SILICONE TECHNOLOGIES DIVISION
1100 Governor Lea Road, Bear, DE 19701
(302) 834-2100   (302) 834-4021 (Fax)

Flex Fatigue of Simple Composites

David C. Timpe Jr.
Arlon Silicone Technologies Division
www.arlon-std.com

Abstract

Flex fatigue resistance of multi-layer composites of silicone rubber and plain weave polyester fabrics is determined with a Bally-type flexometer according to ASTM D 6182. Fabric denier and the interaction between fabric denier and distance between the fabric plies is found to affect flex fatigue resistance. A higher denier fabric is indicative of improved flex fatigue resistance and is more capable of handling the higher stress created by a greater fabric spacing. Two additional high denier fabrics are investigated and indicate a possible effect of yarn twist and/or pick count on flex fatigue resistance.

Keywords: flex fatigue, ASTM D 6182, silicone rubber (PDMS)

Introduction

Simple composites consisting of bi-layer woven fabrics coated with silicone rubber are currently being utilized or investigated for a variety of applications including bellows for articulating buses and trains, gangways for aircraft entryways, and architectural structures. Each application has its own unique set of material requirements, and they all must be resistant to flex fatigue. The soft and flexible nature of woven fabrics coated with silicone rubber, and the unrestrained nature of the fabrics, causes the composites to form tight folds and creases. Flexing action concentrated at a fold or crease in the composite is potentially more severe than simple composite bending. A fair amount of research has been performed and published on flex fatigue of various materials and systems [1 – 5], but almost none has concentrated on the flexing action at a fold or crease in the material.

A Bally type flexometer according to ASTM D 6182 is used in this research to concentrate the flexing action at a material fold [6]. The effect of the distance between multiple fabric layers, and the fabric denier is investigated and correlated to the level of fatigue after 250,000 flex cycles.

Experiment

A two factor, mixed level, design of experiments (DOE) was performed to investigate the effect of Fabric Spacing and Fabric Denier on the flex fatigue of composite samples composed of two fabric layers. The Fabric Spacing was either 0.005 inch or 0.030 inch between the fabric layers and the overall composite thickness was 0.063 inches. Plain weave polyester fabrics with yarn deniers of 250, 600, and 1000 were utilized.

Table 1 – Two factor, mixed level, designed experiment to investigate effect of fabric spacing and yarn denier on flex fatigue.

	Factor A	Factor B
	Fabric Spacing	Yarn Denier
Low Level	0.005 in.	250 (Fabric A)
Middle Level	---	600 (Fabric B)
High Level	0.030 in.	1000(Fabric C)

Two fabric layer composite samples were prepared with each of the polyester fabrics with different fabric spacing distances by first priming the polyester fabric for silicone adhesion, then calendering either 0.005 inch or 0.030 inch of silicone rubber onto one piece of fabric. Depending on fabric spacing and interleaving, a second piece was also prepared to make the core of the composite. Equal amounts of silicone rubber was then calendered on each outer surface of the core to give an overall thickness of 0.063 inch as seen in Figure 1. A 3 minute cure cycle was used in a hot air oven at 177^{o}C after each processing step. No additional processing or conditioning steps were performed.

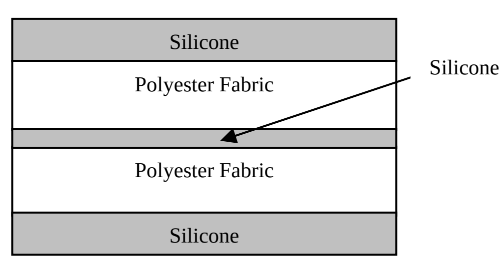

Figure 1 – Composite Sample Construction

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Specimens measuring 2.75 x 1.75 inches were cut from each composite sample so that the long side of the specimen would be the direction of test. Equal numbers of specimens were cut with the direction of the test parallel to the warp and fill directions of the sample. The specimens were secured into the flexometer as shown in Figure 2. Specimens were flexed at ambient temperature and pressure and at a rate of 100 cycles per minute for intervals of 25,000 cycles. After each interval the specimens were removed from the test fixture, visually inspected, and then returned to their original position on the flexometer. The level of damage was determined according to Table 2. The specimens were then dissected and the damage level evaluated at the conclusion of 250,000 flex cycles.

