MODE I RATE DEPENDENT MESO-MECHANICS OF Z-PINS

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Keywords: Z-pin, Composite, Through Thickness Reinforcement, Strain Rate, Mode I

ABSTRACT

In this paper, a rate dependent model is developed to simulate the bridging performance of Z-pins in Mode I loading. The Z-pin is modelled as a rod subject to foundation and frictional forces. The latter are described by means of Ruina's state-dependent friction model, which allows incorporating the rate effect. The model parameters are calibrated by mode I pullout tests carried out at 5 m/s. The model validation is conducted via experimental data gathered from pullout at 12m/s. The predicted force versus opening displacement responses are in excellent agreement with the experimental trends. The predicted apparent fracture toughness is within 8% of the experimental value.

1 INTRODUCTION

1.1. Motivation

Carbon fibre reinforced plastics (CFRP) are progressively finding wider application in primary airframe structures [1]. Laminated CFRPs are prone to delamination, since the matrix-rich ply interfaces are much weaker than the fibre-reinforced laminae [2, 3]. The susceptibility of CFRP to delamination is particularly high under impact loading. Z-pinning is a form of through-thickness reinforcement (TTR) which consists in the orthogonal insertion of either fibrous or metallic rods into CFRP laminates [4]. This provides an effective means for arresting delamination via the frictional pull-out of the TTR elements.

TTR in the form of Z-pins usually yields a 20-fold increase in mode I apparent interlaminar fracture toughness of prepreg based laminates [5-8]. In mode II, the insertion of Z-pins typically leads to a 4-fold gain in apparent toughness compared to standard laminates with no TTR [9]. The amount of Z-pins inserted in a laminate is quantified via the TTR areal density, with typical values ranging between 0.5% and 4%. Regarding low-speed impact behaviour, a 64% reduction of delamination area has been reported, resulting in a 2- to 4-fold increase in compression-after-impact (CAI) strength [10].

Nonetheless, the understanding of the Z-pin performance under high-speed (high strain rate) impact is still very limited and this poses a significant challenge for the design of damage tolerant TTR composite structures.

1.2. Background

1.2.1. Bridging Mechanics

In Z-pinned laminates, the enhancement of the apparent fracture toughness is a result of different micro-mechanisms that absorb fracture energy. These depend on the loading condition, laminate and TTR materials and the Z-pinning configuration (e.g. diameter and areal density) [4-8]. A review of the literature suggests that the main energy absorbing mechanisms in Z-pinned laminates subject to mode I are [4-10]:

1) strain energy in the elastically strained Z-pins;
2) energy spent to propagate a mode II crack along the Z-pin/laminate interface;
3) energy dissipated by frictional forces as the Z-pin is pulled-out from the laminate;

1.2.2. Modelling Aspects

In a modelling perspective, the analysis of composites with embedded TTR requires a multi-scale approach, usually involving two different meso-mechanical levels [11]. Herein, we shall denote as meso-level 1 the characterisation and prediction of the mechanical response of a single Z-pin. The behaviour of multiple Z-pins (i.e. TTR arrays) bridging multiple delaminations will be indicated as meso-level 2 response. The transition from meso-level 1 to meso-level 2 implies the introduction of a suitable homogenization scheme, in order to represent the behaviour of multiple interacting Z-pins in a “smeared" fashion over a bridged interface. In finite element analysis (FEA), the latter can be accomplished via the introduction of a bridging-dependent cohesive zone represented by zero-thickness interface elements. This paper is focussed on meso-level 1, i.e. “single” Z-pin, modelling.

