MODELLING SOFT BODY IMPACT OF THROUGH-THICKNESS REINFORCED COMPOSITES

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Keywords: Through-thickness reinforcement, delamination, damage tolerance, soft-body impact, finite element analysis.

Abstract

The work in this paper simulates the soft-body impact response of pristine and z-pin reinforced composite beams based on a novel 3-point bend type test called the 'soft body beam bend' (SBBB). Numerical results of unreinforced composite beams were compared to experimental impact tests results yielding good agreement in terms of delamination threshold velocity and global deformation behaviour. In the case of reinforced composite beams, previously validated z-pin bridging maps were applied to predict the large-scale bridging response. The numerical results predicted an enhancement to delamination suppression, raising the threshold by almost 15%. However, correlation with experiment test data was only moderately good due to the strain rate effects not being included in the model for the base composite material and z-pins.

1. Introduction

Innovative design of through-thickness reinforced (TTR) polymer laminates has the potential to enhance the impact damage resistance of aerospace structures by increasing the resistance to delamination. The benefits of reinforcing composite laminates using z-pins under impact conditions have been previously investigated for a range of loading cases. For example, Zhang et al. [1] have shown that z-pinning can reduce the post-impact delamination area by 19–64%, depending on the impact energy level and laminate thickness. Impact damage is reduced due to the bridging action of the z-pins, which further enhances the buckling resistance of the delaminated plies. An improvement in post-impact compressive properties was also observed, with a reported increase of 55% in compression-after-impact strength [1]. However, damage resistance is only increased in impact loading conditions that cause inter-laminar cracks to grow large enough for the z-pin bridging zone to develop [2,3]. Furthermore, it has been observed that z-pins are largely ineffective in raising the onset of delamination under impact (threshold impact energy) to initiate damage and retard small delamination growths [2,3]. While experimental tests have demonstrated the potential use of z-pins in structures vulnerable to impact, numerical models that considers large-scale bridging effects, particularly under mode II dominated conditions, to predict the impact damage response of z-pinned laminates remain absent from the open literature.

This paper presents recent progress in developing and implementing an experimental-numerical framework, via non-linear explicit finite element code LS-DYNA, for modelling soft body impact (gelatine) of TTR composite laminates [4]. In the numerical model, the smooth particle hydrodynamics method (SPH) is used in combination with a composite failure model, which includes ply damage and a user-defined interply z-pin cohesive element to predict impact damage and delamination growth. The numerical results obtained for different impact velocities were compared to recent, novel experimental tests of pinned and unpinned composite beam laminates subjected to high-velocity gelatine impact. The accuracy and validity of the numerical strategy is assessed in terms of delamination threshold velocity and global deflection.

2. Description of soft body beam bends tests

The soft body beam bend (SBBB) test is a modified 3-point bend impact test that aims to replicate the dynamic stress state observed by relatively large and flexible composite components during a soft body impact event (Rolls-Royce owned patent US7845207 (B2)). The aforementioned stress state is initially characterized by a shear stress during the initial impact event followed by a flexural load as the structure starts to respond; this flexural load is fully reversed later during the event, as illustrated in Figure 1.

The test method comprises of a composite beam (200 x 20 x 5mm) that is mechanically fastened into relatively heavy fixtures at either end. The fixtures are suspended from ‘long’ cables. The specimen is then impacted with a gelatine cylinder at 100-250m/s.

