Structural Materials Research for Lighter-than-Air Vehicles

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Inflatable systems have widespread applications in military, government, and industrial sectors. Improvements in inflatable materials have followed each salient advancement in textiles. The new organic fiber, Kevlar, is a recent and most significant advancement that justified re-examination of old and new inflatable materials' applications. A fertile frontier exists in integrating Kevler with various other material combinations, in optimization of geometric features, and in selection of thermomechanical characteristics compatible with the environment. Expectations regarding Kevlar have been justified by the performance of experimental materials. Styrene-butadiene-styrene block copolymers appear promising as a constituent adhesive for low-temperature applications. Biaxial testing for both strength and material elastic properties is a technology area needing greater awareness and technology growth along with improved facilities. Because of dramatic materials advancements, inflatable systems appear to be moving toward an increased position in tomorrow's aerospace industry.

Introduction

A RESURGENCE of interest in the use of inflatables and lighter-than-air devices is apparent at this time. Reexamination of applications, cost effectiveness, and advanced concepts of blimps, balloons, dirigibles, semibuoyant vehicles, and assorted hybrids is of widespread scope. The continued progress and fullest realization of the envisioned goals for the inflatables are coupled primarily to technology advances in related materials. Moreover, at this time the bounds and limitations, fortuitously, have been extended by unrelated textile research and development that culminated in the high strength-high modulus fiber, Kevlar. This makes reexamination of goals, technologies, and potentialities imperative.

The lighter-than-aircraft materials problem is not unique but is common and encompassed in the efforts pointed primarily to flexible structural aerospace materials research for tethered and stratosphere balloons, decelerators, and parawings. The vast range of conceptual designs involves applications of flexible material from around 0.3 N/m^2 (1 oz/yd^2) to 6.7 N/m^2 (20 oz/yd^2). Conventional materials often have one or more constituents common to many other materials, particularly the adhesives. The thermomechanical characteristics of constitutents, individually or collectively, are known to affect the strength, durability, and handling characteristics of composites. In additon, the suitability and adequacy of test techniques are dependent on constituent materials, fabrication details, test specimen geometry, and test environments. Thus, flexible materials research is an integrated program involving polymer science, structural analyses, fabrication techniques, and test methods.

Inflatable Materials

Reference 1 documents in detail the development of an isotropic reinforced membrane material of Dacron®‡ and Mylar.® The material was designed, fabricated, tested, and flown repeatedly in connection with the NASA Viking Balloon Launch Decelerator Test (BLDT). This single material development revealed the importance of designing and testing for biaxial stresses, inadequacies of coupon testing, and the impact of thermomechanical phase transitions in constitutents. Also, the critical need for appropriate analytical techniques and optimization procedures for structural design of reinforced films was apparent.

Subsequent efforts to analyze reasonably such reinforced membranes are documented in Ref. 2, where good agreements are reported between analyses and tests for biaxial stressing with shear. This capability provides a basis for predicting the performance of more advanced materials. For example, for the same unit weight material of Ref. 1, optimizing the geometric features and using Kevlar-29® reinforcement in place of Dacron, theoretically, will result in a laminate with six times the strength-to-weight ratio. With some amplification of the analytical process, a similar analytical approach useful for optimization and evaluation of material combinations for multifilm fabrications is possible.

Constituents

The ratio δ/σ_u of the density δ of a material to its ultimate tensile strength σ_u is an important parameter for materials selection. Table 1 shows the δ/σ_u ratios for a list of conventional and contemporary materials. In order to show the comparative standings directly, the ratios are divided by the similar ratio for the high strength aromatic polyamide filaments, Kevlar-29. Values greater than one are not as effective for weight sensitive structures as those values less than one. Only three materials show improvements over the reference Kevlar-29 and these are generally deceptive. For instance, S glass has published characteristics that exceed Kevlar. However, because of the degenerative abrasions that result when glass filaments are used in bundles, the effective ratio should be elevated from 0.9 to about 1.7 as shown by the number in parentheses. A similar factor is considered necessary for silicon filaments. Silicon carbide whiskers have phenomenal properties but are available only as whiskers.

