NC STATE
Wilson College of Textiles
JTATM
Journal of Textile and Apparel,
Technology and Management
Volume 11, Issue 1, 2019

Textile Laminates for High-altitude Airship Hull Materials – a review

Ang Li, Rahul Vallabh, Philip D. Bradford, Abdel-Fattah M. Seyam*
College of Textiles, North Carolina State University
Raleigh, NC 27606
*Corresponding author, email: aseyam@ncsu.edu

ABSTRACT

High-performance textile fabrics are highly desirable for high-altitude airship (HAA) hull materials that are expected to be lightweight and strong, flexible at cryogenic temperature, have outstanding tear resistance, and durable over long period. The hull material must also be able to contain the lifting gas, resist intense UV radiation and high concentrations of ozone. This review starts by covering a background in high performance textile and polymer materials and the requirements that must be met in order to build HAA hull structures. With a better understanding of the materials suitable for HAAs, we then discuss the numerous textile laminate HAA materials developed in the literature with a focus on their reported mechanical properties. A comprehensive specific tensile strength comparison between reviewed materials sheds a light on the future direction of HAA material design for further weight reduction. In addition, tear properties of various textile laminate HAA materials were discussed with an emphasis on tear propagation analysis and modelling.

Keywords: high-performance fiber, high-altitude airship, laminate hull material, mechanical properties

1. Introduction and background

1.1 High-altitude platform

The term High Altitude Platform (HAP) generally refers to an aircraft, usually an unmanned airship, aerostat or airplane, positioned above an altitude of 20 *km* (D'Oliveira, De Melo, & Devezas, 2016). This high altitude produced interest in HAPs being used complement to terrestrial and satellite-based communications networks. In the past two decades, great efforts have been made to explore the potential application of HAPs. Even though many projects and programs all over the world were initiated, none of them has been successfully executed to the end. In 2014, two Internet giants Google and Facebook, announced investments in new HAP projects to provide Internet access in regions without communication infrastructure (terrestrial or satellite), bringing attention back to the development of HAPs.

Commercially, it is anticipated that HAPs can play roles similar to those of artificial satellites at the altitude of stratosphere. Moreover, the advantage of being closer to the ground, compared to satellites, allows for lower propagation loss, shorter transmission distances for relaying ground-based communications and short transmission delay times (Komotsu, Sano, & Kakuta, 2003). The possibility of return for maintenance or payload reconfiguration makes them even more cost-effective (D'Oliveira et al., 2016). Another important application for HAP would be wide-field, high resolution optical and near-infrared imaging of astronomical targets. A reliable HAP maintained at an altitude of 20 *km* or higher should be able to serve as an observatory to provide image quality competitive with space-based telescopes (Fesen & Brown, 2015). Other applications, such as detection of oil spills, reinforcement of GPS in high traffic areas, analysis of coastal erosion and monitoring of beach cleanliness can also be realized easily at such high altitude. They can be used as a cheaper alternative to satellites for meteorological analysis and natural disaster management, as well. In this information era, the other huge impact of HAP systems, would be to enhance access to mobile internet service and serve as reinforcement of connection in deserted, difficult to access areas, facilitating globalization of internet connectedness. With so many potential applications discussed, it is not surprising that many organizations around the world, are interested in these platforms. It was mentioned in (Jamison, Sommer, & Porche, 2005) that more than thirty companies have been involved in the development of commercially available airships and aerostats in many countries e.g. China, France, Germany, India, Japan, South Korea, Russia, United Kingdom, and the United States.

However, the main issues in high altitude flight are 1) generating lift in the rarefied atmosphere and 2) overcoming the impact of high wind and turbulence. The majority of the vehicles that operate at high altitude do so by flying very fast (Colozza, Corporation, Park, & Dolce, 2005). Therefore, long flight is an extreme technical challenge for fixed wing aircrafts. Lighter-Than-Air (LTA) structures generate lifting force from buoyancy instead of through aerodynamics, which showed great potential. It has long been recognized that high wind speed and unpredictable turbulences cause great difficulties for the operation of LTA structures. According to a typical profile of peak wind speeds in (Jamison et al., 2005), significant wind speed variations were observed relative to the altitude. A certain zone in stratosphere (between 19.8 and 24 *km*), which is above the jet stream, severe weather and the FAA air traffic layer (Zhai & Euler, 2005), is identified as most suitable region for the operation of LTA structures. Therefore, airships or aerostats capable of operating at this high-altitude appears to be more ideal solutions to realize the concept of HAPs.

To more effectively materialize the HAP concept, most developmental efforts have been in that of non-rigid airship (Gu, 2007; Kang, Suh, Woo, & Lee, 2006; Komotsu et al., 2003; Xu, 2009; Xu, Zhengming, & Weizhi, 2008; Zhai & Euler, 2005). Due to the fact that the air at this altitude is very thin, with a density of about 7% of that of sea level, a HAA floating at this zone has to be of large volume in order to generate sufficient lifting force (Guchi, Okomaku, Platform, & Team, 2000). To fulfill its size and lightweight requirement, airships with a non-rigid hull configuration is preferred. Practically, non-rigid airships have simple structures and are easy to design, build, and maintain. Non-rigid airships are able to overcome the issue of the inherent weight penalty of rigid structures. In comparison with rigid airships, the fabrication cost of non-rigid airships is also lower, and the manufacturing time cycle is shorter (Liao & Pasternak, 2009). Figure 1 shows a typical configuration of a classical non-rigid airship. The shape of a non-rigid airship is sustained by a pressure differential between the lifting gas in the hull and the atmosphere. The hull material contains the lifting gas (and normally multiple ballonets).

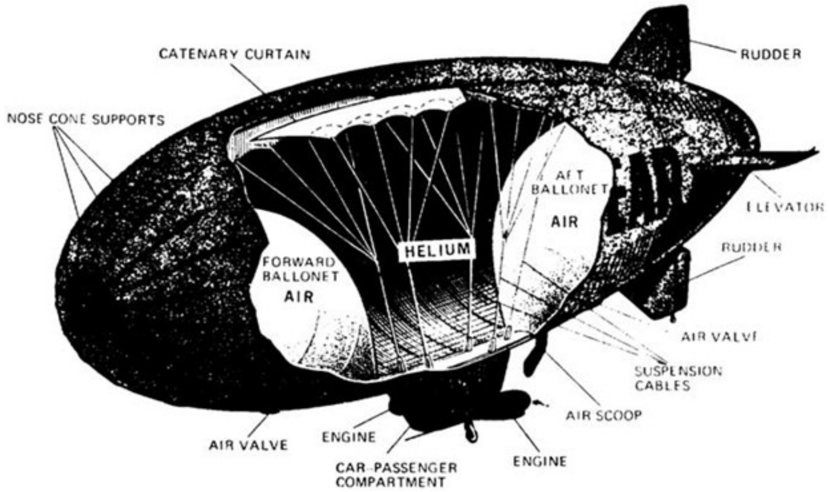


Figure 1. Typical non-rigid airship design (Liao & Pasternak, 2009).

1.2 Challenges in Airship Materials Development

For non-rigid airships, the hull/envelope is the major structural element because it contains the lifting gas and defines the aerodynamic shape of the airship. It is, therefore, required that this part of an airship deserves a high level of engineering and quality control (Miller & Mandel, 2000). Although great advances have been made in general airship material technology over the last three decades, HAAs have unique requirements that demand further improvements. Generally, the challenge is to develop an extremely lightweight (usually expressed as a low areal density) yet strong hull material that is capable of effectively containing lifting gas and enduring harsh environmental conditions.

The strength-to-weight ratio of the hull material effectively determines the feasible size of a non-rigid airship. In addition to the aerodynamic stresses, hoop stresses from the gas pressure differential also rise with diameter, and in a non-rigid airship, this diameter must be relatively large because of the need to resist hull-bending moments (Jamison et al., 2005). The size of HAA is also required to be very large to produce sufficient lifting force in the stratosphere where the air is rarefied, stronger yet lighter materials are needed to build a HAA in optimized dimensions. In addition, the material must also be designed to have proper thermal properties, minimizing the impact of diurnal temperature variation on hull material durability. The high ozone concentration and intense UV radiation can deteriorate hull materials, resulting in a loss of strength and permeability over time. A desirable HAA must stay aloft for a period of months to years to provide valuable and consistent services. Consequently, leakage of the lifting gas through the hull must be minimized, which turns out to be an enormously challenging task. The loss of lifting gas will result in loss of operational capability and increased operational cost. At this high altitude, the extremely low temperature can also cause the material to become brittle resulting in loss of flexibility. Moreover, strong tear resistance is also needed to maximize damage tolerance and prevent catastrophic failure of the hull. Last but not the least, low creep property is extremely important to ensure that the hull shape and dimensional stability can be maintained throughout service life. (Zhai & Euler, 2005).

