

**INVESTIGATION ON FAILURE BEHAVIOUR OF
POLYMER COATED AND LAMINATED FABRICS
FOR INFLATABLE APPLICATIONS**

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Investigation on Failure Behaviour of Polymer Coated and Laminated Fabrics for Inflatable Applications

by

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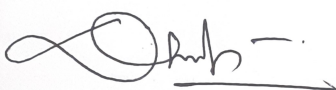
Dedicated to

- 1. My Lab – ADRDE, DRDO, Agra**
- 2. My Family – my parents, wife, daughter and son**

CERTIFICATE

This is to certify that the thesis entitled “**Investigation of Failure Behaviour of Polymer Coated and Laminated Fabrics for Inflatable Applications**” being submitted by **Mr. Gaurav Singh**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy** in the Department of Textile Technology is a record of bonafide research work carried out by him. Mr. Gaurav Singh has worked under our guidance and supervision and fulfilled the requirements for the submission of the thesis.

The results contained in the thesis have not been submitted, in part or full, to any other University or Institute for the award of any degree or Diploma.

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(Gaurav Singh)

Abstract

This thesis is an attempt to develop and improve the envelope materials used in Lighter than Air (LTA) systems such as Aerostats and Airships. The envelope materials are made of coated and laminated fabrics and these materials, being polymeric in nature, are susceptible to degradation due to natural weathering. Therefore, in order to improve upon the envelope material properties it is important to understand in detail the degradation of functional properties over a period of time. The functional properties which are most important are tensile strength, tearing strength, helium barrier and durability of joints. The real-time deployment conditions of LTA systems are best simulated by natural weathering.

Four types of both sides PU coated fabrics were developed, in which there was difference in the type of PU (aliphatic polyester grade and aromatic polyether grade of PU) and additives - TiO₂, carbon black (CB), UV-additives (UV-A) added in the PU formulations. These fabrics were subjected to weathering till the time noticeable trends were observed viz., 1-year for 'natural weathering' and 1000 hours for accelerated ageing using UV-B and metal halide lamps. The fabrics were evaluated for residual functional properties. Various techniques such as FTIR, SEM, and molecular weight determination, etc were used to study the degradation behaviour of PU coated nylon fabrics. From the degradation trends, it was clearly established that in PU coated fabrics the limiting factor in terms of usage life is the helium gas retention property. The gas barrier is provided by underneath (gas facing) layer only, while the top acts as a sacrificial UV protective layer.

It is important to estimate the usage life of Aerostat/Airship envelope and to evolve a methodology for evaluation of service life which closely simulates the actual usage. It is known that the envelope materials of Aerostat/Airship in usage have to sustain biaxial stresses - the Hoop's and longitudinal stresses, which may have deleterious effect on long term usage/deployment in addition to environmental stresses. Moreover, any Aerostat/Airship will invariably have joints which are also under stress in an inflated balloon. The strength of the inflatable is dependent not only on the strength of the material but on the design and strength of its joints/seams. Therefore, a study was conducted to know the influence of in situ mechanical stresses on weathering of PU coated fabric along with joints. An attempt has been made to

evolve a method which better simulates the natural weathering of envelope materials. A number of studies on joints including accelerated creep have been done with an intent to obtain a quick test method to safely determine whether the joint will fail under stress or not and how to find minimum joint overlap so as to minimise the overall weight of envelope.

Inflatables are susceptible to catastrophic tear. The tear strength itself has no definite relationship with the actual tear propagation, therefore, several studies have been carried out to establish relationship between tearing strength and tear propagation in order to ascertain safe tearing limits of envelope material. Aerostat or airship typically have two flexible compartments - one hull that contains the helium and provides the lift and another ballonnet that contains air and is required to maintain the overall pressure inside hull within permissible operational limits. Air blowers are attached with the ballonnet to pump-in or pump-out air to maintain pressure. In real time flying situations of aerostats/airships, it may so happen that the tear may remain undetected and unrepaired for some time. In that eventuality, the blowers of the ballonnet will turn on to pump air inside and the pressure inside the hull may remain nearly constant for some duration wherein the helium escape from the hull is countered by the air pumped in into the ballonnet till it reaches its maximum volume limit. None of the previous studies have reported the influence of time on propagation of tear. This has been attempted by conducting tear tests on (i) uniaxially and biaxially stressed coated fabrics and (ii) on pressurised fabric cylinder made from the same fabric. The effect of time on tear propagation has been studied. Tear propagation was studied by inducing dynamic tear on a biaxially stressed coated fabric through a falling dagger. The influence of traverse rates, 1 to 500mm/min, on tear strength under uniaxial loading was also studied. Thiele's empirical equation has been found to fit the data of biaxial tests and cylinder tests. The instantaneous tear on a bi-axially stressed fabric when left under constant stress for some duration lead to failure of fabric at even 15% lesser than critical tear slit length in about 15min. Therefore, the critical tear length not only depends upon inherent tear strength of material, diameter and pressure of envelope but also on the time for which the tear remains under creep.

