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Review Article

Modeling and Analysis of Composite Bonded Joints

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Abstract: The bonded joints in composite structures is a challenging point in both research study and industry application. Compared with homogeneous and isotropic material, there is higher chance of stress concentration and intrinsic weak for this anisotropic structures. It is most common source of failure in structural laminates. So it is important to model and analyze the composite bonded joint to get the mechanical response and estimate the damage evolution. In this review paper, composite bonded joint are categorized based on bonded methods, materials, loading methods and failure modes. Multiple widely used adhesive bonded joint models including cohesive zone element model (CZM), interface element model, multiple point constraint model, kinking crack model, and repeating RVE model are introduced and discussed. To estimate the damage evolution in the bonded joint, a series of damage criteria have been developed including displacement based, stress based, energy based and modulus based damage criteria. Those damage criteria of bonded joint are also discussed and compared. This review work is important for the development of modeling of composite bonded joint in future.

Keywords: Modeling, Composite Bonded Joint, Adhesive, Damage Criterion

1. Introduction

1.1. Bonded Methods

Due to the increasing demand for energy-efficient vehicles, there is an increasing need to design lightweight structures such as aircraft and vehicle body frames. Because of this factor and due to the increased use of lightweight materials, sheet material joining techniques have been developed rapidly in recent years for joining advanced lightweight materials that are dissimilar, coated and hard to weld. Composite bonded joint is wildly applied in industry, civil engineering and aerospace engineering. The joints in composite structures present a greater challenge than for homogeneous, isotropic materials since anisotropic materials do not easily accommodate stress concentrations and have intrinsic weak directions. [1-5] There is a higher chance of the weakest spot occurring in bonded joint. It is most common source of failure in structural laminates. So it is important to model and analyze the composite bonded joint to get the mechanical response and estimate the damage evolution. [6-9] An ideal structure would be designed without joints, since joints are potentially sources of weakness and additional weight. In practice however, upper limit to component size is generally determined by the manufacturing processes. Further requirements for inspection, accessibility, repair and transportation or assembly mean that load-bearing joints will be part of an engineering structure. Typical problems encountered when using mechanical joints in composite structures include:

- Stress concentrations created by the presence of holes and cut-outs which is worsened by the lack of plasticity limiting stress redistribution [30].
- Delamination originating from the localized wear occurring during drilling [32].
- Differential thermal expansion of fasteners relative to composite.
- Water intrusion between fasteners and composite and fuel seal integrity of fastening system (where applicable).
- Electrical continuity in composite (required for energy dissipation in case of a lightning strike on an airframe for instance) and arcing between fasteners.
- Possible galvanic corrosion at fastened joints.
- Additional weight of fastening system [31].

- Extensive time and labour requirements of hole drilling.

There are two kinds of bonding methods in composite bonded joints, mechanical joint and adhesive bonded joint. In mechanical bonding, drilling is widely used to machine holes in cured composite laminates [10]. The introduction of holes in composites for assembling leads to stress concentrations in the vicinity of the holes. On the other hand, bolts and rivets damage the material around the drilled hole and can greatly affect the overall load-carrying capacity of the structure. Compared with mechanical joint, the adhesive bonded joint is widely used due to the advantages such as reduction of weight, no stress concentration, and no requirement of drilling. [11-16].

1.2. Materials

A considerable amount of FEA has been carried out on different types of adhesively bonded joints over the years. Mackerle [33] and [34] gives bibliographical reviews of the finite element methods applied to the analysis and simulation of adhesive bonding. Baldan [35] and [36] gives very comprehensive reviews on the adhesively bonded joints in different materials. Banea and da Silva [37] give a very comprehensive review on the adhesively bonded joints in composite materials.

Adhesive is defined as a material that adheres or bonds composite laminates together. The epoxy is widely used as adhesive in composite bonded joint. [4, 5, 10, 11, 12] Adherend is defined as any substance bonded to another by an adhesive. It includes both laminates and between laminate layers and metals.

1.3. Loading Methods

There are multiple loading methods in the tests and corresponding bonded specimens. The loading methods include peel off loading [1, 4, 6], shear loading, bending loading [17-19], compressive loading [15, 20], biaxial tension [21], mix modes loadings [5], impact loading [12] and fatigue loading [7, 22].

Adhesively bonded joints occurring in practice are designed to carry a given set of loads. The subsequent loads on the adhesive are then a function of the geometry of the joint. A common type of mechanical loading encountered by adhesively bonded joints such as in civil engineering is static loading. In addition, static analysis of adhesively bonded joints will provide a basis for further fatigue, dynamic analyses of the joints.

