EFFICIENT FINITE ELEMENT MODELLING OF Z-PIN REINFORCED COMPOSITES USING THE BINARY MODEL

Matthew Blacklock, Mathew Joosten, Adham Zeineddine, Adrian Mouritz

Sir Lawrence Wackett Aerospace Research Centre, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71, Bundoora, Victoria, 3087, Australia.
Email: matthew.blacklock@rmit.edu.au, web page: http://www.rmit.edu.au

Keywords: Z-Pins, Composite Laminates, Mode I Delamination, Finite Element Analysis

ABSTRACT

Z-Pins are employed in reinforcing pre-preg composite laminates in the through-thickness direction. Z-pins provide a resistance to crack opening in mode I through a tri-linear process involving elastic stretching, interface debonding and frictional pullout. The effective crack closure force provided by z-pins subsequently improves the delamination resistance of the material. The major challenges associated with the modelling of z-pin reinforced laminates are attributed to the complexity of the material structure, where relatively small diameter pins are inserted into an orthogonal laminate. Meshing of each z-pin and its interaction with the laminate requires an inordinate number of finite elements and detailed, highly localised material properties.

This study investigates the feasibility of the computationally efficient binary model for textile composites in modelling z-pin reinforced composite laminates. In the model, each z-pin is represented by a single one-dimensional truss element that is embedded within the composite laminate. Each truss is given the material properties associated with the global traction response of a z-pin inserted in a laminate. This simplification results in a reduction in the number of degrees of freedom by potentially orders of magnitude. Initial results obtained for double cantilever beam test specimens, for a range of volume fraction of z-pins, demonstrate the ability of the model to rapidly generate z-pin reinforced laminates with a variety of pin sizes, volume fractions, locations and orientations.

1 INTRODUCTION

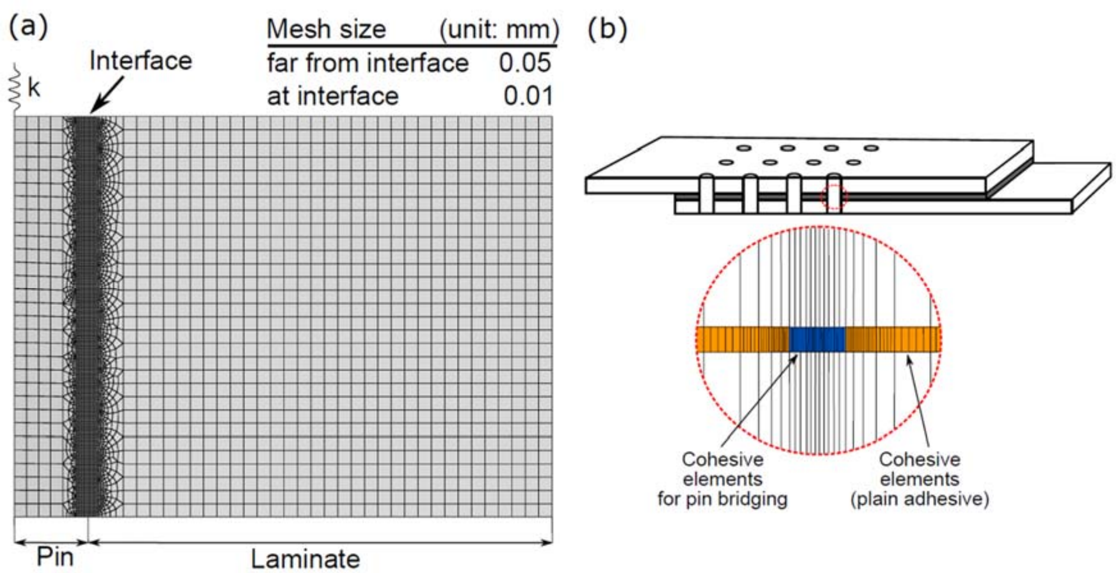

Figure 1. (a) Example of a finite element model where the z-pin, laminate and interface are modelled discretely; and (b) example of a finite element model where the z-pin/laminate interaction is homogenised into the cohesive element properties [1].