Obviously, all these requirements cannot be fulfilled by one single existing material. To meet all these requirements of qualified hull materials for HAA, laminated multi-layer fiber reinforced composite materials are typically considered an effective approach. Currently, most modern products that have been developed as hull materials are laminated composite materials. The best feature of laminated composites is that the overall properties of hull materials can be tailored and optimized by the cautious selection of appropriate components. To balance between strength-to-weight ratio, tear resistance, gas retention, Ozone and UV resistance, flexibility and service durability, the hull material laminate should be comprises of a load-bearing component, gas barrier element and layers to protect against weathering and the environment. (Islam & Bradley, 2012). A typical laminate configuration is shown in Figure 2.

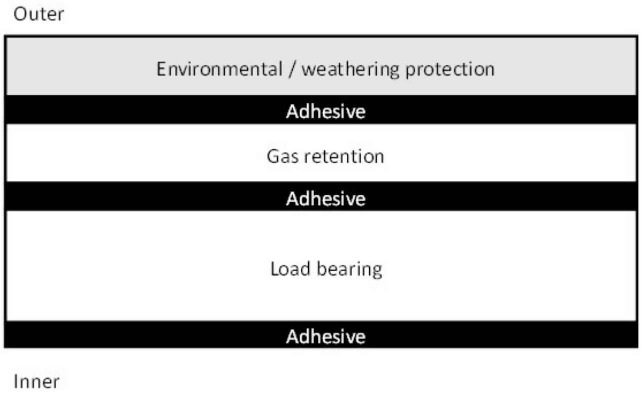


Figure 2. Layout of typical laminated flexible composite (Islam & Bradley, 2012).

The structure typically has distinct inner and outer sides, with the gas-retention component incorporated between the weathering protection and load-bearing layers. The outer side is designed to be exposed to weather, UV, and ozone, whereas the inner side is in direct contact with lifting gases. Prior to the development of high performance polymeric films, adhesives were the main part that could be modified to achieve improved functional properties for the laminate structure. Many additives can be blended in the adhesive system including UV inhibitors, antifungal agents, adhesion promoters, cross-linkers, light and hydrolytic stabilizers, pigments (Islam & Bradley, 2012). In their patent Mater and Kinnel indicated that making multi-layer laminated hull material by using polyester (PET) and polyurethane (PU) films being formed of polymers to which additives for ultraviolet stability, micro-organism resistance, and hydrolytic stability have been added (Mater & Hartly, 1992). The patent claimed that the multi-layer laminate structures created could achieve improved physical and gas retention properties with the integration of additives blended high-modulus thermoplastic polyester films.

Despite considerable effort and expense in the past decades, no self-propelled airship built by any manufacturer has flown at stratospheric altitudes for more than one day. The first successful stratospheric powered airship flight took place in the late 1960s, reaching 20.4 *km* (67k *ft.*) for two hours with a five pounds payload (Fesen & Brown, 2015). In 2005, Raven Industries announced the historic eight-hour flight of a powered stratospheric airship, reaching the altitude of 20 *km* (66k *ft.*). This may still be the current world record for a high-altitude airship flight duration (Smith, Lee, Fortneberry, & Judy, 2011). However, it is the major developments in textile engineering (high performance fibers and polymeric films) that continued to push the boundaries in airship design and development (Jamison et al., 2005). The emergence of novel high-performance fiber and polymeric films is very likely to change the game completely.

This article reviews the evolving research and development status of different types of high-performance fiber reinforced hull materials for HAA applications in a light of their future promise. It covers high-performance fibers, functional polymeric films, mechanical properties analysis of hull materials with various components and structures. An attempt will be made to provide a deep analysis of the numerous publications in the literature and discussions will be presented concerning the limitations of current materials and structures.

2. Materials Evolution

2.1 Strength components – high-performance fibers

To make an envelope material flexible and with sufficient strength, it is required that the load-bearing component to be textile fabric. The most challenging aspect of designing the load-bearing layer is the identification of a high strength fiber with extreme low weight. The low strength-to-weight ratio of traditional natural fibers are not able to meet strict mechanical property requirements of high-altitude LTA systems. With the continuous development of synthetic fibers, the textiles used in airship industry have witnessed many significant breakthroughs, achieving increasingly high strength-to-weight ratios.

At an early stage of airship development, the combination of high strength-to-weight ratio, low creep, low moisture regains, and improved hydrolysis resistance made polyester fiber a good choice for LTA applications. It is not until late twentieth century that the high-performance fibers with higher modulus (over 300 *g/denier*) and tenacity (over 20 *g/denier*) became available. The strongest commercially available fibers in the aspect of specific strength (Strength/Linear Density) are Zylon®, Dyneema® and Spectra®. Other high performance fibers, including Vectran® and Kevlar®, are less strong but possess other great properties (Zhai & Euler, 2005).

2.1.1 Para-aramids - Kevlar®

Compared to the conventional low strength textile fibers, fully aromatic polyamides, have a much higher strength-to-weight ratio, a greater modulus which inevitably lead to a much lower failure strain. Their major disadvantage is typically the issue of degradation when exposed to ultraviolet radiation from sunlight (Islam & Bradley, 2012). It was also found that a para-aramid fiber reinforced laminates are not as capable of effectively dispersing the stress concentrations, which will be unavoidably introduced during the manufacture of large structures. According to conventional knowledge, the tensile deformation of para-aramid fiber is dominated by rotation of its crystallites toward the fiber axis. Tensile load application induces an immediate elastic rotation and a time-dependent creep rotation. Crystallite rotation stiffens the fiber, reducing elastic and creep compliance. Thus, the stress concentrations cannot be relieved in a timely manner. The unrelieved stress concentrations can then initiate catastrophic tear propagation. Before this problem been properly solved or completely eliminated, there won't be further development of stronger and lighter aramid reinforced hull materials (Islam & Bradley, 2012).

2.1.2 Ultra-high molecular weight polyethylene - Spectra® & Dyneema®

The properties of fibers made from ultra-high molecular weight polyethylene (UHMWPE) are substantially distinct from those of typical polyethylene material. In normal polyethylene, the long polymer chains are less oriented, which allows the material to stretch dramatically before failure. The molecular weight is low, and the crystallinity is usually lower than 60%. While in these purposely designed high molecular weight, high-performance fibers, the long chains have been straightened (crystallinity can be as high as 95%) and lie along the fiber length, giving considerably higher strength with much lower failure strain. Although they have the potential to produce the lightest fabrics for a required strength, they suffer from poor creep, and flexural properties (Islam & Bradley, 2012). UHMWPE fibers are not compatible with many industrial resins and adhesives because of a weak boundary of low molecular weight fragments as well as its non-polar nature of molecular structure (Silverstein & Breuer, 1993). Their applications are also restricted by the low melting point, with a heat resistance only up to ~150 °C. But notably, UHMWPE fibers under the trade name of Dyneema® are very resistant to moisture and UV light (DSM, 2008), and much superior to Zylon® and Vectran®. It was also claimed in (Mcdaniels, Downs, Meldner, Beach, & Adams, 2009) that the tradeoff of Dyneema® being with less than ideal creep but excellent UV performance may be easier to design for, and determine life factors from, than from materials with opposite trade-offs. Unfortunately, not much effort has been put into researches on Dyneema® fabric based laminate materials for airship application thus far.

2.1.3 Polyarylate - Vectran®

Vectran® fiber is a commercial product from Kuraray Inc. A high tenacity (HT) polyarylate fiber (Vectran® HT) offers desirable combinations of performance, structure, and properties critical to material development for LTA applications. They include high strength and modulus, excellent creep resistance, high abrasion resistance, superior flex/fold fatigue resistance, minimal moisture regain and excellent chemical resistance (Islam & Bradley, 2012). In addition, other properties like low coefficient of thermal expansion (CTE), and excellent cut resistance, superior property retention at low and elevated temperatures, outstanding damping and impact resistance provide this type of fibers with more advantages, which makes them useful for diverse list of structural fabric applications. Regardless of its lower specific strength, Vectran® offers a superior balance of different properties in comparison to other high-performance fibers. However, Vectran® fibers possess much lower specific strength when compared with Zylon® and HMWPE fibers (see comparison in Table 1), which has inevitably limited its application in high-altitude airships.

2.1.4 Poly(p-phenylene-2,6-benzobisoxazole) - Zylon®

Zylon® fiber, made from rigid-rod chain of an aromatic heterocyclic lyotropic polymer, polybenzaxole (PBO). In spite of a larger density, Zylon® is still claimed to possess a higher specific strength over Dyneema® (Islam & Bradley, 2012). The fiber has better abrasion resistance than aramid fibers but performs significantly lower than Dyneema®. Nevertheless, the extremely high flame resistance and excellent creep resistance are not matched by any other types of high-performance fibers. With all these impressive properties, this “super fiber” looks very promising for HAA application. However, the weaknesses of Zylon® fiber was gradually unveiled after many investigations into different types of properties. It is widely known that prolong exposure to visible light and UV radiation degrades Zylon® fibers over time (Said et al., 2006). Moreover, the strength will also drop significantly when being exposed to an environment with high humidity and heat. As a result, it must be very carefully protected immediately after its production and throughout their conversion to fabric and ultimately lamination. Finally, Zylon® fiber is more expensive when compared to other types of high-performance fibers.

