Airship Envelopes: Requirements, Materials and Test Methods

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Abstract:

Current airships all employ the pressure envelope design principle. Thus the envelope must be considered as a main structural element of the airship. This paper will provide information on the design requirements of airship envelopes and materials from a designer's point of view and material development and qualification information from a manufacturer's point of view. Finally special consideration is given to material tear resistance and test results are presented in detail.

Introduction

For non-rigid and semi-rigid airships, the envelope is one of the major structural elements. It is, therefore, required that this part of an airship deserves special attention. Materials, design and workmanship must be of the highest standard possible.

Additionally, material performance and overall cost need consideration. Since these requirements are in some aspects contradictory, the challenge is to find the best compromise.

Photo 1 – Zeppelin LZ N07

SECTION 1 - Envelope Specification

At the beginning of development, it is necessary to specify all requirements. Form, Fit and Function require detailed investigation and analysis to provide the basis for the materials specification. Additionally, airworthiness regulations must be considered, as these will provide a guideline for the designer.

The FAA - ADC (Airship Design Criteria) or the German LFLS (Lufttüchtigkeitsforderungen für Luftschiffe) are very similar and provide the minimum requirements for non-rigid and semi-rigid airships.

The following is a list of relevant paragraphs taken from the LFLS, which specifically need to be addressed when establishing the means of compliance for the airship envelope.

§ 601 General
The suitability of each questionable design detail and part having an important bearing on safety must be established by tests.

§ 603 Materials and workmanship
(a) The suitability and durability of materials used for parts, the failure of which could adversely affect safety must.…
(b) Workmanship must be of a high standard.

§ 605 Fabrication methods
(a) The methods of fabrication used must produce a consistently sound structure. If a fabrication process requires close control to reach this objective, the process must be performed in accordance with an approved process specification.
(b) Each new aircraft fabrication method must be substantiated by a test program

§ 609 Protection of structure
Each part of the airship must
(a) Be suitably protected against deterioration or loss of strength in service due to weathering, corrosion, abrasion, or other causes;
(b) Have adequate provisions for ventilation and drainage.

§ 613 Material strength properties and design values
(a) Material strength properties must be based on enough tests of material meeting specifications to establish design values on a statistical basis.

§ 627 Fatigue strength
The structure must be designed, as far as practicable, to avoid points of stress concentration where variable stresses above the fatigue limit are likely to occur in normal service.

§ 881 Envelope design
(a) The envelope must be designed to be pressurized .... while supporting the limit design loads for all flight conditions and ground conditions...... The effects of all local aerodynamic pressures ...... must be included in the determination of stresses to arrive at the limit-strength requirements for the envelope fabric.
(b) The envelope fabric must have an ultimate strength not less than four times the limit load determined by the maximum design internal pressure combined with the maximum load resulting from any of the requirements specified herein.
(d) It must be demonstrated by test in accordance with the section Tearing Strength of the appendix that the envelope fabric (in both the warp and woof (fill) directions) can withstand limit design loads without further tearing.
(h) Internal and/or external suspension systems for supporting components such as the car must be designed to transmit and distribute the resulting loads to the envelope in a uniform manner for all flight conditions. The fabric parts of such systems and their connection with the envelope must be designed and constructed in such a manner that the bond are not subjected to peeling loads. ......

SECTION 2 - Compliance Aspects

The following paragraphs will address each relevant paragraph and explain the relationship between the design aspects and the means of compliance.

Suitability of Materials (§ 603)
For the Zeppelin LZ N07 (Photo 1) a laminate of polyester basecloth and poly-vinyl fluoride (PVF or Tedlar®) film was selected for the main hull material (Photo 2). ILC had historical data available from similar laminates used on large aerostats, which had been operational for many years.


Photo 2 - LZ N07 Envelope

This data and experience helped to reduce the risk during certification and minimized the efforts to show compliance with the requirement of suitability and durability. Full qualification testing was performed on the new LZ N07 and was compared with available data from ILC's aerostat material.

