Assessment of laminated damage in natural fibre-reinforced polymer biocomposites using guided ultrasonic waves: A case study

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15.1 Introduction

The importance of biocomposites in current and future applications requires no emphasis, as the material is well established to exhibit remarkable achievement in replacing conventional non-biodegradable petroleum-based materials (Nagalakshmaiah et al., 2018). Among the noteworthy properties of biocomposites are composability, environmental friendliness and complete decomposition in the end product (Shanmugam et al., 2021). Additionally, biocomposites are cost-effective and lightweight (Ilyas et al., 2021). Due to its focus on sustainability, environmental impact and innovative nature, biocomposites align with several Sustainable Development Goals (SGDs), such as SDG 9, SDG 12 and SDG 13. SDG9, which focuses on industry, innovation and infrastructure, aligns with research on biocomposites, as the material can lead to more sustainable and efficient industrial processes. SDG 12, which focuses on responsible consumption and production, aligns with research on biocomposites, as the material uses renewable natural fibre, reducing dependency on non-renewable materials. Many biocomposites are also biodegradable, thus promoting minimising waste and pollution. Lastly, SDG 13, which focuses on climate action, aligns with the benefits displayed by biocomposites, such that the material has a lower carbon footprint compared to traditional composites, contributing to lower greenhouse emissions (SDGs, 2015).

Despite that, it is important to acknowledge the limitations of biocomposite applications in structural components due to its laminate damage. Therefore, understanding the various types of fabrication methods, such as hand lay-up, compression moulding, resin transfer moulding, vacuum infusion, spray lay-up, injection moulding, filament winding, pultrusion method, vacuum bag moulding

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and autoclave method (Bajpai et al. 2017), is important to reduce or eliminate the possible causes of laminate damage. Likewise, it is equally important to understand the mechanism of laminated damage to develop effective ways of enhancing the durability and performance of biocomposites. Most importantly, to keep up with advancing technologies, it is significant to adopt NDT, such as guided wave-based active detection, to detect laminate damage in biocomposites. These techniques allow for early defect detection without compromising the integrity of the material.

This article discusses the various categories of laminated biocomposites, describes some of the common fabrication techniques for laminated biocomposites and elucidates the damage mechanism of the material. Moreover, the method processing on damage detection using GUWs discusses some of the challenges relating to the method as well as recommendations for future work. This can provide researchers with comprehensive guidance on the fabrication of biocomposites, the use of GUW for damage detection in composites and the potential damage mechanisms of the fabricated biocomposites, thereby contributing to the growing of knowledge on this material.

15.2 Laminated biocomposite

Research into eco-friendly materials has intensified due to the non-biodegradable nature of synthetic plastic waste in the environment. In keeping with this, ecologically friendly alternatives such as biocomposites have been developed. 'Green' or 'biocomposites' are fourth-generation composite materials. These materials are considered advanced because of their ability to be composed, their environmentally friendly nature and their complete disintegration in end products (Rosova et al., 2021). Materials that are fully renewable or biodegradable, offer sustainability and are ecologically benign are referred to as green composite or biocomposite materials. These materials are crucial components in the design process. Researchers are interested in biocomposites due to their added advantages, such as cost-effectiveness, lightweight properties and recyclability (Kamaruddin et al., 2022). According to Nagalakshmaiah et al. (2018); Biswas et al. (2020), oil-based, non-renewable plastics may be replaced by biocomposite components such as bio-based polymers and fillers from renewable natural sources. Besides, biocomposites have a lower impact on people and other living ecosystems due to their lower environmental footprints (Amiandamhen et al. 2020). Additionally, the vast majority of biocomposites may be recycled and repurposed. One of the primary benefits of biocomposites, as highlighted by Amiandamhen et al. (2020) and McBee et al. (2022), is their ability to be disposed of in a regulated manner at the end-of-life cycle. The raw materials utilised in biocomposites are separated into two categories, which are first-generation and second-generation (Amiandamhene et al., 2020; Biswas et al., 2020; McBee et al., 2022). Second-generation raw materials are lignocellulosic wastes from food, forest and agricultural residues. First-generation raw materials are wood, and their usage in greater numbers might cause deforestation and harm biodiversity. Up until now, biocomposites have mostly been developed from second-generation waste. However, there has been much limited commercialisation of these materials. Numerous biocomposites have been developed because of the extensive study in the field, yet their applications are limited, and their synthesis and development still need to be fully commercialised (Roy et al., 2020). One possible way to decrease the global use of oil-based plastics is by acknowledging processing techniques, developing biocomposites and applying them to various industries (Correa et al., 2019). Biocomposites can be produced using sustainable natural resources, such as polyvinyl alcohol (PLA) from maize starch, or by utilising readily accessible polymers like bioethanol to form bioethylene for making polyethene (PE). The biocomposite material's structure differs from a typical composite's since it uses natural materials rather than synthetic ones for both the polymer matrix and reinforcement phases (Correa et al., 2019; Guna et al., 2018). Several aerospace companies in the aviation industry started to utilise biocomposite materials for interior usage. However, research into its potential applications for the primary construction of aircraft is still ongoing. The investigation of biocomposite materials for the aerospace industry is captivating due to their favourable mechanical features, such as their low density and cost, biodegradability and abundance behaviour (Mahmud et al., 2021). Fundamentally, biocomposite structures can be categorised based on the type of reinforcement and the arrangement of the materials within the composite. Yıldızhan et al. (2018) and Yildizhan et al. (2018) reported that some of the structure types are laminate biocomposite, sandwich biocomposite, particle-reinforced biocomposite, fibre-reinforced biocomposite and hybrid biocomposite.

A laminated biocomposite is an advanced composite material that is constructed in layers (laminated) and incorporates natural or bio-based components as part of its composition. In addition, a multitude of fibre layers are assembled and combined with the matrix components to create this type of composite (Kadea et al., 2024). These materials combine the advantages of laminated composites, such as tailored mechanical properties and design flexibility, with the environmental benefits of using renewable, biodegradable, or sustainable materials (Faheed et al., 2022). Fig. 15.1 illustrates the structure of laminated composites.

As seen in Fig. 15.1, the fibrous layers can be arranged in various orientations relative to the composite's axis, allowing for the customisation of the material's in-plane properties. Laminated composites possess significant stiffness and strength in-plane. Nonetheless, the primary drawback of laminated composites is their subpar performance in the thickness direction. Delamination of different layers under strain is a common cause of failure in laminated composites (Faheed et al., 2022; Kadea et al., 2024; Mazlan et al., 2022). The delamination issue is addressed by employing various ply-stitching techniques. However, this compromises the in-plane characteristics of the laminates.

The delamination issue is addressed by using various ply-stitching techniques, although this comes at the expense of the laminate's in-plane characteristics being compromised. Recently, several three-dimensional (3D) fibre architectures with through-the-thickness yarns have been used to enhance the Z-directional properties of composite laminates (Fangueiro &Rana, 2015). The concept of a 3D woven fibre architecture with binder yarns that are through the thickness is shown in Fig. 15.2. Mrazova et al. (2013) and Mrazova (2013), claimed that composites made with various 3D fibre architectures may create complex and almost net-shaped composite preforms,

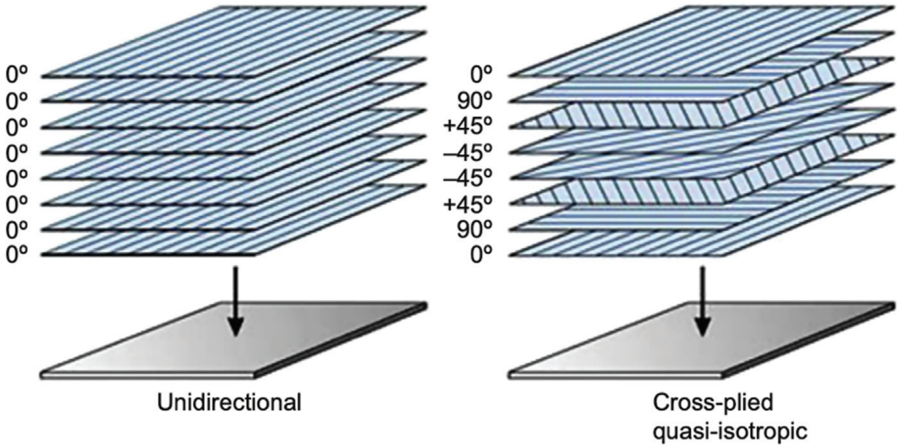


Fig. 15.1 Schematic structure of laminate composite.
From: Mazlan, N., Sapuan, S. M. & Ilyas, R. A. (2022). Advanced composites in aerospace engineering applications. Springer International Publishing. https://doi.org/10.1007/978-3-030-88192-4

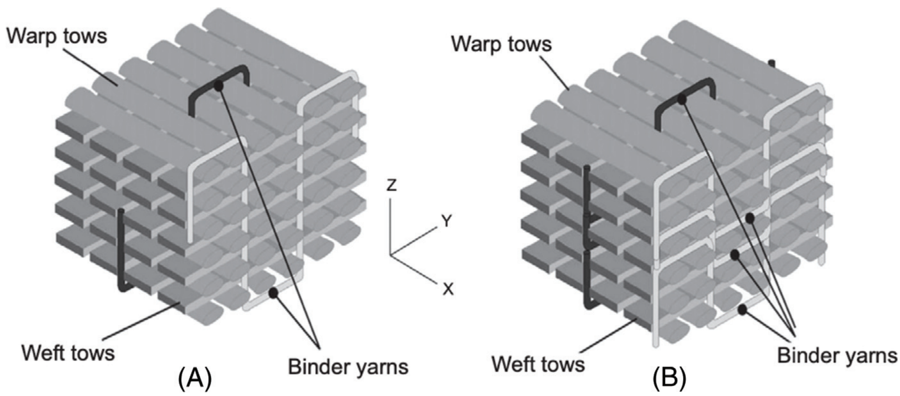


Fig. 15.2 3D woven fibre architectures: (A) orthogonal and (B) layer interlock.
From: Mouritz, A.P., Baini, C., & Herszberg, I. (1999). Mode I interlaminar fracture toughness properties of advanced textile fibreglass composites. Composites Part A: Applied Science and Manufacturing, 30 (7), 859–870, 10.1016/s1359-835x(98)00197-3.

resulting in enhanced impact resistance, damage tolerance and fracture toughness. The various forms of typical damage will be explained and discussed in detail in the following subchapter.

Recently, there has been significant interest in the composites industry in using natural fibre as a potential replacement for petroleum-derived reinforcements. Renewable resources, such as natural fibres, possess exceptional strength, stiffness and

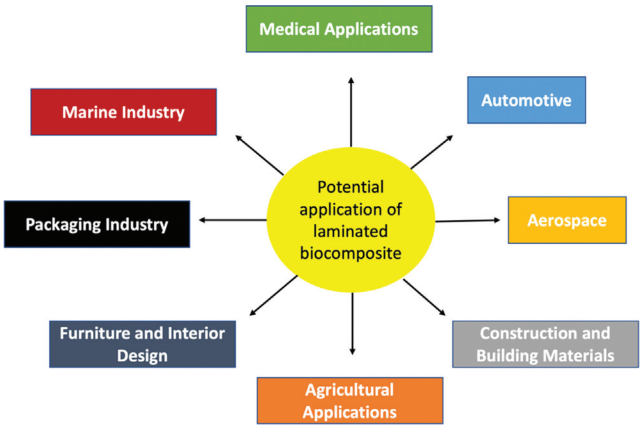


Fig. 15.3 Potential application of laminated biocomposite.

low density. Additionally, a wide range of industries, such as aerospace, biomedical, automotive and construction, can benefit from the developed composite materials, as illustrated in Fig. 15.3 (Abdul Khalil et al., 2011). Due to its benefits in terms of weight, mechanical stability and cost, the aerospace industry in the US and Europe is becoming more interested in using natural fibre-reinforced materials (Kumar et al., 2022; Péron et al., 2019). However, the US Federal Aviation Administration (FAA) and the UK Civil Aviation Authority are currently evaluating the applications of these sustainable materials to determine if they meet the requirements for certification (Kumar et al., 2022).