Table 1 Comparative material factor, $\delta/\sigma_u/\delta/\sigma_u$ (Kevlar-29)

Kevlar-29	1.00	Dacron filaments	2.53
Kevlar-49	1.10	Carbon II filaments	1.13
Music wire	4.49	Carbon I filaments	1.92
Boron filaments	1.51	SiO_2 filaments	0.65 (1.19)
E glass filaments	1.28	SiC whiskers	0.27
S glass filaments	0.93 (1.70)		

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‡Dacron, Mylar, Kevlar, Kapton, Nomex, Hytrel, Hypalon, Neoprene, and Tedlar are registered trademarks of DuPont Co. Doweave is a registered trademark of Doweave Corp.

Currently, no techniques exist for fabricating the whiskers. Excluding these three candidates for the reasons mentioned leaves Kevlar-29 as the most probably fiber for application to weight sensitive structural systems.

A number of candidate films and coatings exist. Table 2 lists seven films that have varied characteristics. Urethane is widely used in laminates but it displays high creep behavior. However, it has superb "handle" characteristics that make it amenable to high density multiple packaging, such as needed in mobile military systems. Mylar is used widely but has the disadvantages of being costly and moderately stiff. It is better than average in strength, has excellent quality, and can be acquired with oriented strengths. Kapton® has good strength properties but is selected primarily for its high-temperature characteristics. Nomex® is another coating that can provide protection to filaments at high temperature. Hytrel® is beginning to appear as a substitute for Mylar. It has greater flexibility and extreme toughness and should perform well as gas barriers.

Biaxially oriented Nylon 6 has been advertised widely as having exceptional film strength. However, these ideal properties must be treated conservatively because of high variability in mechanical characteristics. When this is done, the material is considered competitive with Mylar.

Polyethylene film is noted for its low cost. However, its mechanical properties are proportionately low. Nevertheless, when used conservatively in designs it has performed successfully at a minimum cost. It has a short life in ultraviolet radiation and must be used accordingly.

Although not listed in the table, the adhesive is a constituent involved in most reinforced films, laminates, and coated fabrications. Adhesives generally are selected on their peel strength, adhesive life, and fabrication compatibility without adequate regard for tensile strength and elasticity.

The future developments of inflatable materials most likely will involve the foregoing and other basic constituents in the forms of films, coatings, yarns, weaves, and specialized reinforcement geometries.

Geometries

Typical construction details on some conventional and contemporary flexible materials are shown in Fig. 1. The early barrage balloon (World War II) was fabricated of Neoprene®-coated cotton fabric (Fig. 1a). The material has an orthogonal fabric layer and a bias fabric layer. The typical material weight was 0.40 kg/m^2 (12 oz/yd^2) and its membrane strength was approximately 206 N/cm (118 lb/in.) in the warp direction and 184 N/cm (105 lb/in.) in the fill.

Small improvements in the material performance were accomplished with the advent of Nylon. Figure 1b shows a modified barrage balloon material similar to the earlier balloon material except with Nylon in place of cotton. The unit weight of the material was reduced slightly to 0.38 kg/m^2 (11 oz/yd^2) and the warp and fill strengths were increased slightly to 224 N/cm (128 lb/in.) and 240 N/cm (137 lb/in), respectively. A third evolutionary step occurred with the advent of Dacron. The Family II Aerostat material is shown on Fig. 1c. This material has an outside layer of Hypalon® for ultraviolet protection and for "troop proofing." The latter relates to a durability criterion necessary to mobile military systems that are subjected to abrasion, wear, and tear from a wide spectrum of personnel. Two layers of Dacron fabric are used in a manner similar to the earlier materials with alternate coatings of Neoprene. The improvements of this material were at the expense of a slight increase in unit weight, 0.44 kg/m^2 (13 oz/yd^2). The strength continued to improve to 262 N/cm (150 lb/in.) in both warp and fill. A noticeable forward step was accomplished in the recent development of a multilayer laminate material of Mylar and Dacron for industrial use in the Tele-Communications (TCOM) balloon (Fig. 1d). This material was originally developed as one of two materials for the Family II military balloon. The unit weight was reduced drastically to 0.29 kg/m^2 (8.6 oz/yd^2). Isotropic material strength was achieved at 394 N/cm (225 lb/in.). Even with the reduced weight, the helium permeability was reduced to about one-fourth that characteristic of the earlier materials. In 30 years, technology advancements in a low-priority area resulted in reducing unit weight by 25% while increasing strength by 100%. It should be noted that each forward step in the heavy material evolution has been associated with the availability of new constituent materials. The steps have been from cotton to Nylon, to Dacron, and to Darcron plus high-strength Mylar film. The advent of Kevlar in the last few years signifies the dawning of a fourth step in balloon materials evolution. The exceptional strength-to-weight properties of Kevlar justify predictions that the most dramatic improvements could occur in the last half of this decade if funds and talents are allocated to this technology.

