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Analytical Determination of Fracture Load for Marine Composite Panels

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ABSTRACT— ***Composites have diversity of structural applications in marine field. For the successful design of damage tolerant composite structures, it is necessary to know the failure mechanism as well as the ability of the structure to carry load after damage initiation. The present paper investigates damage mechanism particularly the interlaminar fracture for composite materials. Fracture load that initiates crack growth on flat rectangular laminate with an embedded delamination has been determined using Virtual Crack Closure Technique (VCCT) in conjunction with finite element software ANSYS for mode I type loading (opening mode). A MATLAB code has been generated to find fracture load and to plot load –displacement curve using various classical methods.***

Keywords— Composites, damage tolerant, finite element, interlaminar fracture

Nomenclature

Δa	Length of the elements immediately in front of the crack along the crack growth direction	G_{13}	Shear modulus.
a	Initial crack length	h	Half the thickness of DCB
B	Specimen width	P	Load for given G_I
C	Compliance of the body	Xi	Nodal forces at node i in the x- direction
E_{11}	Elastic modulus along fibre direction	Yi	Nodal forces at node i in the y- direction
G_1 , G_{1I} , G_{1II}	Mode I, Mode II, Mode III strain energy release rate	$\Delta u_{k,j}$ and $\Delta v_{k,j}$	Relative *u* and *v* displacements between nodes *k* and *j* respectively

1. INTRODUCTION

The structural utilization of composites in marine industry is extensive and rapidly expanding today as it enables to build stronger and lighter vessels. The driving popularity of Polymer Matrix Composites (PMC) in marine field is due to its high specific strength and stiffness, low magnetic properties, corrosion and impact resistance, vibration damping, ease of fabrication, maintenance and repair [1].

Marine composites require special features unlike composites used in other sectors. This is mainly due to the presence of seawater and moisture, time depended three dimensional loading, temperature extremes and cost constraints. Glass Fibre Reinforced Polyester (GFRP) is mainly used for the marine applications since these cater to all these needs. Polyester resin should be unsaturated, isophthalic and thermoset. Glass fibre has been used in variety of forms including woven, chopped strand mat, unidirectional tows, stitched and knitted fabrics. Some high performance craft also uses carbon or aramid as fibres along with epoxy or vinyl ester resins.

2. DAMAGE AND FRACTURE MECHANISMS IN COMPOSITES

For the effective use and successful design of laminated composite structures, realisation of structural failure mechanism is necessary. Fracture and failure modes of composite differ from that of metals. For laminated composites fracture is often controlled by numerous microcraks distributed throughout the material rather than a single macroscopic crack as in metals. Composite failure occurs progressively by warning cracks and the crack propagation is arrested to some extend by fibre-matrix interface. Weakest fibre in the laminate is broken first and the load is distributed to remaining unbroken fibre until total failure of laminate occurs.

There are two types of failure mechanisms in composites namely intra-laminar and inter-laminar failures [2]. Intra-laminar failure involves matrix cracking, fibre breakage, debonding of fibre-matrix interface, fibre pullout and fibre bridging. These may occur due to tensile loading of composite laminates [3]. Interlaminar failure or delamination refers to debonding of adjacent laminates.

The failure mechanism of unidirectional composites under tensile loading in fibre direction depends upon the type of composite used. Strain to failure of fibre (ε_{fu}) is greater than strain to failure of matrix (ε_{mu}) for E-glass polyester. So resin cracking occurs before fibre fracture. For carbon epoxy composites fibre fracture precedes resin cracking as $\varepsilon_{fu} < \varepsilon_{mu}$. In the case of typical marine composites, initial damage may occur in the form of resin cracking and fibre debonding. It occurs at tensile strain between 20% to 50% of the ultimate strain. The associated reduction in Young's modulus is up to 40%. In mat reinforcement this damage may occur even earlier loading state. For this reason and in order to avoid water penetration through matrix cracks tensile strain under normal design loads are usually confined between 20% to 30% of ultimate value [4].