For a clear comparison, general mechanical properties of typical commercially available high-performance fibers are summarized in Table 1 (Zhai & Euler, 2005). In general, high performance fibers are attractive to the LTA industry. However, concerns remain for these fibers, such as inability to effectively release stress concentrations (e.g. Kevlar®), poor creep resistant properties (e.g. Spectra®), moisture and UV degradations (e.g. Spectra® and Zylon®). This may change as more scientific investigations and more application based experience with these fibers become available, so that their undesirable properties can be improved, or compensated by some other methods.

Table 1. High Performance Fibers Comparison (Zhai & Euler, 2005)

Material		Strength, *g/den*	Pros	Cons
Zylon®	PBO	42	Strong, excellent creep resistance, extremely high temperature resistance	Low flex resistance, poor UV, visible light, and moisture resistance
Spectra®	UHMWPE	25-40	Strong, flexible, and good weatherability	Low melting point, poor creep resistance, and difficult to bond
Vectran®	LCP	23	Good overall properties and excellent cut resistance	Not as strong as Spectra® or Zylon®, poor UV Resistance
Kevlar®	Aramid	22	Strength comparable to Vectran®	Poor folding and abrasion resistance

2.1.5 Structures of fiber assemblies

With the evolution of fiber/yarn tenacity, another challenge in the core strength material development is to achieve efficient load transfer from the fiber strength to the end-use laminated material. To satisfy the strict requirements for maximum hull weight, single layer woven fabrics are predominantly used in hull laminates as the core strength element. The fiber selection is just the very first step in engineering the mechanical properties of the hull. The weave pattern design, weaving preparation and weaving process as well as other textile processing also significantly influence the physical properties of the finished textile fabric and laminate (Zhai & Euler, 2005). The design of weave pattern determines how the warp and weft yarns are interlaced in a woven fabric. Plain weave is the most common and simple weave design, and it provides very high number of interlacements between the warp and weft yarns (often expressed as fabric tightness). Due to the high interlacements, plain-woven fabrics are dimensionally stable structures with less yarn distortions due to high inter fiber friction, so that the handling stability is very high. A woven fabric can be produced with various yarn linear density and thread count that determine the tensile strength and openness of the fabric. A common variation of plain weave is basket weave (two or more warp and weft yarns woven as one in a plain weave pattern) or modified plain weave with 'rip stop' which improves the tear resistance. Compared with a simple plain weave fabric, basket weave fabrics have lower thickness and crimp. In rip stop patterns, thicker or double yarns are usually woven at intervals to achieve the purpose of increasing the resistance to tear propagation in one or both directions (Islam & Bradley, 2012). With a similar overall structure to the widely investigated coated fabrics, the laminated structure should share some principles when it comes to the hybrid structure of fibers and polymers. For example, the woven fabric design has a significant impact on tear resistance. Nevertheless, the higher original tear strength of a basket weave, as compared with a plain weave, may not be retained when such fabric is coated with a thick layer of polymer. The increased openness of the basket weave causes greater polymer coating to penetrate through the thickness and bind the fibers and yarns in the fabric structure. Yarns may thus become less mobile and unable to slide and jam together. The yarns then break individually rather than in groups, causing the tear strength to reduce significantly (Schwartz, 2008).

Unconventional "non-crimp" laminate structures are being developed by Cubic Tech

(CT) Corp., which can be likened to a classic structural composite laminate structures called “Cross-ply” where the layers are stacked orthogonally and not interlaced. With the same principle, CT has developed improved capability to further produce multidirectional, non-interlaced laminates from oriented filament plies and high-performance films or surface coatings. It has been shown that removal of crimp effectively increased the tensile strength of the as-produced laminates (Mcdaniels et al., 2009). It is claimed that “non-crimp” fabrics have many technical and performance advantages over woven fabrics with high crimp, being easier to manufacture as well as more flexible to optimize weight and thickness. Additionally, tensile loading of high crimp woven fabric brings transverse loads at yarn overlap areas as crimped yarns are straightened; this reduces the conversion of yarn strength to fabric strength and also affects fatigue performance and creep property. It was also stated by Mcdaniels et al. that crimp induced degradation in properties is more noticeable with higher performance structural fibers. This is due to the fact that most of these fibers properties’ are optimized in the axial direction of the fiber filaments properties, which consequently makes them weaker in the transverse direction (Mcdaniels et al., 2009).

The yarn interlacing in woven fabrics causes crimp, which in turn reduces the fabric strength. However, the interlacing also causes inter-fiber-friction at the crossover areas of warp and weft yarns, resulting in very low effective gauge length, which effectively increases the fabric strength and reduce the weak link effect. Weaving flat filament yarns (untwisted) produces extremely low crimp while increases inter-fiber-friction at the cross over areas due to their ribbon-like geometry. The gain in strength due to inter-fiber-friction could be higher than the loss due to crimp, especially in case of fabrics from flat filament yarns. On the contrary, in the case of “cross-ply” structure, since there is no assistance from the fabric interlacing structure, the overall strength of the laminate may be weakened by yarns with non-uniform quality or straightness along their length. To achieve higher strength, equal tension control on every individual yarn should be more rigorous. Careful tension control must be applied on both warp and weft yarns during conversion of yarns to fabric and lamination processes to ensure the proper load sharing of the “cross-ply” fabric.

2.2 Functional components

2.2.1 Gas retention component

All the early stage airship hull materials used layers of polymer coatings as the gas barrier, while lightweight polymeric film materials are usually incorporated to be the major gas barrier for modern laminated hull material (Islam & Bradley, 2012). In practice, polyester is a preferred material, with high-modulus polyester film (Mylar®; DuPont-Teijin) being the most commonly used gas barrier element on existing airship materials. Mylar® has low permeability and relatively high strength and stiffness as well.

Notably, it is recommended in an airship material review (Islam & Bradley, 2012) that polyimide (PI) film, Kapton®, provides outstanding mechanical strength and high modulus and is also suitable to be used as an effective gas barrier component. Aerospace grade PI films are widely used on external surfaces of satellites and spacecraft, yet their applications are still scarcely found in airship laminates, potentially due to their excessive cost. There is only one case of airship hull material found in the literature integrating PI film as a gas barrier layer, being protected by another layer of PVF film as weathering component. This type of material is claimed to have worked on aerostats at an altitude of ~ 21.3 *km* (70k *ft.*). and with a service temperature from -100 °*C* to +60 °*C* (Laven & Kelly, 2005). Many researchers have made efforts to improve the durability of PI film in aerospace applications, mainly addressing the erosion issue caused by atomic oxygen (AO). A recent study (Gouzman, Girshevitz, Grossman, Eliaz, & Sukenik, 2010) showed that a thin layer of Titania coated on the surface of PI films via liquid-phase deposition (LPD) can effectively reduce surface erosions induced by AO. With a practical solution to endure AO, which also exists in abundance in the stratosphere, using modified PI films as weathering component seems feasible. In combination with a decent gas barrier property, they can be used as a multi-functional layer to reduce the overall weight of the envelope material. The decrease in the number of layers will also help to reduce the use of adhesives, reducing the weight as well as the number of locations where delamination can occur.

The other unique polymeric film frequently used as gas retention component in more recent airship material laminate structures is EVAL™ film (EVOH, Kuraray). Without any exceptions, the EVOH (ethylene vinyl alcohol) films were laminated together with other components through various bonding agents (Komotsu et al., 2003; Shoji Maekawa, Nakadate, & Takegaki, 2007). EVOH is a semi-crystalline copolymer of ethylene and vinyl alcohol monomer units (Mokwena & Tang, 2012). In general, the good gas barrier properties of EVOH copolymers are primarily attributed to their inherent high degree of crystallinity. Because it is known that gas transfer occurs mainly through the amorphous regions, and crystallinity hinders the diffusion of gas molecules. Thus, the presence of large amount of impermeable crystalline regions in EVOH reduces gas permeability by creating more complicated and tortuous diffusive pathways for gas molecules (Lagaron, Catalá, & Gavara, 2004). Other than the excellent gas barrier property, EVOH is also known to be very sensitive to moisture, which is primarily caused by the associations between water molecules and the polar hydroxyl groups in EVOH. Thus, care needs to be taken with the handling and storage of EVOH polymers in order to achieve consistent lamination quality and to optimize the barrier performance (Mokwena & Tang, 2012).

