EFFECTS OF STRUCTURAL DETAILS ON DELAMINATION AND FATIGUE LIFE OF FIBERGLASS LAMINATES

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Abstract

Laminates fabricated from stranded glass fiber fabrics commonly used in wind turbine blades have recently been found to exhibit a strong sensitivity to fiber content. The tensile fatigue resistance decreases rapidly over a narrow range of fiber volume fraction as the fiber content is increased. This transition is typically in the range of 40 to 50 percent fiber by volume, depending on the fabric and laminate configuration. Many manufacturing processes produce fiber contents in this range, and local variations in fiber content around details such as stiffeners are often not well controlled. Thus, the fatigue resistance around structural details may drop precipitously if the fibers are locally pinched during manufacturing.

A second problem associated with structural details is delamination between plies of fabric due to out-of-plane stresses. Delamination can lead to breakdown of a structure directly, often with subsequent buckling, or indirectly, by accelerating fatigue breakdown of the fiber strands.

This paper explores the fatigue resistance of a number of structural details which may be associated with local increases in fiber content as well as delamination. The structural details investigated include ply drops, skin-stiffener intersections, local matrix rich and transverse fiber areas, and surface indentation. These are compared to unflawed laminates and laminates containing severe flaws such as through-thickness holes. The results are represented in two ways. First, as the strain required to produce a one-inch delamination in 10^5 cycles; and second, as knockdown factors on the maximum strain to produce total laminate failure in 10^6 cycles. The strain levels to produce a one-inch delamination in 10^5 cycles varied from 0.4% strain to over 1.0%, with several cases showing no delamination. The worst case for delamination was surface ply drops. The knockdown factors on strain for a 10^6 cycle lifetime ranged up to 2.5, with the worst case being a molded-in surface indentation which pinched the strands to produce a locally high fiber content.

Introduction

Details such as ply drops and stiffener intersections are inherent in the structure of most fiberglass wind turbine blades. As part of the fatigue and advanced blade structural development program at Montana State University, the effects of these and other details on the fatigue performance of laminates have been investigated. Detailed results of these and other tests are included in the DOE/MSU Fatigue Database [1].

Structural details are a potential problem in composite material structures for several reasons. They may concentrate stresses simply through changes in geometry, as is common with metal structures. They also may produce local changes in reinforcement architecture (fiber packing, bundle spacing, matrix rich regions, etc.) Which can cause stress concentrations associated with variations in local material modulus. There is also the potential for local property changes associated with fiber orientation and variations in fiber content, which can lead to premature failure. Thus, the skin of a blade, designed for good fatigue performance, could be compromised by the presence of intersecting stiffeners or by ply drops in areas of thickness tapering, with similar effects at ply fabric joints. Figure 1 shows strand packing around a good quality resin transfer molded (RTM) stiffener intersection described in more detail in an associated paper [2], and Figure 2 shows a section through a typical ply drop.

A reason for concern is that the fiber content can

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become locally high as the strands are crowded together in the detail areas. Studies in recent years [3-5] have shown a sharp transition in fatigue resistance associated with increasing fiber contents in the range of 40 -50 % fiber by volume. Figures 3 and 4 taken from Ref. 5 show this transition for typical laminates containing 50 to 100% of the fiber in the load (0º) direction, with the remainder of the layers oriented at ±45º. The lines in Figure 3 show normalized S-N trends of the form:

$$S/S_o=1.0-b \text{ Log } N \qquad (1)$$

where S is the maximum fatigue stress, S_o is static strength, N is the cycles to failure, and the slope, b, is the fatigue coefficient. The results show a change in fatigue coefficient, b, from about 0.10 at low fiber contents, to about 0.14 at higher fiber contents. These coefficients represent the best possible fatigue resistance at low fiber content (b=0.10), and the worst observed resistance at high fiber contents (b=0.14). The triax fabrics, with tightly stitched together 0º and ±45° layers, perform poorly at all fiber contents. The concern is that, even if a blade is manufactured for optimum fatigue resistance, the resistance in the structural detail areas could knock the allowable strains down by a factor of two to three due to local fiber crowding.

