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STRENGTHS OF BALLOON FILMS WITH FLAWS AND REPAIRS

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Summary

An investigation was conducted to study the effects of manufacture flaws and repairs in high altitude scientific balloons. A right circular cylinder was used to induce a biaxial tension-tension stress field in the polyethylene film used to manufacture these balloons. A preliminary investigation of the effect that cylinder geometry has on stress rate as a function of inflation rate was conducted. The ultimate goal of this investigation was to rank, by order of degrading effects, the flaws and repairs commonly found in current high altitude balloons.

Introduction

A balloon recovery program has been conducted under the auspices of NASA Wallops Flight Facility. Every facet of ballooning, including manufacturing, launching, and the flight termination, is under great scrutiny. One issue that has become a primary concern is the presence of manufacture flaws and the repair of these flaws. It has been noticed that, during the assembly of a typical balloon, hundreds of flaws or damaged areas result. Most of these areas get repaired but the effect of these flaws and their repairs on the structural integrity of the balloon is unknown. An attempt at ranking the effects of these flaws and repairs has been conducted for NASA Wallops.

Most of the work that has been conducted by researchers involved in the balloon recovery program has been related to material properties determined by uniaxial tensile testing. Tests have been conducted from room temperature to well below the cold brittleness point of the polyethylene film [Ref.1.]. But a uniaxial test may not correlate with a balloon which is subject to biaxial stresses. To better represent the stress states in an actual balloon a biaxial tension-tension test is needed. Their are no ASTM standards on the biaxial testing of "Balloon Film" so a suitable means needed to be developed.

Their have been various attempts at the biaxial testing of thin specimens. A cruciform test coupon is a popular method of introducing a biaxial field but unfortunately it's not very applicable to thin films because the required geometry of the specimen would be nearly impossible to create. The

"Strip Biaxial" coupon has some promise but an exact biaxial ratio cannot be determined. It is also impossible to apply this method to specimens with holes, seams, or load tapes.

Dr. Dale Webb, while at Texas A & M University, developed an apparatus for biaxial testing [Ref.2]. It was called the "RaceTrack" tester. The film was clamped between two rubber lined, flat plates. The plates contained a semi-circular hole which was 5 times as long as it was wide. Hence the name "Racetrack" was coined from the opening shape. Once the sample was installed it was pressurized from one side until failure. Stresses were calculated using a simple shell analysis. The device worked quite well but specimens tended to fail at the interface of the film and the plates.

The right circular cylinder is used most often to induce biaxial stresses. Winzen International Inc. published a "Cylinder Testing Manual" [Ref.3] offering advice on testing right circular cylinders. This manual describes a testing apparatus and method that has become somewhat of a standard in the ballooning industry. Again a simple shell analysis is used. Stresses in the hoop or circumferential direction and in the longitudinal direction are calculated using thin walled pressure vessel analysis.

Because of the simplicity of testing with right circular cylinders it was decided to use a modified version of Winzens testing method in this flaw and repair study. Before testing was to begin though, a thorough understanding of cylinder size effects was needed. Because the polyethylene film is so highly viscoplastic it was thought that cylinder size, at a given inflation rate, could affect the results. A parametric study of various cylinder

volumes loaded at different inflation rates was conducted to establish what, if any viscoplastic effects would be present during testing. These test were conducted at room temperature.

Upon completion of the cylinder size study a flaw and repair study was conducted. These test were also conducted at room temperature. An average strength for an undamaged cylinder was first determined. The various types of flaws and repairs were then classified according to whether they were related to seams or to the membrane. A series of 7 to 10 replicate tests were then run on each of the different classes of flaws and repairs. These strengths were then compared to that of the undamaged standard cylinder.

Key Words

High altitude balloons, Polyethylene film, Stress Rate, Biaxial testing.

Nomenclature

A	Cross-sectional area, in^2.
E	Young's Modulus of Elasticity, Ksi.
E_{avg}	Average Secant Modulus, Ksi.
L	Length, in.
m	Mass, lbm.
p	Gauge Pressure, psi.
V	Volume, in^3
α	Constant ratio of length to diameter
σ_h	Hoop (circumferential) Stress, psi.
σ_l	Longitudinal Stress, psi.
ϵ_h	Normal Strain in the Hoop Direction
ϵ_l	Normal Strain in the Longitudinal Direction
π	3.14159...
ν	Poissons Ratio,

Test Equipment and Procedures

The method used to inflate the cylinders is similar to that described in Winzen's cylinder test manual. See Ref. 3. The end fitting or spool was identical to Winzen's and is illustrated in figure 1. The spool contained two 1/8 in. diameter orifices, one to introduce the inflation gas and the other to measure internal pressure. An eye bolt was attached to the spool to support the cylinder during testing. A schematic illustration of the testing equipment setup is shown in figure 2. No bottom spool was used to eliminate any preload or creep, caused by the spool's weight.

Shop air was used to inflate the cylinders. The air first flowed through a drier and then through a pressure regulator. The regulator was set for 25 psi. Air flowed into the test cylinder through a fine needle valve and then through a Hastings Digital Flowmeter to measure the flow rate. This flowmeter, model NALL-10KP, has a range of 0 - 610 in^3/Sec (0 -10 L/Min). The flow rates used were 61, 305, and 610 in^3/Sec (1, 5, & 10 L/Min). The pressure inside the cylinder was monitored with a Mensor Digital Pressure Gauge with a 0 - 2 psid range. The output of both the flowmeter and the pressure gauge were recorded on a Hewlett-Packard model 7132A chart recorder.

The diameter of the spool was less than that of the cylinders. When attaching the cylinders to the spool, the film was gathered uniformly around the spool. A strip of paper towel padding was then rapped around the circumference of the spool, on top of the film. A #40 hose clamp was placed on top of the padding and tightened with a screwdriver. An on/off valve in the shop air line was opened to start the inflation process. Before each test the flow meter and pressure gauge calibration were checked and the chart recorder was zeroed. The entire inflation process was recorded on videotape. The pressure readout, a scale, and a stop watch were running in view of the video camera during the inflation After each test the cylinder width and maximum pressure was determined from the video recording. An average of 8 to 10 replicate test were run for each of the test series. All testing was done at room temperature.