15.2.1 Natural fibre

Natural fibres are widely available all over the world and can be easily found, as they are extracted or produced from bio-based ecosystems, such as plants and animals, and occur naturally. Due to their superior biodegradability, renewability, decomposability, stiffness, low cost and higher length-to-weight ratio, natural fibre-based composites are becoming increasingly popular and gradually displacing synthetic fibre composites (Kumar et al., 2019). For example, incorporating plant-based lignocellulose fibres has minimised density and cost while enhancing biodegradability and can be easily recycled (Alam et al., 2021; Ilyas & Sapuan, 2019; Kumar et al., 2019; Syduzzaman et al., 2020). Each fibre possesses unique features and behaviour as a reinforcing agent in the composite material, mainly influenced by the compatibility between the fibre and the matrix. Besides, the chemical composition of these natural fibres also significantly affects the performance of the composite (Ilyas & Sapuan, 2019). Natural fibres can be categorised into three bases, which are animal, plant and mineral, and this can be shown in Fig. 15.4.

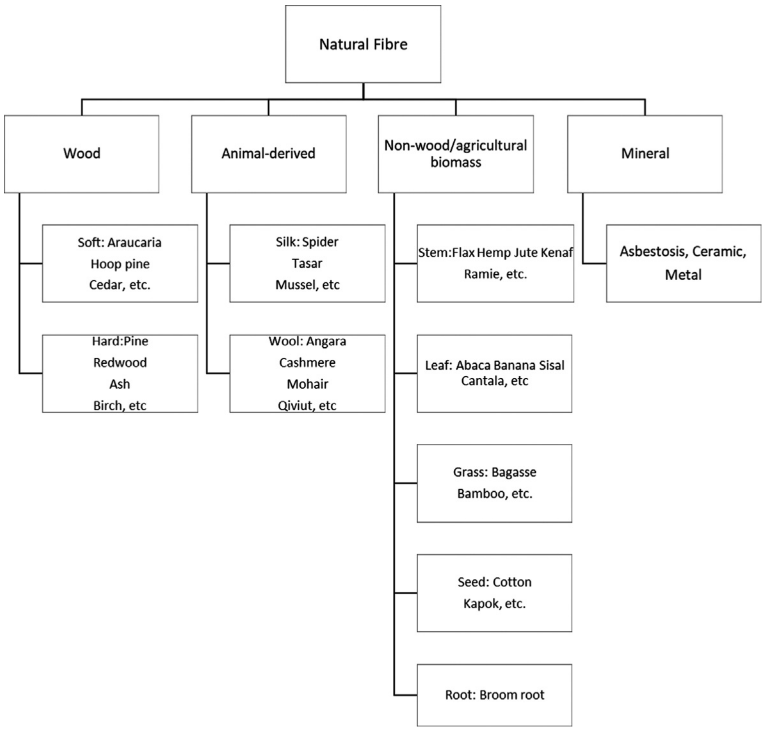


Fig. 15.4 Natural fibre categories and their examples.

15.2.1.1 Reinforcer/Filler

In composite materials, reinforcers often provide composites with rigidity, sufficient strength and control over the end product's qualities. The reinforcing architecture and the manufacturing process are key factors in producing composite structures, which result in good mechanical performances (Kozlowski & Mackiewicz-Talarczyk, 2020). The control and optimisation of thick structures with complicated shapes are achieved by selecting the reinforcement, experimental and numerical approaches. According to the studies by Aisyah et al., 2021 (Aisyah et al., 2021), the interfacial bonding mechanism between the binder and the fibres used significantly impacts the strength of natural fibre-reinforced geopolymer composites. This factor has become an interesting part of the research in developing geopolymer composites as it relates to the topic of compatibility of the fibre-matrix interaction. High load transfer capacity from the matrix to the filler is required to produce high-strength composites (Prakash et al., 2022). This can be determined by the strength of the adhesion interaction of the reinforcer to the polymer matrix, which can be categorised into (Cavalcanti et al., 2019):

1. Chemical interaction;
2. Mechanical adhesion of the filler and matrix;
3. Electrostatic and van der Waals forces.

However, there are a few treatments, such as chemical and thermal treatments, that many researchers widely use to improve the impact toughness and fatigue strength of the geopolymer-based composite. The most efficient form of reinforcement is fibres, as it allows stresses to be transferred from the stronger and frequently stiffer fibres to the typically softer matrix, creating a composite material with improved characteristics (Le Duigou et al., 2020).

15.2.1.2 Plant-based fibre

Plant-based fibres are derived and extracted from specific parts of the plants, for example, from wood, stem and leaf. The primary constituents of plant-based fibres consist of cellulose, hemicellulose, lignin, pectin, waxes and a few water-soluble substances (Zwawi, 2021). This ensures the fibre's hydrophobicity and polarity, reducing its compatibility with hydrophobic or non-polar matrices. Besides, according to Barber et al. (2020), a single plant fibre consists of a lumen, which is the central cavity that regulates the plant's water uptake, and this characteristic causes the plant fibre to absorb a significant amount of water, which is detrimental to the composite properties. As the plant grows, its cells expand through the primary wall, which is made up of randomly orientated cellulose microfibrils, and the secondary layer comprises three distinct layers. To encounter those problems, plant fibres undergo few chemical treatments, including enlargement of the crystalline region, removal of hydrophilic -OH groups and removal of waxy surface contaminants. Scouring, bleaching, mercerising, peroxide, benzoylation, coupling agents and acetylation are common chemical processes used to change the plant fibres' surface chemistry and polymer structure, with or without the heat application (Birniwa et al., 2023; Bourmaud et al., 2020; Gidley & Yakubov, 2019). Fig. 15.5 shows the common type of plant-based fibre used in geopolymer composites, and Luhar et al. (2020) stated that bamboo fibre has good potential as a green sustainable material to be used in biocomposites.

In terms of the thermal properties of plant fibres, each fibre's thermal degradation temperature differs because cellulose, hemicellulose, lignin and pectin have their own thermal degradation temperatures (Talabi et al., 2024). Based on Kumartasli and Avinc (2024), the weight loss in the natural fibre composite is divided into three main stages, which are weight loss due to the dehydration process, weight loss due to the break down of fibre reinforcement and weight loss due to depolymerisation of the matrix.

15.2.1.3 Animal-based fibre

Animal fibres comprise many types of proteins, including keratin (which is insoluble and chemically unreactive) and fibroin. These fibres are derived from either mammals (hairs) or invertebrates (like the silkworm) (Talabi et al., 2024). Wool-bearing animals, such as sheep and goats, and fur-bearing animals, such as rabbits, mink and foxes, are the most common sources of animal fibres (Kumartasli &Avinc, 2024). Protein fibres are crucial in protecting cells, tissues and organisms by facilitating flexibility, providing structural support and ensuring stability (Kumar & Davim, 2021). Most

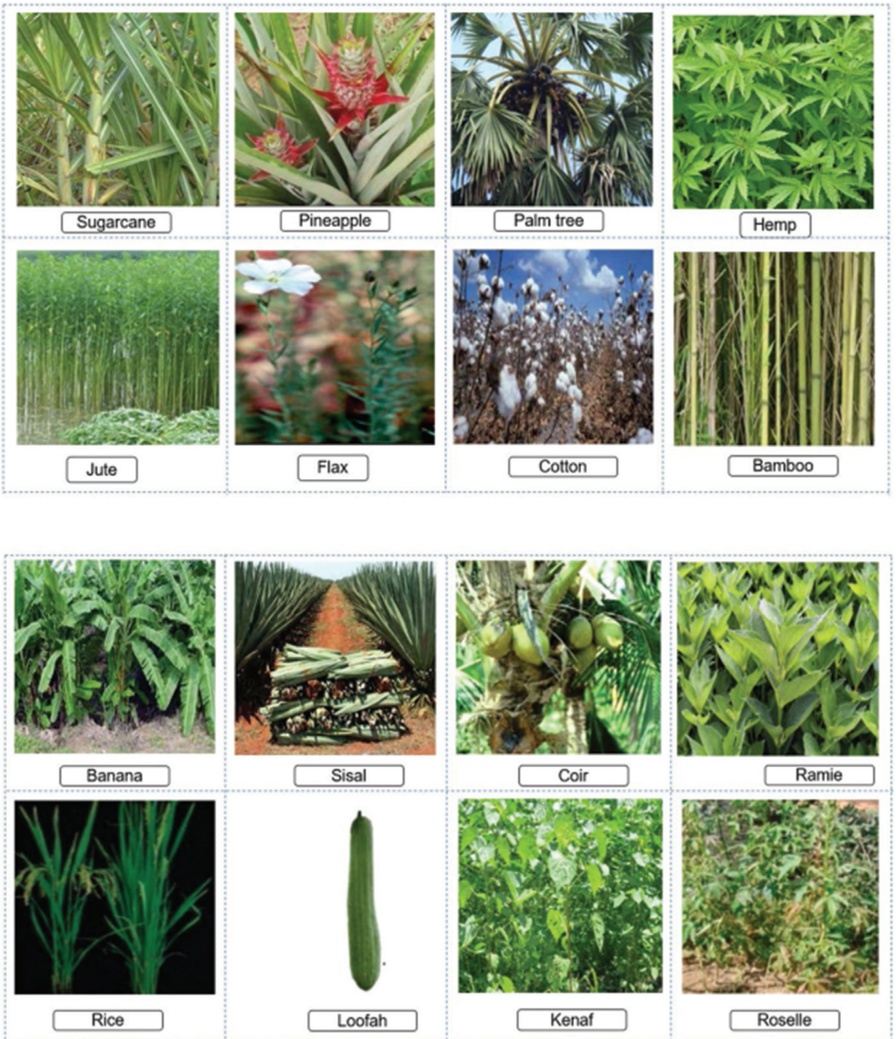


Fig. 15.5 Example of the common plant that is used as fibres in a polymer composite. From: Li, M., Pu, Y., Thomas, V. M., Yoo, C. G., Ozcan, S., Deng, Y., & Ragauskas, A. J. Recent advancements of plant-based natural fiber–reinforced composites and their applications. Composites Part B: Engineering; Ramesh, M., Palanikumar, K., & Reddy, K. H. (2017). Plant fibre based bio-composites: Sustainable and renewable green materials. Renewable and Sustainable Energy Reviews, 79, 558–584, 10.1016/j.rser.2017.05.094.

mammalian fibres consist of three main components, which are the cortex (which dictates the mechanical characteristics), the cuticle (which serves as a protective layer) and the medulla (Kumartasli & Avinc, 2024; Vinod et al., 2020). Besides, according to Chan et al. (2022), the cuticle layer prevents the water from absorbing into the fibre. Nevertheless, the limited strength of these particular characteristics prevents animal fibres from being suitable as reinforcements for polymer composites, as they exhibit a significant level of moisture absorption similar to plant fibres (Oladele et al., 2022). Animal fibres exhibit a chemical composition that enhances their affinity for geopolymer matrices and their ability to withstand exposure to alkali media. In addition, the results from the experimental work conducted by Joy Hoskeri et al. (Joy Hoskeri et al., 2023) demonstrated that the amino acid groups in the wool fibre reacted with the geopolymer matrix's alkalis. This will result in the formation of lanthionine, which reduces the wool's ability to dissolve in alkali to a certain extent. Although animal fibre has the advantage of being used in a polymer composite, the study on the mechanical and thermal properties of the final product of animal fibre-reinforced geopolymer composite must be made intensively. The report on the application of animal fibre as a reinforcer in geopolymer composite is also limited, and there is minimal discussion on using mineral fibre in geopolymer composite.

