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## FATIGUE OF GRAPHITE/EPOXY BUFFER STRIP PANELS WITH CENTER CRACKS

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## SUMMARY

The effects of fatigue loading on the behavior of graphite/epoxy panels with either S-Glass or Kevlar-49 buffer strips were studied. Buffer strip panels were fatigued and tested in tension to measure their residual strength with crack-like damage. Panels were made with  $[45/0/-45/90]_{2S}$  layup with either S-Glass or Kevlar-49 buffer strip material. The buffer strips were parallel to the loading direction and were made by replacing narrow strips of the 0-degree graphite plies with strips of either 0-degree S-Glass/epoxy or Kevlar-49/epoxy on a one-for-one basis.

The panels were subjected to a fatigue loading spectrum, MINITWIST, the shortened version of the standardized load program for the wing lower surface of a transport aircraft. Two levels of maximum strain were used in the spectrum with three durations of the fatigue spectrum. One group of panels were preloaded prior to the application of the fatigue cycling. The preload consisted of statically loading the specimen in tension until the crack-tip damage zone reached the adjacent buffer strips. After fatigue loading, all specimens were statically loaded in tension to failure to determine their residual strengths.

The residual strengths of the panels were not affected by the fatigue loading, with or without preload. The stiffnesses of the specimens were not significantly changed by the fatigue loading. Also, the buffer strips arrested the cracks and increased the residual strengths significantly over those of plain laminates without buffer strips.

## INTRODUCTION

The high strength-to-weight and stiffness-to-weight ratios of advanced fiber-reinforced composites, such as graphite/epoxy, make them one of the outstanding primary structural materials in the aeronautical and automotive industries. Despite many efforts in the past to understand their mechanical performance, there still remain important technical questions to be answered before extensive use of composite materials will occur. One such question concerns the long-term mechanical performance under fatigue loading. When subjected to fatigue loading, composites can exhibit several modes of damage including delamination, fiber failure and matrix cracking. Such damage can lead to changes in the elastic properties of the laminate.

In static tests, the buffer strip configuration has been shown to greatly improve the damage tolerance of graphite/epoxy panels subjected to tension loads (ref. 1). The buffer strips act to contain the damage and result in much higher residual strengths for cracked or damaged panels. In ref. 1, the fractures in the buffer strip panels were shown to initiate at approximately the failing strain of a plain sheet, run into the buffer strips and stop. The load was increased and the panels eventually failed at strains higher than those at which the fractures initiated and at which the plain laminate would have failed.

The purpose of the present investigation is to study the effect of fatigue loading on the behavior of graphite/epoxy buffer strip panels. Accordingly, graphite/epoxy buffer strip panels were subjected to a fatigue spectrum loading and then tested in tension to determine their residual strengths. Some panels were statically preloaded in tension prior to the application of the fatigue loading. Each panel was cut in the center to represent damage. Panels were periodically radiographed and crack-opening-displacements were measured to

indicate specimen stiffness and the extent of damage at the crack tips. One layup was used,  $[45/0/-45/90]_{2s}$ , with two different buffer strip materials: S-Glass and Kevlar-49. The buffer strips were made by replacing narrow strips of the 0-degree graphite plies with strips of the 0-degree buffer material on a one-for-one basis.

The residual strengths of the fatigued panels are compared to the residual strength of a buffer strip panel without preload or spectrum loading and to the strength of a graphite/epoxy panel without buffer strips. Comparisons were made for both buffer materials under a variety of test conditions. Specimen stiffness and any crack-tip damage were periodically measured during the fatigue cycling.

## EXPERIMENTAL PROCEDURES

### Materials and Specimens

The specimens were made with T300/5208 graphite/epoxy in a 16-ply quasi-isotropic layup,  $[45/0/-45/90]_{2s}$ . Each panel had four evenly spaced buffer strips parallel to the load direction. The specimen configuration is shown in figure 1. The buffer strips were made from two different materials: S-Glass/5208 or Kevlar-49/5208 tape. All the panels were 102 mm wide constructed with 5-mm-wide buffer strips spaced 20 mm apart, with slits 10 mm long and 0.020 ( $\pm 0.002$ ) mm wide cut in the center of the panel to represent damage (see fig. 1). The buffer strips were made by replacing narrow strips of the 0-degree graphite plies with strips of either 0-degree S-Glass or Kevlar-49 on a one-for-one basis.

## Test Procedures and Equipment

The panels were tested under a fatigue spectrum loading. MINITWIST (ref. 2), the shortened version of the standardized load program for the wing lower surface of a transport aircraft, was chosen to provide a realistic load history for the specimens. The complete MINITWIST spectrum contains 4000 flights with each flight consisting of about 15 load cycles on average. The maximum load in the MINITWIST spectrum is seen only once. The tests were run at approximately 5 Hz.

Tables I and II show the test matrices that were used for the panels containing the S-Glass and Kevlar-49 buffer strips, respectively. Each group of panels made with the S-Glass or the Kevlar-49 buffer strip material was divided into two subsets: in one set, the spectrum loading only was applied to the specimens; in the other set, the specimens were preloaded in tension before the spectrum loading was applied. The preload consisted of statically loading the specimen in tension until the crack-tip damage zone reached the adjacent buffer strips. This point was determined using the crack-opening-displacement versus load data and the X-ray images. After the fatigue loading, all specimens were statically loaded in tension to failure to determine their residual strength. Within each set, three different durations of the spectrum loading were used. Each duration consists of the designated number of continuous repetitions (as shown in tables I or II) of the MINITWIST spectrum. Additionally, two values of the maximum strain level in the spectrum were used. An average strain of 0.005 is generally used as the ultimate strain in wing panels (ref. 3); thus, the values of 0.005 and 0.006 were chosen as two realistic values of ultimate strain for an actual structure. The corresponding values of maximum strain that were

used in the MINITWIST spectrum were 0.0035 and 0.0042. Guide plates were mounted on the specimens during the fatigue loading to prevent compression buckling during the air-ground-air cycle of the MINITWIST spectrum.

