DOUBLE BEAM SHEAR (DBS) AS A NEW TEST METHOD FOR DETERMINING INTERLAMINAR SHEAR PROPERTIES OF COMPOSITE LAMINATES

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Abstract

We have developed a new test method, the DBS, at Loughborough University for determining interlaminar shear (ILS) properties in a single test. Overcoming the shortcomings of SBS and Iosipescu standards, the DBS method guarantees ILS failure at one of two pure ILS sections by promoting the dominance of ILS stresses. Extensive experimental validations of the DBS have been conducted along with SBS, using different types of composite material systems, involving different lay-ups. DBS ILS strengths are accurate, reliable and significantly greater in magnitude than SBS values. In particular, the DBS method is able to produce ILS failure in some composite laminates, which are unable to fail in delamination, using the SBS standard.

1. Introduction

Conventional composite laminates are devoid of reinforcement in the through-the-thickness direction, their interlaminar shear (ILS) strengths are thus dominated by resins and are relatively weak in comparison with other fibre dominated strengths in both in-plane and out-of-plane directions. The values of ILS strengths are typically just fractions of their tensile, compressive, or flexural strengths. As a result, under transverse deformation, load-bearing composite laminates are prone to delaminating at a relatively early stage of loading if induced ILS stress reaches a critical level. As delamination degrades structural performance and shortens service life, load-bearing composite laminated structures must be designed and manufactured such that a chance of its occurrence is to be minimised. As reliable and accurate ILS properties of composite materials are required early in the development process to ensure ultimately the attainment of a weight-efficient and cost-effective design, their thorough understanding is of paramount importance to structure design, material selection, stress analysis, numerical modelling, components manufacturing, mechanical testing and in-service repairs. Moreover, in the developments of new or novel composite materials within intent to improve their delamination or ILS resistance via, say, resin toughening, stitching/3D weaving, or incorporating carbon nanotubes [1], reliable and accurate ILS characterisation is essential to ascertain its effect on performance to show the effectiveness of the techniques.

2. Test methods for interlaminar shear testing

2.1. Current standard ILS test methods

Over the years, a number of ILS test methods were developed, as described in [2-4] but only a few of them have been established as standard test methods. Among them, the only SBS [5-8] and V-notched Beam (also known as Iosipescu) [9] have gained a wider popularity for different reasons. The popularity of the SBS method lies in its simplicity in terms of testing set-up and specimen preparations and its cost-effectiveness, though it produces only apparent ILS strength. The Iosipescu method is recommended [10] to be the one for generating design data. Nevertheless, both have a limitation in the determination of ILS strength.

The SBS method, using intact beam as specimens, has got two major versions [5-6] with different specimen dimensions, loader and support diameters. The BS EN ISO version [5] recommends a use of 2 mm thick 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 a use of 4 mm thick specimens, the *l*/*t* of 4 and *b*/*t* of 2. There are also two early sub-variants [7-8], differing from [5] only in loader and support diameters. The common limitation to the SBS method of all variants is the lack of a state of pure ILS stress on a longitudinal cross section within the gauge section so that the state of dominant ILS stresses could not be promoted even at a relatively small support span-to-thickness ratio (*l*/*t*) of 4 or 5. As a result, SBS specimens often fail prematurely in various mechanisms and at different locations from mid-span to one end of a beam specimen. This is because a different stress could prevail out of interactions of bending, ILS and transverse normal stresses, dependent on, among others, resin toughness, lay-up, specimen thickness and loader diameter in addition to *l*/*t*. In addition, there is a significant likelihood of overloading, if the occurrence of delamination does not usually lead to catastrophic failure, which is especially common from laminate specimens made of toughened resins. This could not only make a post-mortem identification of ILS failure (delamination) difficult but also overestimate the magnitude of apparent ILS strength. Therefore, it is appropriate that the SBS standard is used only for quality control and a screening of the composite materials.