2.2.2 Weathering/environmental component

Polyvinylfluoride (PVF) film, commonly known by the trade name, Tedlar® (DuPont), has been used for most large LTA applications. Tedlar® has excellent resistance to solar degradation. Pigmented Tedlar® film offers even higher level of UV protection. Other advantages of Tedlar® include chemical and solvent inertness, toughness, flexibility over a wide temperature range (-72 to 107 ℃), and good gas containing properties for low-altitude airship applications (Kang et al., 2006). To understand the long-term weathering effects on SSA hull materials, Nakadate et al. (Nakadate, Maekawa, & Kurose, 2011) applied Tedlar® Film with an evaporated aluminum coating as the weathering protection component, incorporating with Zylon® woven fabric as the load-bearing component and polyurethane as adhesives. The thin reflective metallic coating was intended to improve the UV radiation resistance of the envelope material. The results from weathering exposure testing indicated that the addition of an extra layer of Aluminum was also able to significantly improve the moisture barrier property and thus sustaining long-term outdoor exposure in high humidity environment.

Another widely acceptable and readily used material for weather resistance is polyurethane (PU). PU has outstanding toughness, high tensile strength, tear strength, low temperature flexibility, fair gas permeability, good UV and Ozone resistance (Islam & Bradley, 2012). While most polyurethanes are thermosetting polymers that do not melt when heated, thermoplastic polyurethanes (TPUs) are also readily available. TPU can be heat sealed, adhesively bonded, and laminated with other substrates. Kang et al. integrated a TPU film at the inner side of the envelope material for thermal bonding. Different from the PU layer traditionally coated onto the textile fabrics, it was mentioned (Kang et al., 2006) that laminated TPU film can serve as another gas barrier element within the hull material. In particular, when the external weathering and gas retention layers are damaged, the internal TPU layer can block gas leakage to some extent.

2.2.2.1 Ultraviolet (UV) resistance

To adapt to the working environment in the stratosphere, the surface materials of an envelope exposed to the atmosphere must be able to resist the intense UV radiation. Not only does the material need to withstand the degradation from the UV radiation for an extended period of time, but also prevents the UV radiation and visible light from transmitting through. In most cases of the modern envelope material for SSA applications, the high-performance fibers used to fabricate the core strength layer are UV and even visible light sensitive. The fibers tend to lose strength significantly upon exposure to UV radiation for an extended period of time (Said et al., 2006). Such degradation induced by UV radiation becomes a challenging issue for the development of SSA hull materials. There have been a number of works investigating different methods of effectively protecting the high performance fibers from UV radiations, among which a sheath structure containing UV inhibitors was found to be highly effective in improving the UV-Vis resistance of PBO braids (Vallabh, Hassanin, Said, & Seyam, 2016). Hassanin et al. sheathed the PBO braided tendon with a PU membrane loaded with TiO_2 nanoparticles. The strength of the protected sample retained at a significantly higher level when the fillers loading was optimally controlled. For airship materials, the lightweight requires the UV protection method to be effective with low weight plenty. Thus, another approach to protect the high-performance fibers with minimum weight penalty is to deposit consistent quality thin metallic coatings to reflect the UV radiations and prevent the penetrations. However, the introduction of the metallic surface could potentially cause adhesion issues.

To validate the effectiveness of metallic coatings, an envelope material (Z2929T-AB) consisting of an aluminum evaporated Tedlar® layer, was developed using Zylon® (PBO, Toyobo) as core strength fabric. The detailed layer notation of this laminated envelope material is shown in Figure 3.

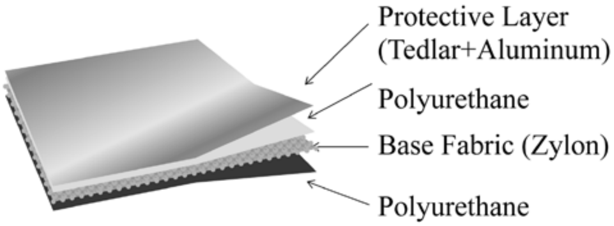


Figure 3. Material composition of Z2929T-AB (S. Maekawa et al., 2008)**.**

The xenon tests were conducted where the specimens were exposed to 180 W/m^2 xenon lights for 100 *hrs*, which is equivalent to half of a year's exposure to UV radiation on the ground. The data demonstrated that the strength retention rate is close to 100% with a negligible reduction of tensile strength, proving that the addition of a thin layer of evaporated Aluminum can effectively block the UV radiation and protect the high-performance fibers. However, a prolonged stratosphere-level-intensity UV-Vis exposure test needs to be done to further confirm the long-term reliability of the UV resistant performance of Aluminum reflective coating. Moreover, in the real operation environment, stresses applied to the hull material will change cyclically, which in turn will cause fatigue degradation on material properties. For instance, micro-cracking induced by stress over time may accumulate and eventually let light penetrate through. Therefore, whether the integrity of the metallic coating can be maintained during long-term use is a key issue for UV resistance property (Maekawa et al., 2008).

Since it takes considerable amount of time to build a large airship before launching, ground level moisture is also an important factor, which tends to affect the performance of the multi-layer envelope laminate materials. Subtle effects can be accumulated and transformed into a significant impact over time. Thus, a two-year long outdoor exposure test was conducted by Nakadate et al. (Nakadate et al., 2011) to investigate the extended impact of weathering to the airship laminate material in Figure 3. Indeed, testing results from this work showed a unique seasonal effect on the tensile strength. Specifically, it was observed that substantial decrease in tensile strength occurred during late spring to early fall of the second year as well as the first year, whereas negligible decrease took place during other seasons.

These results suggested that the high humidity and/or the high temperature during these seasons were/was the cause of the decrease in tensile strength. A six-month long supplemental outdoor exposure test was conducted to separate humidity effect from temperature effect (Figure 4).

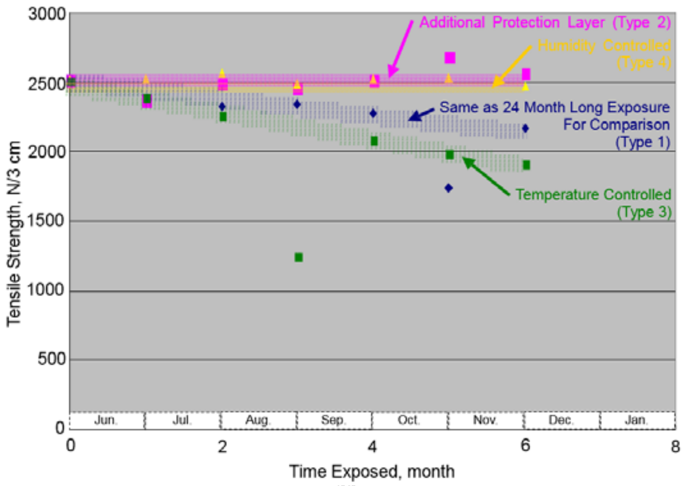


Figure 4. Summary of supplemental outdoor exposure test, effects of an additional protection layer, humidity, and temperature (Nakadate et al., 2011).

The test results suggested that the high humidity was obviously the primary factor causing the decrease in tensile strength. Notable in Figure 4, the tensile strength of the material with an additional protection layer (evaporated Aluminum Tedlar®, Type 2) decreased negligibly for months as that with humidity controlled (Type 4). The added layer to the outer surface might have reduced the overall permeability of the material and blocked the water molecules from passing though the material and penetrating into the core fabric. However, since the primary effect of the aluminum evaporated Tedlar® protection layer is to block the light, the effect of light should be separated from other factors for future work. Nakadate el al. suggested that dried air needs to be used in final airship inflation to maintain its shape and strength for months before launching to the stratosphere where moisture barely exist. Moreover, it is also recommended that the addition of one thin layer or two (e.g. aluminum coating) with low permeability to gas and vapor can be effective for humidity resistance.

2.2.2.2 Ozone and atomic oxygen resistance

Ozone is a strong oxidant and could break some of the molecular chain structures, resulting in degradation of polymer material. Per the study of Maekawa et al. (Maekawa et al., 2008), Ozone at 50 ± 5 *ppm* is applied to the specimen (laminate structure shown in Figure 3) for 24 *hrs* in the exposure test. This ozone concentration is five times higher than that at the altitude of 20 *km*. From the high strength retention percentage obtained in this study, it is confirmed that Tedlar® functioned as a great Ozone resistant element even at a higher concentration. Nonetheless, the short duration of the exposure test is not able to validate the long-term Ozone resistant performance. Due to the existence of the Tedlar® film, it takes time for Ozone to erode and penetrate into the interior structure of the laminate to cause critical damage. While this study showed that Tedlar® film is able to protect load-bearing fabric from the attack of Ozone, long-term Ozone resistance merely from Tedlar® is not guaranteed, which needs to be further verified by exposure to high concentration Ozone for extended period of time. A hybrid exposure test of intensive UV and a high concentration Ozone would better simulate the environment in the stratosphere to help to identify the real weathering resistant performance.

In addition to ozone, Atomic Oxygen (AO) exists in high concentrations in the stratosphere and is also extremely hazardous due to strong erosion to nearly all polymers (Lin, Tan, & Materials, 2011). It is reported (Zhai & Euler, 2005) that Triton Oxygen Resistant (TOR) polymers may be a promising candidate for the protective film layer of SSA. TOR polymers were tested in low earth orbit by NASA and appeared to be a good candidate for weather resistant films or coatings in extreme environments. Preliminary data indicate these polymers have a high resistance to degradation from AO, ozone and UV radiation (Triton, 2001). Another unique feature of this polymer is the formation of an outer oxidized layer for abrasion protection, which can be reformed if surface damage does not penetrate completely through the material.