In the same manner, the ballonet material was selected as a flexible coated nylon fabric (Photo 3). Due to the movement of the ballonet curtain within the envelope it was necessary to develop a lightweight material which provided high flexibility without leakage. Again ILC used extensive historical data from aerostat ballonet material to define the new LZN07 material.


Photo 3 - Upper forward ballonet installed in frame

Protection of structure (§609)
The outer cover of PVF film serves as an excellent environmental barrier to protect the structural member, here the load carrying polyester fabric, as required by §609. Environmental tests to verify behavior were carried out and the data analyzed. Since, as in many other tests, there is no specific pass/fail criteria available, only comparison to materials in use in similar products could be made. Additional data will be analyzed using the standard practice of checking "in service" material, either by installing a weather patch or testing removed envelope material.

Material strength properties and design values (§ 613)
The material construction needs to be designed to fulfill the specified material strength requirements. Material strength is directly related to the selection of the base fabric. Strength data for various types of fabrics is readily available. However, since material performance and cost needed to remain within defined limits, a series of qualification tests were necessary to collect a representative data base from which both compliance and economic justification could be verified. To gain confidence in the selected material strength, all the requirements of § 613 need to be considered. Enough material samples need to be tested to establish statistically sound design data. The reason for this requirement is to minimize the probability of any structural failures due to material variability. Data for the LZN07 envelope was obtained and analyzed from several lots of production material.

Fabrication method § 605
The processes used in airship envelope fabrication must be properly defined to guarantee an airship envelope of consistently high quality. The strength of the airship envelope is dependent not only on the strength of the material but on the design and strength of its seams and accessories, as well as the procedures for fabrication, acceptance, packing and final assembly. ILC's experience as a Lighter Than Air (LTA) envelope supplier and its ISO 9000 quality assurance (QA) system provided a good basis for establishing all appropriate QA System functions during airship envelope production.

New design details must be established by test § 601

In addition to "standard" airship design features, the Zeppelin LZ N07 incorporated many new design features such as the integration of a rigid structure within a pressurized hull (Photo 4). Additionally, many unique subassembly features are incorporated within an airship hull and each needs special qualification testing. Table 1 shows a partial list of design details that were tested during the qualification of LZN07.

Subassy	
Ballonet Attachment	Aft Endcap Attachment
Tie Tab and Cord Tab	Access Port installation
Longeron Lacing to Hull	Hull Sleeve assy
Small V-Patch	Doubler Installation
Tie Patch on Ballonet material	Ballonet Catenary
Loop Tape	Ballonet Kevlar Grommet with Sleeve Installation
Clear Vinyl Material	Ballonet Kevlar Grommet
Longeron Lacing to Hull	Pressure Sense Bulkhead Attachment
Manline Patch	Grommet Insert with Flexible Passthrough
Pressure Sensor Assy attachment	Hull Grommet Installation

Table 1 - List of Design Details

Photo 43 - Example of Design Details

Workmanship must be of high standard (§ 603)

The manufacturing of an airship envelope requires a high degree of craftsmanship. Therefore it is necessary to insure that the production team is properly trained and adequate test and inspection methods are utilized. This is accomplished by establishing a set of manufacturing procedures, which defines a controlled, repeatable process. Quality assurance is provided to document and control these established manufacturing processes.

Envelope design (§ 881)

Specifying the anticipated loads on the envelope is mandatory. To properly define limit load (the maximum load the envelope will see in operation) the following must be considered:

- Static loads resulting from the overpressure of the lifting gas.
- Dynamic loads under all operational conditions (including aerodynamic loads).

- Additional system loads. (including local loads introduced by means of patches and accessories).

Due to the rigid structure of the LZ N07 the load on the envelope is very evenly distributed. Areas of stress concentration are minimized as the main elements of the car, fins, engines, and aft wheel are all interconnected by the internal structure. There are no large suspension system loads or other features, which directly load the envelope. Because of this, strength requirements for the LZN07 hull material are primarily driven by the internal pressure of the lifting gas.