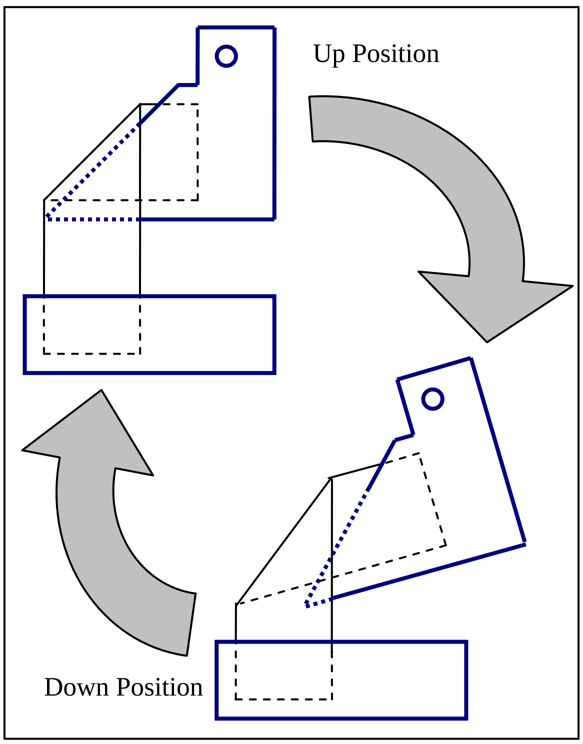

Figure 2 – Clamp position and specimen orientation during a flex cycle. The top clamp moves through a 22.5^{o} arc while the bottom clamp remains stationary.

Table 2 – Damage ranking of flexed composites.

Level	Description
0	no visible damage to specimen with or without bending.
1	by bending the specimen, cracks are visible, no break of fabric
2	without bending the specimen, cracks are visible, no break of fabric.
3	delamination of composite layers, no break of fabric
4	visual damage to a minimum of one layer of the fabric
5	hole, pointed object passes through specimen without expenditure of force.

Results and Discussion

Determining the damage ranking at various intervals proved difficult and misleading because of the inability to visually inspect the fabric layers without damaging the specimen. In general, cracks (damage ranking 1 or 2) formed in the exterior rubber surface of the specimen oriented toward the flexometer within the first 25,000 – 50,000 cycles. Delamination (damage ranking 3) occurred in the specimen within the first 100,000 cycles. At this point it was nearly impossible to assign the location of delamination within the specimen unless it had occurred between the fabric and exterior rubber surface oriented toward the flexometer. Further analysis was not possible in most cases until the specimen was dissected at the conclusion of 250,000 flex cycles. Additional damage, such as fabric breaks (damage ranking 4), observed during dissection was assigned to the 250,000 cycle interval.

Five specimens produced from Fabric B (600 denier) with 0.030 inches of fabric spacing (silicone web) deviated from the general failure mode described previously. Two specimens suffered a break in the fabric between 50,000 and 100,000 cycles before delamination was observed. Three other specimens suffered a break in the fabric between 50,000 and 125,000 cycles shortly after delamination was observed. The fabric breaks on all five specimens occurred in the fabric and exterior rubber layer oriented outward from the flexometer.

Table 3 – General linear model analysis of variance.

	F-value	p-value
Fabric Spacing	1.71	0.790
Yarn Denier	8.12	0.020
Interaction	16.61	0.011

Analysis of variance was performed on the final damage ranking (250,000 cycles) determined after dissection of the specimens (Table 3). Varying the fabric spacing from 0.005 inch to 0.030 inches caused a 0.17 point increase in the mean damage ranking from 3.46 to 3.63. The fabric spacing factor has a p-value of 0.790 indicating the 0.17 point effect of varying the factor is not real and that the mean damage ranking at each fabric spacing belongs to the same larger population. Varying the yarn denier from 250 to 600 caused a 0.33 point decrease in the damage ranking from 4.00 to 3.67 (Figure 2). Varying the yarn denier from 600 to 1000 caused a 0.28 point decrease in the damage ranking from 3.67 to 3.39 (Figure 3). The yarn denier factor has a p-value of 0.020 indicating the effect on damage ranking is statistically significant. The interaction factor has a p-value of 0.011 indicting that an interaction between fabric spacing and yarn denier exists (Figure 4).

