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Evaluating Z-pin performance under high-velocity impact conditions

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Abstract

High-performance aerospace composite structures manufactured from pre-impregnated carbon fibre preforms are highly susceptible to delamination failure in the event of high-velocity impact. An established solution to this problem is to insert Z-pins into the composite structure to enhance through-thickness impact performance. This practice is known as through-thickness reinforcement (TTR). The production and impact testing of full-scale and sub-scale components is expensive and does not yield a suitable environment for the analysis of Z-pin behaviour and effects under the observed complex loading conditions. By contrast, prior small test scales and low strain-rates have not been sufficient to invoke the large-scale bridging action of Z-pins or study their behaviour at strain-rates representative of a real impact event. This study presents a test method which has been designed, using finite element analysis, to be capable of reproducing delamination failure at sub-element scale and high strain-rate using soft-body impact. This test makes use of a simple cantilevered tapered plate which is subjected to impact by a gelatine projectile using a gas-gun. This method will recreate the delamination failure mode observed under high-velocity impact at substantially reduced cost and provide a test-bed for assessing Z-pin performance at larger scales.

1. Introduction

Carbon fibre reinforced plastic (CFRP) aerospace structures have very high in-plane strength and stiffness. These properties make CFRP highly suited for the loading conditions experienced by many aerospace structures within normal operating limits. However, such structures are highly susceptible to delamination failure in the event of high-velocity impact. This is particularly important for aerospace components where foreign-object impact can lead to catastrophic failure of a component due to the lower material interlaminar fracture toughness, a property governed by the matrix (resin) strength. The absence of any fibrous material in the through-thickness direction means that the large interlaminar shear stresses induced by a high-velocity impact event can cause delamination failure [1].

Insertion of fibrous material in the Z-direction to enhance through-thickness performance, known as through-thickness reinforcement (TTR), is a well-established means to manage delamination failure under impact. While several different types of reinforcement are in mainstream use – such as tufts, stitches and Z-pins – the present work will focus on Z-pins, which are the current primary reinforcement type for structures manufactured from carbon fibre pre-preg [2]. The effectiveness of Z-pins in enhancing interlaminar fracture toughness is very well-established at low loading rates and smaller test scales. Special purpose rigs that allow variation of the test mode-ratio have been used to assess the quasi-static, 'apparent' fracture toughness of single Z-pins to be determined [3]. The improvement in fracture toughness for Mode I (opening)-dominated loading, where pull-out of the Z-pin is the primary mode of failure, is shown to be substantial. Modest improvement is obtained for Mode II (sliding) loading, where shearing (or rupture) of the pin is the primary failure mode. Quasi-static [4] tests have been carried out on double-cantilevered beam (DCB) specimens to measure the fracture toughness enhancement attained by arrays of Z-pins at structural level. These tests showed significant improvement for the Z-pinned specimens versus the un-reinforced control specimens and a substantial delay in the onset of ultimate failure due to the load-carrying capacity of the pin arrays. Novel Z-pin configurations, such as insertion of pins at a prescribed (non- surface normal) angle, have also been used in quasi-static tests [5]. Dynamic testing has been undertaken on single-pin coupons and structural level (DCB-type beams) to assess Z-pin performance at high-strain rates [6, 7]. The results indicate similar trends to quasi-static tests; that the pins provide improvement in any failure mode, but the most dramatic improvements are observed for Mode I-dominated loading.

Whilst these test campaigns have demonstrated the effectiveness of individual pins and small arrays of pins at coupon and structural level and at low and high strain-rates, it has been shown that the effectiveness of Z-pins cannot be fully realised until Z-pins undergo large scale interlaminar crack bridging [8]. That is, the delamination crack front must travel through sufficient rows of pins to cause large-scale pull-out or shearing such that the maximum bridging stresses – those acting to inhibit the delamination – are obtained. At the test scales commonly used, this is not possible. A standard test does not exist in the open literature that captures large scale Z-pin bridging behavior, by producing delamination of sufficient scale to be representative of that seen in a real component failure event, and by employing pin arrays large enough to undergo full-scale bridging under such delamination.