Special factor of safety for envelope materials § 881(b)
The current airworthiness requirement, § 881, requires a safety factor of 4 on envelope materials. This is to provide equivalent safety to that required for rigid structures where a fatigue evaluation for major parts must be demonstrated. Fatigue analysis on flexible envelope material is generally not practiced as on rigid structures. This lack of hard data and analytical methods requires other means of compliance resulting in a higher safety factor (based upon historical experience). Also it must be considered that material degradation is a function of load cycles and environmental exposure.

Tearing strength § 881(d)
In the same way that rigid airframe parts need to be analyzed for cracking and crack propagation, the airship envelope needs to be analyzed for tear and tear propagation.
Today's practice is to follow the Cut Slit Test Method according MIL-C-21189 which will be described in detail later. Unfortunately, analytical methods like those utilized on rigid components are not readily available for fabrics. Fabric tear and tear propagation behavior is still a fairly unexplored field. For this reason it was decided not only to collect the data required for compliance by the LBA but also to conduct additional testing in an effort to relate lab test data to real world envelope performance and increase our knowledge of tear propagation. In the next sections, both the standard and the additional test methods and data will be described.

SECTION 3 - Material Development and Qualification

The above-mentioned specification on envelope material and certification requirements helps define the material development and qualification process. However, different requirements including performance, cost, risk, and service life have to be considered. Therefore the material becomes a delicate balance between often competing demands such as:

- Highest tensile strength vs. lowest possible mass
- Maximum tear strength vs. maximum adhesion
- Maximum material life vs. ease of field repair
- Minimum price vs. everything.

To satisfy all these demands, extensive development work and testing must be accomplished. Table 2 provides a partial test matrix of required testing for airship qualification. When multiplied times several materials (hull, ballonet), several test directions (warp/fill/bias), several environmental regimes (hot, cold, humid, high UV) the amount of testing for qualification of an airship material becomes daunting.

TEST	TEST METHOD
Weight	FED-STD-191 TM5041
Bow and Skewness	ASTM D 3882
Surface Finish – Interior	Visual Inspection
Surface Finish - Exterior	Visual Inspection
Water Release - Exterior	FED-STD-191 TM5504
Blocking at Elevated Temperature	FED-STD-191 TM5872
Surface Polymer Characterization	Infrared Spectrophotometry
Tensile Modulus	ASTM D 751
Breaking Strength/Elongation - Strip Method Ultimate Tensile	FED-STD-191 TM5102
Breaking Strength/Elongation - Strip Method, Ultimate Tensile after Weather Exposure (QUV Chamber)	FED-STD-191 TM5102
Seam Tensile Strength - Heat Seal	FED-STD-191 TM5102
Seam Tensile Strength at Elevated Temperature Heat Seal	FED-STD-191 TM5102
Base Cloth Breaking Strength - Ravel Strip Method Ultimate Tensile	FED-STD-191 TM5104
Creep/Hysteresis Evaluation	Vendor Test Method
Tear Strength - Cut Slit	MIL-C-21189 Para 10.2.4 FAA P-8110-2, Appendix A
Tear Strength -Tongue	FED-STD-191 TM5134
Coating Adhesion -Heat Seal Seam, Back/Structural Tape	FED-STD-191 TM5970
Coating Adhesion - Heat Seal Seam, Cover Tape	FED-STD-191 TM5970
Coating Adhesion - Cement	FED-STD-191 TM5970
Film Ply Bond Adhesion (Dry)	FED-STD-191 TM5970
Film Ply Bond Adhesion (Elevated Humidity)	FED-STD-191 TM5970
Seam Deadload - Elevated Temp (Underwater) Heat Seal	Vendor Test Method
Seam Deadload - Elevated Temp (Hot Air) Heat Seal	Vendor Test Method
Seam Deadload -Elevated Temp (Underwater) Cement	Vendor Test Method
Seam Deadload - Elevated Temp (Hot Air) Cement	Vendor Test Method
Cylinder Deadload - Elevated Temp (Underwater)	Vendor Test Method
Inflated Cylinder Flex Testing	Vendor Test Method
Low Temp Flex	ASTM D 2136
Helium Permeability	ASTM D 1434 or Vendor Test Method
Helium Permeability after Weather Exposure (QUV Chamber)	ASTM D 1434 or Vendor Test Method
Seam Helium Permeability	ASTM D 1434 or Vendor Test Method