Specimens

For the cylinder size study, a 5 to 1 ratio of cylinder length to diameter was maintained to minimize the effects of end conditions. Three cylinder lay flat widths were used. (The "Lay Flat Width", which is textile nomenclature, is the width of a cylinder while laying flat on itself or simply half it's circumference.) The lay flat widths were 4.5 in., 8.0 in., and 16.0 in. The corresponding lengths were 14.4 in., 25.5 in. and 51.0 in. respectively. All test cylinders were one layer thick. They were constructed by taking two rectangular sheets of film, laying one on top of the other, folding the edge over so that the edge is four layers thick, and then passing this fold through a hot band seamer. A few trial runs were made to optimize the seaming process before the test cylinders were made.

For the flaw and repair study a cylinder 25.5 inches long with a 8.0 lay flat was used with an inflation rate of 305 in^3/sec (5.0 L/Min). This layflat and inflation rate were determined from the size study.

Results and Discussion

Cylinder Size Study: The advantage in using right circular cylinders is that the geometry of the specimen remains that of a right circular cylinder up to failure (peak internal pressure). Thus, the stress in the circumferential or "Hoop" direction can be calculated from the internal pressure in the cylinder [Ref.4]. From equilibrium the hoop stress is

$$\sigma_h = \frac{Pr}{t} \tag{1}$$

and the longitudinal stress is

$$\sigma_1 = \frac{Pr}{2t} \tag{2}$$

We note from equations (1) and (2) that the hoop stress is twice the longitudinal stress

$$\sigma_h = 2\sigma_1 \tag{3}$$

This relationship is independent of material or volume. It relies only on the premise that the specimen remains a right circular cylinder.

Results from the initial cylinder size tests are shown in Figure 3, a plot of Hoop Stress at failure verses Lay Flat Width. In this figure failing strength increases slightly with decreasing sample width.

Plastics tend to be viscoplastic. Figure 4 is a plot of Hoop Stress verses Inflation Rate. It can be seen in this figure that the strengths vary only slightly with inflation rate and are maximum at an inflation rate of 305 $in^3/$ sec.

Stress rates depend on cylinder size as well as inflation rate. For a generalized Hookian material (i.e. no time dependent material behavior) the cylinder strain rates are [Ref. 5].

$$\dot{\epsilon}_h = \frac{1}{E}\dot{\sigma}_h\left(1 - \frac{\nu}{2}\right) \quad \text{and} \quad \dot{\epsilon}_1 = \frac{1}{E}\dot{\sigma}_1\left(\frac{1}{2} - \nu\right) \qquad (4)$$

Therefore, the rate of change in volume can be expressed as

$$\dot{V} = \frac{V_o \; \dot{\sigma}_h}{E} \left\{ 2(1+\epsilon_h)(1+\epsilon_1)\left(1-\frac{\nu}{2}\right) + (1+\epsilon_h)^2\left(\frac{1}{2} - \nu\right) \right\} \qquad (5)$$

where $V_o = \pi \alpha r_o^3$ (6)

and r_o is the initial radius of the cylinder and $\alpha = \frac{l_o}{r_o}$

In a biaxial stress field the failure strains are much less than 1.0 for the balloon film, averaging 20.23% for the series. For small strains the change in volume can be reduced to

$$\dot{V} = \frac{V_o \ \dot{\sigma}_h}{E} (\frac{5}{2} - 2\nu) \qquad (7)$$

Substituting equations (6) into equation (7), and solving for $\dot{\sigma}_h$

$$\dot{\sigma}_h = \frac{E \ \dot{V}}{\pi \ \alpha \ r_o^3 \ (\frac{5}{2} - 2\nu \ )} \qquad (9)$$

Thus, $\dot{\sigma}_h$ increases in proportion to inflation rate $\dot{V}$ but varies inversely with the volume r_o^3.

The hoop stress in figures 3 and 4 are plotted against stress rates $\dot{\sigma}_h = \frac{\sigma_u}{t_u}$ in figure 5. The average stress rates were calculated by dividing the hoop stress at failure by the time to maximum pressure. The solid line was fit to all the data. Overall, the strengths increase only slightly with stress rates that vary nearly three decades. Thus, viscoplasticity does not seem to be significant here.

The effect of stress rate on Youngs modulus can also be inferred from the data in figure 5. Solving eq. (9) for E,

$$E = \pi \ \alpha \ (\ \frac{5}{2} - 2\nu \ ) \ (\ \frac{\dot{\sigma}_h}{\dot{V} \ / \ r_o^3} \ ) \qquad (10)$$

where

$$\dot{\sigma}_h = \frac{\sigma_u}{t_u} \quad \text{on the average.}$$

Values of E were calculated from the data using eq. (10) with $\nu = \frac{1}{2}$ and plotted in figure 6.

This value of E is actually a Secant Modulus because values of $\frac{\sigma_u}{t_u}$ were used for $\dot{\sigma}_h$. The solid line, best fit to the data, is nearly flat indicating that little viscoplasticity exists. Also shown in figure 6 are dashed lines showing average values for both the elastic modulus and secant modulus from uniaxial tensile tests. These moduli were determined from room temperature stress strain curves published in a previous report, see Ref. 1. The secant modulus from the biaxial tests is greater than that from the uniaxial tests because the biaxial strains at failure are smaller than uniaxial strains at failure.