15.2.2 Matrix

Plastics are the most widely used polymeric material in commercial applications. Thermoplastic resins are a type of plastic material composed of durable polymers with high molecular weight (Rwahwire et al., 2018). These polymers can be either linear or branched form and maintain their chemical composition throughout the process of manufacturing and usage. Thermosets, which are often polymerised in two steps, constitute the second major category and are really the oldest one in terms of commercial use (Rabhi et al., 2021). During the initial phase, the substances undergo polymerisation, resulting in the formation of low-molecular-weight viscous liquids or fusible solids. In the subsequent step, known as moulding, more polymerisations occur, leading to the creation of strongly cross-linked three-dimensional structures (Militello et al., 2020; Priyadarsini et al., 2019 ; Rabhi et al., 2021; Rwahwire et al., 2018). These structures are then rendered stable, insoluble and incapable of being melted. Thermoset and thermoplastic polymers are used in various complex forms, including coatings, adhesives, foams, reinforced plastics and high-temperature materials. These materials can be generically classified as composites. The selection of these materials for end-use applications depends on factors such as design considerations, material qualities and the process techniques required to transform the material into the desired output (Kreit et al., 2019).

Thermosets such as phenolic, polyesters, vinyl esters and epoxy resins are widely used, as documented in the literature (Kopparthy & Netravali, 2021; Kreit et al., 2019). Alternatively, widely utilised thermoplastics are made of polypropylene (PP), polyvinyl alcohol, polyvinyl chloride, polylactic acid and natural rubbers. It is common practice to include fibres in polymeric resins to enhance their mechanical properties. The ultimate composite material should possess superior qualities in terms of thermal, mechanical, rheological and thermo-mechanical aspects as compared to the initial polymer matrix and reinforcing components (Kopparthy & Netravali, 2021). The literature by Mhatre et al. (2018) provides a comprehensive overview of several techniques to enhance the strength and properties of composites, resulting in outstanding performance and specialised features. The reinforcing materials, fillers and fibres can be categorised as either bio-based (derived from natural sources) or synthetic (derived from petroleum) (Mhatre et al., 2018). Bio-based reinforcements encompass materials such as flax, kenaf, sisal, agave, cotton and others. On the other hand, synthetic reinforcements consist of glass and carbon fibres. Natural fibre-reinforced composite materials are well-suited for a wide range of applications, including automotive, construction, biomedical and aerospace (Kopparthy & Netravali, 2021). However, the aerospace industry has widely utilised glass fibres (Ren et al., 2024).

15.3 Fabrication and synthesis of laminated biocomposite

15.3.1 Introduction to biocomposite fabrication methods

Over the last ten years, there has been a significant surge in the demand for products based on biocomposites. Along with the high demand, various fabrication methods of laminated biocomposites have been developed, which include hand lay-up, compression moulding, resin transfer moulding, vacuum infusion, spray lay-up, injection moulding, filament winding, pultrusion method, vacuum bag moulding and autoclave method (Bajpai et al., 2017). This section provides an overview of the commonly selected fabrication methods for laminated biocomposites, such as hand lay-up, compression moulding, resin transfer moulding and vacuum infusion.

15.3.2 Hand lay-up

The hand lay-up method is commonly referred to as the most straightforward and cost-effective production method of fabrication for a relatively simple design (Santos et al., 2021b; Yogeshwaran et al., 2021). This is because this method does not require many fabrication tools and a huge machine. The method usually begins with laying a bottom mould plate, followed by a thin plastic sheet and then a middle plate or a template. This middle plate features a cut-out area that matches the shape and thickness of the final composite. Following that, fibre in the form of woven mats or chopped strand mats is precisely trimmed to match the dimensions of the mould. Then, the thermoset polymer, which has already been mixed with a hardener, is poured onto the fibre and distributed uniformly. The process is repeated until the number of desired layers is achieved. Another thin plastic sheet is laid to cover the material before it is covered with a top mould. Then, pressure is applied, and the composite is left to cure at either ambient temperature or elevated temperatures. This method has been documented for the fabrication of biocomposites such as epoxy/graphene/fish scale and fermented spinach hybrid biocomposite (Yogeshwaran et al., 2021), waste silk fibre-reinforced PLA biocomposites (Mohanavel et al., 2021) and jute-polyester biocomposite (Sengupta, 2022).

15.3.3 Compression moulding

Compression moulding is a fabrication process whereby the material is compressed to conform into a mould, forming a composite with the specified dimensions. The way the process begins depends on the type of resin used for the biocomposite, either thermoset or thermoplastic. Thermosets like epoxy require laying up the resin onto the surface of woven fibre first (Tay et al., 2021). Then, the wetted woven fibres are arranged on a metal plate in a mould before being covered with another piece of metal plate and then pressed under the compression moulding machine at a specific temperature, pressure or load and time. For example, in Mazlan's work, the woven glass/kenaf epoxy composite reinforced with nanoclay was compressed at 85°C, with a force of 40 tonnes, for a duration of 20 minutes (Mazlan et al., 2021). Then, the composite is removed and left to cool down at room temperature (Tay et al., 2021). Huda et al. (2008) reported that for biocomposites using thermoplastic resin, the PLA resin was initially converted into films through compression moulding. Then, the surface-treated pineapple leaf fibres (PALF) were arranged in an alternating pattern between PLA films. The entire structure was then subjected to compression at a temperature of 190°C and a pressure of approximately 700 psi for a duration of 12 minutes. Subsequently, it was further compacted at a pressure of around 1700 psi for 5 minutes. Finally, the assembly was cooled to a temperature of 90°C while maintaining pressure to complete the fabrication process.

15.3.4 Resin transfer moulding

The resin transfer moulding process begins by applying a release agent onto the steel mould through spraying. Then, the preform is placed into the close mould. Preform is a pre-shaped fibre reinforcement that is specifically designed to fit the mould precisely. It typically consists of woven, stitched, or braided fibres. Then, the resin is injected into the closed mould with a specific pressure. The composite is then cured in the closed mould to harden in the specific shape (Gomez et al., 2021; Santos et al., 2021a).

15.3.5 Vacuum infusion

This technique utilises a vacuum to infuse resin into woven fibre mats. The initial step involves applying sealant tape onto the fabrication table, conforming to the final composite's shape (Francucci et al., 2014). Then, the space within the sealant tape is sprayed with a release agent to facilitate the removal of the composite from the table after fabrication. Next, the woven fibre mat is positioned on the fabrication table, and a peel ply is placed on top of it. The tube is then placed on both sides of the woven fibre mat. The T-pipe is appropriately adjusted to accommodate the resin's inlet and outlet. The vacuum infusion machine is switched on, and the resin, mixed with hardener, is vacuumed in. The resin wets all parts of the woven fibre mat. Then, the outlet tube is clamped, and the composite is cured before being removed from the fabrication table (Chai Hua & Norkhairunnisa, 2017; Nissilä et al., 2018).

15.3.6 Defects in laminated biocomposites

Researchers have a wide range of options regarding fabrication processes (Patil et al., 2022). The choice depends on factors such as the fabrication tool and machine, type of natural fibre, matrix properties, desired mechanical properties and production scale. Regardless of the chosen procedure, the fabricator needs to perform the composite preparation to avoid manufacturing defects, hence minimising damage to the laminated structure of biocomposites. These manufacturing defects encompass voids, regions of fibres that are inadequately saturated with resin, areas with excessive resin, pockets of undispersed crosslinker and misaligned fibres (Suriani et al., 2021).

Voids, sometimes referred to as porosity in biocomposites, reduced the contact between the natural fibre and the resin. Moisture absorption in natural fibre can result in the weakening of the composite (Azmah Hanim et al., 2019). Thus, various researchers have conducted extensive work from 2015 to 2020, discussing voids in composite materials. These composites were fabricated using different methods, including hand lay-up with compression moulding (30%), vacuum bagging (14%), compression moulding (14%), hand lay-up with cold curing (12%), hand lay-up with vacuum bagging (7%) and other methods (23%) (Zuhudi et al., 2021). Typically, the void is trapped within the resin while undergoing an intense stirring process. In order to tackle the issue, the resin might undergo degassing to eliminate the void (Bhatt et al., 2022; Dobrosielska et al., 2021).

The inadequate wetting of fibre areas in biocomposites results from low compatibility between the natural fibre and matrix, caused by the fibre's excessive water absorption (Ilyas & Sapuan, 2020; Sakthiguru & Sithique, 2020). In order to mitigate this issue, it is possible to initially treat the natural fibre to improve interfacial adhesion between the fibre and matrix. Natural fibre treatment is divided into two methods: physical techniques and chemical treatment. An instance of a physical technique is plasma treatment, whereas examples of chemical treatments are alkali treatment, silane treatment, acetylation treatment, maleic anhydride treatment and benzoylation treatment (Geremew et al., 2021).

Resin-rich zones are areas characterised by a higher concentration of resin compared to the amount of fibre present. As a result, the resin-rich zones are weaker than zones that are reinforced with fibre. Thus, this induces the weak point in biocomposites. The construction of this region is mostly caused by the tension applied to the fibres as it is being pulled tightly around corners when closed in a mould, leading to the formation of the resin-rich zone (Dong & Tsai, 2010; Holmberg & Berglund, 1997). Incomplete curing, insufficient dispersion of the curing agent, or premature curing led to the formation of localised areas with undispersed crosslinkers (Placet, 2009). As a result, the region of the undispersed crosslinker does not undergo solidification, forming another region of weak points in the biocomposite. Finally, it is crucial to address misaligned fibres, such as wrinkles, waviness, folds and undulation, in natural fibres due to their anisotropic nature (Suriani et al., 2021). This is because it can cause uneven distribution of stress in the biocomposite, which can lead to premature failures in high-stress regions. However, the term 'misaligned fibres' is not now commonly accepted and has not been consistently used. Nevertheless, the definition is constructed for clarity (Thor et al., 2020).

15.4 Characterisation and mechanism of laminated damage

15.4.1 Introduction to laminated damage in biocomposites

Typically, the damage mechanisms in laminated composites can be categorised as either interlaminar or intralaminar damage. Interlaminar damage mechanisms refer to the process of interlaminar crack formation and propagation, resulting in the separation of two laminas (delamination). On the other hand, intralaminar damage mechanisms refer to damages occurring within a single lamina, including matrix cracking, fibre breakage, fibre/matrix debonding and fibre pull-out (Saeedifar & Zarouchas, 2020). Essentially, the interlaminar damage accumulates and extends to intralaminar damage, leading to the separation of laminas. Gaining a comprehensive understanding of the process by which laminate damage occurs is important in order for researchers and engineers to predict the biocomposite's performance, enhance the biocomposite design and improve the fabrication method.

