Double Beam Shear (DBS) – a new test method for determining interlaminar shear properties of composite laminates

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Abstract: A new test method, the Double Beam Shear (DBS), has been developed at Loughborough University for the determination of the interlaminar shear (ILS) mechanical properties of fibre-reinforced laminated composite materials. The DBS uses an intact beam specimen with three equal-spaced supports under two loaders in such a way that each loader is applied at the middle of two supports. Under such set-up, two longitudinal pure ILS sections are induced in the two inner regions where the corresponding bending stresses are zero. It has been validated extensively using various composite laminates including carbon and E-glass fibre reinforcements, each in more than one thickness. The overwhelming majority of the tested specimens failed consistently in one of the inner regions with interior delamination. The magnitudes of the obtained ILS strengths of the composite materials are significantly greater than the corresponding apparent ILS strengths produced by the Short Beam Method. The DBS is especially able to induce ILS failure in certain composite materials, in which the Short Beam Method is not able to. The DBS Method is simple and easy to use.

Keywords: interlaminar shear (ILS) test, ILS strength, delamination and ILS test method

1 Introduction

Since the advent of fibre-reinforced composite laminates decades ago, their interlaminar shear (ILS) resistance has been a significant issue in industrial applications. This is because conventional composite laminates are devoid of reinforcement in the through-the-thickness direction, they are thus prone to delaminating due to the relatively low ILS strengths in comparison with other fibre-dominated strengths and delamination degrades the structural performance of the laminates. While various toughening techniques such as resin interleaving, z-pinning, stitching and 3D weaving have been developed [1] and some still under continued improvement, composite laminates still dominate the majority of industrial applications. As ILS strength characterises the ILS resistance of the laminates, consequently, having reliable and accurate ILS properties available early in the development process of load-bearing laminates is crucial in structural design, stress analysis, numerical modelling and component manufacturing.

2 Overview of ILS test methods

Over the years, a number of mechanical test methods were developed for determining ILS properties of composite laminates, as described in [2-4]. Only a few of them have since been progressed to the standard test methods, including Short Beam (Shear) Method (SBS) [5-8], V-notched Beam (VNB) (also known as Iosipescu) [9], V-notched Rail (VNR) [10] and Double-Notched Shear (DNS) via either tension [11-12] or compression [13]. Although the ASTM version [6] of the Short Beam Method no longer has the word ‘shear’ in its title, the acronym of the SBS is still used here, as it is well known across the community. While the SBS method uses an intact beam specimen, the rest of them use a notched beam or notched coupon specimen. Moreover, the SBS method has got two different versions in terms of specimen dimensions and loader and support diameters with two sub-variants. Specifically, the BS EN ISO version [5] of the SBS recommends the use of 2 mm thick wide beam specimens, the support span-to-thickness ratio (l/t) of 5 and width-to-thickness ratio (b/t) of 5, whereas the ASTM version [6] recommends the use of 4 mm thick specimens, the l/t of 4 and b/t of 2. There are two early BS EN versions [7-8] in the UK, which are still in use. All the SBS versions are simple to use and cost-effective in terms of generating apparent ILS strength. However, they all have substantial shortcomings in terms of stresses leading to failure. Whilst the gauge section of SBS specimens does not contain a pure ILS section, with the varying presence of bending and transverse normal stresses in the 'influence zone' around loader, SBS specimens often fail prematurely in a number of non-delamination modes. A location for the initiation of delamination, if occurs, could be anywhere between the contact region and one of the free ends.

Among all the standardised methods that use notched specimens, the VNB is recommended in [14] to be used for generating ILS strength and modulus design data. The VNR [10] uses a very thick specimen (56 mm) with very similar geometrical features to that of the VNB and induces ILS by directly shearing the notched region. The DNS [11-13] uses a straight coupon specimen with two rectangular across-width notches cut unsymmetrically into its depth (thickness) to its mid-plane from the opposite surfaces at two different longitudinal locations. Under a uniaxial tension/compression, a local bending of the un-notched region between the two unsymmetrical notches could induce a state of ILS. These notched specimens are prone to premature failure at one of their notch roots due to the stress concentrations, micro-cracks and/or broken fibres. In addition, different notch-to-notch longitudinal distances are used in [11-13]. Common to all the methods using the notched specimens is that failure of any kind does not usually occur at the pure ILS spot. These premature failures from these standards could render their ILS strengths unreliable and underestimated, if not invalid.