Z-pin reinforced composite laminates are known to have improved mode I delamination toughness, through-thickness mechanical properties and impact damage tolerance over their unreinforced counterparts [2]. The process of z-pinning involves the insertion of small diameter rods through the thickness of a polymer composite laminate using an Ultrasonically Assisted Z-Fibre™ (UAZ) technique [3-4]. The pins are usually made of a single carbon fibre tow or are thin metallic rods. Z-pins are an effective and simple method to improve through-thickness properties and may be applied in selective areas to target performance at critical regions or as a wide area solution.

Current modelling techniques for z-pinned laminates usually take one of two approaches: the first involves the discrete modelling of a pin using three-dimensional (3D) solid elements [1]. In this approach, the pin, surrounding laminate and the pin-laminate interface must be explicitly modelled. A large number of finite elements are required to mesh this system (e.g. Figure 1a). This approach has the benefit of accuracy, however, the modelling of large-scale structures involving any more than a handful of pins is impractical due to the sheer number of finite elements required. The second approach seeks to take advantage of the fact that z-pins are usually placed at locations where there is a high probability of a crack forming. Such models homogenise the pin-laminate interaction and modify the material properties of the cohesive elements situated along the crack path [1] (e.g. Figure 1b). This approach is computationally efficient, however, the cohesive law must be modified each time the geometry of the structure, pin configuration or material changes. Additionally, a serious limitation exists in that the location of a single crack path must be known *a priori*.

The *Binary Model* (also known as the *embedded element* technique) is a computationally efficient finite element approach originally used to model 3D woven textile composites [5]. In the *Binary Model*, each woven fibre tow is represented as a one-dimensional (1D) truss element in 3D space and is given the axial properties of the fibre tow. These truss elements are then embedded into a solid 3D effective medium that represents all other material properties and has the physical volume of the structure (Figure 2). The response of the host elements constrains the translational degrees of freedom of the embedded trusses through a series of multiple-point constraints. By representing the complex weave architecture of a 3D woven composite through a series of trusses, a high degree of computationally efficiency is possible.

Here, a method is presented to allow discrete modelling of each individual z-pin in a laminate using the *Binary Model*. Each pin will be represented by a single truss element and embedded within the 3D laminate. This approach offers the unique advantage of greater computationally efficiency and superior flexibility over existing models. A parameter study, to demonstrate the flexibility of the model, will be conducted to vary the aerial density of z-pins within a double cantilever beam (DCB) test setup. The mode I interlaminar fracture toughness of pinned and unpinned laminates will be predicted and compared.

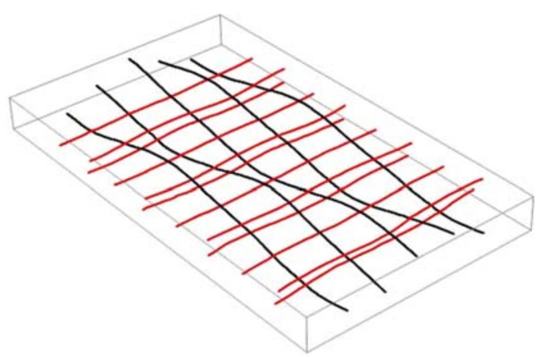

Figure 2. Binary model representation of a 3D woven composite. The warp (black) and weft (red) tows are represented as 1D truss elements and are embedded within a 3D effective medium representing the material volume.