15.4.2 Types of laminated damage

Puech et al. (2018) categorise the damage mechanisms as interrelated and occuring one after another. According to the authors, failure in biocomposites begins with matrix cracking, followed by either fibre breakage or fibre pull-out, indicating the occurrence of interfacial debonding. Delamination is then the major damage that occurred in biocomposites (Puech et al., 2018). According to Curto et al. (2021), matrix cracking is initiated by mechanical stress within an inhomogeneous region. Additionally, matrix cracking can be caused by water absorption by natural fibre. The higher the natural fibre content, the faster the diffusion rate and the higher the water absorbed. This swollen natural fibre then causes an internal blow-up, leading to cracking (Badia et al., 2014).

The strength of interfacial debonding is critical in determining the extent of damage in biocomposite laminates. This damage might appear as either the fibre fracture or the fibre pulled out from the matrix. Komal et al. (2020) discovered from microscopy analysis that enhancing the interfacial adhesion between fibre and matrix leads to fibre breaking instead of being pulled out. It is reasonable to assume that in a composite material where the fibre and matrix are strongly bonded, there is less risk of the fibre and matrix being separated. Consequently, if any fibre breakage were to occur, it would likely affect the fibre first. On the other hand, when the interfacial adhesion is low, where the bond between fibre and matrix is weak, it is easier for the fibre and matrix to be separated. Therefore, the matrix will crack first, leaving the fibre to be pulled after that.

The final stage of the composite manufacturing process commonly requires drilling operations. Composites are known to be one of the most challenging materials to machine due to the resulting induced damage (Díaz-Álvarez et al., 2018; Khashaba & El-Keran, 2017; Khoran et al., 2015; Srinivasan et al., 2017), where delamination is the primary damage caused (Rubio-López et al., 2015). Delamination is the failure phenomenon in which a composite material separates at the interphase, resulting in the separation of its layers. Additionally, as mentioned previously, delamination can

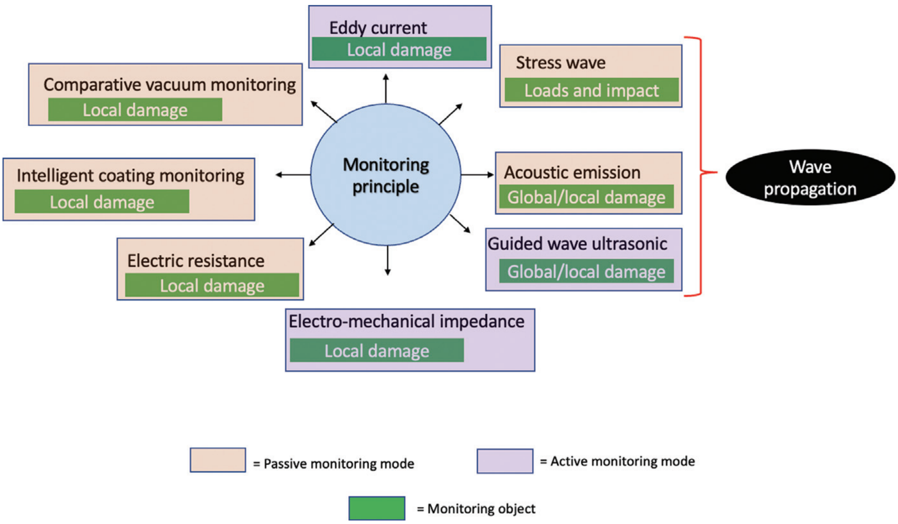


Fig. 15.6 Common method of damage detection for composite materials and their monitoring mode and object.

occur due to intralaminar damage when a crack is initially formed, followed by crack propagation and then separation at the interface between the fibre and matrix. This ultimately leads to delamination of the biocomposite.

15.5 Method processing on damage detection using guided ultrasonic waves

At present, the methods used to identify and evaluate damage mainly involve passive detection technology and active detection technology (Rautela & Gopalakrishnan, 2021). The active detection method involves externally stimulating the structure and assessing its response to stimulation (Mei et al., 2020). In recent years, the utilisation of ultrasound-based non-destructive testing technology has been widespread due to its high level of controllability. This technology allows for precise control over factors such as the type of excitation signal, energy level, layout and size of excitation devices (Yu et al., 2019). Guided wave-based active detection technology has experienced significant advancements. It is now considered one of the most promising and dynamic technologies in the field of non-destructive testing, among many ultrasonic testing techniques. Fig. 15.6 illustrates the commonly used damage detection principle in composite materials.

Several studies have been conducted on detecting composite delamination utilising guided waves (Panda et al., 2017; Ricci et al., 2016). Shoja et al. (2018) performed numerical simulations to detect delamination in composite laminates using low-frequency guided waves. Leckey et al. (Leckey et al., 2018a) performed a simulation to study the propagation of guided wave ultrasound in composite laminate. They compared the results of numerical codes with experimental data to establish benchmarks. Panda et al. (2017) conducted a study on the quick examination of intricate reinforced composite structural parts utilising non-contact air-coupled ultrasound. Zhang et al. (2017) developed a comprehensive numerical model to study guided wave behaviour in composite laminates damaged by impact. Wang et al. (2012) observed the initiation and propagation of delamination during mode I and mode II interlaminar fracture tests by utilising guided waves. Sohn et al. (Sohn et al., 2011) identified delamination in composites by analysing guided wave field images using image processing techniques. Gao et al. (2010) efficiently detected delamination in multilayered materials by utilising ultrasonic guided waves. Leckey et al. (2014) performed a three-dimensional simulation and experiment to identify damage in anisotropic and quasi-isotropic aerospace composites. They used guided waves for this purpose. Pupyrev et al. (2019) investigated the transmission of guided acoustic waves at the junction of interfaces and surfaces. Soleimanpour and Ng (2017) conducted a study on detecting delaminations in laminated composite beams using nonlinear guided waves.

According to the researchers in Soleimanpour and Ng (2017), advancements have been achieved in detecting damage caused by delamination in composites using ultrasonic guided waves. Linear guided wave technology is mostly employed for detecting macro-scale damage, with limited research on detecting micro-scale closed micro-cracks. Simultaneously, most of the research relies on numerical simulation findings to assess the magnitude and nature of damage, which compromises their reliability. So far, most of the research has concentrated on analysing structures that have experienced damage at a single scale. At the same time, only a few studies have addressed identifying composite materials that have sustained damage at several scales. Unfortunately, very few experimental data have been reported on the application of guided ultrasonic waves on damage detection in biocomposite materials. There are several factors, including the fact that biocomposite materials are considered new advanced materials, and the fundamental materials' properties and methods of processing must be standardised and well-known first. However, the principle of the guided ultrasonic wave in damage detection of biocomposite materials should be the same because it depends on the monitoring object and is very little influenced by the materials. Hence, there is ample room for further study in detecting delamination damage in biocomposite materials.

15.5.1 Principle of guided ultrasonic wave for laminated damage detection

A 'guided wave' is a wave that occurs when there is a dielectric barrier in a waveguide structure, and it interacts with the boundary through reflection and refraction. Additionally, this interaction transforms shear waves into longitudinal waves and vice versa (Capineri & Bulletti, 2021). The guided wave within the structure can travel over long distances and cover a large area for detection, making it capable of identifying defects on any part of the structure. Consequently, the detection effectiveness is exceptionally high. Guided wave detection technology utilises advanced guided wave

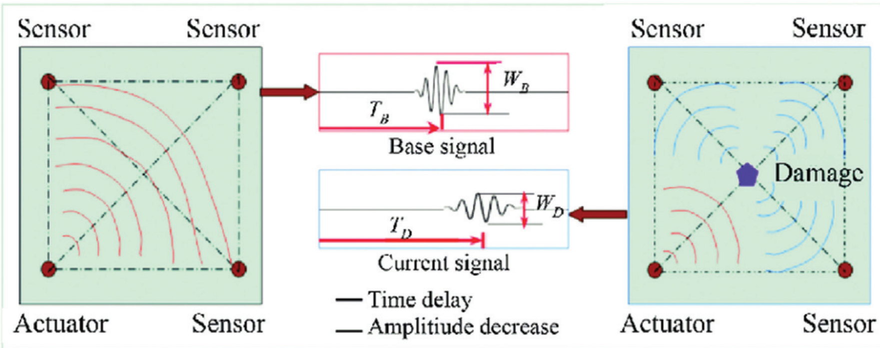


Fig. 15.7 Principle of damage monitoring technology based on ultrasonic guided wave. From: Qing, X., Liao, Y., Wang, Y., Chen, B., Zhang, F., & Wang, Y.(2022). Machine learning based quantitative damage monitoring of composite structure. International Journal of Smart and Nano Materials, 13 (2), 167–202, 10.1080/19475411.2022.2054878.

excitation sensing technology to achieve real-time structural health detection (Capineri & Bulletti, 2021; Pupyrev et al., 2019; Soleimanpour& Ng, 2017). Furthermore, ultrasonic guided wave testing is categorised into linear technology and nonlinear technology, depending on the dimensions of defects in composite structures (Moll et al., 2019a). The linear guided wave method is well-suited for detecting visible damage on a large scale, such as cracking, debonding and delamination. This is achieved by examining the variations in reflection, attention and wave velocity (Capineri & Bulletti, 2021; Moll et al., 2019a; Pupyrev et al., 2019). The contact acoustic nonlinear (CAN) method utilises the nonlinear guided wave technique to detect and diagnose small-scale damage, such as closed micro-cracks, that are not easily visible. The initial step involves constructing the outside framework, followed by measuring the structural response when it is excited.

Ultrasonic guided waves are currently the most effective technology for actively monitoring large areas of damage in composite structures. They can travel long distances within a structure and detect various types of damage, such as delamination, debonding and cracks (Soleimanpour & Ng, 2017). Piezoelectric devices are commonly employed as actuators and sensors, while ultrasonic guided waves serve as a means for transmitting information about damage. This allows the active real-time monitoring of the damage and its progression in composite structures. The fundamental concept of the damage monitoring method utilising ultrasonic guided waves is illustrated in Fig. 15.7. The actuator employs a piezoelectric element to produce ultrasonic-directed waves within the structure, while the sensors, consisting of neighbouring piezoelectric elements, detect the guided waves that propagate through the structure. When damage occurs, the arrival time TD of guided waves detected by the sensors will be delayed, and the amplitude WD will be lower compared to the arrival time TB and amplitude Wb of baseline signals without damage (Qing et al., 2022).