The limiting factor w.r.t. life of PU coated nylon fabrics is the helium im-permeability. Moreover, the only way to mitigate failure due to tear is to increase the tear strength of the fabric. In this context, and based on current trends of envelope materials, it was attempted to develop Tedlar-polyester films based laminated fabric with two objectives - To maximise operational life by using Tedlar film and to maximise tearing strength while keeping the mass and tensile strength nearly the same. Therefore, it was planned to conduct a study to make laminated fabric with various base fabric constructional parameters keeping lamination parameters nearly identical to see the effect on tearing strength. The tearing strength has been improved from about 300N in coated fabrics to 900N in laminated fabrics.

The rate of decay in laminated fabric properties such as tensile strength and tearing strength due to different fabric structure on weathering and accelerated ageing of laminated fabrics was also studied and interesting trends observed. There was practically no change in helium barrier after 1-year of natural weathering.

सार

यह थीसिस लाइटर इन एयर (LTA) सिस्टम जैसे Aerostats और Airships में उपयोग होने वाले खोल सामग्री को विकसित और बेहतर बनाने का एक प्रयास है। खोल सामग्री लेपित (coated) एवं अपक्षय (laminated) कपड़े से बने होते हैं और ये सामग्री, प्रकृति में बहुलक होने के कारण, प्राकृतिक अपक्षय के कारण क्षरण के लिए अतिसंवेदनशील होते हैं। इसलिए, खोल के गुणों पर सुधार करने के लिए समय की अवधि में कार्यात्मक गुणों के क्षरण को विस्तार से समझना महत्वपूर्ण है। कार्यात्मक गुण जो सबसे महत्वपूर्ण हैं वे हैं तन्यता ताकत, फटने शक्ति, हीलियम बाधा और जोड़ों का स्थायित्व। एलटीए सिस्टम की वास्तविक समय पर तैनाती की स्थिति प्राकृतिक अपक्षय द्वारा सबसे अच्छी तरह से अनुकरण की जाती है।

चार प्रकार के पोलियूरेथेन (Polyurethane) लेपित कपड़े विकसित किए गए थे, जिसमें पोलियूरेथेन लेपन के प्रकार में अंतर था (एलिफैटिक पॉलिएस्टर ग्रेड और एरोमेटिक पॉलीईथर ग्रेड) और एडिटिव्स - टीआईओ 2, कार्बन ब्लैक (सीबी), यूवी-एडिटिव्स (यूवी-ए) पोलियूरेथेन में डाले गए। एन कपड़ों में लंबे समय तक 'प्राकृतिक अपक्षय' और UV-B और धातु हलाइड लैंप का उपयोग करते हुए कार्यात्मक गुणों में जो आई कमी उसका मूल्यांकन किया गया था। विभिन्न तकनीकों जैसे कि एफटीआईआर, एसईएम, और आणविक भार निर्धारण, आदि का उपयोग पोलियूरेथेन लेपित नायलॉन कपड़ों के क्षरण व्यवहार का अध्ययन करने के लिए किया गया था। गिरावट के रुझान से, यह स्पष्ट रूप से स्थापित किया गया था कि पोलियूरेथेन लेपित कपड़ों में उपयोग जीवन के मामले में सीमित कारक हीलियम गैस निरोधी गुण है। गैस बाधा केवल नीचे (गैस का सामना करने वाली) परत द्वारा प्रदान की जाती है, जबकि ऊपर वाला लेपन एक बलि तथा यूवी सुरक्षात्मक परत के रूप में कार्य करता है।