1.4. Failure Modes

Differences in mechanical properties between adherents and adhesive may cause stress singularity at the free edge of adhesively bonded joints. The stress singularity leads to the failure of the bonding part in joints. It is very important to analyze a stress singularity field for evaluating the strength of adhesively bonded joints. There are multiple failure modes in the bonded joint of composites due to different loading condition, materials and boundary condition in the joint et al.

So the developed model is supposed to be capable of capturing one or several main failure modes to predict the damage state. The main failure modes in composite bonded joint include adhesive failure [1, 5, 13], cohesive failure [4, 17], matrix failure [17, 18] and mixed failure [12, 21].

2. Modeling of Adhesive Bonded Joint

A lot of models have been developed to represent material property and mechanical response of adhesive and adherend, and to capture damage evolution in the bonded joint. There are several main modeling methods including cohesive zone element model (CZM), interface element model and multiple-point constraint model et al.

2.1. Cohesive Zone Element Model

Cohesive zone element model (CZM) is a widely used in simulation of delamination of bonded joint to model the mechanical behavior of the interface on the basis of damage mechanics and softening plasticity combined with fracture mechanics (see Figure 1) [1, 21, 23]. In this theory, fracture is considered as a gradual phenomenon in which separation takes place across an extended crack 'tip', or cohesive zone, and is resisted by cohesive tractions. Thus cohesive zone elements do not represent any physical material, but describe the cohesive forces which occur when material points are being pulled apart, and reflect the way material loses load carrying capacity. Dugdale [25] first applied CZM in ductile materials for elastoplastic fracture. In his model, cohesive strength is assumed to be equal to the yield strength and to be constant along the cohesive zone. More realistic cohesive models were introduced after that. In these models, the initiation of crack growth occurs when the critical separation is reached. Hadavinia presented analytical solutions for cohesive zone models and calculated correction factors for composite DCB specimens and their extension to peel testing. CZM are now widely used to describe local fracture processes [1, 5, 15, 21, 23, 24].
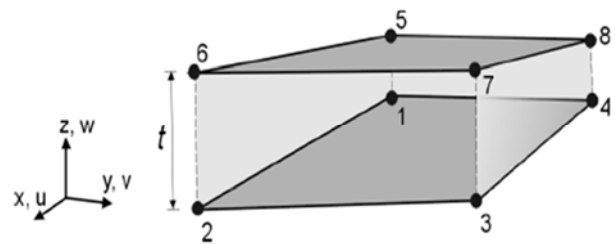

Figure 1. Cohesive zone element model.

Development of CZM is usually based on traction-separation law (stress-displacement). The shape of cohesive law is described by critical crack tip opening function. In the traction-separation law, generally tractions increase reversibly until it reach a maximum, and then approach zero in the softening section with increasing separation. The area under the traction-separation relationship is the fracture energy or work of separation.

These traction-separation laws can be classified as bilinear, trapezoidal (or trilinear), parabolic, and exponential as shown in Figure 2.
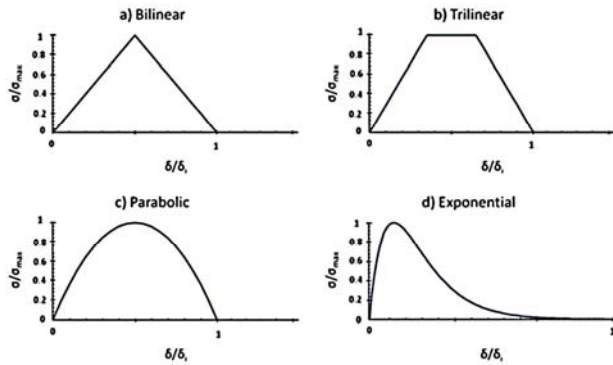

Figure 2. Different forms of the traction-separation law.

One important advantage of CZM is it can represent multiple loading stages, including loading, unloading and reloading. The loading history will affect the mechanical response due to softening plasticity in CZM. Also, all three fracture modes (opening, in plane shear and out of plane shear) are involved in the equivalent relative separation law. So the CZM can capture complex fracture phenomenon. There are several disadvantages of CZM. First, the equivalent displacement is non-negative value. So the compressive loading effect is neglected in this model. Also, the spacing between neighbor nodes in cohesive zone elements will affect the crack growing rate directly, because the crack tip will grow from element node in previous crack tip to its neighbor element node. So the size of meshes needs to be fine enough to assure a reasonable number of elements in cohesive zone.

