

Stress Relaxation and Stiffness of 17-7PH Belleville Springs in a Stacked Configuration

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14. ABSTRACT An investigation was performed to determine the effects of parallel stacking on the stiffness and stress relaxation of 17-7PH Belleville springs. Parallel stacking refers to Belleville washers stacked with the concave side of all washers in the stack facing the same direction. Load versus displacement curves and stress relaxation data were generated for two single-disc experiments and for two double-disc, parallel stack experiments. In theory, the stiffness of a parallel stack of disc springs should be equal to the sum of the stiffness values for the individual springs. However, the measured stiffness values for the two double-disc stacks were only 73% and 85% of the respective sums for the individual discs. Spring force losses due to stress relaxation were always less than 2% for periods up to 1318 h. It was concluded that for displacement-controlled applications having stringent force requirements, spring stiffness must be measured for each disc, and load losses associated with a parallel, stacked configuration must be accounted for in the system design.										
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1. Introduction

Belleville disc springs are frequently used in mechanisms to provide forces or stored energy that is easily controlled by tightening or loosening a bolt to vary the spring deflection. Belleville discs provide the same function as compression coil springs, but can have much higher spring constants than coil springs. Thus, they are preferred for applications requiring very high forces for small spring deflections.

For any application in which a constant spring force is required for long time periods, an understanding of the stress relaxation behavior of the spring is necessary. In the mid 1990s, The Aerospace Corporation's Space Materials Laboratory conducted an investigation into the basic stress relaxation behavior of various spring materials and coil spring designs frequently used on spacecraft.^{1,2} At that time, many assembled spacecraft were being put into long-term storage to be launched and deployed at later dates than originally planned. In some instances, subsystems such as solar arrays and antenna structures were stored in their stowed configuration with deployment mechanisms fully stressed. Thus, it was critical to develop a data base on the stress relaxation behavior of spring materials in order to ensure that adequate spring force margins would be maintained for successful subsystem deployment following long-term storage.

The previous investigation did not address disc springs and was generally limited to initial stresses less than 75% of the yield stress. Disc springs have a more complex stress field than coil springs, making it difficult to predict stress relaxation within a disc spring from the simple uniaxial relaxation data obtained in the previous study.^{1,2} In addition, local stresses within a fully compressed disc spring can exceed the yield stress of the disc material.³ It is well known that stress relaxation increases as the stress level increases, particularly near or above the yield stress. Finally, two or more disc springs are frequently stacked together to achieve the desired spring force or travel distance. The effects of frictional forces and degree of misalignment within the stack on the spring constant and stress relaxation of the assembly are not available in the literature. The current study was conducted to address these issues. The specific disc material, disc design, degree of deflection, and stack configuration studied in this investigation were dictated by a specific spacecraft application. Nevertheless, the relaxation data and lessons learned regarding the effects of disc stacking on the effective spring constant are of general interest.

The objectives of this investigation were as follows.

- Determine the stress relaxation as a function of time for a single 17-7PH disc spring and stacked pair of 17-7PH disc springs compressed to specific initial loads.
- Determine the load-deflection curves for the single-disc and two-disc stacked configuration and the effects of stress relaxation on the load-deflection curves.
- Determine the effects of relative alignment between two stacked discs and disc lubrication on the load-deflection curve.

2. Experimental Procedures

2.1 Specimen Geometry

The discs used in the test series were made by National Disc Spring Division of the Rolex Company. They were fabricated from 17-7PH steel and heat treated by the supplier to the TH1050 condition. Typical room-temperature tensile strength and Young's modulus for this condition are 170 to 200 ksi and 29 Msi, respectively.⁴

The part number for the disc is AM603135. It has a nominal outside diameter (OD) of 2.360 in., an inside diameter (ID) of 1.201 in., a thickness of 0.1378 in., and a free-standing height of 0.1969 in. Figure 1 shows a sketch of the disc spring.

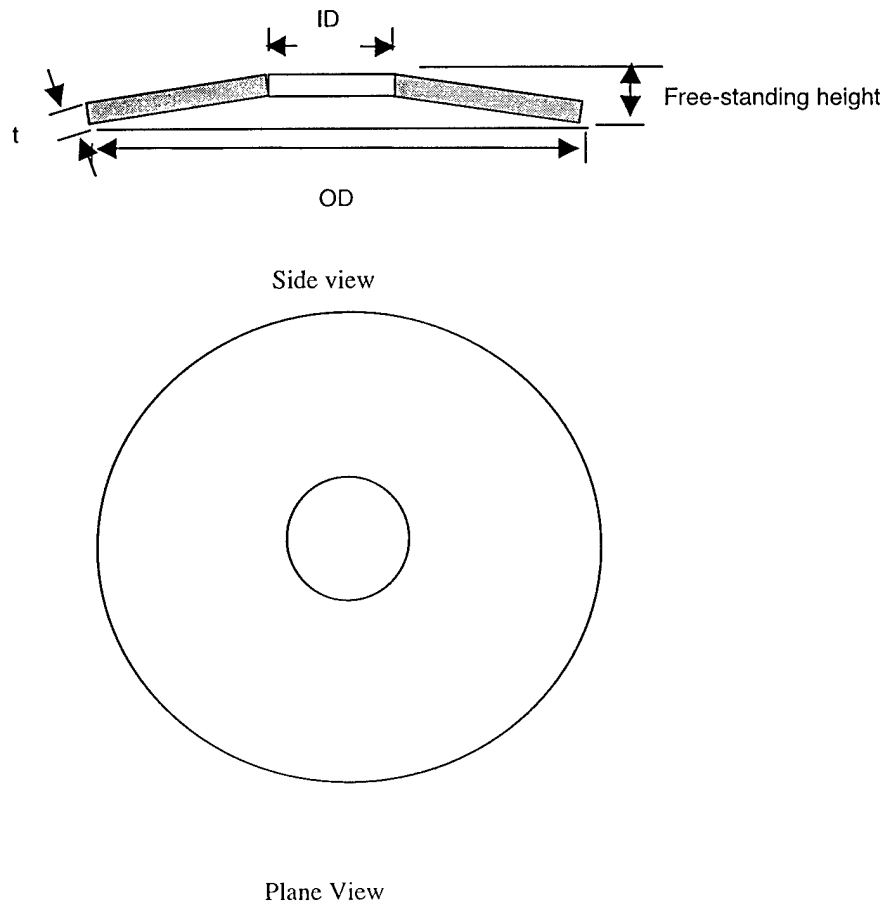


Figure 1. Sketch of Belleville springs.

2.2 Loading Conditions

Eight AM603135 Belleville disc springs were available for stress relaxation testing. Six discs were used for load deflection and stress relaxation tests. Four stress relaxation tests were conducted. Two tests were conducted on a single disc, and the other two tests were conducted on a stack of two discs. The discs were designated as 1st Single-Disc, 2nd Single-Disc, Top of 1st Double-Disc Set, Bottom of 1st Double-Disc Set, Top of 2nd Double-Disc Set, and Bottom of 2nd Double-Disc Set.

For a stack of two discs, the stiffness of the stack will depend upon the orientation of the two discs. If the two discs are mounted with the convex sides facing in opposite directions as shown in Figure 2, the total deflection will be twice the single disc deflection (Δ) for a given load (P). This corresponds to two linear springs of equal length loaded in a series configuration.

In this investigation, all double disc tests were conducted with the discs mounted with the convex sides facing in the same direction as demonstrated in Figure 3. In this configuration, the two discs behave like two linear springs of equal length loaded in parallel. When two linear springs are loaded in parallel, both springs will deform the same. At a deflection Δ , the total applied load, $2P$, is equal to $2K\Delta$, where K is the spring constant for each spring. When two discs are stack loaded in the same

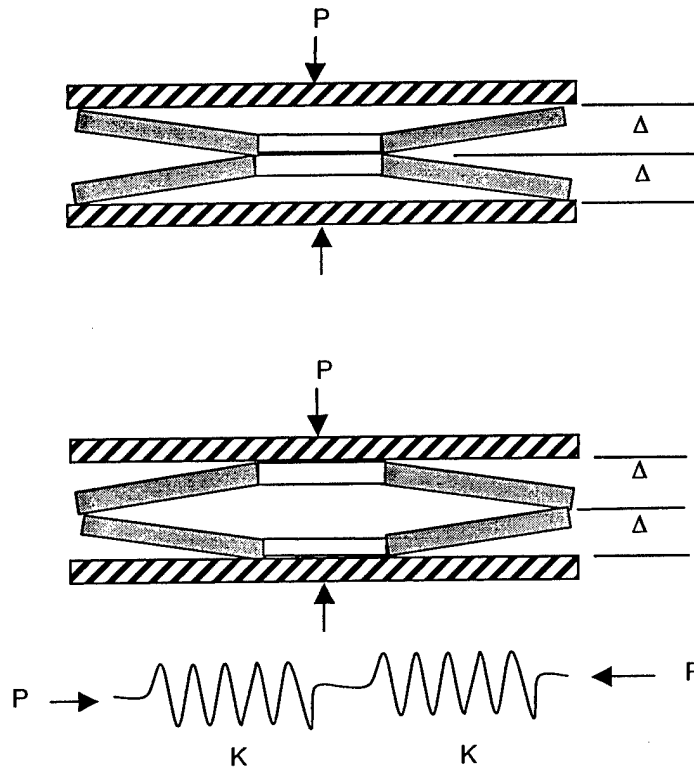


Figure 2. Illustration of Belleville discs and compression springs loaded in series.