The DBS overcomes the aforementioned major shortcomings in those three standards. It uses an intact beam specimen with three equal-spaced supports under two loaders at the respective mid-span, creating a symmetric arrangement, as shown in Fig. 1. A state of pure and dominant ILS sections is induced in the gauge section such that it could initiate ILS failure or delamination with no or little interferences from the other stresses. In addition, the method that uses beam-type specimens without notches offers a simplicity and cost-effectiveness in specimen manufacturing, preparation and testing.

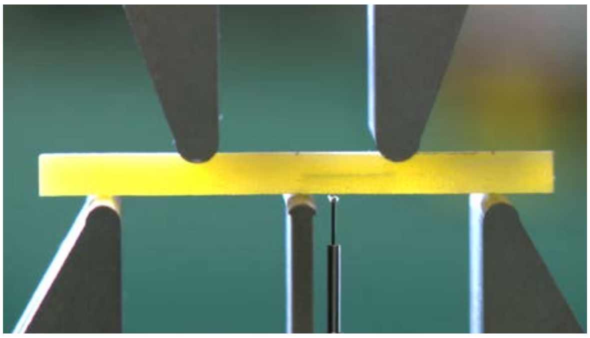

Fig. 1 A test set-up of the DBS method

3 Overview of DBS stress analysis

Loading and support of a DBS specimen are illustrated in Fig. 2 along with terminology. A systematic stress analysis of a composite beam under DBS has been carried out for laminates in various lay-ups and thicknesses at the (single) *l/t* of 5. The analytical results show that in the gauge section of the beam specimen there are four constant regions of ILS stresses with the magnitude of ILS stresses in the inner regions being much greater than those of the outer regions and that the two inner regions with the higher ILS stresses contain two longitudinal pure ILS sections, over which the bending stresses are zero and are not affected by transverse normal stresses from either the central support or the loaders, as indicated by the ILS and bending stress distributions in Fig. 3. These greater and dominant ILS stresses guarantee ILS failure or an occurrence of delamination at one of these pure ILS locations. In addition, the DBS test jig can easily be adjusted to perform SBS ILS tests. Clearly, with the much promoted level of ILS stresses within the two inner regions and the load being split via the two loaders, the DBS method have the lesser need to employ loaders with much larger diameters, like in [5], to minimize local crushing, as the 'influence zones' in the DBS specimens are much smaller with the maximum bending stress occurring at the central support.

4 Details of experimental validations

Extensive experimental validations at room temperature have been conducted using eight different types of composite material systems at the nominal *l*/*t* of 5. Each material has got three different lay-ups, two different thicknesses and width-to-thickness ratios. In each test, a laminate specimen was loaded up to when delamination occurred with a deflection at one middle distance between a loader and the central support being measured using a small LVDT or DVRT. The measured critical load that corresponded to the occurrence of delamination was used to calculate the ILS strength of the specimen and the slope of a load-deflection curve measured from one pure ILS location was used to calculate the ILS modulus. The cross-sectional dimensions of all specimens were measured at the central support for simplicity. In this report, the only small amount of test results was discussed. The corresponding SBS ILS strengths of the same materials were also obtained using the same DBS jig with the same *l*/*t* of 5 for comparison. The ILS test results for 32 ply 34-700/LTM45 carbon/epoxy in a quasi-isotropic lay-up $(-45/0/45/90)_{4s}$ are summarised in Table 1 for the DBS ILS strengths and in Table 2 for the SBS ILS strengths. The ILS test results for 32 ply fabric GF1300/LTM26 E-glass/epoxy in a lay-up of cross ply are summarised in Table 3 for the DBS ILS strengths and in Table 4 for the SBS ILS strengths/critical stresses.

5 Discussion of results

All tested DBS specimens failed consistently in delamination at one of the two pure ILS sections with almost no exception. For the 32 ply carbon/epoxy, the occurrence of delamination was interior within one of the inner regions and was around the mid-plane on the majority of the specimens, as shown in Fig. 4. Although all the SBS specimens also failed in delamination, which generally ran from the mid-span to one physical end and appeared below the mid-plane, it is difficult to establish where the delamination was initiated. In addition, for these quasi-isotropic carbon/epoxy specimens, the fact that multiple delaminations occurred below the mid-plane suggests that the interference of the transverse normal stress under the loader. The average DBS ILS strength of these carbon/epoxy specimens is about 21% greater than the corresponding SBS value.

Fig. 4 A failed DBS quasi-isotropic carbon/epoxy specimen

For the E-glass/epoxy specimens in a quasi-isotropic lay-up, the situation is much simpler. That is, the SBS Method is simply unable to fail these specimens in delamination or ILS. Instead, they all failed in either shear band, as shown in Fig. 5, or in flexure. The use of the DBS Method in this material demonstrates not only the pure ILS sections prevailed and enhanced the dominance of ILS stresses sufficiently to initiate delamination but also local crushing was minimised. One such failed E-glass/epoxy specimen is shown in Fig. 1. If comparison must be made between the two methods for this material, the average DBS ILS strength is about 55% greater than the apparent average ILS stress.

