



A review on the Cohesive Zone Models for crack propagation analysis

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ABSTRACT

The cohesive zone model (CZM) can be regarded as a computational model which provides valuable insights in the prediction of crack initiation and propagation. The concept behind this model considers the process of fracture as a gradual phenomenon in which separation takes place between two adjacent virtual surfaces across an extended crack tip. The role of the CZM in analyzing the crack propagation in different materials and variations in the traction separation law(TSL) are covered in a detailed manner in this paper.

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Introduction

The CZM is a numerical tool for the mechanics of interfaces that was initially developed to model crack initiation and growth. The CZM is employed for a wide variety of problems and materials including metals, ceramics, polymers and composites. The CZM has become an effective way of describing and simulating material behavior in several materials inclusive of monolithic and composite materials with a crack. This model was developed in a continuum damage mechanics framework by making use of fracture mechanics concepts to improve its applicability. The CZM is widely used for simulation of crack propagation. In simulating crack propagation along interfaces, the CZM is applied intensively. CZMs are also used as an alternative method to account for crack growth by means of finite element simulation. CZMs are effective in modeling crack initiation and propagation phenomena. CZMs are applied when fracture takes place as a gradual phenomenon in which separation takes place across an extended crack tip or cohesive zone. The separation is resisted by cohesive tractions.

Review of czms

CZM - BASED ON THE TSL:

The CZM was introduced by Barenblatt[3] which is based on the Griffith's theory of fracture. He described the crack propagation in perfectly brittle materials using his model by assuming that finite molecular cohesion forces exist near the crack faces. Then, Dugdale [2] considered the existence of a process zone at the crack tip and extended the approach to perfectly plastic materials. It was suggested that the cohesive stresses in the CZM as constant and equal to the yield stress of material. Hillerborg et al. [6] implemented CZM in the computational framework of FEM. A crack model was proposed for examining crack growth. This deviates marginally from other works, where the cohesive zone tractions had been defined as a function of the crack tip distance since they define the tractions as a function of the crack opening displacement. Needleman [7] suggested a number of polynomial and exponential functions for defining the traction–separation relationship in a CZM.

Various CZMs which are represented in the form of cohesive laws were proposed by Hillerborg et al[6], Rose et al [9], and Tvergaard[10]. The main difference between these models lies in the shape of the traction–displacement response, and the parameters used to describe that shape. Ural et al [8] puts forward the effective usage of CZMs by coupling with fatigue damage evolution laws which simulates fatigue degradation and damage. Thus the CZMs can be used for predicting the fatigue response of various structures. He also [41] proposes a CZM which is of a bilinear nature under monotonic loading and also shows a degrading peak traction and stiffness behavior under cyclic loading. This model incorporates three parameters namely, crack advance, threshold, and crack retardation. T. Siegmund [13] proposes an irreversible CZM that views fatigue crack growth as a material separation process at and behind the crack tip, and the deformation processes in the surrounding material volume. Transient fatigue crack growth is studied for a material system in which the crack tip is shielded due to crack bridging.

To analyze an interface crack between two isotropic materials, a CZM was developed by Needleman [7], and Tvergaard [10]. P. Beaupaire et al [19] develops a numerical analysis using cohesive zone elements allowing the use of one single model in the finite element simulation of the complete fatigue life. The analysis also includes a damage evolution mechanism that reflects gradual degradation of the cohesive strength under cyclic loading.

M. Lee et al [23] proposes a approach which uses a cohesive law that determines the work of separation or fracture energy required for a formation of a free surface. This is used for simulating the initiation and propagation of multiple cracks leading to a creation of a new surface. H. Tan et al[28] formulates a CZM for the particle/matrix interface in the high explosives PBX 9501. By experimentally conducting a fracture study on this explosive, a macroscopic cohesive law is formulated which gives a non-linear relationship between the tensile cohesive traction and opening displacement ahead of a

macroscopic tensile crack tip. Zhenyu Ouyang et al [29] simultaneously proposes two CZMs based on the equivalent linear elastic cohesive law and the nonlinear cohesive law. This is very essential to investigate the effect of non-linear response at the bond interface on a pipe joint under torsion load. Simultaneously, the maximum torsion load capacity is derived as a function of the interface fracture energy.

