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Flexing behaviour of high strength coated fabrics

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Flexing characteristics of three varieties of thermoplastic polyurethane (TPU) coated high strength fabrics (nylon 6,6, polyester and kevlar) have been evaluated by subjecting them to 5000 cycles in a De-Mattia flex tester. The flexing damage is assessed in terms of % loss of strength by evaluating the residual tensile strength of flexed fabrics. Statistical analysis has been carried out at 95% significance level for assessing the influence of flexing cycles and variation in thermoplastic polyurethane concentration on the residual strength of coated kevlar fabrics. Accordingly, the specific trend exhibited is established. The study shows that the coated kevlar fabric has suffered with maximum strength loss, while nylon and polyester show excellent flex damage resistance with negligible strength loss. Further, the sensitivity to damage of kevlar fabric has been studied by varying the number of flex cycles from 1000 to 5000 and the extent of damage that happened within the structure is thoroughly analyzed using field emission scanning electron microscope. Finally, the possible mean of improving strength retention (22%) of coated kevlar fabric subjected to repeated flexing by the application of a proprietary high viscosity polymer coating has been proposed.

Keywords: Coated fabric, Fibril rupture, Flexing behaviour, High strength fabrics, Kevlar fabric, Polyester fabric, Residual strength

1 Introduction

High performance fibres are gaining more interest in large number of applications because of their attractive properties like ultrahigh modulus, light weight, high thermal and chemical resistance, and longer life[1,2]. Coated and laminated fabrics made with high performance fibres are used in applications like sailcloth, inflatable and temporary structures and are subjected to repeated flex cycles during operation, resulting in strength loss due to folding and unfolding[3]. Some authors have reported the comparative performance of different high strength coated and grey fabrics in terms of toughness, tear resistance, thermal stability and environmental stability[4-9]. Sonawane *et al.*[10] characterized coated nylon and polyester fabrics to test their suitability for use in envelopes of lighter-than-air (LTA) structures. Meng *et al.*[11] studied the damage morphology of a laminated envelope material after subjecting them to flexural fatigue test, and also developed an analytical model that predicts the fatigue life of the envelope, which correlated well with the actual fatigue tests. The flexing and un-flexing of the coated/laminated textiles cause micro-structural damage in the multilayer material, that leads to deteriorating effects like strength loss. The main reasons for flex fatigue failure in composite materials are fibre breakage, fibre splitting, fibre/matrix de-bonding, matrix micro-cracking, delamination, void growth or a combination of them[12-14]. The comparative flex damage resistance of different high strength fibres are reported in some studies[15,16]; however, very rare and limited work on flex fatigue damage of high strength fabrics has been reported in literature.

The structural element (fibre) carries the major stress acting on an envelope during flexing, and failure of envelope material occurs due to damage of structural element. The present work is therefore aimed at studying the effect of flexing on tensile behavior of three varieties of high strength textile fibres (kevlar, nylon and polyester), which are predominantly used in inflatable applications. The main objective of this study is to evaluate and compare the flex damage resistance of coated fabrics, and in order to achieve the target, kevlar, nylon 6, 6 and polyester fabrics were coated with aromatic grade thermoplastic polyurethane (TPU) under identical process condition. The coated fabrics were subjected to desired flexing cycles and subsequently, the flex damage was assessed by using two criteria, viz. (i) microscopic analysis and (ii) measuring residual

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strength[17-19]. Field emission scanning electron microscopy (FESEM) was utilized for microscopic analysis of failure mechanism occurred in different coated fabrics due to flexing.

2 Materials and Methods

2.1 Materials

Kevlar 29 (Pee Cee Textile Stores, Kanpur), nylon 6, 6 (M/s Shankla Industries, Bangalore) and polyester (M/s SRF Private Limited, Chennai) high strength woven fabrics, made with continuous multifilament yarns, were selected for coating. The evaluated test parameters and their referred standards of high strength woven fabrics are mentioned in Table 1. Kevlar fabric of lower mass as compared to nylon and polyester fabrics was judiciously selected, as this is sufficient enough to give strength equivalent or more than the other fabrics. However, nylon and polyester fabrics were selected with similar aerial density and strength for more appropriate comparison. Pearlstick 5702 F3 grade, a thermoplastic polyurethane (TPU) resin, was procured from M/s Lubrizol Engineered Polymers, Mumbai and used for coating. The criterion for selection of such resin is that it is one of the established materials that is widely used for several years in coated textiles[20].

