AIAA-99-0024

SELECTION OF REINFORCING FABRICS FOR WIND TURBINE BLADES

by

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ABSTRACT

The static and fatigue properties of typical wind turbine blade composite materials depend strongly on the architecture of the reinforcing fabric (woven, stitched, etc.) as well as the overall fiber content and fiber orientation. Fabric architecture also has a strong influence on resin flow characteristics during manufacturing and on the sensitivity of the properties to structural detail geometry. The DOE/MSU Fatigue Database contains data on many commercially available reinforcing fabrics tested in a variety of laminate configurations under several loading conditions. Two factors of concern are the low compressive strength of woven fabrics, and a transition to poor tensile fatigue resistance which can plague all stranded fabrics under some conditions. Furthermore, the unidirectional stitched fabrics, which have shown the best overall performance, are not available in the long, or warp direction of the fabric roll, and so cannot be used for the main lengthwise reinforcement in the blade. This paper presents a summary of the merits of several widely used fabrics as well as results for several new fabric types including bonded fabrics which show potential for improved performance. The results include an assessment of manufacturability and performance in structural details.

INTRODUCTION

The selection of reinforcing fabrics for wind turbine blades has historically focused on the materials used in the marine industry. These have been chosen for ease in handling during hand layup fabrication as well as for cost considerations. Extensive testing of various materials as part of the DOE/MSU fatigue database [1] has led to recognition of the significance of fabric architecture to tensile fatigue properties. Convenient "triax" fabrics, with 0° and ±45° layers stitched together perform poorly compared with laminates having separate 0° and ±45° layers.

Testing a broad range of laminates with separate 0° and ±45° layers has indicated additional problems. First, all of the fabrics with clearly delineated strands tend to show poor fatigue resistance if the overall fiber content is moderate to high, with transitions to poor fatigue resistance in the range of 40 to 50% fiber by volume, V_f. The V_f where the transition occurs depends on the fabric architecture and the laminate construction, the latter primarily reflecting the percentage of fibers in the main load (0°) direction [1,2]. A second problem is that fabrics with unidirectional strands in the long, or warp direction (0°) of the fabric roll, use a woven architecture, causing strand distortion in the thickness direction. This significantly reduces the compressive strength for all known weave patterns when compared with fabrics which have straight strands, usually stitched together [1,2]. The third problem, which has recently been identified [3], is that those stitched fabrics with straight, tight strands tend to lose their superior performance when structural details, such as ply drops, locally crowd the strands together. Thus, a blade fabricated by hand layup at a low fiber content, such as 35-40% fibers by volume may show poor tensile fatigue resistance (high knock-down factors in design) if features such as ply drops or stiffeners are molded into the laminate [3].

Fabric selection must also involve manufacturability of the material. Hand layup manufacturing is relatively insensitive to the details of fabric architecture, with the

This work was supported by the U.S. Department of energy and the State of Montana through the Montana DOE EPSCoR Program (contract #DE-FC02-91ER75681) and the Sandia National Laboratories under Subcontract AN0412.

main considerations being the thickness of material which can be added at each step, wet-out rate, and the handlability of the fabric. Other processes which use fabrics, such as resin transfer molding (RTM) and pultrusion, tend to be geared to higher fiber contents where tensile fatigue can become a problem. Good strand integrity, with spaces between strands, is important in RTM in keeping the permeability of the fabric as high as possible.

The foregoing observations indicate that none of the common reinforcing fabrics provides a good balance of properties and manufacturability. This paper provides a more useful comparison of different fabrics than has been available previously. Additionally, several new fabric types and variations suggested by vendors have been explored, and their performance, including manufacturability, is compared with that of commonly used fabrics.

EXPERIMENTAL METHODS

All materials were fabricated by resin transfer molding with the exception of manufacturability studies which also included hand layup. The reinforcing fabrics are noted with the results for each case. The matrix resin in all cases was a prepromoted orthophthalic polyester (CoRezyn 63-AX-051) with 2% methyl ethyl ketone peroxide as a catalyst. Details of molding, test coupon preparation, and test methods can be found in references 1 and 2, and specimen preparation for coupons containing ply drops and indentations can be found in reference 3. The ply delamination tests using specimens containing ply drops followed test procedures outlined in reference 4 and are described in greater detail in reference 5. The interlaminar fracture toughness data were obtained using double-cantilever-beam (DCB) test specimens with an artificial starter crack following test standard ASTM D5528-94a.