Table 2 – Sample Test Matrix for Airship Hull Material

As previously discussed one critical parameter for airship envelope material is its ability to resist tearing after it has been damaged. As this parameter is a function of the overall design of the fabric system, it is important to appreciate the consequences of varying fabric attributes relative to performance properties. To aid in the understanding of these trade-offs, Table 3 was constructed. It shows the effect on selected properties as the fabric attributes are varied for <u>the same given mass of yarns.</u> In general, these trends hold true for most coated/laminated woven fabrics.

Fabric Attributes	**PROPERTY**			
	Tensile Strength	**Tear Strength**	**Amount of Coating Requires (Mass)**	**Fabric Stability**
Smaller Yarn Denier	Same	Decreases	Decreases	Increases
Plain Weave	Same	Decreases	Decreases	Decreases
Ripstop Weave	Same	Increase	Increases	Decreases
Higher Yarn Count	Same	Decreases	Decreases	Increases

Table 3 – Fabric Attributes vs Properties

This table shows the delicate balance in materials design. For example, to minimize mass, you would pick a small denier, high count, plain weave fabric. To maximize tear strength you might choose exactly the opposite, a high denier, low count, rip stop fabric.

SECTION 4 - Cut Slit Tear Testing

Cut slit tear testing is one method of measuring the ability of a fabric to resist tearing after it has been damaged. This test was developed and utilized by U.S. Navy in the 1950s as an acceptance test for the airship hull materials of that era. It is specified in MIL-C-21189, "Cloth Laminated, ZPG2 and ZPG2W Type Airship Envelope", Amendment 1, 15 July 59, and original 13 December 57, Para 10.2.4. It was developed because it better simulated the tearing action of a damaged inflatable than did other standard tear methods of the time (tongue/trapezoid). The Federal Aviation Administration adopted this test in FAA P-8110-2, "Airship Design Criteria", 10 Oct 86, Appendix A as did the German LBA in "Airworthiness Requirements: Normal and Commuter Category, Airships", 15 Sep 95, Page 42.

<u>Description of the Cut Slit Tear test</u>

This method is used to determine the tearing strength of the fabric.
The fabric sample is 102mm (4") wide x 152mm (6") long having a 32mm (1¼") wide razor cut slit across the center of the sample at right angles to the longest dimension (See Photo 5).

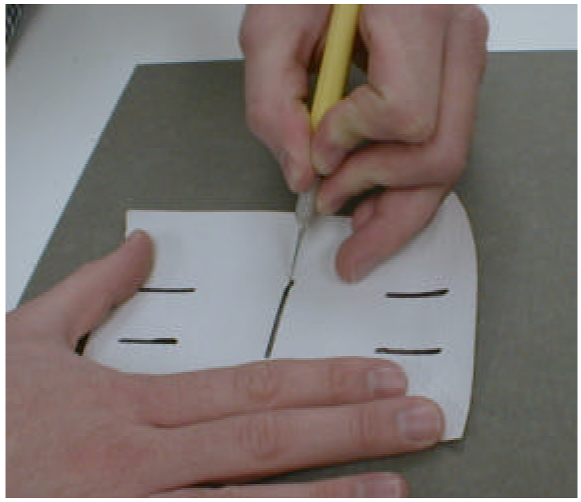

Photo 5 – Cut Slit Tear Sample

The specimen is placed symmetrically into clamps of a universal tester (See Photo 6) with the longest direction parallel to the direction of load applic ation. The clamps must be 25mm (1") wide and must grip the yarns that are cut. At the start of the test the distance between the clamps (gage length) must be 76mm (3") with the slit an equal distance from each clamp.

Breaking force is applied to the sample at a rate of 305 mm/min (12"/min) (See Photo 7). The tearing strength is determined as the average load of the highest recorded peaks of five specimens recorded in pounds.