<u>Flaw and Repair Study:</u> The assortment of flaws encountered in a typical balloon is varied indeed. A list of Flaws provided by Winzen Inc. is shown in table 1. This list contains 28 items, far too numerous to do enough replicate tests to accurately rank them. Instead it was decided to combine related items into groups and then test the most predominant items from each. A list of the groupings is given in Table 2. The two groups included

the two major structural areas of the balloon, the seam/load tape area and the membrane/gore area. The seam/load tape group consisted of burned seams and wrinkles, folds, or tucks. The gore group consisted of surface defects and holes, tears, or cuts. All holes, cuts, or tears were repaired with a special tape produced by the balloon manufacturer called SSA-10 tape. This tape is made of the same polyethylene as the balloon film, but it is 3 mils thick and has an adhesive on one side.

The initial testing established the ultimate strength of an undamaged cylinder. All flaw and repair tests were ranked against this standard. For the undamaged cylinders, the average Hoop stress of 2086 psi was obtained for ten duplicate specimens.

A major problem arose when testing unrepaired cylinders with holes, tears, or cuts. Any type of hole through the membrane allowed the inflating air to escape. Even a small pin hole prevented inflation. A much larger flow rate would have been required to overcome the leak. Various methods of covering the hole failed because the covering either blew off or air seeped under it. For these reasons, holes, tears, or cuts without repair could not be tested.

The next series of tests were conducted on cylinders with a 2 inch by 6 inch piece of SSA-10 tape located at the center of the gore midway up it's length. It was expected that a stress raiser would develop at the corner of the tape edge causing premature failure. What actually happened was that the increase in stiffness caused the cylinder to fail elsewhere in the gore. The test was repeated with a 4 inch long cut in the film that was taped over with SSA-10. The failure mechanism was the same. Failure almost always occurred 180 degrees from the tape at an area located at the same vertical position as the top or bottom edge of the tape. The failure strengths with taped cuts were almost identical (within 5%) to the values obtained from the standard cylinder tests. Thus, the presence of repair tape caused little or no degradation in failure strength. Ten replicate tests were run for this series of tests.

Nonpenetrating surface damage to the membrane was looked at next. Finger pulls were made in the center of the cylinder gore, midway up it's length. During the latter stages of inflation, the wrinkle disappeared. Failure almost always emanated from the damaged area, but the failing stresses were almost identical to that of the undamaged standard cylinder. Taping over the finger pulls resulted in failure stresses identical to those for the patched 4-inch-long cuts. The tape influenced the location of the failure but not the strength. Again ten replicate tests were run to establish an average strength.

Folds or tucks in the seams were looked at next. The failure strengths were almost identical to those of the undamaged cylinders. Ten duplicate specimens were tested with folds or tucks in the seam and there was never a failure at the tucked area. The failures were always in the center of the membrane 40 to 50 percent up it's length.

Burned seams caused a 19 % decrease in strength, relative to the undamaged standard. With tape, strength was restored to the average level of the undamaged standard. This is important because the question of whether a seam is burned badly enough to tape is no longer an issue. If a seam is not perfect it can be taped without concern.

The bar chart in Figure 7 provides a comparison of the strengths for the various types of flaws and repairs. It can be seen that, except for burned seams, strength differed little between the flaws and repairs. The ultimate strength in some cases is greater that that of the standard. The data used to generate this plot is given in Table 3. This table contains a list of each of the test results, the average of each series, and it's standard deviation.

Conclusion

The preliminary study of cylinder size and inflation rate show that right circular cylinders pressurized at or below 610 in^3/sec and having dimensions of no more that 16.0 in. lay flat width and 51.0 in. in length are relatively free of stress rate effects. In addition, a means of determining the secant modulus in a biaxial stress state has been developed. As a result, cylinders with a 8.0 in. lay flat and a 25.5 in. length inflated at 305.0 in^3/sec were used for all testing to determine the effects of flaws and repairs.

A parametric study was made to rank the various flaws and repairs against a standard undamaged cylinder. It was found that the majority of the flaws and repairs resulted in little or no apparent decrease in strength. Thus, most of the flaws that are currently being repaired may not require repair. On the other hand, repairs using SSA-10 tape never decreased the failing strength. The only damage that caused any decrease in strength was burned seams. The strength of cylinders with burned seams averaged 19 percent less than those of undamaged cylinders. It was also found that by covering the burned seams with SSA-10 repair tape the strength was restored to a value slightly higher that the standard undamaged cylinder.

References

[1] Portanova, M.A.: Fracture Characteristics of Balloon Films. NASA CR-181686, January 1989.

[2] Private communication with Dr. L Dale Webb, Texas A & M University, The Department of Civil Engineering, College Station, Texas, August 1988.

[3] "Cylinder Testing Manual" Winzen International, Incorporated. UCAR P.O. No. 03981-86. 1986

[4] Beer, F.P.; Johnston, E.R.: Mechanics of Materials. McGraw-Hill Book Company, 1981.

[5] Popov, E.P.: Mechanics of Materials, second ed. Prentice-Hall, 1976.

Table 1

Standard listing of Flaws Used in Ballooning Supplied by Wintzen International, Inc.

1. White streaks
2. Tucks
3. Abrasion
4. Finger Pull
5. Wrinkles in Back-up tape
6. Wrinkles in Film
7. Gell or "Fish Eye"
8. Burned Seal
9. "Smear" in Seal
10. Saw-Toothed Seal
11. Trash in Seal
12. Teflon in Seal
13. Scratch
14. Holes
15. Back-up tape "Flips"
16. Load Tape "Walks"
17. Load Tape Folds Over
18. Load Tape not Sealed at Top Edge of Seal
19. Grab
20. Dip, Pocket or Narrow spot in Seal
21. Clody Seal
22. Slit or Tear in Film
23. "Hot Poly"
24. Machine Seal Cut-off
25. Tight or Loose Spots in Film
26. Poly in the Seal
27. Red Ink in Seal

