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The adhesive joining of natural fiber-based polymer composites by FEM

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Abstract

The use of adhesive bonding in structures made from composite materials has increased in recent years due to their various advantages such as uniform load distribution, ease of fabrication, lightweight design, good strength, etc. In this paper, a review of research work that has been carried out on adhesively bonded joints of synthetic and natural fiber-reinforced polymer composite materials is presented. The influence of joint configuration, adhesive properties, overlap length, and adherent thickness on joint behavior has been discussed. Additionally, failure analysis of the adhesively bonded joints under uniaxial quasi-static loading conditions is described. It is observed that joint strength is mainly affected by adhesive strength and overlap length. It is also seen that cohesive failure is predominant over adhesive failure in the bond line area.

Keywords; Natural fibers, Epoxy Resins, Hand Layup, Adhesive joining, Autodesk Helius Composite, FEM, ANSYS Workbench

1. Introduction

Recently metals are replaced by composite materials due to their better mechanical properties with reduced weight and cost. A composite material is a combination of two or more materials that results in better properties than the parent material. They are mainly classified as natural and man-made composites depending on fiber reinforcement used. Man-made fiber composites like glass, carbon, aramid, nylon, etc. have better mechanical properties but are not environment-friendly and expensive. Hence many researchers are turning towards natural fiber composites as replacements for man-made composites. Natural fibers are biodegradable as they are extracted from renewable natural sources and due to their low density they are light in weight.

They are low in cost and possess high specific strength compared with artificial fibers. Researchers have investigated many natural fibers such as banana, jute, hemp, kenaf, cotton, coir, bamboo, ramie, sisal, etc. The joining of composites is mostly done by stitching, mechanical fastening (using screws and nuts or bolts, rivets, clamps, etc.), and adhesives. Through the thickness, stitching is a method that increases trans laminar strength and prevents crack propagation but it damages the fibers during the process. Mechanical fasteners are easy to use and can also be easily disassembled; however, this imparts holes leading to weakening of base material. It causes stress concentration on a single point rather than distributing it evenly over a larger area. Adhesive bonding is the process of joining two surfaces using adhesives. Adhesively bonded joints are recently more preferred compared to other joining methods since they distribute the load uniformly without altering the basic design of the assembly. Hence, it increases the fatigue resistance of the composite. Synthetic material-based fiber reinforced polymer composites are widely used in engineering applications. But their non-degradability and non-recyclable nature put a limitation on their use (Gonzalez Murillo et al., 2007). This concern has driven many scientists to investigate the use of natural fiber in composite material for low mechanical strength applications. Moreover, natural fiber composites can be used in automotive body parts without compromising strength and durability. The dashboards, door panels, parcel shelves, cabin linings, seat cushions, backrests are a few applications of natural fiber composites. These composites were produced in simple shapes and easy design structures by positioning the structural elements on top of each other to create the desired design (Ferreira et al., 2005). Every component cannot be fabricated as a whole due to manufacturing limitations such as space required, complex shapes, etc., and hence joining two parts plays a vital role in the field of the composite application. The core joining processes are adhesive bonding, mechanical fastening, welding. Joint strength is an important part of designing a structure. Hence joint strength is the primary criterion while designing joints in composites. For lightweight structures, adhesive bonding is gaining more importance for joining similar or dissimilar structural components. Adhesively bonded joints are also acting as a replacement for fasteners and rivets (Nakano et al., 2014). Hence studying the behavior of adhesively bonded joints in different loading as well as the operating condition has great importance to conclude application area of composites. Materials experts from various automakers estimate that an all-advanced-composite auto-body could be 50–67% lighter than a current similarly sized steel auto-body as compared with a 40–55% mass reduction for an aluminum auto-body and a 25– 30% mass reduction for an optimized steel auto-body. For the widespread use of adhesive joints, a solid understanding of the failure process as well as a precise prediction of the failure load is vital. Therefore, the strength and failure mechanisms of bonded joints between these materials need to be explored in detail.

2. Materials and Method

In the current study, composite materials are fabricated by the hand-layup method. Sisal, jute, and hybrid mat fibers were prepared as per the dimensions of the mold plate size of 300×300×4mm and used to make the specimen. The composite specimen contains completely four layers of sisal and jute fibers for the preparation of different trials but in the case of hybrid composite specimen preparation, we used two layers of sisal and jute (i.e. SJJS, each arrangement of fibers). The amount of epoxy is taken for a specific weight fraction of fibers and matrix and mixed hardener in the ratio of 10:1. The woven fibers were wide-open to sunlight for two days to eliminate the moisture and in the oven at 60 - 80 °C for 2 hrs. The layup was covered with a polyester sheet from top and bottom as a releasing and good surface finishing agent. Fiber layers are placed in order and epoxy is applied until the vital thickness is achieved (Fig 1). At the time of the manufacturing process, care is taken to prevent the formation of voids by a covering of the layup with a polyester sheet because voids can decrease the quality of the composite specimen. In every test, an average of 5 samples is considered for experimental analysis.

