XFEM Damage Analysis of Carbon Fiber Reinforced Composites and Crack Propagation in Mixed-Mode and Implementation of the Method Using ABAQUS

R. F. Swati, W. L. Hua, H. Elahi, and A. A. Khan

***Abstract*—There are numerous numerical studies of particle interface debonding based on the cohesive zone models, In order to validate the integrity of aerospace structures to fatigue damage the study of existing cracks must be studies closely. By applying multiscale method to fiber reinforced composites to study the multicrack behavior and fracture mechanics by using the cohesive zone modelling in ABAQUS with all the necessary parameters. Getting started with a single crack response followed by delamination and then introduced the study for two cracks to validate the results by simulations and experimentations as the same time. Multiscale modelling of CFRCCs executed as a strong and reliable tool for the study of crack propagation further simulating the structural model in different possible conditions. The structure may pertain to any assembly or part depending upon boundary conditions, loading and other parameters. "Carbon fiber reinforced plastics are mostly used in laminates, which consist of several very thin layers piled over each other. The study of these layers is composed of either unidirectional fibers or textile reinforcements which are inserted in an epoxy resin". This 3D material model is incorporated into a solid-shell finite element. A promising strategy to increase the tensile failure strain of carbon fibre-reinforced composites is to hybridise carbon fibres with other, higher-elongation fibres. The procedure of applying cohesive elements in ABAQUS software`s subroutines to model 3D complex crack propagation in different conditions and states.**

***Index Terms*—CFRRCs, eXtended FEM, finite element methods, homogenization.**

I. Introduction

The Extended Finite Element Method (X-FEM) is a numerical technique based on the Finite Element Method (FEM) which is specifically designed for treating discontinuities. Discontinuities are classified as strong and weak on the basis of their intensity and sharpness values. Strong discontinuities are observed in the solution variable. The displacements are the solution variable in structures, strong discontinuities are displacements edges like cracks and holes. Discontinuities in the variable of solution are mostly treated as weak category [1], [2].

A. Extended FEM Application to the Problem

The Extended Finite Element Method (XFEM) is a versatile tool for the analysis of problems which involves discontinuities, singularities, localized deformations and complex geometries [3], [4]. These methods can easily form the solution simplified for many complex situations in material modelling like the propagation of cracks, the evolution of dislocations, the modelling of grain boundaries and the evolution of phase boundaries. By using this method completely independent morphology of these entities and the finite element mesh is independent. 3D crack is shown in Fig. 1, crack positioning is free of mesh which permits for the different models of the cracks because as a crack propagates and increases any dimension then remeshing is not necessary and not needed [5]-[7]. Micromodel of in Fig. 2 illustrates the mesh for the XFEM model (Fig. 2a) as a structured mesh which is completely independent of the location of the grain boundaries. Keeping inview, the mesh for a standard FEM model in Fig. 2b, the element edges must conform to the grain boundaries and nodes with same contents must be brought into the model. This depicts the understanding of grain boundaries morphology for 3D modelling of complex shapes and structures.

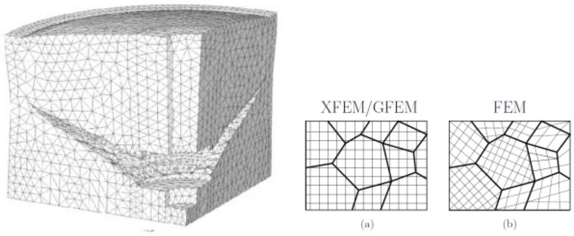

Fig. 1. 3D XFEM crack model for 200X magnification.

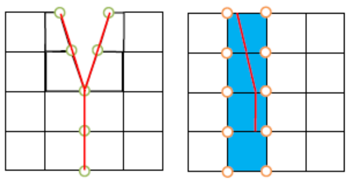

Fig. 2. Discretization for XFEM (a) and FEM (b).

The progress of extended Finite Element Method was an extension of the wide research in meshfree methods, [1], [8]. A number of the techniques that are used in extended FEM are directly related to techniques previously developed in meshfree methods. Therefore, we will also point out the relevant literature in meshfree methods. Some prior research of extended FEM have been given by Karihaloo and Xiao [9]and by Abdelaziz and Hamouine [10] a mathematical survey of XFEM was given by Babuska *et al.* [11]. A monograph on XFEM focused on fracture has also recently

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been published [12]-[14].

B. Treating the Discontinuity, Refinements and Methods

Furthermore, different functions including displacement fields in near-tip for the cracks and the field values for enrichment are the part of the modelling to observe corresponding results with or without including. Likewise, asymptotic singular near-field solution can be embedded closer to the crack fronts or the centres of enrichments and mesh zones whether it is a crack model or dislocation with the elastic media. By inducing the mentioned parameters there is a significant reduction for h-refinement especially for 2D model in these subdomains for the given scenario. For efficient simulation of multicrack propagation in composites the basic governing equations of equilibrium for ECDM is achieved without any additional elements for enrichments degrees of freedom as a first step.

