A Review: Cohesive Zone Modeling of Laminated Composite Beam under Mixed Mode Bending Load

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Abstract

Modern engineering design has always aimed to utilize better material properties, superior physical and chemical properties to arrive at most suitable and apt solution for engineering problems. Among various materials like; metals, ceramics, semiconductors, polymers and composites, much stress has been given to the exploration of the composites for better utility in the last two decades. The design goal of a composite is to achieve a combination of properties that is not displayed by any single material, and also to incorporate the best characteristics of each of the component materials. In the present work, the finite element method based computational tool-COMSOL Multiphyscics is used to implement the cohesive zone model (CZM) for laminated com-posite beam to study the effect of variation of thickness of laminates on the debonding, also the effect of initial crack length on the debonding is presented.

Keywords: - Material properties, Finite element method, CZM, laminate.,

1. INTRODUCTION

The advancements of composite materials in the field of aerospace engineering has poured down rapidly and in large quantities trying to satisfy the demand in domestic and indus- trial applications. Composites, the marvel material has the properties of light in weight, high strength-to-weight ratio and stiffness have replaced the materials like metals, wood to a large extent. A characteristic property of composite materials is that the finished products can be costumed according to the specifications required by selecting the proper type of matrix and the type of reinforcement.

Composites are not only regarded as friends of high performance products as they also used in packaging of good products to reduce polystyrene based packaging. Composites can also reduce environmental issues if we make correct choice of matrices and reinforce- ments. The world would be “greener” if the fibres are taken from oil palm and polymers are extracted from corn starch. Humans have been using composites from a long time for example mud cakes when bent will break easily while on the other hand they are strong when we try to squash or squeeze them. Straws also have a lot of strength when stretched but none when we try to crumple it. However, if

we combine both mud and straw, the properties of both the materials gets combined resulting in a stronger
composite material. Actually the composite materials are not new to the world. A large number of composite materials exist in nature and they are used accordingly. The various examples of composite
materials are

- leaf palm of coconut which is basically a cantilever having the notion of fiber rein- forcements
- wood- a fibrous composite
- cellulose- a lignin matrix
- lignocelluloses in sludge
- pearlite (ferrite combined with cementite) [1, 2]

Composite are multi-functional material systems that provide characteristics that are not obtainable from any discrete material. They are cohesive structures made by physi- cally combining two or more compatible materials, different in form and characteristics and sometimes in form" stated by Jartaz [4]. Consequently, it is to arrange composite materials like bone, wood, shell etc., from that of man-made materials such as pow- der metallurgy products, electrical insulators, resin bonded magnetic materials, powder charged particles, paper laminates etc. The limitation of this definition is that it classifies composites of any mixture without any specification or laws which would have differen- tiated composites from other types of material.Kelly [5] stated that the composite material should not be regarded as simple or complex of two or more materials. In wider sense; the combination of material forming composites has its own peculiar properties. Preferably either the component alone or fundamentally different from other should be selected in case of strength to resistance to heat or some other expedient property. Berghezan [6] defines as "The composites are compound ma- terials which differ from alloys by the fact that the individual components retain their characteristics but are so incorporated into the composite as to take advantage only of their attributes and not of their short comings", in order to obtain improved materials. Van Suchetclan [7] explains composite materials as heterogeneous materials consisting of two or more solid phases, which are in intimate contact with each other on a microscopic scale. They can be also considered as homogeneous materials on a microscopic scale in the sense that any portion of it will have the same physical property. Composite material is also defined as "a multiphase material that is artificially made, as opposed to one that occurs or forms naturally, chemically dissimilar and separated by a distinct interface [10]"

A. *Characteristics of Composite*

The characteristics of composite materials are as follows:

- Composite materials consist of one or more intermittent phases ingrained in ex- tended phase. The intermittent phase is harder and stronger and is known as "reinforcement or reinforcing material", whereas extended phase is known as "ma- trix". The matrix phase supports, surrounds and embeds the reinforcement by preserving their locations. The reinforcements contribute to the specific physical and mechanical assets thus enhancing the properties of matrix material. The com- bining materials, their distribution and the interaction between them determine the properties of the composite material. The properties may be determined as sum of constituent properties in terms of volume fraction or in a collaborative manner in order to have better or improved properties. The properties are affected not only by nature but also by the geometry that is shape, size and size distribution. The properties are also affected by the distribution, orientation and concentration of the properties.