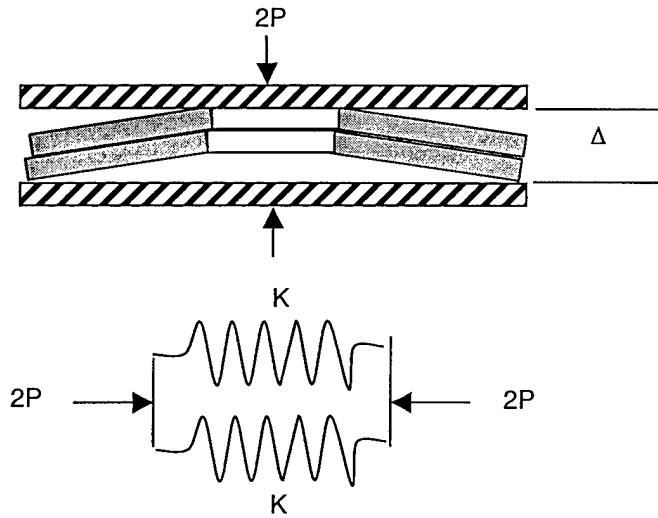


Figure 3. Illustration of Belleville discs and compression springs loaded in parallel.

convex or concave configuration, they also deflect the same. The applied load is theoretically twice the load ($2P$) required to deflect a single disc to the same deflection (Δ). If the two discs have different stiffness, the applied load is theoretically the sum of the loads (P_1 and P_2) required to deflect the individual discs to the same deflection (Δ).

2.3 Hardness Measurements

Hardness measurements were made on 5 discs for comparison with the minimum handbook hardness of 38 HRC (Rockwell C-scale Hardness).⁴ The measurements were made using a Wilson Rockwell hardness tester with a standard 150-kg load. The measurements were made on the two discs that were used for the single-disc stress relaxation tests, the two discs used for the second double-disc stress relaxation test, and one disc that was not used for load deflection or stress relaxation testing.

2.4 Stress Relaxation Test Fixture Design and Assembly

A sketch of the test fixture assembly for performing stress relaxation tests is depicted in Figure 4. Two identical fixtures were designed and fabricated to enable two stress relaxation tests to be performed concurrently. Since the objective of the test series was to obtain load relaxation data for the Belleville discs, the test fixtures were required to have high stiffness and very low stress when the Belleville discs were deformed to the peak loads. The low stress in the test fixture ensured that there was very low or un-measurable relaxation within the fixture so that all measured load relaxation could be attributed to the disc specimens.

The threaded base plate, the spring washer retainer disc, and the loading disc were made from 17-4PH steel. The loading bolts were made from quenched and tempered 4340 steel. In addition to high yield strengths, these materials were selected because they have similar coefficients of thermal expansion.

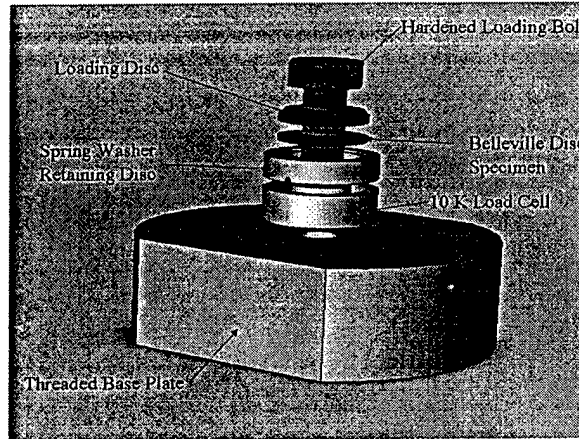


Figure 4. Sketch of stress relaxation test assembly.

Although the stress relaxation tests were conducted in a constant-temperature environment set for 23°C (73.4°F) to minimize thermal expansion effects, the choice of materials helped to ensure constant deflection of the disc specimens throughout the duration of the stress relaxation tests.

The threaded based plate had an OD of 9.5 in., an ID of 3.0 in., and a height of 3.0 in. The base plate was flattened to a width of 8.50 in. in one direction so it could be fitted between two parallel aluminum rails anchored on top of a floating table. The rails prevented the base plate from rotating during torque application to the loading bolt when spring loading the disc specimen.

The bolt was nominally 4.5-in. long by 1.15-in. diameter. The bolt can take a minimum load of 300 kips without yielding. Since this load is more than 35 times of the maximum applied load to the Belleville disc specimen, the amount of the relaxation from the bolt is considered to be negligible. Figure 5 depicts the assembly with a disc specimen in place.

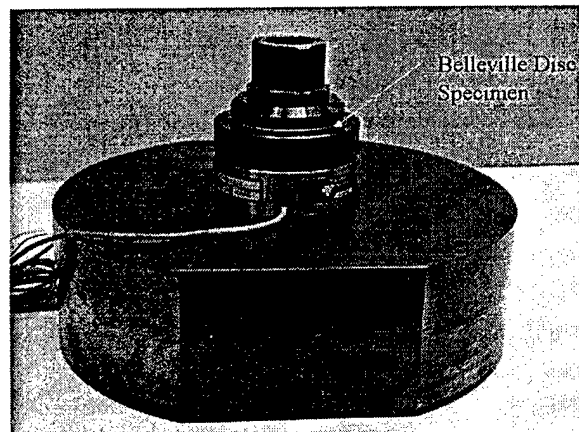


Figure 5. Photograph of test assembly with a disc specimen.

2.5 Instrumentation and Data Acquisition

Two sets of 10,000-lb load cells, fabricated by Transducer Techniques[®], were purchased for the testing. The load cells are of a pan-cake shape and have a center recess with a diameter of 2.425 in. for accepting specimens. This configuration fits the specimen dimension very well. During operation, the load cells are excited with 10 V DC. The output is fed into the data acquisition system of a PC through a Wheatstone bridge such as a strain gage conditioner.

Linear-voltage-displacement-transformers (LVDTs) were used to measure the displacement-time history between the top of the spring washer retainer disc and the loading disc (ref. Fig. 5). Two LVDTs monitored the relative displacement as a function of time between these two points. This displacement represents the amount of deformation of the Belleville disc specimen and should remain constant throughout the stress relaxation test after the initial spring loading of the disc.

Other instrumentation included a Sensotec strip chart and a temperature/humidity recorder. The former recorded both the temperature and the humidity of the laboratory, and the latter recorded only the temperature of the testing laboratory with higher accuracy.

The primary data acquired for the stress relaxation tests included load and displacement as functions of time. The load-time histories were acquired using the Transducer Techniques[®] load cell with a load range of 0 to 10,000 lb. The data were recorded using a 12-bit A-to-D converter card and Lab-View[®] software. Data were recorded at 10 points per second for the initial 30 min of testing. After 30 min, the rate was changed to 1 point per minute. Calibration tests were conducted to verify the load-voltage conversion factors provided by the load-cell manufacturer. The displacement-time and load-time data were analyzed by the use of either the EXCEL or the IGOR program.

2.6 Test Fixture for Load-Deflection Measurements

Each Belleville disc specimen for the stress relaxation tests was first tested to characterize its load vs. normal displacement relationship. The direction of the applied load and the measured displacement are shown in Figure 6. Figure 7 shows the overall loading system along with the instrumentation, and Figure 8 shows a close-up of the specimen and load cell. A 1.5-in.-dia by 6.3-in.-long rod made of stainless steel was used to transmit the load from the loading frame to the top of the disc. A LVDT was mounted to measure the vertical movement of the loading frame. The recorded displacement includes the deflection sum of the steel rod, and the disc spring. The former can be calculated using the applied load, diameter and length of the rod, and the Young's modulus of steel. The measured disc

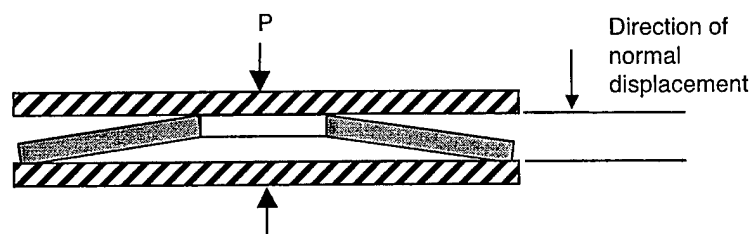


Figure 6. Sketch of load vs. normal displacement testing.

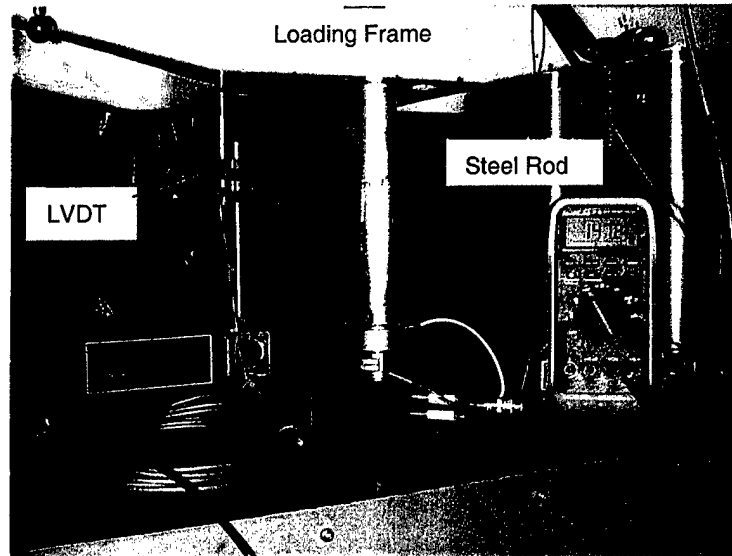


Figure 7. Photograph of test set-up and instrumentation for disc specimen load-displacement measurements.