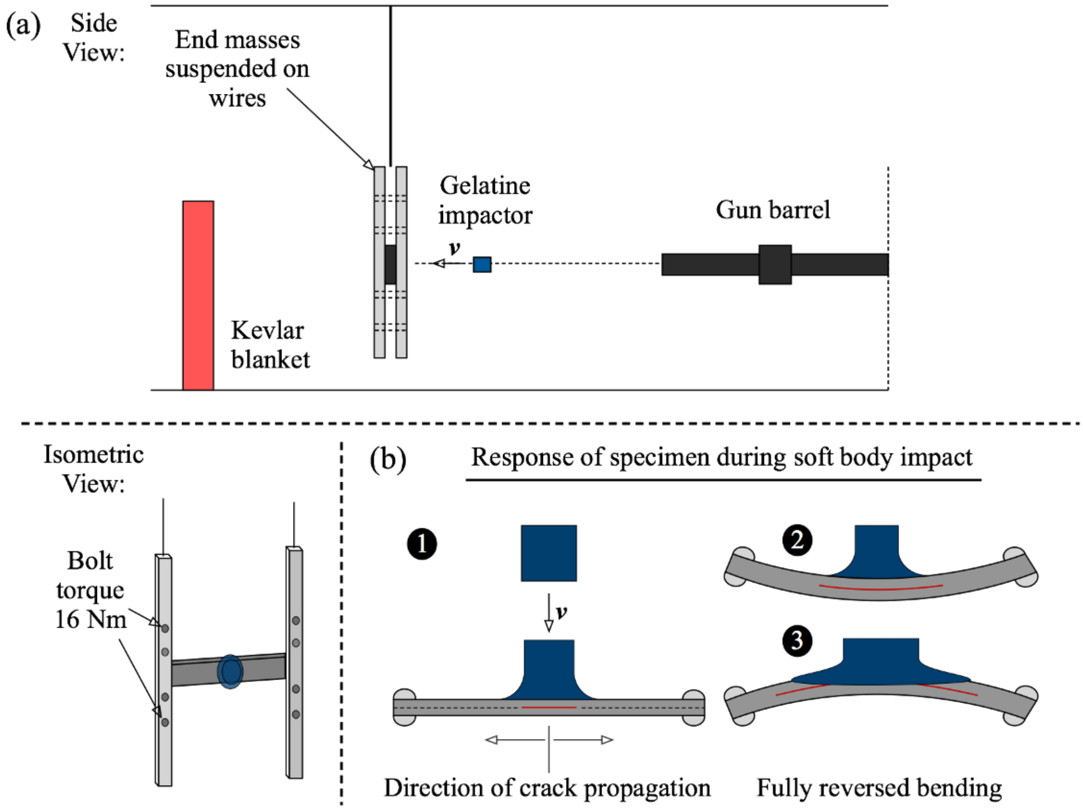

Figure 1. (a) Schematic of SBBB test arrangement showing inertial restraints attached to long suspending wires, (b) Response of SBBB specimen during initial impact and subsequent fully reversed bending.

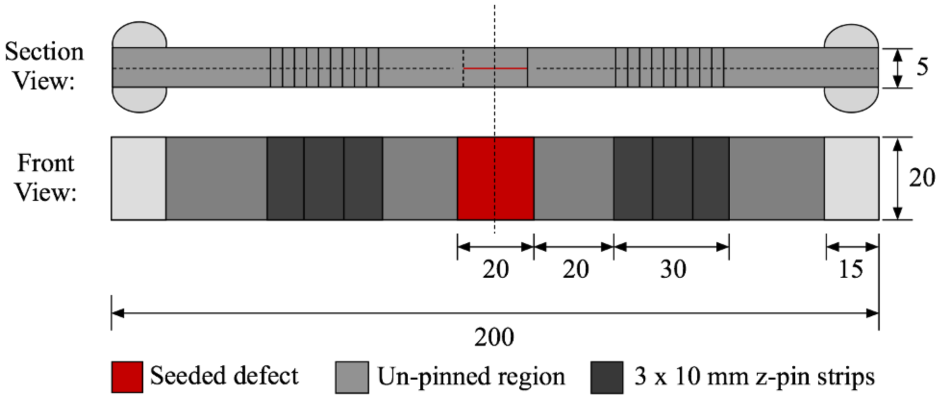

Figure 2. Schematic of SBBB specimen showing unreinforced and z-pinned reinforced region.

