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A Review on Cohesive Zone Modeling For Analysis of Crack Propagation in Adhesive Joints

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ABSTRACT
Adhesive joints are used in a wide range of industrial applications due to their advantages over other joints. The crack propagation analysis in an adhesive joint is very important for its sustained performance. The Cohesive zone model (CZM) is found to be effective in this area due to its advantage over traditional methods. An overview of the CZM, usage with Finite Element Analysis (FEA), comparison with other methods, and implementation by back face strain (BFS) technique are reviewed in a proportional manner

Introduction

Adhesive bonding of metallic plates is an effective joining method in many industrial applications. Adhesive bonding is a material joining process in which an adhesive, placed between the surfaces, solidifies to produce an adhesive bond. Adhesively bonded joints are increasing alternatives to mechanical joints in engineering applications. They provide many advantages over conventional mechanical joints. Adhesive joints provide galvanic isolation, vibration damping, sealing capacity, high corrosion and fatigue resistance, and crack retardation. Also adhesive joints are used to join complex shapes and reduce the weight of structures. The cohesive zone model (CZM) is an approach which is used extensively in the analysis of crack propagation in adhesive joints.

Cohesive zone model (CZM):

The CZM was introduced by Barenblatt[1] which is based on the Griffith's theory of fracture. The CZM was used to describe the crack propagation in perfectly brittle materials by assuming that finite molecular cohesion forces exist near the crack face . Then, Dugdale [2] modified the approach by considering the existence of a process zone at the crack tip and extended it to perfectly plastic materials. It was suggested in this approach that the cohesive stresses in the CZM are constant and equal to the yield stress of material. Because of its flexibility, cohesive zone models are increasingly used in many engineering fields like crack tip plasticity, creep under static and fatigue loading, adhesive bonded joints, crack bridging, and interface cracks in bimaterials .

Need of CZM for fracture analysis of adhesive joints:

CZMs are used for accurate predictions of the adhesive joint strengths, deformations, interface failure, and the change between adhesive failure and the adherend failure which is not possible with conventional fracture mechanics. Because of the presence of increased plasticity in the adherends during deformation, the traditional approaches are not effective for analyzing the fracture of adhesive joints. CZMs use an approach which allows flexibility during adhesive deformation. The following reviews establish the need of the CZM for the fracture analysis of adhesive joints when compared to regular fracture mechanics approaches.

T.Ferracin etal[3] suggests the problems involved in the usage of existing analytical non-linear fracture mechanics models for fracture analysis of adhesive joints when the amount of plasticity within the adhesive bond is extensive. Also the difficulty exists when an attempt is made to characterize the cracking resistance of adhesive bonds experimentally. Development of mechanical tests from which important adhesive fracture properties can be analysed is also complicated.

F.Ascione et al[4] used a CZM which used two approaches for the stress and deformation of the adhesive joints. The CZMs were found to be effective as it considered all the factors important for the adhesive joint behavior namely, adherend and adhesive properties, joint geometry, total length, etc.

S.Li etal[5] in his work suggests that the strength of adhesive joints have been evaluated by two approaches namely strength based criteria and energy based criteria. CZMs strive to combine these two approaches which is a good advantage. Especially when the adherends are subjected to plastic deformation, cohesive models are used for analysis which is not possible by regular methods. CZMs are found to predict quantitatively, the mode-1 fracture of adhesively bonded joints.

S.Marzi etal[6] suggests that a major problem in the regular methods is the assumption of the existence of a crack for its implementation which is solved using a cohesive model. This is done by modeling the adhesive layer as a cohesive surface with properties given by the cohesive law

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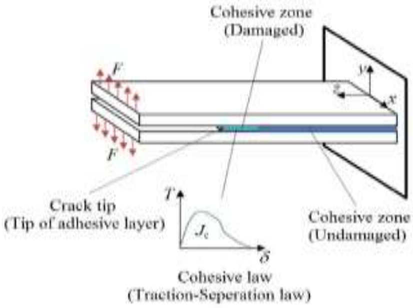
The CZMs provide an alternative solution when the regular methods used for crack prediction like virtual crack closure technique (VCCT), and the J integral are not effective. This is because these methods need geometrical information about the crack profile that is needed for finding the energy release rate (*G*) as suggested by C.Fan etal[7]