Failure of laminate under compressive load acting in fibre direction involves microscopic buckling of individual fibres. The polymer is soft compared to fibres and the fibres are unstable in compression [3]. For flexural loading damage usually starts on the outer plies of the laminate and then progressively spreads to the underlying plies.

The loading applied to the defects in structure can be typically resolved into interlaminar tension and shear stresses. These can be decomposed into three basic fracture modes, namely, Mode I (opening mode), Mode II (in-plane shear mode) and Mode III (out-of-plane shear mode). Fracture and crack growth analysis is identical to each of these modes. In practice majority of the cracks results from Mode I loading. Other modes occur in combination with mode I loading.

3. INTERLAMINAR FRACTURE IN COMOSITE SHIPS

Interlaminar cracking which is commonly known as delamination is the rupture of link between plies due to the lack of reinforcement in thickness direction. Delamination is known to be the most critical damage mode as it limits the fibre load carrying capabilities. The damage caused by delamination is not so visible to the surface but this internal damage may cause substantial reduction in relevant mechanical properties such as reduction in strength and stiffness of the laminates. This failure scenario is one of the major obstacles to the wider utilization of composite in various fields.

Delamination is a function of interlaminar tensile or shear strength which depends primarily on matrix properties. The structural discontinuities such as free edge, notch, ply drop etc., where the interlaminar stresses are high may be the initiation site for delamination damage [1]. The damage may become severe due to the presence of defects or by fatigue due to wave induced cyclic loading. Impact of low to medium energy loads which are often present in marine structures are the main reason for delamination propagation in composite ships or boats. Slamming due to wave loading, berthing loads, floating object impact, dropped objects etc., are some of the typical examples in this area. Naval vessels subjected to underwater explosions or air blasts are also prone to delamination damage. If delamination occurs in bonded structural connections in ship structures such as Tee joint or top hat stiffeners, it can greatly affect the structural integrity of the structure and hence the load bearing capacity of ship as whole [5].

4. FORMULATIONS FOR FRACTURE PARAETER

Linear Elastic Fracture Mechanics (LEFM) is applicable for the evaluation of delamination if local material non linearity in the vicinity of delamination front is neglected. Fracture mechanics of isotropic materials are commonly treated in terms of stress intensity factor (K). However delamination resistance of composite materials is usually characterized by the fracture parameter, Strain Energy Release Rate (SERR/ G).

To predict delamination growth, G is compared with delamination fracture toughness or critical value of SERR, G_{ic} where i is the loading mode. Based on Griffith crack growth criterion, crack propagates if $G \geq G_{ic}$ [6] and corresponding load which cause crack growth is fracture load (P_c). G is related to geometry, loading and constrains of the material while G_{ic} is material property and can be determined experimentally.

4.1 Strain energy release rate analysis using VCCT

The Virtual Crack Closure Technique (VCCT) in conjunction with finite element analysis is widely used for the determination of Strain Energy Release Rate in composite materials and the load required to cause delamination propagation [7]. The prime assumption of VCCT is that the energy released when the crack is extended by a length Δa is equal to the energy required to close the crack over the same length Δa.

To determine SERR for each fracture mode, the VCCT utilizes nodal forces at the delamination front and displacements behind the delamination front if the assumption of self similar crack growth is justified [8]. Fig.1 shows modelling near a delamination tip in two-dimensional finite element analysis modeled with 4-noded quadrilateral elements and the corresponding equation for SERR calculation using VCCT is given as (1) and (2) which is available via [9].

$$G_I = \frac{1}{2\Delta a} Y_i \ \Delta v_{k,j} \qquad (1)$$

$$G_{II} = \frac{1}{2\Delta a} X_i \ \Delta u_{k,j} \qquad (2)$$

where $\Delta \mathrm{v}_{\mathrm{k,j}} = (\mathrm{v_k} - \mathrm{v_j})$ and $\Delta \mathrm{u}_{\mathrm{k,j}} = (\mathrm{u_k} - \mathrm{u_j})$

