PROGRESSIVE MATRIX CRACKING INDUCED DELAMINATION: A COMPARISON OF FINITE ELEMENT MODELLING TECHNIQUES

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Abstract

One of the major failure modes in composite laminates is interlaminar delamination which can initiate from stress concentration at transverse matrix crack tips. This failure interaction is referred to as Matrix Cracking Induced Delamination (MCID). MCID in $[90_4/0_7/90_4]$ HTA/6376 carbon fibre reinforced cross-ply laminates subjected to four-point bending is numerically investigated. Failure interaction is quantitatively studied in a Finite Element (FE) framework by means of two different modelling techniques in the standard FE analysis software Abaqus. One modelling technique includes user-defined Advanced Phantom Node Method (APNM) elements which allow for arbitrary fracture modelling while preserving elemental locality. Another model exclusively uses built-in functions and pre-inserted matrix cracks in Abaqus. Numerical results are compared to experimentally obtained fracture measures. Both models are able to predict the overall load response, matrix crack density and progressive MCID growth in the interface with reasonable accuracy. However, APNM does not require *a priori* knowledge about location of matrix cracks and a number of assumptions and simplifications in the advanced model reduces runtime analysis by up to 50%. It is concluded that APNM is a promising effective numerical tool which is applicable to standard FE software packages.

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1. Introduction

Failure in composite laminates occurs in their constituents: fibre, matrix and interface. As one of the major failure modes, interlaminar delamination results in stiffness and strength reduction which may eventually lead to structural collapse. Delamination can originate from interlaminar stress concentration at interfacial voids or at free edges and transverse matrix crack tips. The latter is referred to as Matrix Cracking Induced Delamination (MCID).

Progressive in-situ failure inspection of MCID is challenging. Mortell et al. [1] successfully quantify MCID in $[90_n/0_7/90_n]_s$ $n = 2, 3, 4$ Carbon Fibre Reinforced Polymer (CFRP) composite laminates under flexural loading in three- and four-point bending tests respectively.

The Phantom Node Method (PNM) is a computational enrichment method to avoid *a priori* knowledge about crack location and propagation. It is based on the ideas of Hansbo and Hansbo [2]. A crack is modelled by superposition of two independent continuous elements with standard shape functions. It therefore requires additional (phantom) nodes. PNM is applied to a wide range of problems including three dimensional applications [3], dynamic crack propagation [4] or multiscale failure processes [5].
Chen et al. [6] developed an extended PNM formulation to represent MCID realistically by allowing the cohesive interface at transverse matrix crack tips to break. Cohesive transverse matrix cracks are usually pre-inserted at various locations. Coupling PNM elements to breakable cohesive interfaces offers a mesh independent numerical tool for MCID prediction without *a priori* knowledge about crack location and propagation. This extension to PNM has only been applied to uniaxial tensile tests on cross-ply laminates $[0_m/90_n]_s$ [6, 7]. In regards to CFRP composite laminates, experimental studies conclude that transverse cracks only occur in thick-ply laminates whereas thinner samples fail due to free edge delamination [8–10]. More complex loading cases are required to numerically simulate real applications. Advanced PNM (APNM) [11] accounts for geometrical and material nonlinearities by incorporating the total Lagrangian formulation for large displacements and the cohesive concept at crack surfaces respectively. Hence, APNM can be applied to CFRP composite laminates under flexural loading to numerically predict MCID.

This paper compares two different modelling techniques to numerically predict MCID in CFRP composite laminates under four-point bending: the first model includes user-defined APNM elements which enable MCID simulation without *a priori* knowledge about crack location and propagation. Formulation and explanation of APNM are presented by the same authors in [11]. The second model contains pre-inserted transverse matrix cracks based on experimental observations and only uses built-in functions in the commercial FE software Abaqus.

2. Computational Models

A four-point bending test of $[90_4/0_7/90_4]$ HTA/6376 CFRP cross-ply laminates is investigated to quantitatively determine MCID. Numerical results are compared to experimental findings by Mortell et al. [1]. Each ply is 0.125 mm thick and 7 mm wide. Table 1 shows elastic properties to model orthotropic laminae on the mesolevel.
Fig. 2 illustrates the computational model. Semicircle steel pins with 8 mm diameter are used to model loading and support of the beam. Interlaminar interfaces are described by cohesive properties in Table 2. In the following, two different modelling approaches are considered.