Experimental Methods

All materials were fabricated at MSU by resin transfer molding. Reinforcing fabrics from Knytex were used in all cases, with an orthophthalic polyester resin (CoRezyn 63-AX-051) with 2% methyl ethyl ketone peroxide as a catalyst. Plates were cured under ambient conditions, followed by a post cure at 60°C for two hours. Details of molding , specimen preparation, and testing can be found in Refs. 6 and 7. These materials are typical of those from hand lay-up and other processes used by blade manufacturers. The reinforcing fabrics included D155 stitched weft unidirectional, A130 woven warp unidirectional, and DB120 stitched ±45°.

Structural details were incorporated into the materials during molding in most cases. Ply drops were incorporated in area of thickness tapering as shown in Figure 2. A tough epoxy adhesive, Hysol EA 9303.2NA, was used to reinforce the ply drop area, where indicated. Other features such as surface indentations and matrix rich areas were either molded in or bonded on to simulate possible effects of stiffener intersections, etc., as described later. Actual stiffeners were included in the form of I-beam web-flange intersections, following fabrication procedures described elsewhere (mostly secondary bonding of the stiffener to the flange [8]).

Results and Discussion

Delamination at Ply Drops

Detailed results for the growth of delamination cracks at various ply drop geometries were reported last year [8]. Fatigue tests were run under tensile loading (R=0.1, where R is the min. force/max. force) at relatively low cycles, on the order of 10^5, at various maximum stress levels. Table 1 presents a summary of the results reduced to a form which may be of use to designers. The base laminate is identified in the database [2,5] as DD5 which has a ply configuration $[0/\pm45/0]_s$, with 72% 0° layers and an overall fiber content of 36% fiber by volume. This material is a typical structural laminate for wind turbine blades and it has good tensile fatigue resistance, see Figure 3. Most of the laminates in Table 1 had fiber contents in the range of 30-36% as detailed in Ref. 7.

When plies are added to this approximate laminate configuration, then dropped in the coupon gage section, they are indicated by an (*) in Table 1. Thus, laminate type ESA has an single 0º surface ply dropped , while ESB has a single 0º interior ply dropped. When the data presented in Ref. 2 are reduced to obtain an approximate strain to produce significant (25 mm) delamination length within 10^5 cycles, the various laminate types in Table 1 can be compared. Cases ESJ, ESK, and ESM represent special treatment to increase delamination resistance at the ply drop boundaries. As detailed in Ref's. 6 and 7, "z-spiked" refers to plunging some of the fiber from the ply drop edge into the adjacent layers (the z-direction). ESK and ESM contain a tough Hysol epoxy adhesive at the ply drop edge, applied prior to molding.

All of the strain levels shown for delamination are above the typical working strains of blades. However , those strain levels might be reached in service in stress concentration areas, and in many cases are well below the fatigue strain capability of the base laminate at the strain level shown. Thus, those strain values below about 1.0% would likely produce delamination prior to laminate fatigue failure, as discussed later. The results clearly show that surface ply drops delaminate at much lower strains than interior ply drops (ESA and ESE vs. ESB, ESC, and ESF). The surface ply drop delamination resistance can be increased by the treatments in ESJ and ESK, but it is probably easier to simply embed the ply drops, as in ESB, ESC, and ESF. Dropping two internal plies at the same location produces delamination at lower strains (ESH vs. ESB) that are equivalent to a surface ply drop. Multiple internal ply drops, when spaced at various distances from 13 to 48mm, rather than at the same spot as in ESH, produced delamination similar to a single internal ply drop (ESI vs. ESB). Figure 5 shows no clear trend with ply drop spacing, with all spacings giving similar results to a single ply drop (ESB), and much better resistance than for a double ply drop at the same location (ESH). It did appear that the delamination rate could approximate that of ESH if the delamination at the closer spacing grew to where they overlapped, producing a geometry like ESH. While complete data are not available to explore this question, a ply drop spacing of at least 25mm, with interior, single ply drops, should avoid this problem.

A related parameter is the thickness of the plies dropped vs. the total laminate thickness. As indicated by modeling [7], delamination is reduced if the percent thickness reduction is smaller, as with a thicker base laminate.