The composite beam is manufactured according to the dimensions given in Figure 2 using an aerospace-grade carbon-fibre epoxy material. A PTFE film was inserted before curing to seed internal delamination at the mid plane of the composite specimen. To give a clear indication of the bridging effects of the pins and develop a fast propagating crack, an unreinforced region was left between the PTFE inserts and z-pinned region. The z-pins were inserted in 10mm wide strips and consist of 0.28 mm diameter T300/BMI z-pins of 2% areal density. The normalized results for full delamination threshold velocity, V_{TN}, of the SBBB tests on 5 mm thick composite beams are summarized in Figure 3. The threshold velocity is defined as the velocity at which the mid-plane delamination fully propagated towards the end of the constraints.

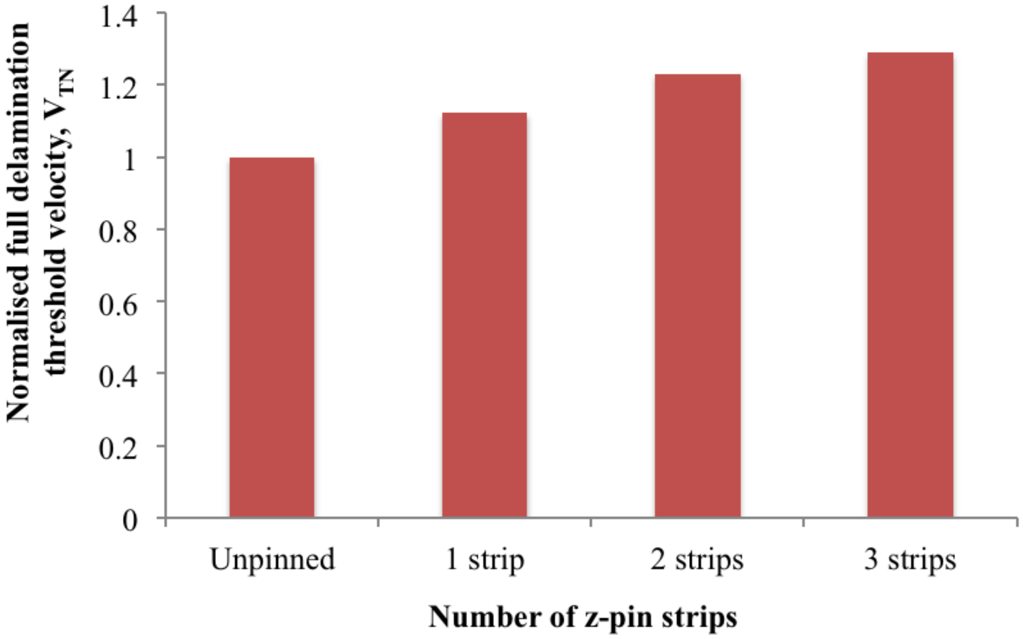

Figure 3. Summary of SBBB test results for 2% areal density 0.28 mm diameter z-pins

It is clear, for this particular configuration, that the z-pins enhance the resistance to delamination under impact, raising the full delamination threshold velocity, in the 3-strip case, by almost 30%. A more in-depth qualitative discussion of these results is presented in Ref. [5].

3. Numerical methods

A numerical approach was developed [4] and employed in this paper to predict the soft body impact of through-thickness reinforced composite beams. To realize this goal, the numerical methodology is considered in terms of composite material modeling with intra and inter-laminate damage, hydrodynamic behavior of ballistic soft-body gelatine and capturing the inertial constraints of the boundary conditions.

Under impact conditions, soft body gelatine behaves in a fluid-like manner and exerts a pressure (few ms of contact duration) over a relatively large surface area. Thus, a water-like hydrodynamic equation of state (EOS) response was considered to describe the constitutive (pressure-volume) behavior of the water-based gelatine. Problems associated with a Lagrangian-based soft body impact model, such as hour-glassing, severe element distortion and reduced time-step (which can be avoided using element erosion criteria), can significantly affect the accuracy and computational efficiency of the problem. To overcome some of these limitations, the smooth-particle hydrodynamic (SPH) approach was employed which yielded accurate results when validated against experimental bird strike test data [6], as shown in Figure 4.