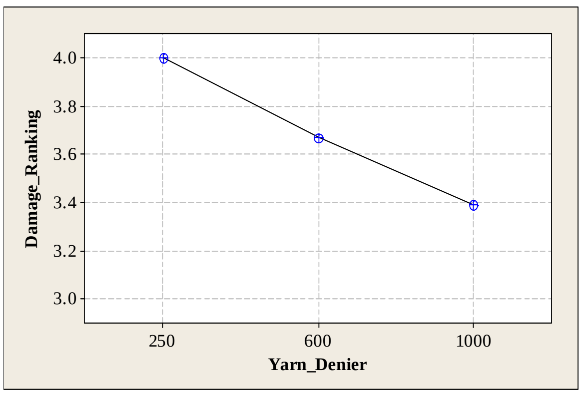

Figure 3 – Damage ranking as a function of yarn denier (250,000 flex cycles)

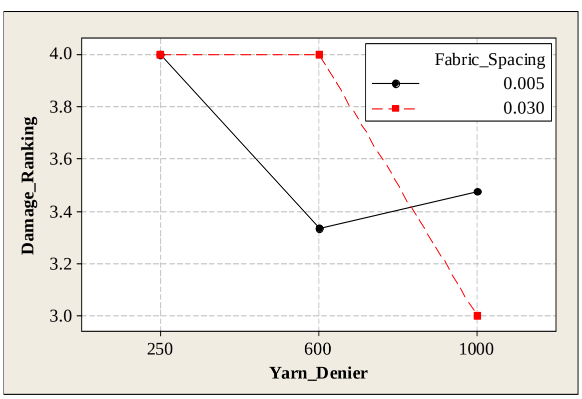

Figure 4 – Factor level interaction (250,000 flex cycles)

The effect of varying the fabric spacing from 0.005 inches to 0.030 inches had varying effects on the final damage ranking determined at 250,000 flex cycles depending on the denier of the fabric. The fabric spacing did not make a difference when the fabric denier was 250. All specimens had broken fabric yarns (damage ranking 4) after 250,000 flex cycles. However, the fabric spacing did make a difference when the fabric denier was 600. Specimens with 0.030 inch of fabric spacing always had broken fabric yarns after 250,000 cycles. Specimens with 0.005 inch of fabric spacing had broken fabric yarns 30% of the time. This effect of fabric spacing is reversed when the fabric denier was 1000. Specimens with 0.030 inch fabric spacing did not have broken fabric yarns. Specimens with 0.005 inch of fabric spacing had broken fabric yarns 47% of the time. The interaction may also depend on fabric characteristics not captured or factors such as the interlayer adhesion strength, level of silicone impregnation in the fabric yarns, and other stress relief mechanisms such as delamination.

Two additional 1000 denier fabrics (Fabric D and E) were evaluated and compared to the original 1000 denier fabric (Fabric C) for flex fatigue resistance. Fabric C is a 19 x 18 yarn count, plain weave fabric woven with untwisted yarns (Image 1a). Fabric D is a 25 x 27 yarn count plain weave fabric woven with twisted yarns (Images 1b). Fabric E is a 23 x 24 yarn count, plain weave fabric woven with twisted yarns (Image 1c). It was anticipated that Fabric C woven with untwisted yarns would display higher flex fatigue resistance (lower damage rating) than either Fabric D or E because the filaments of the untwisted yarns would be able to reorient themselves during flexing to alleviate stress. Fabric C had an average damage ranking of 3.39 versus 3.50 for Fabric D and 3.13 for Fabric E (Figure 5). Fabric E had the lowest fabric damage ranking and was constructed of twisted yarns and a more open weave than the other two fabrics. The twisted yarns restrict filament movement but the open weave allows greater movement of the yarns. Analysis of variance on the damage rankings of the three 1000 denier fabrics yields a p-value of 0.257 indicating that the fabric differences do not affect the damage ranking. Comparing Fabric C to Fabric E with a T-test yields the lowest p-value of any direct comparison at 0.120.