एरोस्टेट / एयरशिप खोल के उपयोग के जीवन का अनुमान लगाने के लिए एक पद्धति का विकास करना महत्वपूर्ण है जो वास्तविक उपयोग को बारीकी से अनुकरण करता है। यह ज्ञात है कि उपयोग में आने वाली एयरोस्टेट / एयरशिप की खोल सामग्री को द्विअर्थी तनावों - हूप और अनुदैर्घ्य तनावों को बनाए रखना पड़ता है, जिसका पर्यावरणीय तनावों के अलावा दीर्घकालिक उपयोग / तैनाती पर निंदनीय प्रभाव हो सकता है। इसके अलावा, किसी भी एरोस्टेट / एयरशिप में हमेशा जोड़ों में तनाव होता है जो फुलाए हुए गुब्बारे में तनाव में होता है। Inflatable की ताकत न केवल सामग्री की ताकत पर निर्भर करती है, बल्कि इसके जोड़ों / सीम के डिजाइन और ताकत पर भी निर्भर करती है। इसलिए, जोड़ों के साथ-साथ पोलियूरेथेन लेपित कपड़े के अपक्षय पर यांत्रिक तनाव के प्रभाव को जानने के लिए एक अध्ययन किया गया था। एक ऐसी विधि को विकसित करने का प्रयास किया गया है जो खोल सामग्री की प्राकृतिक अपक्षय को बेहतर ढंग से अनुकरण करती है। त्वरित रेंगना सहित जोड़ों पर कई अध्ययनों से यह सुनिश्चित करने के इरादे से त्वरित परीक्षण विधि प्राप्त करने के इरादे से किया गया है कि संयुक्त तनाव के तहत विफल होगा या नहीं और खोल के समग्र वजन को कम करने के लिए न्यूनतम संयुक्त ओवरलैप कैसे खोजें।

Aerostats और Airships चीरे के कारण भयावह तरह से फटने के लिए अतिसंवेदनशील होते हैं। फटने की प्रक्रिया का कपड़े की फटने की ताकत से संबंध है, इसलिए, खोल सामग्री की सुरक्षित फटने की सीमा का पता लगाने के लिए फटने की ताकत और फटने का प्रसार के बीच संबंध स्थापित करने के लिए कई अध्ययन किए गए हैं। एयरोस्टेट या एयरशिप में आम तौर पर दो लचीले डिब्बे होते हैं - एक पतवार जिसमें हीलियम होता है जो लिफ्ट देता है और दूसरा बैलोनट होता

है जिसमें हवा होती है और अनुमत परिचालन सीमाओं के भीतर पतवार के अंदर समग्र दबाव बनाए रखने के लिए आवश्यक होता है। दबाव को बनाए रखने के लिए एयर ब्लोअर को बैलून से पंप-इन या पंप-आउट किया जाता है। एरोटैट्स / एयरशिप की वास्तविक समय में उड़ान की स्थिति में, ऐसा हो सकता है कि चीरा कुछ समय के लिए अनिर्धारित और अप्रभावित रह सकते हैं। उस स्थिति में, बैलून के ब्लोअर अंदर हवा को पंप करने के लिए चालू हो जाते हैं और पतवार के अंदर दबाव कुछ अवधि तक लगभग स्थिर रह सकता है, जिसमें पतवार से हीलियम का बहाव हवा बलोनेट में हवा के भरने से दबाव समान रह सकता है जो की बलोनेट आयतन सीमा तक नहीं पहुँच जाता। पिछले अध्ययनों में से किसी ने भी चीरे के प्रसार पर समय के प्रभाव की सूचना नहीं दी है। एक ही कपड़े से बने i) दबाव वाले कपड़े सिलिंडर पर ii) द्वि-अक्षीय रूप से तनाव होने पर फटने पर कई परीक्षण करके यह प्रयास किया गया है। चीरे का प्रसार पर समय के प्रभाव का अध्ययन किया गया है। चीरे के प्रसार का अध्ययन एक गिरते हुए खंजर के माध्यम से द्विपदीय रूप से तनाव में लेपित कपड़े पर गतिशील चीरे को प्रेरित करके किया गया था। लोडिंग के तहत फटने की ताकत पर 1 से 500 मिमी / मिनट तक अनुप्रस्थ दरों का प्रभाव भी अध्ययन किया गया था। थिएल के अनुभवजन्य समीकरण को द्वि-अक्षीय परीक्षणों और सिलेंडर परीक्षणों के डेटा को फिट पाया गया है। द्वि-अक्षीय रूप से तनाव वाले कपड़े पर तात्कालिक चीरा जब कुछ अवधि के लिए निरंतर तनाव के तहत छोड़ दिया जाता है, तो कपड़े की विफलता लगभग 15 मिनट में अधिकतम चीरा लंबाई की तुलना में 15% कम होती है। इसलिए, अधिकतम चीरे की लंबाई न केवल खोल की सामग्री, व्यास और दबाव की अंतर्निहित फाड़ शक्ति पर निर्भर करती है, बल्कि उस समय के लिए भी होती है, जिसके लिए चीरा खुला रहता है।