The EOS parameters for this particular study were derived from Hugoniot ballistic gelatine tests for 20-w.t % porcine gelatine. In the Us-up space, the Hugoniot had the form $Us = 1.57 + 1.77\,up$, where Us and up refer to the shock and particle velocity, respectively.

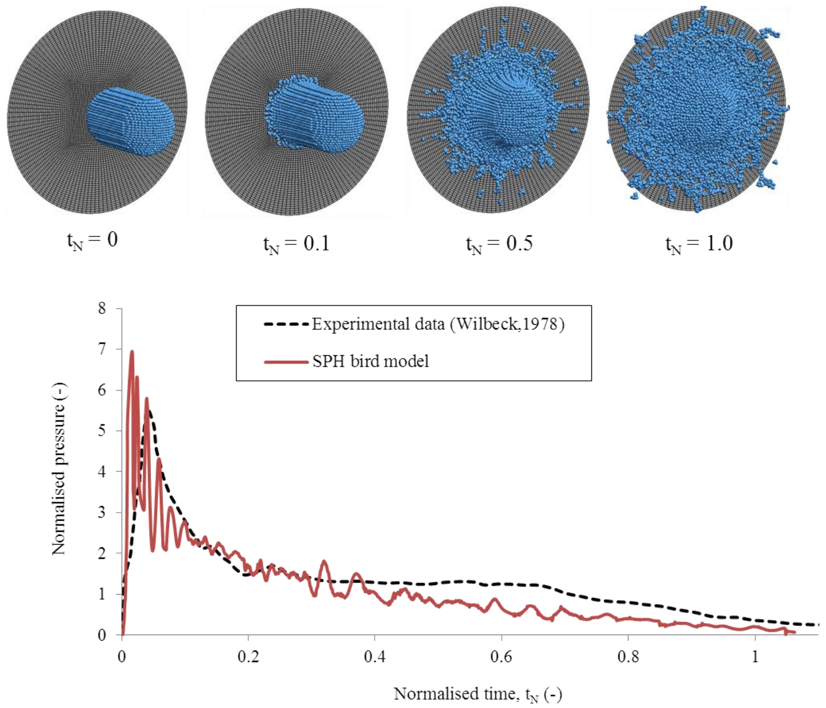

Figure 4. Pressure-profile comparison of SPH bird model against experimental data [6]

The initial impact of the soft-body gelatine causes a multitude of failure mechanisms such as matrix cracking, fibre failure and interlaminar delaminations in the composite specimen. Such failure mechanisms are strongly dependent on the geometry of the specimen (thickness, stacking sequence and slenderness), mass & velocity for the impactor and the boundary constraints. Figure 5 shows a schematic of the finite element model employed in this paper and the appropriate boundary, loading, constitutive material models and element type formulations.

Interlaminar delamination is captured using special user-defined cohesive elements which can simulate both the mixed-mode constitutive behavior of the resin rich interface and the large-scale bridging mechanism of the z-pins – orthogonally inserted through the thickness of the composite specimens, as shown in Figure 5. The latter is achieved by incorporating a semi-analytical micro-mechanical model into a cohesive element formulation. The micro-mechanical model postulates that the z-pins behave as Euler-Bernoulli beams embedded in a Winkler elastic foundation. The efficacy of this comprehensive numerical framework was assessed and validated against coupon fracture toughness specimens [4].