RESULTS AND DISCUSSION

Table 1 describes various reinforcing fabrics studied, and Figure 1 shows photographs of several fabrics. As indicated earlier, the greatest problem with reinforcing fabrics lies in the lack of fabric with straight unidirectional fibers in the warp direction of the fabric roll, which can provide the primary load carrying structure in a blade. The widely used A130 class of woven fabric produces poor compressive strength, as will be shown later. Adaptations of the weft-direction D155 class of stitched unidirectional fabrics into the warp direction by stitching to ±45° fabric, producing a "triax" fabric, result in very poor tensile fatigue resistance for several stitching variations investigated [1]. The work reported here gives more complete data for the baseline D155 and A130 fabrics than has been reported previously, and compares their properties. Results are also presented for the best of the previously tested triax materials, CDB200. Three new fabric types have been studied including CM1701, with D155-like fabric stitched to a light veil mat; TV-3400, a very loosely stitched triax fabric; and UC1010V and UC1018V, both of which contain unidirectional strands bonded to a thin veil mat with no stitching. The ±45° fabric used in all laminates except triax is DB120, with stitched + and - 45° layers.

Tensile Fatigue Resistance

Table 2 compares the tensile fatigue resistance of laminates using the three new types of fabric with the baseline D155 weft unidirectional fabric and CDB200 Triax. Laminates with separate 0° and ±45° plies (Figure 2) contain 70-75% 0° fibers with the indicated fabrics in the ply configuration $[0/\pm45°/0]_s$. The triax materials in Figure 3 each contain about 50% 0° fibers.

The DD14 laminate in Figure 2 and Table 2 shows a relatively low tensile fatigue resistance, with a maximum strain capability at 10^6 cycles of 0.60%, compared with the baseline DD5P* value of 1.15%. This low tensile fatigue resistance, even at a low overall fiber volume content of 35%, is only slightly better than the usual range for triax fabrics (about 0.35% to 0.60% [1]), and is about half the tensile fatigue capability of the DD5P laminate based on D155 0° fabric. The A130 fabric produces slightly better tensile fatigue resistance compared to D155 at higher fiber contents (Table 2).

Tests of unidirectional laminates with no ±45° layers present (Table 3) show corresponding 10^6 cycle strain values of 0.64% for the CM1701 fabric and 1.12% for the D155 fabric. These values are consistent with the $[0/\pm45/0]_s$ laminate results. A new stitched warp unidirectional fabric, A1010, was briefly studied. The results for the corresponding laminate DD20 in Table 2 were very poor in tensile fatigue.

The bonded unidirectional warp fabrics, UC1010V and UC1018V, are the closest architecture to typical aerospace composites fabricated from prepreg. The 0° strands in the fabric are nested together with no stitching or weave crossover points to pinch the fibers together. It is anticipated that these fabrics might produce laminate properties at low fiber contents which are similar to the baseline D155 stitched fabric. As noted earlier, at higher fiber contents and in structural details which pinch the strands together, the D155 fabric laminates go through a transition to poor tensile fatigue resistance [1,2]. Earlier data for the D155 fabrics with all stitching removed by hand showed good tensile fatigue resistance retained to higher fiber contents. Thus, it is also anticipated that the bonded fabrics might produce much improved fatigue properties even at high fiber contents. The results in Table 2 and Figure 2 indicate that the bonded fabric laminate, DD24, performs in tension only slightly below the baseline DD5P laminate, with a 10^6 cycle maximum strain of 0.94% compared with 1.15% for the D155 fabric baseline DD5P laminate. The results presented here are for the first few series of tests on the bonded fabric laminates. The manufacturer is currently producing fabrics with variations in binder content for further study.