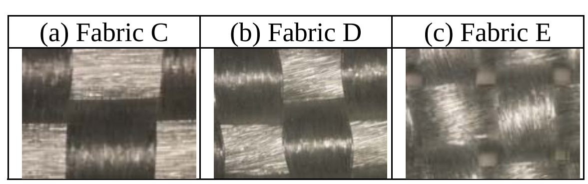

Image 1 – Micrographs of three 1000 denier fabrics.

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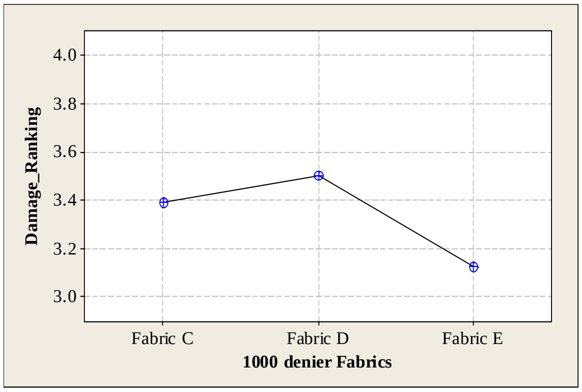


Figure 5 – Damage ranking of three different 1000 denier fabrics. (250,000 flex cycles)

One disadvantage of the untwisted yarns and low pick count (Fabric C) is the tendency for the yarns to spread out and become flattened in comparison to the twisted yarns of Fabric D and E (Image 2a – c). During calendering, the silicone rubber is partially impregnated into the yarns (Image 3). More of the yarn becomes impregnated by the silicone rubber, when a greater surface area, normal to the application method, is exposed. A higher level of impregnation binds more filaments with silicone rubber and restricts yarn movement. This offsets any anticipated advantage gained by eliminating yarn twist.

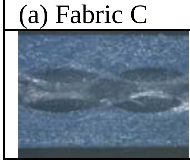
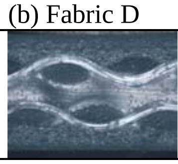
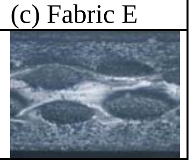
(a) Fabric C	(b) Fabric D	(c) Fabric E
		

Image 2 – Micrographs of product cross-sections utilizing each of the three 1000 denier fabrics.

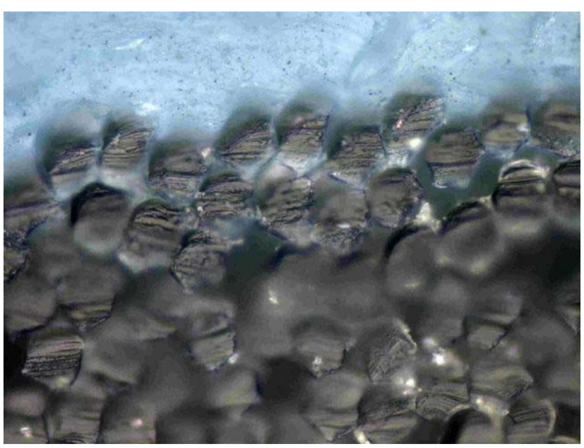


Image 3 – Micrograph of Fabric C cross-section showing impregnation of silicone rubber layer into yarn. (Light blue is silicone and dark gray are yarn filaments)

Conclusion

Simple composites consisting of a bi-layer of woven polyester fabric and three layers of silicone rubber displayed varying levels of flex fatigue resistance as determined with a Bally-type flexometer. The level of flex resistance depends on the denier of the fabric and the interaction between the denier and the fabric spacing between the fabric plies. The fabric spacing did not affect the flex resistance. A higher denier fabric yielded improved flex fatigue resistance and is capable of handling higher stresses caused by a greater fabric spacing. Interlayer adhesion strength, impregnation of silicone rubber into the fiber yarns, and composite stress through delamination were identified as additional factors for follow-up.

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