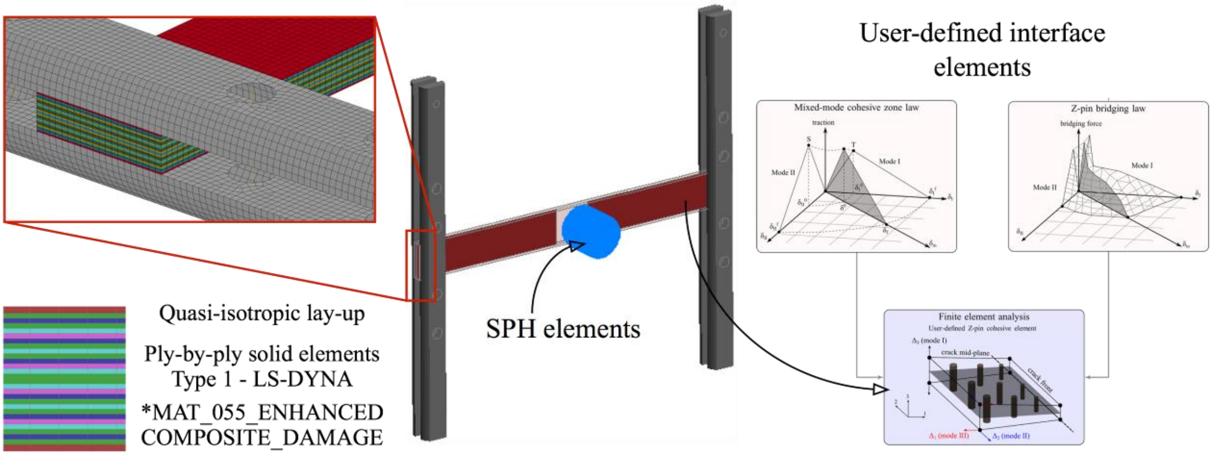

Figure 5. LS-DYNA finite element model of soft body beam bend test. Cohesive elements are ‘only’ inserted at the mid-plane of the specimen.

4. Results

Finite element models were initially performed on unreinforced specimens at impact velocities in which experimental visual and quantitative metrics for available for verification and validation. Figure 6 shows the dynamic soft-body response of a composite beam subject to a normalised velocity (as per Figure 3), V_N, of 0.78 in comparison with discrete high-speed images taken from SBBB tests [5]. During initial impact, the soft-body impact exerts a shear stress wave with little or no global deformation. This shear stress state is proceeded by a flexural wave as the beam starts to deflect, firstly in the direction of the impact load and then a fully reversal deflection. The inertial constraints imposed by the end mass support were correctly modeled in that they did not translate during this event. The global bending deformation of the beam was measured from the high-speed images and assessed against the numerical simulations to verify the boundary and loading conditions. This is illustrated in Figure 7. At this impact velocity, partial delamination was reported and confirmed by C-scanning of the post-impacted specimen, also shown in Figure 7.

To determine the full delamination threshold, a series of test cases were performed at increasing impact velocities, as shown in Figure 8. It is clear from this figure that the normalised delamination threshold velocity, V_{TN}, is between approximately 0.97 which is in good agreement with the experimental benchmark V_{TN} of 1.00.

The result of the pinned (3 x strips) is summarized in Figure 9. The numerical model predicts an increase of V_{TN} by almost 15% to 1.12, however this result is notably below the experimentally reported value of V_{TN} =1.29. Although, post-processing of the numerical model clearly showed a reduction in the crack growth rates as the delamination front reached the first row of z-pins, the predicted bridging response of the z-pins were not captured accurately. The reasons for this may be attributed to the fact that rate effects were not explicitly included in the composite material or z-pin interface models. Better characterization of rate effects in through-thickness reinforced composites will be the subject of future investigations.