Compressive Strength

The compressive strength of the DD24 laminate, 511 MPa, is also slightly below the 574 MPa for DD5P (another D155 fabric laminate with a V_f of 35% had a compressive strength of 534 MPa; this fiber content is closer to the 38% fiber content of DD24). The heavier bonded fabric, UC1018V, showed a laminate ultimate compressive strength of 629 MPa at a higher fiber content of 48% in material DD25A, which is comparable to values for D155 laminates at similar fiber content such as DD4, 50% fiber, 556 MPa strength; DD, 49% fiber, 788 MPa; and DD7, 54% fiber, 581 MPa [1]. Comparisons of the bonded fabric laminates with the woven fabric laminates in Table 2 show much higher values of compressive ultimate strength for the bonded fabric laminates, 511 and 629 MPa, compared with the woven fabric laminates, DD11 and DD13 with in compressive strengths of 314 and 319 MPa for fiber contents of 31 and 50%.

Thus, the ultimate compressive strength of the bonded fabric laminates is similar to that of the stitched fabric laminates, which is expected based on the straight strands in each material. However, the stitched D155 unidirectional fabric is not available with the fibers parallel to the warp (long) direction of the fabric roll unless they are stitched to a backing material, such as the mat used with the CM1701 fabric. The latter fabric, CM1701, while producing a fair compressive strength ranging from 428 to 439 MPa in the database [1] for fiber contents ranging from 25-36%, (laminates DD14, 15, 16), shows poorest tensile fatigue resistance as noted earlier. It should be noted that the ultimate compressive strength is the parameter of interest in compression, since the fatigue sensitivity in compression is similar, relative to the ultimate strength, for all laminates [1].

There is a problem with fiber waviness (deviations from straight 0^0 in the plane of the sheet) in most of the fabrics discussed here. This may occur in applications even when it is not present in coupon tests used to establish the database. Future studies will investigate the fiber waviness tendency in this series of fabrics, and its effect on compressive strength.

Delamination Resistance

The delamination resistance has been determined in two types of experiments. First, a direct interlaminar fracture toughness has been run on unidirectional specimens containing a starter crack. This is an opening mode (mode I) test using a double cantilever beam specimen. Table 4 compares the delamination resistance for the baseline stitched and bonded fabric laminates. The results show no significant difference in delamination resistance between the two fabrics, eliminating concern that the bonded fabric, with its thin veil mat backing, would provide a favorable path for delamination crack.

The second delamination test uses a more realistic geometry of a ply drop, which is typical of a thickness-tapering section of a blade. Results of this type have been presented earlier for a variety of ply drop geometries [4, 5]. Figure 4 compares the rate of delamination growth in fatigue from a single ply drop for laminates based on different fabrics. The ply arrangement in all cases is $[0/0^*/\pm45/0]_s$, where the 0* ply is dropped from the specimen at mid-length (see references 4 and 5). Little significant effect of fabric type is evident in Figure 4, with only a slightly more rapid crack growth for the A130 fabric based laminate for this particular ply arrangement. Results for the bonded fabrics are not yet available.

Effects of Structural Details on Fatigue Lifetime

A previous paper [3] presented a variety of results for different simulated and actual structural details molded into coupons. Design knockdown factors of up to 2.5 on fatigue strain capability were reported, with the most severe values found for the baseline D155 fabric laminates, which had the best spectrum of tensile and compressive properties at low fiber contents typical of hand layup. Additional results have now been obtained in compression fatigue and for other reinforcing fabrics.

Reference 3 presented tensile fatigue results for laminates based on D155 fabric in the ply configuration

$[[0/\pm45/0]_s$ which contained flaws. The flaws were molded-in areas of transverse material to represent matrix rich areas, and surface indentations to represent skin-stiffener intersections. Neither of these features involved cutting or terminating any of the fabric plies. Figure 5 depicts these geometries and presents design knockdown factors for strain allowable at 10^6 cycles in compression fatigue (R=10) as well as tension fatigue (R= .1). Figure 6 shows compression fatigue data relative to trends for the baseline laminates with no defects. Although the A130 based fabric has a lower ultimate compressive strength, the results for laminates containing defects are much closer together with much lower knockdown factors. Thus, the advantages of the D155 fabric in compression, with its straight strands, may not be realized in real blade structures containing typical defects.