Laminates with ±45° layers dropped were also tested, but these failed in tension prior to any delamination. Thus, it appears that single or double ±45° ply drops with the DB 120 fabric will not produce delamination [7].

Two other representations of delamination resistance are given in Table 1, the apparent arrest strain for a growing delamination (typical data shown in Figure 5), and the threshold strain where delaminations were not observed to initiate in the 10^5 cycles tests. These are approximate values from the limited test data in Ref. 7. These results generally follow the trends described above for a 25mm long delamination in 10^5 cycles, but at lower strain values. It should be noted, as shown in the next section, that the ply drop might shorten laminate lifetime in some cases, even if it does not produce any delamination.

Effect of Ply Drops on Fatigue Lifetime

As noted in the introduction, a structural detail such as a ply drop can concentrate stresses, and can also rearrange local reinforcement packing and orientation. This may result in reduced lifetime, whether or not delamination occurs. In fact, some delamination and matrix cracking at stress concentrations, such as holes, in composites is widely recognized to reduce the stress concentration in the load bearing fiber strands, improving the fatigue performance [9].

Figure 6 compares the S-N fatigue data under tensile fatigue for high and low fiber content (V_f) laminates, with and without a double ply drop. The high fiber content results are about the same , whether or not there is a ply drop present. The low fiber content laminates, which show much improved fatigue resistance in the absence of ply drops, are adversely affected by the double ply drop, producing a steeper S-N curve which is now similar to the high fiber content cases here and in Figures 3 and 4. Thus, it appears that the more fatigue resistant materials in Figures 3 and 4 (those with lower fiber contents) lose their advantage when used in conjunction with a double ply drop. This may be due to locally higher fiber packing in the ply drop area (Fig. 2). The laminates in Figure 6 used weft unidirectional D155 fabric for the 0° layers; similar findings are presented in Ref. 7 for the warp unidirectional fabric A130 in similar cases.

Somewhat less severe results were obtained when a single layer ply drop was used (ESB) instead of the double ply drop in ESH. Figure 7 compares these two cases. The fatigue resistance for ESB is now about midway between values for good and bad materials in Figures 3 and 4, but the laminates in Figure 7 were at a medium overall fiber content of 44%.

Delamination may appear to be significant in terms of compromising the integrity of the laminate. However, when specimens were fatigued to a significant fraction of their lifetime (n/N), then tested for residual tensile strength, Sr, the residual strengths given for individual tests in Table 2, normalized by the initial strength, S_o, are between 0.85 and 0.95. Thus, delamination at ply drops does not severely reduce laminate strength over most of the lifetime range. Further residual strength results will be available in the future.

Ref. 7 presents additional results for ply drops under compression loading and in I-beam substructural elements.. In general, strains to produce delamination in beam flanges were consistent with those in the coupon studies. While delamination occurred sooner on the tensile flange than on the compression flange, the compression flange delamination was sudden and extensive. Delamination under compression fatigue will be investigated in more detail in the future.

Effect of Other Structural Details

As indicated in Figures 8 and 9, a number of cases have been investigated which simulate possible effects of structural details, like stiffeners, on base laminate fatigue resistance. These cases involve variations of resin rich areas, crowding of fibers, and exterior geometry. Fatigue S-N at R=0.1(tension) have been obtained for all cases, and the strain to produce failure in 10^6 cycles determined. The knockdown factor for design, F, is the ratio of 10^6 cycle strain without and with the detail present. Thus, the allowable fatigue strain in the design should be reduced by dividing by F if a similar feature is present. Figure 8 gives S-N data for several cases from Figure 9. The base laminate is $[0/\pm45/0]_s$ with V_f=36%, which has good fatigue resistance, as shown in Figures 3 and 4.

Composites have remarkable tolerance of many types of flaws which would produce problems in metals. For example, the cracked 90° material patch simulation, a resin rich area on the order of the laminate thickness, produces no measurable fatigue life reduction, even though a crack grows through the patch, as shown, early in the lifetime. However, if the 90° ply patch is molded into the interior, it reduces the lifetime significantly, apparently due to the increase in fiber content this forces on the remainder of the laminate in the area (34 to 47% fiber). This moves the base laminate into the poor fatigue condition in Figure 4, due to the higher local fiber content.