In the Iosipescu standard, a typical tall beam specimen (19.1 mm) has two centrally symmetrical 90^0 notches and a pure ILS could be induced only at the middle of the two notch roots under an unsymmetrical ‘4-point bending’. As normal stresses in the notch region exist away from the notch roots in addition to stress concentrations at the notch roots, premature failure can often be initiated there. Moreover, machining notch roots break up reinforcing fibres at the roots and create micro-cracks in resin. This is compounded by the fact that ensuring the two notch roots to be located at the same ply orientation symmetrically of a non-directional (UD) specimen after machining is extremely difficult. Even if delamination or ILS failure occurs at one of the notch roots, it may well be induced by the existence of broken fibres, micro-cracks and local stress concentrations, aided with normal stresses. This type of premature failure could therefore lead again to an underestimation of ILS strengths, as the notch roots are far away from the pure ILS point. In addition, expensive and time-consuming specimen preparations make this method less favourable.

2.2. Double Beam Shear – New ILS test method

Against this backdrop, it has been highly desirable to develop a new ILS test method, which could overcome the aforementioned major shortcomings in current SBS and V-notched Beam standards and therefore is able to deliver reliable and accurate ILS strengths. In particular, the new method uses beam-type specimens without notches for simplicity and cost-effectiveness of specimen manufacturing and preparation and be able to induce a state of pure yet dominant ILS sections in the gauge section under load such that some overloading during testing to reach maximum load would not bring in a non-delamination damage mechanism. Such pure ILS state must initiate ILS or delamination failure with no or little interferences from other stresses.

The new Double Beam Shear (DBS) ILS test method [15] was developed at Loughborough University for determining both ILS strength and modulus of composite laminates in a single test. It uses an intact beam specimen of rectangular cross section with two cylindrical loaders and three cylindrical supports, as illustrated in Figures 1 and 2. Whilst the beam specimen is symmetrically supported vertically at three longitudinal locations with equal space (*l*), it is loaded vertically on the opposite side at two different longitudinal locations in such a way that each loader is applied at the middle of two support spans (*l*/4 and 3*l*/4), as illustrated in Figure 1. Thus the beam specimen has got two equal support spans (*l*) and the distance between the two loaders (i.e. loader span length *l*) is equal to both two support spans, giving the name of DBS. The gauge section of the beam specimen under load has got four stress regions. While each of the two inner regions (*l*/2) has got much greater ILS stresses than that of the two outer regions (*l*/2), it particularly contains a longitudinal section, at which the corresponding bending stress is zero, as indicated in Figure 2. Such pure ILS sections within the gauge section guarantee a dominance of the ILS stresses. Since they are fractionally away (closer to the loaders) from the two middle locations between the central support and one of the two loaders, those sections are likely to be away from the influence zones of normal stresses (here the central support in addition to the two loaders). As a result, test specimens, when set up with the single *l*/*t* ratio of 5, fail consistently in delamination at one of the two interior pure ILS sections. Their ILS strengths are more likely to be accurate, reliable and substantially greater in magnitude than those produced using either standard, as there is no interference from other stresses at the pure ILS sections. An ILS modulus of the specimen can be determined by using the slope of a measured load-displacement curve where displacement is measured at one of the two pure ILS sections.