2.2. Interface Element Model

Interface element model is another widely used methodology to model debonding process of crack tip in composite bonded joint (Figure 3), which is implemented between adherend to evaluate fracture energy based damage in interface [4, 7, 12]. The load in simulation using interface element model is applied in two steps. In the first loading phase, load is applied monotonically to a maximum load point. Then in the second step, load oscillates between maximum and zero values to simulate the fatigue loading condition [7]. From a numerical point of view, this method is close to the experimental loading procedure and hence avoids numerical instability. So the interface element model is capable of solving fatigue loading problem. In interface element model, material and stress are continuous between interface and adherend. And the damage mechanics and linear elastic fracture mechanics (LEFM) are approached in this model.

Figure 3. Interface element model in crack tip.

The interface element model is capable of being applied under compressive loading. This is an advantage compared with CZM, which is unable of being applied in compressive loading because the theory of separation law. In addition, the interface element model can capture all failure modes including adhesive, cohesive and matrix failures. This is different from CZM which only consider the general delamination. One major drawback of interface element model is that the unloading/reloading effect is not considered.

2.3. Multiple Point Constraint Model

Multiple point constraint (MPC) model is a finite element (FE) analysis methodology developed to predict the collapse of structures taking degradation into account [13, 26]. One aspect of this methodology is a strength-based approach for analyzing undamaged or intact structures that uses a global-local technique. Another aspect is a degradation model that applies user-defined MPCs controlled by fracture mechanics to represent damage growth in bonded joint. The critical phenomena and damage mechanisms for collapse include fiber failure, delamination, cohesive debonding, matrix cracking and fiber-matrix shear can be captured in this model.

In the damage growth model, pre-existing damage in the interface is represented as a debonded region between laminates. The shell layers are usually connected with user-defined MPCs. The user-defined MPCs are given one of three 'states', which were used to define the intact (State 0), crack front (State 1) and debonded (State 2) regions as shown in Figure 4. Gap elements were used in any debonded region to prevent crossover of the two sublaminates.

Values of energy release rate, G_I, G_{II} and G_{III}, reduced based on the shape of local crack front to be created upon release of failing MPCs. The failing crack front MPCs released or set from state 1 to state 2 for the start of the next increment.
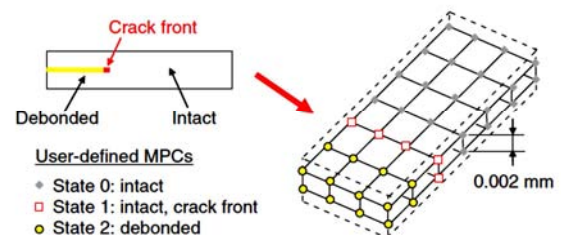

Figure 4. Interlaminar damage modeling with user-defined multiple point constraint model.

One advantage of MPC model is that it can capture multiple failure modes, including adhesive, cohesive and matrix failure. The user-defined MPC can also solve compressive loading cases. One limitation of MPC model is that the pre-existing crack must be implemented in the model. Also, the probable crack path must be set before simulation. In other words, the crack only grows in the path where MPCs are implemented in the FE model.

2.4. Other Models

Besides the three main models mentioned above, there are still some other models developed for different applications. In this section, two important models, kinking crack model [6] and representative volume element (RVE) model with pre-existing crack [21] are introduced and discussed.

2.4.1. Kinking Crack Model

For a crack lying at the interface between two composite laminates, crack growth can occur either along the interface or by kinking out of the interface into one of the adherend materials [21]. This competition can be assessed by comparing the ratio of the energy release rate for interface cracking and for kinking out of the interface, to the ratio of interface toughness to substrate toughness. First, the kinking crack model is embedded in crack tip of cohesive zone (see Figure 5). The maximum total energy release rate is defined to occur at the angle where G_I reaches its maximum value.

The advantage of the kinking crack model is the capability of predicting both crack growth rate and direction simultaneously. One limitation of this method is the simulation accuracy is dependent on mesh refinement.
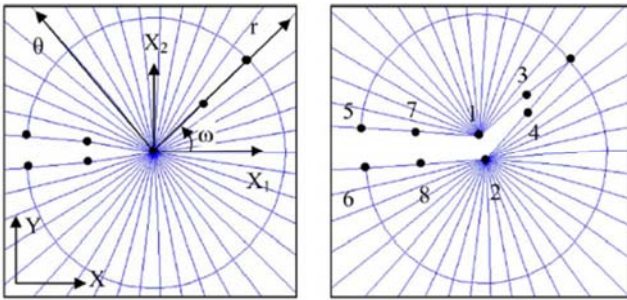

Figure 5. Kinking crack tip in bonded joint.