The most severe structural detail shown in Figure 9 is, somewhat surprisingly, a simple molded-in indentation in the laminate surface, caused by a bump on the mold surface. No fibers are cut, but the fibers are locally compressed together to increase the local fiber volume from 36% away from the indentations, to 52% at the minimum thickness. This again shifts the material into the high fiber content, poor fatigue resistance condition in Figures 3 and 4. The surface indentation is intended to simulate the compression of the fibers over a molded-in stiffener, but the surface geometry may also contribute to the effect; local delaminations at the shoulder of the indentation were observed prior to failure. The case with smooth surfaces, but a similar fiber content increase caused by inserted 90° material may be more representative of typical structure. The knockdown factor here is 1.4 compared to 2.5 for the indentation.

By way of comparison, the I-beam structure shows very little effect on fatigue when the tensile flange fatigue performance is considered [8]. Here, the web is bonded to the flange after molding each part separately, so that no local strand compression occurs, as compared with a molded-in stiffener. As discussed in the previous section, ply drops can have a significant effect on fatigue life, and significant knockdown factors if the laminate has a low fiber content.

An important aspect of Figure 8 is that the base laminate, except where noted, has a low fiber content, and good fatigue performance. This can then be degenerated to poorer fatigue performance if the local fiber content increases and/or the surface geometry changes, inducing local delamination.

Conclusions and Implications

The results from the ply drop experiments indicate that ply drops of the D155-0° weft unidirectional fabric need not lead to delamination prior to laminate failure if the following conditions are met: drop only individual plies at a particular point; drop the plies on the interior rather at the surface; and space adjacent ply drops at least 25mm apart where multiple ply drops are needed. These recommendations are not optimum for manufacturing, but neither are they a major expense. While properly configured ply drops need not lead to premature delamination, they are likely to require a knock down factor in design if the base laminate has a low fiber content and other characteristics such as a high 0° material content [5] which produce good tensile fatigue performance.

The fatigue data and knockdown factors for ply drops and other structural details suggest several implications. First, even some simple variations such as surface indentations can produce a significant increase in fatigue sensitivity in laminates with good base material fatigue characteristics. Second, it is not clear that a complex composite structure such as a blade can be manufactured without some details of this type. Third, there may be little benefit in choosing fatigue resistant laminate types if they are this sensitive to detail features, and if the poorer-behaving laminates do not show these effects. Further work is needed to explore whether materials such as triax would require only low knockdown factors. Finally, in the long run, there is a clear need to develop manufacturing approaches which give control over reinforcement architecture near structural details. This is particularly important for processes such as resin transfer molding (RTM) which may involve molded-in design details. Testing of more realistic RTM molded blades and substructural elements is planned in future work.

References

1. Mandell, J.F., et. al., "MSU/DOE Wind Turbine Blade Composite Material Fatigue Database" Released November 1995.

2. Cairns, D. S., Haugen, D. J., Mandell, J. F., and Samborsky, D. D., "Fracture of Skin/Stiffener Intersections in Composite Wind Turbine Structures," Wind Energy 1998, ASME/AIAA, January, 1998 (to be published).

3. Samborsky, D. and Mandell, J.F., "Fatigue Resistant Fiberglass Laminates for Wind Turbine Blades" Wind Energy 1996, ASME, pp 46-51 (1996).

4. Mandell, J. F., Cairns, D. S., and Samborsky, D.D., "Montana State University Program for the Development of Fatigue Resistant Wind Turbine Blade Structures" Wind Energy 1997, AIAA/ASME, January, 1997.

5. Mandell, J.F. and Samborsky, D.D., "DOE/MSU Composite Material Fatigue Database: Test Methods, Materials, and Analysis," Sandia National Laboratories Contractors Report (to be published).

6. Cairns, D.S., Mandell, J.F., Scott, M.E., and Macagnano, J.Z., "Design Considerations for Ply Drops in Composite Wind Turbine Blades" Wind Energy 1997, January 1997.

7. Scott, M.E., "Effects of Ply Drops on the Fatigue Resistance of Composite Materials and Structures," M.S. Thesis, Chemical Engineering, Montana State University, (1997).