Table 1. Elastic properties of unidirectional HTA/6376 composite ply [12].

E_1 (GPa)	$E_2 = E_3$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	thickness (mm)
140	10	5.2	3.9	0.3	0.5	0.125

Table 2. Intrinsic cohesive properties in HTA/6376 [13].

K (MPa)	N (MPa)	S (MPa)	G_{Ic} (kJ/m^2)	G_{IIc} (kJ/m^2)
125*	105	140	0.432	1.002*

* assumed value

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2.1. Advanced Phantom Node Method

In order to model MCID without *a priori* knowledge about matrix crack location, different user-defined elements in Fig. 1 are defined to incorporate breakable cohesive interfaces. Additional phantom nodes are used to model matrix cracking in 90° plies and induced delamination. When a simple maximum stress criterion is met, matrix cracks initiate in *PNM* elements and propagate through the ply thickness into the interlaminar interface. Elements across the interface are activated when adjacent *hybrid* elements are cracked. Unlike nodal constraints at the crack tip in the interface, this element type stabilises the numerical procedure by naturally incorporating nodes at crack tips. Nonlinear cohesive traction forces at transverse crack surfaces model smooth crack opening. A similar formulation is used to represent interlaminar cohesive elements by applying properties in Table 2. User-defined elements are implemented via Abaqus user subroutine UEL. Mixed-mode decohesion by Camanho et al. [14] is applied with B-K parameter $\eta = 1.75$ which is typically used for brittle epoxy resins. Cohesive interface elements are removed when the internal damage variable reaches a critical value $d_{\max} = 0.9$. The total Lagrangian formulation enables element types in Fig. 1 to account for large strains and rotations.

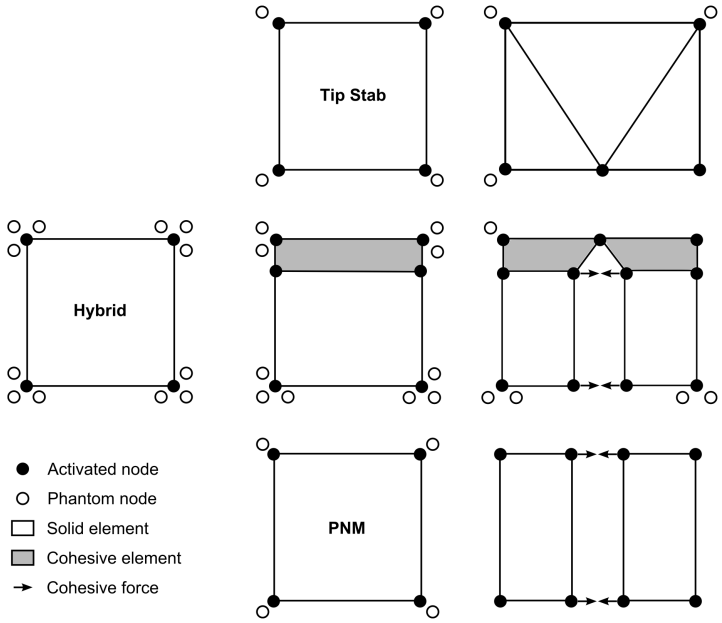

Figure 1. Illustration of APNM implementation.

The displacement-controlled four-point bending model in Fig. 2 contains standard solid quadrilateral plain stress CPS4 elements as well as user-defined APNM elements in lower 90_4 plies as mentioned above. *Tip_Stab* formulation in adjacent elements in lower 0_7 plies increase numerical stability incorporating crack tips penetrating the interface. Abaqus built-in tangential frictionless '*hard*' contact definition is applied to the surface between pin and beam in normal direction. Geometrically nonlinear deformation (*NLGEOM*) is activated in CPS4 elements. The model contains 6606 nodes and 5864 elements.

Model Assumptions

Statistical Strength Distribution

A maximum transverse tensile strength criterion initiates transverse matrix cracking in lower 90_4 plies. First transverse cracks are experimentally observed at $N_{\text{tr}} = 62$ MPa [1]. The initially uniform stress field

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in lower 90_4 plies requires a statistical Weibull strength distribution which also accounts for material variability [15].