The appropriate type of test for this purpose is a high-velocity, soft-body impact test using a gas-gun [9]. Full scale industry gelatine impact tests on real components are expensive, the failure modes observed in these tests are difficult to control and are computationally expensive thus prohibiting the use of high fidelity finite element models. There is requirement need for an affordable test which produces repeatable and measurable delamination behaviour at sufficient scale and strain-rate to exercise large-scale Z-pin bridging action. Such a test would also provide a useful validation case for future development of cohesive element-based modelling simulations.

In order to minimise the cost and risk of developing this new test it is desirable to adopt a design-by-analysis approach using validated computational tools, such as those developed at the University of Bristol for LS-DYNA. A standard gelatine impact test has therefore been conceived which satisfies all of the aforementioned requirements.

2. Test design

The test design deliverables were set as follows:

1. To produce sufficient delamination to invoke large-scale bridging action in a specimen reinforced with Z-pins;
2. To ensure repeatable, stable delamination behaviour, measurable by C-scan, across a range of test velocities ensuring robustness considering fluctuations in gas-gun test velocity;
3. To prevent failure modes such as fibre-breakage at the specimen root.

A design, including the specimen and projectile, was down-selected to a tapered, cantilevered plate impact test. Figure 1 shows the general configuration of this test.

Iteration of the parameters detailed in Figure 1 was undertaken in order to achieve an output that satisfied the deliverables stated above. This design-by-analysis procedure was conducted using the LS-DYNA explicit finite element analysis (FEA) solver.

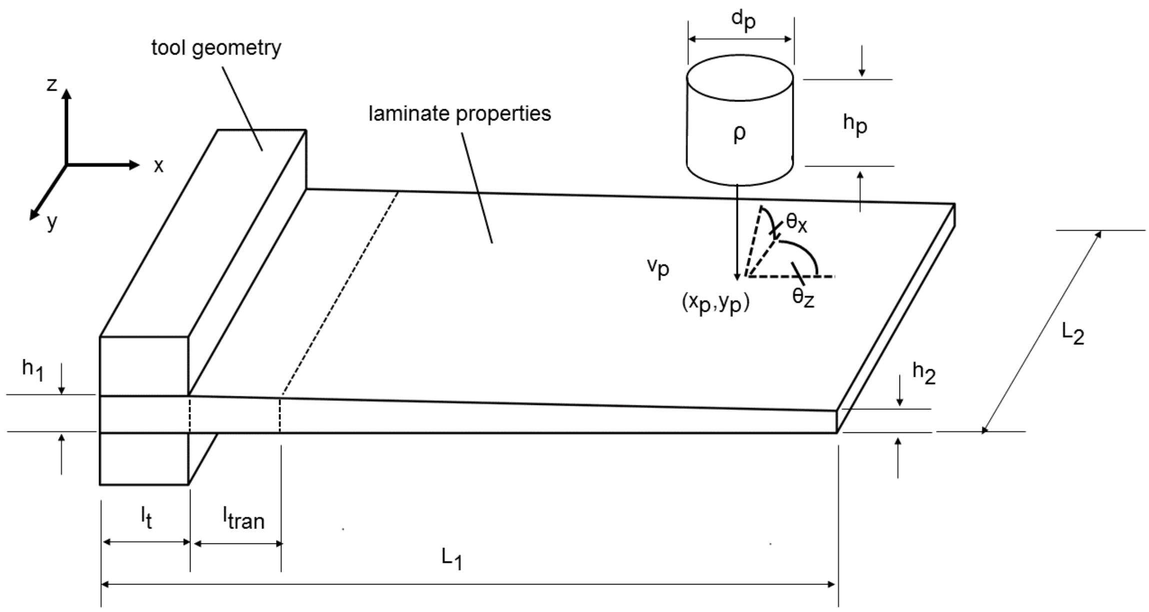


Figure 1: Schematic diagram illustrating general test design with key test and geometric parameters indicated.

