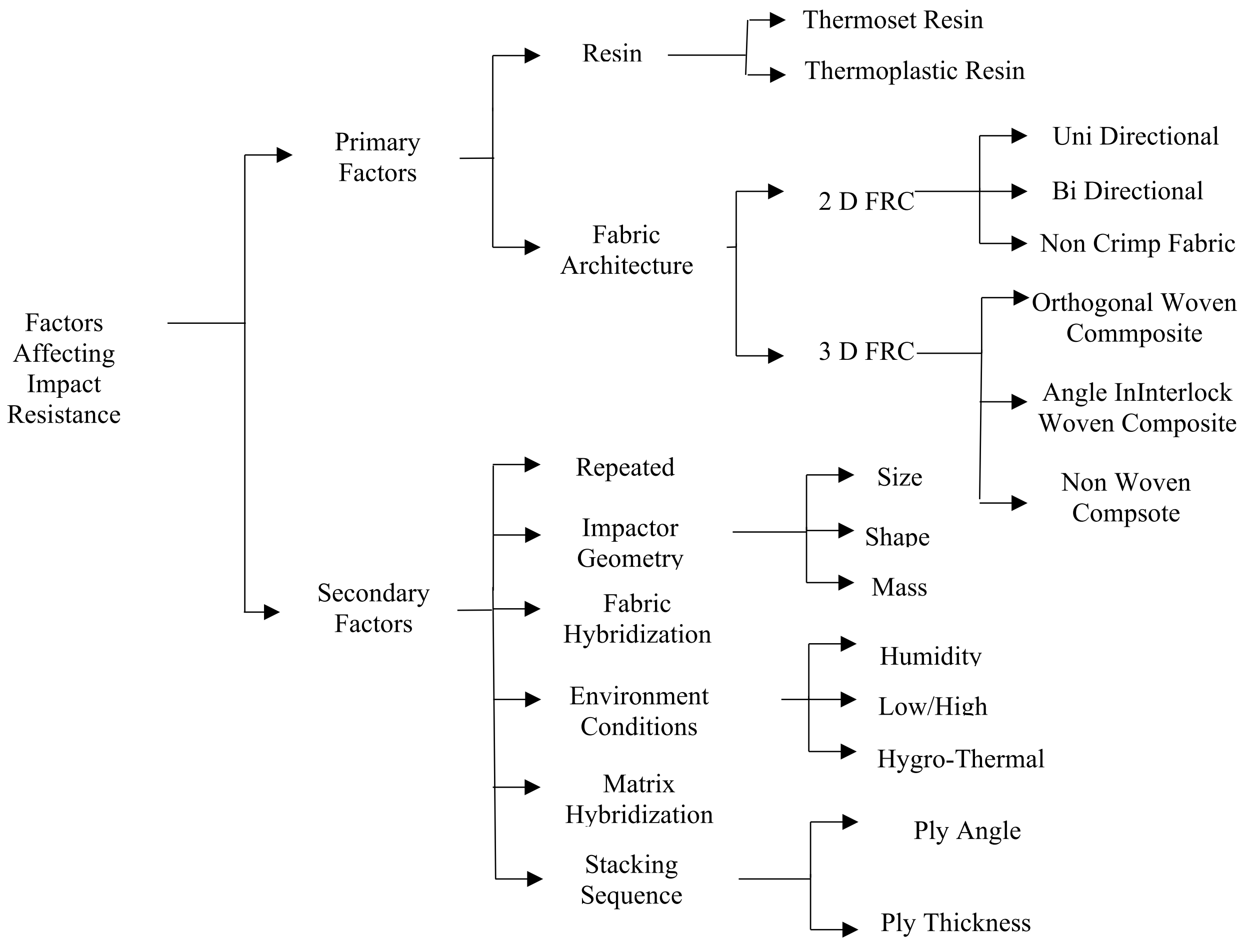


Fig. 2 Factors Affecting Impact Resistance of Fibre Reinforced Composites [16]