At the meso-level 1, Cox [12] proposed an approach to describe the traction-displacement response of TTR elements under pure mode II loading. This model was further developed [13, 14] to model the bridging performance when the TTR element is inserted at an angle and thus subject to mixed-mode loading. Cox’s model is based on the assumption that the TTR shear behaviour is perfectly plastic. Composite Z-pin are seen to be brittle in shear and thus the assumption of plastic behaviour may not be strictly valid in this case, albeit transversal splitting may induce pseudo-ductility. In addition, Refs. [12-14] describe the interaction between the Z-pin and the laminate as that of a rigid punch ploughing through a perfectly plastic medium. This hypothesis could only be valid in unidirectional laminate if the Z-pin ploughs though the resin rich pocket and in the direction parallel to the fibres. Finally, the approach proposed in Refs. [12-14] assumes that the pull-out of the Z-pin is resisted by frictional forces. Residual friction arises from the curing process due to thermal residual stresses, while a friction enhancement is due to “snubbing”, which consists in a localised increase in friction due to increased contact pressure in the vicinity of the delamination plane [14]. Plain and Tong [15] developed a model specifically for TTR in the form of stitches. The model assumed a rope-like behaviour for the TTR (i.e. a stitch does not support axial bending). Another model was proposed by Tong and Sun [16, 17] for describing the bridging performance of metallic Z-pin. The TTR was assumed to behave as an Euler-Bernoulli beam embedded in an elastic-plastic foundation. A similar approach was adopted by Bianchi and Zhang [18] to model single Z-pin pull-out under pure mode II loading. Allegri et al. [19] proposed a mixed-mode model of Z-pin pullout based on geometrically nonlinear beam theory coupled with Weibull’s strength theory to predict the TTR failure.

The approaches in Ref. [12-19] are all based on a 1D idealization of TTR elements. However, various “high fidelity” simulation strategies have been proposed to predict the bridging performance of Z-pins via 2D and 3D finite element analysis (FEA). Meo et. al. [20] obtained results in good agreement with mode I pullout tests, but they observed that the shear stress in their model had to be capped to a pre-defined maximum value in order to match the experimental results. A more advanced 2D plane-strain FE model was developed by Cui et al. [21] in order to simulate the bridging performance of Z-pins under mixed-mode loading. This approach included the introduction of cohesive elements to simulate the de-bonding between the TTR and the embedding laminate, as well as the internal splitting of the Z-pin. Finally, Zhang et al. [22] developed a full 3D model for Z-pin pullout and progressive failure, which is also able to account for the effect of thermal residual stresses on the response of TTR.

Although high fidelity FEA can provide a comprehensive description of the complex behaviour displayed by Z-pins, the associated computational cost is too high both for concurrent runs at meso-2 level and at the macro-scale. Hence, the usage/implementation of “reduced order” models based on rod/beam theory, such as those in Refs. [12-19], is still paramount. Moreover, all of the models summarised above have been developed for TTR subject to quasi-static loading. The literature is actually devoid of Z-pin bridging models suitable for describing high strain-rate, e.g. impact, behaviour.

1.3. Paper Overview

This paper focusses on the introduction of a meso-level 1 model describing the rate-dependent response of single Z-pins when bridging mode I interlaminar cracks. The main aim is to represent the mode I meso-mechanics of single Z-pins via a computationally cheap model that accounts for all the physical phenomena governing the TTR response. More in detail, our approach is based on describing Z-pins as elastic rods embedded in an elastic foundation and experiencing progressive de-bonding and frictional pullout.

2 MODEL FORMULATION

2.1. Problem Statement

A Z-pin of length L is orthogonally embedded into a composite laminate. The composite laminate is split into two sub-laminates by a delamination plane. The delamination plane intersects the Z-pin at a known depth cutting the Z-pin into two segments ("lower" and "upper") having lengths L^- and L^+, respectively. This is illustrated in Figure 1. An insertion asymmetry parameter α is introduced as:

$$\alpha = \frac{L^-}{L^- + L^+} \tag{1}$$

Therefore, for a mid-plane delamination one has $\alpha = 1/2$. The Z-pin counteracts the opening displacement by exerting bridging forces on the delamination surfaces. Prior to the application of any mechanical loading, the Z-pin is assumed to be fully bonded to the surrounding laminate, yet with a weakened interface due to the curing process [8, 22]. As the opening displacement increases, the Z-pin progressively de-bonds from the embedding laminate. Once the de-bond is completed, increasing the opening displacement further causes a rigid pull-out displacement W, which is counteracted by frictional forces acting on the Z-pin/laminate interface.