Periodically during the fatigue cycling in all tests, the spectrum loading was stopped and the specimen was statically loaded in tension to the prescribed level of maximum strain. During these static load segments, load versus remote strain, load versus strain in the buffer strip next to the crack tip and load versus crack-opening-displacement (COD) were recorded. The specimen strains were measured using strain gages located on the panels as indicated in fig. 1. The COD was measured using a ring gage. Also after the static load segments, the specimens were radiographed using a dye-penetrant to enhance the image of any existing damage. These data were used to determine if the fatigue loading had produced any change in the specimen stiffness (as measured by the slope of the load-strain curves or the load-COD curves) or resulted in any damage growth at the crack tip.

## RESULTS AND DISCUSSION

Tables I and II show the residual strengths and the maximum strains of the panels for each test condition for the S-Glass and Kevlar-49 buffer strip panels, respectively.

Figures 2 and 3 show the residual strengths for all the S-Glass buffer strip panels. Also shown in both the figures are the residual strengths of a S-Glass buffer strip panel with the same configuration and a graphite/epoxy panel with no buffer strips. The panel with no buffer strips had a crack equal in length to the buffer strip spacing of the other panels. Both these specimen

were loaded to failure in tension with neither preloading nor spectrum loading and both specimens were made at the same time and from the same batch of material as the rest of the panels.

For the specimens subjected to spectrum loading only, figure 2 shows that neither the level of the maximum strain nor the number of repetitions of the MINITWIST spectrum had a significant effect on the residual strength of the S-Glass buffer strip panels. Figure 3 shows that preloading the buffer strip panels and then applying the spectrum loading also did not significantly affect the residual strength. Also, in all of the panels, the failing stresses are much higher than for a similar graphite/epoxy panel without buffer strips; thus, the fractures were arrested by the buffer strips.

Figures 4 and 5 show similar results for the residual strengths of the buffer strip panels with the Kevlar-49 buffer material. The static tensile strength of a panel with Kevlar-49 buffer strips is also shown as well as the static strength of a similar panel without buffer strips. Again, these panels were made from the same batch of material as the rest of the panels. Figure 4 shows the residual strengths for the panels subjected to the spectrum loading only while figure 5 shows the results for the panels with preload and spectrum loading. As was the case with the S-Glass buffer strip panels, the fatigue load had little effect on the residual strengths of the panels with the Kevlar-49 buffer strips with or without the preload and the buffer strips arrested the cracks.

These observations were also confirmed by the load-strain and COD-load plots made periodically during the fatigue cycles. Figures 6 and 7 show a set of typical plots that were used to monitor the specimen stiffness and the damage state at the crack tips. Figure 6 shows the series of strain versus load plots while figure 7 shows the COD versus load plots. These plots were made for a



specimen that was subjected to three repetitions of the MINITWIST spectrum with a maximum strain of 0.0042. One repetition of the MINITWIST spectrum simulates 4000 flights for a transport wing structure and during the normal MINITWIST cycle, the maximum load is applied only once. As shown in the figure, data was plotted before the spectrum loading began (0 flights) then the fatigue cycling was stopped and data was plotted after 1 repetition (4000 flights), after 2 repetitions (8000 flights), after 2 1/2 repetitions (10000 flights), after 2 3/4 repetitions (11000 flights) and after 3 repetitions (12000 flights) of the spectrum. In this test program, each buffer strip panel was loaded to the maximum load level during every periodic plot such as those shown in figures 6 and 7. This means that the maximum load level was applied several more times than called for in the MINITWIST spectrum itself. For the results shown in figures 6 and 7, the maximum load was applied six times beyond what was applied in the repetitions of MINITWIST. The number of extra maximum loads applied depended upon the number of times the fatigue cycling was interrupted to statically load the specimen to the prescribed maximum strain level and ranged from three to eight. These extra applications of the maximum load produced a more severe test of the specimen than the spectrum loading alone. For the panel whose results are shown in figures 6 and 7, the maximum strain level was approximately 54% of the failing strain. The maximum strain levels used in the spectrum ranged from 45% to 60% of the failing strains for all the panels tested without preload. The failing strains of the buffer strip panels are listed in tables I and II.

From the data shown in tables I and II, it is seen that the actual failing strains of the panels were much higher than the assumed ultimate strains levels of 0.005 and 0.006. Thus, the spectrum loading did not test the panels as severely as if the actual failing strains were used as ultimate values.

Although there was some damage growth at the crack tips, as indicated in figure 7(a) by the sharp jump in the COD versus load plot for the initial load segment, there was no significant change in the slope of the subsequent plots nor in the slopes of the load versus strain plots shown in figure 6. The data shown in figures 6 and 7 are typical for all the specimens tested without preload. None of the stress-strain plots showed any significant change in slope, i.e. specimen stiffness, due to the application of the spectrum loading. Some of the load versus COD plots indicated damage growth at the crack tips by small jumps in the initial load segment, like that shown in figure 6, but these did not significantly affect the overall specimen stiffness in any cases. There was no significant (<5%) change in the slope of the COD versus load plots. The jumps in the COD plots were seen only for the specimens loaded to the maximum strain value of 0.0042 and only in the initial load segment. There was no indication of any initial damage growth for the specimen with the maximum strain of 0.0035.