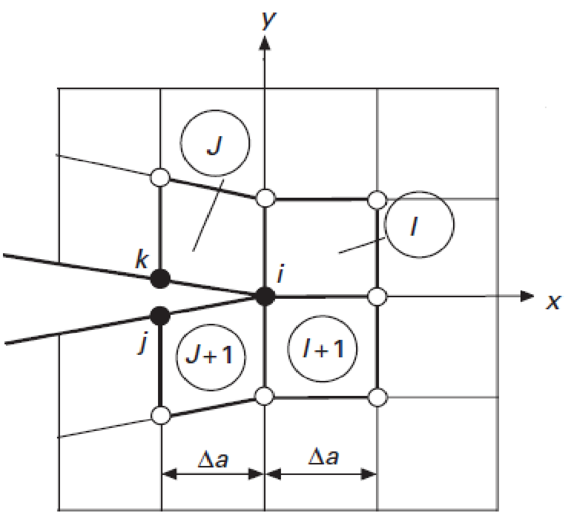

Figure 1: VCCT Scheme for 4-Noded Quadrilateral Elements in Two-Dimensional Analysis [9]

G_{III} = 0 for two dimensional cases. For geometric nonlinear analysis in which large deformations may occur, both displacements and forces evaluated in the global coordinate system have to be changed into a local coordinate system which originates at the crack tip [10]. The commercial finite element software which currently handle such techniques are ABAQUS, MSC Nastran, MSC Marc, ANSYS etc.,.

4.2 Strain energy release rate analysis using Classical Methods

At laminate level analytical solution is available to examine the stability of panel under delamination. For mode I Double Cantilever Beam (DCB) is used and for Mode II End Notch Flexure (ENF) specimen is used. In real composite structures, delamination involves a mixed mode failure phenomena consisting of all three fracture modes but Mode I is the most critical fracture mode [11].

Analytical solutions for SERR and compliance, C (inverse of stiffness) of orthotropic materials for Mode I fracture have been discussed and are given in Table 1.

Table 1: Analytical Solutions for SERR and Compliance of Orthotropic Materials for Mode I Fracture

Theory	**Mode I Strain Energy Release Rate**	**Compliance**
Classical beam theory [6]	$G_I = \frac{12\,P^2\,a^2}{E_{11}\,B^2\,h^3}$	$C = \frac{8\ a^3}{B\,h^3 E_{11}}$
Transverse shear deformation theory [12]	$G_I = \frac{12\,P^2\,a^2}{E_{11}\,B^2\,h^3}\left[1 + \frac{1}{10}\frac{E_{11}}{G_{13}}\left(\frac{h}{a}\right)^2\right]$	$C = \frac{8\,P\,a^3}{E_{11}\,B\,h^3}\left[1 + \frac{3}{10}\frac{E_{11}}{G_{13}}\left(\frac{h}{a}\right)^2\right]$
Modified beam theory [13]	$G_I = \frac{12\,P^2\,(a + Xh)^2}{E_{11}\,B^2\,h^3}$ where, $X = \left(\frac{E_{11}}{11G_{12}}\right)^{\frac{1}{2}}\left[3 - 2\left(\frac{\tau}{1+\tau}\right)^2\right]^{\frac{1}{2}}$ $\tau = \frac{1.18\,(E_{11}\,E_{22})^{\frac{1}{2}}}{G_{12}}$	$C = \frac{8\ (a + Xh)^3}{B\,h^3 E_{11}}$

5. NUMERICAL INVESTIGATIONS

5.1 Panel description

A Double Cantilever Beam (DCB) specimen which is made of stitch bonded unidirectional E-glass polyester is considered for the present study. The unidirectional marine E-glass polyester has a Critical Strain Energy Release Rate of 100 J/m^2 [14]. The panel is 1-m long (L), 0.500 m wide (B), 8mm thick (2h) and with an initial crack length of 100mm (a). The panel has 20 plies each having 0.4mm thick. Schematic representation of the DCB panel is shown in Fig. 2 and the constituent material properties are given in Table 2.