- Shape- spherical, cylindrical, rectangular, cross- sectioned prism, platelets.
- Size and size distribution -controls texture of material
- Volume fraction – determines interfacial area, which determines the extent of interaction between reinforcement and matrix.
- Concentration-the contribution of single constituent material to the overall properties of composite material
- Composites materials also show a property of anisotropy i.e. their behaviour changes in accordance with the direction of strain applied. This property deter- mines the rigidity, strength and the thermal effects. The possible number of combi- nations for manufacturing composite materials is infinite .Consequently, composite materials are bespoke developments.
- Composite materials show a wide range of variety because of the behaviour between matrix and resin. They result in different materials having different characteristics due to the amount of fiber, type of reinforcement and fiber orientation. It is possible to have material with high performance and fragile elastic behaviour e.g. beam made from pre-impregnated carbon/epoxy fiber.The technique used for composite materials is called as homogenization technique. The aim of this technique is to determine the behaviour of microstructure of the material.
- The important perks of the composite materials are high specific strength and high specific modulus. Specific strength is the ratio of strength to density and specific modulus is the ratio of modulus to density. These two factors determine the load bearing capacity as well as stiffness properties which are very important in case aerospace structural materials.
- The composite materials have medium fatigue resistance and high damage resis- tance. The fiber/matrix interface can avoid the crack propagation. The fatigue strength for the metallic materials varies from 30-50% while in some of the com- posite materials it varies from 70-80 %.
- The composite materials consist of high natural frequency, so the generation of resonance is not so easy. The fiber/matrix interface in them helps in absorbing the vibrational energy thus composite materials have good damping characteristics.

- Another important characteristic of composite materials is that fiber/matrix cab be selected according to their utilisation and performance requirements of the products needed.

B. *Classification of Composite*

Delamination is a failure which affects the structural performance the composite materials and differentiates it from metallic structures. Delaminations arise from the manufactur- ing imperfections; cracks are generated from fatigue or impact, stress concentration near the joints and high inter-laminar stresses. Delamination affects the compressive strength and it will cause the material to fail through buckling