Listing of Flaws used in the Flaw & Repair Study

1. Load Tape / Seam Flaws
    a. Wrinkles, Folds, or Tucks
    b. Burns / White Streaks

2. Membrane / Gore Flaws
    a. Holes, Tears, or Cuts
    b. Abrasions and Finger Pulls

Listing of Repairs used in the Flaw & Repair Study

1. Load Tape / Seam Flaws
    a. Resealing seam with hot iron
    b. Patching with SSA-10 tape

2. Membrane / Gore Repairs
    a. Patching with SSA-10 tape
    b. Various sizes and shapes of patches

Table 2

Cylinder Strengths
Flaw and Repair Study

Flaw Type	Std. No Damage psi	Tape No Flaw psi	Tape 4in Cut psi	Finger Pull psi	Taped Finger Pull psi	Tucks psi	Burned Seams psi	Taped Burned Seams psi
Test Data	2386	2297	2403	2339	2430	2144	1885	1979
	2273	1796	1892	1903	2018	2242	1742	2056
	1939	2158	2382	2292	2389	2031	1656	2492
	1861	2072	2368	2267	2114	2458	1577	1927
	2287	1857	1925	2121	2190	2406	1597	2092
	1846	1870	2051	1978	2069	1890	1627	2147
	1898	1962	2187	1929	2206	1988	1701	1953
	2332	1991	2202	2091	2092	1927	1872	2276
	1849	2259	2352	2031	2027	2093	1841	2207
	2191	2162	1911	2122	2168	2388	1495	1862
Average	2086	2042	2167	2107	2170	2157	1699	2099
Std. Dev.	214.0	165.6	197.8	144.9	134.3	196.5	126.7	179.8