2 Z-PIN MODEL SETUP

2.1 Double Cantilever Beam Setup

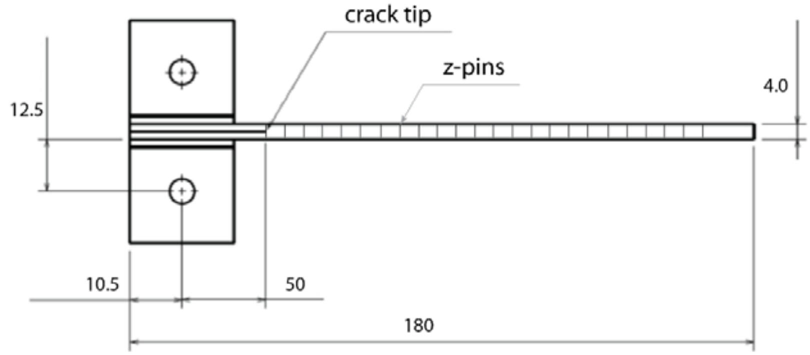

Figure 3. DCB geometry (all units in mm).

z-pin content	Pin length (mm)	Pin diameter (mm)	Pin spacing/DCB width (mm)
unpinned	-	-	3.5
0.5%	4.0	0.28	3.5
2.0%	4.0	0.28	2.0
4.0%	4.0	0.28	1.0

Table 1: Geometry and spacing of z-pins.

E_{11}^{C}	E_{22}^{C}	E_{33}^{C}	υ_{12}^{C}	υ_{13}^{C}	υ_{23}^{C}	G_{12}^{C}	G_{13}^{C}	G_{23}^{C}
MPa	*MPa*	*MPa*	-	-	-	*MPa*	*MPa*	*MPa*
120,000	7,500	7,500	0.32	0.32	0.33	3,900	3,900	2,520
S_{11}	S_{22}	S_{33}	S_{12}	S_{13}	S_{23}	G_{IC}	G_{IIC}	G_{IIC}
MPa	*MPa*	*MPa*	*MPa*	*MPa*	*MPa*	kJ/m^2	kJ/m^2	kJ/m^2
1,700	40	40	78	78	40	1.0	1.6	1.6

Table 2: Input material properties for the DCB [7].

A finite element model of a standard DCB setup (Figure 3) was created in *ABAQUS* [6]. The width of the DCB for each pinned case varied based upon the pin spacing and is given in Table 1. Each beam was assumed to be transversely isotropic and meshed with solid 3D elements with incompatible modes (C3D8I). An element length of 1mm was chosen for all models. A layer of cohesive elements (COH3D8) was placed along the centre of the two beams. For the cohesive law, damage initiation was controlled by a maximum nominal stress criterion:

$$max\left\{\frac{\langle\sigma_{22}\rangle}{S_{22}},\frac{\sigma_{12}}{S_{12}},\frac{\sigma_{13}}{S_{13}}\right\} \tag{1}$$

where S denotes the material strengths in the normal (22) and shear (12 and 13) directions. Damage evolution was governed by the fracture energy. The dependence of the fracture energy on the mode mix is defined based on a power law fracture criterion with the power, α = 1.78:

$$\left\{\frac{G_I}{G_{IC}}\right\}^{\alpha} + \left\{\frac{G_{II}}{G_{IIC}}\right\}^{\alpha} + \left\{\frac{G_{II}}{G_{IIC}}\right\}^{\alpha} = 1 \qquad (2)$$

where the quantities G_{IC} G_{IIC} and G_{IIIC} refer to the critical fracture energies in the mode I, II and III respectively. The elastic and cohesive input properties are given in Table 2. These properties represent a unidirectional T700-VTM pre-preg laminate [7].

The mode I interlaminar fracture toughness was determined by applying a monotonically increasing crack opening displacement at the load points, which were connected to the beams using a *Rigid Body* constraint. The force (P) and displacement (δ) at the load point were calculated along with the crack length (a). Using these data, the mode I interlaminar fracture toughness was calculated using [8]:

$$G_I = \frac{3P\delta}{2ba} \qquad (3)$$

where b is the width of the DCB. The load was scaled by ($25P$ / b) to allow a meaningful comparison between each DCB model.