Thus we can clearly understand that the CZMs can be used effectively in analyzing the crack propagation in adhesive joints when compared to the regular methods as seen by the following points.

a) Regular methods need accurate geometrical information about the crack profile.
b) Assumption of the existence of a crack is needed for implementation of the methods.
c) Regular methods are inaccurate when plasticity in the adhesive joints is large

Overview of the CZM application in the crack propagation study in adhesive joints:

The procedure for applying the CZM to analyse crack propagation in adhesive joints generally involves a cohesive zone. This zone is considered as two cohesive surfaces which are attached by a cohesive traction. The failure is approximated by the complete separation of the two surfaces. This is explained with the help of a cohesive law which relates the cohesive traction and separation of the surfaces.



At the starting point of the crack, a damage zone is formed. Based on the beginning of damage, a stress limit is set based on the material strength. When the stress limit is attained, the damage starts. After this, due to the increase of the relative displacement between the two cohesive surfaces, the stress begins to decrease. Finally, the stress is reduced to zero resulting in a new area of crack as outlined by C.Fan etal[7]

In analysis of crack propagation in adhesive joints, a predefined crack path needs to be defined. Along this path, the CZM specifies a traction-seperation law which is a relation between coincident surfaces on either side. As the separation increases, the traction across the interface reaches a maximum limit and decreases. The crack finally propagates resulting in a total detachment of the surfaces as suggested by MD Banea et al [8].

Usage of CZM with FEA in the analysis of crack propagation in adhesive joints:

The use of cohesive zone models (CZM's) with FEA is the most prevalent method of predicting crack propagation in adhesive joints. Within finite element calculations, the CZM is used to analyse both the fatigue and failure loads of adhesive joints. Both cohesive strength and toughness are used to describe the failure behavior of adhesive joints in the implementation of CZM with FEA.

A simple model with an assumption that the adherends are in tension and the adhesive is in shear and both the stresses do not vary across the thickness was given by Volkerson[19] for the analysis of Crack propagation in adhesive joints. The effects of the peel stress and shear stress and also bending of the adherend were taken into account by Goland and Reissner[20].

The finite element method was more superior to the finite difference method as it can adopt any geometric shape under loading and also the numerical simulation. FEA has the ability to consider the stress variation throughout the thickness of the adhesive joint. The material and geometrical non-linearity can be included in the analysis. H.Kim and K.Edward[21] used the finite difference method to analyse the adhesive joints. The finite element method was used by Penado and Dropek[22] for adhesive joint analysis.

The CZM with FEA is used to replicate the adhesive failure by using two approaches namely the Adherent Cohesive zone and the Adherent Adhesive Cohesive zone. The first approach considers the adherents and the adhesive layer which is considered as a cohesive zone where the traction-separation replicates the behavior of the adhesive. The second approach has a finite thickness layer in addition to the adhesive layer. This has an advantage for more accuracy in simulation of adhesive behavior as suggested by Imanaka et al[23]

A non-linear finite element method was used for failure mode and load prediction by Harris and Adams[24]. Single lap joints with Aluminium adherends were used for the analysis. The finite element method established the need for different criteria for different adhesive systems. A.Ozel et al[25] also used non-linear FEM for analyzing crack propagation in a SLJ. For this analysis, two adhesives having varying mechanical behavior were used. The adherend was hard steel having four different thicknesses. Comparison between the FEA results and the experimental work were found to coincide to a certain level

Jie Feng et al[26] used a CZM based finite element model to verify the fracture behavior of a rubber toughened epoxy. The fracture behavior was dependent on thickness and also related to the plastic zone developed in the adhesive layer which was confirmed by FEA.

Andruet et al[27] used both two and three dimensional elements which was developed for displacement and stress analysis in adhesively bonded joints. The analysis was done on a single lap joint in which both two and three dimensional stress analysis was done.

Ljungqvist[28] used spring elements in a FEM used for simulating the adhesive behavior in adhesive joints. Different methods which replicated the adhesive behavior were done in the analysis.