Figure 8 shows a typical set of radiographs made for a S-Glass buffer strip panel; this panel was subjected to three repetitions of the MINITWIST spectrum with a maximum strain of 0.0042, the same specimen used in figures 6 and 7. The two dark strips in the pictures are the S-Glass buffer strips which are more opaque to X-rays than the graphite/epoxy. The first radiograph shows that there is still very little damage after one repetition of the MINITWIST spectrum. Most of this damage, if not all of it, was caused by the initial application of the maximum load (see figure 7(a)). There is some evidence of damage in the center of the slit which was caused by the machining of the slit. Even after 3 repetition of MINITWIST there is very little evidence of damage growth beyond the initial damage shown in figure 8(a).

Figures 9 and 10 show a set of typical plots that were used to monitor the specimen stiffness and the damage state at the crack tips for a panel subjected to a preload and spectrum loading. Figure 9 shows the series of strain versus load plots while figure 10 shows the COD versus load plots. These plots were made for a specimen subjected to two repetitions of the MINITWIST spectrum with a maximum strain of 0.0042. As shown in the figure, data were plotted for the preload segment, before the fatigue cycling began (0 flights), after 1 repetition (4000 flights), after 1 1/2 repetitions (6000 flights) and finally after 2 repetitions (8000 flights) of the spectrum. In this test, in addition to the maximum load seen by the panel once during each repetition of the MINITWIST spectrum, the maximum load level was applied four additional times (to obtain the load-strain and load-COD data). As indicated in figure 9(a), for this test the preload was 80% of the failing load. The preloads ranged from 70% to 80% of the failing loads.

For the panel results shown in figures 9 and 10, the maximum strain level was approximately 55% of the failing strain. For the panels with preload, the maximum strains levels ranged from approximately 40% to 68% of the failing strains. The data shown in figures 9 and 10 are typical for all the specimens with preload. Except for the initial plot of the preload segment, none of the stress-strain plots showed any significant change in slope, i.e. specimen stiffness, due to the application of the spectrum loading. Also, after the initial preload segment, none of the load versus COD plots indicated any damage growth at the crack tips. Any change in the slope of the COD versus load plots was less than 2% for the specimens with preload.

Figure 11 shows a typical set of radiographs made for a S-Glass buffer strip panel with a preload; this panel was subjected to two repetitions of the MINITWIST spectrum with a maximum strain of 0.0042, the same specimen used in

figures 9 and 10. The first radiograph shows the damage state after the preload segment. The crack-tip damage has reached the adjacent buffer strips. Figure 11 shows that even after two repetitions of the MINITWIST spectrum, the damage area has not increased much over that shown in figure 11(a).

#### CONCLUDING REMARKS

Graphite/epoxy buffer strip panels were tested to measure their residual tension strength after fatigue spectrum loading. Panels were made with a  $[45/0/-45/90]_{2s}$  layup. The buffer strips were made by replacing narrow strips of the 0-degree graphite plies with strips of either 0-degree S-Glass or Kevlar-49 on a one-for-one basis. The panels were cut at the center between buffer strips to represent damage. The panels were subjected to a fatigue loading spectrum, MINITWIST, the shortened version of the standardized load program for the wing lower surface of a transport aircraft. Three levels of maximum strain were used in the spectrum with three fatigue repetitions. One group of specimens were statically loaded in tension as a preload before applying the fatigue cycling. After the fatigue loading, all the specimens were statically loaded in tension to failure to determine their residual strengths.

The ability of the buffer strip configuration to arrest crack growth was not affected by fatiguing the panels prior to loading in tension to failure. The residual strengths of the fatigued panels were still much higher than the residual strengths of similar panels without buffer strips. Although in a few cases, there was some evidence of damage growth at the crack tips, there was no significant effect on the overall specimen stiffness in any of the tests due to

the fatigue cycling alone or in combination with the preload. And finally, the residual strengths of the panels were not significantly affected by the fatigue loading, with or without preload on the specimens.

## REFERENCES

1. Poe, C. C., Jr.; and Kennedy, J. M.: An Assessment of Buffer Strips for Improving Damage Tolerance of Composite Laminates. Journal of Composite Materials Supplement, vol. 14, 1980, pp. 57-70.
2. Lowak, H.; de Jonge, J. B.; Franz, J.; and Schutz, D.: MINITWIST A Shortened Version of TWIST. Nationaal Lucht - En Ruimtevaartlaboratorium, NRL MP 79018 U, ICAF Document 1147, Jan. 1979.
3. Williams, J. G.; Anderson, M. S.; Rhodes, M. D.; Starnes, J. H., Jr.; and Stroud, W. J.: Recent Developments in the Design, Testing and Impact-Damage Tolerance of Stiffened Composite Panels. NASA TM-80077, April 1979.

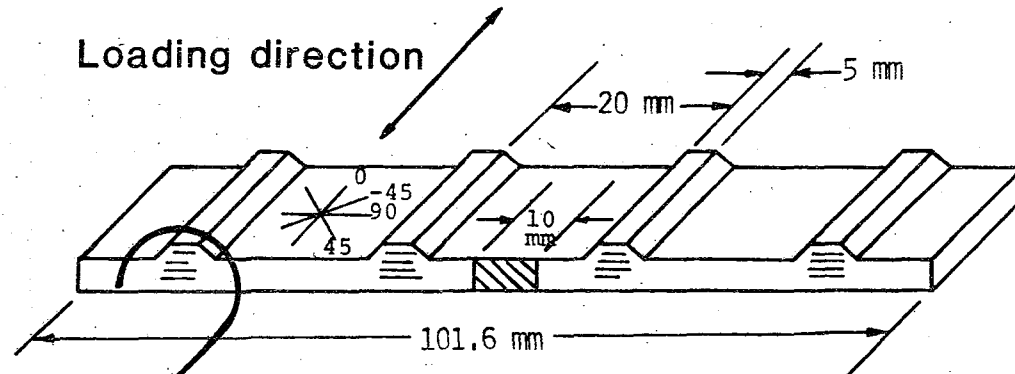
Table I. Residual Strengths and failing strains for graphite/epoxy panels with S-Glass buffer strips.