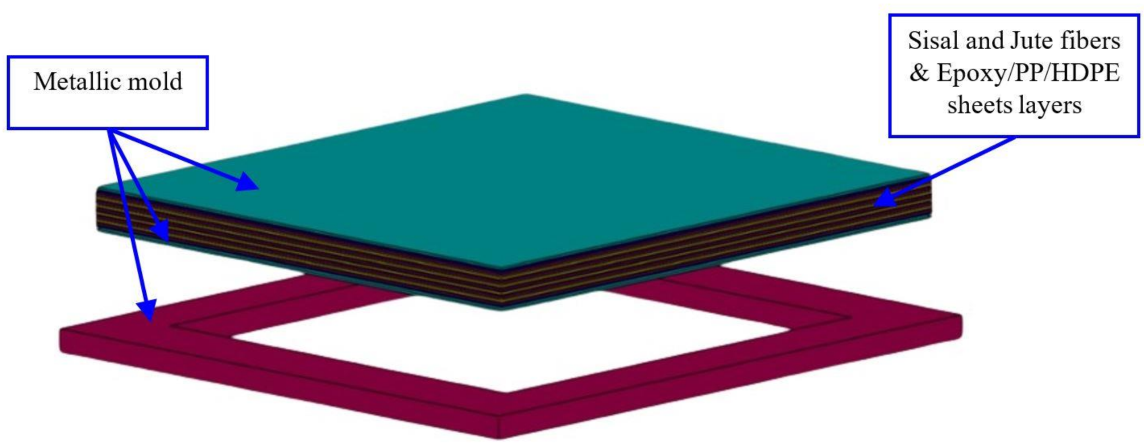

Figure 1. Schematic diagram of metallic mold of composite materials.

2.1 Literature Reviews

Adhesive joining is a joining process in which two similar or dissimilar parts are joined together through an adhesive. Specimens that are going to be joined are called adherends. Adhesive joining is used for most FRPs composite materials. Adhesive joining has become more efficient in the last few decades due to the development of adhesives granting higher strength and ductility. It is a cheap, easy, and fast joining process and does not need material removal operation. Therefore, this joining process is accepted in many areas like automobile, aircraft, and household product-based industry (Campilho & Fernandes, 2015). Most of the research articles have been reported on the adhesive joining behavior of artificial fiber-based polymer composites. There are only a few articles available on the adhesive joining of natural fiber-based composite materials.

Kumar et al. investigated the strength of adhesively bonded single lap joints subjected to tensile, bending, impact, and fatigue loads. They used glass-reinforced composites as adherend and epoxy reinforced with micro glass powder, unidirectional and chopped glass fiber as adhesive. They varied the volume fraction of glass fiber in the adhesive region. They also examined modes of failure such as cohesive failure, light fiber tear failure, and thin layer cohesive failure. They had used adherends of E-glass fiber-polyester composites. The adhesive used was epoxy and its hardener. The surface preparation of adherends was done by cleaning it with acetone and then sanding it with 1000-grit silicon carbide paper. They controlled the thickness of the adhesive layer as it affects adhesive strength. While testing, specimens were loaded in quasi-static tension in tensile testing, and ASTM D-3039 was followed. In tensile testing they found, reinforcement in the adhesive layer is effective when fibers are in direction of loading. Also concluded that failure stress for chopped fiber reinforcement is higher than others, as joint strength of value 17.41 MPa which is 46% (5.52 MPa) greater than joints with the neat adhesive used. The addition of micro glass powder increases the strength and stiffness of the adhesive layer by 71% as compared to specimens with the neat adhesive used (Kumar et al., 2021).

Antonio F. Avila and Plinio de O. Bueno compared adhesive strengths of wavy lap and single lap joints in tensile loading. As mentioned by them, in some cases, single lap joints have load eccentricity problems in loading. They took the overlap length of the single lap joint as 25.4mm and slightly more for a wavy lap joint. They had used E-glass-epoxy composite laminate as adherend and adhesive of designation AW106 and its hardener. In tensile testing, they have followed ASTM D5868-01 and found that the maximum load that wavy-lap joint carries was 7.24 kN whereas single lap joint carries 7.18kN. They also observed light fiber tear failure mode in all specimens. They observed that the fracture path begins at the overlap area edge. They carried out finite element simulation to account for failure mode and load and found results similar to one obtained from experiments. It was indicative that the strength of a wavy lap joint is more than a single lap joint but it was difficult to manufacture (Ávila & Bueno, 2004).