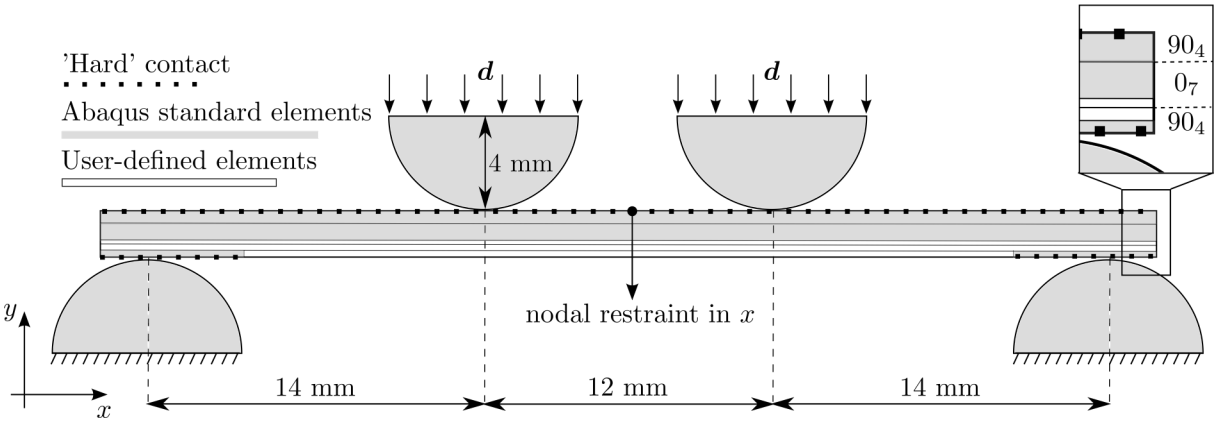

Figure 2. Illustration of computational four-point bending model using standard and user-defined elements in Abaqus.

Crack Spacing Algorithm
In order to prevent initiation of multiple, non-physical damage within an uniform stress field in the vicinity of matrix cracks, an artificial minimum crack spacing of 1.8 mm is enforced. Crack spacing of about 2 mm is observed experimentally [1].

Traction-free Surface at Transverse Matrix Cracks
It is experimentally shown that delamination growth initiates after matrix crack saturation [1]. This numerical study is mainly focussed on progressive delamination. Hence a traction-free surface at transverse matrix cracks is applied to avoid numerical instability in a geometrically nonlinear model under complex loading.

Local Reinforcement of Cohesive Interface
High interface strength values of $N = 300$ N and $S = 400$ N in normal and tangential direction relative to the cohesive surface are applied in interface elements near the support rollers to prevent edge delamination which is justified by experimental observations.

2.2. Built-in Abaqus Model

A similar model to Fig. 2 is implemented in Abaqus by using pre-inserted transverse matrix cracks. User-defined elements are replaced by standard Abaqus elements (CPS4). Discretisation, boundary conditions, loading, contact definition as well as material and interface properties in Table 1 and 2 are identical to the previously described APNM model. In experimental observations [1], 15 matrix cracks develop along the length in a periodic array starting from the centre of the beam [1]. Therefore, the same number of matrix cracks in Abaqus are equidistantly inserted every 2 mm. In contrast to the APNM model, transverse cracks are pre-inserted so that they penetrate the interlaminar interface and split the cohesive element in two. COH2D4 elements model the interlaminar interface with activated element deletion at maximum degradation $d_{\max} = 0.9$. The initial transverse strength is set to $N_{\text{tr}} = 62$ MPa. In order to achieve progressive matrix crack initiation starting from the centre of the beam, N_{tr} is manually increased up to approximately $N = 105$ MPa. To be able to study the effect of traction forces acting on transverse crack surfaces, a mixed-mode cohesive formulation with initial stiffness $K = 150$ MPa, fracture energies $G_{Ic} = 0.26$ kJ/m^2, $G_{IIc} = 1.002$ kJ/m^2 and B-K parameter $\eta = 1.75$ is applied to

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pre-inserted matrix cracks.