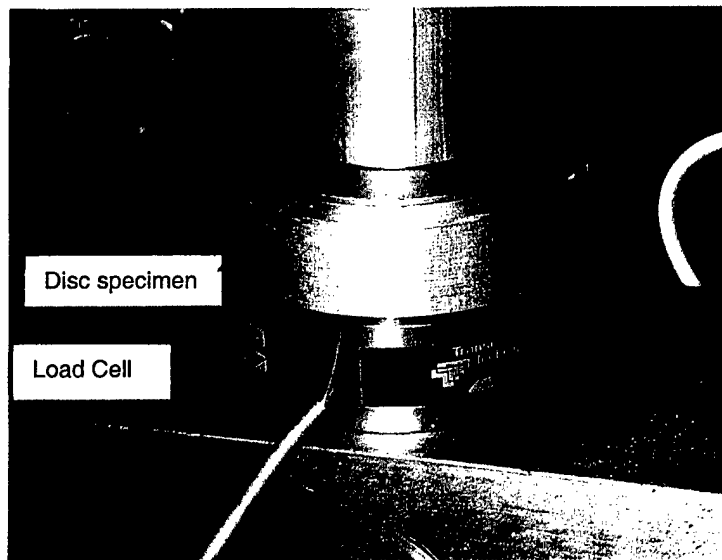


Figure 8. Photograph showing relative positions of disc specimen and load cell for load-displacement measurements.

spring deflection vs. load was obtained by subtracting the calculated rod displacement from the measured total displacement. Both the load and the total deflection were fed electronically to a data acquisition system.

2.7 Load Cell Calibration

Both Transducer Techniques load cells (S/N 152976 and 152977) were calibrated using an in-house Instron testing machine. Plots of transducer output voltage vs. load are shown in Figures 9 and 10. The recorded voltage-to-load ratio was approximately 5% higher than the vendor-provided calibration factor for S/N 152976 cell and 7% lower than the vendor-provided calibration factor for S/N 152977.

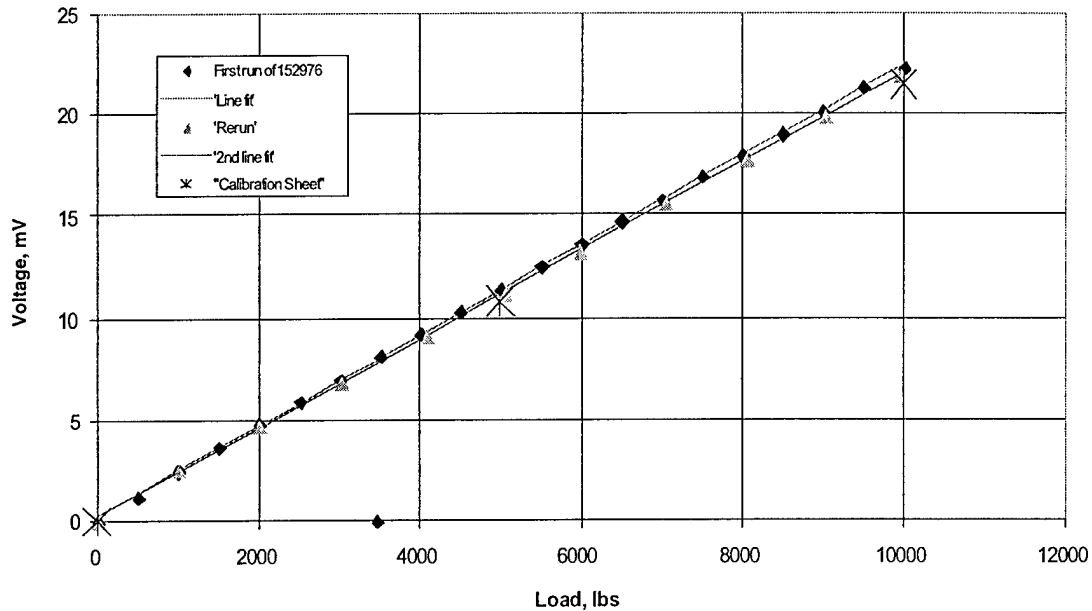


Figure 9. Calibration curve for load cell S/N 152976.

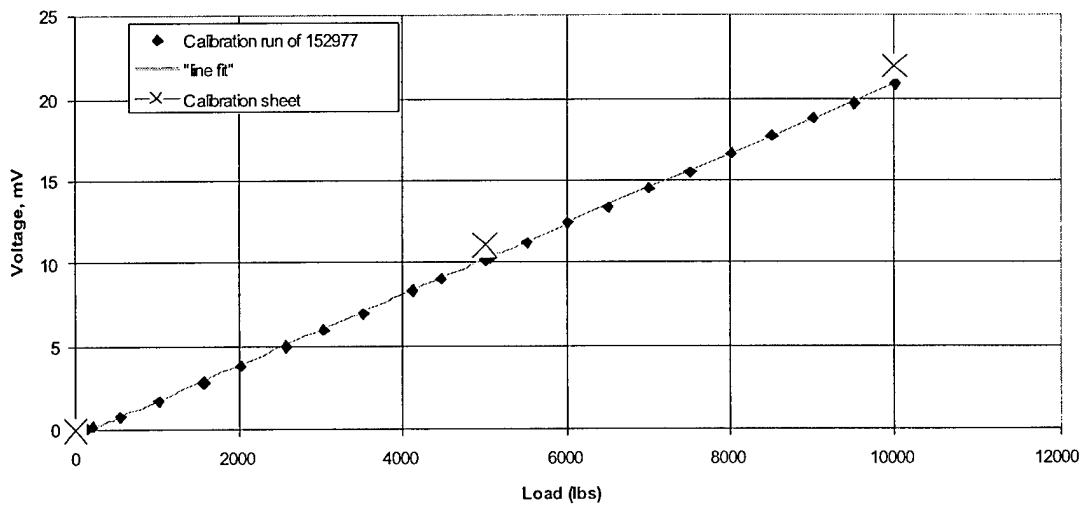


Figure 10. Calibration curve for load cell S/N 152977.

3. Results and Discussion

3.1 Hardness Measurements

The results of hardness measurements on five discs are summarized in Table 1. Four of the discs, 1st Single, 2nd Single, Bottom of 2nd Double-Disc Set, and Top of 2nd Double-Disc Set, were used in the stress relaxation and load deflection tests. The other disc for hardness measurements was not used for any other testing. The hardness of all five discs exceeded the minimum hardness requirement, 38 HRC, for the TH1050 heat treatment. However, it is apparent that the 1st Single and 2nd Single discs had lower hardness values than the other three discs. Subsequent to these measurements, it was learned that the as-received discs were from two separate lots that were purchased at different times. Acceptance testing by the contractor providing the discs indicated that the discs from one of the lots had lower stiffness values than discs from the other lot. It is shown in Subsection 3.2.1 that the 1st Single and 2nd Single discs had lower stiffness values than discs for the 1st and 2nd Double-Disc Sets. It is assumed that the discs used in the single-disc stress relaxation tests were from one lot and those used in the double-disc sets were from the other lot.

Table 1. Rockwell C Hardness of 17-7PH Discs

Disc	Hardness Values, HRC	Average Hardness, HRC
1 st Single	47.0, 46.1, 46.5	46.5
2 nd Single	47.2, 47.0	47.1
Top 2 nd Double-Disc Set	48.3, 48.7	48.5
Bottom 2 nd Double-Disc Set	49.1, 49.8	49.5
Untested	49.0, 48.7, 49.0	48.9

3.2 Load-Deflection Measurements

3.2.1 Pre-test Load-Deflection Curves for Stress Relaxation Discs

Before the stress relaxation tests, each disc was first loaded in a single-disc configuration as shown in Figures 6–8 to measure the load-deflection relationship. The two sets of double discs were also loaded in the stacked configuration after the individual measurements. There was no lubricant used between the top and bottom discs, and the alignment between the two discs was random as explained in Section 3.2.2. The double-disc sets were loaded to a peak load of 6900 lb, and the single discs were loaded to 3450 lb. These loads were selected based on the requirements of a specific application. Figures 11 and 12 depict the corresponding load vs. displacement curves for the 1st and 2nd sets of double discs. The curves for the 1st Single and 2nd Single discs are plotted in Figures 13 and 14, respectively.