The mechanical properties such as tensile strength, flexural strength, impact toughness, and fracture toughness will be improved with the increment of the fibre loadings in the NFRC and the values of the fracture toughness and fibre loadings are proportional to each other up to a certain limit and decrease thereon. The amount of fibres present in the composites should be enough to transfer the loads from the matrix. Attention should be given to the uniform distribution of the reinforcements specifically if they are in the random discrete particles to avoid forming agglomeration. The agglomerated regions can act as a stress concentrator and require less energy for the propagation of the crack, thereby reducing the fracture toughness of the composite. The ability of the natural fibres to dissipate energy is also dependent on the orientation of the reinforcing fibres. The fibers have more fibre pull-out energy when they are oblique relative to the direction of the crack when compared to those of parallel and perpendicular arrangements [2].

The combination of two or more fiber reinforcements in a single polymeric matrix can be termed as a hybrid composite. From the available literature, it can be seen that different combinations of reinforcements have been studied ie., (i) combination of two natural fibres, (ii) combination of natural and synthetic fibres, (iii) combination of two synthetic fibres [17]. Recently some researchers started to explore hybridization to improve the ballistic performance of the composite using biopolymer as matrix and a combination of natural and synthetic fibres as reinforcements [18]. The addition of nanofillers at small loadings will help in the bridging of micro cracks and toughen the matrix and hence results in improving the impact strength of NFRCs. Some studies are available in the literature that studied the effects of nanofillers on the improvement of NFRC toughness. The most familiar natural and synthetic nanofiller is nano clay filler and carbon nanotubes respectively [2].

2. Results

As per the impact properties are concerned, many researchers reported improvement of impact strength with the adoption of some physical and chemical techniques, where few results are shown in Table 2. The improvement is associated with good interfacial bonding with matrix and fibre. However, it is to be noted that too strong interfacial interaction between matrix and fibres will enable the easy propagation of crack and will reduce the toughness of the composite [19]. Table 3 shows the tensile and impact properties that were obtained from the experimental results of various researchers during the last 6 years. It was observed that a few chemical treatments such as alkaline, silane, borax treatments, and hybridization techniques were used for the improvement of the tensile and impact properties of the green composites.

Table 3 Tensile and Impact Properties of Biopolymers Reinforced with Different Natural Fibres

Fibres wt (%)	Matrix	Fibres	Process	Tensile Strength (MPa)	Impact Energy (J/m)	Additional Information	Ref
5	PLA	Sisal	IM	55.35	30.65	UT-CMF	[20]
5	PLA	Sisal	IM	67.22	28.92	NCMF	
5	PLA	Sisal	IM	65.46	34.39	GCMF	
5	PLA	Sisal	IM	62.33	32.85	CMF with 5 wt % MAH	
55-5	PLA	OPEFBF-KCF	CM	35.59	12.29	No treatments	[21]
55-5	PLA	OPEFBF-KCF	CM	30.92	16.12	PLA with MA	
55-5	PLA	BR(OPEFBF-KCF)	CM	37.44	16.75	Borax treated	
55-5	PLA	BR(OPEFBF-KCF)	CM	47.54	32.53	Borax treated and PLA with MAH	
40	PBAT/PBS	Miscanthus	IM	21.9	82.34	40:60 wt % blend of PBAT and PBS	[11]
40	PVB	Kenaf	HP	10.71	122.23	Orientation, 45°/-45°	[22]

CM- Compression Molding; CMF- Cellulose Microfibrils; GCMF- Saline treated CMF; HP - Hot Press; IM- Injection Molding; KCF- Kenaf Core Fiber; MA- Maleic Anhydride; PBAT - Poly(butylene adipate-co-terephthalate); PBS - poly(butylene succinate); PBV – Polyvinyl Butyral; PC- Polymer Coated; NCMF- Alkali treated CMF; OPEFBF- Oil Palm Empty Fruit Bunch Fiber; ST-Silane Treated; UT- Untreated; WCF- Waste Cellulose Fibres.