Jianfeng Li et al. studied adhesively bonded carbon fiber-reinforced composites in tensile loading. They had varied design parameters such as overlap length, adherend thickness, scarf angle, and adherend width. The stacking sequence used was [45/0/-45/90] s and [45/0/-45/90]2s. The overlap length chosen was 2mm, 5mm, 10mm, and 20mm. They tested specimens by following ASTM D5868-01 in axial tension INSTRON universal machine in displacement control mode. From that, they found that ultimate failure load increases with an increase in overlap length for a single lap joint. The increasing rate got slower as overlap length exceeds 10mm and adhesive shear failure for small overlap length. Equivalent stiffness increases with an increase in adherend thickness. The failure area of adhesive shear failure mode increase with an increase in adherend thickness. Equivalent stiffness and failure load increase with the increase in adherend width for double lap joint. Also with an increase in adherend thickness stiffness and failure load increased for double lap joints. They had observed adherend delamination failure. In the case of varying scarf angle, stiffness remains constant, however, ultimate failure load decreases with an increase in scarf angle, and lap shear strength increases with an increase in scarf angle. In this case, the combination of adhesive shear failure and adherend delamination failure mode is observed (Li et al., 2016).

Kassahun G.M. and I. Singh studied the natural fiber-based polymeric composites are being used extensively in various engineering applications, especially in the non-structural parts and components. Although a large number of primary processing techniques, such as hand-layup and compression molding are available for the fabrication of parts, still secondary processing in terms of joining and machining is inevitable. The joining of composite parts becomes necessary in case of complicated and intricate product designs. Adhesive joining is one of the most commonly used processes for polymer-based composite materials. It is a cheap, easy, and smooth bonding process and does not necessitate the drilling of holes for mechanical fastening. In the present experimental investigation, the joint strength of woven fiber mat (sisal, jute, and hybrid) reinforced epoxy composites has been investigated using different joint configurations, namely, single lap, double-strap butt, and scarf joint. The effect of adhesives has also been explored by joining composites with two types of epoxy resins and corresponding hardeners. It was observed that the hybrid composites recorded better-joining performance for both types of adhesives. Moreover, the Field Emission Scanning Electron Microscopy (FE-SEM) has been used to understand the failure mechanisms during tensile testing of adhesively bonded natural fiber-reinforced composite laminates. The three-dimensional assembly models of adherend specimens were created using the SOLIDWORK V.16 modeling software. ANSYS-V.18.2 WORKBENCH was employed for the analysis of the joint performance. The maximum shear stress and the total deformation results were determined. The finite element analysis (FEA) results were compared with experimental findings and were found to be in good agreement (K. G. K. G. Melese & Singh, 2020).

K. G. Melese, Rana, et al. the recent global pandemic has created a grave concern and awareness about the importance of the environment. The researchers/engineers/scientists are now focusing their efforts on the development of technologies that can ensure the sustainable growth of communities. Materials are at the core of every technological advancement. Natural fiber-based composites are a class of sustainable materials being used in diverse engineering applications, ranging from automotive to household goods. The processing methods, such as hand lay-up, injection, and compression molding are used extensively to fabricate simple composite parts. However, for complex/intricate product designs, the parts/components are made independently and these are assembled to get the final product. Joining thus becomes an inevitable process ensuring the assembly of parts/components. In the current experimental investigation, the hot-plate welding (HPW) behavior of sisal/jute fiber (both woven and short) reinforced polypropylene (PP) composite specimens fabricated using direct compression molding(DCM) and Extrusion injection molding (EIM) have been analyzed. The process parameters optimization has been achieved using the Taguchi experimental design approach. The hot plate welded joints of jute/sisal/PP composites were further investigated based on their flexural and tensile properties. The failed joint specimens were characterized using TGA and XRD characterization techniques to analyze any changes that occurred in their thermal degradation and crystalline behavior during the welding process. The failure mechanisms of the joints have been thoroughly analyzed using SEM micrographs (K. G. Melese, Rana, et al., 2022).

Yao et al. studied the adhesive strength of single lap joints under in-plane and out-of-plane loading with help of the three-dimensional finite element method. They varied the behavior of adhesive, the volume fraction of glass fiber, and the orientation of fibers in the adhesive region. The overlap length, adherend thickness, and adhesive layer thickness were taken as 25mm. 3mm and 0.3mm respectively. They used ANSYS-10 software with SOLID46 element type to study stress distribution and failure in single lap joint. They considered adherend of carbon fiber and adhesive as resin-fusion 8604 epoxies. They performed a static elastic analysis in both tensile and transverse loading. The load transferred on the adhesive layer is by shear and peel stress. They found that maximum shear and peel stress occurred near both ends of the adhesive region. Out of these, peel stress was responsible for failure in tensile loading while both shear and peel stresses were responsible for failure in transverse loading. By changing adhesive from neat epoxy to composite adhesive, ultimate joint strength increases (Yao et al., 2016).

Campilho, Moura, et al. studied tensile fracture toughness of adhesive joints in natural fiber composites. They had used ductile polyurethane adhesive to carry out this work. Conventional methods were used to obtain tensile fracture toughness for the co-cured specimens, while for the adhesively-bonded joints, the J-integral was selected. The adherends used in this work consist of a jute-epoxy composite, with jute weave as reinforcement. The double cantilever beam specimens were developed for analyzing strength. From this, they found that fracture toughness increases from initiation in co-cured specimens due to fiber bridging between the adherends while the crack grows. Results showed that bonded joint is tougher than a co-cured joint. In that work, the two bonding methods were compared and tensile fracture data was provided for the strength prediction of joints in natural fiber composites (Campilho, Moura, et al., 2013).