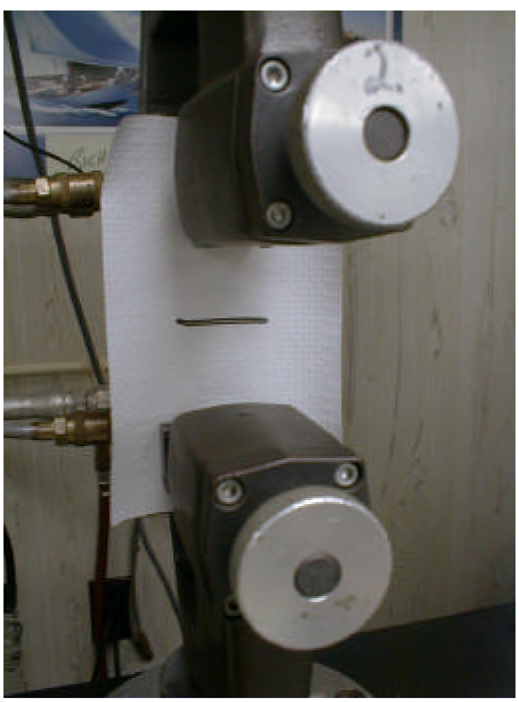

Photo 6 – Cut Slit Tear Testing Initial

Photo 7 – Cut Slit Tear Testing In Progress

SECTION 5 – Hull Material Slit Testing On Inflated Cylinders

While the cut slit tear testing provides a valuable tool for comparison testing of two fabrics and quality control testing, it has no direct correlation to tear propagation in an operational airship.

Dr. A. D. Topping investigated critical slit length vs. stress levels in a paper titled, " The Critical Slit Length of Pressurized Coated Fabric Cylinders" published in October 1973. Dr. Topping utilized inflatable cylinders in sizes ranging from a diameter of 69mm (2.7") to 152mm (6"). J. R. Thiele furthered this investigation by attempting to correlate cut slit tear strength with "critical slit length." Critical slit length was defined as the point at which the threads at the ends of a tear can no longer hold the stress and break. The tear becomes larger and puts increased load on the next yarns until they in turn break and the tear rapidly propagates until the stress is sufficiently reduced. Mr. Thiele's testing included additional cylinders of actual airship hull material in a diameter of 389mm (15.3"). He also performed testing on two full size airship envelopes with diameters near 9400mm (370"). Mr. Thiele's testing showed good correlation between cut slit tear strength and critical slit length using the following equation that he derived from Dr. Topping's work.

$$Pr = \frac{C_S * 1.4}{L^{0.525}(1 + (L/r))}$$

Where:
P = inflation pressure
r = cylinder radius
C_s= Cut slit tear strength
L = Critical longitudinal slit length

Zeppelin and ILC Dover decided to perform similar tests on the LZN07 hull material. This testing attempted to correlate cut slit tear testing to tear propagation testing on an inflatable cylinder using the equations derived by J. R. Thiele.

ILC fabricated several inflatable cylinders using LZN07 airship hull material (see Figure 8 and Photo 9). The cylinders were approximately 3700mm (144") long and 900mm (36") in diameter. An initial cut was slit prior to sealing the closing seam. A lightweight polyurethane film was installed inside of the slit with duct tape to prevent gross leakage during the test. All testing was video taped to allow for accurate measurement of slit lengths.