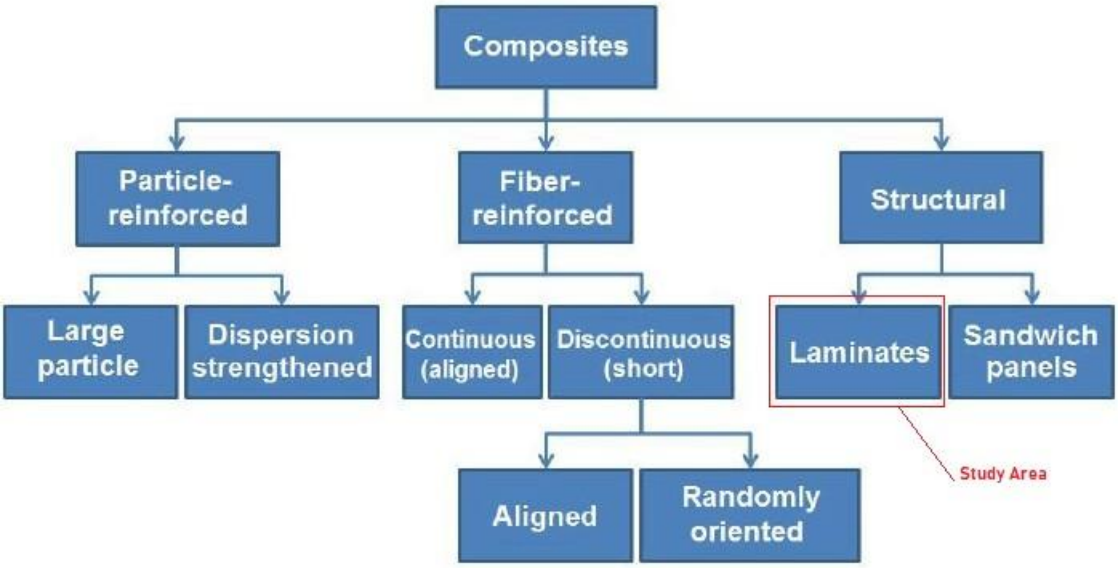

Figure 1: Classification of composite

2. RELATED WORK

Uniyal and Misra [15] carried out a failure study of cantilever beam made up of boron- epoxy laminated composites. Finite element ANSYS software was used to perform a failure analysis. Maximum stress and Tsai-Wu failure theories have been applied to estimate the failure index for various lamination systems. Unidirectional and angle ply laminates were tested for different fiber orientation angles. The angle ply laminates demonstrated higher failure strength relative to unidirectional laminates. The Cantilever beam with fibers aligned along the direction of loading showed a maximum strength loss, while the unidirectional and angle ply laminates with 45 gradient orientation showed a minimal resistance.

Based on the first-order shear deformation theory, [16] introduced a dynamic finite element method for the free vibration analysis of generally laminated composite beams. The effects of Poisson, couplings between extension, bending and torsional deformation, shear deformation and rotary inertia are incorporated in the formulation. The dynamic stiffness matrix was constructed on the basis of the exact solutions of the differential motion equations governing the free vibration of the typically laminated composite beam. The effects of the Poisson effect, the material anisotropy, the slender ratio, the shear de- formation and the boundary condition on the natural frequencies of the composite beams are studied in detail by carefully selected examples. The numerical results of natural frequencies and mode shapes are presented and compared to the solutions previously published in order to demonstrate the correctness and accuracy of their method.[17]has derived a new finite element model that can be used for laminated composite beams. The model includes separate rotational degrees of freedom for each laminate, but does not require additional axial or transverse degrees of freedom beyond those required for a single laminate. The shape functions ensure compatibility between laminates. Shear deformation was included but did not require interfacial slip or delamination. The product can also be used for short beams with a large number of laminates.derived a 3D laminated composite beam model, that is, beams that can vibrate in space and undergo longitudinal and torsional deformation. The model was based on Timoshenko's bending theory and assumes that, under torsion, the cross section rotates like a rigid body but can deform longitudinally due to warping. The warping function, which is essential for correct torsional deformations, was preliminary calculated using the finite element method. Geometric nonlinearity was taken into account when considering Green's strain tensor. The motion equation was derived from the virtual work theory and the-version finite element approach was discreet. The laminates were considered to be of orthotropic material. The impact of the laminate orientation angle on the natural frequencies and on the nonlinear modes of vibration was reported. It has been shown that there is a bending-longitudinal and bending-torsional coupling in linear analysis due to asymmetric laminates. Complex reactions in the time domain were introduced and the couplings between transverse displacements and torsion were investigated.of shear deformation and warping effects on the in-plane and out-plane responses of the beam. The stability analysis was performed through a path-following procedure and a bordering algorithm. Several numerical results were given and comparisons with classical beam theories and other theories available in the relevant literature were established. The given results highlighted the fact that the proposed finite element model is well suited to study the stability of structures that incorporate laminated composite beams, such as, e.g., light-weight roof structures and arch bridges.