2.2 Preparation of Coated Fabrics

The coating was carried out on both the sides of fabrics using Mathis Laboratory Coater, and in this equipment the fabrics were initially tightly fixed in a metal frame and subsequently, coated with 20% (w/v) TPU, considering knife coating principle. The coated fabrics were then cured at 70^0C for 120 min, and 65% add-on was maintained for all the fabrics.

2.3 Evaluation of Functional Parameters of Coated Fabrics

Stiffness

The stiffness of coated fabrics was determined by calculating their flexural rigidity and bending modulus, and for this calculation the bending lengths of coated fabrics were determined using Shirley Stiffness Tester according to the ASTM D1388 standard. The flexural rigidity and bending modulus were calculated from the measured mean bending length values, using the following formulae[21,22]:

$$G = 9.8\, MC^3 \times 10^{-6}$$

where G is the flexural rigidity (µNm); M, the sample mass (g/m^2); and C, the bending length (mm).

$$q = \frac{12G \times 10^3}{t^3}$$

where q is the bending modulus (N/m^2); G, the flexural rigidity (µNm); and t, the cloth thickness (mm).

Flexing

The flexing of the coated fabrics was carried out in De-Mattia Flex Tester according to IS: 7016 Pt-IV standard, and the samples were subjected to repeated folding and unfolding, which simulates their operation conditions in actual use and the samples for flexing were cut with dimensions of 50 mm × 175 mm. The samples were subjected to a total number of 5000 flex cycles at a rate of 300 flex cycles/min. The test samples after flexing on this machine were removed and tested for their residual tensile strength[23] to assess the damage occurred due to repeated flexing.

Table 1 — Evaluated test parameters and their referred test standards of the high strength fabrics

Physical properties	Test standards	Materials		
		Kevlar	Nylon	Polyester
Weave	-	Plain	Plain	Plain
Ends/inch and picks/inch	IS 1963	30 and 30	63 and 41	23 and 23
Count of yarn, den (warp and weft)	IS 3442	514 and 470	300 and 440	1018 and 1001
Yarn tenacity, g/den (warp and weft)	ASTM 2256	15.9 and 16.5	8.9 and 8.3	7.2 and 7.3
Crimp % of yarns (warp and weft)	IS 3442	1 and 0.6	1.8 and 1.6	1.7 and 1.7
Mass, g/m^2	IS 1964	109	180	190
Thickness, mm	IS 1964	0.15	0.32	0.25
Breaking load, N/cm (warp and weft)	IS: 7016	1063.3 and 960.8	567.3 and 571.1	587.9 and 597.6
Breaking elongation, % (warp and weft)	IS: 7016	12.2 and 10.9	39.8 and 31.7	33.4 and 31.2

Tensile Strength

Universal Tensile Testing machine (Tinius Olesen) was used for tensile testing of coated and flexed samples following the test standard IS: 7016 Pt-II, according to constant rate of elongation (CRE) principle. Testing was carried out with 75 mm gauge length and 100 mm/min extension rate.

Microscopic Image

The micro-level damage due to flexing was analyzed by capturing the magnified view of cross-section of flexed samples using field emission scanning electron microscope (FESEM) instrument (JSM-7100F). The images were captured after coating the samples with very thin layer of gold.

2.4 Statistical Analysis

The prediction of the population behaviour from the sample behaviour involves probability factor, which is statistically called as significance level. The confidence interval comprising the population means:

$$\bar{x} - t \times S/\sqrt{n} \le \mu \le \bar{x} + t \times S/\sqrt{n}$$

where $\bar{x}$ is the sample mean; *t*, the standard normal variate (SNV); *S*, the sample standard deviation; *n*, the number of samples; and μ, the population mean.

When comparison is drawn between two populations parameter based on the mean values of the sample parameter, hypothesis testing is followed. The brief procedure of the hypothesis testing is mentioned below (for sample strength, $n < 30$):

Ho — Null hypothesis: There is no difference between the sample means

H_1 — Alternate hypothesis: $\overline{x_1} \ge \overline{x_2}$, where $\overline{x_1}$, $\overline{x_2}$ are sample means

The calculated *t* statistics is defined as follows:

$$t = \frac{\left|\overline{x_1} - \overline{x_2}\right|}{SE\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where *SE* is the estimated standard deviation of the distribution of differences between independent sample means; and n_1 & n_2, the number of samples. SE can be calculated using the following equation:

$$SE = \sqrt{\frac{(n_1 - 1)\, s_1^{\,2} + (n_2 - 1)\, s_2^{\,2}}{n_1 + n_2 - 2}}$$

where s_1, s_2 are the sample standard deviations.