2.2.2.3 Temperature resistance

Substantial diurnal temperature variations at high altitude has a great impact on the altitude control and power consumption of LTA structures. The surface properties of a hull material can significantly affect the thermal control of the whole airship system. Generally, a low solar absorptivity (α) in combination with a high infrared emissivity (ε) is desirable to prevent the airship temperature from increasing dramatically. In this case, a reflective metallic surface is theoretically more beneficial than a white non-metallic surface. As reported in a material review paper (Zhai & Euler, 2005), the calculated α / ε ratio of a lab-made metallic sample is only one-fourth of that of white Tedlar®, demonstrating significantly better thermal control functionality. The effect of temperature on mechanical properties of Z2929T-AB airship envelope material was also investigated (Maekawa et al., 2008). Tensile tests were performed at different temperature levels to attain the tensile strength of the laminates and their seams. With the increase of temperature from -90 °*C* to 60 °*C*, the tensile strength of laminate samples in warp and weft directions reduced by ~14% and ~34%, respectively. A similar trend of strength loss to temperature increase was observed from seam samples as well.

3. Mechanical analysis of laminated hull materials

3.1 Tensile property

3.1.1 Uni-axial Tensile strength

Uni-axial tensile strength is probably the most often quoted property for evaluation of an airship hull material mechanical performance. Serving as the most fundamental data to support the SSA design, high specific strength (strength/density) is always preferred. Komatsu et al. (Komotsu et al., 2003) from Japan Aerospace Exploration Agency (JAXA) experimentally developed and evaluated the uni-axial tensile strength of more than thirty high-specific-strength laminated fabrics for SSA platforms, involving the applications of a large number of different high performance fiber and film materials. Among all these laminated hull material prototypes, high performance fibers including Vectran®, Kevlar® and Zylon® were used as the load-bearing components. Tedlar® films with and without Aluminum evaporation were used as the weathering layer, and Mylar® and ethylene vinyl alcohol (EVOH) films integrated as gas retention layers. Based upon the comparisons of strength results, the laminated envelope with Zylon® fabrics as the core layers exhibited the most satisfactory mechanical performance. Further study of the temperature effects on mechanical properties also verified that the high specific strength of

Zylon® based envelope materials could be well maintained at both high and low temperatures. Among high-performance fibers, Zylon® fibers also have the best creep resistant performance, with a creep failure time of two years at 60 % breaking load at room temperature (PBO, Toyobo). Hence, it was confirmed by Komotsu et al. that Zylon® fiber is undoubtedly the most promising candidate to build a reliable, enduring load-bearing element for SSA applications.

To visualize the uni-axial tensile strength and weight correlations of hull materials, published experimental results (Jianwen Chen, Chen, Zhou, et al., 2017; Gu, 2007; Kang et al., 2006; Komotsu et al., 2003; B. Li, Xing, & Zhou, 2010; S. Maekawa et al., 2008; Mcdaniels et al., 2009; Junhui Meng, Lv, Qu, & Li, 2016; F. X. Wang, Xu, Chen, & Fu, 2016; Xu, 2009) were put together to obtain a more comprehensive evaluation. Comparisons of the material strength-to-weight ratio vs. weight of the laminate materials are presented in Figure 5.

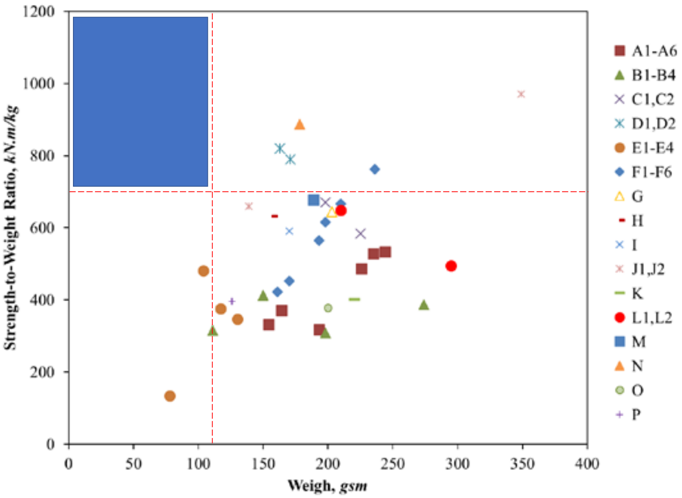


Figure 5. Comparison of the strength-to-weight ratio of the laminate materials developed in the literature.

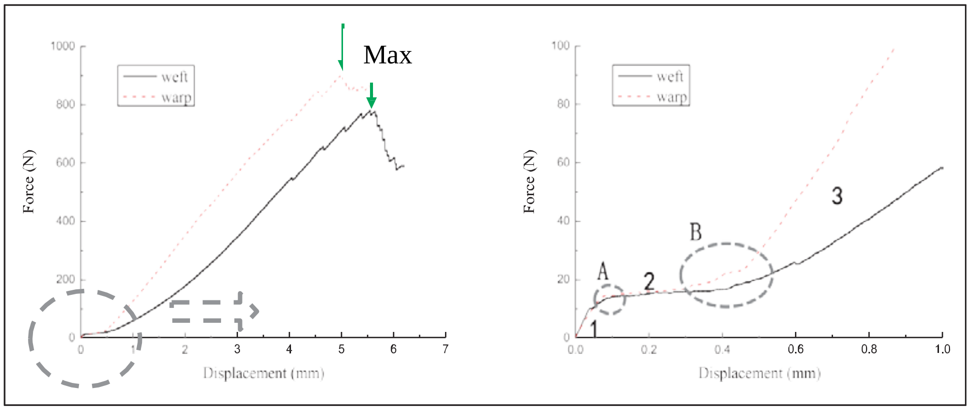
Detailed material and structure information of all collected airship hull material samples can be found in (Li, 2018). It is obvious that Zylon® is predominantly used as the core strength element of the laminated hull materials studied in most recent years. Generally, we saw a leap in the specific strength of the Zylon® fabric reinforced hull materials. Nonetheless, there is still room for further improvement of specific tensile strength, namely reducing laminate weight by integrating thinner and lighter polymeric films and depositing considerably thinner functional coatings to eliminate one or two unnecessary layers. Besides modifications of gas retention and weathering components, load-bearing layer and adhesives layers can also be adjusted for the purpose of weight reduction. The most direct approach has to be making woven fabrics with lower denier Zylon® yarns to further reduce the net weight and thickness of the textile reinforcement. Observed from the collected data, the lowest linear density of Zylon® yarns used to make woven fabrics was 250 *denier*. Preliminary work were conducted by our team to successfully produce plain weave fabrics with 150 *denier* Zylon® yarns, attaining a significantly reduced weight compared with weight of fabrics reported in the literature. In addition to the net weight reduction of fabrics, thinner fabrics will allow the utilization of less adhesives to attain adequate interfacial adhesion.

The next generation laminated hull materials should be either lighter than materials with similar tensile strength, or stronger than materials with the similar weight. The strength-to-weight ratio are expected to be higher than all the hull material samples developed in previous studies, meaning that the mechanical strength data should fall into the blue square zones in Figure 5 to be qualified as promising candidate for HAA applications. In practice, lighter hull material will be more beneficial for airship operation. Thus, achieving high strength-to-weight ratio by adding more fiber reinforcement is not considered effective approach. The other approaches of reducing overall weight without sacrificing tensile strength seems to be a more feasible practice.

More comprehensive and in-depth studies on the tensile property of the laminated envelope materials were also conducted to help better understand their behaviors toward the mechanical loading in varied conditions. Kang et al. (Kang et al., 2006) conducted uni-axial tensile tests for Vectran® fabric reinforced envelope materials to attain experimental results of tensile properties and then compared with the results predicted by the geometrically non-linear finite element analyses. As observed from the plots in the paper, the typical stress-strain curve of an envelope material was a smooth curve with significant nonlinearity, showing an increasing modulus with the increase of tensile strain. They also performed uni-axial tensile tests in a thermal chamber at low, medium (room condition), and high temperatures to investigate the dependence of tensile strength on temperature. It was revealed that the steady-state stiffness modulus calculated at the lowest temperature of -75 °*C* was 47% larger than that calculated at the room temperature of approximately 25 °*C*. This behavior correlates well with the stiffening of Vectran® fibers with a 40% modulus increase at a cryogenic temperature. The decrease of tensile strength to temperature increase agrees with the results observed in the above mentioned work of Maekawa et al. (Maekawa et al., 2008).

With a similar Kevlar® fabric as reinforcement in the hull material, Meng et al. investigated failure mode of uni-axial tensile testing by observing SEM images of fractured specimens. Two distinct failure modes of the envelope material were identified, namely interface failure and fiber bundle fracture. The failure mode of debonding between fibers and polymer films correlated well with the force-displacement curve obtained (Meng, Lv, Tan, & Li, 2016).