For the bending analysis of laminated composites by [20], a layered beam element based on a higher-order theory was introduced. They used an N-layer element containing (9N+7) degrees of freedom. The element stiffness matrix was derived from the Lagrange equations. Deflections and stresses in laminated beams with varying end conditions and stacking order are determined numerically. The findings were compared to those found in the literature to demonstrate the accuracy of the function.

Jauhari et al [21] studied three different configurations of defects of hole with tensile testing machine. Definite changes were observed between defects and properties. The results are in good agreement with general behaviour of FRP composite material. Fibers are the main constituents used in the composite for increasing strength taking into account the orientation. From it shows it has good load carrying capacity with a less deflection and more strength.

Kalyana Chakravarthy et al [22] studied composite materials subjected to three point loading. Material used is GFRP AND software used was ANSYS .For loading simulation is carried out and results are found.

Chopade et al [23] focussed on decreased weight with increased loading capacity. To solve the problem he replaced the existing material by composite material.FEA and experimental analysis are carried out and the comparison between the existing material and E-glass/epoxy material.

Esmael Adaema et al [24] studied the characterisation properties of E-glass/epoxy and e-glass/polyester material. Strain rate effect of E-glass/epoxy and E-glass/polyester are studied. The graphs that are obtained from the tests were documented. Results showthat the mechanical properties are dependent on rate of strain.Bhatt et al [25]studied the laminate composite material having different types of layers and orientations. The values for maximum stress and shear stress were calculated. The specimen is modelled in ANSYS software based on the FRP composite laminate plate and FEA analysis is being done with the ANSYS software.

Kumar et al [26] used a new composite material for wind turbine replacing alu- minium.FEA was used to determine complex geometries as well as natural frequencies and vibration modes of specified wind material turbine. The results were used to determine the structured fitness to use.

Ratnaparikhi et al [27] studied the specimens of woven glass fiber with the help of hand lay-up technique. He analysed the experimental results with modal analysis technique to determine the natural frequencies of the material. The experiment is used to validate the results from the FEA using ANSYS. The effects of different parameters including aspect ratio, and fiber orientation of woven fiber composite plates are studied in free-free boundary conditions.

Ghayour et al [28] said that the non-composite beams has the application of some useful technique and studied it. The equations of motion are used to determine the dimensionless parameters and the combined effects of the dimensionless parameters on the modal characteristics of the rotating composite beams are investigated through numerical studies.

Wang et al [29] described that the stress and vibrational analysis procedure is used to determine the static and dynamic characteristics of the woven composite axial impeller under loading conditions particularly centrifugal force. The procedure is analysed with respect to FEA analysis.

using equivalent modulus beam theory with shear deformation, rotary inertia and gy- roscopic effects has been modified and used for the analysis. The modifications take into account effects of stacking sequence and different coupling mechanisms present in composite materials. Results obtained have been compared with that available in the lit- erature using different modeling. The close agreement in the results obtained clearly show that, in spite of its simplicity, modified EMBT can be used effectively for rotor-dynamic analysis of tubular composite shafts.

Rarani et al [32] used analytical and finite element methods for prediction of buckling behaviour, including critical buckling load and modes of failure of thin laminated com- posites with different stacking sequences. A semi-analytical approach is first developed to calculate the critical buckling loads of square composite laminates with SFSF boundary conditions. Then, these laminates are simulated under axially compression loading us- ing the commercial finite element software, ABAQUS. Critical buckling loads and failure modes are predicted by both Eigen value linear and nonlinear analysis.