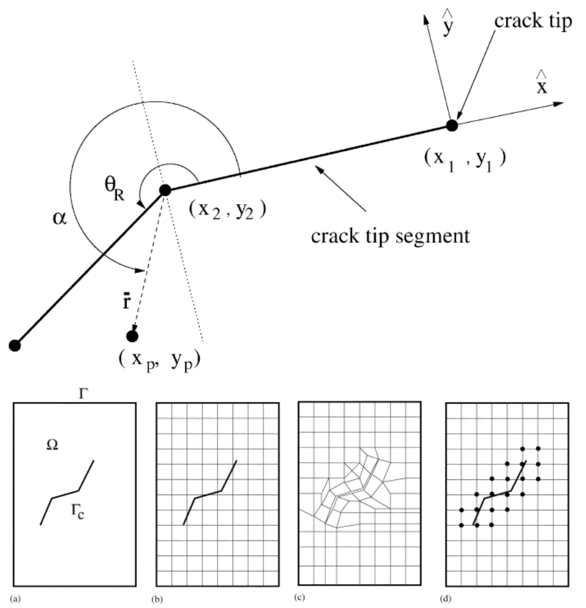

Fig. 3. Initial geometry for the mapping of the enrichment functions.

C. Combination with Level Sets

The major advantage of these methods for problems in materials science is the simplification of the modelling of discontinuous phenomena. As already mentioned, in conventional finite element methods, the mesh has to be constructed so that element edges/faces coincide with the crack surface and nodes must be placed on each side of the crack to allow material separation along the crack surface [15], [16]. The representation of level set defines delamination crack by 2 fields which are orthogonally placed. One labels the crack surface $\{x{:}\phi(x) = 0 \text{ and } \psi(x) \leqslant 0\}$, whereas the other shows the crack front $\{x{:}\ \phi(x) = 0 \text{ and } \psi(x) = 0\}$. This implicit description of the crack surface by level sets can be illustrated in Fig. 3; the orthogonal level set functions (ϕ and ψ) are tracked and updated momentarily. While in case of a complex three dimensional crack model, the mutual distance and fields are calculated as functions (ϕ and ψ) which happen to be computationally costly regarding the designed finite difference grids tracked by their mapping to the equivalent finite element nodal points. Furthermore, as the crack grows and propagates, another method known as fast marching method (FMM) updates and reload the surrounding of propagating and growing values for the crack model throughout the vicinity and the field. The method is primarily designed to reduce the computational burden and make it effective, reliable and robust regarding the overall behavior [17].

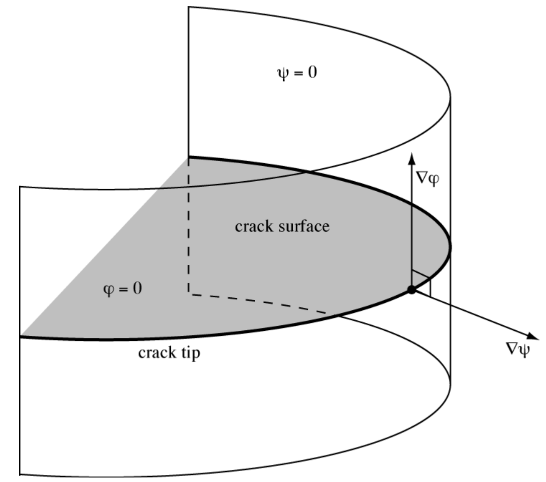

Fig. 4. Surface and crack-tip function.

II. Modelling and Framework of the Method

Structured meshes are appealing for many studies in materials science, where the objective is to determine the properties of a unit cell of the material. Unstructured meshes, on the other hand, tend to be widely used for analysis of engineering structures and components since it is often desirable to conform the mesh to the external boundaries of the component, although some methods under development today are able to treat even complicated geometries to structured meshes [18], [19].

