73N18880

MECHANICALLY PRESTRESSED WINDOWS

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ABSTRACT

Microscopic cracks are present in the surface of any mechanically finished glass. Because glass does not yield, these surface cracks are the source of stress concentrations that can cause crack propagation and ultimate glass failure.

Mechanically prestressing glass, by means of placing a metal ring (in tension) around the periphery of the glass, eliminates this problem. The interference fit between the ring and the glass fixes the glass in a state of uniform compression. When the glass is subjected to a pressure loading, the compressive prestress prevents tension loading of the outer surface and, therefore, eliminates the tendency for propagation of surface imperfections.

INTRODUCTION

Spacecraft windows have been round, rectangular, triangular, flat, and curved. The glasses have been made of quartz, aluminosilicate, pyrex, leaded glass, and many other materials. Some glass has been chemically tempered, some thermally tempered, and others annealed. Many "windows" would not even be recognized as such. Telescope lenses, viewports in experiment packages, or any piece of glass that, if broken, would deplete the pressure in a habitable portion of the space vehicle must be considered windows. For example, the Skylab contains 29 such "windows."

Glass is a very strong material. Tests on fine glass fibers have indicated breaking strengths of 690 000 N/cm^2 (1 000 000 psi) or more. This is difficult to believe by anyone who has dropped a drinking glass. However, there are sound technical reasons for this apparent discrepancy. Glass develops surface flaws that may be seen easily or that may be so small as to be undetectable visually. These surface flaws are the source of stress concentrations when the surface is placed in tension and the bottoms of these slight imperfections are subjected to extremely high loads. Unlike ductile metals, glass does not yield and relieve these stress concentrations. The surface flaws propagate in a futile attempt to relieve the load and continue to propagate until rupture is complete. When glass is placed in compression, these flaws tend to close and have no tendency to grow.

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A method has been developed for mechanically prestressing glass. Glass is placed in a state of high uniform compression. Then, when the window or viewport is subjected to a pressure load, the glass bows outward and relieves some of the compression induced by the prestressing. By properly selecting the amount of preload, the glass will never be subjected to a tensile load, and the surface flaws will have no tendency to propagate.

The contributions of Clarence J. Wesselski and Charles M. Vibbart, NASA Manned Spacecraft Center, are acknowledged gratefully.

SYMBOLS

a radius

h thickness

P pressure

P_u ultimate rupture pressure

Q reaction force

ν Poisson ratio

σ_{pl} preload stress

σ_u modulus of rupture

DESIGN AND FABRICATION

Materials

For economic reasons, all developmental work has been with Pyrex glass; however, quartz will be used for flight glass. All tests on Pyrex are assumed applicable to quartz.

Mechanically prestressing glass is accomplished by placing a highly stressed metal ring around the periphery of a circular piece of window glass. The edge of the glass is polished and the corners of the glass are rounded to prevent local stresses when installing the ring.

The working temperature range required for spacecraft windows is 173.15° to 394.15° K (-100° to 121° C). This temperature range makes thermal compatibility between the glass and the ring mandatory in order to maintain uniform compression in the glass. Because the coefficient of thermal expansion of quartz is 0.56×10^{-6} $\Delta L/L/°C$, the material that was selected for the ring was an alloy of

36 percent nickel (Invar) that has a coefficient of thermal expansion of 0.50×10^{-6} $\Delta L/L/°C$. The inside diameter of the ring was ground to a 2.54×10^{-6}-centimeter (16 microinch) finish to prevent further local stresses in the glass. Invar was used in the annealed condition because only thin sections could be obtained in the cold-worked condition.

Installation

The installation of the ring on the glass may be the key to the mechanical prestressing of glass. The original intention was to install the ring by thermal expansion because the ring-material expansion rate jumps sharply at approximately 300° C. However, the ring oxidized heavily at installation temperatures, it was difficult to center the glass, and some yielding of the ring occurred caused by the load increasing as the ring contracted onto the glass while the ring was still at an elevated temperature.