Table 3

TOP SPOOL FITTING

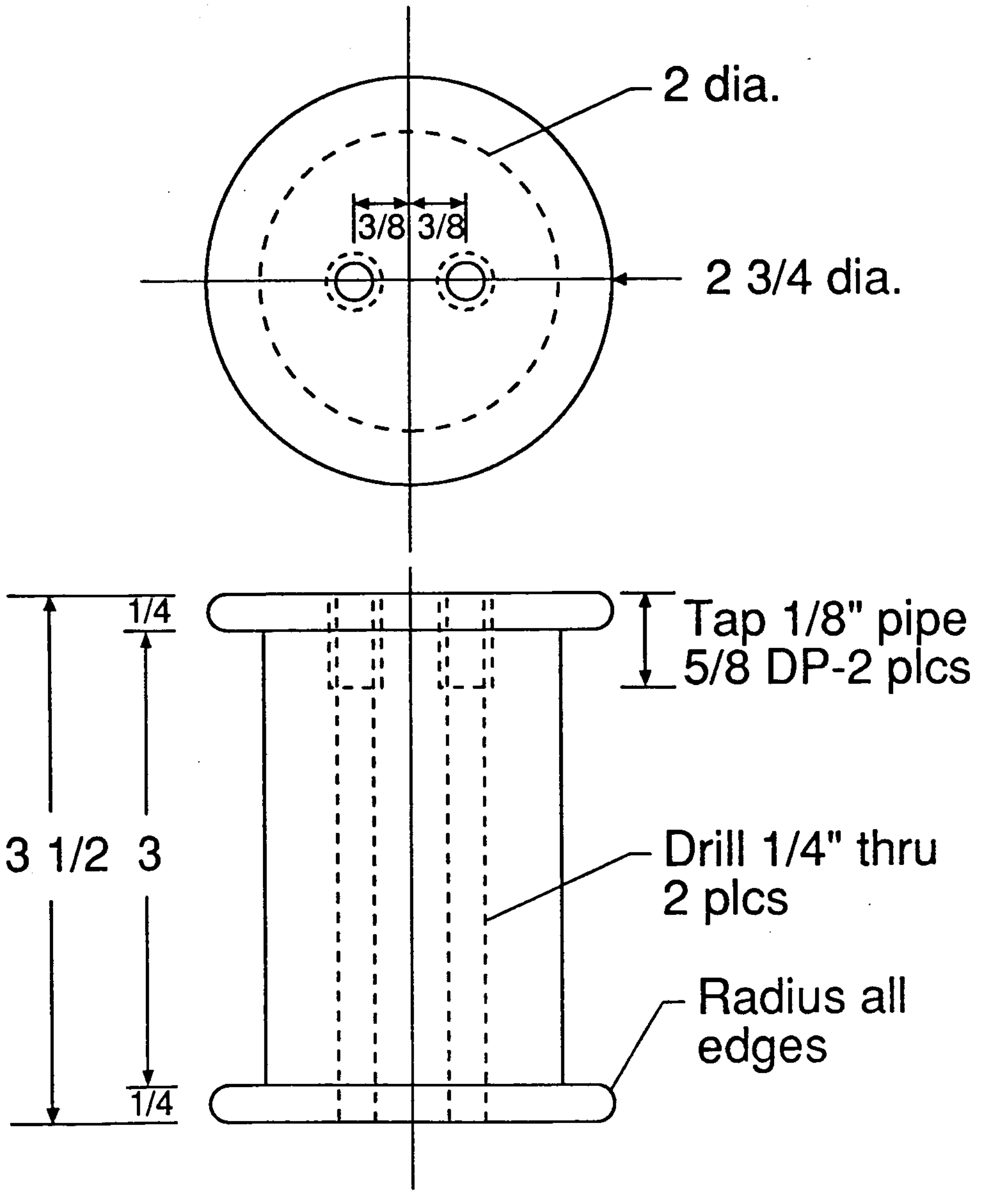


Figure 1

CYLINDER TESTING SET - UP