M. Werwer et al [33] proposes a CZM for studying the fracture mechanisms in lamellar γ TiAl. The constitutive cohesive traction–separation law (TSL) is defined by two parameters which are the maximum traction, and the maximum separation work. These two cohesive parameters are identified by comparing numerical fracture simulations with experimental data.

CZM - COMPOSITE MATERIALS

F.Moroni et al [4] suggests the usage of CZM for the prediction of fracture in bonded joints in composite materials. This CZM incorporates a relationship between the normal/tangential stress and opening/sliding of crack faces over a region ahead of the crack tip [4]. R. Haj-Ali et al [24] presents an approach which incorporates an overall assessment on the use of combined micromechanical and cohesive fracture models to predict the failure loads and crack growth behavior of cracked pultruded composites under combined mode-I and II loading conditions. C.T. Sun et al [30] addresses some basic issues in the application of cohesive zone and bridging models to analyze fracture in composites with fiber bridging. Linear softening bridging and cohesive laws are used together to study the crack growth

CZM - Adhesive joints

H.Kromishad et al [5] describes a bi-linear traction–separation description of the CZM which is coupled with a strain-based fatigue damage model for simulating progressive fatigue damage specifically in adhesively bonded joints. Min Jung Etal [11] describes the progressive failure of the adhesive layer in an adhesive joint using a CZM whose failure behaviour is expressed by a bilinear traction–separation law. Furthermore, he also defines this law by three cohesive parameters namely the critical cohesive strength, the initial stiffness and the fracture toughness. Todd W. Bjerke [12] formulates a thermally dissipative CZM for predicting the temperature increase at the tip of a crack propagating dynamically in a brittle material exhibiting a cohesive-type failure. The model assumes that fracture energy supplied to the crack tip region needed for creating new free surfaces during crack advancement is converted to heat within the cohesive zone.

K.B.Katnam et al [16] suggests an experimental–numerical approach to characterise the environment-dependent cohesive zone properties of adhesive joints based on a miniature cantilever peel test. CZMs are employed in the numerical analysis of adhesively bonded structural joints. To accurately model these bonded joints, the characterisation of the cohesive zone properties for different environmental conditions is important.

Li et al [21] presents a CZM which concentrates on enhancing the predictive capabilities of the cohesive zone approach for mixed-mode geometries especially in an adhesively bonded composite system. A polypropylene matrix with randomly oriented glass fibres is the composite used in the system. Y.T. Kim et al [22] includes the material behavior of the adhesive and the interface between the adhesive and the substrate in the cohesive layer and applies a TSL to determine it. A. Mubashar et al [31] proposes a methodology for predicting the

transient moisture distribution in adhesive joints under cyclic moisture conditions. This methodology is used in combination with CZMs to determine the progressive damage and failure in single lap joints subjected to cyclic environmental ageing. The model was calibrated using a combination of experimental and numerical methods. The calibrated model was used to predict the strength of single lap joints, conditioned for different time intervals. A. Abdul-Baqi [12] suggests a CZM to model the fatigue damage process in a solder bump subjected to cyclic loading conditions. Fatigue damage is simulated using the cohesive zone methodology

CZM – VISCO ELASTIC MATERIALS AND POLYMERS

P.Rahul Kumar et al [14] presents a CZM for analyzing the fracture propagation in visco-elastic materials using the cohesive elements for the zone ahead of the crack tip. The model is used to study the problem of increase in fracture energy with peel velocity in peel testing of polymers. F.J. Gómez [17] proposes a CZM to predict the fracture of round-notched samples of a material that should remain essentially in the linear elastic regime up to the crack initiation. The material selected is a glassy polymer (PMMA) that at -60° C behaves as a linear elastic material.