The test design process was based around an unreinforced laminate and included three levels of fidelity in the finite element models. In each case, the impactor was represented by smooth-particle hydrodynamic (SPH) elements. During phase 1, with a wide set of potential design parameters to consider, parameterised models using homogenised average effective stiffness properties were employed with a small number of delamination interfaces between blocks of plies. During phase 2, as the test design became more refined and parameter ranges were narrowed, more delamination interfaces were included and the homogenisation procedure was improved to take account of sub-laminates within each ply block and the adjustment of sub-laminate properties along the span to account for ply drop-offs. Bespoke pre-processors were developed during phases 1 and 2 using MATLAB/Python to automate the generation of models. . During phase 3, once the major test parameters were fixed, the test design was further refined by including a full ply-by-ply representation with details such as resin pockets at ply termination locations included. A thermal analysis step was also included to assess the effect of thermal residual stresses on the predicted delamination result resulting from cool down from the composite material cure temperature.

The final general test configuration is illustrated in Figure 2.Initial predictions from the design process are given in Section 5. The final test design includes features such as:

- Tailored laminate thickness to allow for sufficient root strength and pin length while minimising bending stiffness to aid delamination;
- Angle of incidence of plate to impactor to ensure repeatability in shot direction and help control flow of mass onto the plate surface;
- Increased impactor depth to lengthen pressure pulse on plate to increase bending deflections;
- Ply-blocking of full-length plies and inclusion of 0/90 interfaces in stacking sequence to increase delamination potential.

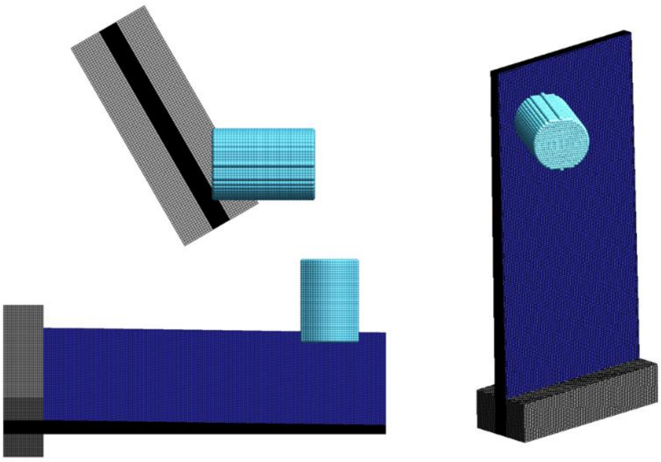


Figure 2 Final test design shown using an LS-DYNA finite element model.

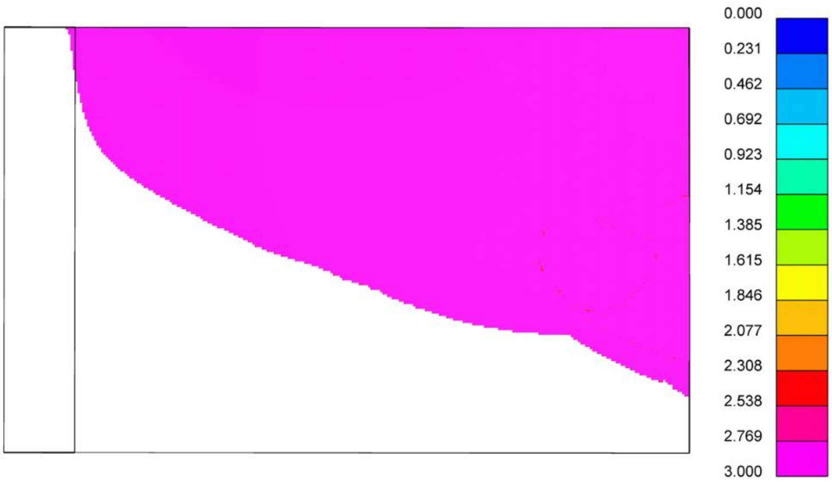
For the un-reinforced test design, the predicted delamination behaviour was assessed to understand the extent of its propagation through the laminate and the instantaneous mode ratio at the point of failure of the ply interfaces. With this information an appropriate Z-pin reinforcement pattern was designed to prevent delamination reaching the root region of the specimen, or significantly inhibit delamination propagation along the specimen length.