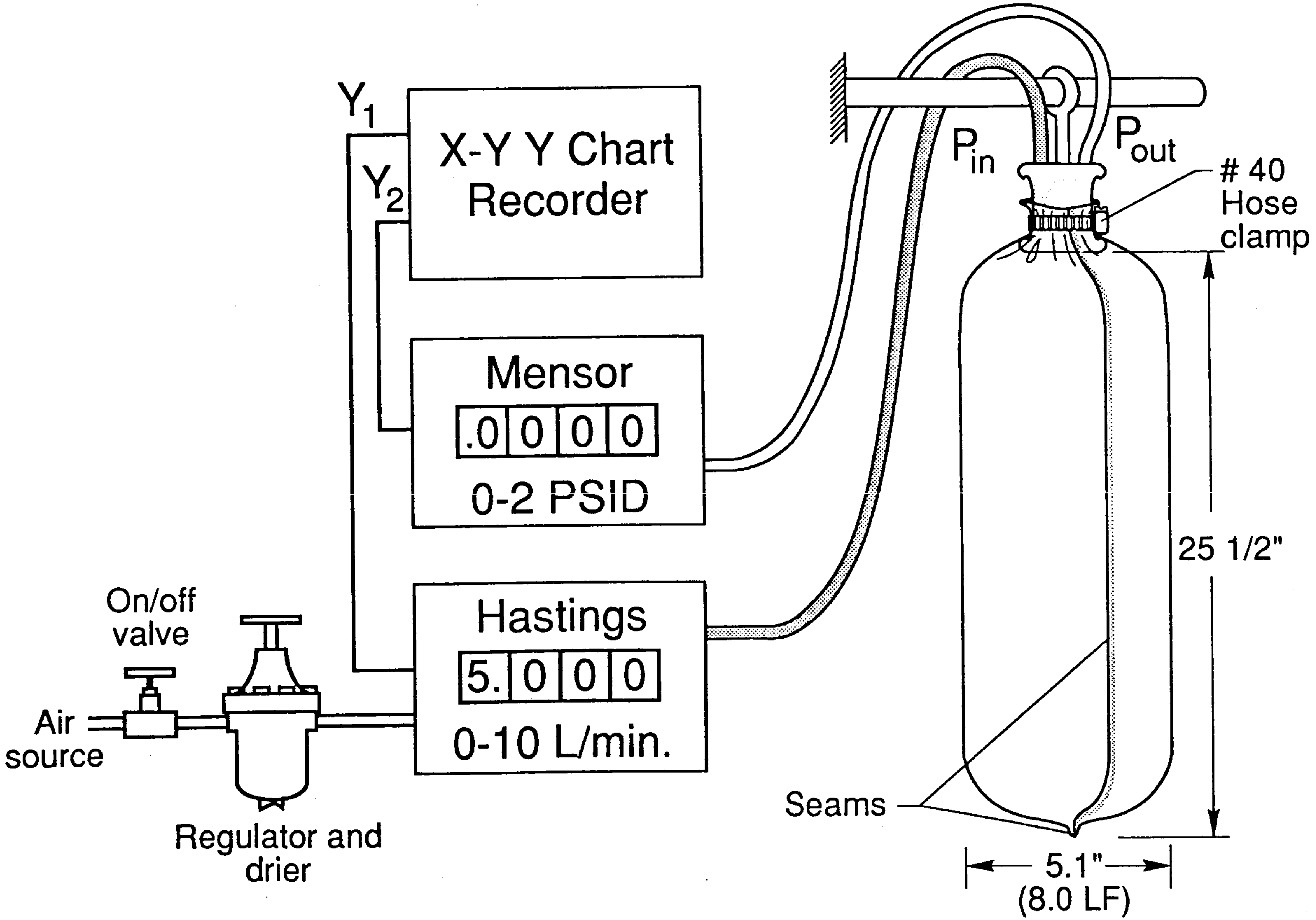


Figure 2

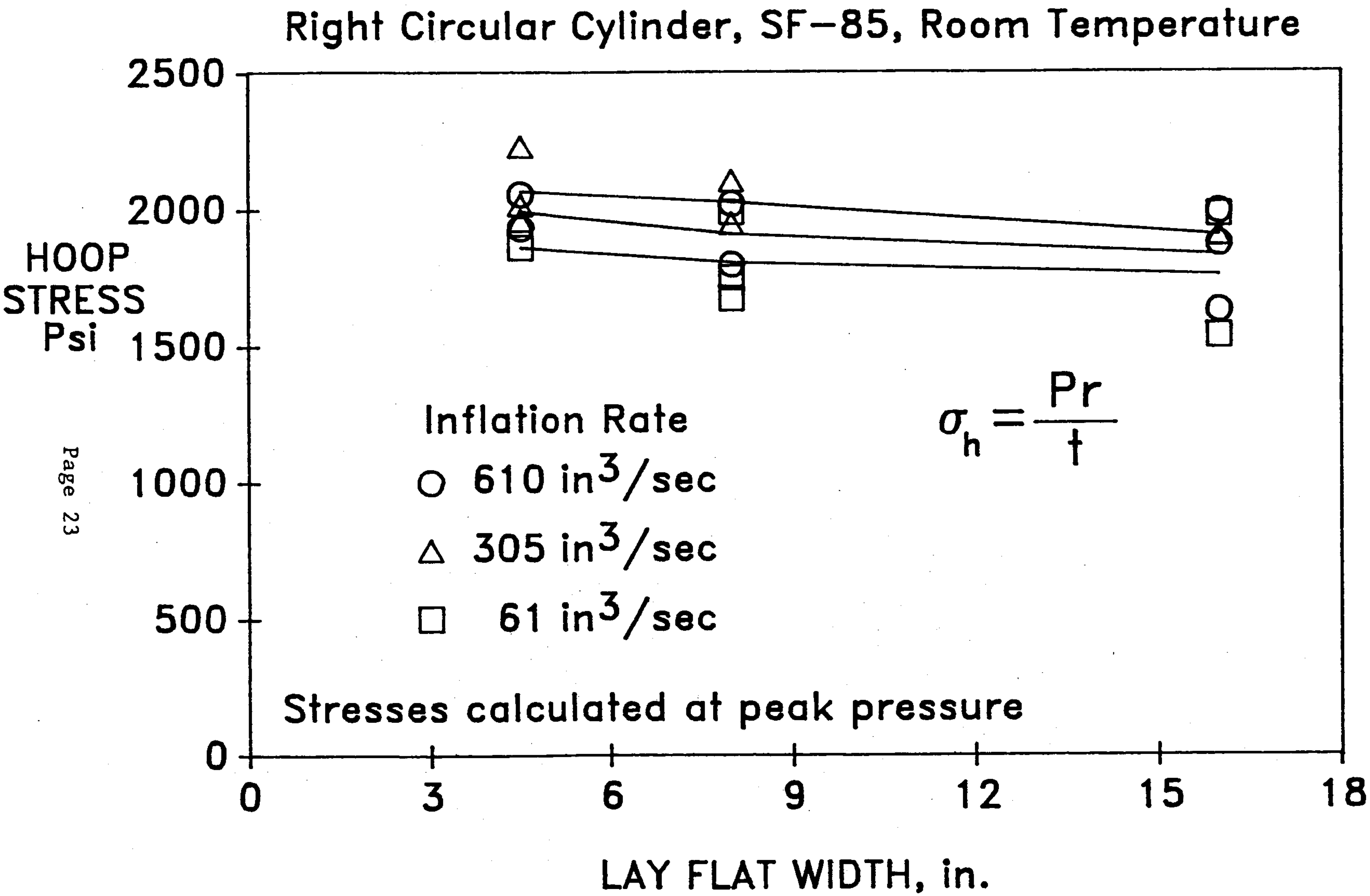
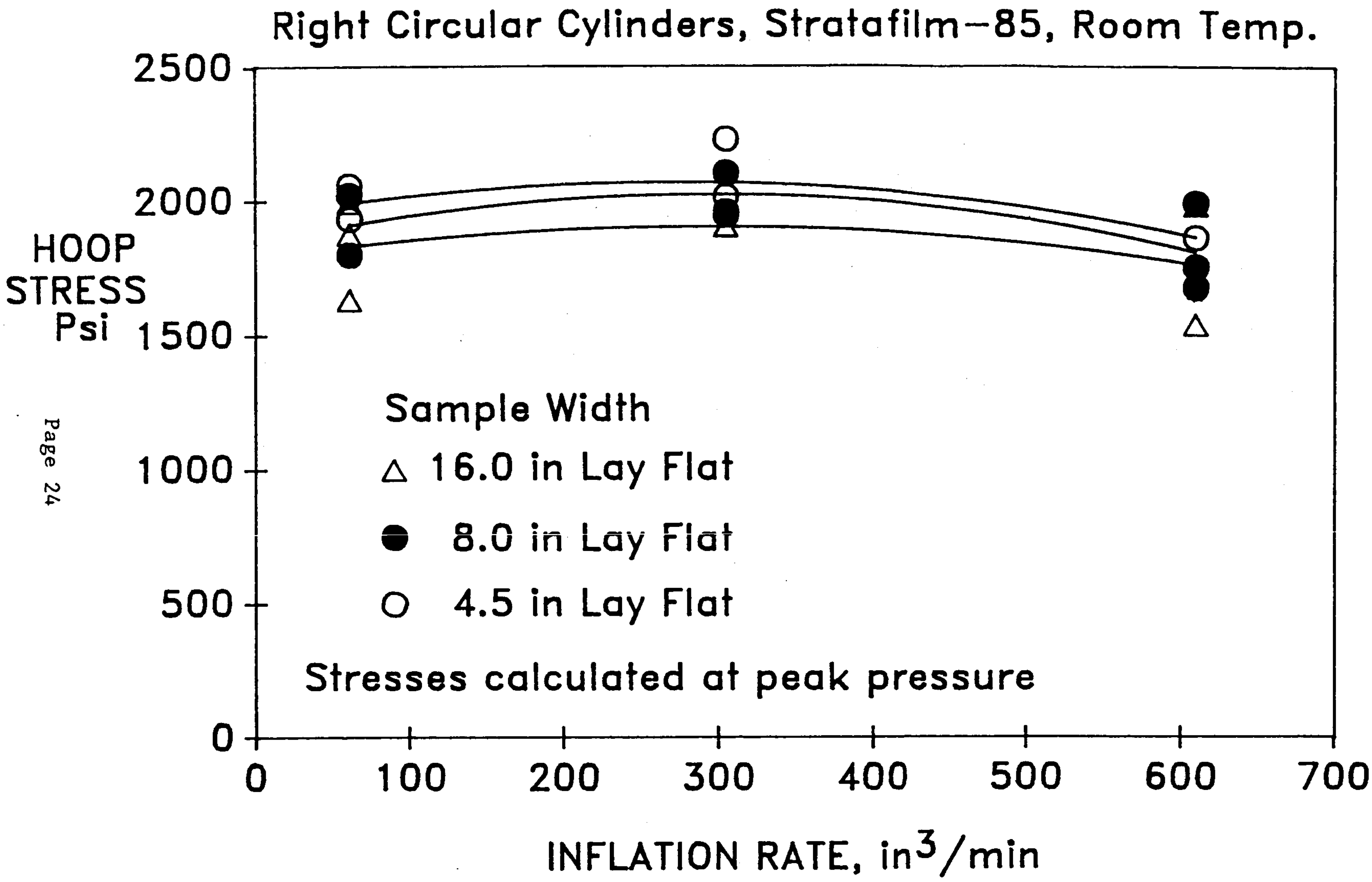