	maximum strain $\epsilon_m$	no. of repetitions of MINITWIST	residual strength (MPa)	failing strain
spectrum loading only	.0035	1	359	.0077
	.0042	1	368	.0080
	.0042	1	376	.0081
	.0042	2	385	.0084
	.0042	2	345	.0075
	.0042	3	360	.0078
	.0042	3	323	.0068
preload and spectrum loading	.0035	1	369	.0077
	.0035	1	368	.0080
	.0042	1	402	.0078
	.0042	1	387	.0085
	.0042	2	376	.0080
	.0042	2	343	.0075
	.0042	2	336	.0072
	.0042	3	365	.0079
	.0042	3	370	.0081

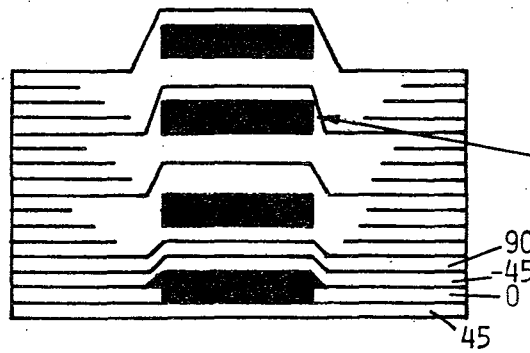
Table II. Residual strengths and failing strains for graphite/epoxy panels with Kevlar-49 buffer strips.

	maximum strain $\epsilon_m$	no. of repetitions of MINITWIST	residual strength (MPa)	failing strain
spectrum loading only	.0035	1	381	.0081
	.0042	1	312	.0065
	.0042	1	381	.0081
	.0042	2	355	.0074
	.0042	2	369	.0078
	.0042	3	370	.0079
	.0042	3	342	.0072
preload and spectrum loading	.0035	1	399	.0084
	.0035	2	323	.0072
	.0042	1	290	.0062
	.0042	1	372	.0079
	.0042	2	340	.0073
	.0042	2	335	.0071
	.0042	3	379	.0080
.0042	3	359	.0080	

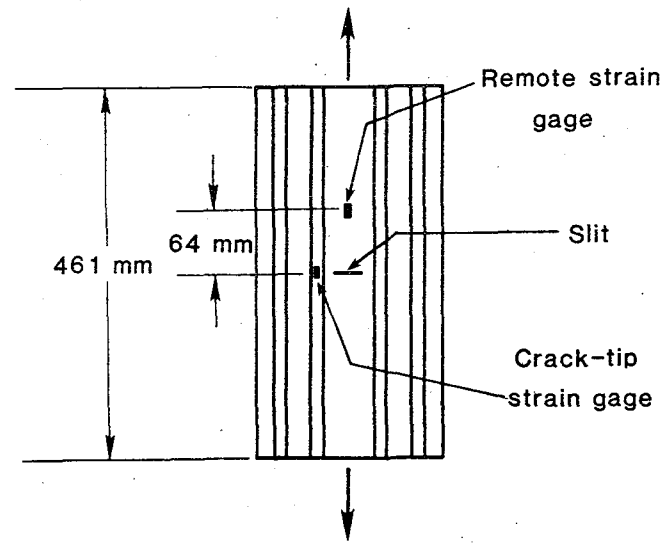




(a) Cross-sectional view.



(b) Buffer strip detail.



(c) Plan view.

Figure 1. Buffer strip configuration.