A. Multiscale Phenomena and Mesh Generation

The Multiscale phenomena induced by the crack are not treated efficiently. If the refined mesh and the coarse mesh are not compatible, one can resort to global-local analysis. The displacements (or forces, depending on the method) are extracted from the response of the coarse mesh and prescribed at the boundary of the refined mesh. Then, a local reanalysis is carried out on the refined mesh [14], [20], [21]. The local response is taken into account on the global level by recovering forces (or displacements) at the boundary of this reanalyzed refined zone and applying these to the rest of the coarse mesh. To model the complex scenario of the complicated response, it needs different scales to be applied and validated so that the intrinsic microstructure may be computed precisely and accurately for the whole structure on the macro-scale. For this there exist several different methodologies in the literature [22]. The study reveals that asymptotic homogenization method for periodic structure and FE2-method are widely applied because of their realistic results [23], [24]. The parameter of microstructure can be accounted through anisotropic model applying the theory of structural tensors. Such models are specifically applied in the field of biomedical and bioinformatics because of their common characteristics and suitability. A summary of anisotropic material models established for reinforced fiber composites are present in various research studies. The experimental validation needs to be done through such models and study of the behaviour into finite element analysis, whereas, layered composites in micro to macro scale shift are mostly done by different techniques such as meso FE analysis of textile composites [25], [26]. One of the examples [18] is shown in Fig. 5 and Fig. 6.

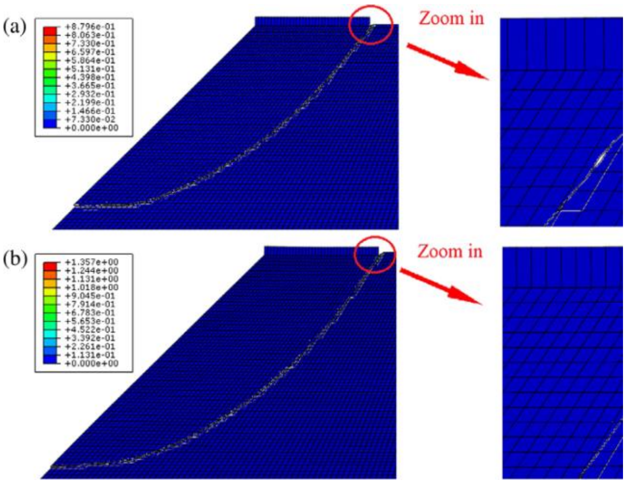

Fig. 5. Equivalent strain fields for a model a) non-associative and b) associative plasticity with fine mesh model.

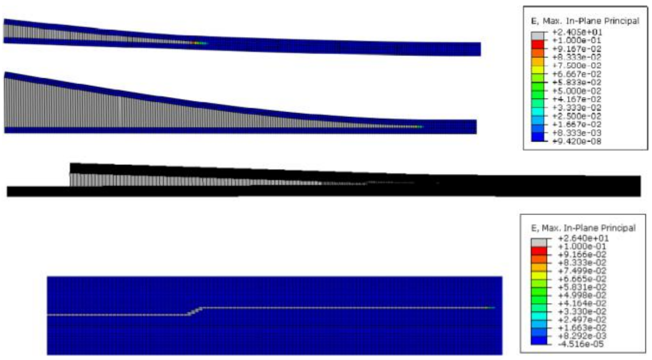

Fig. 6. The ECDM simulated delamination shift and matrix crack.

B. Application to Carbon Fiber Reinforced Polymers (CFRP)

Carbon fibre reinforce polymer (CFRP) composites have been commonly used in aerospace, shipbuilding and automobile engineering for several decades. Recently, the application of CFRP is increased in the constructional industry [24], [25] and manufacture of sports instruments [15], etc. It is still challenging to fully understand the complex damage mechanism of fibre composites. With the extensive application of CFRP, the investigation of damage mechanisms of CFRP structures has been a major concern for the further development of CFRP in engineering structures. Currently there is a lack of reliable numerical approaches which provide engineers and researchers with efficient prediction for damage and failure when designing fibre composite structures [5], [24].

The recent developments focussed on interlaminar interface as a special zone regarding modelling of delamination propagations. Multi Layered delamination is result of damage in composite laminates most of the times, further it grows up and transforms into various interlaminar interfaces. The research and development emphasized the assembling a promising mathematical model which is capable of computing and further remodelling multiple failure mechanisms including delamination shift, matrix failure and fibre damage [27]-[29].

C. Framework and Computational Algorithm

Normally, multiple damage behaviour rather than single mode damage is observed within fibre composite structures and they often couple and interact with each other as a complex failure mode during damage propagation. The numerical prediction for this multiple damage procedure is significantly important in the design of composite structures. Many researchers made a lot of effort in the aspect of computational damage mechanics in the past two decades. However, effective and efficient predicting multicrack behaviour in laminated composite structures is still challenge [3], [24].

In both cases, the particle debonding process is modelled using a bilinear cohesive law which relates cohesive tractions to displacement jumps along the particle–matrix interface.

