Adhesively bonded joints in synthetic and natural fiber based composite materials: An overview

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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 on research work that have 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 bondline area.

Index Terms—Composites, Joints

I. INTRODUCTION

Recently metals are replaced by composite materials due to their better mechanical properties with reduced weight and cost. A composite material is 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 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 its 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 fiber 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 process. Mechanical fasteners are easy to use and can also be easily disassembled; however this impart holes leading to weakening of base material. It causes stress concentration on 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 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 puts limitation on their use [9]. This concern driven many scientist to investigate use of natural fiber in composite material for low mechanical strength application. Moreover, natural fiber composites can be used in automotive body parts without compromising to strength and durability. The dashboards, door panels, parcel shelves, cabin linings, seat cushions, backrests are few application 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 [14]. Every component cannot be fabricated as whole due to manufacturing limitations such as space required, complex shapes etc, and hence joining two parts plays vital role in field of composite application. The core joining processes are: adhesive bonding, mechanical fastening, welding. The joint strength is important part of in designing a structure. Hence joint strength is primary criteria while designing joints in composites. For light weight structures adhesive bonding is gaining more importance for joining similar or dissimilar structural components. Adhesively bonded joints are also acting as replacement for fasteners and rivets [11]. Hence studying behavior of adhesively bonded joints in different loading as well as operating condition has great importance in order 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 are vital. Therefore strength and failure mechanisms of bonded joints between these materials needs to be explored in detail.

II. LITERATURE SURVEY

S.M.R. Khalilii investigated strength of adhesively bonded
single lap joint 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 volume fraction of glass fiber in 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 sanded it with 1000-grit silicon carbide paper. They controlled thickness of adhesive layer as it affect 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 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 neat adhesive used. Addition of micro glass powder increases strength and stiffness of adhesive layer by 71% as compared to specimens with neat adhesive used [1].

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 overlap length of single lap joint as 25.4mm and slightly more for 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 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 fracture path begins at overlap area edge. They carried out finite element simulation to account for failure mode and load and found results similar to one that obtained from experiments. It was indicative that strength of wavy lap joint is more than single lap joint but it was difficult to manufacture [2].

Jianfeng Li 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 increase in overlap length for single lap joint. Increasing rate got slower as overlap length exceeds 10mm and adhesive shear failure for small overlap length. Equivalent stiffness increases with increase in adherend thickness. The failure area of adhesive shear failure mode increase with increase in adherend thickness. Equivalent stiffness and failure load increase with increase in adherend width for double lap joint. Also with increase in adherend thickness stiffness and failure load increased for double lap joints. They had observed adherend delamination failure. In case of varying scarf angle, stiffness remains constant, however ultimate failure load decrease with increase in scarf angle and lap shear strength increases with increase in scarf angle. In this case, combination of adhesive shear failure and adherend delamination failure mode is observed [3].

S.M.R. Khalili studied adhesive strength of single lap joints under in-plane and out-of plane loading with help of three dimensional finite element method. They varied behavior of adhesive, volume fraction of glass fiber and orientation of fibers in adhesive region. The overlap length, adherend thickness and adhesive layer thickness taken as 25mm, 3mm and 0.3mm respectively. They used ANSYS-10 software with SOLID46 element type in order to study stress distribution and failure in single lap joint. They considered adherend of carbon fiber and adhesive as resin-fusion 8604 epoxy. They performed static elastic analysis in both tensile and transverse loading. The load transferred on adhesive layer is by shear and peel stress. They found that maximum shear and peel stress was occurred near both ends of 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 [4].

R.D.S.G. Campilho studied tensile fracture toughness of adhesive joints in natural fiber composites. They had used ductile polyurethane adhesive in order 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 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 [5].

D.C.O’Mahoney studied behavior of adhesively bonded composite joint. They found that bonding strength is dependent upon strength of adhesive, composite-adhesive interfacial adhesion and strength of adherend. Hence they carried out Taguchi analysis in order to present order of most influencing parameter to determine ultimate failure load. They modelled composite adherend with linear elastic material model, with layup sequence of [0/90]4s, adherend thickness of 2 mm and 0.2 mm bondline thickness. Composite-adhesive interface was modelled with cohesive zone model. Bulk adhesive was modelled with isotropic continuum material model. They solved this problem in ABAQUS software. Also finite element model was calibrated against previously obtained experimental results and from that prediction of strength obtained by numerical results are found to be in acceptable condition. In Taguchi analysis, they found that adhesive strength, interface fracture energy and adhesive
ductility are main parameters that primarily affects failure loads [6].