K. G. Melese, Naik, et al. studied the growing awareness about sustainable development and the environmental problems involved in using non-biodegradable materials has motivated the research community to develop environment-friendly materials. Developments have been achieved in the field of natural fibers and biopolymers, still there remain unanswered questions regarding the high-quality cost-effective manufacturing of natural fiber reinforced composites. Natural fiber-based polymeric composites are being used extensively in engineering applications, especially in the nonstructural parts and components. Near-net processing techniques such as compression molding, extrusion, and injection molding are well-developed for natural fiber reinforced composites. However, secondary processes such as joining, machining, and surface modification are still unexplored and need to be investigated in detail. The present research endeavor is an attempt to experimentally investigate the adhesive joining behavior of jute/sisal reinforced epoxy composites. The laminates based on three different material configurations in woven mat form, namely, pure jute, pure sisal, and hybrid jute/sisal reinforced epoxy have been fabricated by hand layup process. Different lap joint configurations with through holes in adherends overlapping areas have been investigated. It has been established experimentally that the holes in the adherends provide a hinge-effect in the overlapping area and help in defining the failure load of the composite joint. The different arrangement of holes has been investigated and the best design of hole arrangement has been proposed for adhesive joining of jute/sisal fiber-reinforced epoxy laminates. It was found that the holes (filled with an epoxy adhesive) in the overlap area result in a 6–18% improvement in the failure load for different materials as compared to the joints with only adhesive bonding. Moreover, the field-emission scanning electron microscopy micrographs have been used to understand the failure mechanism of the adhesively bonded natural fiber reinforced composite laminates (K. G. Melese, Naik, et al., 2022).

Da Silva & Öchsner, studied the behavior of adhesively bonded composite joints. They found that bonding strength is dependent upon the strength of adhesive, composite-adhesive interfacial adhesion, and strength of adherend. Hence they carried out Taguchi analysis to present the order of most influencing parameters to determine ultimate failure load. They modeled composite adherend with the linear elastic material model, with layup sequence of [0/90]4s, adherend thickness of 2 mm, and 0.2 mm bond line thickness. The composite-adhesive interface was modeled with a cohesive zone model. The bulk adhesive was modeled with an isotropic continuum material model. They solved this problem in ABAQUS software. Also, the finite element model was calibrated against previously obtained experimental results, and from that prediction of strength obtained by numerical results is found to be in acceptable condition. In Taguchi's analysis, they found that adhesive strength, interface fracture energy and adhesive ductility are the main parameters that primarily affect failure loads (Da Silva & Öchsner, 2011).

Campilho, Banea, et al. carried out a parametric study of adhesively bonded joints in composites to predict failure in joints. Experimental tests were carried out by varying overlap lengths and the adhesive used was a ductile and brittle type. They used carbon epoxy composites as adherends with [0]16 layups. The specimens were fabricated according to EN ISO 527-2 standard. They had varied overlap lengths from 10mm to 80mm with an increment of 10mm and adhesive thickness was kept constant at 0.2mm. They had predicted strength in joints with help of analytical and numerical models. For analytical calculation, Hart-Smith elastic model was used. For the numerical model, the non-linear behavior of joint with orthotropic properties of materials was taken into account. They found that joints with smaller overlap lengths from 10mm to 20mm show cohesive failure while for overlap length greater than 30mm, interlinear failure is shown. The strength prediction by Hart-Smith elastic model gives reasonable results up to 30mm overlap length following experimental results (Campilho, Banea, et al., 2013).

Thomas et al. studied the application of twofold criteria involving stress and energy conditions to predict interfacial failure in adhesive joints. The adherends used were steel and polyester resin as adhesive. The double lap and butt joints made of this material were tested in a universal testing machine under tensile loading. The overlap length in the double lap joint was varied with values 10 mm, 15 mm, and 20 mm with adhesive layer thickness kept constant at 0.5 mm. This prediction of interfacial failure was based on finite element calculations and twofold criteria. They had used COMSOL Multiphasic 3.3 software to analyze stress and structural analysis of joints. It can be seen that joint strength increases as overlap length increases (Thomas et al., 2017).

Gonzalez Murillo et al. investigated the influence of joint geometry on the strength of joints. They manufactured and tested Epoxy bonded single lap shear joints (SLJs) between henequen and sisal fiber composite elements to assess the strength of the structural bonds. They compared their experimental results with the Finite element method results and found them to be in good agreement. They found that for SLJs the ultimate load and displacement increases when the overlap length is increased(Gonzalez-Murillo & Ansell, 2010).

Sayman et al. studied the behavior of adhesively bonded single lap joints in impact loading. The finite element model is based on cohesive failure in the bonded joint when the ultimate failure strain of the adhesive under transverse normal load is reached. They found that the transverse normal load produces higher peel stress than in-plane loading which is due to deflection of joint. Stress is distributed symmetrically over the entire joint area. The cohesive failure mode was observed by the author in transverse loading. The adherends used were carbon/epoxy and adhesives were of three types, neat epoxy, two-part adhesive, and paste adhesives. The young's modulus of adhesive was increased by the addition of Nano-clay, conversely decreasing ultimate failure strain by 33%. Also, the load-bearing capacity of the joint was found to be dependent upon the toughness of the adhesive. The paste adhesive used has higher failure energy than two-part adhesives. They have also compared experimental results with FEM solution and found that cohesive zone modeling in FEM gives the best results for bonded joint design (Sayman et al., 2015).