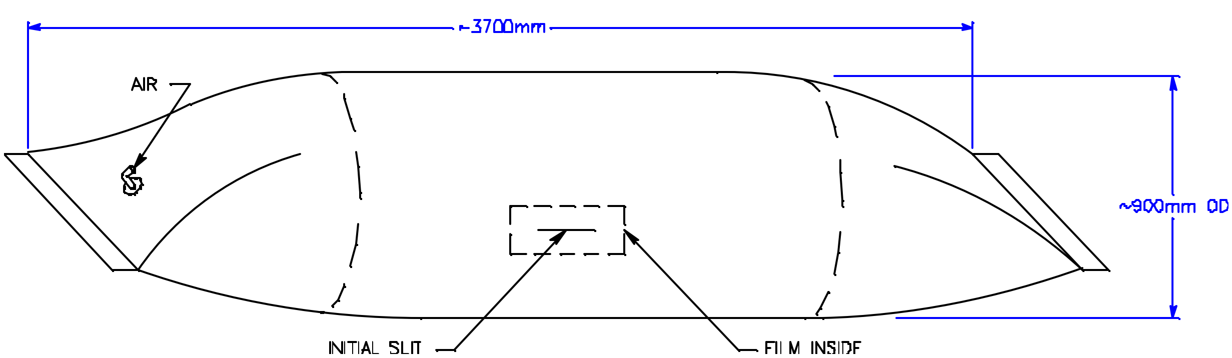

Figure 8 – Sketch of ILC Cylinder


Photo 9 – Photo of ILC Cylinder

The following test procedure was utilized:
Note: Limit Load is defined as maximum operational load.

1. Measure initial slit length.
2. Pressurize cylinder with air. At any time, if tear began to propagate, stop pressure increase and maintain constant pressure until catastrophic failure. Measure final cut length prior to catastrophic failure using videotape replay.
3. Maintain stress at ½ limit load (Stress level to be determined by measurement of circumference and pressure of bag) for 5 minutes.
4. Maintain stress at ¾ limit load for 5 minutes.
5. Maintain stress at limit load for 5 minutes.
6. If no tear propagation, shut down air.
7. Adjust or repair bag-repeating test with various initial slit sizes.

Seven tests were performed using various initial cut lengths ranging from 41mm (1.625") to 241mm (9.5"). One test was taken to full limit load with no failure. The six other tests concluded in full catastrophic rupture. Each of these tests started with an initial cut length that grew to a final cut length (critical slit length) just before going catastrophic. The results from this test are shown in Figure 10. The dashed lines represent the curves using theoretical equation derived by Thiele for a cut slit tear value of 267 N (60 lbs) (Zeppelin minimum specification value for cut slit tear strength) and 356 N (80 lbs) (nominal Zeppelin for cut slit tear strength).

Good correlation was obtained between data and theory. The critical slit length was very close to that predicted by Mr. Thiele's equation using the nominal value for cut slit tear strength of LZN07 hull material. Additionally, in all cases, the critical slit length was greater than the Zeppelin minimum requirement for cut slit tear strength would predict.

This cylinder tear testing showed that the LZN07 hull material performed in a similar and predictable manner when compared to other airship materials that have been previously tested. It is anticipated therefore that the LZN07 would have an equivalent level of safety.

Although this data is valuable, several items should be discussed that are not part of this testing and require further investigation.

First, no attempt was made to investigate the function of time into this testing. For example a tear of 25mm (1”) may not propagate at 70 N/cm (40lb/in) during the 5-minute dwell of this test but it may propagate given enough time under load. This was experienced during the test when the slit would increase in size and then stabilize, not growing until the stress was increased.

Second, no attempt was made to induce the failure dynamically into the as would likely happen in an operational airship. These tests began with the slit made in the unstressed (uninflated) state. This testing would be similar to having an unknown defect in the airship prior to inflation. More likely would be the case where the slit was induced in an already pressurized (stressed) hull.