An examination of all the load-displacement curves led to several observations. First, the six single-disc load-displacement curves suggest that non-linearity may exist. Data for the top and bottom discs for the 1st Double-Disc Set and for the 1st Single-Disc and 2nd Single-Disc show non-linear load-

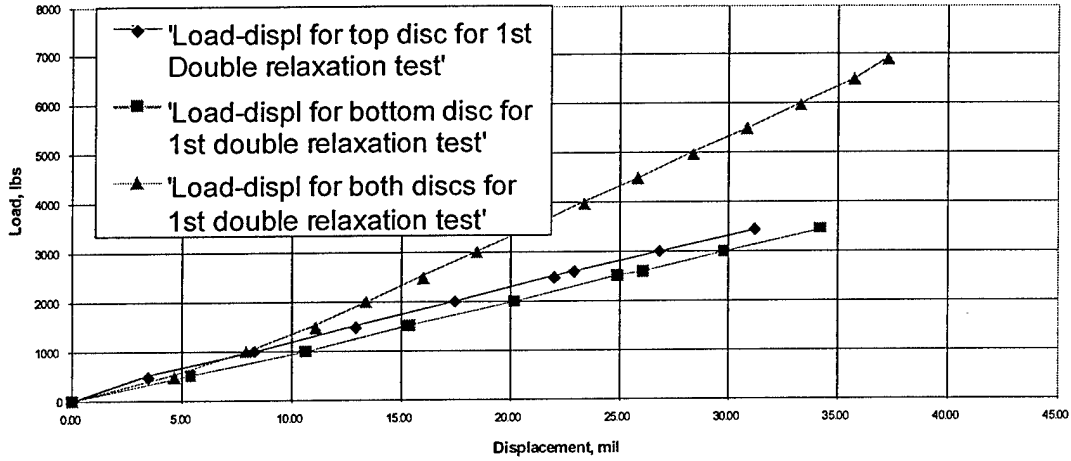


Figure 11. Pre-test load vs. displacement curves for 1st Double-Disc Set.

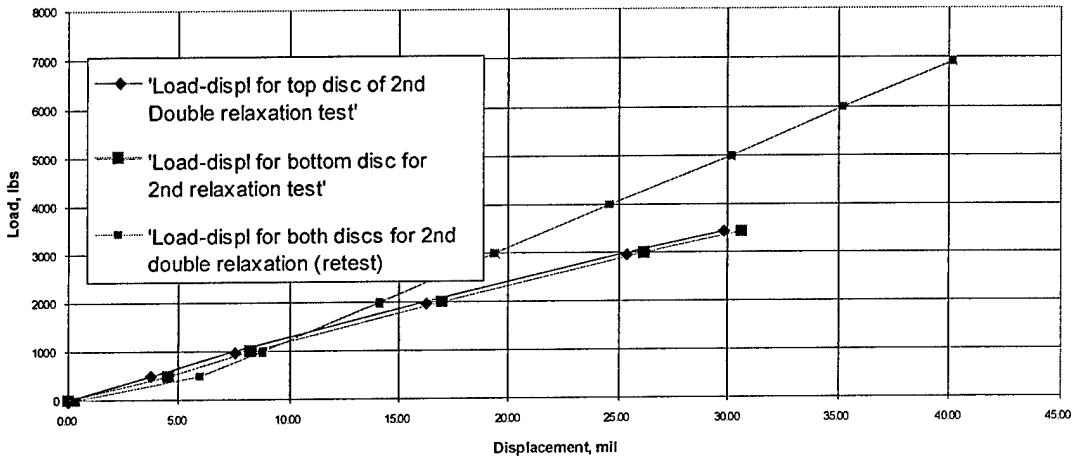


Figure 12. Pre-test load vs. displacement curves for 2nd Double Disc Set.

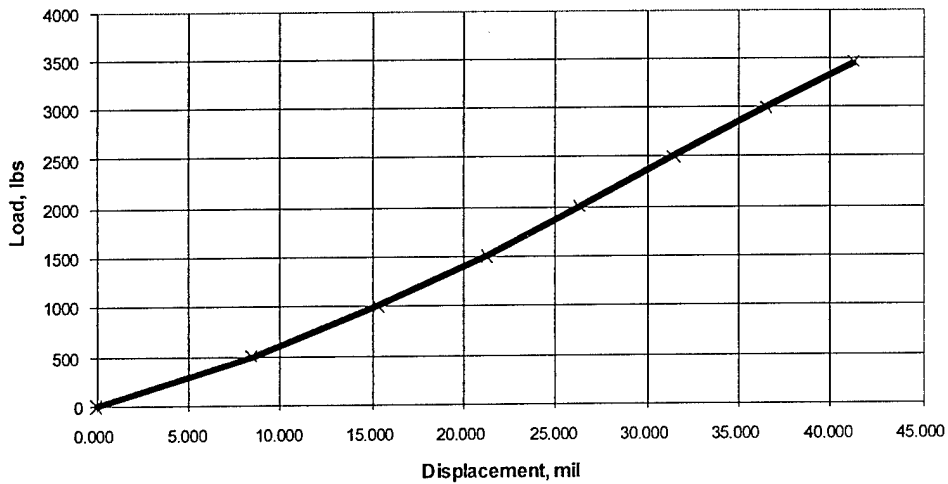


Figure 13. Load vs. displacement curve for 1st Single Disc.

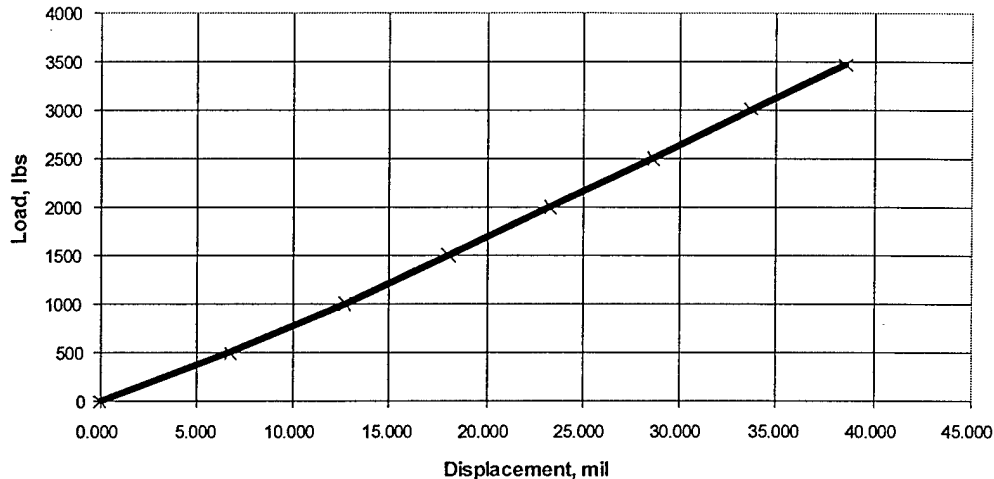


Figure 14. Load vs. displacement curve for 2nd Single Disc.

displacement curves at loads between 0 and approximately 1000 lb. Secondly, large variations in disc stiffness exist among different discs. Table 2 shows load values for all six single-disc load-deflection tests for displacements of 30 and 35 mils. For the two singles, the measured stiffness was low. At a displacement of 30 mils, the measured loads were 2400 lb for the 1st Single-Disc and 2640 lb for 2nd Single-Disc. Meanwhile, the loads for the top and bottom disc of the double-disc sets varied from 3020 to 3480 lb at a displacement of 30 mils. Thus, the loads for the 1st and 2nd single discs were up to 31% lower than for the discs used in the double-disc sets. As discussed above, the single-disc specimens were probably from a different lot than the double-disc specimens. If we concentrate our attention only on the top and bottom discs for the double-disc sets, the loads were more consistent. For these four discs, the maximum load variation was 13% at displacements of 30 and 35 mils.

In addition, it was observed that the slope of the load-deflection curve for a stacked condition was not twice that of a single-disc specimen. The curves were nonlinear with shallow slopes for displacements up to approximately 10 mils (\approx 1000 lb), but became linear with significantly higher slopes at higher displacements. The stiffness values of the discs (slope of the curves in the linear region) were

Table 2. Load Values at Two Displacement Levels for Single and Stacked Configurations

Load Condition	Displacement value (mil)	Top Load (lb)	Bottom Load (lb)	Stacked Load (lb)
1 st Double-Disc Set	30	3340	3020	5340
	35	3860 (est.)	3540 (est.)	6360
2 nd Double-Disc Set	30	3480	3400	4980
	35	4010 (est.)	3920 (est.)	5970
1 st Single	30	2400	NA	NA
	35	2850	NA	NA
2 nd Single	30	2640	NA	NA
	35	3130	NA	NA

111, 101, and 206 kip/in for the top disc, bottom disc, and stack, respectively, for the 1st Double-Disc Set. Stiffness values for the 2nd Double Disc Set were 116, 113, and 188 kip/in for the top disc, bottom disc, and stack, respectively. The stiffness ratio between the stacked configuration and the average stiffness of the individual discs was 1.94 for the 1st Double-Disc Set and 1.64 for the 2nd Double-Disc Set. Examination of the mating surfaces of both sets, indicated that they had only limited contact. We can postulate that only one of the two discs was effectively loaded at small displacements. As the displacement was increased, the two surfaces had more contact, and both discs were loaded, but not to the point that one would predict from the individual disc tests. This explains why the initial slope of the load-deflection curve was very low. Thus, due to the imperfect surface mating between the two discs in a parallel stack, the stiffness of a double-disc stack is less than twice the stiffness of a single disc. Or, if the two single discs have different stiffness, less than the sum of the stiffness values for the two single discs.