3. Results

3.1. Load-Displacement Analysis

Fig. 3 (a) shows the predicted load due to the prescribed displacement at the loading pins. The numerical prediction by APNM and Abaqus initially coincides with the experimentally measured load [1]. With onset of matrix cracking at around 100 N, the load response is underestimated by the two numerical models. At time of experimental failure, the models underestimate the load response by about 15%. In Abaqus, softening due to matrix cracking initially occurs to a higher extent compared to APNM. Delamination initiates approximately at 260 N. With delamination onset, APNM predicts a slightly stiffer load response than Abaqus models. At maximum displacement of APNM, the difference between the two numerical models is about 3.5%. Differences in the two numerical models in regards to matrix cracking onset can be explained by the two modelling techniques for matrix crack insertion in Section 2.1 and 2.2. Statistical transverse strength distribution in APNM differs from the manually implemented strength distribution which is required in the built-in Abaqus model, resulting in shifted matrix crack initiation. Differences due to delamination growth and resulting stiffness reduction will be discussed in Section 3.3. Overall, the result shows that the chosen material parameters and nonlinear FEM implementation capture the main damage behaviour of the composite laminate beam under flexural loading.

3.2. Crack Density

In Mortell's experiment [1], matrix crack density and MCID are accurately determined within the span length. Therefore, numerical results are compared to failure in the vicinity of this area. In Fig. 3 (b), prediction of matrix crack density around the span length is compared to experimental findings. In APNM models, crack count increases when the tensile strength criterion in bottom *PNM* elements is activated. In built-in Abaqus models, an internal variable CSDMG at transverse cracks characterises damage along the thickness. When CSDMG reaches the threshold of one, the matrix crack surface is considered to break and crack count increases. Five matrix cracks within the span length are observed numerically and experimentally. The progression of crack density in both simulations is covered well. The overall prediction is slightly delayed which can be explained by a softer load response in Fig. 3 (a). A comparison between built-in Abaqus and APNM shows that the application of traction forces at matrix cracks slightly increases accuracy in density prediction. Even outside the span length, the total number of matrix cracks in APNM agrees well with experimental data. It predicts 16 cracks compared to 15 experimentally observed transverse cracks along the entire length of the beam.

3.3. Matrix Cracking Induced Delamination

Progressive delamination growth within the span length is evaluated by a Local Delamination Ratio (LDR) parameter which relates length of a delamination e to thickness h of the 90_4 plies,

$$\mathrm{LDR} = \frac{e}{h}. \tag{1}$$

Delamination length is experimentally and numerically measured from each transverse matrix crack in the span length. In APNM models, the interface is considered to break when the internal damage variable d reaches a threshold of $d_{\max} = 0.9$. The equivalent damage variable in Abaqus is SDEG (scalar Stiffness DEGradation).
Fig. 4 shows that delamination onset in the span length is predicted accurately by both models. Furthermore, progression of delamination initiated from the five transverse cracks agrees well with

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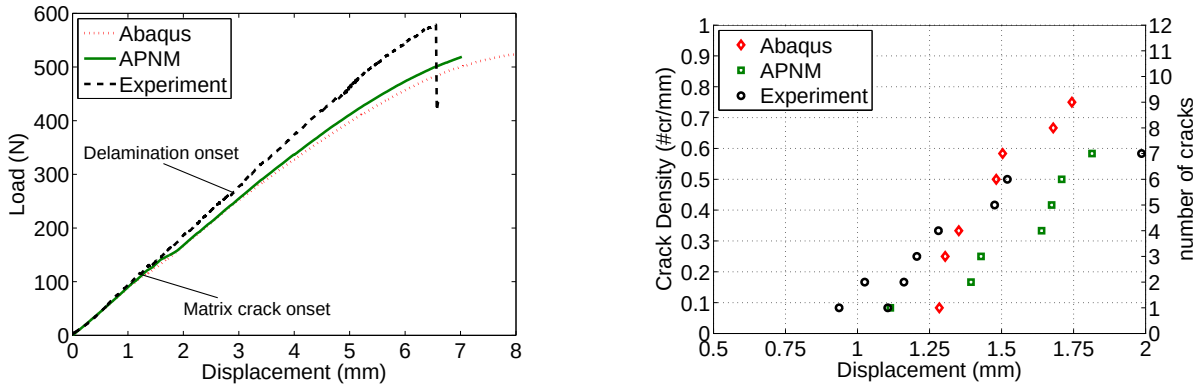

(a) Load-Displacement at loading pins.

(b) Crack density analysis.