Figure 7 presents data for tensile fatigue of laminates with three base 0° fabrics, D155, A130, and UC1018V, all containing similar surface indentations in coupons. Relative to the trend lines for coupons without indentations, the laminates with bonded fabric, UC1018V, show somewhat less effect of the presence of the indentation compared with the D155 fabric. On an absolute basis, the bonded fabric laminate with the surface indentation shows similar fatigue resistance to laminates containing the other two fabrics. The data are very scattered for the A130 based DD11 laminate with the surface indentation; this apparently relates to whether the bead over which the strands are woven (Fig.1) falls in the area of the indentation. The lower range of the data was used to estimate the knockdown factor for this case, while the mean data trend was used in the other two laminates. The 10^6 cycle tensile strain knockdown factors in Figure 5 are 2.5, 2.3, and 1.7 for the D155, A130, and UC1018V fabrics, respectively. Thus, the bonded fabric again yields encouraging results for this case.

Manufacturability

Laminates containing the three 0° fabric types, D155, A130, and UC1018V, have also been evaluated for manufacturability by fabricating flat plates at different fiber contents by RTM, and at low fiber content by hand layup. All fabrics are in the same general price range. As indicated in Table 5, all laminates were easily manufactured by hand layup in the 30-40% fiber by volume range, but the A130 fabric caused some difficulties in handling and wet-out. The D155 fabric laminates were easily manufactured by RTM at both low (30-40%) and moderate (40-50%) fiber content ranges. The A130 based laminates were more difficult to mold at the higher fiber content, and the bonded fabric (UC1018V) was difficult at low fiber content and nearly impossible at high fiber content by RTM. The reason for the relatively easy molding of the D155 laminates by RTM is the resin flow paths between the stitched strands, which are not present in the other fabrics. As noted earlier, variations in the bonded fabric are being pursued to improve manufacturability. Additionally, process variations to the RTM method are also being investigated for low permeability fabrics.

CONCLUSIONS

The results allow some overall conclusions as to the application of these fabrics to wind turbine blades. For blade areas where compression stresses are not limiting, the A130 class of fabrics provide good performance. While low in compression strength, these laminates require very low knockdown factors at structural details in compression. For general cases with tension and compression as well as structural detail variations, the bonded fabrics such as UC1018V appear very promising for hand layup, but manufacturability may limit their use for processes such as RTM which require resin flow in the plane of the fabric. The D155 fabric is available in the weft direction of the roll of fabric only, and so cannot be used for lengthwise reinforcement down the blade. Fabrics such as triax and CM1701, based on stitched 0° layers, are appropriate if tensile fatigue is not limiting in the design. They are easily handled and molded. The CM1701 can be used with separate ±45° fabrics to produce a higher 0° fiber content than is available in triax fabrics. Both the CM1701 warp unidirectional fabric and the TV3400 triax fabric provide convenient reinforcement with a moderate sacrifice in tensile fatigue resistance which may be less significant if structural details are present. Compressive strength is also relatively low for these materials, as noted earlier, in part due to fiber waviness.

References

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TABLE 1 Fiberglass Fabric Description

Fabric	Manufacturer	Type	Weight (g/m^2)
D155	Knytex	Weft Unidirectional, Stitched	527
A130	Knytex	Warp Unidirectional, Woven	444
DB120	Knytex	±45 Bias Ply, Stitched	393
A1010	Collins Craft	Warp Unidirectional, Stitched	351
UC1010V	Collins Craft	Warp Unidirectional, bonded to veil	351
UC1018V	Collins Craft	Warp Unidirectional, bonded to veil	632
CM1701	Knytex	Warp Unidirectional, Stitched to mat	587
CDB200	Knytex	Triax 0/±45, Stitched	759
TV3400	Brunswick	Triax 0/±45, Stitched	1150