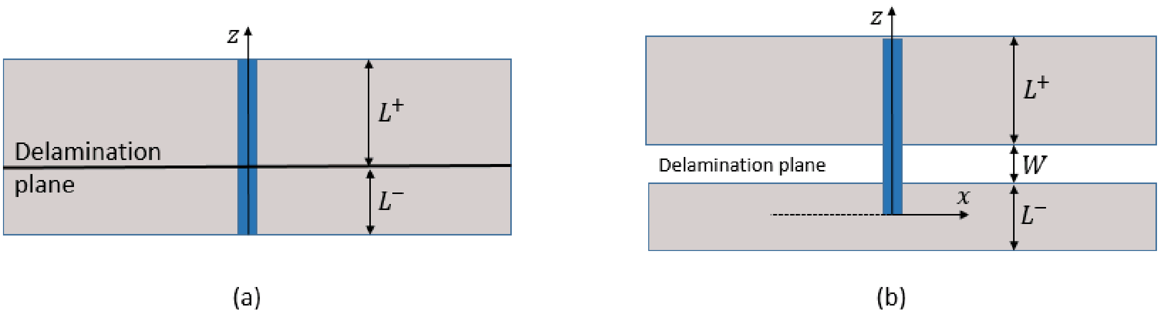

Figure 1: Mode I bridging kinematics of Z-pins. (a) Reference configuration. (b) Opening mode

2.2. Model Formulation

Taking into account external, inertial and damping forces, the general governing equation for the rod representing the Z-pin is obtained as follows:

$$\rho A \frac{\partial^2 w}{\partial t^2} + b_w \frac{\partial w}{\partial t} = EA \frac{\partial^2 w}{\partial z^2} + p, \tag{2}$$

where E is the Z-pin Young's modulus and A is the cross-sectional area; w is the displacement of the Z-pin along the z axis; b_w is the viscous damping coefficient; p is the axial distributed load per unit length. The latter arises from the shear deformation of the matrix layer between the Z-pin and the laminate in the "bonded" stage of the TTR response. Once de-bonding has occurred, the axially distributed load consists only of frictional forces.

In the bonded stage, the distributed force acting on the Z-pin surface is here postulated as

$$p = k_z w_{rel}, \tag{3}$$

where w_{rel} is the relative displacement between the Z-pin and the embedding laminate and k_z is an elastic foundation stiffness. Note that the relative displacement is just w for the lower Z-pin segment, whereas, for the upper segment, the relative displacement is given by $w - W$. During the progressing de-bond of the Z-pin from the laminate, it is hereby assumed that a cylindrical mode II crack propagates on the lateral surface of the TTR element, from the delamination plane to the Z-pin tips. Hence, the de-bonded segments of the Z-pin experience a frictional force, which is always opposed to the local relative speed V between the TTR rod and the surrounding laminate. Such frictional force is here modelled using Ruina's state-based friction model [23], summarised by the following equations

$$\begin{cases} \tau = \sigma\left[\mu_0 + \theta + A ln\left(\frac{V}{V_c}\right)\right] \\ \frac{d\theta}{dt} = -\frac{V}{l}\left[\theta + B ln\left(\frac{V}{V_c}\right)\right] \end{cases}, \tag{4}$$

where τ is frictional shear stress and σ is the normal applied stress; μ_0 is the friciton coefficient; θ is the state variable and V is the relative slip velocity. The model comprises four empirically determined parameters. The latter are: the reference speed V_c, the characteristic length scale l and the constants A and B.

2.3. Normalised Equations

The following definitions are adopted to normalize the axial abscissa z, the axial displacement w, the applied displacement W, the distributed force per unit length p and the shear foundation stiffness k_z:

$$\zeta = \frac{z}{L}\ ;\ \lambda = \frac{w}{L}\ ;\ \Lambda = \frac{W}{L}; \Pi = \frac{pL}{EA};\ \beta = L\sqrt{\frac{k_z}{EA}}. \tag{5}$$

Noting that the speed of the elastic waves in the rod is $c = \sqrt{E/\rho}$, the characteristic time required for a stress wave to travel along the full length of the Z-pin is $\tau_0 = L/c$. Hence, a normalised time is here introduced as $\tau = t/\tau_0$.