III. Modelling and Analysis for Validating

This modelling and analysis primarily deals with the implementation aspects for two-dimensional LEFM applications containing single or multiple cracks. Furthermore, placed emphasis on the data input format and subroutines that interact with ABAQUS as a finite element solver through the user subroutine s and direct simulations in the software interface as previously shown [30]. Some of the important steps in an extended finite element analysis are additionally formed by altering the positions and geometries to verify the solution variables. The following are the major highlights towards attaining the complete framework of research study with application to CFRRCs and PRECs towards the damage model.

- Combination of Interface/cohesive model with X-FEM
- Numerical study for the models and existing theories
- Experimental study for Tensile/Compression/ shear specimen
- Characterization and prediction of the properties for CFRRC and PREC
- Asymptotic damage analysis and the process

In the case of two crack crossing through the line of symmetry or front on front contact, they are considered as major crack regardless of previous conditions or cumulative strain energies, they are considered as dependent while in case of 2D multiply diverged crack, the degrees of freedom is equal and equivalent per node as twice the number of fragments its base are changed into. This is because it is discretized into major and secondary cracks emerging from the main crack.

A. Crack Propagation under Mixed Mode Condition

Here is an example for mixed-mode crack growth under quasi-static conditions using ABAQUS for simulation for mixed-mode crack growth. The values of KI and KII depicts crack orientation angle which can be numerically calculated through set of equations [20], [31]. The detailed view of enriched nodes is shown for the crack growth.

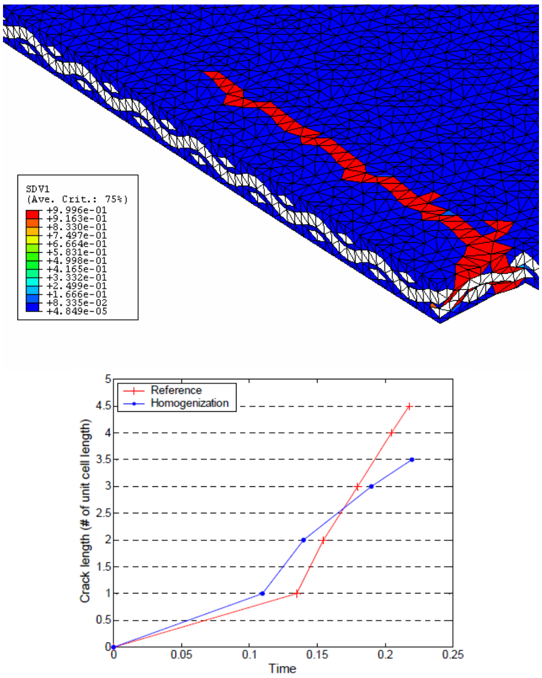

Fig. 7. Crack propagation using single scale finite element analysis.

B. Asymptotic Homogenisation

Asymptotic analysis is capable to find the solution for whole the structural study or analysis and find out the equivalent material properties throughout the structure at micro or any local scale dealing with. In most of the studies it has been applied for linear and two scale problems however its extension may lead to non-linearities and particular mixed mode cases [32]-[34].

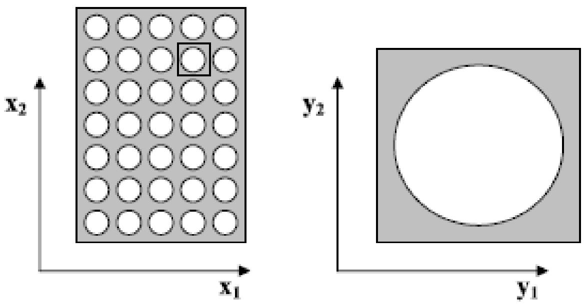

Fig. 8. Global and Local levels.

Resultantly, the method the major procedure of meshing is reduced and enrichment of the element across the crack-tip and along the crack faces the partition of unity is incorporated to encounter the presence of crack as singular crack tip asymptotic displacement fields [35].

IV. Conclusions and Future Aspects

Simplified and effective finite element method applied to analyse fracture to simulate 3D complex cohesive crack propagation in multiscale modelling for multicrack model specifically to CFRCCs and modelling the problem using ABAQUS's cohesive elements analysis tool. The subroutines and programs are designed for the same XFEM problem. Other studies with same examples were also verified and modelled to determine the efficiency of the method. By embedding the algorithm with the theory of XFEM in Abaqus, the developed methodology seems efficient and effective to provide a practical simulation tool for modelling realistic 3D fracture in various industries. The future study includes the validation of the results from the previous models and observations carried out, the values of strain energies, strain fields and the positional displacements and shifts for various loading cases are to be studied thoroughly of the multicrack systems of CFRCCs. Additionally, the experimentally results mapping to the homogenized outputs and contour plots of the multiscale method after being bridged is also one of the major concerns. A similar approach has also been discussed and verified by one of the researchers in [22] which is considered as a vital step towards the experimental study.

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