Figure 3. A comparison of Hoop Stress at Failure versus Lay Flat Width

F&R-F4.grf



F&R–F3.grf

Figure 4. A compairson of Hoop Stress at Failure versus Inflation Rate

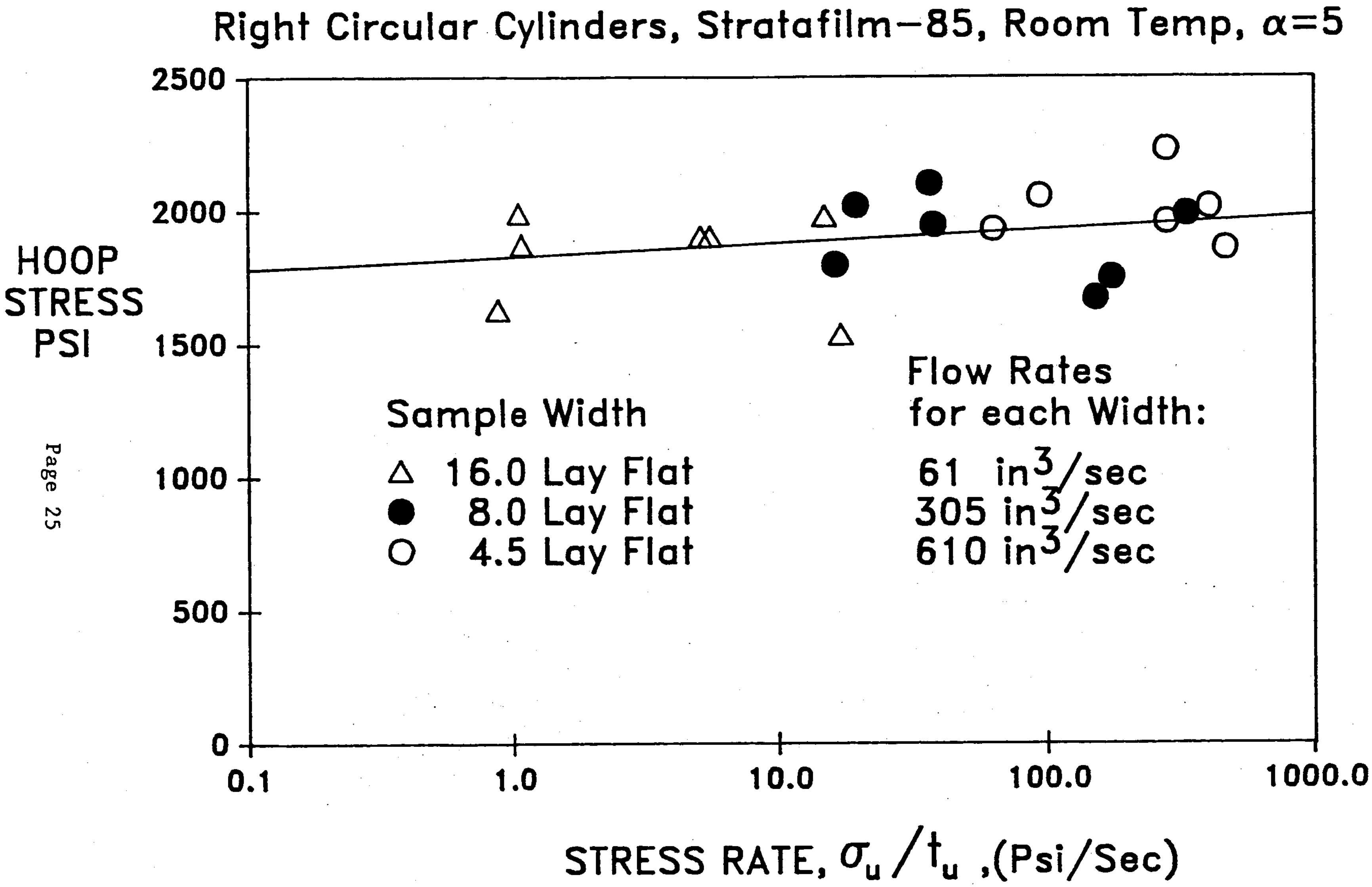
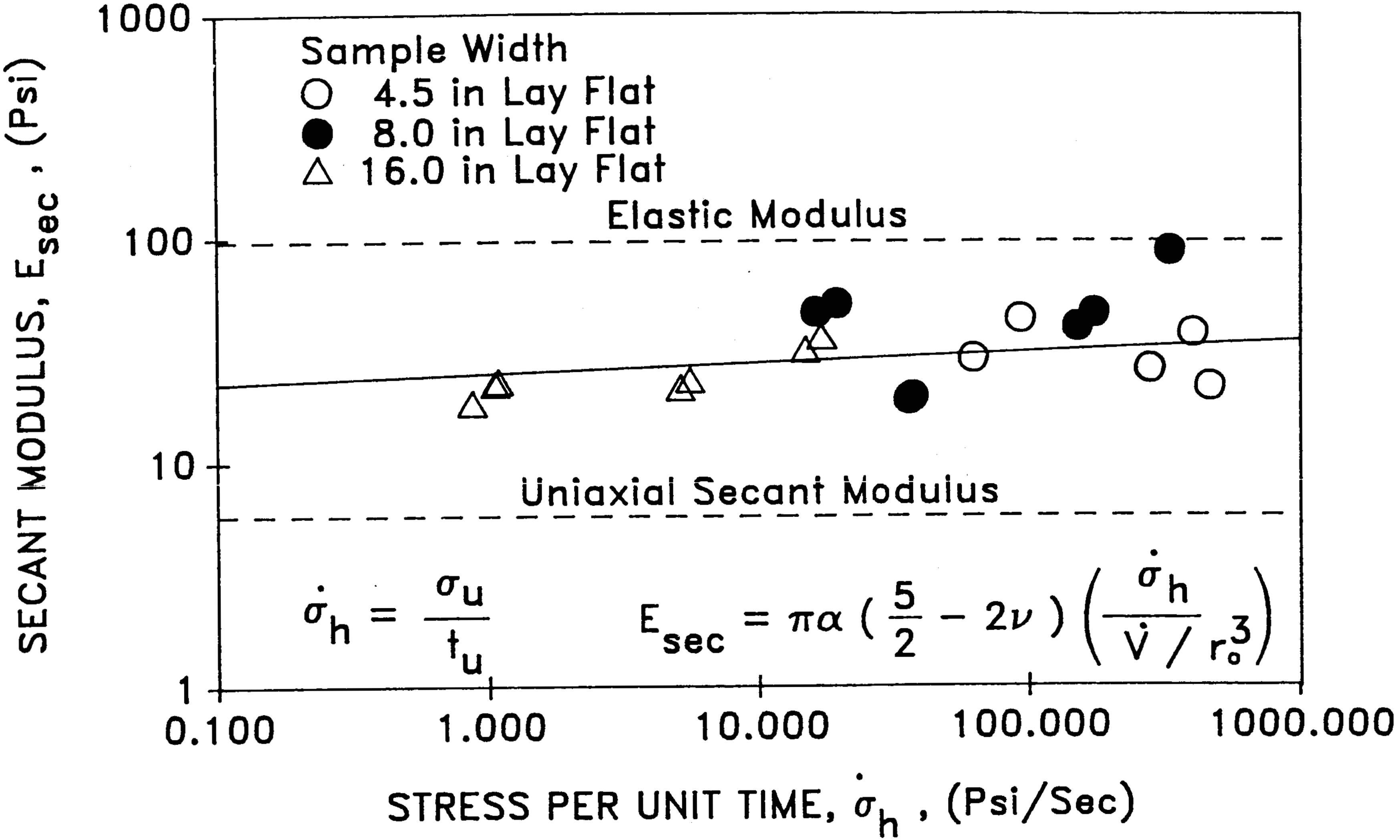