TABLE 2 Comparison of Properties for Laminates Containing 0° and ±45° Layers, Based on Different Fabrics

Laminate*	0° Fabric	V_F,(%)	Ultimate Compressive Strength (MPa)	Ultimate Tensile Strength (MPa)	Fatigue R=0.1 strain for 10^6 cycles (%)	0° Elastic Modulus(GPa)
DD5P	D155	36	574	661	1.15	23.6
DD4	D155	50	556	895	0.65	31.0
DD11	A130	31	319	592	1.25	20.0
DD13	A130	50	314	821	0.80	29.5
DD14	CM1701	35	439	728	0.60	25.1
DD20	A1010	34	313	587	0.50	22.2
DD24	UC1010V	39	511	730	0.94	23.9
DD25A	UC1018V	48	629	783	0.75	28.5
DD25B	UC1018V	31	419	514	1.03	19.3
AA Triax	CDB200	35	348	452	0.50	18.8
AA4 Triax	TV3400	37	449	399	0.67	20.4

* The Material is the designation for this laminate in the DOE/MSU Database.
**All DD series materials are in the ply configuration $[0/\pm45/0]_s$, where the ±45 plies are DB120 fabric.

TABLE 3 Comparison of Properties for Unidirectional Laminates Containing a Single Fabric Type

Fabric	V_F (%)	Ultimate Compressive Strength (MPa)	Ultimate Tensile Strength (MPa)	Fatigue R=0.1 strain for 10^6 cycles (%)	0° Elastic Modulus E, (GPa)
D155	39	675	802	1.12	31.0
A130	35	430	728	1.10	31.0
CM1701	38	573	796	0.64	30.5

TABLE 4 Interlaminar Fracture Toughness, G_{IC}

Material	Fabric	Initiation G_{IC} (J/m^2)
DD5P	D155	140
DD25B	UC1018V	176

TABLE 5 Manufacturability with Different 0° Fabrics*

Fabric	Hand Layup (30-40% Fiber)	Resin Transfer Molding (30-40% Fiber)	Resin Transfer Molding (40-50% Fiber)**
D155	Excellent	Excellent	Good
A130	Fair	Good	Fair
UC1018V	Good	Fair	Poor

* Laminate configuration $[0/\pm45/0]_s$, ±45° layers are DB120 fabric.
** Vacuum assist helps at high fiber content