3.2.2 Effects of Lubricant and Alignment on Load-Deflection Curves for Stacked Discs

Tests were also conducted on the 1st Double-Disc Set in the stacked configuration to investigate the effects of lubrication and alignment between the top and bottom discs on the load-deflection curves. MoS₂ dry lubricant was used. The test conditions were: no lubricant/random alignment, lubricant/random alignment, no lubricant/careful alignment, and lubricant/careful alignment. The term “alignment” refers to the degree of alignment between the outside diameter of the top and bottom discs. Figures 15 through 18 depict the load-displacement curves for these four conditions.

Regardless of the lubrication and alignment conditions, the curves were always nonlinear for displacements up to approximately 10 mils (\cong 1000 lb), but were linear for higher displacements. In addition, the curves always exhibited considerable hysteresis between the loading and unloading curves. Thus, the effective stiffness of the stacked configuration was always higher during loading than for unloading. The measured spring forces at displacements of 31 and 36 mils are tabulated for

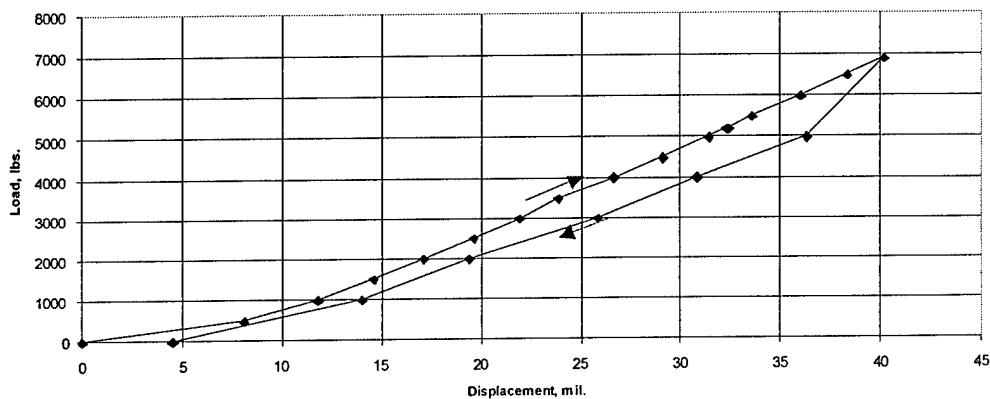


Figure 15. Load vs. displacement curve for “no lubricant/random alignment” condition for stacked configuration.

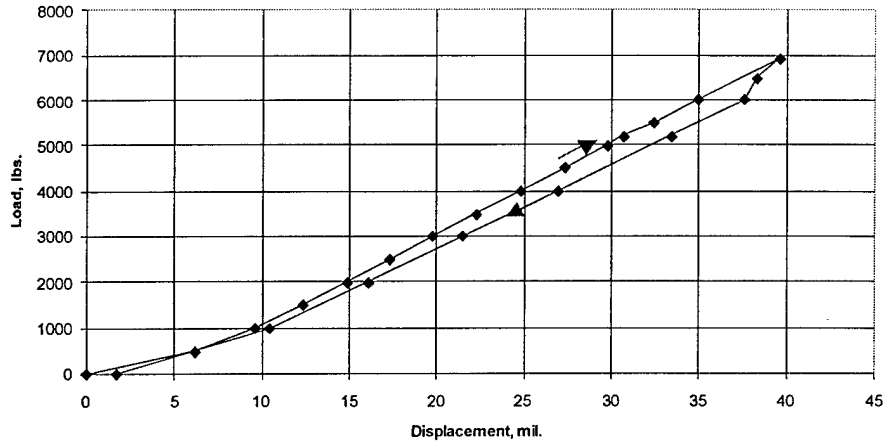


Figure 16. Load vs. displacement curve for "MoS₂ lubricant/random alignment" condition for stacked configuration.

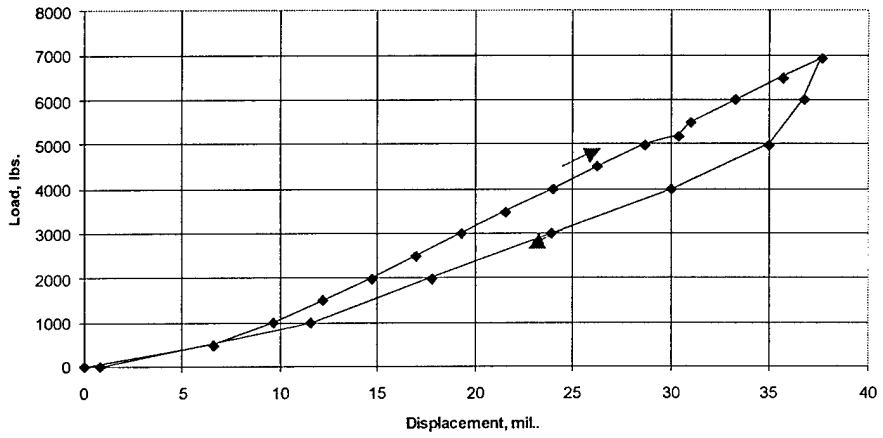


Figure 17. Load vs. displacement curve for "no lubricant/careful alignment" condition for stacked configuration.

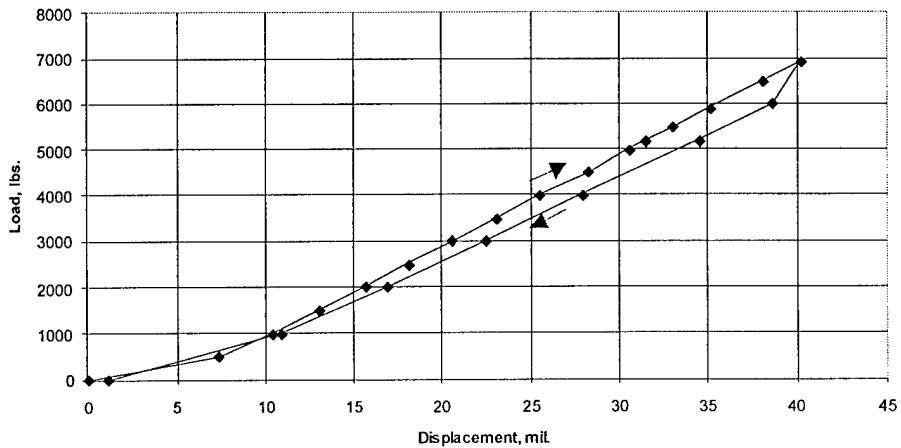


Figure 18. Load vs. displacement curve for "MoS₂ lubricant/careful alignment" condition for stacked configuration.

the four test cases in Table 3. Although the measured loads varied by around 10% at both displacement values, there were no systematic trends in the data. The loads for the extreme cases, no lubricant/random alignment and MoS₂/careful alignment, were within 2% of one another at both displacements in the table.

Table 3. Load Values at Two Displacement Levels for Stacked Configuration with Various Lubrication and Alignment Conditions.

Test Case	Lubricant Used	Alignment Condition	Load at 31- mil Displacement (lb)	Load at 36-mil Displacement (lb)
1	No	Random	5000	6000
2	MoS ₂	Random	5558	6216
3	No	Careful	5517	6584
4	MoS ₂	Careful	5095	6083

3.3 Stress Relaxation Tests

The stress relaxation tests were conducted by torquing the nut of the hardened loading bolt while monitoring the voltage output from the load cell transducer. The bolt was torqued until an initial load equal to the maximum anticipated service load, 6900 for the double-disc sets and 3450 lb for the single discs was achieved. The double-disc stress relaxation tests were conducted with no lubricant and random alignment between discs. The temperature of the laboratory was set at 23°C (73.4°F), and the humidity was set at 50%. This environmental condition was maintained by a Liebert air-conditioning control unit.

Prior to the Belleville disc stress relaxation tests, a relaxation test was conducted on the fixture without installing a specimen. The loading bolt was torqued to an initial load of 6874 lb, and the load was monitored as a function of time as it would be in a disc stress relaxation test. After 215 h, there was no measured load drop. Therefore, it was concluded that there was no stress relaxation of the test fixture, and any measured relaxation in the disc tests could be attributed entirely to the Belleville discs.

The first 1st Double-Disc Set was loaded to an initial load of 6948 lb. The test was conducted for a total of 1318 h. The load vs. time history in a semi-log format is plotted in Figure 19. The linear-scale plot for the same data is shown in Figure 20. The load decreased by 1.67% over the course of the 1318-h test. It is apparent from the linear curve that a significant fraction of the relaxation occurred within the first 200 h. The output of the LVDTs verified that the deflection of the disc specimens was maintained at a constant value throughout this test and all subsequent stress relaxation tests.

The 2nd Double-Disc Set was loaded to 6938 lb, as indicated in Figure 21. The load was applied following the same procedure used for the first set. Based upon the results of the first test and previous experience with 17-7PH compression springs, the test duration was reduced to 187 h for the second set. The load reduction for the 1st Double-Disc Set at 187 h was 0.72% compared with 0.59% for the 2nd Double-Disc Set. Thus, excellent correlation was achieved in the results for the two double-disc tests. Very low stress relaxation rates were measured for the 17-7PH Belleville discs.