Three highly probable geometries for the structural matrix of coated or laminated composites are shown in Fig. 2. The triaxial fabric Doweave® has excellent potentialities when woven of Kevlar and by virtue of its self-locking characteristics and inherent shear stiffness. Documentation of work on application and testing of this material by International Latex Corporation (ILC) of Dover, Del. is found in Ref. 3. The ¼-pitch 60° overlayed yarn reinforcement shown in the upper right of Fig. 2 has been studied and offers a second technique. It is a modification of the ½-pitch Viking BLDT material discussed earlier and produced commercially by the

Table 2 Typical film materials

Material	Characteristics
Urethane	High creep, good handle
Mylar	High strength, costly, stiff
Kapton	Good strength, high temperature
Nomex	High temperature
Hytrel	High flexibility, good toughness
Nylon 6 (oriented)	High strength, high variability
Polyethylene	Low cost, low strengh

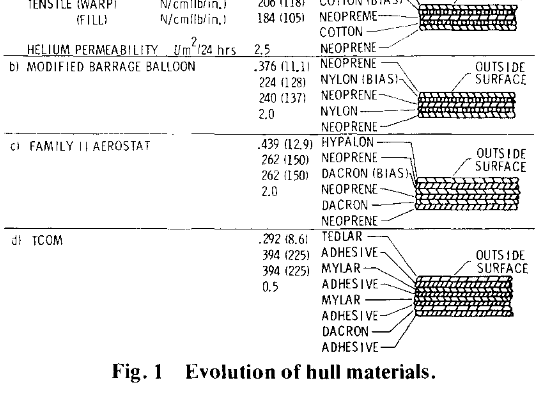

Fig. 1 Evolution of hull materials.

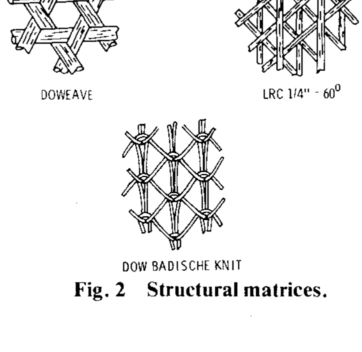

Fig. 2 Structural matrices.

G. T. Sheldahl Co. The ½-pitch geometry will require production machinery changes in order to provide the desired accuracy in apeci interceptions. A third geometry that can be produced by Dow Badische of Williamsburg, Va., is 60° knit that is anticipated to give improved "handle" characteristics to the diagonalized weaves made out of high modulus Kevlar. The dimensional stability of loose knits suggests their application to conventional scrim laminator techniques.

Analytical studies have been made of the ¼-pitch 60° overlayed yarn reinforcement with bilaminates of Mylar. Results are shown on Fig. 3 for various sizes of yarn reinforcements. The ultimate equivalent membrane force $P_{y,u}$ is plotted against unit weight for the bilaminate with various denier yarn. The base weight of the composite films and adhesives is about 75 g/m^2 (2.2 oz/yd^2). The basic films include an external film of 0.02 mm (0.75 mil) of Tedlar® for abrasive resistance and for uv rediation protection. For short duration missions, this layer could be omitted at considerable weight savings. For long duration missions, a thinner layer could be used. However, the particular Tedlar layer shown was based on commercial availability.

Observe that a 170 g/m^2 (5 oz/yd^2) laminate using 1700 denier yarns will provide nearly 613 N/cm (350 lb/in.) axial membrane forces with a tristress loading of $P_x/P_y = 0.6$ and $P_{xy}/P_y = 0.4$. In the laminate, better "handle" would be had if the Kevlar reinforcement could be near the middle plane. However, in order to obtain high-strength splicing of panels or gores of such materials, it is customary to maintain the structural matrix where it can be adjacent to the structural constituents of the gusset tapes. Little research has been done on acquiring high-strength splices of Kevlar-reinforced laminates. This is an area of investigation that should accompany further development of the basic composites.