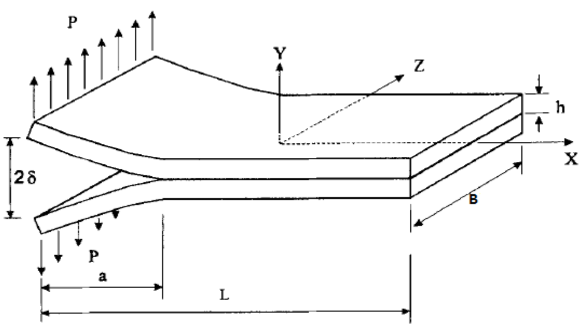

Figure 2: Schematic Representation of the DCB

Table 2: Material Properties of Stitch-Bonded Unidirectional E-glass polyester [15]

Elastic modulus		**Poisson's ratio**		**Shear modulus**	
Notation	Value (GPa)	Notation	Value	Notation	Value (GPa)
E_x	26.7	ν_{xy}	0.29	G_{xy}	3.5
E_y	8.4	ν_{yz}	0.29	G_{yz}	2.8
E_z	9.6	ν_{xz}	0.29	G_{xz}	2.8

5.2 Analysis of DCB

5.2.1 Finite Element Analysis

A simulation of DCB has been made in ANSYS 14.5. The Finite Element model of DCB consists of three zones viz., the upper beam, lower beam and a layer of interface zone. The upper beam and the lower beam have been modelled using 4-noded quadrilateral plane strain element PLANE182. The crack growth generally occurs along the interface between the layers in composite structures. This is because in composite structures, the fracture toughness of the interface between layers is much less than the fracture toughness of layers [8]. This crack path is defined via 4-noded interface element INTER202.

All elements have been modeled with 1mm size along the length. One end of the DCB is fully constrained and the displacement loading is given at the other end. To find the SERR, VCCT is performed. A geometric nonlinear analysis is carried out to plot load-displacement curve and to find out the fracture load which causes delamination propagation. The deformed DCB model is shown in Fig. 3 and the contour plot of maximum principal stress is shown in Fig. 4.