The alternate method of installation is to press the ring over a tapered mandrel and then onto the glass. This method seems to be severe but no problems have been encountered when using properly prepared parts. The edge of the glass is polished, the corners of the glass are rounded, and the inside diameter of the ring is ground. The mandrel, the ring, and the glass are lubricated thoroughly with spray Teflon; then, the ring is pressed on. The forces required for installation of a 22.2-centimeter (8.75 inch) diameter ring are approximately 31 000 newtons (7000 pounds force) for sliding friction and 35 000 newtons (7900 pounds force) for static friction.

ANALYSIS

The rupture pressure of the window glass before prestressing is a function of the tensile load and the amount of time under tensile load. As was stated, the microscopic imperfections in the surface under tension propagate until failure occurs. A rigorous analysis, using fracture mechanics, is necessary to predict the test results accurately. A simple analysis will be used, omitting the time factor and assuming a simple supported edge condition. Using a modulus of rupture σ_u of 4200 N/cm^2 (6100 psi) and a Poisson ratio ν of 0.2, the ultimate rupture pressure P_u of the glass (fig. 1) is

$$P_u = \frac{8h^2 \sigma_u}{3\nu a^2\left(\frac{3}{\nu} + 1\right)}$$

$$P_u = 42.8 \text{ N/cm}^2 \text{ (62 psi)}$$

When the compression ring is added to the glass (fig. 2), the rupture pressure is increased in proportion to the amount of compression applied to the glass. When the preload (compression) equals 3110 N/cm^2 (4500 psi), σ_{pl}, the rupture pressure is

$$P_u = \frac{8h^2}{3\nu a^2\left(\frac{3}{2} + 1\right)}\left(\sigma_u + \sigma_{pl}\right)$$

$$P_u = 74.5\ \mathrm{N/cm^2}\ (108\ \mathrm{psi})$$

TEST RESULTS

Failure of the windows during hydrostatic testing is indicative of the value of prestressing. These windows have zero tension up to 27.6 N/cm^2 (40 psi) and should support this pressure indefinitely. At pressures greater than 27.6 N/cm^2 (40 psi), the outer surface goes into tension and failure becomes a function of load, time under load, humidity, and several other factors, just as with an ordinary window.

The first hydrostatic test (table I) was conducted on a window equipped with a 4340 steel ring (fig. 3). The pressure when cracking occurred was 62 N/cm^2 (90 psi) and resulted in the crack pattern shown in figure 4. In the control test on a window without a ring, the window blew out completely at a pressure of 34.5 N/cm^2 (50 psi).

The second test on a prestressed window resulted in the window cracking at a pressure of 61 N/cm^2 (88 psi); then, an attempt was made to make the window blow out. By the use of a hand pump, the pressure was raised to 83 N/cm^2 (120 psi). The window would not be blown out at this pressure and the pressure could not be increased because the leak rate was equal to the pumping rate. The third test was conducted using an electrically driven gear pump. The cracking pressure on this test was 69 N/cm^2 (100 psi) and was higher than on the previous tests because of the faster pumping rate and the amount of time under load. After the window cracked, the center of the window blew out at a pressure of 86 N/cm^2 (125 psi).

A thermal-cycle test was conducted to verify the theory that compatible thermal-expansion rates between the ring and the glass prevent the window from cracking around the edges as a result of localized stresses. The test was conducted with atmospheric pressure on one side of the window and a vacuum on the other side. The window assembly was thermally cycled from room temperature to 173.15° to 394.15° K (-100° to 121° C), and then back to room temperature. There was no trace of cracking of the glass.

CONCLUDING REMARKS

A mechanically prestressed window will maintain cabin pressure even when the glass is cracked and can withstand eight times the normal working pressure of the spacecraft before the glass will blow out. The surface imperfections that result from mechanical finishing of the glass cannot propagate and cause failure. The use of mechanically prestressed windows, that have apparently unlimited life expectancy, should make them extremely attractive for use on long-term missions. Currently, planned testing includes meteoroid-impact studies, high-mass impact (accidental bumping), and continued hydrostatic and thermal testing.