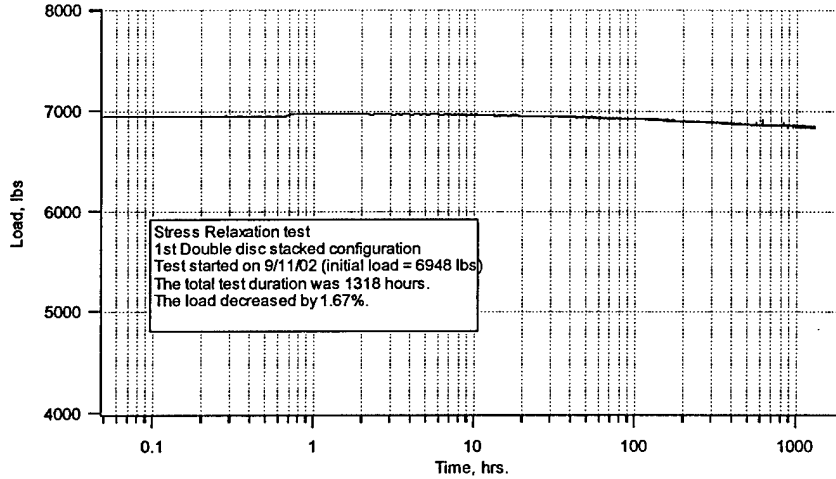


Figure 19. Semi-log plot of load relaxation data for 1st Double-Disc Set.

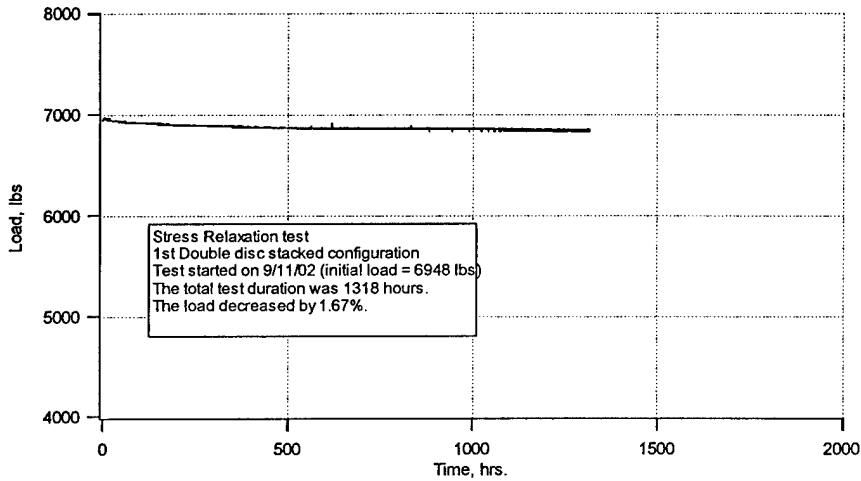


Figure 20. Load relaxation plot for 1st Double-Disc Set.

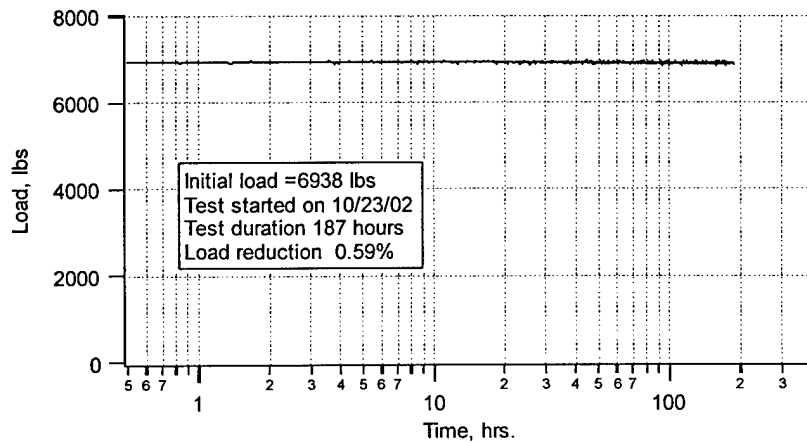


Figure 21. Semi-log plot of load relaxation data for 2nd Double-Disc Set.

The Stress relaxation data for the 1st Single-Disc and 2nd Single-Disc tests are presented in Figures 22 and 23, respectively. The 1st Single-Disc was loaded to an initial load of 3824 lb and was tested for 286 h. The relaxation was 2% at the end of the test. The 2nd Single-Disc was loaded to 3545 lb. The test was conducted for 258 h with a load reduction of approximately 0.4%. The 1st Single-Disc had the highest stress relaxation of the four tests. However, the initial load for this test exceeded the target load of 3450 lb by 11%. Thus, the stress level was significantly higher for this disc than for the discs in the other single-disc and double-disc tests.

Unidirectional stress relaxation data on 17-7PH wires loaded to approximately 75% of the yield stress in the previous study had load reductions of approximately 0.8% after 200 h and 1% after 1,000 h. It is difficult to make direct comparisons between the wire data and disc data due to the complicated

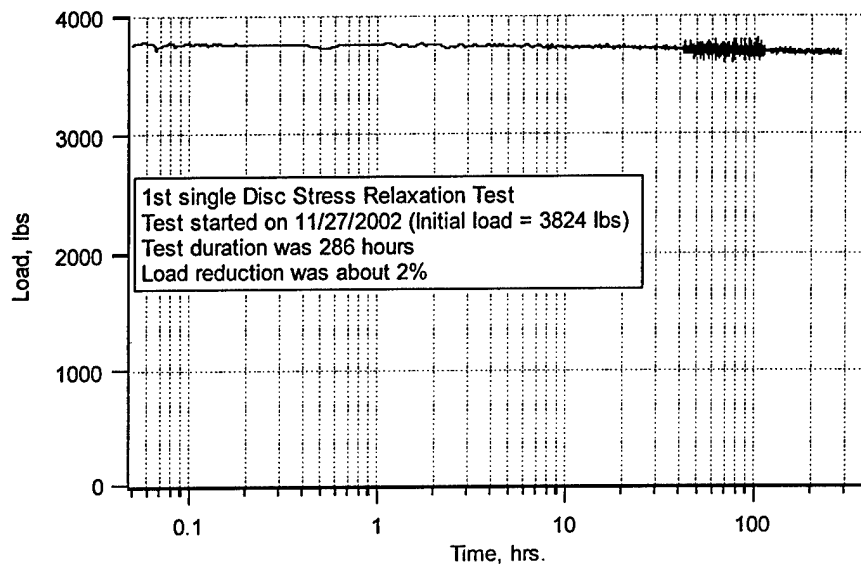


Figure 22. Semi-log plot of load relaxation data for 1st Single.

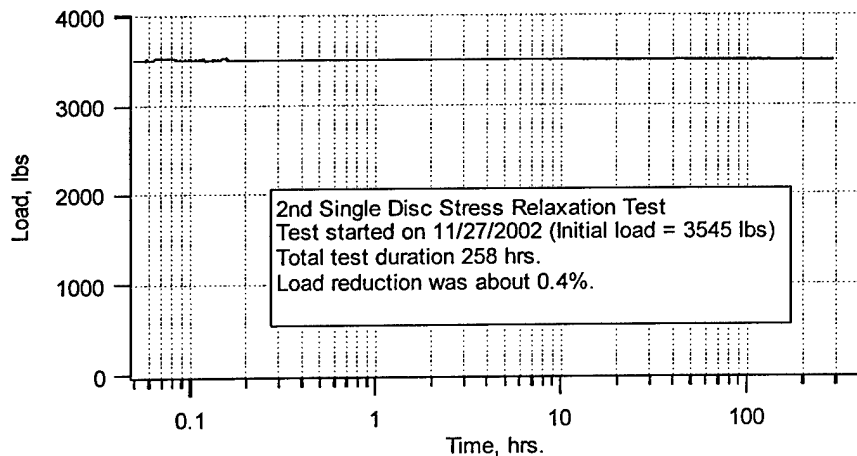


Figure 23. Semi-log plot of load relaxation data for 2nd Single.

stress state in a compressed disc. However, it can be shown from the equations in Ref. 3 that the peak stresses in the discs were on the order of 160 ksi for the double-disc tests and the 2nd Single-Disc and 190 ksi for the 1st Single-Disc. 17-7PH TH1050 has a typical yield strength of 180 ksi. Therefore, with the peak stresses in the discs at or above the yield stress, it is not surprising that the stress relaxation rates were higher than the earlier measurements. Considering the high stress levels, the measured stress relaxation was very low for all four tests.

3.4 Post-test Load-Deflection Curves for Stress Relaxation Discs

All six discs, i.e., two sets of double-discs and two single discs, were retested to characterize their load vs. displacement relationship after the stress relaxation tests were completed. The purpose of these tests was to determine any effects of the stress relaxation tests on the stiffness of the discs. The tests were conducted identically to the pre-test load-displacement tests.

The load vs. displacement curves for the 1st and 2nd Double-Disc Sets following the stress relaxation tests are shown in Figures 24 and 25. The loads at 30 and 35 mils displacement for the individual discs were comparable to the pre-relaxation data for the two top discs. However, much to our surprise, the loads at 30 and 35 mils displacement for the bottom discs were reduced by 20% for first set and 25% for the second set relative to the pre-relaxation values. The post-relaxation load-deflection curves in the stacked configuration showed an 18% load reduction at 30 mils displacement for the 1st Double-Disc Set, but no significant change for the 2nd Double-Disc Set.