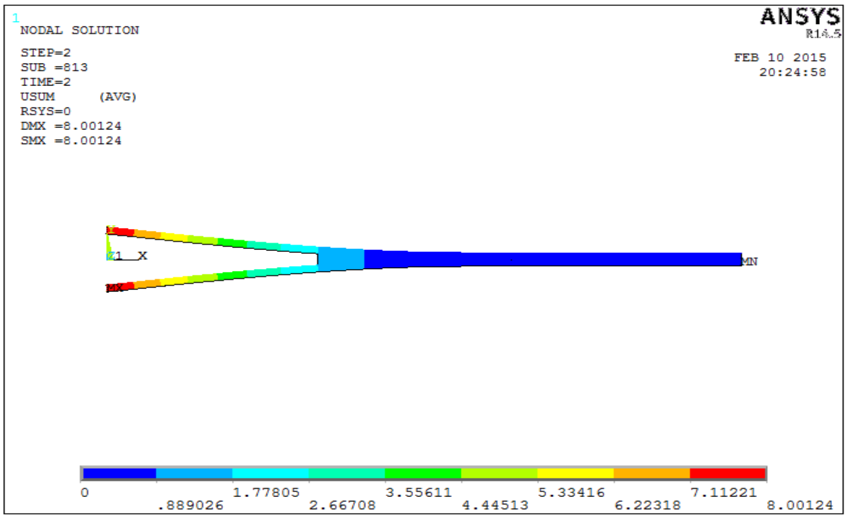

Figure 3: Deformed DCB Model

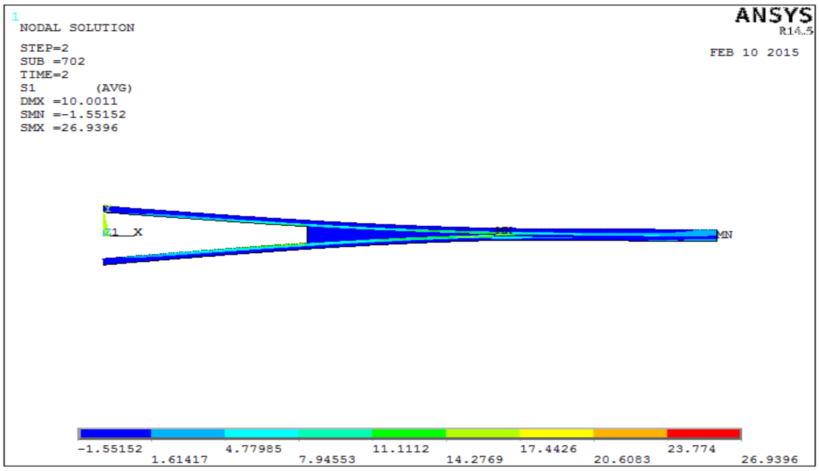

Figure 4: Contour Plot of Maximum Principal Stress

The load-displacement curve for DCB obtained from ANSYS is shown in Fig. 5. The load–displacement curve consists of two parts. Initial part is linear and there is no crack extension. The final part is nonlinear which indicates a crack growth. The onset of nonlinear curve gives fracture load for the delaminated panel. The obtained fracture load for mode I loading is 579.5N.

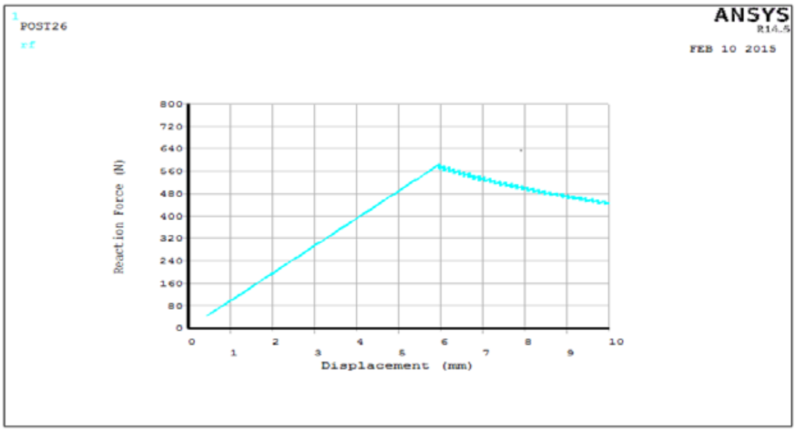

Figure 5: Load –Displacement Plot of DCB Using FEM

5.2.2 Classical methods

Fracture load that initiate crack growth on flat rectangular laminate with an embedded delamination has been determined analytically for mode I type loading. A MATLAB code has been generated to find fracture load and to plot load–displacement curve using various classical equations which is given in Table 1. Fig. 6 shows the comparison of load–displacement plot obtained from MATLAB using Classical beam theory and Modified beam theory.

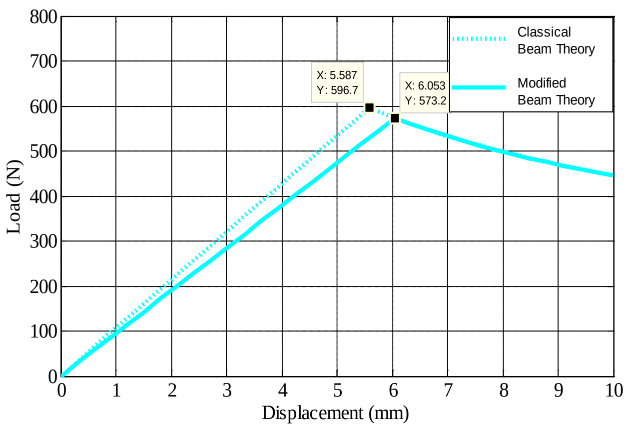

Figure 6: Comparison of Load –Displacement Plot of DCB Using Classical Methods

5.3 Results and discussion

The evaluated fracture loads and corresponding critical displacements are given in Table 3.