Exploratory research with respect to the value of a structural matrix of Kevlar in coated and laminated balloon materials is reported in detail in Ref. 4.§ Out of this effort, it can be concluded that the practicality of using Kevlar has been demonstrated for the two configurations shown in Fig. 4. The 0.200-mm-thick single-ply laminate was designed to provide a 25% weight reduction to the TCOM material mentioned previously while maintaining the equivalent strength. Actually, a 20% reduction was obtained but considerable additional strength was acquired. The produced material weighed 0.21 kg/m^2 (6.1 oz/yd^2) as compared to 0.29 kg/m^2 (8.6 oz/yd^2) for the TCOM. The laminate is comprised of an outer layer of Tedlar for uv protection and troop proofing. Two layers of Mylar provide a low permeability and shear strength integrity to the structure. A 0.06 kg/m^2 (1.8 oz/yd^2) loose weave Kevlar-29 fabric was added to provide the orthogonal strengths desired. All film interfaces were bonded by adhesive layers and a protective adhesive wash was applied on the inside to protect the Kevlar fabric. The bonus strength gains acquired by this material are shown by the comparisons between the 1-ply control and the 1-ply experimental data given on Fig. 5.

The experimental laminate showed improvements with one exception. The material showed undesirable rigidity (or poor handle) which inherently is associated with the high elastic modulus of the Kevlar filaments. This feature may or may not be a disadvantage depending upon the application. For mobile balloon systems, the ability to have high density packaging and multiple repackaging is an important specification along with troop proofing. Special packaging techniques would seem necessary with the present material.

The 0.391-mm-thick, 2-ply coated fabric (Fig. 4) is the second experimental Kevlar material. The design goal was to develop a material of comparable weight to contemporary 2-ply coated Dacron materials and strive for greater strength. The product as manufactured turned out 10% lighter than the control material while providing over 100% increase in strength. Its weight is 0.41 kg/m^2 (12.1 oz/yd^2) and it has a uniaxial strength of 690 N/cm (394 lb/in.) as compared to 320 N/cm (184 lb/in.) for its predecessor. The coated material is comprised of a Hypalon uv and troop proofing outer surface, a urethane layer, a Dacron bias fabric to provide shear capability, an additional gas barrier of Neoprene, and an orthogonal structural matrix of 0.09 kg/m^2 (2.7 oz/yd^2) plain weave Kevlar-49 fabric. The superior strength characteristics to the control material are highly evident from inspection of the biaxial strength data of Fig. 5. The achievement of a material of ultimate biaxial strength around 600 N/cm (340 lb/in.) at conventional unit weights, 0.4 kg/m^2 (12 oz/yd^2), should be noted. Whereas it took one-third of a century to achieve 100% increases in strengths prior to Kevlar an additional 100% increase has been demonstrated in the one-half decade subsequent to Kevlar. It is interesting to note that the strength of the 2-ply coated Kevlar material is almost identical to that of a high-strength aluminum sheet having the same weight per unit area. It is approximately 40% higher than steel sheet having 8.3×10^4 N/cm^2 (120,000 psi) ultimate strength and having the same unit weight, 0.4 kg/m^2 (12 oz/yd^2). Moreover, the particular research material is not

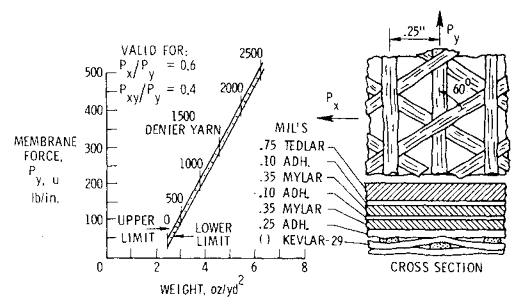

Fig. 3 Kevlar-29 bilaminate.

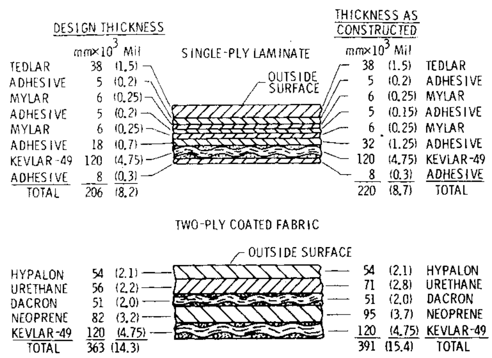

Fig. 4 Geometric configurations of experimental materials.

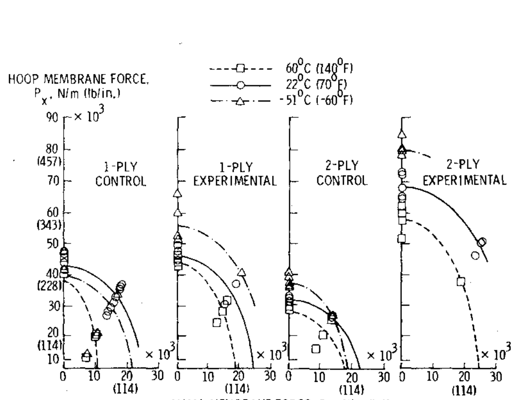

Fig. 5 Failure stress at zero shear stress, $P_{xy} = 0$.