Close comparison of the pre-relaxation curves (Figures 11 and 12) with the post-relaxation curves (Figures 24 and 25) indicates that a significant portion of the apparent stiffness changes for the bottom discs was associated with the nonlinear deformation at low displacements. The post-relaxation curves had lower initial slopes. The displacement required to achieve a load of 1000 lb increased from 10.6 mils pre-relaxation to 15 mils post-relaxation for the bottom disc of the 1st Double-Disc Set and from 8.4 mils pre-relaxation to 14.5 mils post-relaxation for the bottom disc of the 2nd Double-Disc Set. A calculation of the slope of the load-displacement curves between 1000 and 3450 lb, reveals that the disc stiffness over this load range decreased from 104 kip/in. pre-relaxation to 98 kip/in. post-relaxation for the bottom disc of the 1st Double-Disc Set and from 111 kip/in. pre-

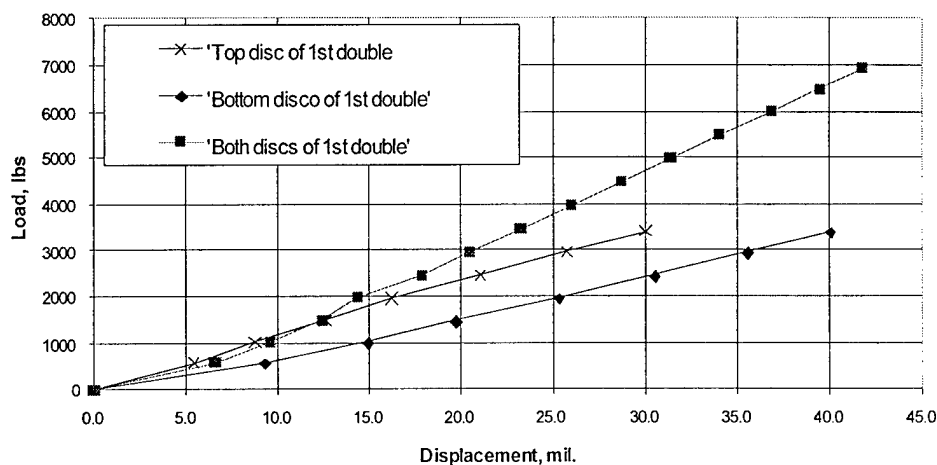


Figure 24. Post-relaxation load vs. displacement for 1st Double-Disc Set.

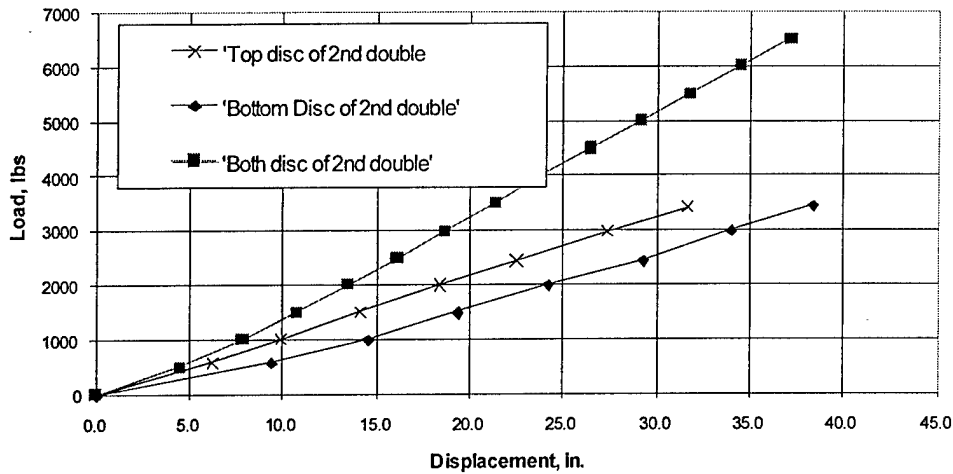


Figure 25. Post-relaxation load vs. displacement for 2nd Double-Disc Set.

relaxation to 103 kip/in. post-relaxation for the bottom disc of the 2nd Double-Disc Set. Thus, whereas the load reduction at 30 and 35 mils displacement was 20–25% lower after the stress relaxation tests, the slope of the load-displacements curves was only 5–10% lower over the linear portion of the curves.

Since it was observed that the two bottom discs had the lowest stiffness values after the stress relaxation tests, a test with these two discs in a parallel stack was conducted so that their load displacement curve could be compared with those for the 1st and 2nd Double-Disc Sets. The curve is shown in Figure 26. In this test, the bottom disc from the 1st Double-Disc Set was put on top and the bottom disc from the 2nd Double-Disc Set was put on bottom. This set of discs clearly had a lower stiffness than 1st Double-Disc and 2nd Double-Disc Sets. A displacement of 45 mil was required to reach a load of 6900 lb versus around 42 mil for the 1st Double-Disc Set and 39 mils for the 2nd Double-Disc Set.

The post-relaxation load vs. displacement curves for the 1st Single-Disc and 2nd Single-Disc are plotted in Figures 27 and 28, respectively. Comparing the data in these figures with the pre-test curves

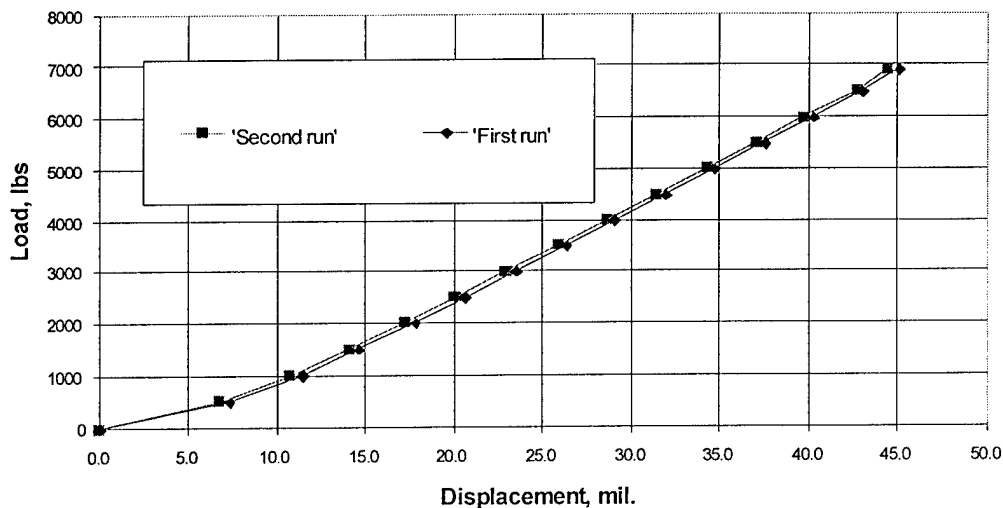


Figure 26. Post-relaxation load vs. displacement for bottom discs from 1st and 2nd Double-Disc Sets.

(Figures 13 and 14), indicates that the displacement required to reach a load of 3450 lb was approximately 41 mils for the 1st Single-Disc for both the pre-relaxation and post-relaxation tests. For the 2nd Single-Disc, the displacement to reach 3450 lb increased from 39 mils in the pre-relaxation test to 42 mils in the post-relaxation tests. Thus, the 1st Single-Disc, which had the largest stress relaxation, showed no change in stiffness, while the 2nd Single-Disc, which had the lowest stress relaxation, apparently had a significant reduction in stiffness following the relaxation test. These differences can be partially attributed to the initial nonlinear portion of the curve, which may be indicative of alignment issues. However, the slope of the curve between 1000 and 3450 lb for the 2nd Single-Disc decreased from approximately 94.6 kip/in. for the pre-relaxation test to 89.7 kip/in. for the post-relaxation test, indicating a 5% reduction in stiffness. Thus, the post-relaxation stiffness change for the 2nd Single-Disc was similar to that measured for the bottom discs of the 1st and 2nd Double-Discs Sets.

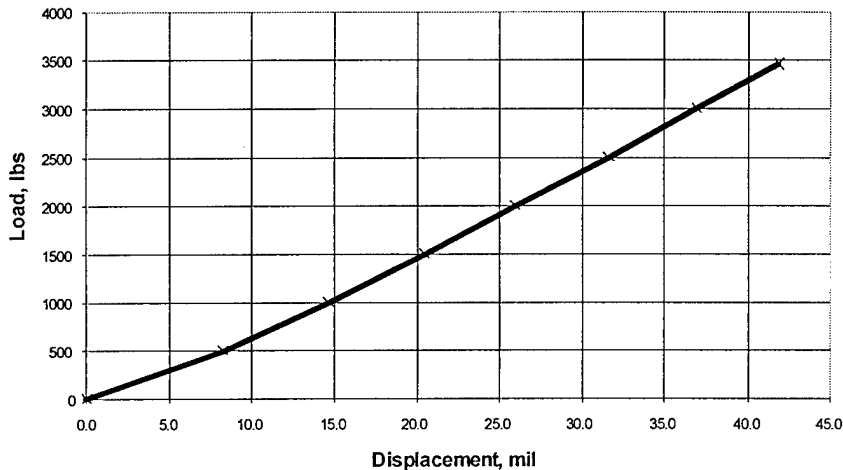


Figure 27. Post-relaxation load vs. displacement curve for 1st Single-Disc.