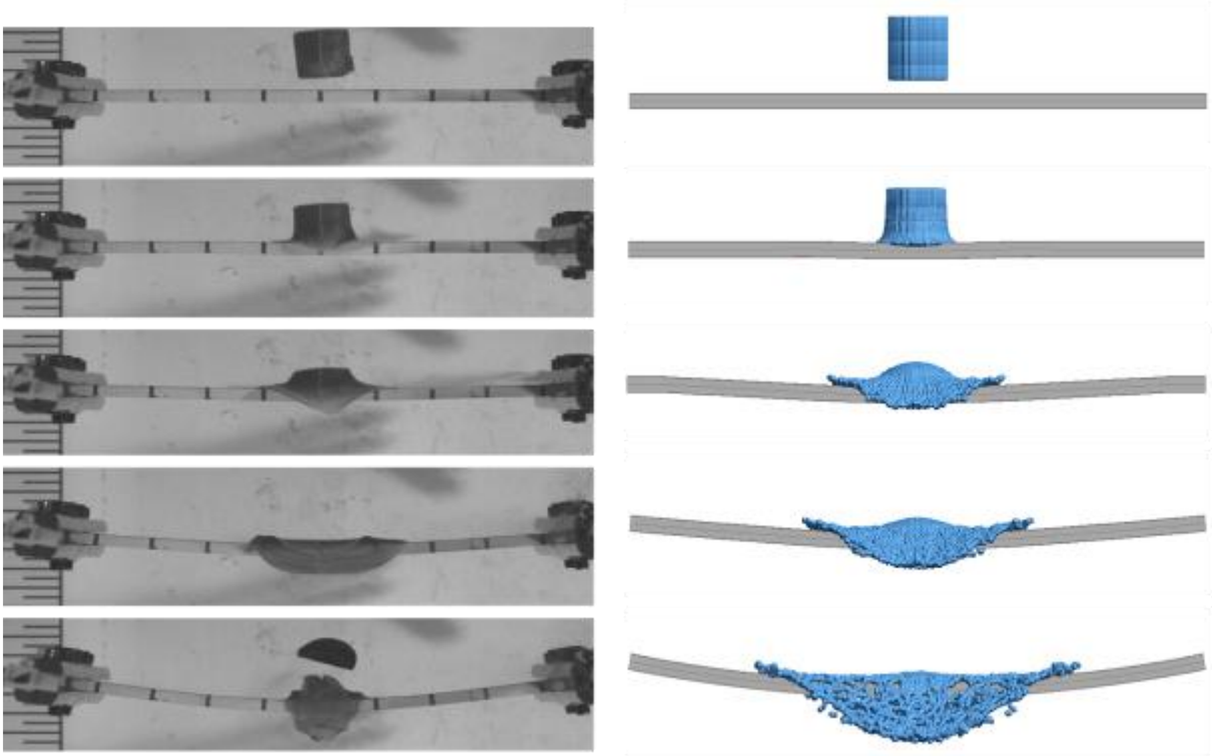

Figure 6. Comparison of experimental and numerical soft body impact event (V_N = 0.78) over a period of 1 ms