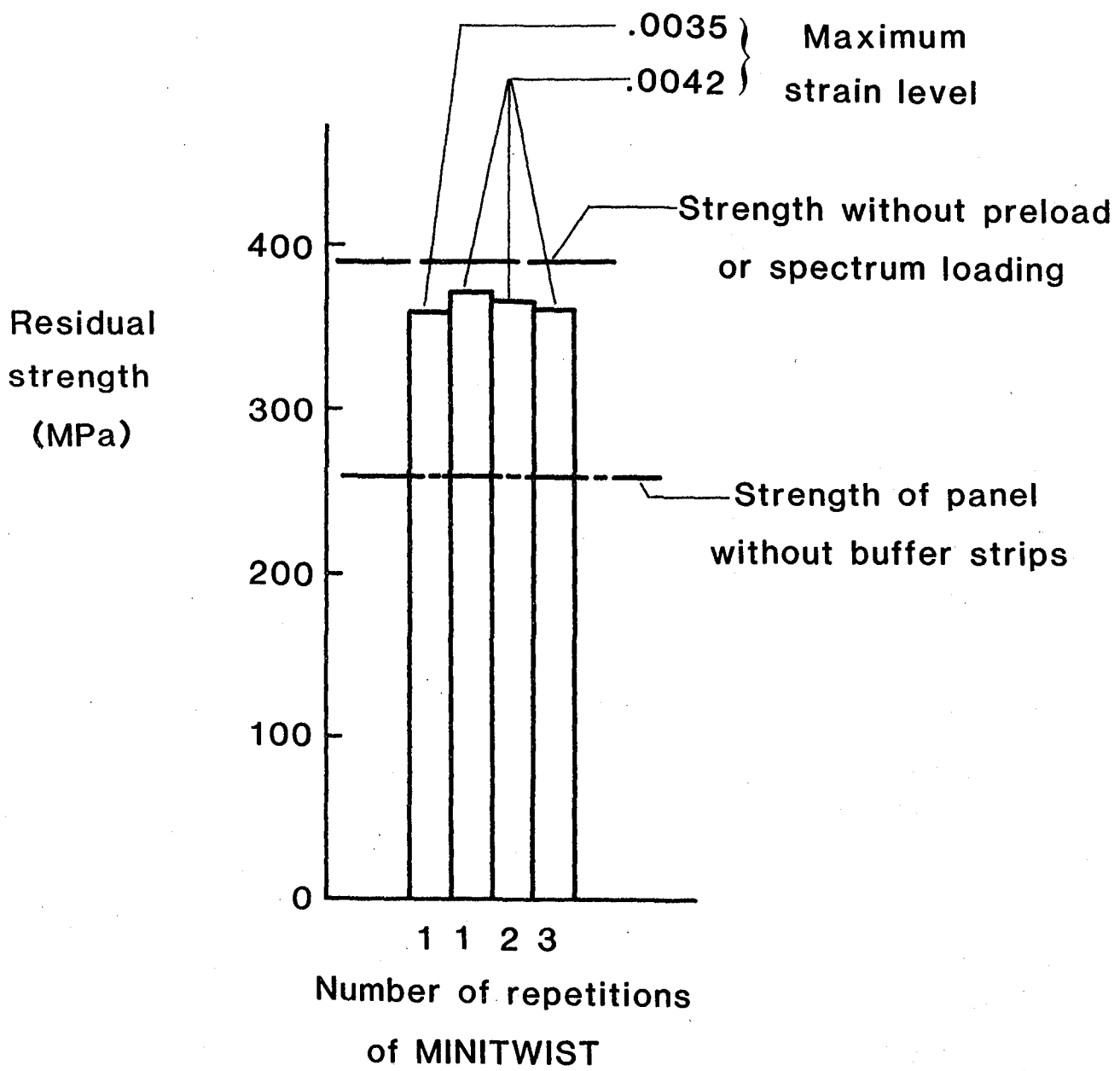


Figure 2. Residual strengths of S-Glass buffer strip panels with spectrum loading only.

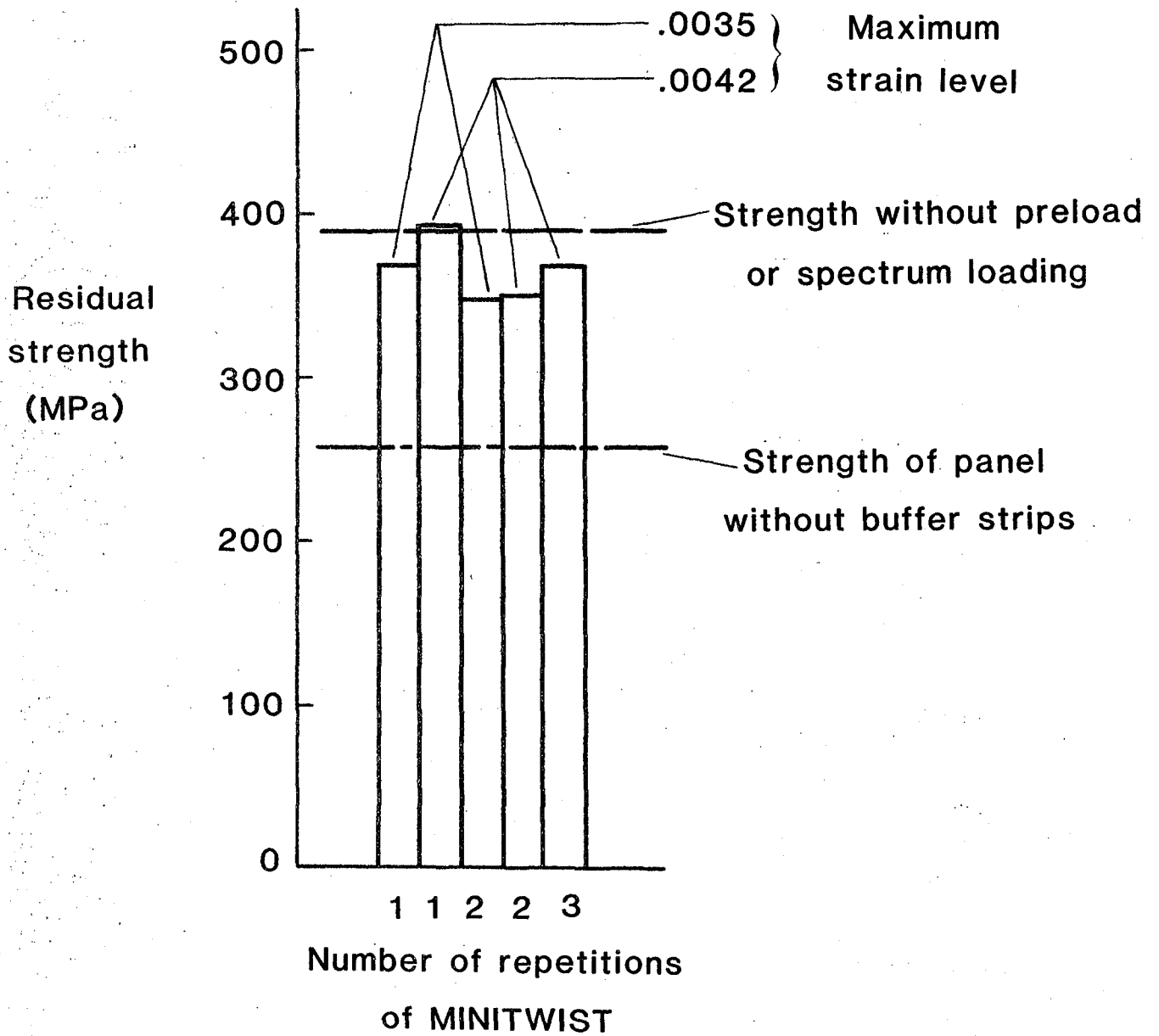


Figure 3. Residual strengths of S-Glass buffer strip panels with preload and spectrum loading.