8. Mandell, J.F., Combs, D.E., and Samborsky, D., "Fatigue of Fiberglass Beam Substructures" Wind Energy 1995, W.D. Musial, S.M. Hock, D.E. Berg(eds), SED-Vol. 16, ASME, pp 99-106 (1995).

9. Mandell, J.F., "Fatigue Behavior of Short Fiber Composite Materials (Ch. 7)," The Fatigue Behavior of Composite Materials, K.L. Reifsnider, Ed., Elsevier (1990).

Table 1. Comparison of delamination resistance of different ply drop configurations.

Laminate	Lay-up (* indicates dropped ply)	% Strain for 25.4 mm delamination in 10^5 cycles	Arrest % strain[1]	Threshold % strain[2]
ESA	$[0^*/(0/\pm45/0)_s]$	0.6	0.5	0.4
ESB	[0/0*/±45/0/0/±45/0]	1.1	1.1	0.8
ESC	[0/±45/0/0*/0/±45/0]	1.1	1.1	0.8
ESE	$[0^*/(0/\pm45/0)_3]$	0.6	0.4	0.4
ESF	$[0/0^*/\pm45/0/(0/\pm45/0)_2]$	1.0	1.0	0.7
ESG	$[0^*/0^*/(0/\pm45/0)_3]$	0.4	--	--
ESH	$[0/0^*/0^*/\pm45/0/(0/\pm45/0)_2]$	0.7	0.6	0.5
ESI	[0/0*/0*/±45/0/0/±45/0]	1.1[A]	1.0	0.7
ESJ	$[0^*/(0/\pm45/0)_s]$ "Z-Spiked"	0.8	--	--
ESK	$[0^*/(0/\pm45/0)_s]$ Hysol EA 9309.2NA	0.7	--	--
ESM	[0/0*/±45/0/0/±45/0] Hysol EA 9309.2NA	1.1[B]	--	--

[1]- no further growth over most of the 10^5 cycles
[2]- no delamination after at least 10^5 cycles.
Fabrics: 0°: D155; ±45°: DB120
Laminates ESO, ESR and ESP not shown, ±45° layers did not delaminate.
[A]- Same as ESB, except multiple ply drops.
[B]- No delamination; however, failure of coupon occurred at ply drop.

Table 2. Residual strength of ESH laminate after being fatigued (R=0.1)*

Residual Strength of ESH laminate after being fatigued							
Coupon #	Fiber content %	Max. Cyclic Stress, MPa	Cycles	n/N_o	Initial Strength, S_o, MPa	Residual Strength, S_r MPa	S_r/S_o
ESH 205	36	276	40,000	0.8	703	600	0.853
ESH 213	36	276	20,000	0.4	703	675	0.960
ESH 409	44	207	1.1E6	1.1	746	686	0.920
ESH 404	44	176	1.1E6	0.11[A]	746	717	0.961

[A]- Lifetime estimate used was 10^7 cycles, however test was stopped at 10^6 cycles after no delamination.
* Individual specimen results

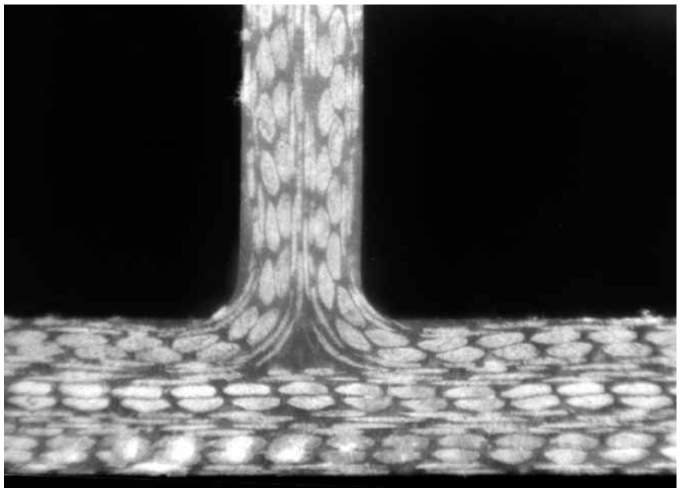


Figure 1. Cross - section through integrally molded skin-stiffener intersection showing fiber strands for 0° (large strands) and ±45° (small strands) layers