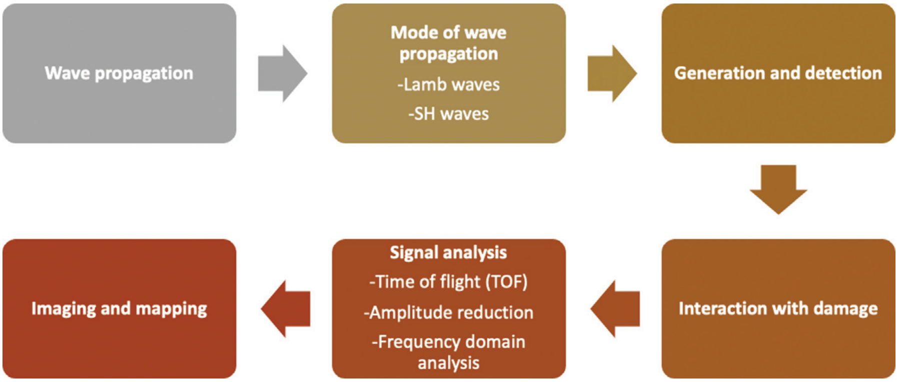


Fig. 15.8 Principle method in guided ultrasonic wave in damage detection

The damage diagnostic algorithm is the fundamental component of damage monitoring using ultrasonic guided waves. Several damage monitoring algorithms have been created, such as phased array, delay and sum (DAS), tomograph, elliptical weighted distribution damage imaging and time reversal (Olisa et al., 2021a;Rautela et al., 2021; Shi et al., 2019). The phased array technique utilises many piezoelectric (PZT) sensors in the sensor network to create a dense sensor array. The principle of radar is applied here, where the phase of the excitation signal of each PZT can be adjusted independently (Yang et al., 2023). This allows for focusing Lamb wave propagation in a specific direction for the far field or at a specific location for the near field. This is achieved by summing the Lamb wave fields excited by all PZT. The DAS method utilises the damage scattering signal collected from several pitch-catch pathways to find the damage based on the group velocity and propagation duration of guided waves (Lyu et al., 2024). In the tomography algorithm, sensors are often positioned throughout the monitored region, creating a multitude of transmitting-receiving channels. The monitoring principle involves exploiting the variations in guided wave signals to detect and map the damage (He et al., 2019). Fig. 15.8 shows the overview of the guided ultrasonic wave method of principle.

The propagation of guided waves in these structures is particularly complex because of composite structures' material properties and structural complexity (material anisotropy, variable thickness structures, structures with curvature, reinforced structures, etc.) (De Luca et al., 2020a). Accurately measuring wave speeds and mitigating the impact of ambient noise are demanding tasks, and most approaches have reliability and effectiveness challenges when used on real-world composite structures. Bolted joints are one of the important components of composite structures that not only support cyclic loads but also have intricate nonlinear coupling aspects (Bombarda et al., 2021). These crucial locations have a comparatively high chance of experiencing damage. Techniques for diagnosing localised damage to these structures need to be developed. Cho et al. (2019) reported that several new sensor technology-based local damage monitoring techniques have been proposed as below:

- Acoustic emission (AE) sensors
- Flexible eddy current (FEC) sensors
- PZT sensors
- Intelligent coating monitoring (ICM)
- Comparative vacuum monitoring (CVM)

15.5.2 Guided ultrasonic wave setup using different sensors

The typical ultrasonic examination of large structures is very time-consuming due to the requirement to scan the transducer over each point of the structure being inspected. Utilising guided waves is a highly appealing approach to address this issue, as they may be stimulated at a specific location inside the structure and can travel significant distances (Serey et al., 2021). Over the past two decades, ultrasonic guided waves have shown promise in detecting defects in tube, pipe, or plate structures that cannot be easily and efficiently identified using other approaches (Soman et al., 2019). A significant advantage of guided waves is their capacity to evaluate structures on a global scale quickly. Highly sensitive and accurate sensing devices are crucial in SHM systems, as they are responsible for detecting damage-induced ultrasonic guided waves, which can be challenging to differentiate at times (Moll et al., 2019b). Various transducers have been employed thus far to collect ultrasonic guided waves in structures. PZT and fibre optic sensors are commonly used for ultrasonic detection (Cantero-Chinchilla et al., 2021). However, the PZT sensor's performance in practical applications is occasionally hindered by electromagnetic interference (Sherwood et al., 2021). Furthermore, the applications of fibre optic sensors are rapidly expanding due to their remarkable attributes, such as flexibility, high strength, heat resistance, immunity to electromagnetic interference, durability and resistance to corrosion (Cantero-Chinchilla et al., 2021; Moll et al., 2019b; Sherwood et al., 2021; Soman et al., 2019). Therefore, fibre optic sensors are the most promising sensors currently being researched for ultrasonic detection (Sherwood et al., 2021).

While optical interferometric sensors provide excellent sensitivity for ultrasonic detection, their main drawback is the requirement for a phase control mechanism to ensure optimal sensitivity (Cantero-Chinchilla et al., 2021). The FBG is currently the primary area of interest in the fibre optic sensor community. FBG comprises a set of parallel gratings imprinted onto the core of an optical fibre. When a broadband light is shone on the sensors, they reflect a narrow range of wavelengths (Melville et al., 2018). The relationship between the wavelength at the peak of the reflected signal and the grating period allows for the measurement of axial strain through the observation of peak shift (Li et al., 2009b). In addition, the FBG sensor may be readily multiplexed. Consequently, several research papers (Hall et al., 2014; Li et al., 2009b; Torkamani et al., 2014) have documented various experiments on ultrasonic detection utilising FBG technology. FBG ultrasonic sensing systems may be categorised into two categories based on the light source used. One refers to a system comprising a broadband light source and an optical filter (Clarke et al., 2009). An optical filter can detect an ultrasonic wave by processing the light reflected from an FBG sensor. Another method incorporates a tuneable laser source, where the intensity of the light reflected from the FBG sensor is precisely proportional to the ultrasonic response (Clarke et al., 2009; Torkamani et al., 2014). In earlier works conducted by the authors (Purekar & Pines, 2010), they suggested an FOD that utilised the Doppler effect of light wave transmission in optical fibre. This sensor served as a vibration/acoustic sensor (Mustapha et al., 2014). In addition, when compared to the FBG sensor, the FOD sensor offers several distinct advantages (Guan et al., 2017). Firstly, it can detect ultrasonic waves in all directions. Secondly, it can be shaped in various forms, such as circular loops, U-shapes and elongated circular loops, allowing it to be used in structures with intricate geometries. Lastly, the manufacturing and construction of an SHM system using FOD sensors is relatively inexpensive. Table 15.1 illustrates the type of sensor utilised in damage detection of laminated damage of composites using various sensors and their applications.

15.5.2.1 Guided wave detection using fibre bragg grating (FBG)

FBG is a component in an optical fibre that exhibits periodic variations in the refractive index within its core. It functions as a narrowband reflection filter. The Bragg wavelength, denoted as the centre wavelength of light reflected from an FBG, can be calculated using the equation (Campanella et al., 2018) (Nagalakshmaiah et al., 2018):

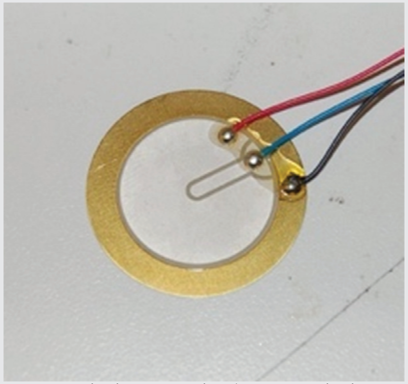
$$\lambda_B = 2n\Lambda$$

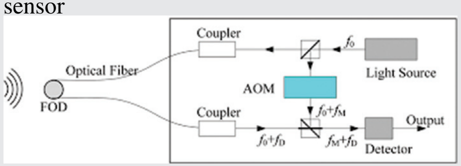
where n and Λ stand for the grating period and the fibre core's respective effective refractive indices. The applied strain (ε)along the fibre axis is directly proportional to the relative shift in the Bragg wavelength $\Delta\lambda_B$ under constant temperature conditions. When the FBG grows, there is a positive shift in the Bragg wavelength (Campanella et al., 2018; Guan et al., 2017). In contrast, as the FBG decreases, the Bragg wavelength changes to a negative value (Mieloszyk et al., 2021).

In the current work by Li et al. (2009a) and Mieloszyk et al. (2021), a laser source that can be adjusted was utilised for the purpose of detecting guided waves. Fig. 15.9 demonstrates the dual functionality of a PXI-6115 (National Instruments Co., USA) as both a wave generator and wave acquisition device. The incident wave produced was amplified using a Piezo-Amplifier (M-2643, MESS-TEK Co., Japan) and then released into the specimen using a PRYY-0929 PZT actuator (Physik Instrumente GmbH & Co. KG, Germany) in order to stimulate Lamb-directed waves. The FBG detects guided waves by measuring the strain variations in the laminate over time. As a result, the wavelength of the reflected light from the FBG shifts accordingly. The change in wavelength is detected using the high-speed optical wavelength interrogation technology. The PXI-6115 device is used to capture guided waves that have been filtered by the FV-628B filter, which is manufactured by NF Corporation in Japan. The current work utilised FBGs (Fujikura Ltd., Japan) with a gauge length of 3 mm, a wavelength of about 1,550 nm, a full width at half maximum (FWHM) of approximately 0.5 nm and a reflectivity of 90%.

In the ultrasonic detection system utilising a tuneable laser source, the intensity of the light reflected from the FBG sensor is exactly proportional to the ultrasonic

Table 15.1 Comparison of the current used sensor in guided ultrasonic wave for composite laminated damage detection.

Type of sensor	**Advantages**	**Disadvantages**	**Application**	**References**
1.Piezoelectric transducers  No Permission RequiredNo Permission Required	• High sensitivity and bandwidth, capable of detecting a wide range of ultrasonic frequencies. • Well-established technology with robust and mature industry support • Easy to implement with straightforward signal processing	• Susceptible to electromagnetic interference • Bulky and potentially invasive when attached to structures, which may affect the material properties. • Limited capability for distributed sensing over large areas	• Commonly used for generating and detecting ultrasonic waves in materials	Cantero-Chinchilla et al. (2021); Serey et al. (2021); Soman et al. (2019)
2. Strain gauges  No Permission RequiredNo Permission Required	• High Accuracy and Sensitivity • Cost-Effectiveness • Ease of Integration • Real-Time Monitoring	• Limited to Point Measurements • Durability and Maintenance • Lower Sensitivity to High-Frequency Waves	• Widely used in structural health monitoring and NDT for composite materials	Hall et al. (2014); Melville et al., 2018; Moll et al. (2019b)

3. Fibre Bragg grating (FBG)  No Permission RequiredNo Permission Required	• High Sensitivity and Resolution • Distributed Sensing • Embedded Capability • Long-Term Stability	• Complex Interrogation Systems • Temperature Cross-Sensitivity • Multiplexing Capability	• Widely used in structural health monitoring and NDT for complex composite design and size	Clarke et al. (2009) ; Torkamani et al. (2014)
4. Doppler effect-based fibre optic (FOD) sensor  No Permission RequiredNo Permission Required	• High Sensitivity • High Spatial Resolution • Non-Invasive and Lightweight • Immunity to Electromagnetic Interference	• Complexity and Cost • Environmental Sensitivity Installation Challenges • Limited Commercial Availability	• Used in damage detection for composites, including high sensitivity, spatial resolution and immunity to electromagnetic interference.	Campanella et al. (2018) ; Guan et al. (2017); ; Mustapha et al. (2014); Torkamani et al,(2014