Xia & Liu examined stepped lap joints for estimating stress distribution in tensile loading with the use of finite element calculations. They had used ANSYS software to study the stepped joint behavior for variable adhesives, adhesive layer thickness, and butted steps. They found that the maximum value of the maximum principal stress occurs at the edge of the adhesive interfaces. If adhesive Young's modulus and butted steps were increased the principal stress decreases. They have also carried out experiments to verify the FEM solution and it appeared to be in good agreement (Xia & Liu, 2015).

Da Silva & Öchsner projected the feasibility of cohesive and continuum damage models for the analysis of bonded joints in composites. They carried out a double cantilever beam and the end-notched flexure tests to assess the cohesive properties of the adhesive under mode I and mode II. They have also proposed an inverse method to calculate cohesive parameters in trapezoidal softening law. The model simulated the different shapes of the fracture process zone as a function of adhesive thickness and its influence on the R-curve profile. It was concluded that fracture energy has similar values for variable thickness between 0.1 to 0.5 mm (Da Silva & Öchsner, 2011).

Bak et al. studied the AE (acoustic emission) characterization of failure modes in three prominent joining methods namely, bonded, riveted, and hybrid joints during the tensile testing. The joint strength of the basalt/epoxy composite hybrid joint was reported as higher than the bonded and riveted joints (Bak et al., 2014).

Yoon et al. evaluated the fracture strength and stress distribution in bamboo/polyester polymer composite. Under High-stress concentration was reported and subsequence failure started at the edge of the joint area (Yoon et al., 2007).

Campilho et al. compared the joint strength of a single lap joint fabricated using three different types of epoxy adhesives, namely; brittle and strong Araldite-AV138, ductile, and less strong Araldite-2015, and the strong and ductile, Sikaforce-7888. The authors also compared the experimental results with the findings of the Finite Element Analysis (FEA) using the Cohesive Zone Modelling technique (Campilho, Moura, et al., 2013).

Afendi et al. evaluated the adhesive joint performance using scarf angles of 45°, 60°, and 75°. The joint thickness between the different adherends was in the range of 0.1 and 1.2 mm. The effect of joint width, thickness, and scarf angle on the strength of scarf joints of different adherends joined with a brittle epoxy adhesive was investigated (experimentally and numerically) (Afendi et al., 2011).

Song et al. experimentally evaluated the effect of different fabrication methods on the strength of joints. The joining process was accomplished by four different methods. For the individual method, numerous lengths of the bonded region, thicknesses of the adherend, and various arrangements of layup were examined. The failure strength was more in joints with thicker adherends and less in case of larger overlap length. The outcomes indicated that the secondary bonded joints were stronger than the co-bonded type (Song et al., 2010).

Liao et al. investigated the effect of thickness of adhesive joint and scarf angles on the mechanical behavior of a scarf type of adhesive joint (SJ) subjected to uniaxial tensile loading, by using a mixed-mode cohesive zone model. Results indicated that as the thickness of brittle adhesive decreases; it causes an increment in failure energy, but in the case of ductile adhesive, the situation is vice versa (Liao et al., 2013).

J. M. Ferreira studied the fatigue behavior of composite adhesive lap joints. The specimens used by them were manufactured with various stacking sequences such as bidirectional woven E-glass/polypropylene composites and hybrid composites. However, the fatigue strength of hybrid composite with hemp/polypropylene was lower than single fiber composites due to lower adhesion between hemp and adhesive layer. Also, the adhesive strength of the joint was higher in the case of a single fiber composite. They observed peeling of adherend layer adjacent to adhesive was failure mode of thermoplastic composites while few specimens failed at adhesive (Ferreira et al., 2005).

Raza carried out a comparative study between Mg-Mg, steel-steel, and Mg-steel composite adherends bonded joints. They had followed ASTM D 1002-99 standard to evaluate joint strength and failure mode. They also studied finite element modeling techniques using an ABAQUS processor. The failure mode of Mg-Mg balanced failed either at an interface (adhesive failure) or substrate and the system is flexible with lower failure load. While steel-steel balanced system failed only at substrate and system is rigid with higher load and lower displacement. Mg-steel system provides flexibility in between them and only adherend failure (either out of plane Magnesium failure or steel-beta mate in-plane substrate failure) observed. From experiments and FEM results they found that, for Mg-Mg, the shear stress distribution in the adhesive is poor while for steel-beta mate-steel it was better. The FEA models were compared and were reasonably in good agreement with test results (Raza, 2019).