As it can be seen from Figure 6(a), a significant orthotropy is observed for the load-displacement curve of the envelope material. Potentially owing to the fact that slightly higher initial crimps were introduced to weft yarns, the maximum tensile force in the weft direction is about 13.4% lower than that in the warp direction. However, the authors' statement that weft yarn sustained more damage than warp yarns from weaving process may not be entirely correct. As is shown in Figure 6(b), there are two significant nonlinear regions on the force-displacement curves in both warp and weft directions. This may be attributed to the occurrence of debonding between the fabric substrate and the polymeric adhesives/coating, which was also found by Chen et al. (J. Chen, Chen, & Zhang, 2014).



(a) (b)

Figure 6. Measured force-displacement curves of the uni-axial tensile tests; (a) global curve and (b) magnification at the low strain range (Meng et al., 2016).

The stress-strain curve is important for characterizing the mechanical behavior of airship hull materials. Meng et al. developed Monte Carlo simulation method based on the Ising model to analyze the stress-strain curve of their hull material samples, achieving a good fit of the simulated curves to the experimental data. It was also found that the fabric strength, functional film strength and interfacial bonding strength are important parameters affecting the mechanical properties, which will decide the shape of stress-strain curve.

For the specific laminated fabric developed in the study of Chen et al., they also proposed a stress-strain model based on the uni-axial tensile testing, as shown in Figure 7. The stress-strain curve consists of three linear regions and two non-linear regions (Chen et al., 2014). Initially in region OA, the laminate sample behaves as an undamaged, linear elastic material, indicating that the fabric and coating are extended together. In the first and second non-linear regions (AB and CD), the coating may be debonded from the fabric, and the fabric behaved as a non-linear material. There is also a second linear stage BC, where the behavior laminate material is primarily controlled by yarns. The yarns elongate linearly again with a smaller slope (elastic modulus) than that of OA region. In the end region DE, fabric elongates linearly again after point D, and at point E most of yarns fractured (Chen et al., 2014).

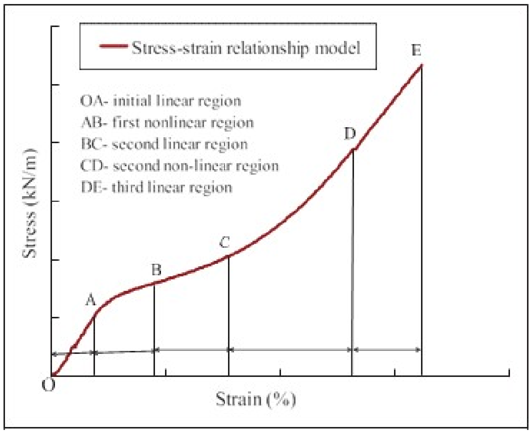


Figure 7. The stress-strain model of the coated fabric (J. Chen et al., 2014).

In these five regions, the stress-strain relationships were expressed as:

$$OA, BC, DE: \sigma = a \cdot \varepsilon + b$$

$$AB: \sigma = a \cdot \ln \varepsilon + b$$

$$CD: \sigma = a \cdot e^{b \cdot \varepsilon}$$

where σ is the stress, ε is the strain, and a and b are the best-fit constant parameters that were determined by the experimental data (Chen et al., 2014).

3.2 Tear resistance properties

The flexible airship hull materials tend to be damaged by sharp articles in the manufacturing and assembling process. The presence of small holes, defects and even invisible cracks can lead to degradation of mechanical performance and even catastrophic failure. Therefore, per the discussion in (Miller & Mandel, 2000), one critical property for airship hull material is its tear resistance after sustaining damage. In recent decades, there has been a considerable effort made to investigate the tear resistance performance of various types of textile-reinforced laminate materials. Bai et al. (2011) evaluated the tear resistance of a laminate material used in high-altitude balloon, which consists of a Kevlar woven fabric as the reinforcement and TPU as adhesive and protection layer. It was found that the tensile and tear resistance had significant sensitivity to the size and geometry of the notches applied to the material. Chen et al. (Chen & Chen, 2016) and Meng et al. (Meng et al., 2016) also conducted tear tests under uniaxial and bi-axial loadings to study the mechanical behavior and damage morphology of laminated airship materials. They found that the failure modes of airship materials are dependent on the size and orientation of the initial crack as well as the loading control systems. They also found that the tear strength of the laminated materials are heavily affected by the elongation at break, elastic modulus of yarns and the thread density of woven fabrics.

3.2.1 Central cut slit tear testing

It was reported in (Miller & Mandel, 2000) that central cut slit tear testing is an effective method of measuring the material capability to resist tearing after initial damaged. The Federal Aviation Administration (FAA) adopted this test in FAA P-8110-2, “Airship Design Criteria”. The Test setup is shown in Figure 8 below.

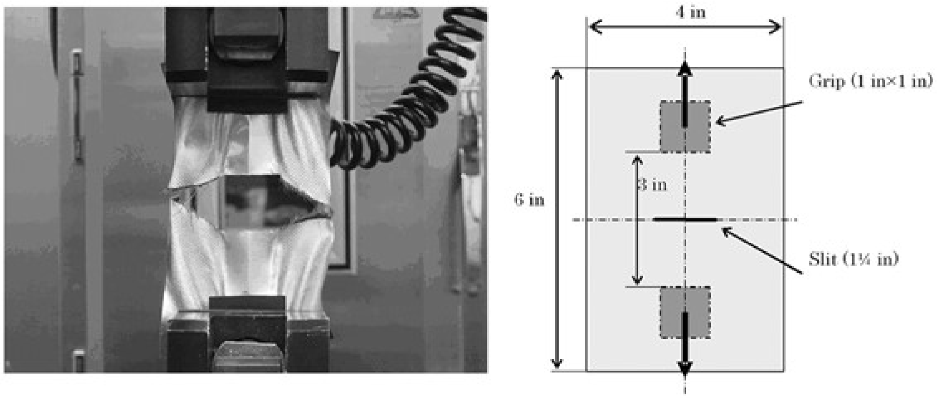


Figure 8. Central cut slit tear test (Maekawa et al., 2008).

This method can better simulate the tearing action of a damaged material than do other standard tear testing methods, e.g. tongue tear test and trapezoid tear test, which do not simulate the tear propagation of inflated structure. As shown in Figure 8, the test sample is required to be 101.6 *mm* (4 *inch*) wide x 152.4 *mm* (6 *inch*) long, having a 32 *mm* (1-1/4 *inch*) wide razor cut slit across the center of the sample normal to the longest dimension.

3.2.2 Tear propagation analysis

Cut slit tear test may be a proper method to measure the tear strength of certain coated/laminated fabrics, yet the tear strength simply has no direct relationship with the actual tear propagation characteristics of the airship hull material (Maekawa et al., 2008). Therefore, there have been much effort made to establish the relationship.

3.2.2.1 Tear propagation of bi-axial Tear Test

Cruciform specimens are used for bi-axial test, shown in Figure 9(a). The slit is cut at the center of the specimen by a razor. Restricted by the size of the cruciform specimen, the length of the slit can be relatively short. Chen and Chen (Chen & Chen, 2016) found from the bi-axial tearing analysis that the crack length, crack orientation, and stress ratio can be considered as the parameters to affect the tearing strength and tearing stress-displacement curves. It is also stated that stressed parallel to the crack can build the barrier for tear propagation, and therefore, for the same crack length, the bi-axial test can show a greater tearing strength than the uni-axial test.

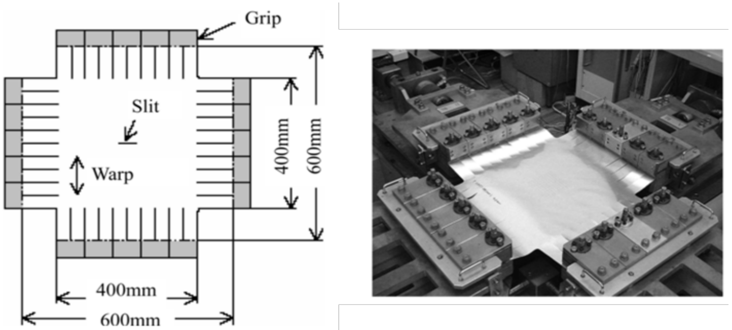


Figure 9. (a) Cruciform specimen for bi-axial testing, (b) Bi-axial test setup (Maekawa et al., 2008).

3.2.2.2 Tear propagation of pressurized cylinder test

Using the air-pressurized cylinder to generate the bi-axial tensile field is the most reliable method for the development of airships (Maekawa et al., 2008; Miller & Mandel, 2000). This method is able to maximally simulate the actual stress field, and longer tear length can be tested compared to the bi-axial tensile test (Chen & Chen, 2016; Jianwen Chen, Chen, & Wang, 2017; Liu, Cao, & Zhu, 2015; F. Wang, Chen, Xu, Song, & Fu, 2016; Zhang, Lv, Gu, & Meng, 2012). In this test, the bi-axial load is applied in stress-control mode. A generic sketch and a picture of the real specimen produced were shown in Figure 10.