Mechanically prestressed windows for use on future spacecraft can be of the highest optical quality because glass selection and glass finishing are independent of structural considerations. A single-pane prestressed window will be superior to conventional multipane installations because it has less light-transmission loss, because it has fewer surfaces, and there is no condensation between panes. The use of prestressed windows is not limited to spacecraft; it can be used on any structure in which glass must support a pressure load (for example, underwater vessels, vacuum chambers, and airplane cabins).

DISCUSSION

R. J. Peterson:
Are you able to prestress noncircular windows?

Keathley:
We have made no attempt to prestress noncircular windows.

G. W. H. Stevens:
Are there any problems related to size and compression loads that affect the vibration responses of windows and buckling when windows are subjected to acceleration loads?

Keathley:
At this time I do not know.

TABLE I. - HYDROSTATIC TESTS ON 22.2-CM (8.75 IN.) DIAMETER WINDOW[a]

Test	Cracking pressure, N/cm^2 (psi)	Blowout pressure, N/cm^2 (psi)	Ring material and interference, mm (in.)	Compression load on glass, N/cm^2 (psi)	Comments
Control test	34.5 (50)	34.5 (50)	- -	- -	Slow pressurization
1	62.0 (90)	- -	4340 Steel 1.12 (0.044)	2880 (4180)	Did not pressurize beyond cracking
2	60.7 (88)	82.8^+ (120^+)	17-4 Stainless 0.94 (0.037)	3100 (4500)	Leak rate exceeded pumping rate at 82.8 N/cm^2
Control test	56.5 (82)	56.5 (82)	- -	- -	Very high pumping rate
3	69.0 (100)	86.3 (125)	17-4 Stainless 0.94 (0.037)	3100 (4500)	Very high pumping rate

[a]Clear-view diameter was 19.1 cm (7.5 in.) on all tests.

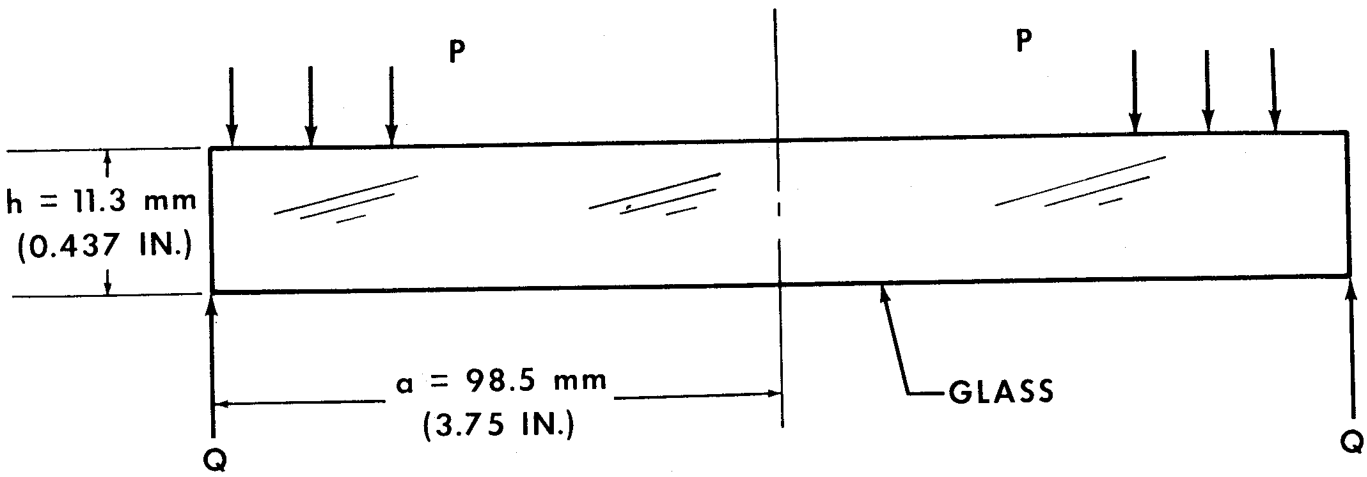

Figure 1. - Force diagram for test without compression ring.