2.2 Embedding Z-pins using the Binary Model

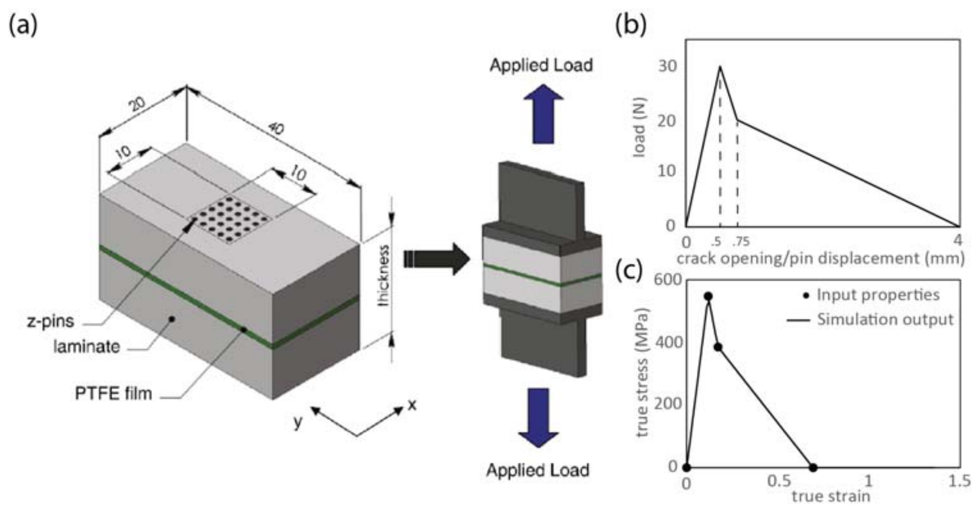

Figure 4. (a) Pin pullout test setup and load configuration [9]; (b) assumed z-pin traction separation law; and (c) input material properties for the z-pins and output from the FE simulation for the first pin in the 0.5% case.

Z-pins were generated as 1D truss elements and spaced along the beam according to the desired aerial density. Four different aerial densities were simulated: unpinned, 0.5%, 2%, and 4%. The geometry and spacing of the pins for each model is given in Table 1. Each pin was constrained by the DCB elements using the *Embedded Element* option within *ABAQUS.* This constrained the translational degrees of freedom of the truss elements relative to the response of the DCB.

The pins were assigned an elastic-plastic material model, which is based upon the traction separation law of the pins embedded within a laminate. In practice, the traction law is measured using a pin pullout test (Figure 4a). The resulting curve (assumed data in Figure 4b) will have three distinct parts: the first represents the elastic response of the pin-laminate interface, the second involves debonding of the interface, and the third is the result of interfacial friction. The force-displacement plot shown in Figure 4b was converted to true stress-true strain and input into the model as a tri-linear elastic-plastic response.

3 RESULTS AND DISCUSSION

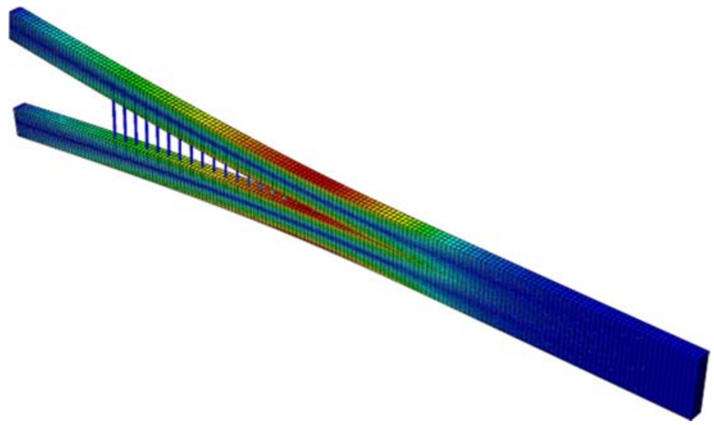

Figure 5. von Mises contour plot (legend not shown) for the 0.5% pinned case. For clarity the diameter of the pin elements has been increased.

A sanity check was performed to ensure the model was working correctly. The stress-strain response of the first pin for each model was output from the simulation and compared to the input properties. This is shown in Figure 4c.

A von Mises stress contour plot is shown in Figure 5 for the 0.5% pinned model. Here, the DCB mesh and pins can be seen.