3. COHESIVE ZONE METHOD

The cohesive zone method is based on the fact that the stress transfer capacity between two delaminating faces is not lost at the start of the damage rather results in the stiffness reduction of the separating faces. Cohesive crack models are used to predict cracking processes in the materials. The significance of the cohesive zone approach is stressed to analyse the localization and failure in engineering materials. The micromechanical mod- elling detects a new problem that contrasts from assumption of continuum mechanics. A material element has its own complex microstructure in spite of being non-uniform and the idea of a representative volume element (RVE) is introduced. The material separation and damage of the structure are defined by the interface element. Using this technique, the behaviour of the material is divided into two parts: the damage of the free continuum with arbitrary material law and the cohesive interface between the continuum elements. In several damage models the cohesive models seem perspective for practical applications. Cohesive zone models (CZM) helps in simulating fracture and fragmentation processes in metallic, polymeric, ceramic materials and composites. An infinitely sharp crack an- ticipates in linear elastic fracture and the energy from the process zone is transported from external work both in the forward direction and wake regions of the expanding crack. Base principle of CZM makes use of cohesive elements for crack and damage model. A cohesive model determines the behaviour of materials and is realized by two types of elements. The former element is for classical continuum and the latter one is the connecting cohesive element. The separating up of these connecting cohesive elements is calculated from the displacement of neighbouring continuum elements. An example where the potential of cohesive–zone models takes advantage of using traditional discrete interface elements is the analysis of delamination in layered composite materials. The multiplication of delaminations is restricted to the interfaces between the plies, inserting interface elements at these locations permits an exact simulation of the failure mode.

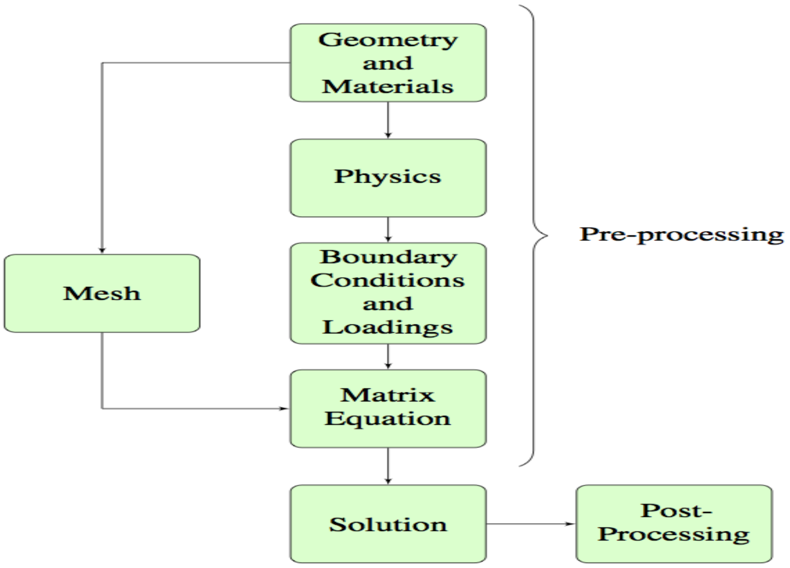

Figure 2: Basics of FEA

A. Objectives

- Von-Mises stress distribution as a function of laminate thickness.
- Interface health as a function of laminated beam thickness
- Load point displacement variation with laminate thickness
- von Mises stress distribution as a function of ini- tial crack length

4. CONCLUSION

From the above reviews The finite element model developed in this study paved a way to carry out a parameteric study of various factors influencing the behaviour of laminated composite beams like thickness of the laminates of the beam and initial crack length. The influence of these fac- tors on the mechanical strength, crack (delamination and debonding) propagation using mixed mode bending testing procedure was ascertained.

References

1. Idowu D Ibrahim et al. “The use of polypropylene in bamboo fibre composites and their mechanical properties–A review”. In: Journal of Reinforced Plastics and Composites 34.16 (2015), pp. 1347–1356.

2. Holm Altenbach and Johannes Altenbach. Mechanics of composite structural ele- ments. Springer, 2004.

3. Raymond Benedict Seymour et al. History of polymer science and technology. 1982.

4. AE Jartiz. Design. 1965.

5. Anthony Kelly. “The nature of composite materials”. In: Scientific American 217.3 (1967), pp. 160–179.

6. A Berghezan. “Non-ferrous materials”. In: Nucleus 8.5 (1966), pp. 5–11.

7. J Van Suchtelen. “Product properties: a new application of composite materials”. In: Philips Res. Rep 27.1 (1972), pp. 28–37.