M.M.Abdel Wahab et al[29] used a Finite Element procedure which was used to predict the fatigue behavior of an adhesively bonded composite joint. The procedure involved an experiment consisting of a DCB specimen which was used to determine a crack growth law. The law was further implemented within a finite element method which was used to generate the load-life response of joints having different configurations.

H.Khoromishad et al[30] developed a Finite Element method which was used to predict the static response of a Single lap adhesive joint. The model was developed in ABAQUS where four noded plane stress elements were used for the substrates and four noded Cohesive elements were used to analyse the adhesive bond-line.

The CZM coupled with FEA was used for a comparative study of strain distribution in adhesively bonded joints by Colavito et al[31]. The FEA results were validated by experiments done using Digital Image Correlation(DIC).

S.Yang et al[32] used a FEM in ABAQUS which successfully simulated composite adhesive joints with delaminations and cracks between the adherend and the adhesive.

P.Raos et al[33] implemented both 2D and 3D methodologies in FEM to analyse fatigue behavior in SLJs. The variations were adopted for overlap length and the physical characteristics of the adhesive and the adherend.

The usage of CZM and FEA involving modeling of both the adhesive and the adherends using shell elements was done by Naboulsi and Mall[34]. The modeling met the requirement related to the bending properties of the adhesive joints as it was found to give reasonable results.

The CZM application with FEM was done by modeling the adhesive as an elastoplastic continuum using solid FE elements by Pardoen et al[35].

Comparison of CZM with Virtual Crack Closure Technique (VCCT) in the analysis of crack propagation in adhesive joints

The VCCT is a methodology which is used for calculating the Strain Energy Release Rate (SERR) in the analysis of crack propagation in adhesive joints. Several literatures are reviewed in the process of comparison of VCCT and CZM to validate the effectiveness of CZM in crack propagation analysis.

The CZM is considered for modeling both crack initiation and propagation which has an edge over the VCCT in the analysis of crack propagation in adhesive joints according to the works of Rybicki E F[36] and Wood MDK [37].

Ye Zhang et al[38] compared the VCCT and CZM in an experimental study of an Adhesive joint involving Double Cantilever Beam (DCB) specimens of Glass Fiber-Reinforced Polmer(GFRP) laminates. The outcome established the validity of both the methods and outlined the advantages of each technique. The CZM allowed accommodating ductile fracture behavior to be modeled and also gave results which were coincident with the experimental data.

Ruixyang Bai et al[39] obtained the values of SERR using both the VCCT and the CZM in an analysis of an adhesive joint involving piezo-electric composites. The CZM provided a superior degree of coincidence in the load-displacement reaction when compared with VCCT. The VCCT was not able to simulate the crack initiation phase like the CZM.

When compared with VCCT, the CZM is able to calculate the commencement and spread of a crack without the need to apply a pre-existing crack

The usage of back-face strain technique in the framework of the CZM:

The Back-face strain (BFS) values are basically used to validate the results obtained in the analysis of crack initiation and propagation in an adhesive joint using the CZM. BFS technique was basically developed to detect the crack initiation in adhesive joints. Initially, the BFS technique was employed by Abe and Satoh [40] in the analysis of crack initiation and propagation of welded joints.

The crack initiation in an adhesive joint can be assessed by noticing the change in the direction of the back-face strain as proved in the work of Zhang et al[41]. Furthermore, Crocombe et al[42] was able to establish that the crack initiation in the adhesive joint was detected based on the response of the BFS location. Khoromishad et al[43] was able to extend the BFS technique for the crack initiation along with the propagation in single lap adhesive joints.

Graner Solana et al [44] developed an elasto-plastic damage model which predicted the backface strain observed from experiments and fatigue life at different fatigue loads. An experiment was conducted in which six strain gauges were placed along the overlap in a Single Lap adhesive joint which monitored the crack initiation and propagation inside the adhesive layer.

Conclusions

The role of a CZM in the crack propagation analysis of an adhesive joint was explored by considering the advantages over other methods which have their limitations. This was made cleared by comparing the CZM with the VCCT in the calculation of the SERR. The CZM together with FEA provided results which coincided with the experimental data. The procedure for applying the CZM for crack propagation in the adhesive joints was reviewed in a detailed manner. Finally the BFS technique in the framework of the CZM for studying the crack initiation phase in the adhesive joints was reviewed.

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