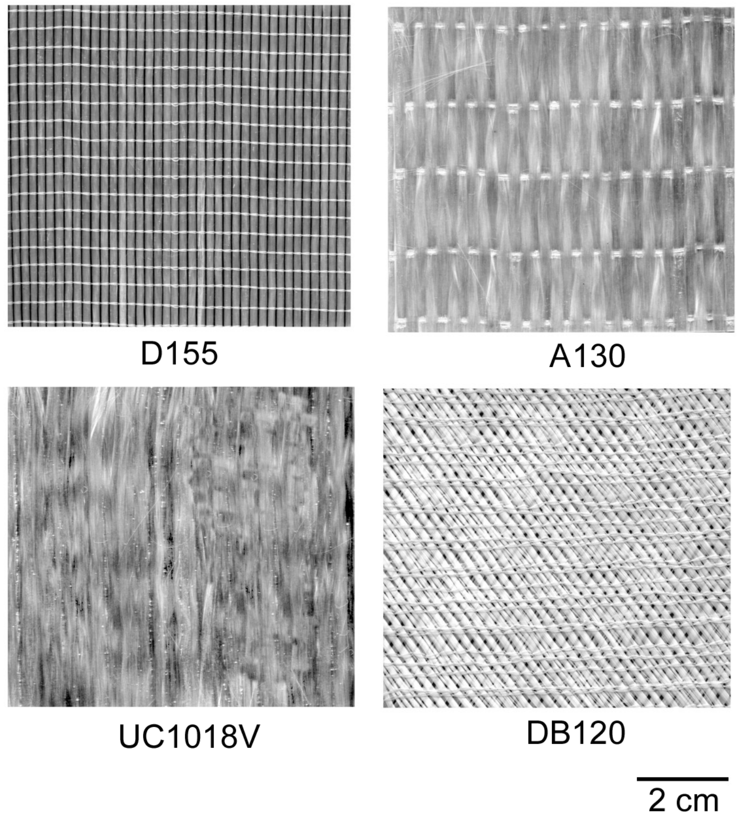
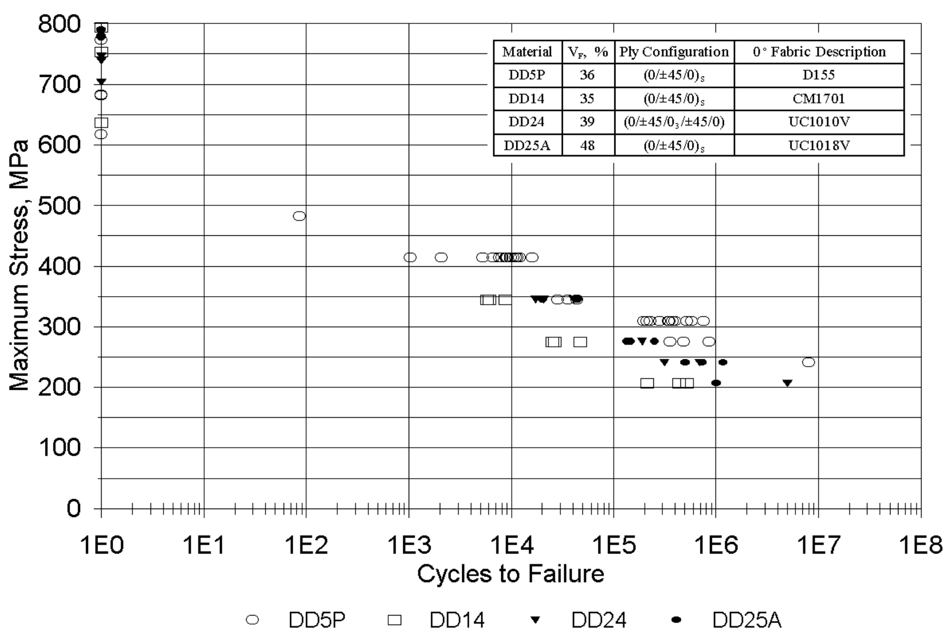


Figure 1. Dry Fabric Samples



Material	V_F, %	Ply Configuration	0° Fabric Description
DD5P	36	$(0/\pm45/0)_S$	D155
DD14	35	$(0/\pm45/0)_S$	CM1701
DD24	39	$(0/\pm45/0_3/\pm45/0)$	UC1010V
DD25A	48	$(0/\pm45/0)_S$	UC1018V

Figure 2. Tensile Fatigue Data Comparing Baseline Laminate (DD5P) With Laminates Based on Warp Unidirectional Fabrics, R = 0.1