§This research was conducted at the Langley Research Center under contract with the G. T. Sheldahl Co. of Northfield,[8] Minn., with funding from the Advanced Research Projects Agency.

optimized in the strength-to-weight parameter since it was biased strongly in design by the selection of weaves and yarn deniers available to the manufacturer at the time of production. The use of the Dacron bias fabric to provide shear strength is not an ideal geometric design and was made necessary by unavailable Kevlar yarns and/or fabrics in the light range needed for the bias control. The fact that the orthogonal Kevlar fabric and the bias Dacron fabric are uncoupled in their mechanical functions suggests the improvement that could be gained by using a triaxial weave that is more isotropic in behavior. It appears quite feasible that coated Kevlar fabric materials can be made with strength-to-weight ratios up to 50% greater than high-strength aluminum. This can be achieved with the added freedom and versatility of the material as a packageable and inflatable product.

A follow-up program to manufacture and test 10 prototype materials of near similar geometry to those of Fig. 4 has been completed under a NASA Langley Research Center contract with the G. T. Sheldahl Co. This effort is documented in Ref. 5, and provides performance data on materials ranging in unit weights from 1.9 N/m^2 (5.6 oz/yd^2) to 4.3 N/m^2 (13.0 oz/yd^2).

The main objectives of the research were to evaluate the effects of transverse geometric orientation of constituents, the use of elastometric film in place of high modulus films, and the use of Kevlar-49 FTL bias reinforcements in place of bias fabric. All of these features were designed to reduce crease damage and improve packageability; facets of the material "handle" characteristics.

The 10 reference materials were compared with numerous other flexible materials by a quantitative "handle modulus" characterization method proposed by the authors.[6] This test procedure gave numerical verification of the importance and benefits on "handle" of geometric positioning high-modulus Kevlar constituents near the midplane of composites. Also, it was found that coated materials have considerably improved handle characteristics over comparative laminates.

Thermomechanical Design

As a consequence of the materials test program for the NASA Viking BLDT program, it was observed that the composite material strength was degraded for temperatures below that at which the adhesive constituent underwent phase transition from an amorphous to a glasseous state. Additional evidence of the impact on performance of phase transition was reported in Ref. 5. The seemingly inordinate temperature reactions of test data on the ultimate strengths and elongations of multilayer laminates and coated composites were found to be related systematically to the adhesive phase transitions. Whether the phase transition effect was beneficial or degrading on strength was interrelated with the specimens' orientations in testings as well as the specific geometric details of the fabrications.

A rather specialized and indirect solution to avoid the adhesive embrittlement problem is proposed in Ref. 7. For transparent composite materials, raising the ratio of thermal absorptivity to emissivity through appropriate tinting makes it possible for some mission to maintain the adhesive constituents at temperatures above the critical phase transition.

A more direct approach to solve the adhesive problem is reported in Ref. 8. This paper documents a rather extensive research effort to develop and/or modify the thermomechanical properties of adhesives such that the glasseous transition occurs below the minimum use temperature (usually −50° C below the troposphere and −70°C for the tropopause). The thermomechanical transitions are determined from amplitude and frequency data obtained from the Torsional Braid Analyses method.[9,10] Acquiring an adhesive suitable for a specific thermal environment appears feasible from the ranges of thermomechanical spectra measured and recorded in Ref. 8, from which data are shown here as Fig. 6. These data are for four characteristic types of polymeric

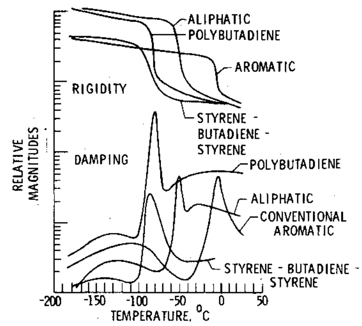

Fig. 6 Thermomechanical spectra of four classes of polymers.