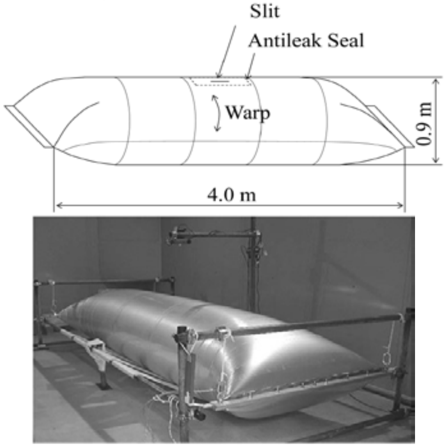


Figure 10. Pressurized cylinder test specimen (Maekawa et al., 2008).

The specimen is a cylinder closed at both ends and the slit is covered from inside by an expandable film to prevent air leakage. The specimen was set in a stand and the pressure is increased at a constant speed. The slit was recorded by a video camera. The gas filling was stopped immediately when the tear starts to propagate, and then the cylinder was depressurized

Based upon the testing results from both bi-axial and pressurized cylinder methods, Thiele's empirical formula proved to best fit the experimental data, and is therefore recommended to be used on Zylon® fiber reinforced hull materials (Maekawa et al., 2008). Chen and Chen (Chen & Chen, 2016) compared several typical theories predicting tearing strength based on the results of Vectran® uni-axial tearing of laminate material. It was also concluded that the results of Thiele's empirical formula fits the experimental data.

The general expression of Thiele's empirical formula can be written as followed:

$$\sigma = pr = \frac{C_l C_s}{L^n(1 + L/r)}$$

where p is the inflation pressure, r is the cylinder radius, C_s is the cut slit tear strength, L is the cut slit length. In this equation, C_l and n are constants.

Maekawa et al. (Maekawa et al., 2008) completed a tear propagation study of a lightweight and high strength hull material using the same pressurized cylinder method. The envelope material used in this work, Z2929T-AB, was developed using Zylon® fabric as its load-bearing component. The average tensile strength in the warp direction was 997 *N/cm* and the areal density was measured to be 157 *gsm*. The measurements were made to find the stress that initiated the tear propagation, and the experimental results were fitted to Thiele's empirical formula with a good correlation. Moreover, by using Thiele's empirical equation, the minimum slit length of the tear propagation under the limit load condition is estimated to be ~40 *mm*.

3.2.2.3 Tear propagation of uni-axial tear test

Although satisfactory results were generated from previous work on tear propagation, the testing procedures for both the bi-axial tensile test and pressurized cylinder test are much more complicated than that of uni-axial tear test. Regardless of the inability to better simulate the real stress field on the hull material, uni-axial tear test is still an effective way to evaluate the tear strength. Wang et al. (Wang et al., 2016) experimentally investigated the tear propagation properties of a new stratospheric airship hull material by uni-axial tear test. The strength element of this airship material is a woven fabric made of ultra-high molecular weight polyethylene (UHMWPE) fibers. Effect of the stretching rate is determined to be not significant to the tear performance of specimens in uni-axial tensile test. Nonetheless, the initial crack length does make a difference concerning the maximum tearing force. In general, larger initial cracks are to cause reduced maximum tearing force when subjected to uni-axial tensile loading. Since the fabric is woven structure, the difference of initial crack orientations will affect the tear propagation by changing the number of cutting yarns in the loading direction. To predict the tear propagation upon initial cracks, analytical models were developed based on the uni-axial testing data. By analyzing three of the most critical methods for tear propagation modelling, i.e. Griffith energy theory, the stress intensity factor theory, and the Thiele's empirical theory, it was found that the stress intensity factor theory gives the best correlation with the test data from uni-axial tear test, shown in Figure 11.

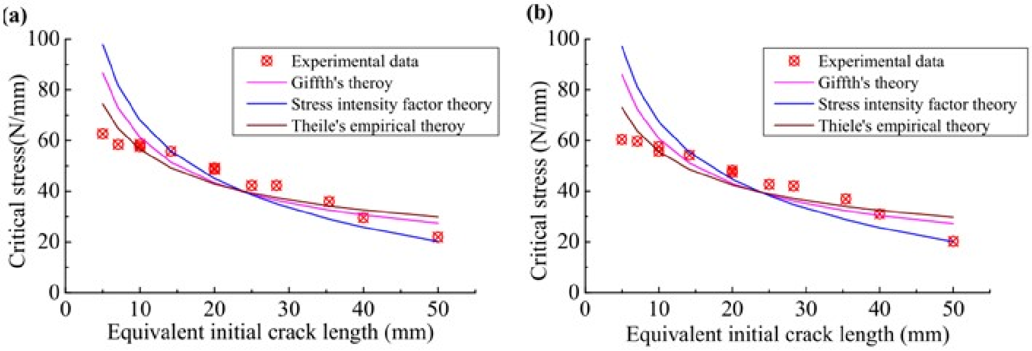


Figure 11. Comparison between experimental data and the theoretical values for uni-axial specimens (a) the warp specimens and (b) the weft specimens (F. X. Wang et al., 2016).

It was common to observe high theoretical values when the equivalent initial crack length is approaching zero, so the theoretical data within 10 *mm* of initial crack length was clearly much higher than the experimental results. When the equivalent initial crack length was increased from 10 *mm* to 40 *mm*, the theoretical calculations were found to be close to the experimental results. However, the variation became more obvious with the increase of the crack length. At the crack lengths higher than 40 *mm*, the stress intensity factor theory is obviously the most approximate to the experimental results. The form of stress intensity factor (K_I) is applied as:

$$K_I = F_T \sigma (\pi a)^{1/2}$$

where σ is maximum tensile stress, a is half of the initial central crack length (*L/2*), and F_T is a geometrical factor calculated from specimen dimensions. According to the research output of Isida (Isida, 1973), when the specific geometric ratio γ is < 0.8, the fitting function is written as:

$$F_T = 2.08(\gamma)^2 + 0.078\gamma + 1$$

Hence, the stress intensity factor, K_I, can then be deduced by the warp and weft experimental data, respectively. Considering that Griffith theory is based on the infinite plank and the Thiele's empirical theory based on the pressurized cylinder tests, the influence of sample dimension is thought to be insignificant. Whereas, for the stress intensity factor theory presented above, the specimen's dimension is strictly considered and therefore such theory is the most suitable one for tear tests under uni-axial tensile loading (Wang et al., 2016).

4. Summary

The main challenge for HAA hull materials still lie in the strength component. Although there is still no long-term airship flight success in the stratosphere, much progress has been made over the past few decades in the field of HAA hull material development using high-performance fiber reinforcement. Zylon fiber is generally considered the best candidate to achieve the highest possible strength-to-weight ratio. However, concerns such as moisture and UV sensitivity remain as hindrance. Great care needs to be taken during the Zylon yarn production throughout the entire conversion to fabric and laminate. Additionally, special attention must be paid to packaging, shipping, and handling. Since the Zylon yarns used in the literature are relatively thick, the weight reduction of textile fabrics and ultimately laminate still have great potential. Proper usage of ultra-thin polymeric films and functional coatings will also effectively improve the overall performance of laminate while still keeping the weight light. Generally, the thorough material tensile strength comparison introduced a clear guidance or standard for airship hull material development concerning the increase of specific strength. Also, with the discussion on tear propagation testing, analysis and modeling, the tear strength and overall tear resistant property can be predicted by using Thiele's empirical formula. However, if the target is to meet the requirements for long duration and multiple flights, any defect that leads to tear would end the flight prematurely. Tight quality control to produce zero-defect hull materials and seam must be practiced.

REFERENCES

Chen, J., & Chen, W. (2016). Central Crack Tearing Testing of Laminated Fabric Uretek3216LV under Uniaxial and Biaxial Static Tensile Loads. *Journal of Materials in Civil Engineering, 28*(7), 4016028. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001537

Chen, J., Chen, W., & Wang, M. (2017). Mechanical Behaviors and Elastic Parameters of Laminated Fabric URETEK3216LV Subjected to Uniaxial and Biaxial Loading. *Applied Composite Materials*. https://doi.org/10.1007/s10443-016-9576-2

Chen, J., Chen, W., & Zhang, D. (2014). Experimental study on uniaxial and biaxial tensile properties of coated fabric for airship envelopes. *Journal of Reinforced Plastics and Composites*, *33*(7), 630–647. https://doi.org/10.1177/0731684413515540

Chen, J., Chen, W., Zhou, H., Zhao, B., Wang, M., Sun, W., & He, S. (2017). *Fracture failure analysis and bias tearing strength criterion for a laminated fabric*. https://doi.org/10.1177/1528083717695839

Colozza, A., Corporation, A., Park, B., & Dolce, J. L. (2005). High-Altitude , Long-Endurance Airships for Coastal Surveillance, (February).