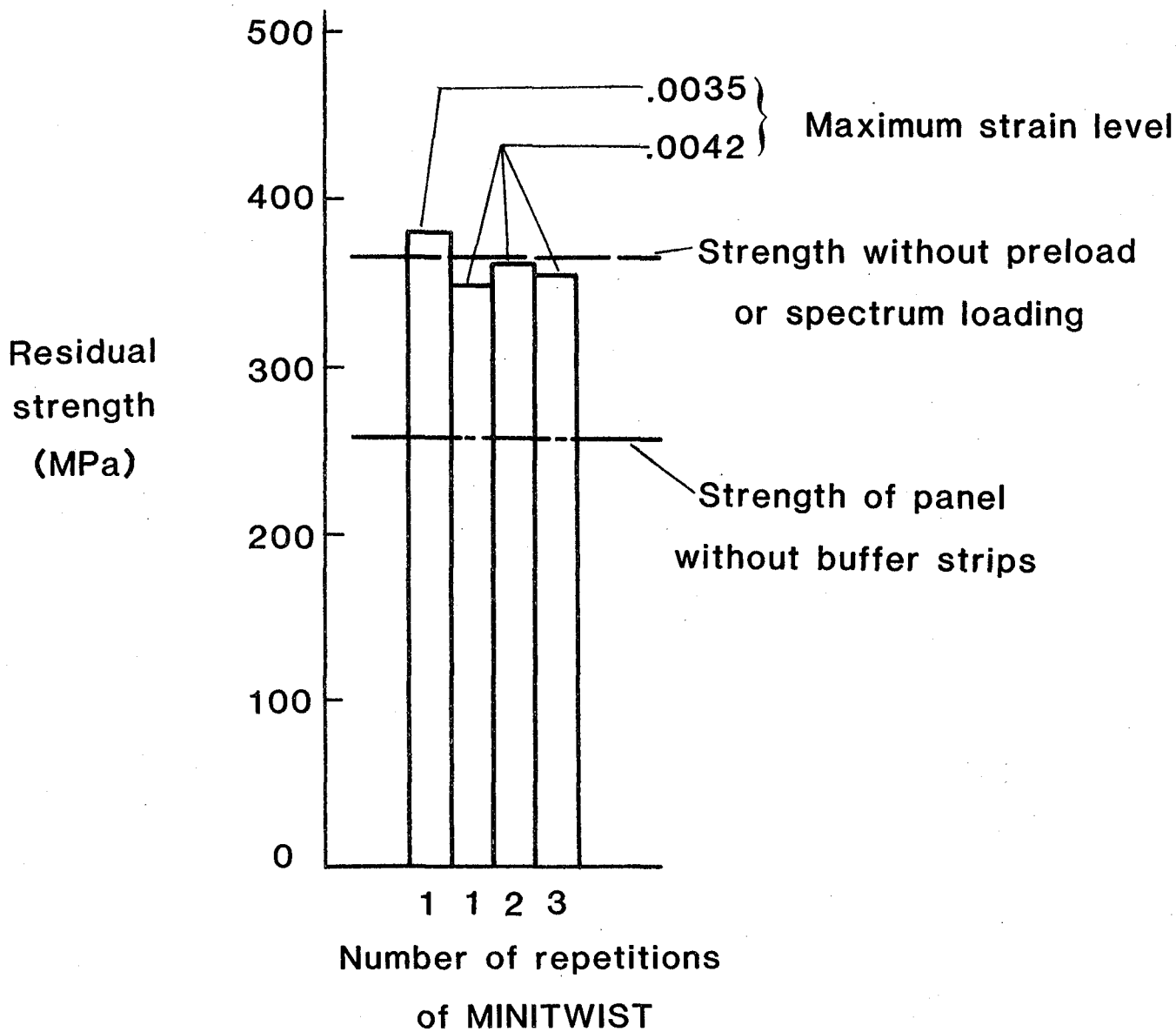


Figure 4. Residual strengths of Kevlar-49 buffer strip panels with spectrum loading only.