Fig. 5 A failed SBS quasi-isotropic E-glass/epoxy specimen

6 Conclusions

A new ILS test method, the DBS, has been validated extensively using various types of composite materials with different lay-ups, thicknesses and width-to-thickness ratios, though the only small portion of the ILS strength data was presented here. The DBS method is able to generate two longitudinal pure ILS sections within the two inner regions where not only the level of ILS stresses is much greater than that of the outer regions but also the corresponding bending stresses are zero. The overwhelming majority of the tested specimens failed consistently in one of the inner regions with interior delamination. The magnitudes of the obtained ILS strengths of the composite materials are significantly greater than the corresponding apparent ILS strengths produced by the Short Beam Method. The DBS is especially able to induce ILS failure in certain composite materials, in which the Short Beam Method is not able to. The DBS has been submitted to the ISO for standardisation.

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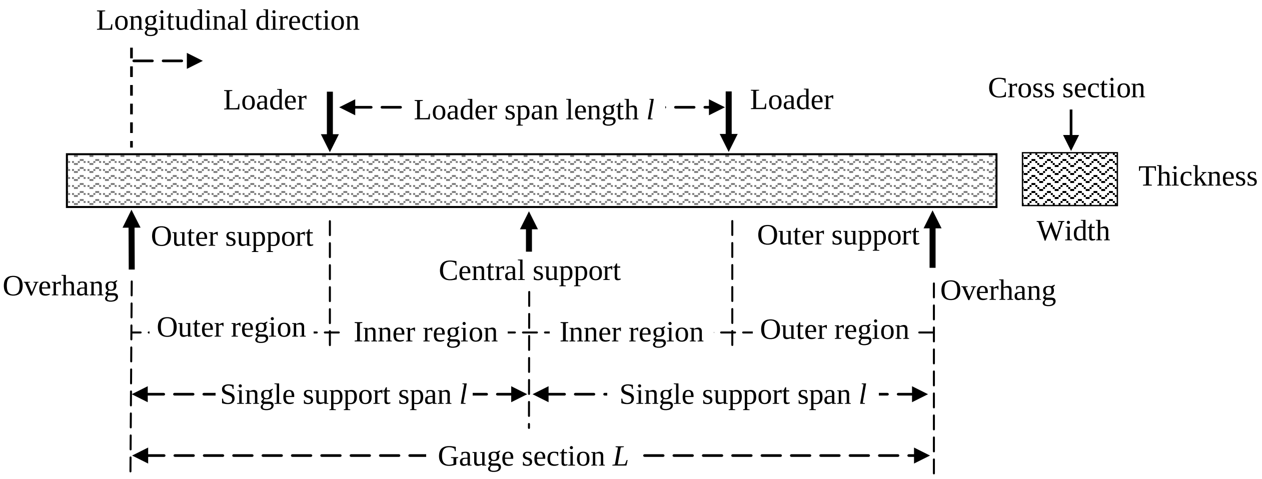