Gonzalez-Murillo & Ansell, studied glass-fiber-reinforced vinyl ester composite laminates manufactured by resin infusion and bonded with an epoxy adhesive to affect various joint configurations, adhesive layer thickness, defects, humidity, spew fillet, and adherend utilizing tension tests. The joint configuration was: two configurations joggle lap joints (JLJ) and the L-section joints (LSJ) and two configurations representing the single lap joint (SLJ) and the double strap joints (DSJ). Out of these, they found that SLJ and DSJ show higher ultimate loads and displacements to failure than the JLJ and LSJ. The failure load and displacement were found to decrease dramatically when the adhesive layer thickness was increased or when the joint was aged in a hot-humid environment. It was found that the ultimate load and displacement decrease significantly when the adhesive layer thickness was increased (Gonzalez-Murillo & Ansell, 2010).

3. Results and Discussion

The ANSYS 18.2 computer program is a large-scale multipurpose finite element program, which may be used for solving several classes of engineering analyses. Analysis of any problem in ANSYS has to go through three main steps. They are,

- Pre-processor
- Solution
- General Postprocessor

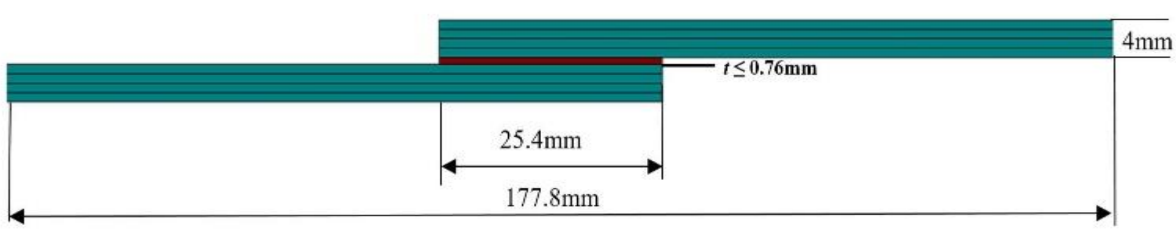

Figure 2. Schematic view of the overall dimensions of the single-lap joint (ASTM D5868)

The ANSYS finite element method software incorporates adhesive modeling of the three-dimensional solid model of single-lap composite joints was modeled by using Autodesk Helius Composite V.16 software. composites have been modeled (as per ASTM D5868 standard) using SOLIDWORK V.16. The results of the finite element analysis (FEA) have been compared with experimental results. The mesh density, number of elements, number of nodes, and type of analysis were selected based on the number of iterations. A very fine mesh was created in the overlap area to precisely match the actual conditions.

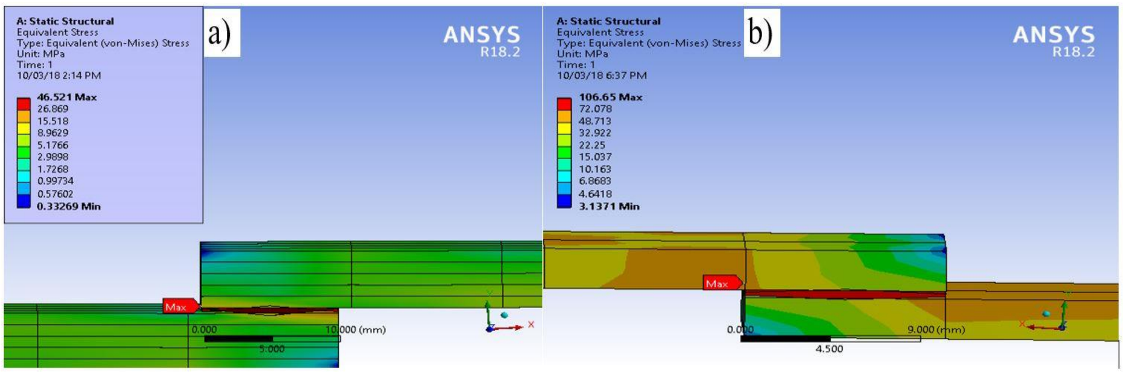

Figure 3 (a) Von-Mises Stress bamboo fiber (b) Von-Mises Stress sisal fiber ANSYS Workbench