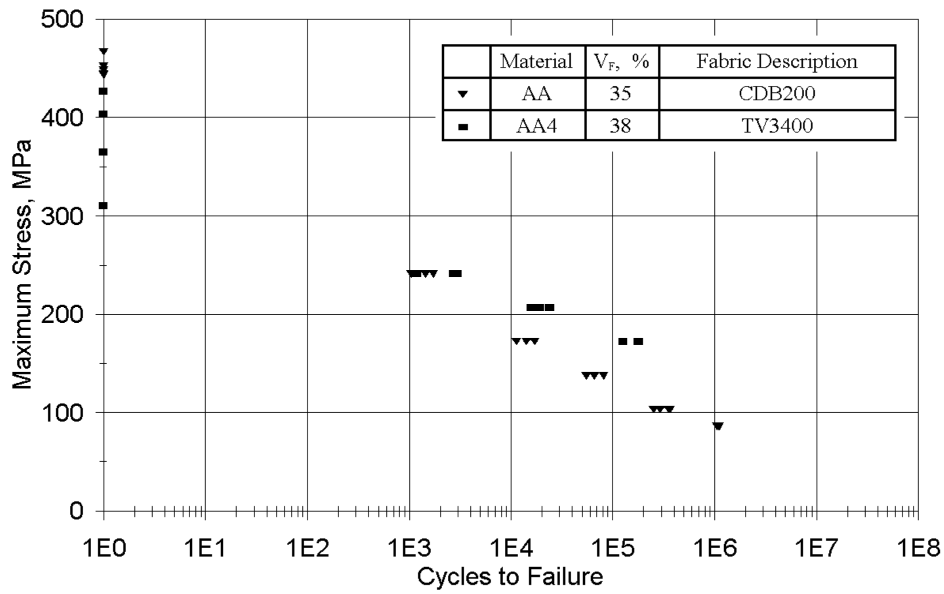


Figure 3. Comparison of Tensile Fatigue Data For Triax Fabric Laminates, R = 0.1

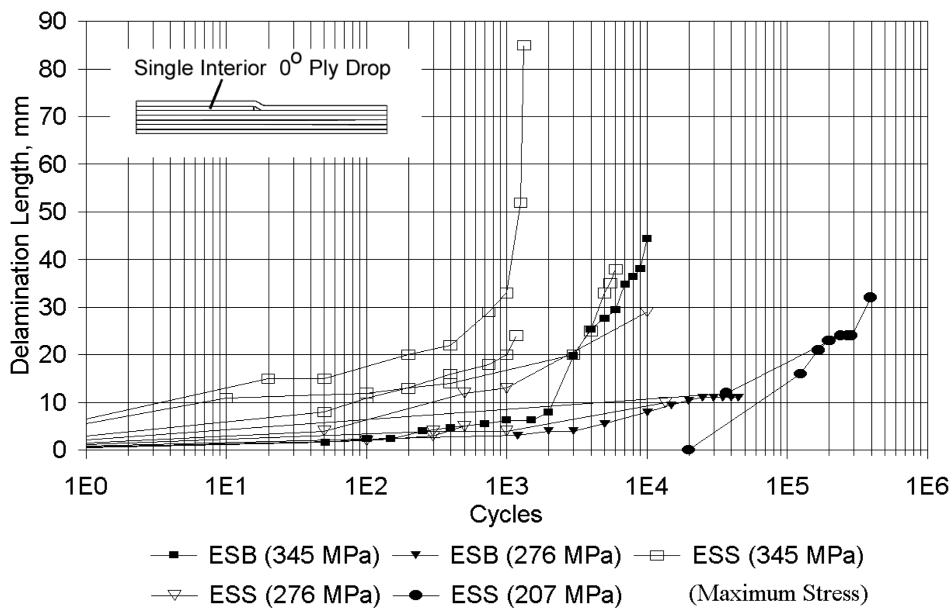
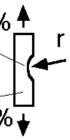
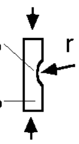
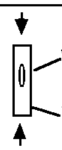


Figure 4. Typical Delamination Length vs. Cycle Data for Laminates ESB (D155 fabric) and ESS (A130 fabric) With a Single Interior Ply Drop.

Detail	Sketch	Knock-Down Factor, F		
		A130 fabric	D155 fabric	UC1018V fabric
Simple Coupon (Straight Material)		1.0	1.0	1.0
Surface Indentation Tension, R = 0.1 (V_f increased, thickness reduced by 25%)	 V_F = 45 - 52%; r = 6mm; V_F = 35 - 37%	2.3	2.5	1.7
Surface Indentation Compression, R = 10 (V_f increased, thickness reduced by 25%)	 V_F = 52%; r = 6mm; V_F = 37%	1.0	1.4	-----
Locally Higher Fiber Content (2 - 90° plies in center) Tension, R = 0.1	 V_F = 47%; V_F = 34%	2.1	1.5	-----
Locally Higher Fiber Content (2 - 90° plies in center) Compression, R = 10	 V_F = 47%; V_F = 34%	1.0	1.4	-----

$$10^6 \text{ Cycle Strain} = \frac{(\text{Coupon } 10^6 \text{ Cycle Strain})}{F}$$

Figure 5. Knock - Down Factors For Tension and Compression. Laminates Based on D155, A130 and UC1018V 0° Fabrics.