8. Denis DR Carti´e. “Effect of z-fibresTM on the delamination behaviour of carbon-fibre/epoxy laminates”. PhD thesis. Cranfield University, 2000.

9. Bhavam V Sankar and Shoufeng Hu. “Dynamic delamination propagation in com- posite beams”. In: Journal of composite materials 25.11 (1991), pp. 1414–1426.

10. P Robinson and S Das. “Mode I DCB testing of composite laminates reinforced with z-direction pins: a simple model for the investigation of data reduction strategies”. In: Engineering Fracture Mechanics 71.3 (2004), pp. 345–364.

11. Larry W Byrd and Victor Birman. “The estimate of the effect of z-pins on the strain release rate, fracture and fatigue in a composite co-cured z-pinned double cantilever beam”. In: Composite Structures 68.1 (2005), pp. 53–63.

12. JG Ratcliffe and R Krueger. “A Finite Element Analysis for Predicting Mode I-Dominated Delamination Growth in Laminated Structure with Through-Thickness Reinforcement”. In: Failure in Composites 4 (2013), p. 117.

13. Venkata Dantuluri et al. “Cohesive modeling of delamination in Z-pin reinforced composite laminates”. In: Composites science and technology 67.3-4 (2007), pp. 616–631.

14. Marcello Grassi and Xiang Zhang. “Finite element analyses of mode I interlaminar delamination in z-fibre reinforced composite laminates”. In: Composites science and technology 63.12 (2003), pp. 1815–1832.

15. P Uniyal and A Misra. “Finite element analysis of laminated composite cantilever beam”. In: International Journal of Advancements in Technology 7.4 (2016), pp. 1– 4.

16. Li Jun, Hua Hongxing, and Shen Rongying. “Dynamic finite element method for generally laminated composite beams”. In: International Journal of Mechanical Sciences 50.3 (2008), pp. 466–480.

17. Yuan Fuh-Gwo and Robert E Miller. "A new finite element for laminated composite beams". In: Computers & structures 31.5 (1989), pp. 737–745.

18. S Stoykov and S Margenov. "Nonlinear vibrations of 3D laminated composite beams". In: Mathematical Problems in Engineering 2014 (2014).

19. Ida Mascolo et al. "A Finite Element Analysis of the Stability of Composite Beams With Arbitrary Curvature". In: Frontiers in Built Environment 4 (2018), p. 57.

20. V Kahya and M Turan. "Bending of laminated composite beams by a multi-layer finite element based on a higher-order theory". In: Acta Physica Polonica A 132.3 (2017), pp. 473–475.

21. Nitin Jauhari, Raghvendra Mishra, and Harischandra Thakur. "Stress analysis in FRP composites". In: Perspectives in Science 8 (2016), pp. 50–52.

22. Kalyana Chakravarthy and K Raghunandana. "Stress analysis of glass fibre rein- forced composites used in wind turbines". In: (2015).

23. SushilB Chopade, KM Narkar, and Pratik K Satav. "Design and Analysis of E-Glass/Epoxy Composite Monoleaf Spring for Light Vehicle". In: Int. J. Innov. Res. Sci. Engg. Technol 4.1 (2015), pp. 18801–18808.

24. Esmael Adem et al. "Experimental Analysis of E-Glass/Epoxy & E-Glass/polyester Composites for Auto Body Panel". In: American International Journal of Research in Science, Technology, Engineering & Mathematics 10.4 (2015), pp. 377–383.

25. Deepanshu Bhatt, Yogesh Mishra, and Dr PK Sharma. "A Review of Static and Free Vibration Analysis of Laminated Composite Plate by using Finite Element Method". In: International Journal of Advanced Engineering and Global Technology 2 ().