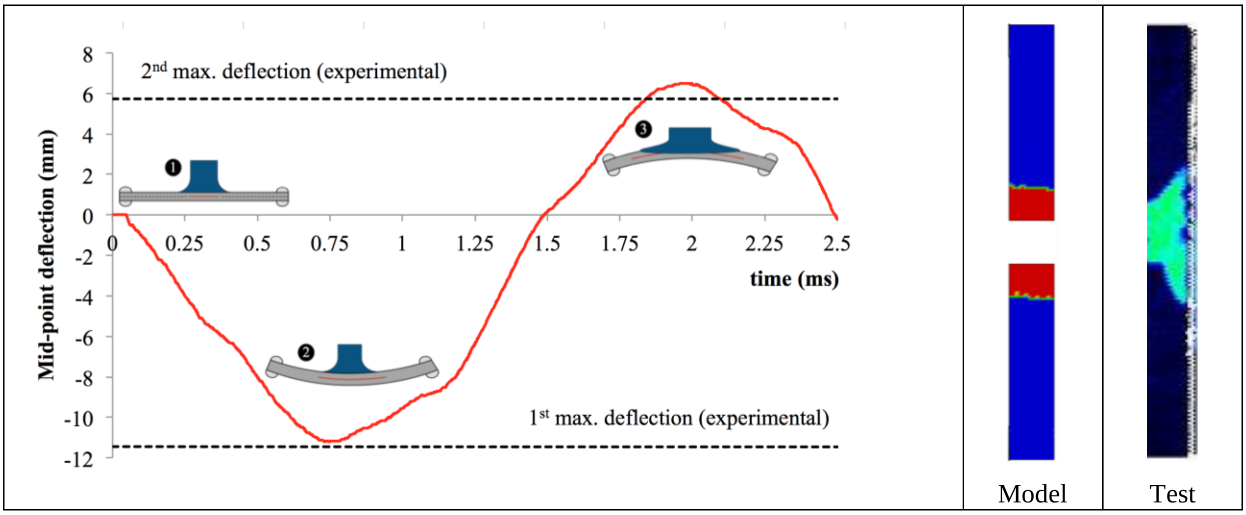

Figure 7. Numerical prediction of mid-point maximum deflection in comparison with equivalent metrics obtained from experimental high speed images (V_N = 0.78).

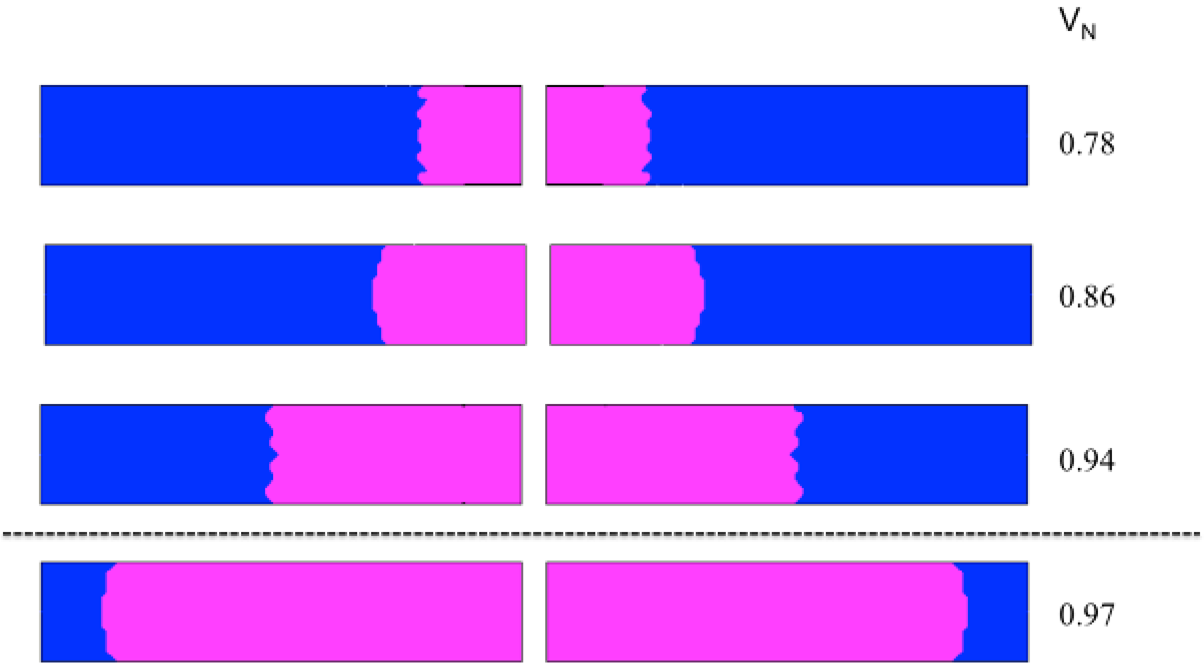

Figure 8. Numerical study to predict the full delamination threshold velocity of inertia constrained composite beams.