Fig. 2 Loading and supporting of a composite beam in the DBS method

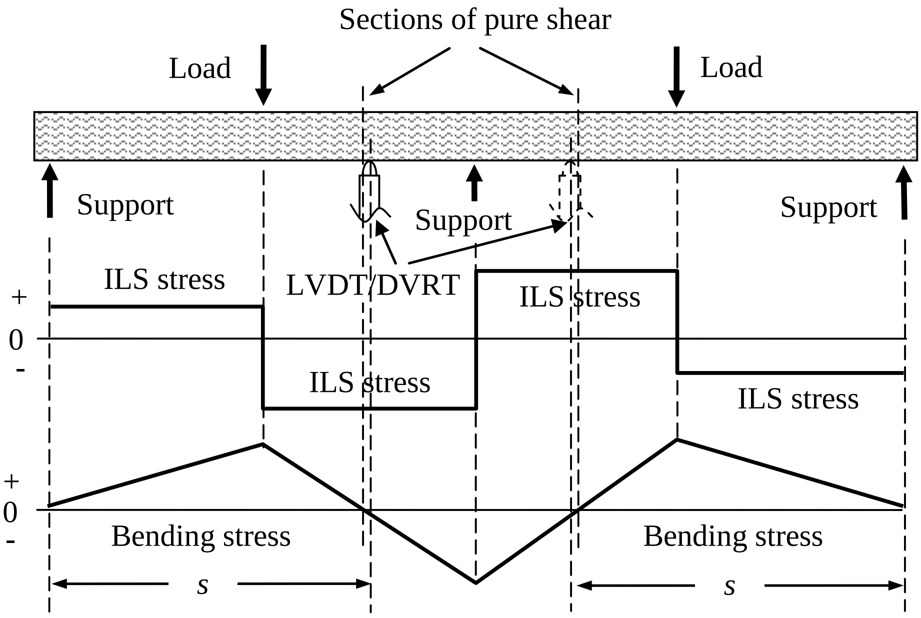

Fig. 3 ILS and bending stress distributions in the DBS specimen

Table 1 DBS ILS data of 34-700/LTM45 carbon/epoxy

Specimen ID	Width	Thickness	Critical load	ILS strength	Failure description
	mm	mm	kN	MPa	-
1-1	3.73	3.92	2.17	76.52	Delamination in an inner region
1-2	3.82	3.93	2.26	77.62	Delamination in an inner region
1-3	4.05	3.97	2.44	78.25	Delamination in an inner region
1-4	3.80	3.93	2.19	75.61	Delamination in an inner region
1-5	3.90	3.92	2.31	77.91	Delamination in an inner region
1-6	3.90	3.96	2.20	73.45	Delamination in an inner region
Av. of 6	3.87	3.94	2.26	76.56	Delamination in an inner region
S.D.	0.11	0.02	0.10	1.81	-

Table 2 SBS ILS data of 34-700/LTM45 carbon/epoxy

Specimen ID	Width	Thickness	Critical load	ILS strength	Failure description
	mm	mm	kN	MPa	-
C4QI5-1-1	6.41	4.06	2.111	60.37	Delamination on the left side
C4QI5-1-2	6.30	4.11	2.331	67.32	2 delaminations on the left side
C4QI5-1-4	6.50	4.10	2.249	63.22	2 delaminations on the left side
C4QI5-1-5	6.24	4.11	2.171	63.38	2 delaminations on the left side
C4QI5-1-6	6.43	4.10	2.195	62.41	2 delaminations on the left side
C4QI5-1-7	6.61	4.10	2.301	63.42	2 delaminations on the right side
Av. of 6	6.42	4.10	2.23	63.35	Delamination
S.D.	0.13	0.02	0.08	2.26	-

Table 3 DBS ILS strength data of fabric E-glass/epoxy in a quasi-isotropic lay-up

Specimen ID	Width	Thickness	Critical load	ILS strength	Failure description
	mm	mm	kN	MPa	-
32QI55DSB	7.08	5.29	5.107	70.71	Delamination
32QI56DSB	7.14	5.30	5.084	69.77	Delamination
32QI57DSB	7.16	5.29	5.147	70.57	Delamination
32QI58DSB	7.22	5.27	4.648	64.32	Delamination
32QI59DSB	7.13	5.26	4.679	64.76	Delamination
32QI60DSB	7.12	5.27	4.745	65.42	Delamination
32QI61DSB	7.15	5.29	4.780	65.32	Delamination
32QI62DSB	7.29	5.29	4.771	64.03	Delamination
32QI63DSB	6.72	5.31	4.350	62.98	Delamination
32QI64DSB	6.81	5.32	4.449	63.56	Delamination
Av. of 10	7.08	5.29	4.776	66.14	Delamination
S.D.	0.18	0.02	0.270	3.00	-

Table 4 SBS ILS test results of fabric E-glass/epoxy in a quasi-isotropic lay-up

Specimen ID	Width	Thickness	Critical load	ILS strength	Failure description
	mm	mm	kN	MPa	-
32QI1SBS	7.11	5.27	2.172	43.62	Shear band
32QI2SBS	7.45	5.27	2.125	40.67	Flexural failure
32QI3SBS	7.04	5.29	2.026	40.88	Flexural failure
32QI4SBS	7.50	5.30	2.266	42.75	Shear band & flexural failure
32QI5SBS	6.50	5.26	1.998	43.54	Shear band & flexural failure
32QI6SBS	7.72	5.27	2.305	42.57	Flexural failure
32QI7SBS	6.84	5.27	1.973	41.13	Flexural failure
32QI8SBS	7.33	5.26	2.271	44.09	Flexural failure
32QI9SBS	7.19	5.26	2.271	44.95	Flexural failure
32QI10SBS	7.25	5.26	2.182	42.75	Shear band & flexural failure
Av. of 10	7.19	5.27	2.159	42.70	-
S.D.	0.35	0.01	0.124	1.43	-