Figure 5. A compairson of Hoop Stress at Failure versus Stress Rate

F&R-F6.grf



F&R-F7A.grf

Figure 6. A comparison of the Average Modulus to Stress Rate

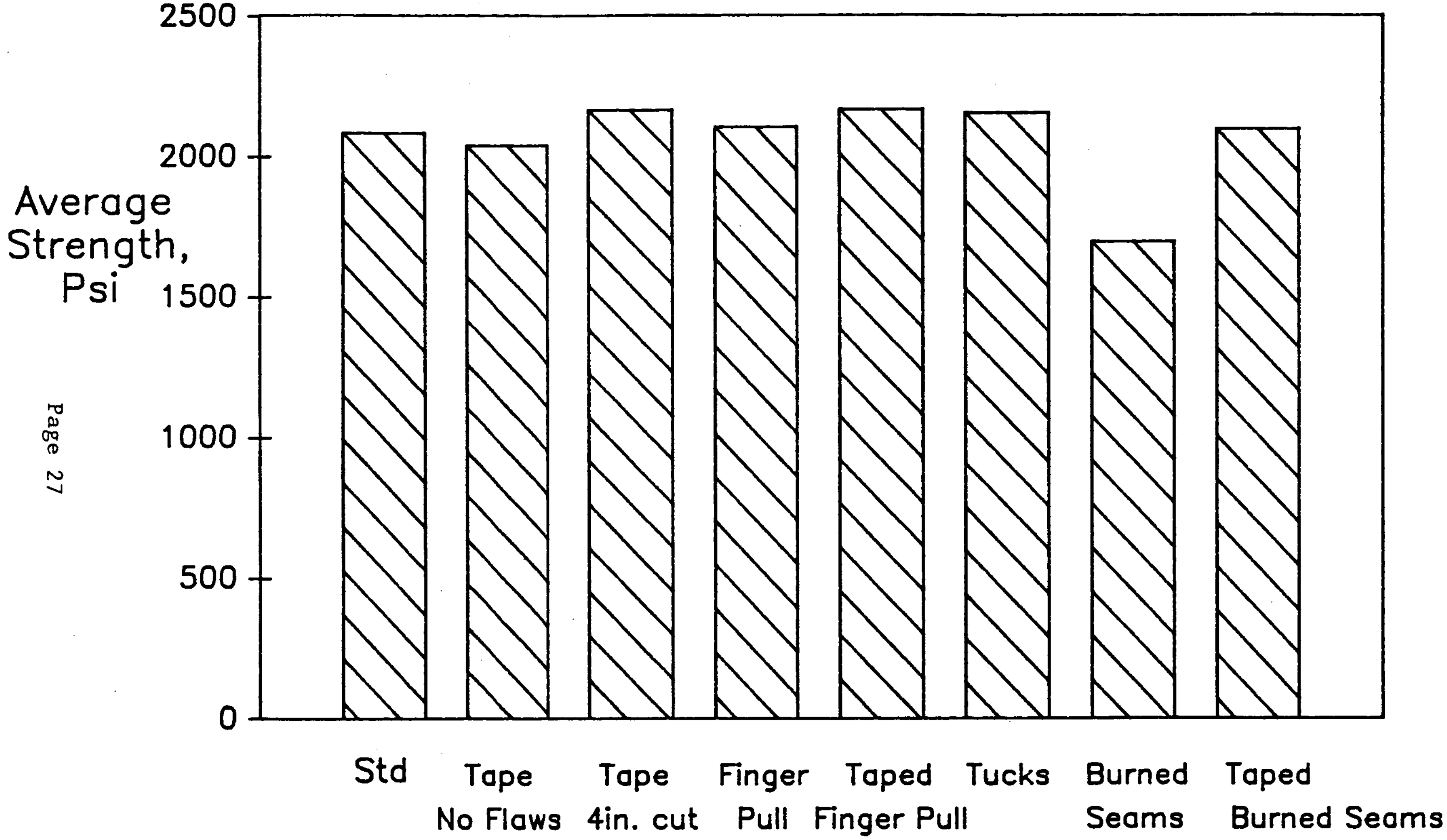


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Figure 7. A compairson of the various types of Flaws & Repairs

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16. Abstract

An investigation was conducted to study the effects of manufacture flaws and repairs in high altitude scientific balloons. A right circular cylinder was used to induce a biaxial tension-tension stress field in the polyethlene film used to manufacture these balloons. A preliminary investigation of the effect that cylinder geometry has on stress rate as a function of inflation rate was conducted. The ultimate goal of this investigation was to rank, by order of degrading effects, the flaws and repairs commonly found in current high altitude balloons.

17. Key Words (Suggested by Author(s))

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