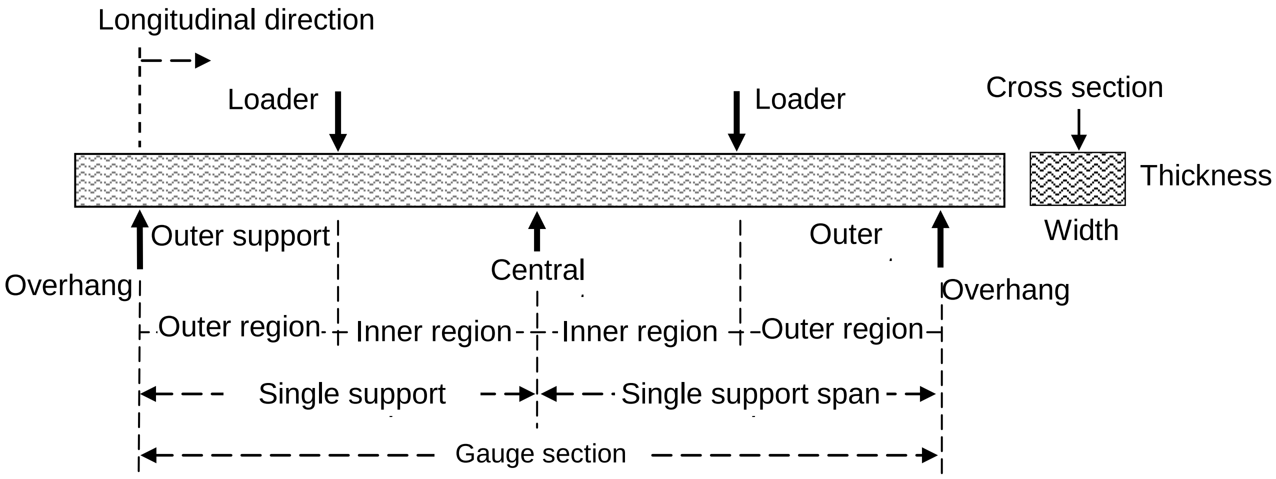

Figure 1. Terminology of loading and supporting of a composite beam in DBS method

Although this approach of loading and supporting composite beams was reported in [11-14] where authors called five-point bending (5PB), there has been no stress analysis or details of the stress distributions in both through-the-thickness and longitudinal directions of laminate beams ever reported in open literatures. A detailed stress analysis for the distributions of ILS and bending stresses in the beams along with the results of extensive experimental validations and industrial round-robin inter-laboratory will be presented elsewhere [15-17]. Nevertheless, interlaminar shear strength from the DBS theory is given by

$$\tau^{s}_{\max} = \frac{3\overline{V}}{2A} = \frac{33P_{\text{crit}}}{64bt} \tag{1}$$

in which P_{crit} is the load corresponding to the occurrence of delamination, b the beam width, and t the beam thickness.