Table 3: Fracture Load and Vertical Deflection at the Loading Point

Methods	**Fracture load (N)**	**Total vertical deflection at the loading point (mm)**
Classical Beam Theory	596.7	5.6
Transverse Shear Deformation Theory	596.2	5.6
Modified Beam Theory	573.2	6.1
VCCT using ANSYS	579.5	6.0

The fracture load predicted by FEA is around 3% less than that for Classical Beam Theory and the Transverse Shear Deformation Theory and 1.1% than that of the Modified Beam Theory. This variation may due to the assumption that the delamination front is clamped. In actual case, rotation in delamination front may occur and has been accounted in VCCT.

6. CONCLUSIONS

Various methods to determine the fracture load in marine composite structural components using Strain Energy Release Rate have been addressed. Numerical methods based on fracture mechanics concept have been proved to be reliable for the prediction of delamination crack in composites. Fracture load of a laminated rectangular panel with an embedded delamination has been analysed using Virtual Crack Closure Technique (VCCT) in conjunction with Finite Element Analysis (FEA). A MATLAB code based on classical equations has been generated to find the fracture load and to plot load-displacement curve. A good match of fracture load between the VCCT results based on FEA and classical results has been established. Based on the fracture load prediction subsequent loading on the component can be monitored and restricted till repair or retrofitting if necessary.

7. REFERENCES

[1] E. Greene, Marine Composites 2nd Edition, Eric Greene Associates, Inc. USA, 1999.

[2] M. Nikbakht, N. Choupani and S.R. Hosseini, "2D and 3D interlaminar fracture assessment under mixed-mode loading conditions", Materials Science and Engineering A 516, pp 162–168, March 2009.

[3] F L Matthews and G A O Davies, "Finite Element Modelling Of Composite Materials And Structures", Woodhead Publishing Limited, Abington Hall, Abington.

[4] C S Smith, "Design of Marine Structure In Composite Materials", Elsevier Applied Science, London And New York.

[5] H.C.H Li, F. Dharmawan, I. Herszberg and S. John, "Fracture behaviour of composite maritime T-joints", Composite Structures vol: 75, pp 339–350, June 2006.

[6] P Kumar, Elements Of Fracture Mechanics, Tata McGraw Hill Education Private Limited, New Delhi.

[7] R Krueger, "Virtual crack closure technique: History, approach and applications", Appl Mech Rev vol 57, no 2, March 2004.

[8] G Wimmer, C. Schuecker and H. E. Pettermann (2009) "Numerical simulation of delamination in laminated composite components–A combination of a strength criterion and fracture mechanics", Composites: Part B. **40**.158–165.

[9] S.Sridharan, Delamination behaviour of composites, Woodhead Publishing Limited, Cambridge England, 2008.

[10] R Krueger, "Computational Fracture Mechanics For Composites State of the Art And Challenges", Presented at the NAFEMS Nordic Seminar: Prediction and Modelling of Failure Using FEA, Copenhagen/Roskilde, Denmark, June 2006.

[11] M. H Heydari, N. Choupani and M. Shameli, "Experimental and Numerical Investigation of Mixed-Mode Interlaminar Fracture of Carbon-Polyester Laminated Woven Composite by Using Arcan Set-up", Applied Composite Materials 18:499–511, 2011.

[12] Klaus Friedrich, "Application Of Fracture Mechanics To Composite Materials", Elsevier Science Publishing Company INC, New York.

[13] J G Williams, S Hashemi and A J Kinloch, " The Analysis Of Interlaminar Fracture In Unidirectional Fibre-Polymer Composites", Proceedings Of Royel Society, London, pp 173-190.

[14] P Davies , "Fracture of marine composites in Fracture of Composite"s, ed. Armanios E A, Transtec Publications, Switzerland, 583–596, 1996.

[15] Det Norske Veritas (DNV), offshore standard DNV-OS-C501, composite components October2003.

[16] P A Agrawal and Y. Ben Jar "Analysis of specimen thickness effect on interlaminar fracture toughness of fibre composites using finite element models", Composites Science and Technology 63, pp 1393–1402, January 2003.