The mechanism responsible for the improvement of impact properties due to different methods are described earlier in the report. The most critical factors affecting the fracture toughness and impact energy of biocomposites are the physical and chemical treatments that improve the interfacial adhesion at the fiber-matrix interface and also the type of hybridization process [2]. The observed improvements in the results are in parallel with the results mentioned in Table 2.

2.1 Failure Modes Due to Impact Test in Biocomposites

Researchers have used low-velocity impact tests such as the Izod impact test, Charpy impact test, and drop weight test for studying the behaviour of the green composites when subjected to impact loading. It is observed that there are different modes of failure such as matrix cracking, debonding, delamination, fibre breakage, and fibre pull-out depending on the impact loading. The kinetic energy is absorbed by the plastic deformation and formation of indentation on the surface of the impact [6]. The subsequent sequence for the failure mechanism under the impact loading is made of five phases: (i) matrix cracking and fiber/matrix interface debonding damage mode owing to high transverse shear stresses in the top layers; (ii) transverse bending crack owing to high flexural stresses in the bottom layers; (iii) interlaminar delamination owing to cracks restricted and diverted through the interlaminar area; (iv) fiber failure damage mode under tension and fiber micro-buckling under compression loading; (v) penetration [7]. The damage modes that comprise the matrix or fiber/matrix interface lead to low fracture energies, while the damages that comprise fibre failure lead to considerably higher energy dissipation [7]. For studying the low-velocity impact behaviour, the drop weight test was performed. The test setup is shown in Fig.3 and the damage modes that may be obtained as a result of this test are shown in Fig.4.

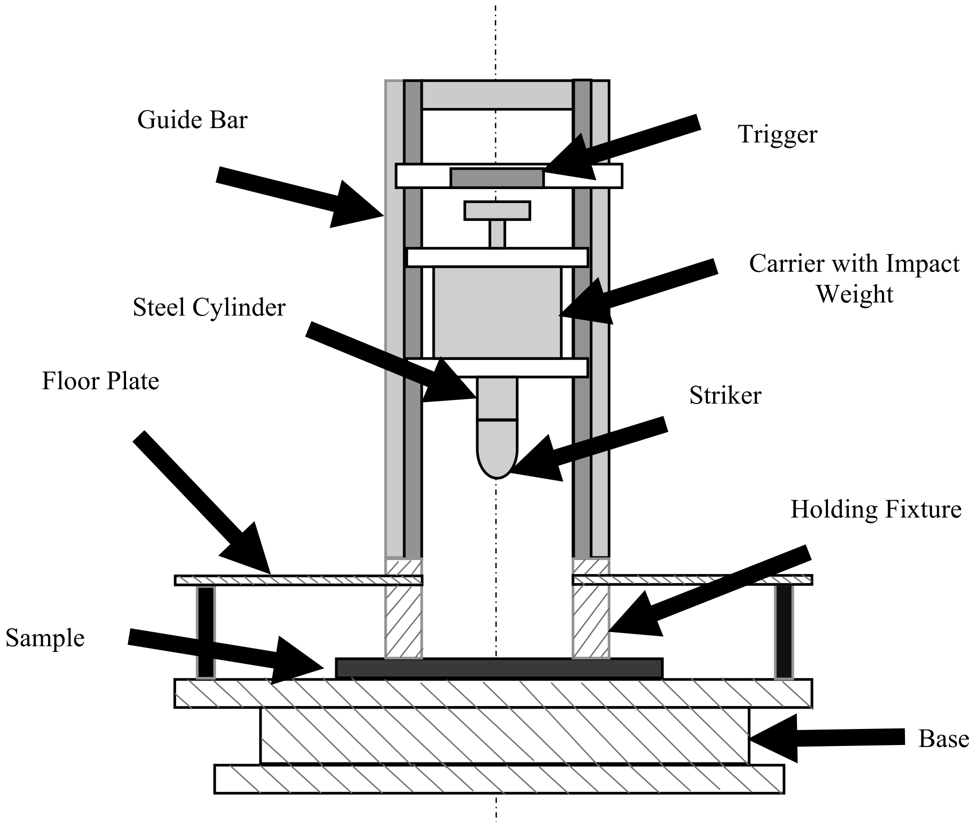


Fig.3 Drop Weight Test Setup Adopted From [23]