2.4.2 Repeating RVE Model

In the theory of composite materials, the representative volume elementary (REV) (also called the representative volume element (RVE) or the unit cell) is the smallest volume over which a measurement can be made that will yield a value representative of the whole. In the case of periodic materials, one simply chooses a periodic unit cell (which, however, may be non-unique), but in random media, the situation is much more complicated. For volumes smaller than the RVE, a representative property cannot be defined and the continuum description of the material involves Statistical Volume Element (SVE) and random fields. The property of interest can include mechanical properties such as elastic moduli, hydrogeological properties, electromagnetic properties,

thermal properties, and other averaged quantities that are used to describe physical systems. Statistical volume element (SVE) which is also referred to as stochastic volume element in finite element analysis, takes into account the variability in the microstructure. Zhang et al. developed a noval SVE model to represent homogeneous material properties in different length scales. [8, 9] In their work, the SVE model has been developed to study polycrystalline microstructures. Grain features, including orientation, misorientation, grain size, grain shape, grain aspect ratio are considered in SVE model. SVE model was applied in the material characterization and damage prediction in microscale. Compared with RVE, Zhang's SVE can provide a comprehensive representation of microstructure of materials.

The RVE model with pre-existing crack consists of interface zone with pre-exsiting crack and two laminate materials (see Figure 6). The repeating RVE models are embedded in the interface zone of bonded joint [21]. The crack growth rate in the interface is governed by energy release rate based damage criterion.
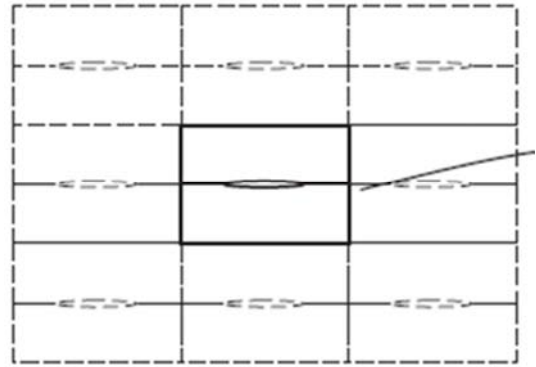

Figure 6. Repeating RVE model.

The repeating RVE model can take into account both tensile and compressive failure modes. Also, this model has high efficiency for the repeating construction method. One drawback of this model is that the crack must be pre-set into the RVE model before simulation. Also, this model only considers the adhesive failure mode.

3. Damage Criteria

In order to capture and measure the damage evolution in composite bonded joint, a series of damage criteria have been developed. The damage indexes include displacement, strain, stress, energy and modulus et al.

3.1. Displacement/Strain Based Criterion

In this criterion, displacement/strain is chosen as damage index to measure damage and determine crack growth process [5, 10, 11]. First, the displacements/strains in crack tip based on three fracture modes have been derived from Griffith's theory of fracture and traction-displacement relation respectively. And then the displacement/strain based damage indexes are defined. The functions of onset, maximum and

final relative displacements for three fracture modes are obtained. Finally, the total mixed-mode relative displacement (mix-mode damage index) is derived to criticize the damage in the crack tip zone.

One advantage of displacement/strain based criterion is that this method is straightforward and easy to use. This criterion is of high efficiency because of simple deriving process. In addition, the displacement/strain based criterion is capable of capturing mix modes of delamination using equivalent index. One disadvantage of this criterion is that the displacement is non-negative. So it is not available for compressive loading. Also, the accuracy of this criterion is highly dependent on mesh size.

3.2. Stress Based Criterion

Another damage criterion is stress based criterion [21]. It is similar to the displacement based criterion. The damage index is derived based on fracture mechanics, energy release rate. The stress based damage index is obtained as a function of loading and compared with failure strength to evaluate failure state.

Similar to displacement based criterion, the stress based criterion has high efficiency and is straightforward and easy to apply. Mix-modes of fracture are taken into account using equivalent approach. The drawback of this criterion is there is singularity problem in crack tip. So the corresponding accuracy is highly dependent on mesh size. This singularity issue has been solve in Li's model [21], in which the Fast Fourier Transform (FFT) method has been applied in high stress concentration zone around crack tip.