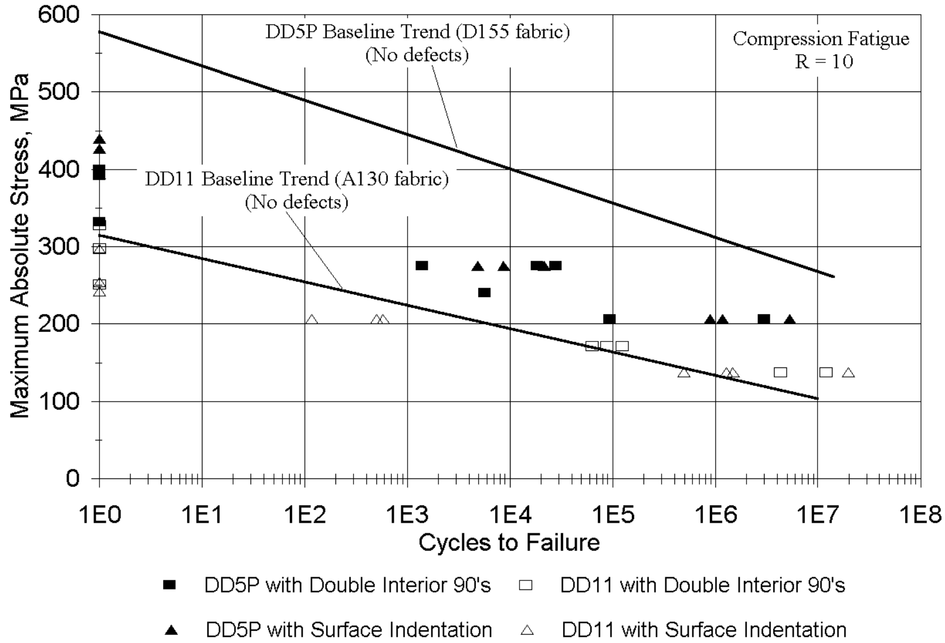


Figure 6. Effects of Surface Indentation and Interior Inclusions on Compression Fatigue Resistance, R = 10.

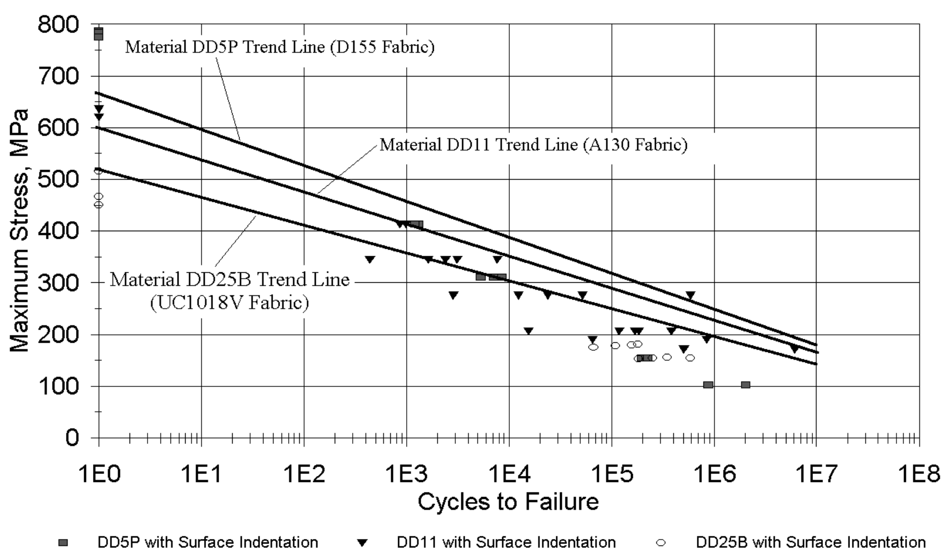


Figure 7. Tensile Fatigue For Coupons Containing a Surface Indentation Compared With Trend Line For Base Laminates Without Indentations, R = 0.1 (See Figure 5).