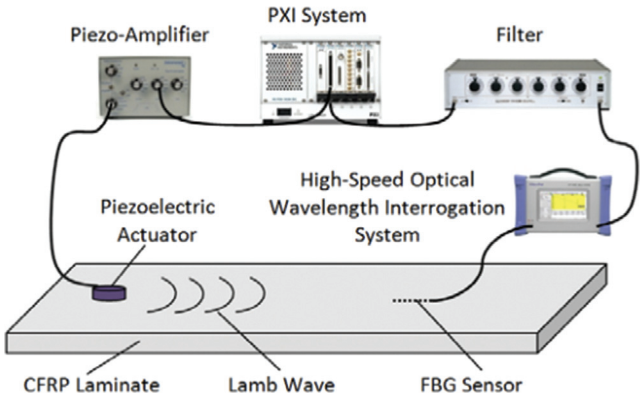


Fig. 15.9 Guided ultrasonic wave setup using FBG an sensor and piezoelectric as an actuator. From: Li, F., Murayama, H., Kageyama, K., & Shirai, T. (2009b). Guided wave and damage detection in composite laminates using different fiber optic sensors. Sensors, 9 (5), 4005–4021, 10.3390/s90504005.

response of the host structures (Annamdas & Annamdas, 2010). Fig. 15.10(A) displays a diagram of the high-speed optical wavelength interrogation system, which relies on a tuneable laser source. The laser emission wavelength of the 'Tenable Laser' in Fig. 15.10(A) (Agilent 8164A, Agilent Technologies, USA) is adjusted to a certain value, denoted as λ_{out}, at which the reflectivity of the sensor is decreased by 50% compared to its strain-free state, as seen in Fig. 15.10(B). The optical circulator, photodetector and low noise amplifier used in this system are the YC-1100-155 (FDK Corp., Japan), PDA10CS (Thorlabs, USA) and SA-230F5 (NF Corp., Japan), respectively. When the FBG grows, the Bragg wavelength undergoes a shift towards a longer wavelength, as seen by the 'FBG-Shift' curve in Fig. 15.10(B). Consequently, the reflectivity of the FBG at the lasing wavelength drops. The opposite effect occurs when the FBG contracts. The studies yielded a photodetector gain of 4.75×10^(-2) (10 dB setting) and an optical power of the laser source of 2.375 mW.

15.5.2.2 Guided wave detection using doppler effect-based fibre optic (FOD) sensor

The FOD sensor operates based on the Doppler effect, which involves the change in frequency of light waves as they travel through an optical fibre. Annamdas et al. (Annamdas & Annamdas, 2010) examined the transmission of a light wave with a frequency of f_0 via an optical fibre with a refractive index of n and a length of L. When an event, such as a change in strain rate in the host structure of the optical fibre, causes the length of the fibre to change from L to L + dL in a very little amount of time dt, the Doppler frequency shift f_d may be calculated using the following formula (Shanmugam et al., 2021):

$$f_d = -\frac{n}{\lambda_0}.\frac{dL}{dt}$$

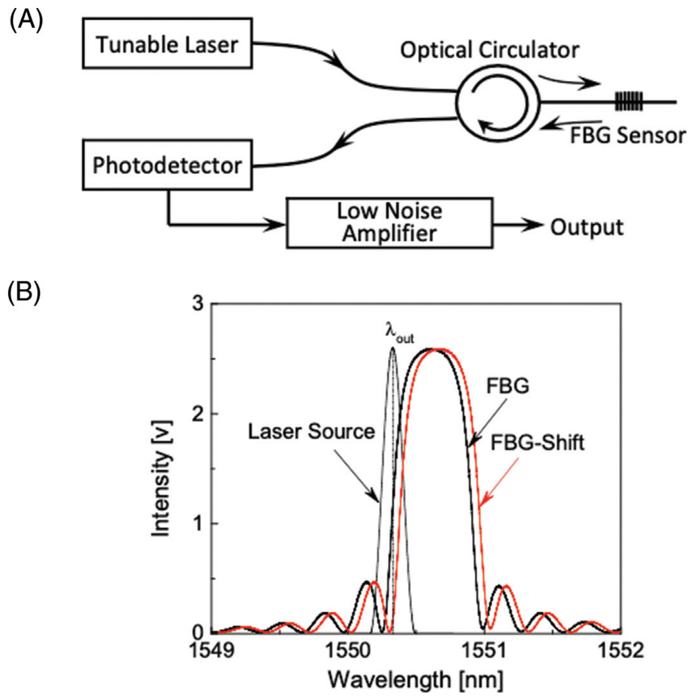


Fig. 15.10 (A) A system for detecting ultrasonic waves using FBG technology. (B) A diagram depicting the changes in reflectance at the lasing wavelength when the FBG sensor undergoes expansion.
From: Li, F., Murayama, H., Kageyama, K., & Shirai, T. (2009b). Guided wave and damage detection in composite laminates using different fiber optic sensors. *Sensors*, 9 (5), 4005–4021, 10.3390/s90504005.

Where λ_0 is the light wavelength in the vacuum, and λ_0/n is the light wavelength in the optical fibre.

In earlier investigations by Kageyama et al. (Kageyama et al., 2006), three types of FOD sensors with distinct geometries were suggested. The typical form of these FOD sensors is their circular component, as seen in Fig. 15.11(A), with points A and B representing the light source and observer, respectively. The theoretical Doppler frequency shift f_d of the circular loop FOD sensor, as computed according to reference (Li et al., 2009a), is determined by (Ilyas et al., 2021):

$$f_D = -\frac{\pi R n_{eq}}{2\lambda_0}\left(\dot{\varepsilon}_x + \dot{\varepsilon}_y\right)$$

where $\dot{\varepsilon}_x$ and $\dot{\varepsilon}_y$ are the strain rates in the x- and y- directions, respectively, R and D are the radius and diameter of the circular part of the FOD sensor, respectively; n_{eq} is the equivalent refractive index of the waveguide and λ_0/n_{eq} is the equivalent length of the light wave in the waveguide. The Doppler frequency shift f_d, which represents

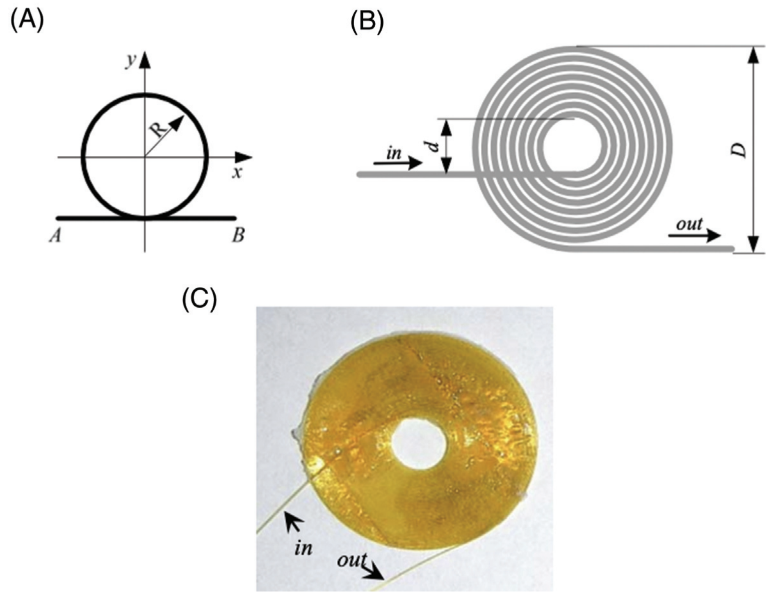


Fig. 15.11 (A) Diagram illustrating the design of a circular loop fibre optic displacement FOD sensor. (B) Diagram illustrating the structure of a spiral FOD sensor. (C) Image depicting the spiral FOD sensor, measuring 21.2 mm in outer diameter.
From: Gungor, S., & Bakis, C. E. (2016). Indentation damage detection in glass/epoxy composite laminates with electrically tailored conductive nanofiller. Journal of Intelligent Material Systems and Structures, 27 (5), 679–688, http://jim.sagepub.com/10.1177/1045389×15577644.

the sensitivity of the FOD sensor, is directly proportional to the sensing length of the FOD sensor. For guided wave detection, a spiral form was chosen for the FOD sensor to facilitate its adhesion onto the surface of carbon fibre-reinforced polymer (CFRP) laminate (Aymerich & Staszewski, 2010). Fig. 15.11(B) and (C) display a drawing and photograph of the spiral FOD sensor, respectively. The spiral FOD sensor in this work was constructed using HEATOP®, an optical fibre that is resistant to high temperatures, manufactured by Totoku Electric Co., Ltd. in Japan. Additionally, the FOD sensor may be constructed manually using just optical fibre, resulting in a significantly lower cost compared to FBG (Annamdas & Annamdas, 2010; Aymerich & Staszewski, 2010; Gungor & Bakis, 2016; Kageyama et al., 2006).

In an experimental work by Willberry et al. (2020), the frequency shift of the FOD sensor was detected using a Laser Doppler Velocimeter (LDV), which evaluated the extension/compression of the optical fibre. The f_D between the reflected light from the fibre end and the reference plane, is directly related to the relative rate of displacement (strain rate) $V = d_L/d_t$. During the detecting process, the frequency of the reflected laser beam varies from f_0 to $f_0 + f_D$. The sensitivity is contingent upon the length of the optical fibre affixed to the specimen, while the remaining portion of the optical

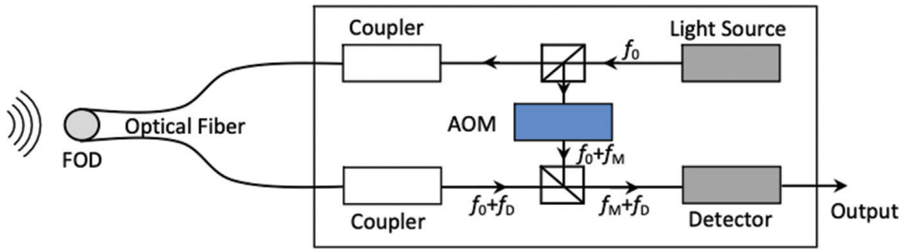


Fig. 15.12 Installation of the laser Doppler velocimeter for the FOD sensor.
From: Willberry, J. O., Papaelias, M.s, & Fernando, G. F. (2020). Structural health monitoring using fibre optic acoustic emission sensors. Sensors, 20(21), 6369, 10.3390/s20216369.

fibre remains free from stress. The arrangement of the ultrasonic detection system employing LDV and the spiral FOD sensor is illustrated in Fig. 15.12. The light source used is a He-Ne laser with an output power of 1 mW and a wavelength of 632.8 nm. The measurement is performed using the heterodyne interference technique. An acousto-optical modulator (AOM) alters the frequency of the reference light source from f_0 to a value of $f_0 + f_m(f_m = 80MHz)$ to generate beating signals with a frequency of $f_0 + f_m$. A frequency-voltage converter is employed in the detector to provide a voltage output specifically for direct ultrasonic acquisition, as seen in Fig. 15.12. The spiral FOD sensor utilised in the work has an outer diameter (D) of 21.2 mm and an inner diameter (d) of 8.0 mm.

The spiral FOD-based ultrasonic detection system is identical to the FBG-based system, with the exception that the high-speed optical wavelength interrogation system found in the FBG-based system is replaced by the laser Doppler velocimeter. Additionally, the FBG-based system requires a filter due to the relatively low signal-to-noise ratio (SNR) of guided wave signals obtained using FBG (Wang et al., 2019). In contrast, the FOD-based ultrasonic detection system does not require such a filter (Gungor & Bakis, 2016; Wang et al., 2019; Willberry et al., 2020). Hence, the expense of the FOD-based system is lower compared to the FBG-based system when excluding the filter and the adjustable laser source.