adhesives: aromatic, aliphatic, polybutadiene, and sytrene-butadiene-styrene polymers. The most conventional adhesives are partially aromatic polymers. Early research indicated considerable improvement could be had in lowering the glasseous transition by employing aliphatic materials. This transition is evidenced on the figure by approximately one order of magnitude increase in rigidity as temperature is lowered. The aromatic transition is around −5°C, whereas the aliphatic transition is around −50°C. Although showing considerable reduction in the glasseous transition temperature, the aliphatic materials were still above the tropopause temperature of −70°C. Polybutadiene compositions were characterized and the results show transition temperature around −80°C. Sensitive and critical reactive curing processes stimulated interest in chemicals having nonreactive cures such as styrene-butadiene-sytrene block copolymers (SBS). These materials provide the low-temperature transitions sought for the most severe applications while being more amenable to production processes. Disadvantages to be resolved are low peel strength and the thermosetting nature of SBS materials. The delayed use of adhesive coated materials makes thermoplastic materials more adaptable and practical to most fabrication techniques.

The related damping data shown on the bottom of Fig. 6 provide a second method of defining the transtion points. In some respects, the temperatures of interest are made more salient by the sudden peaks in damping associated with the midrange of the glass transition.

Test Qualifications

For complete qualification of a new material suitable for airship, balloon, or decelerator application, a voluminous test program is required. Excellent detailed descriptions of comprehensive test programs are documented in Refs. 4 and 5. These tests and others are tabulated in Table 3.

In general, standard test machines and procedures exist in the textile and balloon industries for performing the preponderance of the tabulated tests. The major deficiencies exist in the ability to handle ultra high-strength materials in biaxial testing and for acquiring and processing data for adequate Hookian coefficients. The data acquisition and reduction are a significant undertaking.[3,11,12] Helium permeability tests generally are not done under stressing, although it has been the authors' experience that in some

Table 3 Test qualifications

Uniaxial tensile tests	"Handle" tests
Biaxial tensile tests	Helium permeability test (stress related)
Peel strength tests	Accelerated UV tests
Wear and durability tests	Dielectric properties
Bond strength testing	Solar absorptivity
Crease effects	Surface emittance
Blocking tests	Heat capacity and temperature tolerances
Abrasion tests	Hookian coefficients
Trapezoidal tear tests	Optical specularity
Flex tests	Weight and dimensions and variability
Puncture tests	

materials stress is a strong parameter. "Handle" tests have been devised only recently[6] and are not standards but are needed badly. This property is related perhaps to crease and flex and appears to be a strong psychological factor in acceptance or rejections of Kevlar products in particular. For applications in solar energy systems, knowledge of the thermal and optical characteristics will become more important.

Conclusions

Today, inflatables have widespread applications in military, government, and industrial sectors. Current re-examinations of lighter-than-air applications point to a budding new industry of wide scope being stimulated by favorable energy features, cost effectiveness, and an impressive industrial potential.

New material developments that offer higher strength and higher temperature tolerances permit expanding the capability and applications of inflatable systems. Textile mileposts have been followed by related forward steps in inflatable material. In the 30 years subsequent to World War II, 100% advancement in strength took place as the textile industry went from cotton to Nylon, from Nylon to Dacron, and then to Dacron and structured films. In the first half of this decade another 100% advancement has been demonstrated by LRC and industry teamwork in developing materials using the new organic fiber, Kevlar.

Emphasis is needed on developing and optimizing material combinations and geometries of contemporary constituents such as Urethane, Mylar, Kapton, Nomex, Hytrel, Nylon-6, polyethylene, and Kevlar. Also, promising geometrics needing further study are compositions of Doweave, the LRC ¼-60° configuration, and fabrications of Dow Badische knits.

Selections of materials should be made such that thermomechanical properties are compatible with the environment. The glasseous transitions have been defined for four clasees of polymeric adhesives; namely, aromatic, aliphatic, polybutadiene, and styrene-butadiene-sytrene block copolymers. The latter have been found most suitable for extremely cold environments but need further research to improve adhesive strength.

A number of prototype laminates and coated materials have been fabricated having Kevlar-49 constituents. These materials show expected increases in strength-to-weight performance but are crease sensitive and have poor handle characteristics. Research is needed to overcome these weaknesses and to realize the full potential of such composites. The most promising of the prototype composites are coated materials with Kevlar constituents located near the midplane of the fabrication.

Testing of films, coated fabrics, and laminates is largely deficient in the ability to create uniform biaxial stress fields, provide adequate grips and test capacity for new high-strength fabrications, to quantitatively characterize material "handle" properties, and to adequately load and involve all constituents of triaxial or biased reinforced materials.

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