The results of the four simulations are shown in Figures 6-8. Figure 6 presents the force-displacement curves as measured at the loading point. The pins essentially provide a closing force that resists the opening of the crack. Therefore, for the same beam displacement, more force is required for the pinned cases. The model predicts this effect well. Shown in Figure 7 is a plot of crack length against crack opening displacement at the loading point. As expected, the higher the percentage of pins, the slower the crack growth. Figure 8 presents the R-curve behaviour. The z-pin model clearly captures the increased toughening effect of the pins. An increase in mode I fracture toughness of a factor of approximately 10x is predicted for the 2% model in comparison with the unpinned case. For the 4% case, there is a huge increase in interlaminar fracture toughness and for the displacement applied in this study, a steady-state value was not reached.

Whilst the input properties of the pins are arbitrary, this study does demonstrate the power and flexibility of this model for predicting the mode I interlaminar fracture toughness of z-pinned laminates.

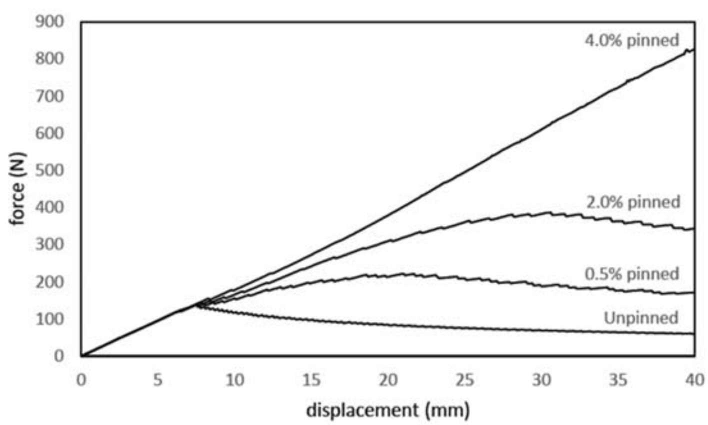

Figure 6. Load-displacement curves as measured at the loading point for the unpinned, 0.5%, 2% and 4% models.

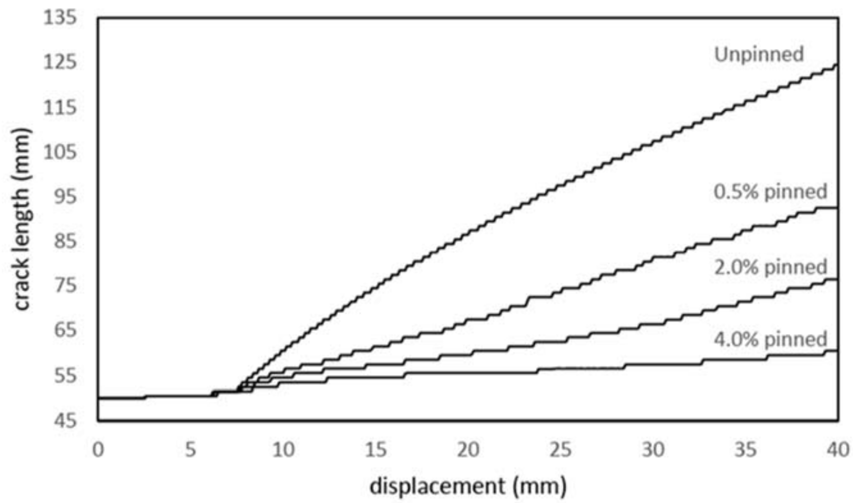

Figure 7. Crack length-crack opening displacement curves for the unpinned, 0.5%, 2% and 4% models.