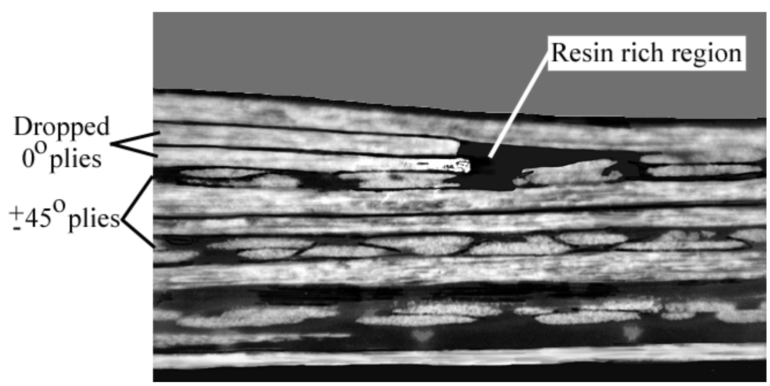


Figure 2. Photomicrograph of ESH laminate (Table 1) showing resin rich region ahead of ply drops and ply crowding behind.

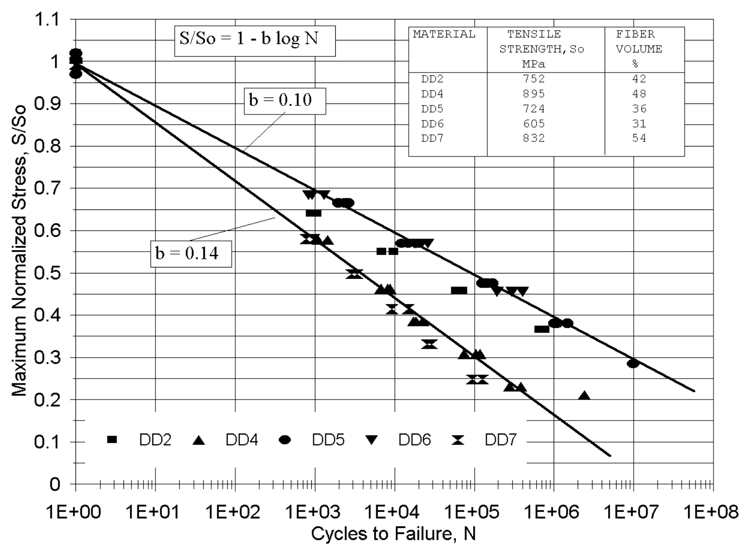


Figure 3. Normalized tensile fatigue data for DD materials $[0/\pm45/0]_S$, S/So = 1-b log N

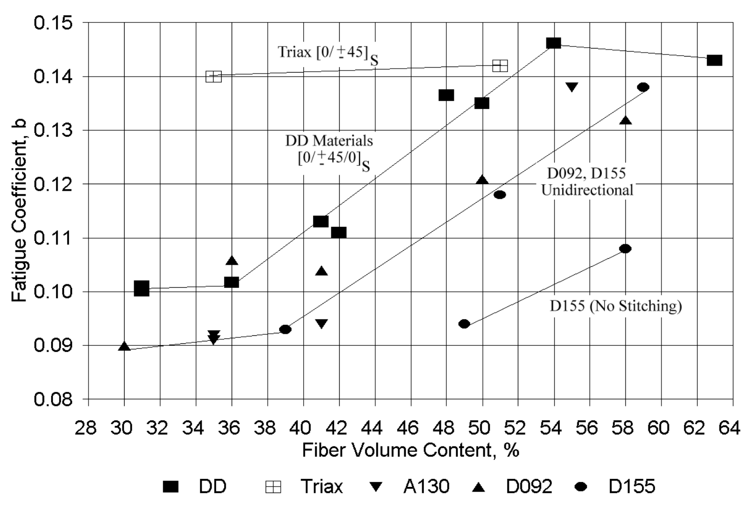


Figure 4. Fiber content vs. fatigue sensitivity coefficient, b. S/So = 1 - b log N,
A130, D092, D155, DD and Triax materials, R = 0.1.