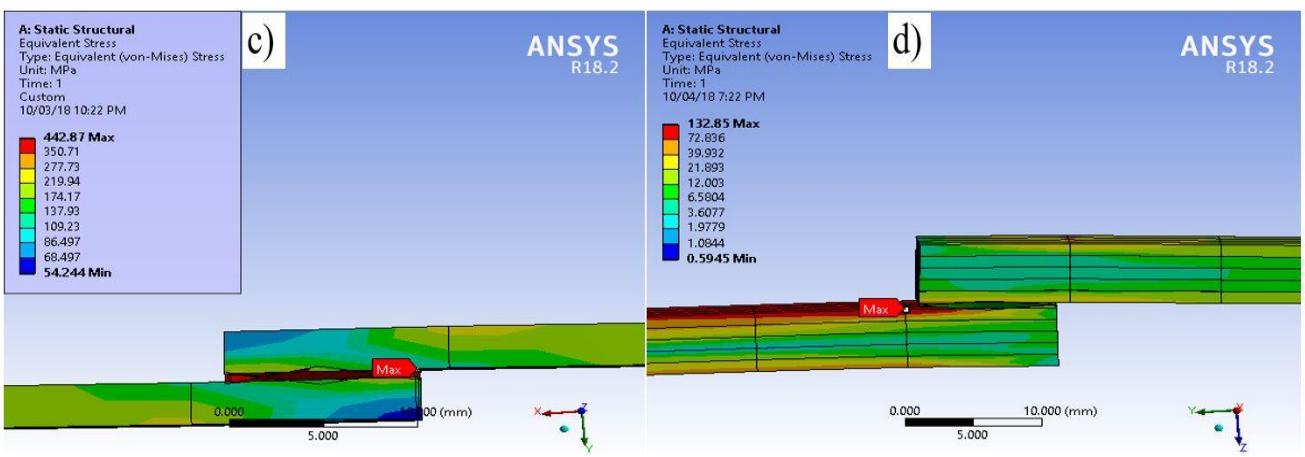

Figure 3 (c) Von-Mises Stress basalt fiber (d) Von-Mises Stress hemp fiber ANSYS Workbench

4. Conclusions

Due to its low manufacturing cost, low-stress concentration, and ease of maintenance, adhesive bonding is now one of the most commonly and widely used joining systems in various industrial applications. Adequate understanding of the behavior of adhesively bonded joints is necessary to ensure the efficiency, safety, and reliability of such joints.

- Surface preparation plays a vital role in efficient joint preparation. Washing with acetone, grinding with 200grit sandpaper increases adhesion in the join area.
- The adhesive thickness should be maintained between 0.1 mm to 2 mm to obtain precise results because increasing adhesive thickness reduces joint strength due to void formation.
- The overlap length beyond 20 mm will slightly increase joint strength and an overlap length of 25.4 mm was seen to be optimum.
- The environmental condition also affects joint strength strongly as specimen kept at 85% decreases joint strength.
- The FEA modeling of the adhesive joint in composites is quite challenging due to material nonlinearity. It is necessary to study joints in natural fiber composites as this area of composite joints was not yet addressed deeply. Also, the fatigue behavior of synthetic and natural fiber composites has to study in the way to develop FEM to benefit from costing and application points of view.
- It can be observed that the failure was initiated from the predicted location. Based on the qualitative analysis, it can be concluded that the proposed model can predict the failure zone with a fair degree of accuracy. On the quantitative analysis, the stress values calculated based on the experimental results were in good agreement with the numerical predictions.

In this paper, the research and progress in adhesively bonded joints in natural and synthetic fiber-based composites are critically reviewed and current trends in the application of FEA are mentioned. It is concluded that the studying behavior of adhesively bonded joints will help future applications of adhesive bonding by allowing different parameters to be selected to give as large a process window as possible for joint manufacture.

References

Afendi, M., Teramoto, T., & Bakri, H. Bin. (2011). Strength prediction of epoxy adhesively bonded scarf joints of dissimilar adherends. *International Journal of Adhesion and Adhesives*, *31*(6), 402–411. https://doi.org/10.1016/j.ijadhadh.2011.03.001

Ávila, A. F., & Bueno, P. de O. (2004). An experimental and numerical study on adhesive joints for composites. *Composite Structures*, *64*(3–4), 531–537. https://doi.org/10.1016/j.compstruct.2003.09.052

Bak, K. M., Kalaichelvan, K., & Arumugam, V. (2014). A novel approach for classification of failure modes in single lap joints using acoustic emission data. *Journal of Composite Materials*, *48*(24), 3003–3017. https://doi.org/10.1177/0021998313504323

Campilho, R. D. S. G., Banea, M. D., Neto, J. A. B. P., & Da Silva, L. F. M. (2013). Modelling adhesive joints with cohesive zone models: Effect of the cohesive law shape of the adhesive layer. *International Journal of Adhesion and Adhesives*, *44*, 48–56. https://doi.org/10.1016/j.ijadhadh.2013.02.006

Campilho, R. D. S. G., & Fernandes, T. A. B. (2015). Comparative Evaluation of Single-lap Joints Bonded with Different Adhesives by Cohesive Zone Modelling. *Procedia Engineering*, *114*, 102–109. https://doi.org/10.1016/j.proeng.2015.08.047

Campilho, R. D. S. G., Moura, D. C., & Gonçalves, D. J. S. (2013). Adhesive joints in natural fibre composites: Estimation of fracture properties. *Ciencia e Tecnologia Dos Materiais*, *25*(1), 31–37. https://doi.org/10.1016/j.ctmat.2013.12.007

Da Silva, L. F. M., & Öchsner, A. (2011). International Journal of Adhesion and Adhesives: Guest editorial. *International Journal of Adhesion and Adhesives*, *31*(5), 271–272. https://doi.org/10.1016/j.ijadhadh.2011.02.003

Ferreira, J. M., Silva, H., Costa, J. D., & Richardson, M. (2005). Stress analysis of lap joints involving natural fibre reinforced interface layers. *Composites Part B: Engineering*, *36*(1), 1–7. https://doi.org/10.1016/j.compositesb.2004.04.011

Gonzalez-Murillo, C., & Ansell, M. P. (2010). Co-cured in-line joints for natural fibre composites. *Composites Science and Technology*, *70*(3), 442–449. https://doi.org/10.1016/j.compscitech.2009.11.017

Gonzalez Murillo, C., Fagan, M., Ansell, M. P., & Meo, M. (2007). Experimental and finite element studies of adhesively bonded lap joints for natural fibre composites. *ICCM International Conferences on Composite Materials*.