Applying the definitions in Eq. (5) to Eq. (2) and rearranging, the following partial differential equation is sought

$$\frac{\partial^2\lambda}{\partial\tau^2} + \chi_w\frac{\partial\lambda}{\partial\tau} = \frac{\partial^2\lambda}{\partial\zeta^2} + \Pi \tag{6}$$

The distributed force has different forms depending on the bonding/de-bonding status along the Z-pin. In the bonded region, one has $\Pi = \beta^2\lambda_{rel}$, where λ_{rel} is the relative normalised axial displacement between the Z-pin and the laminate. On the other hand, in the de-bonded region one has $\Pi = \Pi_0$, where $\Pi_0 = p_0L/EA$ is the dimensionless residual friction force. During the pull-out phase one has $\Pi = \Pi_{sl}$, where Π_{sl} is the rate dependent sliding friction force that is obtained from the equations governing Ruina's model, i.e.

$$\begin{cases} \Pi_{sl} = S^* + A^* ln\left(\frac{V}{V_c}\right) + \theta^* \\ \frac{\mathrm{d}\theta^*}{\mathrm{d}\tau} = -\frac{V}{c}\frac{L}{l}\left[\theta^* + \mathrm{B}^* ln\left(\frac{V}{V_c}\right)\right] \end{cases} \tag{7}$$

Defining $\lambda^{II} = \frac{\partial^2\lambda}{\partial\zeta^2}, \ddot{\lambda} = \frac{\partial^2\lambda}{\partial\tau^2}, \dot{\lambda} = \frac{\partial\lambda}{\partial\tau}$ and exploiting Eqs. (5)-(7), the governing equation for the normalised axial displacement before the Z-pin pullout stage are

$$\begin{cases} \ddot{\lambda} + \chi_w\dot{\lambda} = \lambda^{II} - \beta^2\lambda_{rel} & -\alpha < \zeta \le -\alpha\xi^- \\ \ddot{\lambda} + \chi_w\dot{\lambda} = \lambda^{II} - \Pi_0\frac{\dot{\lambda}_{rel}}{|\dot{\lambda}_{rel}|} & -\alpha\xi^- < \zeta \le 0 \\ \ddot{\lambda} + \chi_w\dot{\lambda} = \lambda^{II} - \Pi_0\frac{\dot{\lambda}_{rel}}{|\dot{\lambda}_{rel}|} & 0 < \zeta \le (1-\alpha)\xi^+ \\ \ddot{\lambda} + \chi_w\dot{\lambda} = \lambda^{II} - \beta^2\lambda_{rel} & (1-\alpha)\xi^+ < \zeta < 1-\alpha \end{cases} \tag{8}$$

where $\alpha\xi^-$ and $\alpha\xi^+$ are the normalised de-bonding lengths in the lower and upper laminate segments, respectively.

Assuming, without loss of generality, that the Z-pin experiences full de-bond in the bottom laminate first, then the governing equation in the pull-out phase can be expressed as:

$$\begin{cases} \ddot{\lambda} + \chi_w \dot{\lambda} &= \lambda^{II} - \Pi_{sl} \frac{\dot{\lambda}_{rel}}{|\dot{\lambda}_{rel}|} & -\alpha + \eta < \zeta \leq 0 \\ \ddot{\lambda} + \chi_w \dot{\lambda} &= \lambda^{II} & 0 < \zeta \leq \eta \\ \ddot{\lambda} + \chi_w \dot{\lambda} &= \lambda^{II} - \Pi_0 \frac{\dot{\lambda}_{rel}}{|\dot{\lambda}_{rel}|} & \eta < \zeta < (1-\alpha)\xi^+ + \eta \\ \ddot{\lambda} + \chi_w \dot{\lambda} &= \lambda^{II} - \beta^2 \lambda_{rel} & (1-\alpha)\xi^+ + \eta < \zeta < 1 - \alpha + \eta \end{cases} \tag{9}$$

where η represent the normalised pull-out axial displacement of the Z-pin. In terms of boundary conditions, the Z-pin is assumed to have traction free ends.

The local de-bonding of the Z-pin from the surrounding laminate is identified by means of the Griffith criterion. It is here assumed that the Z-pin/laminate interface has a characteristic fracture toughness G_{IIc}, while the energy release rate associated with the de-bond propagation is given by the elastic energy stored per unit length in the foundation. Hence, the de-bonding condition for a Z-pin with diameter D reads

$$\frac{1}{2} k_z \pi D L^2 \lambda^2 = G_{IIc} \tag{10}$$

Using Eq. (10), the local normalised displacement for the failure of the interface can be readily calculated.