J.A.B.P. Neto carried out parametric study of adhesively bonded joints in composites in order to predict failure in joints. Experimental tests were carried by varying overlap lengths and adhesive used were ductile and brittle type. They used carbon epoxy composites as adherends with [0][16] layup. The specimens were fabricated according to EN ISO 527-2 standard. They had varied overlap length from 10mm to 80mm with increment of 10mm and adhesive thickness 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 numerical model, non-linear behavior of joint with orthotropic properties of materials were taken into account. They found that joints with smaller overlap length from 10mm to 20mm shows cohesive failure while for overlap length greater than 30mm, interlaminar failure shown. The strength prediction by Hart-Smith elastic model gives reasonable results up to 30mm overlap length in accordance with experimental results [7].

Alberto Diaz-Diaz studied application of twofold criterion involving stress and energy conditions to predict interfacial failure in adhesive joints. The adherends used were of steel and polyester resin as adhesive. The double lap and butt joints made of these material was tested in universal testing machine under tensile loading. The overlap length in 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 criterion. They had used COMSOL Multiphysics 3.3 software in order to analyse stress and structural analysis of joints. It can be seen that joint strength increases as overlap length increases [8].

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 fibre composite elements to assess the strength of the structural bonds. They compared their experimental results with 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 [9].

Vaidya studied the behavior of adhesively bonded single lap joint 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 distributed symmetrically over entire joint area. The cohesive failure mode was observed by 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 increases by addition of nano-clay, conversely decreases ultimate failure strain by 33%. Also the load bearing capacity of joint was found to be dependent upon toughness of 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 modelling in FEM gives best results for bonded joint design [10].

Kohei Ichikava examined stepped lap joint for estimating stress distribution in tensile loading with 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 Youngs modulus and butted steps were increased the principal stress decreases. They have also carried out experimentation to verify FEM solution and it appeared to be in good agreement [11].

MFSF De Moura projected feasibility of cohesive and continuum damage model for analysis of bonded joints in composites. They carried out double cantilever beam and the end-notched flexure tests in order to assess cohesive properties of the adhesive under mode I and mode II. They have also proposed 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 [12].

Jean-Pierre Jeandreau characterized bonded lap joint with use of tensile testing on bulk specimens and Arcan-Mines tests. While Arcan-Mines tests were carried out for different angular direction loading. The fatigue testing of joints was done by keeping frequency of loading at 12 Hz. The strength of joint was highest for 0.3 mm bond thickness in Arcan testing while it was lower for 0.2 mm bond thickness in single lap testing. Also SN curve in fatigue loading was weaker for single lap joint due to peeling effect hence author concluded that Arcan-Mines specimens were best suitable for fatigue life calculation of bonded joints and cohesive failure was predominant in adhesive joints [13].

J. M. Ferreira studied fatigue behavior of composite adhesive lap joints. The specimens used by them were manufactured with various stacking sequence such as bi-directional 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 adhesive strength of joint was higher in case of single fiber composite. They observed peeling of adherend layer adjacent to adhesive was failure mode of thermoplastic composites while few specimens failed at adhesive [14].

Niat M Rehman carried out 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 ABAQUS processor. The failure mode of Mg-Mg balanced failed either at interface (adhesive failure) or at substrate and 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-betamate 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-betamate-steel it was better. The FEA models were compared and were reasonably in good agreement with test results [15].

Abdelaziz Taib studied glass-fiber-reinforced vinyl ester composite laminates manufactured by resin infusion and bonded with an epoxy adhesive to affect various joint configuration, adhesive layer thickness, defects, humidity, spew fillet, and adherend by means of 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 [16].

Finite element approach
The ANSYS finite element method software incorporates adhesive modelling by using cohesive zone modelling and composite modelling for adherends. Vaidya and Khalili used layered solid elements to model adherends. The results obtained by them are comparable with results obtained by experimental results. The cohesive zone modelling in ABAQUS given best results for brittle adhesives as investigated by Neto but it deviates strongly from standard results for ductile adhesives. The element types used by Rehman for modelling Mg-Steel bonded joints were fully integrated, incompatible, plane strain quadratic elements (CPE4I) and fully integrated, plane strain triangular elements (CPE3).

Fig.1 Shear stress concentration in the adhesive

SUMMARY
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 efficiency, safety and reliability of such joints.

1. The surface preparation plays vital role in efficient joint preparation. Washing with acetone, grinding with 200-grit sand paper increases adhesion in join area.
2. 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 voids formation.
3. The overlap length beyond 20 mm will slightly increase joint strength and overlap length of 25.4 mm was seen to be optimum.
4. The environmental condition also affects joint strength strongly as specimen kept at 85% decreases joint strength.
5. The FEA modelling of 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 point of view.

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