Figure 3. Experimental results of four point bending test from Mortell [1].

experiments. Only three LDR curves are shown for the built-in Abaqus model as delamination growth is symmetric with respect to the central crack. Abaqus models overestimate LDR to a higher extent of about 12.33% compared to APNM results. This can be explained by cohesive traction forces acting on matrix crack surfaces. Until their deactivation at complete failure, application of traction forces lead to stress concentration around crack tips and hence higher stresses in the interface. Traction-free surfaces are assumed in APNM. The higher LDR value in built-in Abaqus models also explains the slightly softer load response in Fig. 3 (a). The difference of the the two numerical models was found to be 3.5% in Section 3.1. Taking into account experimental uncertainty on delamination length measurements e, the

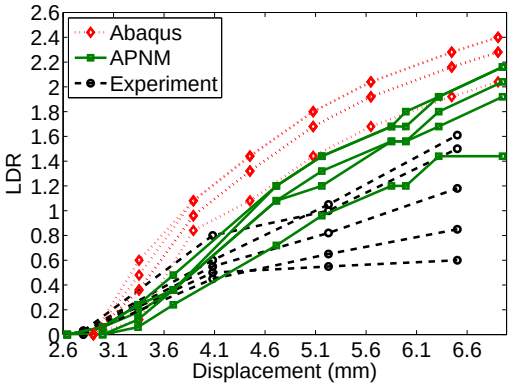

Figure 4. Discrete analysis of Local Delamination Ratio (LDR) within the span length. APNM and Abaqus compared to experimental results [1].

overall response in terms of initiation and evolution of numerically predicted LDR at transverse crack tips within the span length is considered to be very good.

4. Discussion

Both numerical models yield softer load-displacement prediction compared to experimental findings. On the one hand, this effect can be explained by a coarse discretisation through the thickness of the bottom composite plies. Only two elements are used to represent the lower 90_4 plies. More importantly, the computational models neglect stiffening effects such as matrix bonding at transverse cracks and fibre bridging in the interface which are present in experimental observations [1]. Fig. 5 shows experimental

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observation of these stiffening effects.

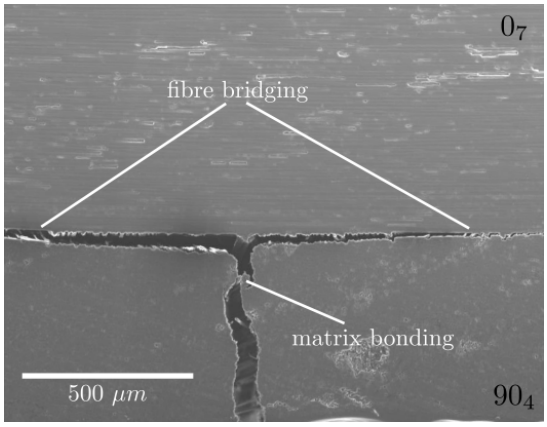

Figure 5. Failure investigation using SEM in Mortell's experiments for a $[90_4/0_7/90_4]$ composite laminate under three-point bending. Symmetric delamination growth from matrix crack tip with visible matrix bonding and fibre bridging opposite the central loading pin. Similar failure was identified in four-point bending tests.

Average crack spacing in APNM models is found to be over 1.9 mm which justifies the use of an enforced minimum distance of 1.8 mm in the crack spacing algorithm. Note that crack spacing in the built-in Abaqus model is about 2 mm. The dissimilar matrix crack distance in the two models results in a different stress distribution and hence in different delamination growth as seen in Fig. 4.
The effect of applied traction forces at matrix crack surfaces can be seen in crack density analysis Fig. 3 (b) and MCID prediction in Fig. 4. Traction forces slightly improve progressive matrix crack initiation whereas higher LDR values due to stress concentrations are observed in MCID analyses. Compared to the built-in Abaqus model, APNM does not require *a priori* knowledge about matrix crack location and propagation. In addition to this major advantage, APNM outperforms Abaqus models in regards to computation time and prediction accuracy. APNM seems to be much more effective with a runtime analysis of about 75 min on a conventional machine. Computation time is 50% less than Abaqus analyses with similar or even better accuracy in predicting load response and MCID. A traction-free surface at matrix cracks helps to improve numerical stability and leads to significantly reduced computation time.