The statistical inference is drawn at 95% confidence level with single tail test and the calculated *t* value is compared with the *t* value obtained from the statistical table (degree of freedom $df = n_1 + n_2 - 2$). When the calculated *t* value was found higher than the *t* value obtained from the table, then the null hypothesis was rejected and alternate hypothesis was accepted[24].

This statistical significance test was performed for assessing the influence of flexing cycles on the residual tensile strength of coated kevlar fabrics and also utilized to bring out the combined influence of TPU concentration% and effect of flexing on the residual tensile strength in terms of the difference in their absolute values at 95% confidence level and accordingly, the conclusion was drawn and decreasing/increasing trend was established.

3 Results and Discussion

3.1 Stiffness of Coated Fabrics

Bending modulus is the estimation of force required for bending of fabrics, the higher value of bending modulus indicates greater resistance of fabrics to bend during the flexing operation. The bending modulus is the function of fibre type, yarn fineness and fabric construction parameters (mass, thickness and yarn density) and can be used to compare the stiffness of fabrics having different structures[25]. The stiffer the fabric, the higher is the bending length and bending modulus. The calculated values of flexural rigidity and bending modulus of coated fabrics are given in Table 2. It is observed that the bending modulus of coated kevlar fabric is the highest followed by polyester and nylon fabrics, though the mass and thickness of the fabric are lower than those of the other two coated fabrics. The fineness of the constituent multifilament yarns used in kevlar fabric is also lower than that of polyester fabric. The highest bending modulus for coated kevlar fabric could be ascribable to the inherent stiffness of

Table 2 — Flexural rigidity and bending modulus of coated fabrics

Materials	Mass g/m^2	Thickness mm	Bending length, mm	Flexural rigidity, µNm	Bending modulus, MPa
Kevlar	180	0.20	Warp -71 Weft - 70	Warp - 631 Weft - 605	Warp - 947 Weft - 908
Nylon	297	0.36	Warp - 47 Weft - 48	Warp - 302 Weft - 322	Warp -78 Weft - 83
Polyester	314	0.31	Warp- 66 Weft - 66	Warp - 885 Weft - 885	Warp - 356 Weft - 356

the component filaments and it can be extrapolated further to conclude that the most predominant factor among the three properties (fibre type, yarn fineness and construction parameter), affecting the coated fabric bending modulus is the inherent stiffness and rigidity of fibre used. Between the coated polyester and nylon fabrics, the earlier displays the higher bending modulus, and the reason behind such finding is the superior inherent fibre stiffness and rigidity and higher yarn fineness as compared to the nylon fabric. Both the polyester and nylon fabrics are possessing the similar mass. The polyester fabric is having lesser yarn density (ends/inch and picks/inch) & thickness as compared to the nylon fabric. One more finding observed that the yarn denier for kevlar is lower than polyester, but it displayed the higher bending modulus. Hence, it can be concluded that the yarn fineness is the second predominant factor in deciding the bending modulus. The trend of the governing factor affecting the bending modulus of the fabrics is mentioned below:

Fibre type (inherent stiffness and rigidity) > yarn fineness (warp and weft) > construction parameters (mass, thickness and yarn density)

3.2 Flex Resistance of Coated Fabrics

The research work is aimed to assess the suitability of kevlar fabric for inflatable textile application with the expected shelf-life of ten years and service-life of five years. But, initially, it is tested for 5000 flex cycles corresponding to ten years of service-life to judge the comparative performance of the three varieties of selected high strength fabrics. The strength requirement for the intended inflatable textile application is 450 N/cm for both warp and weft directions, and the residual strength, upon repeated cyclic flexing above the critical tensile strength of 450 N/cm, will decide the life of the materials. Hence, the inherent resistance to flex damage of coated fabrics has been studied by subjecting to flexing of 5000 cycles followed by tensile testing for estimation of residual strength, as reported in Table 3. It is observed that there is significant variability in degree of flex damage resistance of coated fabrics made of different fibre types. Coated kevlar fabric shows the maximum strength loss of around 55% of its inherent strength. However, coated nylon and polyester fabrics show better flex fatigue resistance and there is evidence of almost no strength loss after flexing for coated nylon fabric. Though, there is observation of 3.8% strength loss due to repeated flexing for the coated polyester fabric, but the strength difference of absolute values is found to be statistically insignificant at 95% confidence level. This proves that the damage due to flexing is totally the function of fibre type used in construction of fabric and kevlar fibre is the most sensitive material to flex damage as compared to nylon and polyester.