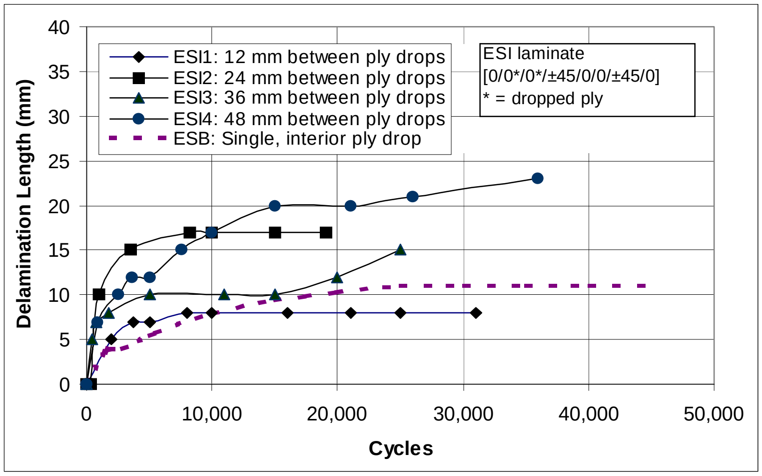


Figure 5. Effect of different spacing between ply drops, R=0.1, ESI laminate (Two 0° ply drops) at 276 MPa.

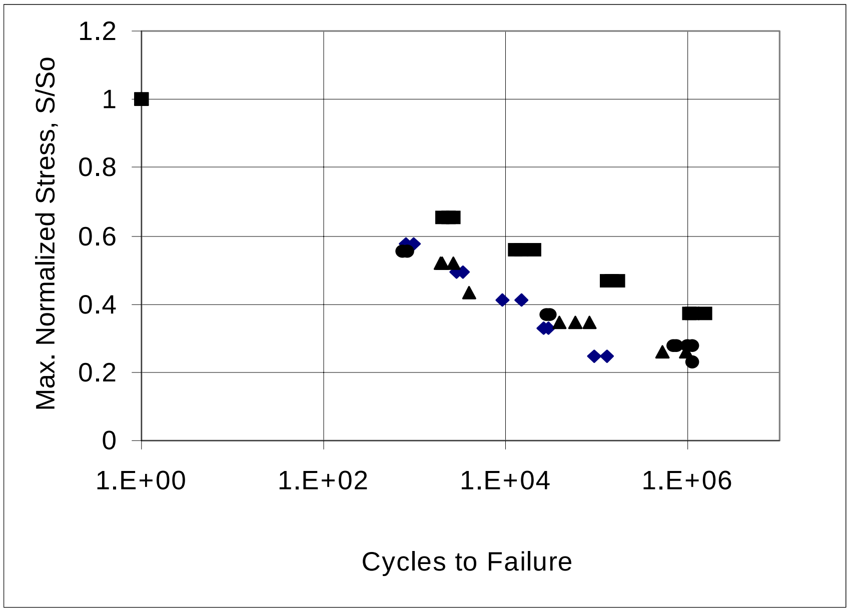


Figure 6. Effect of fiber content on the normalized S-N Data, R=0.1, for control DD materials [0/±45/0]s compared to ESH laminate (Two interior 0° ply drops).