3.3. Energy Based Criterion

In energy based criterion, the energy release rates are derived as functions of strains (displacements) for all three fracture modes respectively [4, 7, 12, 13, 23, 24]. And then the equivalent energy release rate is derived as a combination of energy release rates and compared with critical value to identify crack growth.

For energy based criterion, energy release rate is selected as the damage index. There is no singularity problem and the index is independent on nodes in FE model. So one important advantage of energy based criterion is the simulation accuracy is independent on mesh refinement. This is especially different from displacement/strain/stress based criteria. Also, the energy based criterion is capable of solving impact problem [12]. One limitation of this method is the critical energy release rates need to be obtained from experiments.

3.4. Modulus Based Criterion

The modulus of materials can also be used as a damage index [22]. The load carrying capacity of cohesive zone decreases with coalescence of crazes, then corresponding modulus decreases. First, the damage index is related to initial elastic modulus E_0 and fatigue modulus E_N after N cycles. In addition, the relation between crack density and fatigue modulus is defined using experimental power law. Finally, the damage index is derived as a function of fatigue cycles.

The modulus based damage criterion is capable of solving fatigue loading cases. Also, the modulus is decreased with increasing loading cycles. This approach corresponds with physical phenomena as mentioned before: the coalescence of crazes in materials affect load carrying capacity. One disadvantage is the relation between crack density and fatigue modulus must be obtained from tests. So the development of the energy based criterion is dependent on experimental results.

4. Conclusion

In modeling and analysis of composite bonded joint, there are two important approaches: model development to characterize material property and mechanical response of cohesive zone in bonded joint, and the damage criterion to capture damage evolution and relate it to the physical crack growth, debonding and failures et al.

Among all the models, the cohesive zone model has been most widely used. It is commonly related to displacement/strain based criterion because the development of CZM is based on traction-separation law, which shows the relation between loading and displacement. One important advantage of CZM and displacement/strain based criterion is straightforward and easy to apply. High efficiency can be got compared with other models and criteria. This is important for onsite structure health monitoring (SHM) application. In addition, all three fracture modes effect can be captured due to the relevant mixed damage index. However, there are also several limitations. First, the crack can only grow through the CZM area. So there is a limitation of the probable crack direction for CZM. Also, there might be a singularity problem for the displacement/strain based criterion. It should be mentioned that the simulation accuracy is highly dependent on refinement of mesh size around crack tip. It should be mentioned that although the displacement/strain based criterion is usually applied in CZM, the energy or modulus based criteria can be used in CZM as well. In summary, the key point of the combination of CZM and displacement/strain based criterion is high efficiency but low accuracy.

Another important model, interface element model is developed based on mixed-mode energy release rate and energy balance principle of LEFM. Due to the different deriving process, the interface element model can solve the compressive loading problems. The interface element represents the physical property of adhesive materials. This is different from the CZM which only considers the traction-separation law instead of physics based material property. So the interface element model can capture multiple failure modes, including cohesive, adhesive and matrix failures. However, compared with CZM, the interface element model doesn't take into account the loading history effect. In other words, the unloading/reloading effect is not considered.

In MPC model, there are three states of the nodes: intact (State 0), crack front (State 1) and debonding (State 2). The crack growing path is determined by the states of element

nodes in MPC model. The MPC model can be implemented in adhesive, adherend and interface. So it can capture multiple failure modes, including adhesive, cohesive and matrix failure. However, similar to CZM, the crack path must be set before simulation in MPC model. There are also some other models including kinking crack model and repeating RVE model. The crack growing rate and direction can be calculated simultaneously in kinking crack model. The repeating RVE model has high simulation efficiency. It should be mentioned that in the repeating RVE model, the stress singularity problem has been solved using a FFT approach [21, 27-29, 38].

The displacement/strain/stress based criteria are straightforward and easy to use but dependent on mesh size in crack tip. Compared with that, the energy based criterion, which has been developed based on energy release rate, is independent on mesh refinement (no singularity problem) and can take into account mix-mode fracture effects. In the modulus based criterion, the damaged modulus is selected as the damage index. It is a material property instead of mechanical values such as stress or energy. In this model, the physical phenomena in microscale are related to the mechanical response (modulus) in macroscale. The only limitation of modulus based criterion is that it is dependent on experimental results.

In summary, there are different advantages and limitations for all the models and damage criteria. The model and criterion should be selected considering different cases (bonding materials, loading modes, bonded methods, requirement of simulation efficiency and accuracy et al.).

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