5. Conclusion

A novel computational strategy to model MCID in composite laminates was presented and compared to a numerical model in standard FE software Abaqus only using built-in functions. Considering experimental uncertainty, the Advanced Phantom Node Method (APNM) is able to accurately and effectively predict matrix crack density and MCID in CFRP composites. In particular, the quantitative computational analysis of progressive MCID is the first comparison between experimentally measured and numerically predicted delamination growth initiated by matrix cracking. Built-in Abaqus models yield similar results. However, modelling of pre-inserted transverse matrix cracks is required and runtime analysis is significantly increased by up to 50%. It is concluded that application of nonlinear cohesive traction surfaces at matrix cracks in Abaqus models makes the computation numerically challenging and expensive. APNM models using traction-free surfaces at transverse matrix cracks model MCID more effectively without loss of accuracy. Overall, APNM is a promising effective numerical tool which is applicable to standard FEM software packages.

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References

[1] D.J. Mortell, D.A. Tanner, and C.T. McCarthy. In-situ sem study of transverse cracking and delamination in laminated composite materials. *Composites Science and Technology*, 105:118–126, 2014.

[2] A. Turon, P.P. Camanho, J. Costa, and C.G. Dávila. A damage model for the simulation of delamination in advanced composites under variable-mode loading. *Mechanics of Materials*, 38(11):1072–1089, 2006.

[3] J. Mergheim, E. Kuhl, and P. Steinmann. Towards the algorithmic treatment of 3d strong discontinuities. *Communications in Numerical Methods in Engineering*, 23(2):97–108, 2007.

[4] J.-H. Song, P.M.A. Areias, and T. Belytschko. A method for dynamic crack and shear band propagation with phantom nodes. *International Journal for Numerical Methods in Engineering*, 67(6):868–893, 2006.

[5] J. Mergheim. A variational multiscale method to model crack propagation at finite strains. *International Journal for Numerical Methods in Engineering*, 80(3):269–289, 2009.

[6] B.Y. Chen, S.T. Pinho, N.V. De Carvalho, P.M. Baiz, and T.E. Tay. A floating node method for the modelling of discontinuities in composites. *Engineering Fracture Mechanics*, 127:104–134, 2014.

[7] J. Reiner, M. Veidt, M. Dargusch, and L. Gross. A computational investigation of failure modes in fibre metal laminates. *8th Australasian Congress on Applied Mechanics, ACAM 2014, as Part of Engineers Australia Convention 2014*, pages 112–121, 2014.

[8] G. Guillamet, A. Turon, J. Costa, J. Renart, P. Linde, and J.A. Mayugo. Damage occurrence at edges of non-crimp-fabric thin-ply laminates under off-axis uniaxial loading. *Composites Science and Technology*, 98:44–50, 2014.

[9] M. Jalalvand, M.R. Wisnom, H. Hosseini-Toudeshky, and B. Mohammadi. Experimental and numerical study of oblique transverse cracking in cross-ply laminates under tension. *Composites Part A: Applied Science and Manufacturing*, 67:140–148, 2015.

[10] T.A. Sebaey, J. Costa, P. Maimi, Y. Batista, N. Blanco, and J.A. Mayugo. Measurement of the in situ transverse tensile strength of composite plies by means of the real time monitoring of microcracking. *Composites Part B: Engineering*, 65:40–46, 2014.

[11] J. Reiner, M. Veidt, M. Dargusch, and L. Gross. A progressive analysis of matrix cracking induced delamination in composite laminates using an advanced phantom node method. *Journal of Composite Materials (submitted)*, 2016.

[12] M.A. McCarthy and C.T. McCarthy. Finite element analysis of effects of clearance on single shear composite bolted joints. *Plastics, Rubber and Composites*, 32(2):65–70, 2003.

[13] Hexcel Corporation. *HexPly 6376 Product Data*, 3 2007.

[14] P.P. Camanho, C.G. Dávila, and M.F. De Moura. Numerical simulation of mixed-mode progressive delamination in composite materials. *Journal of Composite Materials*, 37(16):1415–1438, 2003.

[15] E.V. Iarve, M.R. Gurvich, D.H. Mollenhauer, C.A. Rose, and C.G. Davila. Mesh-independent matrix cracking and delamination modeling in laminated composites. *International Journal for Numerical Methods in Engineering*, 2011.

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