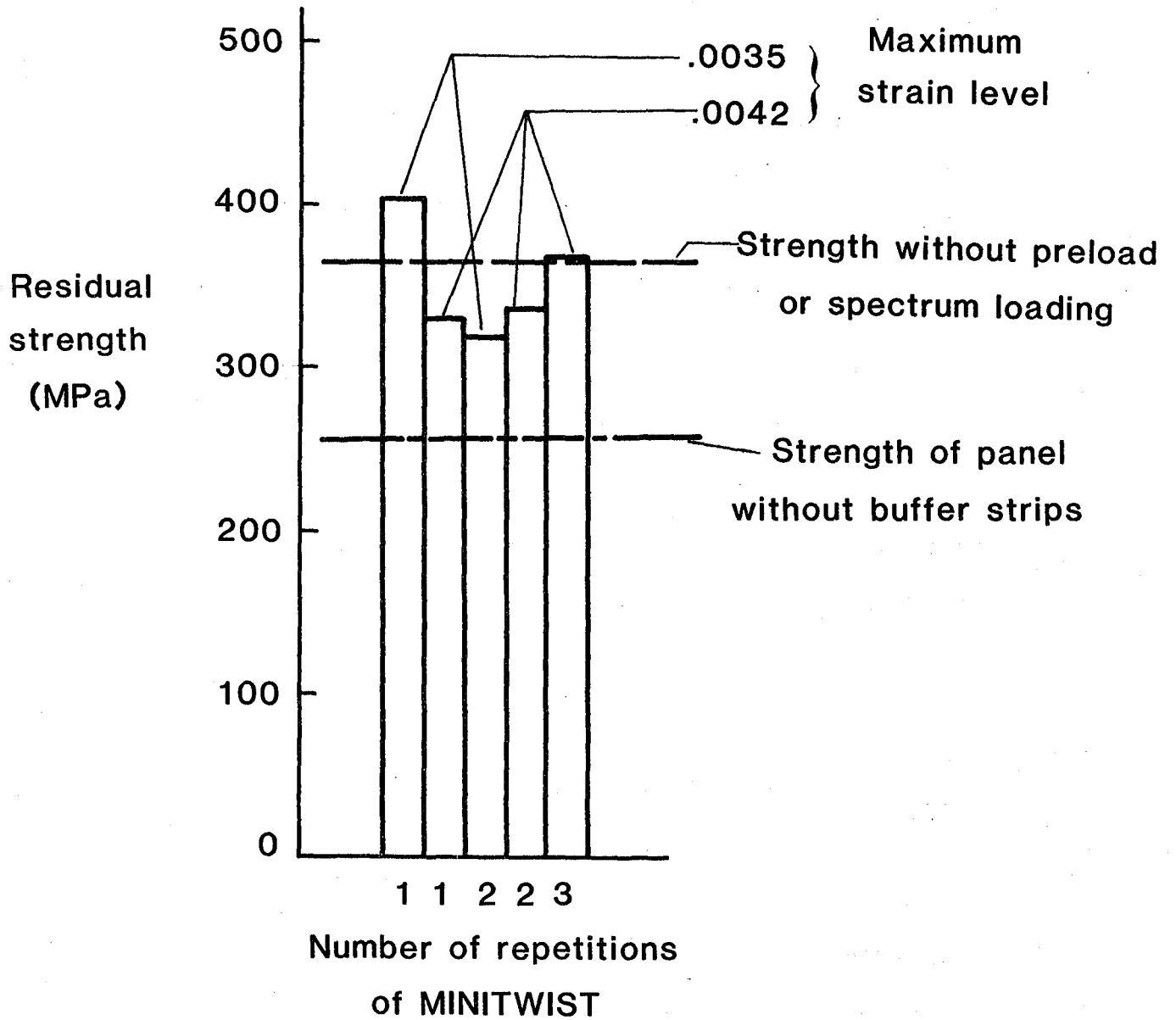
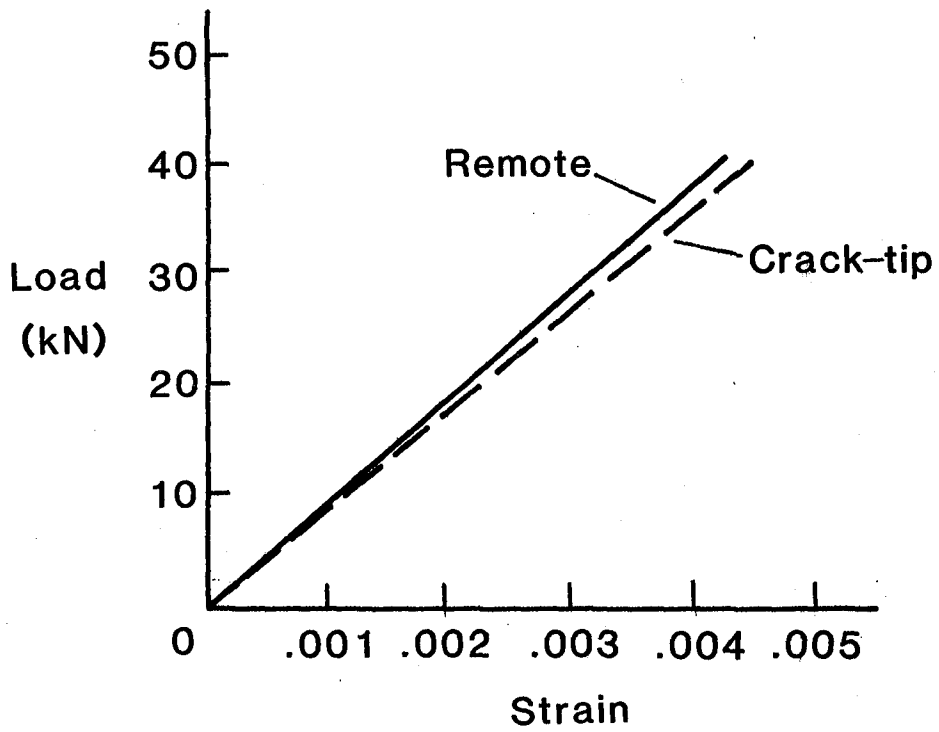
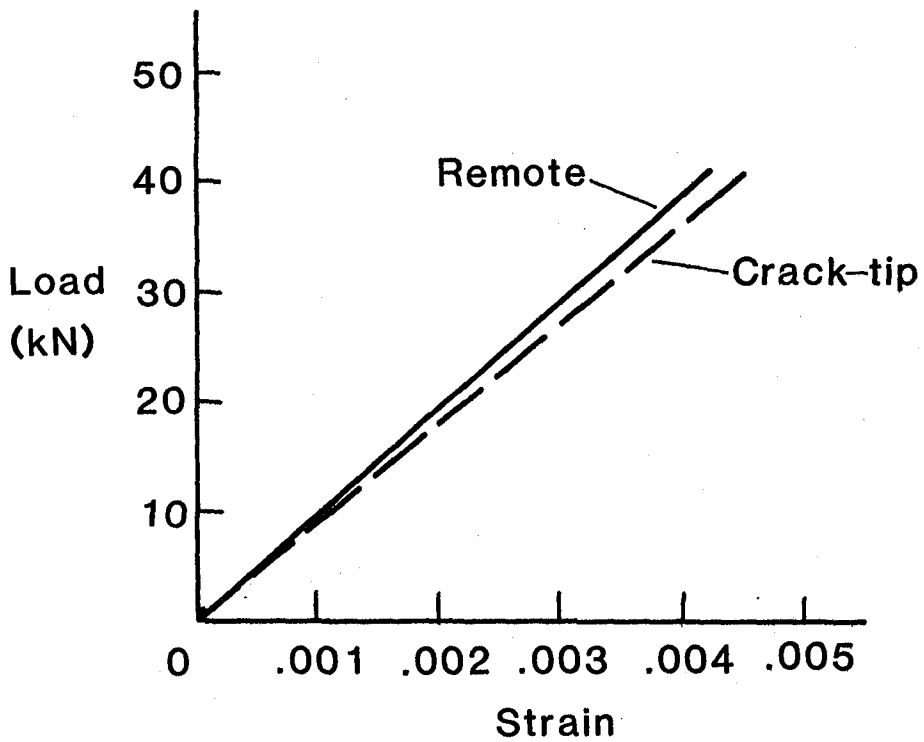