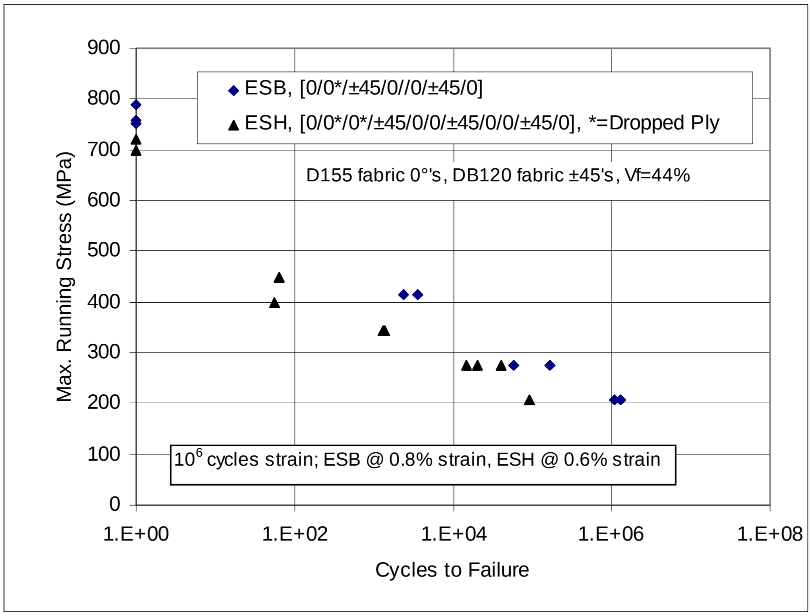


Figure 7. Tensile fatigue (R=0.1) S-N curves for ESB (Single 0° internal ply drop) and ESH (Two interior 0° ply drops).

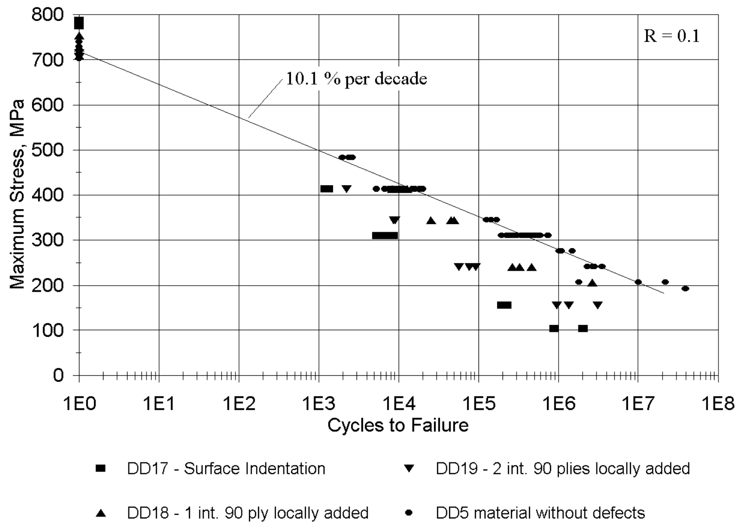


Figure 8. Effect of defects which produce locally higher fiber content on the tensile fatigue behavior of DD5 material with D155 0° Fabric and DB120 ±45° Fabric.

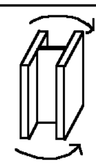
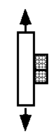
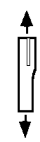
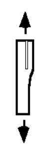
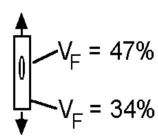
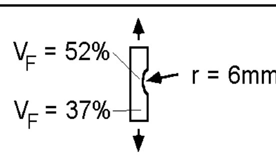
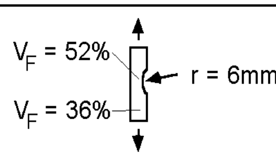
Detail	Sketch		F
Simple Coupon (Straight Material)			1.0
Bonded Stiffener (Beam - Web)			1.2
Cracked Transverse 90° Patch			1.0
Single Interior 0° Ply Drop		$V_F < 0.4$	- - -
		$V_F > 0.4$	1.2
Double Interior 0° Ply Drop		$V_F < 0.4$	1.6
		$V_F > 0.4$	1.0
Locally Higher Fiber Content D155 / DB120 Fabrics (2 - 90° plies in center)			1.4
Surface Indentation A130 / DB120 Fabrics (V_f increased, thickness reduced by 25%)			1.8
Surface Indentation D155 / DB120 Fabrics (V_f increased, thickness reduced by 25%)			2.5

Figure 9. Tensile fatigue knock - down factors (F) for selected structural details relative to simple coupons of DD5 material (F = (10^6 cycle strain without defect) / (10^6 cycle strain with defect))

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Laminate	So, MPa	VF, %	
DD7	832	54	no ply drop
DD5	724	36	no ply drop
ESH High	798	52	double ply drop
ESH Low	747	35	double ply drop