Table 3 — Residual tensile strength of coated fabrics after flexing of 5000 cycles

Materials (coated)	Breaking load, N/cm		Strength loss %
	Before flexing	After flexing	
Kevlar			
Warp	1022.7 (38.7)	437.4 (18.9)	57.1
Weft	944.8 (35.4)	412.4 (17.7)	56.3
Nylon			
Warp	601.6 (27.9)	593.7 (27.6)	1.4
Weft	524.3 (23.4)	525.9 (22.5)	0
Polyester			
Warp	552.1 (24.3)	532.4 (23.2)	3.8
Weft	551.9 (23.6)	531.6 (23.1)	3.8

*Values in parenthesis indicate the standard deviation.

The actual mechanism of flex damage resistance has been a subject of considerable study, due to significant variability in flex resistance of fibres made from linear chain polymers. The difference in the flex damage resistance of coated fabrics can be attributed to micro-structure of fibres. The first visual manifestation of flex damage is the appearance of crease in the coated fabrics caused due to repeated folding and unfolding. Maximum damage is found to occur at points of crease. Further detailed study to examine the cause of strength loss due to micro-level damage that might have happened due to flexing is pursued by capturing magnified image at the point of maximum damage. The FESEM images of the cross-sections of samples before and after flexing are shown in the Fig. 1. It is noticed that no significant fibre damages are observed in cross-sections of nylon and polyester samples after flexing and this correlates well with the strength retention values of coated nylon and polyester fabrics. But with kevlar sample, a detailed comprehension of its micro-structure is necessary to analyze the cause for its strength loss after flexing. Much literature has reported about the micro-structure of different classes of kevlar fibres and they found that all the fibre classes of the kevlar are composed of pleated sheets of crystalline domains. Kevlar fibre is composed of many pleats that are arranged parallel to the fibre axis. Each of the pleats has fibrils, which are the aggregates of PPTA (poly pphenyleneterephthalamide) crystalline domains that lie along the axis of pleat[26, 27]. The structural schematic of pleated kevlar fibre is shown in Fig 2.

With the anticipation that the strength loss may be due to the rupture of kevlar fibrils, the damage of coated kevlar samples that happens due to flexing is intensified by subjecting the samples to flexing of one lakh cycles and then the cross-section of the flexed kevlar sample is observed under microscope. Figure 3 clearly shows the rupture of micro-fibrils of the kevlar fibre, which has resulted in the strength loss of the flexed kevlar sample. It is confirmed that the strength loss of flexed kevlar sample is due to weakening and rupture of micro-fibrils that has happened within structure of kevlar fibres (Fig. 3).

Kevlar fabric inherently possesses high strength, but it suffers from serious strength loss after flexing, which needs to be considered before selection of this material for any particular application. The residual strength evaluated after 5000 cycles of repeated flexing is 437.4 N/cm and 412.4 N/cm for the warp and weft directions respectively, and the tensile strength critical value required for the intended application is 450 N/cm. Hence, it is understood from the findings that the kevlar fabric will not serve for ten years for the proposed inflatable textile application. Hence, the coated kevlar fabric is subjected to repeated flexing from 1000 cycles to 5000 cycles with interval of 1000 to trace out the optimum flex cycles corresponding to the critical tensile strength, and accordingly the service-life is predicted. The coated fabric is subjected to different number of flex cycles followed by residual strength evaluation of the flexed samples. The residual strength values of kevlar samples evaluated for different flex cycles in steps of 1000 are tabulated in Table 4.

It is evident that the number of flex cycles involved in particular application greatly affects the strength of this material. Deterioration in strength of