15.5.3 Guide ultrasonic wave damage detection processing method

15.5.3.1 Laminated damage composite samples

A study by Su et al. (2006) reported that quasi-isotropic CFRP laminates are employed as the main structures for fibre optic sensors-based guided wave and damage detection for the purpose of illustration and to ensure the results are applicable in a wide range of scenarios. The quasi-isotropic laminates were arranged in a $[45/0/\text{-}45/90]_{2s}$ stacking sequence using Pyrofil™ carbon fibre (TR30S, Mitsubishi Rayon Co., Ltd., Japan). The laminates were manufactured with dimensions of 500 mm x 30 mm x 1.92 mm. The investigation utilised two types of CFRP laminates, which are intact and delaminated

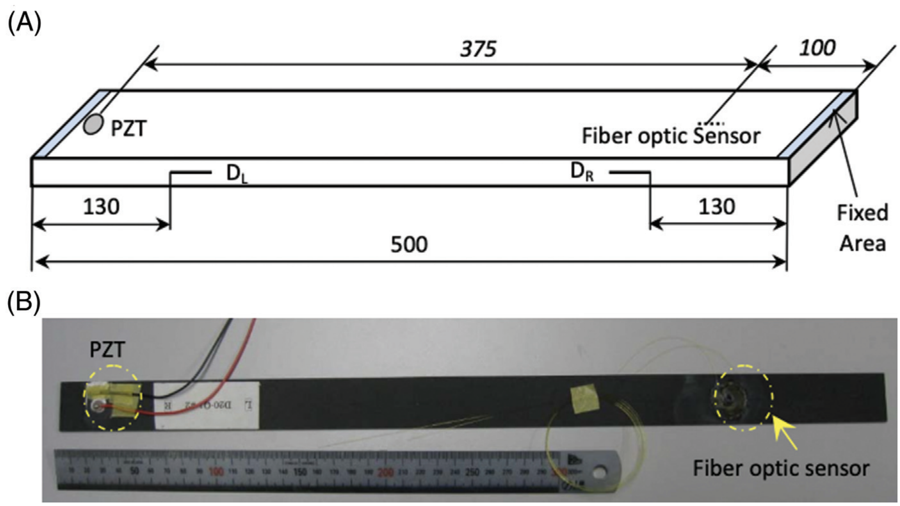


Fig. 15.13 Diagram illustrating (A) sketching of the quasi-isotropic CFRP laminate and (B) CFRP laminate sample.
From: Su, Z., Wang, X., Chen, Z., Ye, L., & Wang, D. (2006). A built-in active sensor network for health monitoring of composite structures. Smart Materials and Structures, 15(6), 1939. doi:10.1088/0964-1726/15/6/050.

laminates. Fig. 15.13(A) and (B) display a sketch and photograph of the specimen, respectively. It also indicates the positions of the PZT actuator, fibre optic sensors and delaminations. Besides, an experimental work by Li et al. (2009b) did the same work, and it involved fixing the left and right ends of the specimens with a length of approximately 2 mm each. Single and double damage situations were created in the delaminated CFRP laminates by introducing one and two thin Teflon® films between the 8th and 9th laminas of the laminate, respectively. The two delaminations are designated as D_L and D_R, respectively. Only the D_L (damage length) is present in the single-damage laminate. However, the CFRP laminate contains both the D_L and D_R with two instances of delamination. To confirm that the guided wave signals are obtained under consistent excitation conditions for a given specimen, the authors in Su et al. (2006) were conducted using three different approaches for each specimen:

1. Obtaining guided wave signal using an FOD sensor.
2. Detaching the FOD sensor from the sample and attaching an FBG sensor at the exact same location as the FOD sensor.
3. Obtaining a guided wave signal using the FBG sensor.

15.5.3.2 Damage detection

Guided wave-based damage detection in the literature (Lu et al., 2021) commonly relied on the utilisation of reflected or transmitted waves. Regarding composite materials, delamination is characterised by the reflection of minimal energy (Yuan et al., 2008), or it occurs specifically when delamination is present in layers of the laminates. In the instance of semi-infinite delaminated damage, the highest ratio of reflected energy from

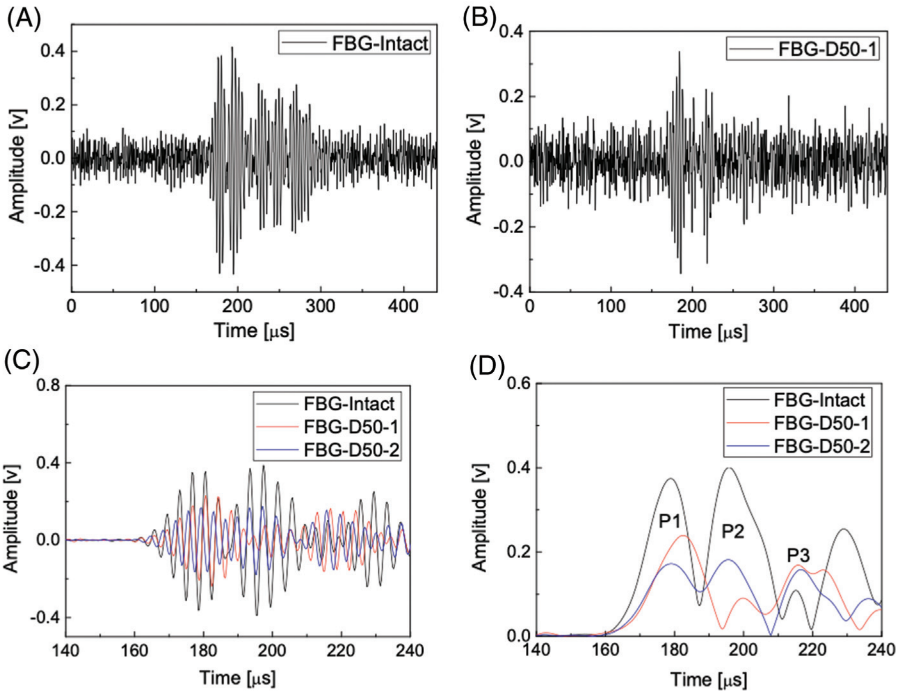


Fig. 15.14 Results obtained using FBG technology. Guided wave signals of the undamaged (A) and the singly delaminated (B) CFRP laminates. The waveforms of the filtered guided wave signals from both the intact (C) and damaged CFRP laminates, as well as their envelopes (D). From: Li, F., Murayama, H., Kageyama, K., & Shirai, T. (2009b). Guided wave and damage detection in composite laminates using different fiber optic sensors. Sensors, 9 (5), 4005–4021, 10.3390/s90504005.

the delamination was found to be less than 0.012. This small value poses challenges for extracting features and detecting damage using the reflected wave due to the presence of noise and the unavoidable dispersion (Lu et al., 2021; Su et al., 2006; Yuan et al., 2008). Furthermore, when the structure is compromised at a minimum of two locations, the issue gets significantly more intricate. Until now, only a small number of studies have focused on evaluating the extent of damage in structures from numerous perspectives. The study by Soman et al. (2020) focuses on utilising transmitted guided waves for the purpose of guided wave and damage detection in fibre optic sensors.

The investigation made by Apalowo et al. (2018) utilised a Hanning-windowed 5-cycle sinusoidal toneburst with a core frequency of 300 kHz as the incident signal. Guided waves were recorded at a sampling rate of 4 MHz. Fig. 15.14(A) and (B) show the guided wave signals collected using FBG technology by Li et al. (2009b). The signals are from an intact CFRP laminate and a laminate with a single delamination of length 50 mm. The intact laminate is labelled as ‘FBG-Intact’, and the delaminated laminate is labelled as ‘FBG-D50-1’. The signal of the delaminated laminate is predominantly noisy compared to the guided wave signal of the intact CFRP laminate.

This is since the delamination reduces the energy of the transmitted guided wave. Furthermore, the precise location of each wave package cannot be determined in both Fig. 15.14(A) and (B) due to the presence of intense background noise and the overlapping of adjacent wave packages. Signal processing techniques are necessary to provide succinct characteristics of the guided wave signals. To mitigate the impact of noise and extract the envelope of each guided wave signal, a bandpass filter was chosen for the sinusoidal toneburst incident signal with a centre frequency of 300 kHz, and a Hilbert transform was applied (Munian et al., 2018; Prakasha et al., 2023).

The signal processing technique employed in this work comprises three sequential steps (Pupyrev et al., 2019):

1. The original guided wave signals are purified by averaging them.
2. The averaged signal is then filtered using a bandpass linear-phase finite impulse response (FIR) filter with a passband of 100 to 500 kHz.
3. The filtered signal is subjected to a Hilbert transform to extract its envelope, which is used for feature extraction and damage detection.

The principles of FIR filter and Hilbert transform are explained in References (Mutlu, 2018). Fig. 15.14(C) and (D) display the waveforms and envelopes of guided wave signals obtained from both the intact and delaminated CFRP laminates. Only a certain portion of each signal, ranging from 140 μs to 240 μs, is focused on and displayed to minimise the impact of wave bundles created by repeated reflections. The interval between 0 μs and 140 μs is considered the noise section, as is the interval between 140 μs and 160 μs, because the transmitted waves did not reach until approximately 160 μs. Conversely, the signal portion after 240 μs has several reflection components. The guided wave signals obtained from the undamaged CFRP laminate are utilised as reference points to calibrate the condition of additional specimens. In the initial stage of the signal processing technique mentioned above, the guided wave signals based on FBG were averaged from a set of 60 original signals. When comparing the filtered signals in Fig. 15.14(C) with the guided wave signals in Fig. 15.14(D), the features of the guided wave signals are more prominently revealed by utilising the Hilbert transform. In Fig. 15.14(C) and (D), the labels 'FBG-Intact', 'FBG-D50-1' and 'FBG-D50-2' represent the results obtained from intact CFRP laminates, single-50 mm-delaminated CFRP laminates and double-50 mm-delaminated CFRP laminates, respectively, using FBG technology.

FBG-based guided wave signals are measured for both undamaged and damaged CFRP laminates. The results from experimental works are in Philibert et al. (2018). To disregard the impact of wave packages created by numerous reflections, Philibert et al. (2018) only consider the initial three peaks, which are designated as P1, P2 and P3, respectively. Lamb waves are elastic disturbances that can travel through a solid plate, as described in the literature. There are two distinct categories of waves, namely symmetric and asymmetric, that meet the requirements of the wave equation and boundary conditions for this problem. Each of these waves can propagate separately from the other (Philibert et al., 2018; Pudipeddi et al., 2019a, 2019b, 2019c). The dispersion curves are the main method for describing the propagation of Lamb waves in a certain material. The dispersion of these curves originates from the solution of the wave equation for the asymmetric Lamb wave (Pudipeddi et al., 2019a). Only the basic symmetric (S_0) and basic asymmetric (A_0) wave modes may be stimulated at the central frequency of 300 kHz. The calculated group velocities for the S_0 and A_0 modes are about 5,880 $m{\cdot}s^{-1}$ and 3,500 $m{\cdot}s^{-1}$, respectively.