S. Maiti et al [26] formulates a new cohesive model specialized for polymers with higher fatigue crack growth sensitivity based on the range of cyclic loading. Special emphasis is placed on the mode I fatigue failure of quasi-brittle glassy polymers such as PMMA, PC, epoxy etc. The CZM accounts for all the nonlinear effects associated with the failure process. The implementation of the CZM in a finite element framework allowing for the solution of a variety of structural problems is also described.

CZM – concrete

A.L.Rosa et al [18] proposes a time dependent cohesive model to account for the influence of loading rate on concrete fracture. Viscous-cohesive parameters are introduced in the crack model to represent a time dependent stress-crack opening zone in an elastic solid. Furthermore an implementation of a macroscopically time-dependent model which accounts for loading rate effects is also described in his work.

I.Scheider et al [20] uses the CZM to investigate the effect of hydrogen diffusion on stable crack propagation by using numerical finite element simulations. This is a very important in analyzing the extent of stress corrosion cracking in components influenced by hydrogen diffusion. X.Li et al [41] proposes a CZM to estimate the size of the fracture process zone in asphalt mixtures at low temperatures. The CZM used for this purpose is calibrated with the experimental data from the semi-circular bending configuration type of specimen subjected to fracture tests.

CZM – interface between identical materials

P.D. Zavattieri et al [34] proposes a CZM for modeling crack propagation along a cohesive interface between identical materials. The key geometric parameter for the interface is its aspect ratio or ratio of amplitude to wavelength. A set of critical parameters which includes the aspect ratio, material and cohesive properties is predicted such that crack growth is subdued. O.Voloshko et al [35] suggests the utilization of a CZM for the determination of fracture parameters for a crack situated in a thin adhesive layer which connects two identical isotropic materials. The normal stress distribution in the cohesive zone is defined numerically using a FEM.

S. Li et al [36] proposes the utilization of a CZM which uses micro-mechanics technique to study the effective constitutive

behaviors of a solid having randomly distributed cohesive cracks. This led to the formulation of the CZM which simulates the interactions among atomistic bond forces in the micro level which will help in prediction of damage effects macroscopically. F. Cazes et al [37] advocates the CZM as a nonlocal continuous model which is necessary to accurately model a localized damaged state. This model takes into account the complex mechanisms of micro cracking that occurs in a spatially extended zone.

I. Scheider et al [38] successfully uses the CZM to analyse the cup-cone fracture therein predicting the crack path during stable crack extension in ductile materials. The CZM is able to predict the failure mechanism including the normal fracture at the center and the normal and shear fracture at the rim of the specimen. J.L. Bouvard et al. [39] proposes a CZM for simulating the fatigue crack growth in a structure made of a single crystal material. This is done by initially developing a damage model and subsequently considering the geometry of the test specimen. Then extension of the damage model is done to time effects and calibrations from experiments previously done on single crystals.

P. Feraren et al [40] uses a CZM to simulate crack propagation through a square bond region containing a row of periodically elliptically shaped flaws. The CZM is also used to analyse the effect of flaw shape on the joint strength and the crack front shape during the propagation which is significant for the determination of fracture process zone parameters. P.S. Koutsourelakis et al [27] proposes a CZM for carrying out fatigue life calculations in aircraft fuselages which incorporates a Rankine type activation criterion for sufficient accuracy in the modeling of crack formation and computational efficiency.

CZM – Hydraulic and bone fractures

Zuorong Chen et al [32] uses the cohesive element method to simulate the propagation of a hydraulic fracture. This CZM effectively avoids the singularity at the crack tip region which proves to be a major hurdle in numerical modeling using the classic fracture mechanics. Ani Ural [25] proposes a CZM which is effective for analyzing bone fracture. Due to the fracture behavior of bone involving a process zone, cohesive models are appropriate for characterizing fracture in bone. This is very helpful in the assessment of macro- and microscale fracture mechanisms in bone.

Conclusion

The CZM as a computational model to analyse the process of fatigue crack propagation is reviewed based on the TSL and the interface between identical materials. Also a wide range of materials are also considered for the role of the CZM to explore the crack propagation. Finally, some categories of fracture is also considered to investigate the role of the CZM in the process of fatigue crack propagation..

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