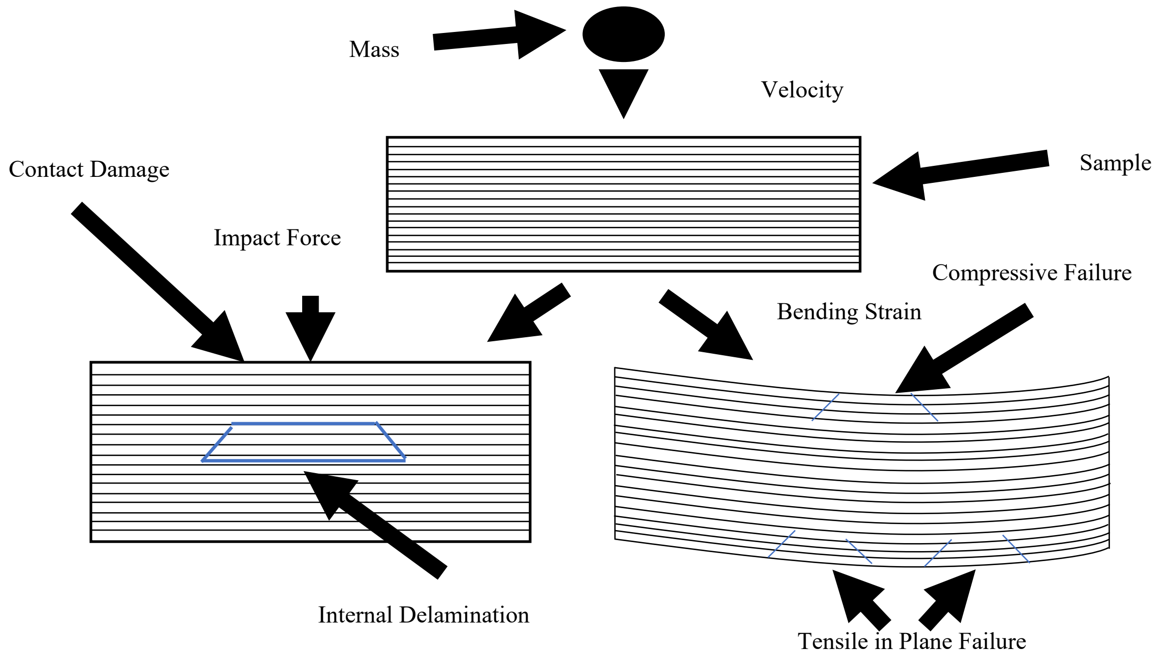


Fig.4 Drop Weight Impact Damage Adopted From [23]

3. Conclusions

It is essential to study the behaviour of the biocomposites when subjected to low-velocity impact as these impacts do not create visible damage. When left unnoticed, these impact effects could lead to the decrement of the strength of the composite and lead to the failure of the composite. Factors such as the toughness of the matrix, fibre orientation, stacking sequence, matrix hybridization, and fibers hybridization are presented as vital factors for the improvement of the impact resistance of the biocomposites. The hybridization of fibres is one of the important methods to improve the impact properties. Few researchers have considered the mixing of synthetic fibers with natural fibers to withstand ballistic impact. It was observed that a few chemical treatments such as alkaline, silane, borax treatments, and hybridization techniques are used for the improvement of the tensile and impact properties of the green composites. There is still room for improving the impact energy of green composites so that they will replace synthetic composites in some of the applications.

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