Based on the distance of 375 mm between the actuator and the fibre optic sensor and the arrival time of P1 in Fig. 15.14(D), the estimated actual velocity at which the wave packets P1 propagate is approximately 5,580 $m{\cdot}s^{-1}$. Thus, the initial set of packages, denoted as P1, corresponds to the propagation of the S0 Lamb wave. Nevertheless, it is apparent that determining the arrival timings of the second wave of packages, P2, is challenging due to the superposition of the wave packages P1 and P2. Thus, the arrival times of the peaks of P2 and the incident signal were utilised as alternatives to determine the precise group velocity of the wave packets P2. The calculated group velocity is 3,880 $m{\cdot}s^{-1}$, with the arrival time of the incident wave peak being 99 μs. Therefore, the wave packages P2 may be considered as the transmitted A_0 Lamb wave, whereas the wave packages P3 can be determined as the right end reflected S_0 Lamb waves. Fig. 15.14(D) also shows that the FBG sensor can identify all the transmitted S_0, A_0 and the right end reflected S_0 Lamb waves based on the information provided by the envelopes (Pudipeddi et al., 2019b). The amplitudes of both the transmitted S_0 and A_0 Lamb waves (P1 and P2) drop when delamination faults occur in the CFRP laminates. In addition, when comparing the curves of 'FBG-D50-1' and 'FBG-D50-2', it can be observed that the second delamination consistently reduces the magnitude of the transmitted S0. Hence, the amplitude characteristics of the Lamb wave signals obtained from FBG sensors can be utilised to identify damage detection in composite materials (Pudipeddi et al. 2019c).

15.6 Challenge and future research

15.6.1 Challenges

Many sectors are using natural fibre-reinforced polymer (NFRP) biocomposites more and more because they are environmentally friendly, have strong mechanical qualities and are lightweight. Nevertheless, the strength and stability of these structures are significantly dependent on the quality of the connection between the natural fibres and the polymer matrix. It is essential to detect and analyse any damage in these layered structures in order to guarantee their safe and dependable functioning. GUWs provide a very promising method for NDT in this context. GUWs are often used for damage detection in large composite plates owing to their extensive detection range and exceptional detection effectiveness (De Luca et al., 2020b). Although GUWs have several potential uses in NFRP biocomposite applications, the process currently encounters certain challenges.

15.6.1.1 Development of materials

The field has seen an increase in development and direction due to the introduction of new technology and approaches. Nevertheless, despite the ongoing advancements in the creation of complex composite materials, there are still obstacles to overcome in effectively, dependably and precisely detecting and assessing different sorts of damage that may occur in these materials. Unlike synthetic fibre composites, which have uniform properties, NRFP displays significant variability owing to the intrinsic characteristics of natural fibres. Various factors, including the kind of fibre (such as flax, hemp and jute), the environment in which it is grown and the techniques used to prepare it, may all affect the qualities of the fibre, such as its strength, stiffness and moisture content (Yan et al., 2014). This variation leads to differences in the overall mechanical characteristics and acoustic behaviour of the NFRP laminate. Therefore, it becomes challenging to develop a consistent standard for the spread and detection of GUWs and its associated damage. Various composite materials show notable differences, each possessing unique performance benefits (Petrone, 2018). Additionally, it is necessary to create acoustic models of composite materials that have varied structures in order to effectively identify damage in settings that are either covered in water or ice. Crucially, the kinds and origins of damage differ in different settings.

15.6.1.2 Computational modelling

GUWs need lengthy numerical solution calculation periods, a requirement often encountered in finite element modelling (FEM), especially when dealing with high frequencies and solutions located far from the actuator (Leckey et al., 2018b). The accuracy of a model is highly reliant on the precision of the input parameters. FEM is a useful methodology for modelling the propagation of ultrasonic waves in NRFP. It aids in comprehending wave characteristics in various damage situations and optimising inspection methods. Understanding anisotropic and viscoelastic qualities, contact factors and defect features is of utmost importance. Nevertheless, precisely depicting the range of natural fibre diversity in these models continues to be a difficult task. Developing robust and trustworthy models for NFRP materials is challenging due to the intricate microstructure and inherent unpredictability in fibre characteristics.

15.6.1.3 Data analysis

NDT using GUWs depends on the interpretation of variations in the received signal, such as changes in velocity and amplitude, in order to detect and diagnose damage. Nevertheless, these alterations may be inconspicuous, particularly for minor instances of damage or when situated at a greater depth inside the laminate. Signal interpretations may be challenging because of the presence of multimode propagation, mode conversion and the complex geometric aspects of particular test structures. In order to get precise damage data from complex wave signals, it is necessary to use sophisticated signal processing techniques, such as mode separation algorithms, filtering and denoising (Diogo et al., 2022). To optimise penetration power and fault detection sensitivity for particular flaws and structures in the laminate NFRP biocomposite, the mode and frequency need to be carefully adjusted. Furthermore, it is crucial to use rigorous data interpretation techniques in order to distinguish between damage and other variables that affect wave propagation, such as variations in material characteristics.

15.6.2 Future works

Moreover, additional efforts are necessary to quantify the magnitude and location of damage in composite structures as they undergo development and expansion. To fully harness the potential of GUWs for NFRP biocomposite damage assessment, it is necessary to concentrate on certain specific areas in order to overcome the associated challenges.

15.6.2.1 Advanced material characterisation

It is essential to develop thorough techniques for analysing the mechanical and acoustic characteristics of NFRP materials, with particular attention to accurately representing the range of natural fibre variations. Methods such as micro-computed tomography (micro-CT) may provide vital information on the microstructure of the composite material, while sophisticated statistical analysis can assist in accurately measuring the inherent differences (Peters, 2021). Micro-CT can generate a digital representation of the microstructure of NFRP, revealing the distribution of fibres, the presence of voids and any potential defects.

15.6.2.2 Methods for processing signals

It is crucial to provide strong signal processing algorithms that can effectively filter out noise, separate overlapping wave modes and enhance signal qualities caused by damage. In addition to knowledge, it is possible to train machine learning and deep learning algorithms using real-world NFRP data that contains known damage types. High-frequency wave signals are mostly used for investigating tiny variations in the material structure, such as corrosion. Conversely, low-frequency signals are mostly used for the purpose of examining and identifying large-scale flaws in material constructions (Olisa et al., 2021b). These algorithms possess the ability to acquire intricate patterns from the data and detect subtle alterations that signify harm, even in the midst of interference and variations in materials. Scientists are now working on creating techniques employing guided wave-phased array focusing to improve the ability to penetrate materials, increase sensitivity and raise the signal-to-noise ratio (Rose, 2004). Wave resonance can automatically adjust algorithms for frequency, phase velocity and mode type to identify defects in NRFP biocomposites.

15.6.3.3 Advanced methods for detecting damage

Advanced damage detection techniques go beyond basic amplitude and velocity analysis by taking into account other factors such as wave mode conversion, variations in time-of-flight and changes in spectral characteristics. Wave mode conversion is the phenomenon when the incident wave undergoes a transformation into a different mode, such as a Lamb wave, due to its interaction with damage. Deterioration can impact the fluctuations in the time it takes for a wave to travel through a substance, known as time-of-flight variations. Thanks to localised response characteristics, Lamb wave techniques have shown their effectiveness in accurately assessing the existence and extent of damage in composite materials in their original position. Moreover, they have the capability to precisely identify the specific areas of the damage (Kessler et al., 2002).

15.7 Conclusion

Damage detection in laminated biocomposites using guided ultrasonic waves is an advanced NDT method. Guided ultrasonic waves are elastic waves that propagate along the structure's surface or within the material, providing valuable information about its integrity. Based on the case study made, it can be determined that both FBG and FOD sensors are suitable for detecting guided waves and damage in biocomposite laminates. The FOD sensor outperforms the FBG sensor in detecting damage because it can detect the delamination-induced guided wave, which the FBG sensor is unable to detect. According to the theory of ultrasonic detection utilising FBG as shown in Fig. 15.2(B), it can be inferred that FBG exhibits directivity in ultrasonic detection (Bajpai et al., 2017). Fig. 15.3 clearly demonstrates that the FOD sensor, due to its spiral design, is capable of omnidirectional ultrasonic detection. As a result, it can detect all the propagating guided wave modes in the biocomposite laminates. From the study made, some of the other important points were summed up:

1. Some types of laminated damage in biocomposites are matrix cracking, followed by fibre breakage or fibre pull-out and interfacial bonding between fibre and matrix.
2. The manufacturing process of laminated biocomposite may face some defects such as voids, fibre regions poorly wetted by resin, resin-rich zones, pockets of undispersed crosslinker and misaligned fibres.
3. The principle of guided ultrasonic waves in detecting the laminated damage in biocomposite materials consists of the type of waves, propagation conditions and modes.
4. The process of damage detection of biocomposite materials using guided ultrasonic waves consists of wave generation, wave propagation, data acquisition and damage characterisation and analysis.
5. The guided ultrasonic wave method has several challenges in the application of laminated damage detection of biocomposite materials, such as complex signal interpretation in computational modelling, material variability since the biocomposite is considered an advanced material and environmental sensitivity issues.

AI Disclosure

During the preparation of this work, the author(s) used Quillbot in order to rephrase some words. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Non-Print Items

Abstract

Biocomposite materials, made from natural fibres and polymer matrix, have a wide range of applications. These materials' design flexibility, exceptional characteristics and aesthetic appeal drive their increasing use. The application of biocomposites depends on the interaction at the fibre-matrix interface. Because of their unique properties and the complexities of load and environment, analysing the integrity and durability of composite buildings is difficult. Over the past few decades, researchers have developed damage models and experimental evidence to better understand the structural behaviour of laminated biocomposites. Guided ultrasonic waves (GUWs) are a type of elastic wave that can propagate along the surfaces and through the thickness of laminated composite materials, such as biocomposites. These waves are used for non-destructive techniques (NDT) to detect and characterise damage within the material. Many researchers have recently used this technique for several reasons, such as its high sensitivity to defects, ability to inspect large areas and cost-effectiveness. Due to the complexity of the structural design of biocomposite, this technique is also very practical for use in structure health monitoring (SHM). This case study will explore and discuss the use of GUWs for detecting laminate damage in biocomposite materials. Besides, the process and analysis of detecting the laminated damage of biocomposite using GUWs will also be reviewed. Currently, two types of fibre optic sensors have been addressed, which are fibre Bragg gratings (FBG) and Doppler effect-based fibre optic (FOD) sensors, with guided wave detection systems built for both. These fibre optic sensors detected guided waves generated by a piezoelectric transducer as they travelled through a quasi-isotropic biocomposite laminate. It is shown that both the FBG and FOD sensors successfully detect the presence of delamination damage in composite laminates by reducing the amplitude of processed guided wave signals. Furthermore, the FOD sensor was able to capture the delamination-induced fundamental shear horizontal guided waves, which the FBG sensor was unable to do. This is because the spiral FOD sensor is omnidirectional in ultrasonic detection, while the sensitivity of the FBG sensor is dependent on the bonding direction. Besides, the properties of these fibre optic sensors in GUW wave detection were thoroughly compared. In every section, efforts have been made to analyse the most relevant literature, discuss in a critical manner the results and conclusions and identify possibilities for future work. This study will contribute to the development of the sustainability of biocomposite as an advanced material in SHM.

Keywords

Biocomposite; Guided ultrasonic waves; Laminated damage; Materials science engineering; Natural fibre; Polymer