2.4. Numerical Solution

Either explicit or implicit schemes can be used in order to solve the model equations presented in the previous sections. Explicit schemes usually require very small time step to ensure stability, while implicit integration is able to cope with larger time steps, but it requires matrix inversions. Here, an explicit time scheme is employed to solve the second order hyperbolic partial differential equations (PDE) in Eqs. (7-9). Namely, both time and space derivatives are approximated using centred finite differences.

Once the pull-out stage is reached, the local sliding frictional force is obtained by solving Eq. (7), again using a centred difference scheme for the state variable. Hence, such a solution is obtained concurrently with Eqs. (9).

3 MODEL CALIBRATION

The experimental tests considered in this paper are those reported by Cui et al. in Ref. [24]. The coupons were prismatic, with an in-plane area of 10 mm x 10 mm and a thickness of 8 mm, and they had a quasi-isotropic stacking sequence; 16 Z-pins were inserted in each coupon, thus giving a 2% TTR areal density. The specimens were loaded in pure mode I in a split Hopkinson bar; two set of tests were performed at speeds of 5 m/s and 12 m/s, respectively.

The model proposed has been implemented in Matlab for a Z-pin with the geometrical and mechanical properties listed in Table 1 [8, 19]. Hence, there are six remaining parameters that need to be estimated from experimental data. The latter include the axial foundation stiffness k_z, the interface fracture toughness G_{IIc} and the characteristic constants appearing in Ruina's model in Eq. (7), i.e. S^*, A^*, B^* and l. This calibration is here carried out using the experimental data obtained at 5 m/s. Note that the reference speed V_c is here fixed at 10^{-5} m/s.

A genetic algorithm (GA) is used to identify the six parameters listed above. The cost function to be minimised is defined as

$$C = \sqrt{\varepsilon_I^2 + \varepsilon_G^2}. \tag{11}$$

In Eq. (11), ε_G is the relative error between the predicted and experimental areas under the force-displacement curves. Similarly, ε_I^2 is the sum of the squared relative errors between each experimental force and displacement datum points and the model results.

4 DISCUSSION AND VALIDATION

Using the calibrated parameters, the model presented in Sec. 2 was used to predict the mode I delamination bridging response at a pull-out rate of 12m/s. The model predictive capability can be appreciated in Figures 2 and 3, where the bridging force is shown as a function of the opening displacement. For both the 5m/s and the 12m/s cases, the numerical solution is in good agreement with the experimental results, i.e. within the standard deviation from the test data. Moreover, the amount of energy dissipation during the Z-pin pullout predicted by the model is within 8% of the actual experimental value for both the speeds considered.

E (GPa)	ρ (kg/mm^3)	L (mm)	D (mm)	α
115	1.6e-06	8	0.28	0.5

Table 1: Z-pin parameters

It is also worth stressing that the model runs in under a minute on a desktop PC. A detailed dynamic FEA model of a Z-pinned coupon as the one considered here requires a runtime in the order of days [22] on a state-of-the-art cluster. Hence, the advantage provided by the model proposed here in terms of computational cost is huge. The approach outlined in this paper can be employed as part of a multi-scale modelling strategy, whereby 1D rod models representing individual Z-pins can be run concurrently with an FEA simulation at structural level. Such a coupling can be directly implemented within any explicit FEA solver by considering relative displacements, speeds and forces at bridged interfaces.