Kumar, J., Kumar, V., Singh, I., & Rakesh, P. K. (2021). Joining behavior of polymeric composites fabricated using agricultural waste as fillers. *Journal of Adhesion Science and Technology*, *35*(15), 1652–1663. https://doi.org/10.1080/01694243.2020.1855909

Li, J., Yan, Y., Liang, Z., & Zhang, T. (2016). Experimental and numerical study of adhesively bonded cfrp scarf-lap joints subjected to tensile loads. *Journal of Adhesion*, *92*(1), 1–17. https://doi.org/10.1080/00218464.2014.987343

Liao, L., Huang, C., & Sawa, T. (2013). Effect of adhesive thickness, adhesive type, and scarf angle on the mechanical properties of scarf adhesive joints. *International Journal of Solids and Structures*, *50*(25–26), 4333–4340. https://doi.org/10.1016/j.ijsolstr.2013.09.005

Melese, K. G. K. G., & Singh, I. (2020). Joining Behavior of Jute/Sisal Fibers Based Epoxy Laminates

Using Different Joint Configurations. *Journal of Natural Fibers*, *00*(00), 1–12. https://doi.org/10.1080/15440478.2020.1798843

Melese, K. G., Naik, T. P., Gairola, S., & Singh, I. (2022). Joining techniques for polymer matrix composites. *Joining Processes for Dissimilar and Advanced Materials*, 11–32. https://doi.org/10.1016/B978-0-323-85399-6.00001-1

Melese, K. G., Rana, R. S., & Singh, I. (2022). *Hot-Plate welding behavior of Sisal and Jute Polypropylene composites Hot-Plate welding behavior of Sisal and Jute Polypropylene composites*. https://doi.org/10.1080/10426914.2022.2049295

Nakano, H., Omiya, Y., Sekiguchi, Y., & Sawa, T. (2014). Three-dimensional FEM stress analysis and strength prediction of scarf adhesive joints with similar adherends subjected to static tensile loadings. *International Journal of Adhesion and Adhesives*, *54*, 40–50. https://doi.org/10.1016/j.ijadhadh.2014.05.006

Raza, S. F. (2019). *Optimizing the weld factors affecting ultrasonic welding of thermoplastics*. 2053–2067.

Sayman, O., Soykok, I. F., Dogan, T., Dogan, A., & Arikan, V. (2015). Effects of axial impacts at different temperatures on failure response of adhesively bonded woven fabric glass fiber/epoxy composite joints. *Journal of Composite Materials*, *49*(11). https://doi.org/10.1177/0021998314533598

Song, M. G., Kweon, J. H., Choi, J. H., Byun, J. H., Song, M. H., Shin, S. J., & Lee, T. J. (2010). Effect of manufacturing methods on the shear strength of composite single-lap bonded joints. *Composite Structures*, *92*(9), 2194–2202. https://doi.org/10.1016/j.compstruct.2009.08.041

Thomas, S., Joseph, K., Malhotra, S. K., Goda, K., Example, A., Review, A., ELS Queen Margaret University, Started, G., Review, I. Y., The, O., Of, B., Review, Y., What, E., Skim, R., Examine, A., Reasons, M., Kiss, Z., Temesi, T., Czigány, T., … de Rooij, N. F. (2017). Effects of adhesive joint on the failure strength properties of natural fiber reinforced composite. *Composites Part B: Engineering*, *32*(1), 1–18. https://doi.org/10.1243/14644207JMDA219

Xia, Y., & Liu, Q. (2015). Design and analysis of horizontal-axis wind turbine main shaft. *Future Information Engineering and Manufacturing Science - Proceedings of the 2014 International Conference on Future Information Engineering and Manufacturing Science, FIEMS 2014*, *3*(11), 83–86.

Yao, M., Zhu, D., Yao, Y., Zhang, H., & Mobasher, B. (2016). Experimental study on basalt FRP/steel single-lap joints under different loading rates and temperatures. *Composite Structures*, *145*, 68–79. https://doi.org/10.1016/j.compstruct.2016.02.061

Yoon, H. C., Wang, R., Jeon, Y. B., Choi, J. Y., Lee, S. Y., Thai, P. Q., & Lim, J. K. (2007). Effects of adhesive joint on the failure strength properties of natural fiber reinforced composite. *Key Engineering Materials*, *353–358*(PART 3), 1960–1964. https://doi.org/10.4028/www.scientific.net/kem.353-358.1960.