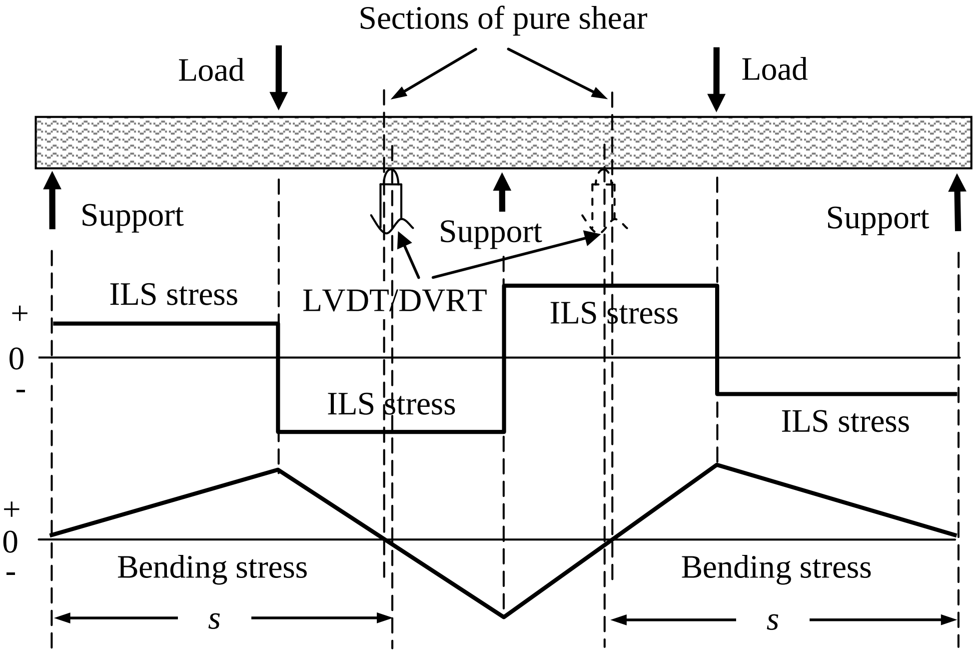

Figure 2. Loading and supporting configuration of DBS method

3. Experimental validations

3.1. Composite materials and specimen manufacture

Two types of composite systems used are unidirectional (UD) prepreg-based 34-700/LTM45 carbon/epoxy and woven fabric-based LTM26/PPG1062 E-glass/epoxy. For the former material, laminate panels of 32 plies were fabricated in lay-ups of $[(0°)]_{16s}$ (UD), $[(0°/90°)]_{8s}$ (cross ply) and $(-45^o/0^o/45^o/90^o)_{4s}$ (quasi-isotropic). All panels were cured in an autoclave using the manufacturer's recommended curing cycle of 18 hours at 60^oC under a pressure of 0.55 MPa (90 psi) and using a ramp rate of 2^oC/min. A nominal thickness of these panels is 4.0 mm with a cured nominal ply thickness of 0.128 mm. The UD mechanical properties of this composite system were determined as E_{11} of 127 GPa, E_{22} of 9.1 GPa, G_{12} of 5.6 GPa, and ν_{12} of 0.31. For the latter material, laminate panels of 32 plies were fabricated in lay-ups of $[(0°/90°)_F]_{16s}$ (cross ply) and $[(0^o/90^o)_F(\pm45^o)_F]_{16s}$ (quasi-isotropic). They were cured in an autoclave at 60°C under a pressure of 0.62 MPa (90 psi) for 6 hours. A nominal thickness of these panels is 5.3 mm with a cured nominal ply thickness of 0.166 mm. The translucent nature of E-glass fibres makes the occurrence of delamination or any other damage mechanisms very visible.

3.2. Experimental procedures

All cylindrical supports and loaders are 6.4 mm in diameter. For each 4 mm thickness specimen with the nominal support span-to-depth ratio of 5, a single support span was 20 mm with each overhang of the beam thickness. On one side of the specimen, all the anticipated contact locations were marked up with the vertical lines being drawn through the thickness. On the opposite side, the gauge section was painted with a thin layer of white correction liquid (carbon/epoxy specimens only) so that the occurrence of delamination could readily be visible. To execute a test, a 90^0 angle guide was placed over the supports from the distal side, then a specimen was placed over the supports against the edge of the angle guide to ensure that the specimen was perpendicular to the supports and loaders and that the specimen was aligned up with a mid-span marker. A miniature DVRT (differential variable reluctance transformer) was positioned at one of the pure ILS locations to measure beam deflection. An experimental set-up with the old jig is shown in Fig. 3. All the tests were carried out on a MAND universal testing machine at the crosshead speed of 3mm/min for ILS specimens. Load, crosshead displacement and deflection were recorded through an Orion delta 3530D data acquisition system at a sampling rate of 1 Hz. Short beam shear (SBS) tests were also carried out using the DBS jig with specimens being prepared following ASTM D2344 [6].

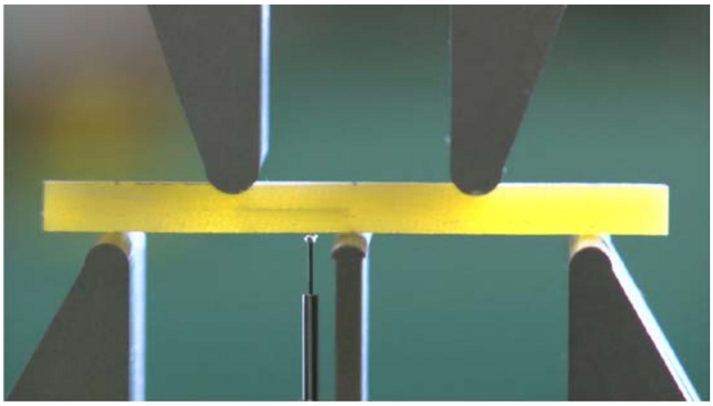

Figure 3. Test set-up of Double Beam Shear method

4. Test results and discussion

4.1. Failure characteristics in DBS and SBS composite beams

Part of experimental results are summarised in Tables 1-3 for carbon/epoxy laminates of three different lay-ups and in Table 4 for cross play fabric-based E-glass/epoxy laminates with the description of delamination/failure characteristics and locations. All carbon/epoxy and E-glass/epoxy specimens failed unanimously in delamination around one of the pure locations. Photographs of failed specimens are shown in Fig. 4 and Fig. 3, respectively. Specifically, all the longitudinal locations of ILS failure were found to be within one of the two inner regions of the beams where a state of pure shear existed and the highest ILS stresses were analytically predicted to occur in [15]. Whilst carbon/epoxy specimens tested in SBS also failed in delamination, SBS E-glass/epoxy specimens simply could not develop delamination and instead failed primarily in a through-the-thickness shear band.

4.2. ILS strengths from both DBS and SBS methods

The effect of lay-ups on the ILS strengths of carbon/epoxy specimens are clearly seen from Tables 1-3 with the ILS strength values decreased steadily with a decrease of percentage of longitudinal reinforcements, even though all specimens failed in delamination. For the UD carbon/epoxy specimens, the average DBS ILS strength generated is 32% greater than SBS value. A similar observation could be made for E-glass/epoxy specimens with the average DBS ILS strength being 35% greater, even though the SBS E-glass/epoxy specimens did not even fail in delamination.