पोलीयूरेथेन लेपित नायलॉन कपड़े का जीवन हीलियम रोकने की अवधि तक सीमित है। इसके अलावा, चीरे के कारण विफलता को कम करने का एकमात्र तरीका कपड़े की फटने की शक्ति को बढ़ाना है। इस संदर्भ में, और खोल सामग्री के मौजूदा रज्जानों के आधार पर, दो उद्देश्यों के साथ टेडलर-पॉलिएस्टर फिल्मों पर आधारित laminated कपड़ों को विकसित करने का प्रयास किया गया था - टेडलर फिल्म का उपयोग करके परिचालन जीवन को अधिकतम करने के लिए और द्रव्यमान और दसियों की ताकत को बनाए रखते हुए अधिकतम ताकत को अधिकतम करने के लिए। इसलिए, फटने की शक्ति पर प्रभाव को देखने के लिए मानकों को लगभग समान रखते हुए विभिन्न कपड़ों का निर्माण कर एक अध्ययन करने की योजना बनाई गई थी। laminated कपड़े में लगभग 300N से 900N तक फटने की शक्ति में सुधार किया गया है।

अपक्षय वाले कपड़े की गुणों में क्षय की दर जैसे तन्य शक्ति और अपक्षय के कारण कपड़े की विभिन्न संरचना के कारण अध्ययन भी किया गया और दिलचस्प रज्जान देखा गया। प्राकृतिक अपक्षय के 1 वर्ष के बाद हीलियम बाधा में व्यावहारिक रूप से कोई परिवर्तन नहीं हुआ।

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Nomenclature

°C	Degree Celsius
3L	Three end leno weave
3L+RP	Three end leno with rip stop weave
ADRDE	Aerial Delivery Research and Development Establishment
ATR	Attenuated total reflectance
B	Black side (aromatic polyether grade of PU) coated fabric surface
B-B	Black side (aromatic polyether grade of PU) surface in contact with black side (aromatic polyether grade of PU)
BS	Breaking strength
B-W	Black side (aromatic polyether grade of PU) surface in contact with white side (aliphatic polyester grade of PU)
CV%	Coefficient of variation in percentage
Den	Denier
DRDO	Defence Research and Development Organisation
EB	Environmental barrier
FTIR	Fourier transformation Infra-red
GB	Gas barrier
GSM	Grams per square metre (g/m ²)
HALS	hindered amine light stabilizer
HF	High frequency
i.e.	That is
LTA	Lighter than air
M2/2	Mat2/2 weave
M3/3	Mat3/3 weave
P	Plain weave
PU	Polyurethane
RF	Radio frequency
RH	Relative humidity

RP2/2	Rip stop 2/2 weave
SEM	Scanning electron microscopy
T	Twisted
TiO ₂	Titanium di-oxide
TPU	Thermoplastic polyurethane
TS	Tearing strength
UBS	Ultimate breaking strength
UT	Untwisted
UV-A	UV additives
W	White side (aliphatic polyester grade of PU) coated surface
W-W	White side (aliphatic polyester grade of PU) surface in contact with white side (aliphatic polyester grade of PU)