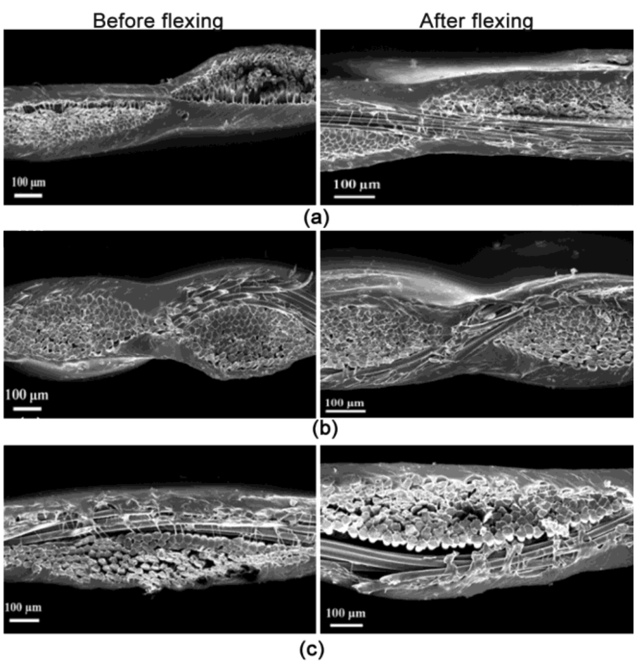

Fig. 1 — FESEM images of cross-sections of coated fabrics (a) Kevlar, (b) nylon, and (c) polyester

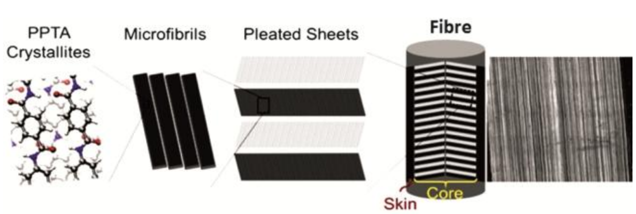

Fig. 2 — Kevlar® fibre structural schematic[26]

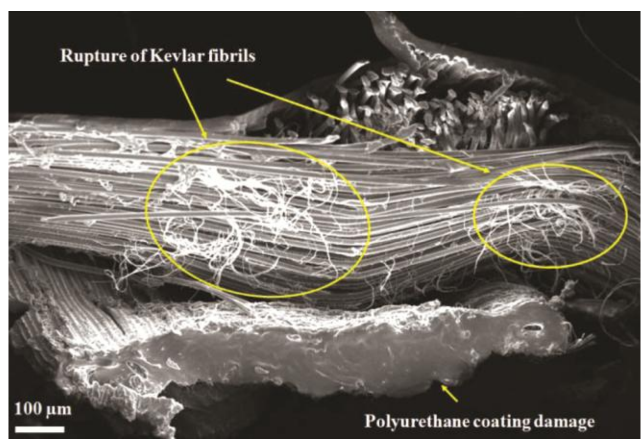

Fig. 3 — FESEM image of flexed kevlar fabric cross-section indicating micro-fibrillar damage

Table 4 — Strength retention with flex cycles of kevlar coated fabric

No. of flex cycles	Residual breaking load N/cm	Breaking extension %
1000	Warp - 604.4 (28.3) Weft - 558.5 (25.9)	7.8
2000	Warp - 554.0 (26.5) Weft - 512.3 (24.6)	7.4
3000	Warp - 502.8 (24.9) Weft - 464.2 (22.7)	7.1
4000	Warp - 477.2 (23.7) Weft - 441.1 (22.3)	6.8
5000	Warp - 437.4 (20.9) Weft - 405.7 (18.7)	6.0

*Values in parenthesis indicate the standard deviation.

Table 5 — Effect of TPU concentration on the breaking load of kevlar fabric

TPU conc. %	Breaking load, N/cm	Breaking extension, %	Strength loss %
20	437.4 (20.9)	6.0	57.2
30	510.6 (21.7)	6.2	50.1
40	511.8 (22.5)	7.1	50.0
50	532.4 (24.6)	7.3	47.9

*Values inside the parenthesis indicate the standard deviation

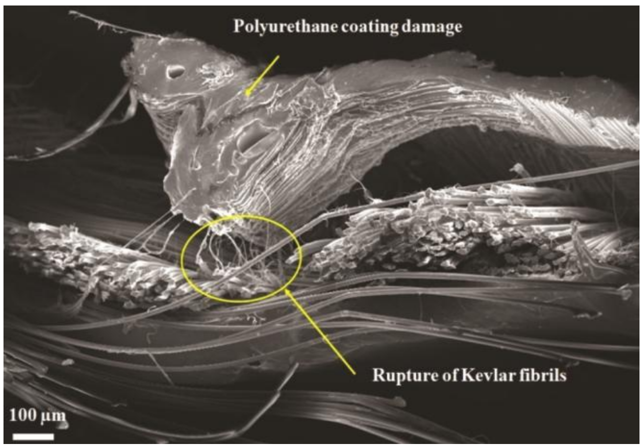

Fig. 4 — Cross-section image of kevlar fabric coated with 50 (w/v) % concentration of TPU and subjected to 100000 cycles of flexing