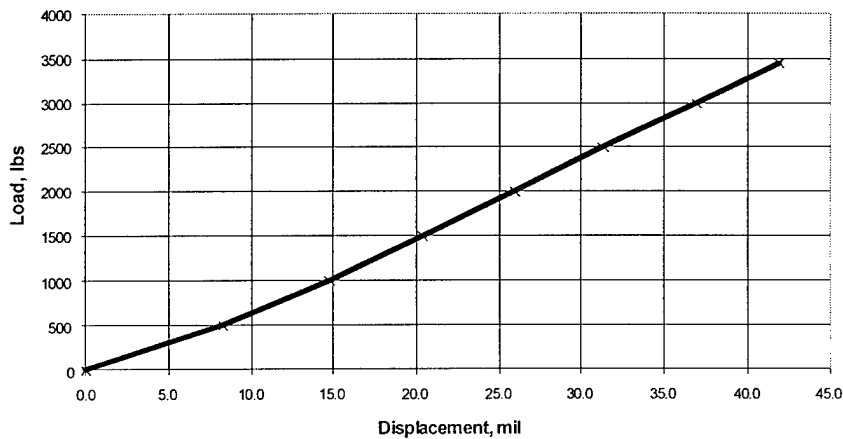


Figure 28. Post-relaxation load vs. displacement curve for 2nd Single-Disc.

3.5 Effective Spring Constants for Double-Disc Sets

The spring forces at 30- and 35-mil displacements for the individual discs and the stacked discs from the pre-relaxation and post-relaxation load deflection tests on the double-disc sets are summarized in Table 4. The table also includes the sum of the forces from the individual tests on the top and bottom discs and the ratio of the stacked to summed forces. For perfect contact and alignment between the two discs in a parallel stack, the stacked/sum ratio should be 1. Therefore, the stacked/sum ratio readily shows the efficiency of the double-disc stack in delivering the spring forces of the individual discs. For four of the five double-disc sets, the stacked discs delivered 82–88% of the force predicted by summing the loads from the individual disc tests. The exception was the pre-relaxation test for the 2nd Double-Disc Set, which had only 72 and 75% of the predicted loads at 30- and 35-mil displacements, respectively.

Effective spring constants can be calculated from the data in Table 4 by dividing the measured loads by the displacements. The effective spring constants are given in Table 5. These are referred to as

Table 4. Spring Forces from Double-Disc Load-Displacement Tests

Belleville Washer Identification	Top	Bottom	Sum	Stacked	Stacked/Sum
Load at 0.030 in. Displacement, lb					
First Double Disc Set, Pre-Relaxation	3340	3020	6360	5340	0.84
First Double Disc Set, Post-Relaxation	3400	2400	5800	4800	0.83
Second Double Disc Set, Pre-Relaxation	3480	3400	6880	4980	0.72
Second Double Disc Set, Post-Relaxation	3300	2600	5900	5200	0.88
Bottom Discs, Post-Relaxation	2400	2600	5000	4200	0.84
Load at 0.035 in. Displacement, lb					
First Double Disc Set, Pre-Relaxation	3860	3540	7400	6360	0.86
First Double Disc Set, Post-Relaxation	3950	2900	6850	5650	0.82
Second Double Disc Set, Pre-Relaxation	4010	3920	7930	5970	0.75
Second Double Disc Set, Post-Relaxation	3800	3100	6900	6100	0.88
Bottom Discs, Post-Relaxation	2900	3100	6000	5100	0.85

Table 5. Effective Spring Constants from Double-Disc Load-Displacement Tests

Belleville Washer Identification	Top	Bottom	Sum	Stacked	Stacked/Sum
Spring Constant at 0.030 in. Displacement, kip/in					
First Double Disc Set, Pre-Relaxation	111	101	212	178	0.84
First Double Disc Set, Post-Relaxation	113	80	193	160	0.83
Second Double Disc Set, Pre-Relaxation	116	113	229	166	0.72
Second Double Disc Set, Post-Relaxation	110	87	197	173	0.88
Bottom Discs, Post-Relaxation	80	87	167	140	0.84
Spring Constant at 0.035 in. Displacement, kip/in					
First Double Disc Set, Pre-Relaxation	110	101	211	182	0.86
First Double Disc Set, Post-Relaxation	113	83	196	161	0.82
Second Double Disc Set, Pre-Relaxation	115	112	227	171	0.75
Second Double Disc Set, Post-Relaxation	109	89	198	174	0.88
Bottom Discs, Post-Relaxation	83	89	172	146	0.85

“effective” spring constants because they are only valid at displacements of 30 and 35 mil due to the initial nonlinearity in the load-displacement curves.

3.6 Free-Height Measurements

Free-height measurements were made on the discs used in the stress relaxation tests and are presented in Table 6. Compared with the specified free height of 0.1969 in., the deviations were from -0.0030 to $+0.0041$ in. These deviations correspond to a range from -1.5 to $+2.1\%$ with a maximum variation of 3.6% . Assuming the discs for the 1st Single and 2nd Single were from a different lot than the disc used in the double-disc sets, the variation was 2.9% for the double-disc lot and 0.5% for the single-disc lot. We believe that the lower stiffness of the single-disc lot can probably be attributed to the greater free height. Although this lot also had a slightly lower hardness than the double-disc lot (Table 1), the hardness variation is indicative of a lower yield strength, but not a lower elastic modulus. Thus, within the elastic range of the disc spring, hardness variations should not affect stiffness.

For most of the discs, the free-height measurements were made before and after the stress relaxation tests. Two of the disc showed a slight increase in free height after the relaxation test, and the other two showed a slight decrease. The changes were less than 1% for three of the four discs and only 2.6% for the other disc (top of 2nd double-disc set). These variations are probably within the scatter band of the measurement technique.

Table 6. Free Height Measurements for Stress Relaxation Specimens

Disc ID	Pre-relaxation Free Height (in.)	Post-relaxation Free Height (in.)
Top 1 st Double Disc Set		0.19695
Bottom 1 st Double Disc Set		0.19680
Top 2 nd Double Disc Set	0.19960	0.19435
Bottom 2 nd Double Disc Set	0.19390	0.19395
1 st Single	0.20095	0.20003
2 nd Single	0.20035	0.20048

4. Summary and Conclusions

Several observations were made from an evaluation of all of the test data.

- All of the load vs. displacement curves for the Belleville springs were non-linear at displacements less than approximately 10 mil. The degree of non-linearity was more pronounced for the double-disc stacks than for the single-disc tests. All of the load-displacement curves were linear for displacements greater than approximately 10 mil.
- The 1st Single-Disc and 2nd Single-Disc had free heights that were typically 2.5% greater than those for discs tested in the double-disc sets. Furthermore, the spring force at 30 or 35 mil displacement was up to 31% lower for the single-disc specimens. This may be compared to variations in spring force of 15% among the double-disc specimens and 10% among the single-disc specimens. It was concluded that the single-disc specimens were from a different lot than the double-disc specimens. It follows that significant variations in spring stiffness were measured within each lot, and lot-to-lot variations were even higher. Therefore, for displacement-controlled applications having stringent force requirements, spring stiffness must be measured for each disc to ensure that the required force is achieved.
- The load-displacement data demonstrate that the attainable spring force at a given displacement for a double-disc, parallel stack is not equal to the sum of the spring forces measured for the individual discs. The ratio of the stacked force to the sum of the single-disc forces was about 85% for the 1st Double-Disc Set and 73% for the 2nd Double-Disc Set. The load reduction illustrates that stacked Belleville disc springs do not behave exactly like compression springs in a parallel configuration. The load path of the stacked discs is complicated. It is believed that the matching of the contour of the contact surfaces is very important. Therefore, for displacement-controlled applications having stringent force requirements, the load losses associated with a parallel, stacked configuration must be accounted for in the system design.
- All double-disc tests performed in this investigation used discs from the same lot with similar free heights. It is anticipated that the ratio of the stacked force to the sum of the single-disc forces may be significantly lower than the values reported if the two discs have different free-heights.
- Stress relaxation is a less significant issue than factors affecting disc stiffness. For the double-disc stress relaxation tests, the load reduction was less than 2% after 1318 h. This load loss is small relative to the 15% variations in spring stiffness measured for individual discs from a single lot and the load losses of 12–28% associated with parallel disc stacks.

- This testing program provided significant data on the stiffness and stress relaxation of stacked Belleville springs that are currently unavailable in the technical literature.

References

1. W. D. Hanna, D. J. Chang, and G. L. Steckel, "Stress Relaxation in Spring Materials," *Proceedings of 32nd Aerospace Mechanisms Conference*, NASA Conference Publication No. NASA/CP-1998-207191, Cocoa Beach, FL, May 1998, pp. 125–140.
2. D. J. Chang, "Prediction of Stress Relaxation for Compression and Torsion Springs," Aerospace Report No. TR-96(8565)-1, November 1, 1995.
3. B. J. Almen and A. Laszlo, "The Uniform-Section Disc Spring," *Transactions of ASME*, RP-58-10, May 1936, pp. 305–314.
4. Aerospace Structural Metals Handbook, Vol. 2, 37th Edition, CINDA/USAF CRD Handbooks Operation, Purdue University, 2001.

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