For verification testing, it will be necessary to perform a series of tests on both unreinforced (baseline) and reinforced (Z-pin) laminates to demonstrate the effect of the reinforcement on the impact response. A series of high velocity gelatine impact tests will be conducted using the prescribed test conditions and parameters.

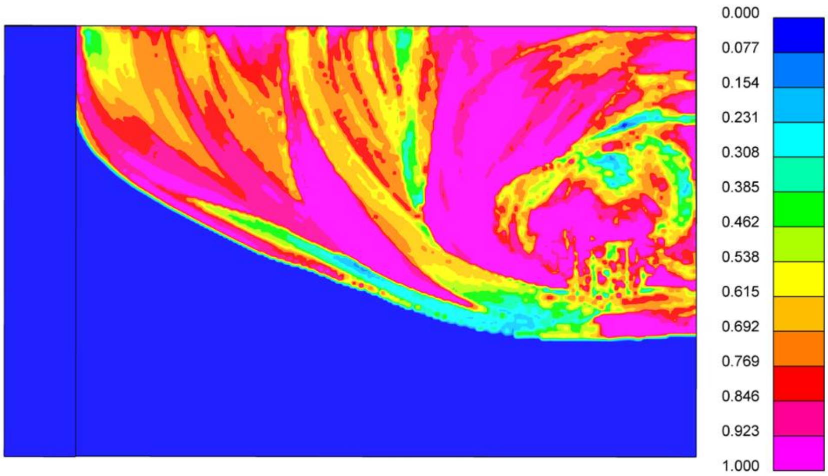
3. Results & discussion

Delamination across different specimen interfaces can be visualised in the commercial OASYS® D3PLOT software package. The output from an example analysis shown in Figure 3a. This is for a phase 2 type model with tapered stiffness properties and includes seven interface planes. The corresponding plot of mode-ratio at the time of element failure is shown in Figure 3b.

Standard C-scanning inspection of the tested specimen will be used to look for agreement between the predicted and experimental results for both unreinforced and reinforced test types, in terms of overall delamination profile. Fractography may also be used to verify the failure mode at the time of delamination through characterisation of features on the delaminated surfaces.



(a)



(b)

Figure 3: Fig 3(a) shows the predicted delamination result in terms of the damage parameter D at failure (D =3 for delaminated elements) when viewed along the plate z-axis, while Fig 3(b) shows the corresponding mode-ratio Ø at failure of the primary delamination plane (0 ≤ Ø ≤ 1) .

4. Summary

Review of the open literature has shown a lack of research into the larger-scale, higher-strain rate delamination behaviour of Z-pinned composites. This work has outlined a standard, more affordable test to produce delamination failure at a scale and strain-rate to exercise the large-scale bridging action of Z-pins typically seen at a structural level. The test also provides a validation article for new Z-pin modelling capability.

The specific test requirements and test design methodology has been outlined. A high-velocity soft-body impact test has been designed using a design-by-analysis approach by predicting the specimen behaviour using the explicit finite element solver LS-DYNA and novel cohesive element formulations developed at the University of Bristol.

The test design has taken a phased approach: with initial low-fidelity models using homogenised stiffness properties and a small number of delamination interfaces through to high-fidelity models containing each discrete ply, interface and details around ply drops. A thermal residual stress analysis has been undertaken at this final high-fidelity stage to assess the effect of cool-down ply stresses on delamination.

The predicted results for delamination and mode-ratio at failure have been obtained and reviewed. Comparison between these predicted results and the actual experimental results is now required. Delamination inspections techniques, e.g. C-scan and fractography, have been identified as the appropriate tools for conducting the post-test failure analysis. The planned verification tests have been outlined. A series of impact tests will be conducted on both unreinforced and reinforced laminate configurations.

Acknowledgement

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