43% is noticed for 1000 flex cycles and the damage is found to be higher with the increase in number of flex cycles. The trend of residual strength loss, upon repeated flexing is found statistically significant at 95% confidence level. It is observed that the residual strength is failing to meet the critical tensile strength of 450 N/cm after 4000 cycles in the weft direction (441.1 N/cm), and hence the optimum flex cycles the coated kevlar fabric can resist during its service is selected as 3000, and it corresponds to six years of service-life tentatively. This shows that it is not only the initial strength that matters, but the strength retention over usage should also be considered for selection of this material for the specific intended application. Since strength loss is caused due to micro-fibril rupture, the only way of improving strength retention of flexed kevlar sample is to minimize rupture of kevlar fibrils. In Fig. 3, it can be noticed that fibres in structure of kevlar fabric are bonded with adjacent fibres of individual yarn, which has restricted the movement of individual fibres. The higher stiffness of yarns is caused due to consolidated bonding of fibres. This consolidated bonding of fibres leaves no space to relieve stresses acting on them during flexing. One criterion for improving the flex fatigue resistance is to provide free space within the structure of coated fabric for free mobility of kevlar fibres. This effort to improve the strength retention after flexing is carried out by preparing samples of coated kevlar fabric with TPU polymer solution of higher concentration (30, 40 and 50%). Increasing the concentration of coating solution makes it more viscous, which restricts the penetration of coating material into fabric. This creates free space within the structure of fabric to relive stress built on the fibres. Samples of kevlar fabric coated with TPU solution of different concentrations are prepared and then tested to find out the effect of coating penetration on the strength retention of flexed kevlar sample. The breaking load values of kevlar samples coated with polymer solution of different concentrations are given in Table 5. It is observed that the residual strength increases with the increase in TPU concentration from 20% to 30% and afterwards the increase in the absolute value is found statistically insignificant at 95% confidence level. An improvement in strength retention of around 21.5% has been achieved by coating fabrics with higher viscous polymer solution. The high viscosity has restricted the penetration of polymer solution into the structures. This makes the kevlar fibres to move freely during flexing, which results in less fibril damage. Figure 4 shows lesser fibril damage in the kevlar fabric coated with 50% TPU concentration as compared to the damage in the kevlar fabric coated with 20% TPU concentration (Fig. 3). This shows that consolidated bonding of fibre bundles within the structure seriously impairs their ability to resist flexural strains, which, in turn, results in weakening and rupture of kevlar fibrils.

4 Conclusion

The quantum of loss at different degrees of flexing cycles has been assessed and accordingly, a suitable technical solution is offered for reducing strength loss and in this study, an improvement of 22% strength retention is achieved as compared to the inherent loss, upon repeated flexing. The following conclusions are drawn from the present research work:

4.1 Bending modulus of fabric is mostly dependent on the three important factors, viz. fibre type, yarn fineness and the construction parameters and it is successfully established the ranking of the above variables in governing the bending modulus as shown below:

Fibre type (inherent stiffness and rigidity) > yarn fineness (warp and weft) > construction parameters (mass, thickness and yarn density).

4.2 Kevlar fabric displays the highest bending modulus followed by polyester and nylon. The more inherent stiffness and rigidity of kevlar fibre makes its fabric possessing highest bending rigidity. Polyester fabric possessing higher inherent fibre stiffness and rigidity and coarser constituent yarns displays higher bending rigidity than the nylon fabric.

4.3 The effect of flexing has very negligible influence on nylon and polyester fabrics due to their very high extensibility. However, kevlar fabric is found very sensitive to flexing and causes serious strength loss upon flexing due to micro-fibrillar damage. Increase in flex cycles causes increase in strength loss for kevlar fabric.

4.4 The polymer coating solution concentration is found to significantly influence the flexing behaviour and ultimately, the strength loss. Higher concentration results in less strength loss upon flexing due to restricted penetration of more viscous solution into the fabric pores and makes it more flexible to offer lower resistance for deformation.

4.5 The study has established the suitability of utilizing the kevlar fabric for inflatable textile application (military tent, radome and air ships etc) with the predicted five years of service-life and ten years of shelf-life. Apart from that, the solution is also offered for improving the strength loss upon repeated flexing.

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