Table 1 DBS and SBS test results of 32 ply UD carbon/epoxy specimens

Type of test	Specimen ID	Width mm	Depth mm	Load kN	ILSS MPa	ILS failure location*	
DBS	UD-1-1	4.24	4.21	3.365	97.278	IL	
	UD-1-2	4.30	4.24	3.722	105.345	IL	
	UD-1-3	4.30	3.87	3.439	106.567	IL	
	UD-1-4	4.28	3.85	2.892	90.488	IR	
	UD-1-5	4.20	3.80	2.927	94.481	IL&IR	
	UD-1-6	4.25	3.82	2.874	91.350	IR	
	UD-1-7	4.30	4.25	3.201	90.316	IR	
	UD-1-8	4.26	4.21	3.474	99.721	IL	
	UD-1-9	4.26	4.25	3.670	104.357	OL	
	UD-1-10	4.29	3.86	2.880	89.608	IL	
	UD-2-1	4.34	4.40	3.890	104.956	IL	
	UD-2-2	3.86	4.44	3.387	101.913	IL	
	Av. of 12				**98.03±6.59**	-	-
SBS	PNUD1SBS	5.28	3.71	1.807	69.18	LIR, TIU 1.66d	
	PNUD2SBS	5.20	3.71	1.875	72.89	LIL, TIU 1.47d	
	PNUD3SBS	5.29	3.72	2.027	77.25	LIR, TIU 1.73d	
	PNUD4SBS	5.04	3.75	1.940	76.98	LIL, TIU 1.72d	
	PNUD5SBS	5.09	3.75	1.844	72.46	LIL, TID 2.20d	
	PNUD6SBS	5.44	3.76	1.918	70.33	LIL, TIU 1.57d	
	PNUD7SBS	4.90	3.77	1.946	79.01	M, TID 2.10d	
	Av. of 7	5.18	3.74	1.899	**74.00±3.48**	-	-

* IL, IR and MP denote the inner left region, inner right region and mid-plane, respectively. LIQ, LEQ, UIQ and UEQ denote respectively the lower interior quarter, lower exterior quarter, upper interior quarter and upper exterior quarter. LIL & LIR - Longitudinal inner left & right, TIU & TID - Through-thickness inner up & down.

Table 2 DBS test results of 32-ply cross-ply carbon/epoxy specimens

Type of test	Specimen ID	Width mm	Depth mm	Load kN	ILSS MPa	ILS failure location	
1-1	4.43	3.87	3.09	0.88	93.0	IR	IQ
1-2	4.01	3.94	2.94	0.91	95.8	IR	UIQ
1-5	4.94	3.89	3.45	0.66	92.5	IR	IQ
1-6	3.85	3.93	2.72	0.84	92.6	IR	IQ
1-7	4.60	3.93	3.43	0.90	97.8	IL	IQ
1-8	4.09	3.89	3.02	0.90	98.0	IR	IQ
1-9	4.08	3.93	3.00	0.88	96.5	IR	IQ
1-10	4.09	3.91	3.04	0.91	97.8	IL	IQ
3-1	3.78	3.92	2.28	0.66	79.34	IL	MP
3-2	3.82	3.92	2.60	0.47	89.53	IL	MP
3-4	4.08	3.93	2.49	0.50	80.07	IR, IL	MP, LIQ, UQ
3-6	3.86	3.95	2.28	0.46	77.11	IR, IL	MP
3-7	4.11	3.91	2.31	0.49	74.12	IL	UIQ
3-12	3.94	3.81	2.59	0.49	88.96	IR, IL	MP, LIQ, UIQ
Av. of 14	3.93	3.91	2.43	0.51	**81.52±6.33**	-	-