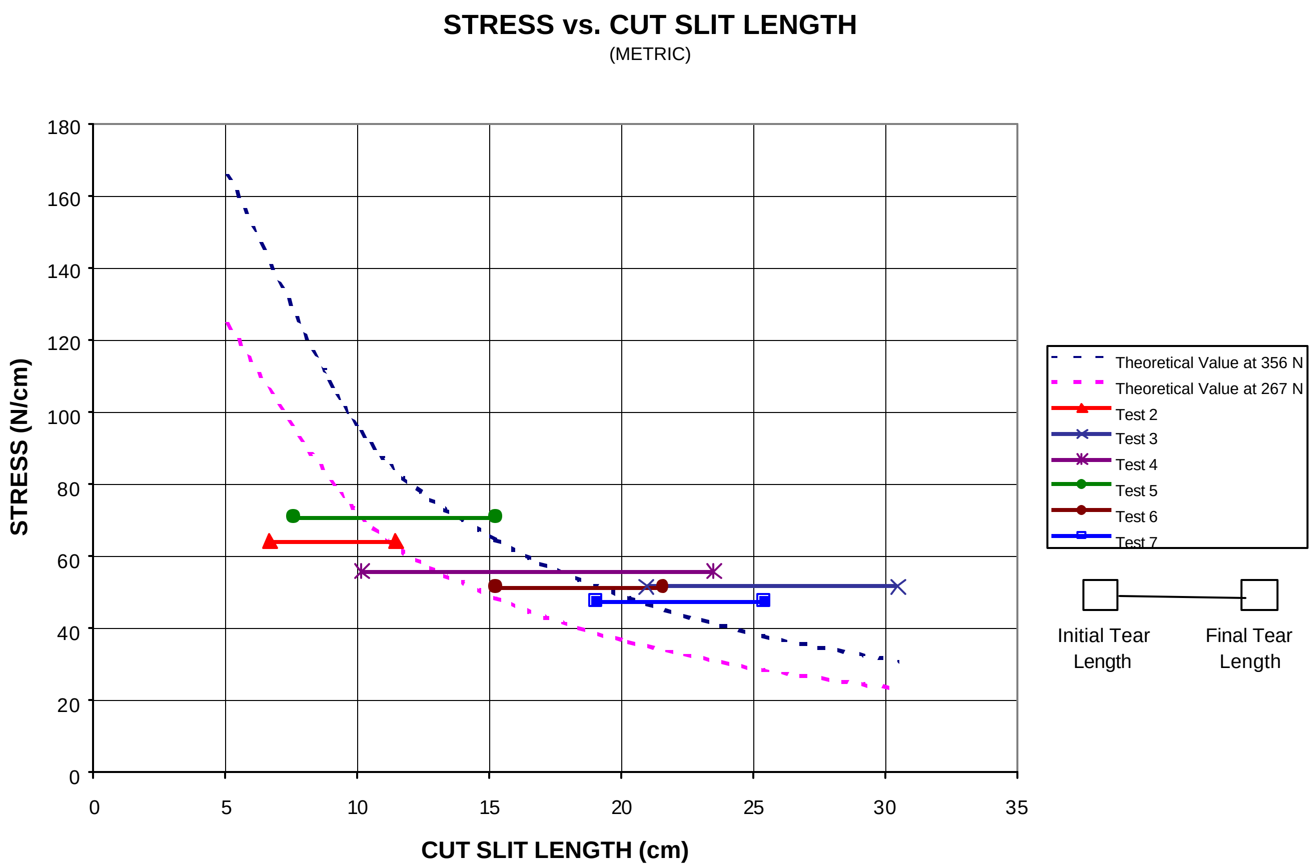

Figure10 - Stress vs Cut Slit Length

Conclusions

As all current and most planned airships continue to use the pressure envelope design principle, the envelope must be considered a main structural element of the airship.

The development of design requirements and compliance to these requirements in airship envelopes continues to be a difficult and laborsome practice. New methods, both analytical and test, need to be established and verified to reduce this effort and to ensure a robust, cost effective aircraft.

Tear strength was used as one example where current test methods do not accurately depict real world performance. New methods for collecting additional data were discussed along with recommendations for future investigation.

References:

1. ILC Test Report 6309-70104, "HULL MATERIAL SLIT TEAR TESTING ON INFLATED CYLINDERS"
2. AIAA 95-1620, "Approximation of Envelope Critical Envelope Critical Slit Length", J. R. Thiele, 15-18 May 95
3. LBA Airworthiness Requirements: Normal and Commuter Category, Airships, 15 Sep 95
4. MIL-C-21189, Cloth Laminated, ZPG2 and ZPG2W Type Airship Envelope, Amendment 1, 15 July 59, and original 13 December 57.
5. FAA P-8110-2, "Airship Design Criteria", 10 Oct 86