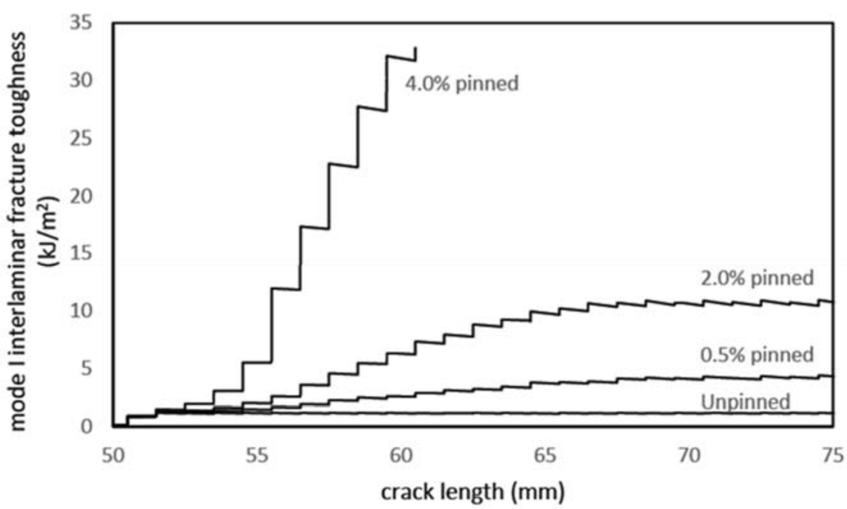

Figure 8. Mode I interlaminar fracture toughness vs crack length curves for the unpinned, 0.5%, 2% and 4% models.

4 CONCLUSIONS

A computationally efficient model for the prediction of mode I interlaminar fracture toughness of z-pinned laminates has been developed where pins are represented as 1D trusses and embedded within a 3D laminate.

This model offers the opportunity, for the first time, for a large number of z-pins to be modelled within a structural material.

The flexibility of the model allows the fast generation of geometries with pins of varying aerial density, length, cross-section and material properties.

The input material properties of the pin are obtained from a simple experimental test. Future work will focus on validation of the model for a range of pin materials.

The limitation of the approach, in its current form, is the inability to model mode II and mixed mode loading. This is due to the use of truss elements. The model could be developed in the future to account for rotational degrees of freedom using beam elements. This would require modification of the embedded element constraint.

REFERENCES

[1] F. Bianchi, Numerical modelling of through-thickness reinforced structural joints, PhD Thesis, Cranfield University, 2012.

[2] A. P. Mouritz, Review of z-pinned composite laminates, Composites A, **38**, 2007, pp. 2383-2397 (doi: 10.1016/j.compositesa.2007.08.016).

[3] J. S. Boyce, G. A. Freitas, C. L. Magee, T. M. Fusco, J. J. Harris and E. Kunkle, Ultrasonic fastening system and method. Patent WO 98/29243, 1998.

[4] G. A. Frietas, C. L. Magee, J. S. Boyce and R. Bott, Service tough composite structures using z-fibre process, Proceedings of the 9th DoD/NASA/FAA conference on fibrous composites, Lake Tahoe, Nevada, 1991.

[5] B. Cox, W. Carter and N. Fleck, A binary model of textile composites – I. Formulation, Acta metallurgica et materialia, 42(10), 1994, pp. 3463–3479 (doi: 10.1016/0956-7151(94)90479-0).

[6] ABAQUS v6.12. Dassault Systemes, Rhode Island.

[7] M. W. Joosten, C. H. Wang, A. P. Mouritz, A. Afaghi Khatibi, S. Agius, B. Trippit and B. Cox, Modelling failure in composite structures using the enhanced embedded element technique, Proceedings of the 8th Australasian Congress on Applied Mechanics (ACAM8), November 23-26, 2014, Melbourne, Australia.

[8] S. Hashemi, A. J. Kinloch and J. G. Williams. The analysis of interlaminar fracture in uniaxial fibre–polymer composites. *Proc. Royal Society London*, **427**, 1990, pp. 173–199, (doi: 10.1098/rspa.1990.0007).

[9] T. M. Koh, S. Feih and A. P. Mouritz. Strengthening mechanics of thin and thick composite T-joints reinforced with z-pins. Composites A, **43**, 2012, pp. 1308–17 (doi: 10.1016/j.compositesa.2012.03.023).