D’Oliveira, F. A., De Melo, F. C. L., & Devezas, T. C. (2016). High-altitude platforms - Present situation and technology trends. *Journal of Aerospace Technology and Management*, *8*(3), 249–262. https://doi.org/10.5028/jatm.v8i3.699

DSM. (2008). Technical brochure: Dyneema in marine and industrial applications. Retrieved from http://www.pelicanrope.com/pdfs/DyneemaSK75_Tech_Sheet.pdf

Fesen, R., & Brown, Y. (2015). A method for establishing a long duration , stratospheric platform for astronomical research, 475–493. https://doi.org/10.1007/s10686-015-9459-9

Gouzman, I., Girshevitz, O., Grossman, E., Eliaz, N., & Sukenik, C. N. (2010). Thin Film Oxide Barrier Layers : Protection of Kapton from Space Environment by Liquid Phase Deposition of Titanium Oxide, *2*(7), 1835–1843. https://doi.org/10.1021/am100113t

Gu, Z. (2007). Research of Stratospheric Airships. Skin Material. *Spacecraft Recovery& Remote Sensing*, *28*(1), 62–66.

Guchi, K. E., Okomaku, Y. Y., Platform, S., & Team, A. (2000). 2000 Overview of Stratospheric Platform Airship R & D Program in Japan, 12–15.

Isida, M. (1973). Analysis of Stress Intensity Factors for the Tension of a Centrally Cracked Strip with Stiffened Edges. *Engineering Fracture Mechanics*, *5*, 647–665.

Islam, S., & Bradley, P. (2012). Materials. In *Airship Technology* (pp. 113–148). https://doi.org/10.1016/B978-0-08-044951-7.50029-4

Jamison, L., Sommer, G., & Porche, I. (2005). *High-Altitude Airships for the Future Force Army*. *Security*.

Kang, W., Suh, Y., Woo, K., & Lee, I. (2006). Mechanical property characterization of film-fabric laminate for stratospheric airship envelope. *Composite Structures*, *75*, 151–155. https://doi.org/10.1016/j.compstruct.2006.04.060

Komotsu, K., Sano, M., & Kakuta, Y. (2003). Development of high-specific-strength envelope materials.pdf. In *AIAA’s 3rd Annual Aviation Technolog, Integration, and Operations (ATIO) Tech 17-19 November 2003, Denver, Colorado* (pp. 17–19). Denver.

Lagaron, J. M., Catalá, R., & Gavara, R. (2004). Structural characteristics defining high barrier properties in polymeric materials. *Materials Science and Technology*, *20*(1), 1–7. https://doi.org/10.1179/026708304225010442

Laven, C. K., & Kelly, D. J. (2005). Flexible Material for Lighter-Than-Air Vehichles.

Li, A. (2018). *Evaluation of Laminated Hull Material for High Altitude Airship*. North Carolina State University.

Li, B., Xing, L., & Zhou, Z. (2010). Study on Mechanical Properties of High Performance Envelope Materials, 1–5.

Liao, L., & Pasternak, I. (2009). A review of airship structural research and development. *Progress in Aerospace Sciences*, *45*(4–5), 83–96. https://doi.org/10.1016/j.paerosci.2009.03.001

Lin, G., Tan, H., & Materials, A. (2011). The Influence of Ozone on the Property of Envelop Materials of Near Space Vehicle, 1413–1416.

Liu, L. B., Cao, S., & Zhu, M. (2015). Mechanical characteristics of stratospheric airship envelope of vectran fibre-reinforced-laminated composite. *Materials Research Innovations*, *19*(S5), S5-606-S5-612. https://doi.org/10.1179/1432891714Z.0000000001162

Maekawa, S., Nakadate, M., & Takegaki, A. (2007). Structures of the Low-Altitude Stationary Flight Test Vehicle. *Journal of Aircraft*, *44*(2), 662–666.

Maekawa, S., Shibasaki, K., Kurose, T., Maeda, T., Sasaki, Y., & Yoshino, T. (2008). Tear Propagation of a High-Performance Airship Envelope Material. *Journal of Aircraft*, *45*(5), 1546–1553. https://doi.org/10.2514/1.32264

Mater, E. C., & Kinnel, J. M. (1992). Laminate Material Particularly Adapted for Hull of Aerostats, U.S. Patent No. 5,118,558. Washington, DC: U.S. Patent and Trademark Office.

Mcdaniels, K., Downs, R. J., Meldner, H., Beach, C., & Adams, C. (2009). High Strength-to-Weight Ratio Non-Woven Technical Fabrics for Aerospace Applications, 1–9. Retrieved from http://www.cubictechnology.com/Technical Fabrics for Aerospace Applications.pdf

Meng, J., Lv, M., Qu, Z., & Li, P. (2016). Mechanical Properties and Strength Criteria of Fabric Membrane for the Stratospheric Airship Envelope. *Applied Composite Materials*, (37), 1–19. https://doi.org/10.1007/s10443-016-9515-2

Meng, J., Lv, M., Tan, D., & Li, P. (2016). Mechanical properties of woven fabric composite for stratospheric airship envelope based on stochastic simulation. *Journal of Reinforced Plastics and Composites*, *35*(19), 1434–1443. https://doi.org/10.1177/0731684416652947

Miller, T., & Mandel, M. (2000). Airship Envelopes : Requirements, Materials and Test Methods. *3rd International Airship Convention and Exhibition*, 1–5.

Mokwena, K. K., & Tang, J. (2012). Ethylene vinyl alcohol: a review of barrier properties for packaging shelf stable foods. *Critical Reviews in Food Science and Nutrition*, *52*(7), 640–50. https://doi.org/10.1080/10408398.2010.504903

Nakadate, M., Maekawa, S., & Kurose, T. (2011). Investigation of Long Term Weathering Characteristics on High Strength and Light Weight Envelope Material Zylon. In *11th AIAA Aviation Technology, Integration, and Operations (AITO) Conference* (pp. 1–6). https://doi.org/10.2514/6.2011-6938

Said, M. A., Dingwall, B., Gupta, A., Seyam, A. M., Mock, G., & Theyson, T. (2006). Investigation of ultra violet (UV) resistance for high strength fibers. *Advances in Space Research*, *37*(11), 2052–2058. https://doi.org/10.1016/j.asr.2005.04.098

Schwartz, P. (2008). *Structure and Mechanics of Textile Fibre Assemblies*. *Structure and Mechanics of Textile Fibre Assemblies*. https://doi.org/10.1533/9781845695231.141

Silverstein, M. S., & Breuer, O. (1993). Adhesive properties and failure of etched UHMW-PE fibres. *Journal of Materials Science*, *28*(17), 4718–4724. https://doi.org/10.1007/BF00414263

Smith, S., Lee, M., Fortneberry, M., & Judy, R. (2011). HiSentinel80: Flight of a High Altitude Airship. In *11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference* (pp. 1–14). https://doi.org/10.2514/6.2011-6973

Triton. (2001). More Than Just a Polymer. *NASA SPINOFF*, 110.

Vallabh, R., Hassanin, A. H., Said, M. A., & Seyam, A. F. M. (2016). Improving high-altitude UV-Vis resistance of PBO braided tendons of NASA's super pressure balloons. *Journal of the Textile Institute*, *107*(1), 136–143. https://doi.org/10.1080/00405000.2015.1077021

Wang, F., Chen, Y., Xu, W., Song, Z., & Fu, G. (2016). Experimental study on uniaxial tensile and welding performance of a new coated fabric for airship envelopes. *Journal of Industrial Textiles*, *0*(00), 1–24. https://doi.org/Doi 10.1177/0731684413515540

Wang, F. X., Xu, W., Chen, Y. L., & Fu, G. Y. (2016). Tearing analysis of a new airship envelope material under uniaxial tensile load. *IOP Conference Series: Materials Science and Engineering*, *137*(1). https://doi.org/10.1088/1757-899X/137/1/012024

Xu, C. (2009). Fabrication and Investigation of Envelope Materials for Strato-spheric Aircraft with PBO Fabric as Load-carriers. *Hi-Tech Fiber & Application*, *34*(4), 0–5.

Xu, C., Zhengming, G., & Weizhi, W. (2008). Weave and Performance Investigation of PBO Fabric for Stratosphere Airship Envelope. *Spacecraft Recovery& Remote Sensing*.

Zhai, H., & Euler, A. (2005). Material challenges for lighter-than-air systems in high altitude applications. In *AIAA 5th Aviation, Technology, Integration, and Operations Conference (ATIO)* (pp. 1–12). Retrieved from http://arc.aiaa.org/doi/pdf/10.2514/6.2005-7488

Zhang, Y., Lv, M., Gu, S., & Meng, J. (2012). Simulational Studyon Biaxial Tensile Test of the Envelope Material of Stratospheric Airship, *593*, 1006–1011. https://doi.org/10.4028/www.scientific.net/AMR.591-593.1006