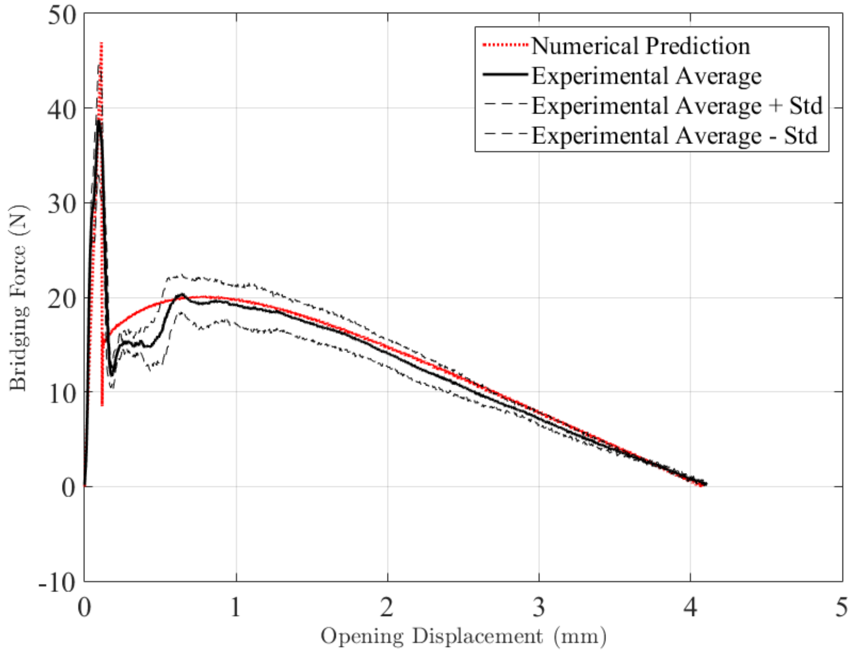

Figure 2: Bridging force versus opening displacement at pullout speed of 5 m/s. The average experimental results plus/minus standard deviation are from Ref. [24]

6 CONCLUSION

A rate dependent model has been proposed to predict dynamic performance of Z-pins bridging mode I delaminations. The Z-pin has been modelled as a rod embedded in an elastic foundation, which is subject to progressive de-bond followed by friction. The state-based model proposed by Ruina [24] was employed to account for the effect of the relative sliding speed on the friction that develops during the Z-pin pullout. The parameters were obtained by calibration against experimental data obtained at a pullout velocity of 5 m/s. These parameters were then used to assess the model predictive capability at a pullout rate of 12m/s.

The model provides a robust prediction of both the bridging force exerted by individual Z-pins during pullout and the fracture toughness enhancement obtained by the insertion of TTR. The main advantage of the proposed model is the very low computational cost when compared to detailed meso-scale FEA simulations.

Future work will be focussed on the extension of the proposed model to a mixed-mode scenario.

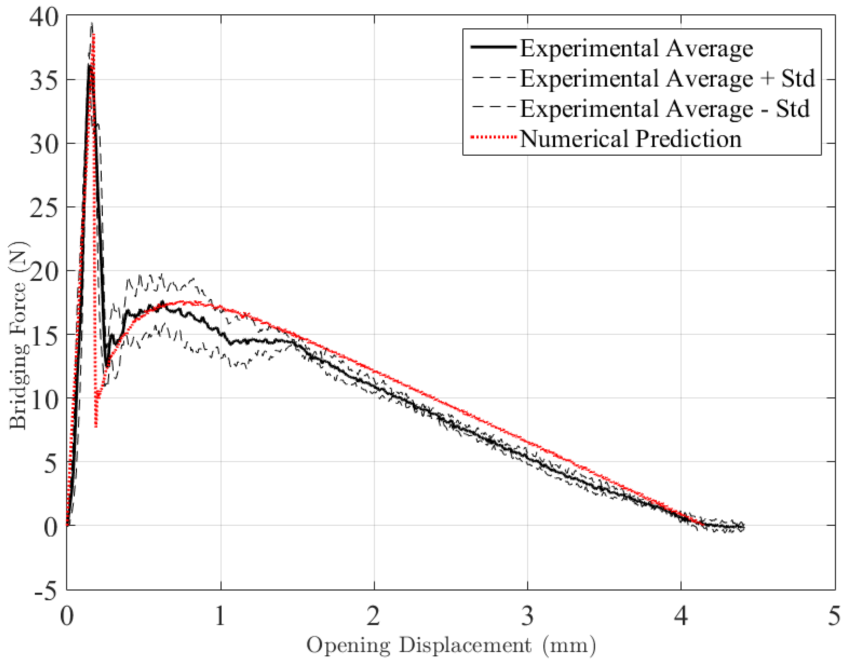

Figure 3: Bridging force versus opening displacement at pullout speed of 12m/s. The average experimental results plus/minus standard deviation are from Ref. [24]

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support to this research provided by the EPSRC through the grant "Understanding Delamination Suppression at High Deformation Rates in Through-Thickness Reinforced Laminated Composites" (EP/M015319/1, EP/M012905/1, EP/M014800/1).

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