Figure 4. Failed DBS carbon/epoxy specimen

Figure 5. Failed SBS carbon/epoxy specimen

Table 3 DBS test results of 32-ply quasi-isotropic carbon/epoxy specimens

Type of test	**Specimen ID**	**Width mm**	**Depth mm**	**Load kN**	**ILSS MPa**	**ILS failure location**	
1-1	3.73	3.92	2.17	0.40	76.52	IL	UIQ
1-2	3.82	3.93	2.26	0.36	77.62	IL	UIQ
1-3	4.05	3.97	2.44	0.34	78.25	IL	MP, UIQ
1-4	3.80	3.93	2.19	0.36	75.61	IL	MP, UIQ
1-5	3.90	3.92	2.31	0.34	77.91	IR	MP
1-6	3.90	3.96	2.20	0.32	73.45	IL	UIQ
Av. of 6	3.87	3.94	2.26	0.35	**76.56±1.81**	-	-

Table 4 DBS and SBS test results of 32 ply cross ply fabric E-glass/epoxy specimens

Type of test	**Specimen ID**	**Width mm**	**Depth mm**	**Load kN**	**ILSS MPa**	**ILS failure location**	
DBS	32CP29DSB	7.41	5.41	5.531	71.14		
	32CP30DSB	7.19	5.40	5.300	70.39		
	32CP31DSB	7.59	5.40	5.745	72.28		
	32CP32DSB	7.02	5.40	5.303	72.13		
	32CP33DSB	6.91	5.33	5.311	74.35		
	32CP34DSB	7.21	5.33	5.250	70.44		
	32CP49DSB	6.74	5.37	4.980	70.95	LIL	TID 2.73d
	32CP50DSB	7.02	5.34	5.227	71.90	LIR	TIU 2.56d
	32CP51DSB	7.19	5.32	5.076	68.43	LIL	TID 2.70d
	32CP52DSB	7.24	5.34	5.085	67.82	-	-
	32CP53DSB	7.19	5.35	4.972	66.65	LIR	TID 2.73d
	32CP54DSB	7.18	5.35	4.919	66.02	LIR	TID 2.83d
	32CP55DSB	7.25	5.35	5.319	70.81	LIL	TID 2.70d
	32CP56DSB	7.11	5.33	5.044	68.63	LIL	TID 2.70d
	32CP57DSB	7.14	5.33	5.120	69.37	LIL	TID 2.74d
	32CP58DSB	7.11	5.32	4.661	63.54	LIL	TID 2.68d
	32CP59DSB	7.10	5.30	4.662	63.88	LIL	TID 3.17d
	32CP60DSB	7.12	5.32	4.663	63.48	LIL	TID 2.73d
	32CP61DSB	7.14	5.33	4.630	62.67	LIL	TID 2.71d
	32CP62DSB	7.19	5.31	4.759	64.26	LIL	TID 2.73d
	32CP63DSB	7.27	5.33	5.299	70.51	LIL/R	TID 2.73d
	32CP64DSB	7.14	5.32	5.100	69.23	LIR	TIU 2.59d
	Av. of 22	7.14	5.32	4.943	**68.02±3.49**	-	**-**
SBS	32CP1SBS	7.38	5.30	2.520	48.32	LSB	-
	32CP2SBS	7.35	5.31	2.564	49.27	LSB	-
	32CP3SBS	6.69	5.28	2.285	48.52	LC	-
	32CP4SBS	7.31	5.30	2.482	48.05	LC	-
	32CP5SBS	6.95	5.31	2.343	47.62	RSB	-
	32CP6SBS	7.34	5.28	2.559	49.52	RSB	-
	32CP7SBS	7.48	5.31	2.773	52.36	RSB	-
	32CP8SBS	7.19	5.30	2.631	51.78	LSB	-
	32CP9SBS	7.11	5.30	2.711	53.96	LSB	-
	32CP10SBS	6.80	5.32	2.572	53.32	RSB	-
	Av. of 10	7.16	5.30	2.540	**50.27±2.24**	-	-

LSB/RSBwD - left and right shear band with delamination, LC - local crushing, CFF - Central flexural failure under loader & at the tensile surface

5. Conclusions

The DBS method shows two dominant longitudinal pure ILS sections. The experimental data generated using two different composites material systems along with three different lay-ups demonstrate that delamination occurs consistently at where the DBS method predicts. Moreover, the DBS method promoted the dominance of ILS stresses in E-glass/epoxy specimens, whereas SBS standard simply could not do. In particular, from both material systems, their corresponding average DBS ILS strength values are significantly greater than the SBS values. This shows the significant advantages of the DBS method and offers the much better alternative to future determination of ILS strengths of composite laminates.

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