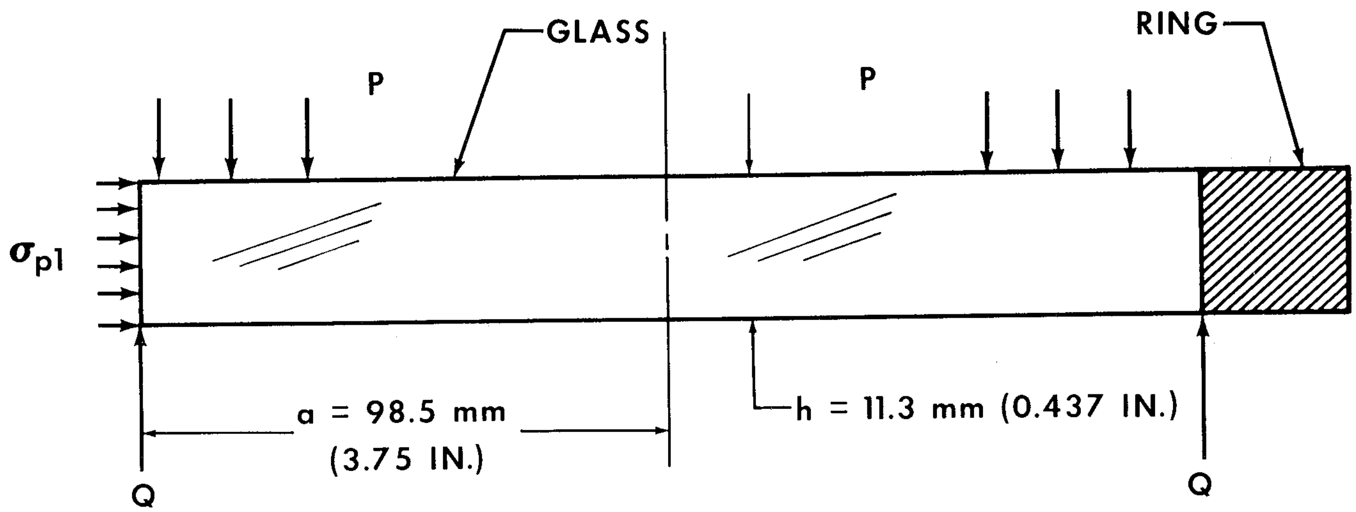

Figure 2. - Force diagram for test with compression ring.