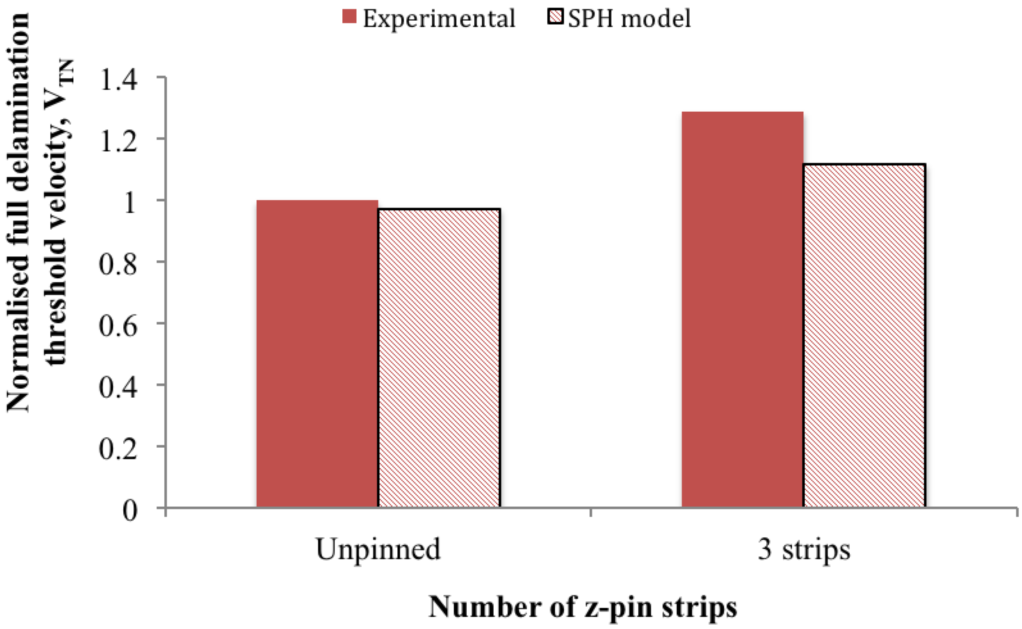

Figure 9. Summary of SBBB test simulations against experimental data [5].

6. Conclusion

The focus of this paper is to simulate, using the explicit finite element software LS-DYNA, the high velocity impact by soft-body gelatine projectiles on unreinforced and reinforced composite beams based on a novel 3-point bend type test called the 'soft body beam bend' (SBBB).

Initially, the impact response of unreinforced specimens was studied at different impact velocities to determine the full delamination threshold velocity and global bending behavior of the beams. Numerical results were compared to experimental impact tests results yielding good agreement. In the case of reinforced composite beams, previously validated z-pin bridging maps were applied to predict the large-scale bridging response. The numerical results predicted an enhancement to delamination suppression, raising the threshold by almost 15%. However, this value wasn't as great an increase as observed in the experiment test data due to the lack of high strain rate data for the base composite material and z-pins. This paper highlights the need to address these issues in soft-body impact assessment and damage tolerance, work in which the authors are currently engaged.

Acknowledgements

The authors would like to acknowledge the support of Rolls-Royce plc. for the support of this research through the Composites University Technology Centre (UTC) at the University of Bristol, UK.

References

[1] X. Zhang, L. Hounslow, M. Grassi. Improvement of Low-Velocity Impact and Compression-after-Impact Performance by Z-pin Pinning. *Composites Science & Technology*, Volume 66, Issue 15, pp. 2785-94, 2006.

[2] IK Partridge IK, DDR Cartié, M. Troulis, M. Grassi and X. Zhang. Evaluating the mechanical effectiveness of z-pinning. *In: Proceedings of the SAMPE technical conference*, September 2004.

[3] A. Mouritz. Review of z-pinned composite laminates. *Composites Part A: Applied Science and Manufacturing*, Vol. 38, No. 12, pp 2383-2397, 2007.

[4] G. Mohamed, S.R. Hallett, G. Allegri, F. Helenon, M. Yasaee. Predicting the through-thickness enhancement of z-pinned composite laminates. In: *19th International Conference on Composite Materials,* July-August 2013.

[5] G. Kalwak, S. Read, M. Jevons, N. Petrinic. Investigation of the delamination characteristics of composite specimens with through thickness reinforcement using an inertia constrained soft body beam bend test specimen. *16th European Conference on Composite Materials*, June 22nd -26th 2014.

[6] J.S. Wilbeck. Impact Behavior of Low Strength Projectiles. Report AFML-TR-77-134, Wright-Patterson Air Force Base, 1978.