26. Ashwani Kumar et al. "Free vibration analysis of Al 2024 wind turbine blade de- signed for Uttarakhand region based on FEA". In: Procedia Technology 14 (2014), pp. 336–347.

27. Sharayu U Ratnaparkhi and SS Sarnobat. "Vibration analysis of composite plate". In: International Journal of Modern Engineering Research (IJMER) 3.1 (2013), pp. 377–380.

28. Rasoul Ghayour, Mostafa Ghayour, and Saeed Ziaei-Rad. "Vibration analysis of tapered rotating composite beams using the hierarchical finite element". In: (2010).

29. Jifeng Wang, Jorge Olortegui-Yume, and Norbert Mu¨ ller. "Stress and vibration analysis for woven composite axial impeller". In: Power Conference. Vol. 49354. 2010, pp. 443–449.

30. Mehmet Akta¸s et al. "An experimental investigation of the impact response of composite laminates". In: Composite Structures 87.4 (2009), pp. 307–313.

31. HBH Gubran and K Gupta. "The effect of stacking sequence and coupling mech- anisms on the natural frequencies of composite shafts". In: Journal of sound and vibration 282.1-2 (2005), pp. 231–248.

32. M Heidari-Rarani, SS Khalkhali-Sharifi, and MM Shokrieh. "Effect of ply stacking sequence on buckling behavior of E-glass/epoxy laminated composites". In: Computational Materials Science 89 (2014), pp. 89–96.

33. COMSOL Multiphysics. "v. 5.2, COMSOL AB, Stockholm, Sweden". In: (2019).

34. James M Whitney and Ralph J Nuismer. “Stress fracture criteria for laminated composites containing stress concentrations”. In: Journal of composite materials 8.3 (1974), pp. 253–265.

35. RY Kim and SR Soni. “Experimental and analytical studies on the onset of delam- ination in laminated composites”. In: Journal of composite materials 18.1 (1984), pp. 70–80.

36. GA Schoeppner and NJ Pagano. “Stress fields and energy release rates in cross- ply laminates”. In: International Journal of Solids and Structures 35.11 (1998), pp. 1025–1055.

37. Ch T Sun and CJ Jih. “On strain energy release rates for interfacial cracks in bi-material media”. In: Engineering fracture mechanics 28.1 (1987), pp. 13–20.

38. Edmund F Rybicki and Melvin F Kanninen. “A finite element calculation of stress intensity factors by a modified crack closure integral”. In: Engineering fracture mechanics 9.4 (1977), pp. 931–938.

39. Donald S Dugdale. “Yielding of steel sheets containing slits”. In: Journal of the Mechanics and Physics of Solids 8.2 (1960), pp. 100–104.

40. Sohrabuddin Ahmad, Bruce M Irons, and OC Zienkiewicz. “Analysis of thick and thin shell structures by curved finite elements”. In: International Journal for Nu- merical Methods in Engineering 2.3 (1970), pp. 419–451.

41. ASTM Standard. “D6671-13,””. In: Test Method for Mixed Mode I-Mode II Interlaminar Fracture Toughness of Unidirectional Fiber Reinforced Polymer Matrix Composites,” American Society for Testing and Materials, West Conshohocken, Pennsylvania (first published in 2001) ().

42. John H Crews Jr and James R Reeder. “A mixed-mode bending apparatus for delamination testing”. In: (1988).

43. James R Reeder and JH Crews. “Redesign of the mixed-mode bending delamina- tion test to reduce nonlinear effects”. In: Journal of Composites, Technology and Research 14.1 (1992), pp. 12–19.

44. Alfred Franklin and T Christopher. “Generation of mixed mode I/II failure criteria from MMB specimens: an experimental study”. In: Materials Research Express 6.12 (2019), p. 125616.

45. Funda Aksu Denli et al. “A phase-field model for fracture of unidirectional fiber-reinforced polymer matrix composites”. In: Computational Mechanics (2020), pp. 1– 18.