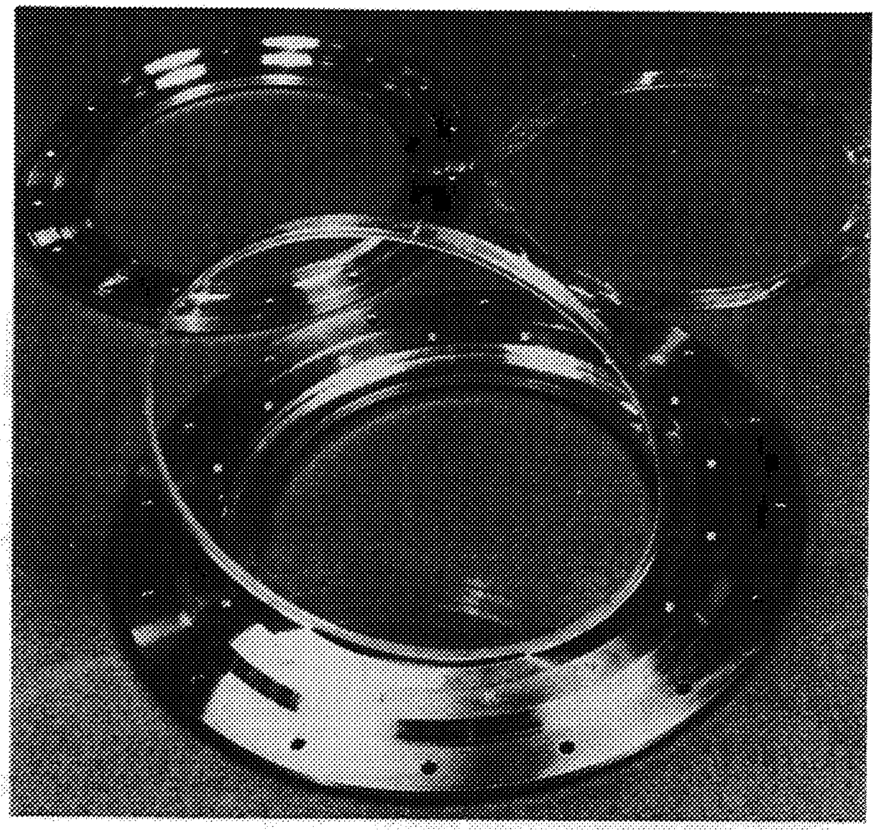

Figure 3. - Test window.

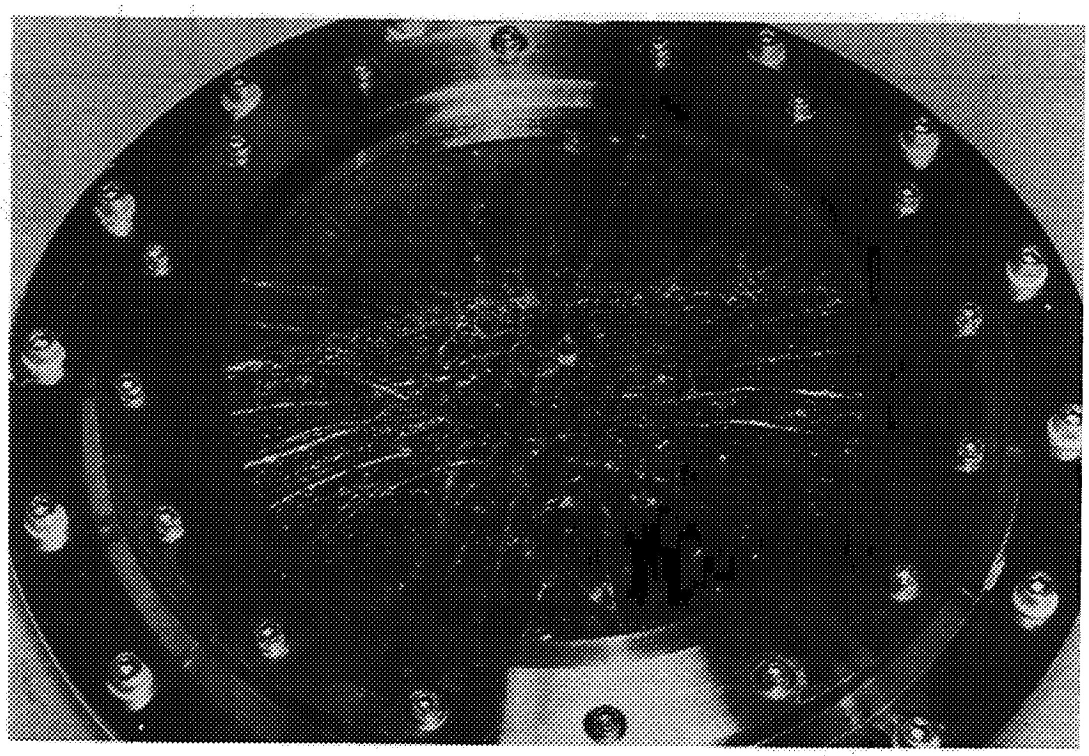

Figure 4. - Test window after failure.