Figure 5. Residual strengths of Kevlar-49 buffer strip panels with preload and spectrum loading.

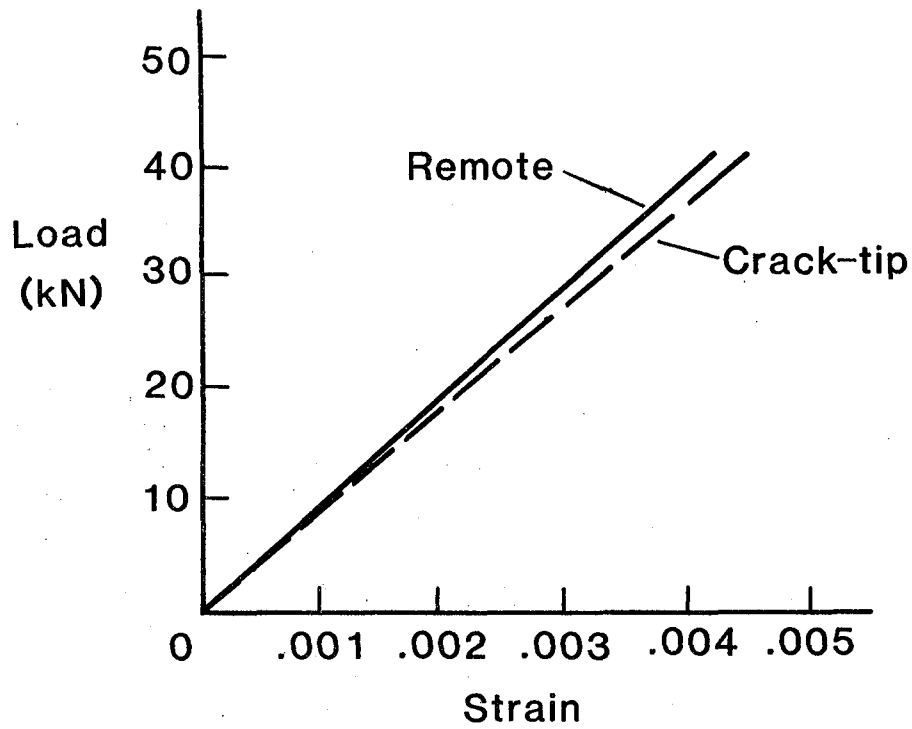


(a) Initial load, 50% of failure.

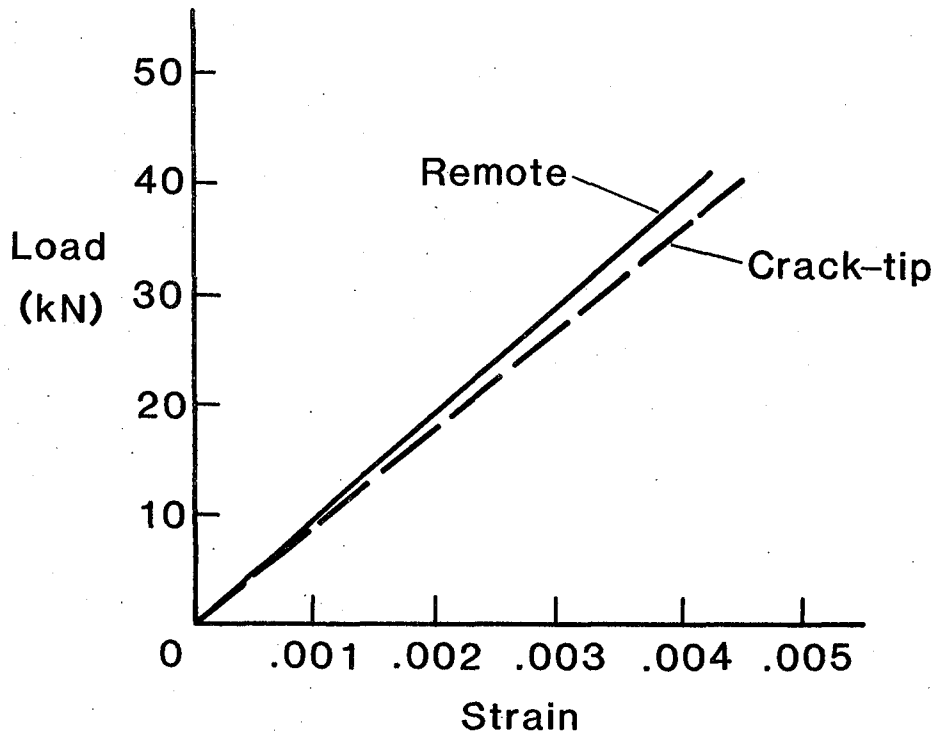


(b) After 1 repetition.

Figure 6. Periodic plots of load versus strain for three repetitions of MINITWIST spectrum.  $\epsilon_m = 0.0042$ .

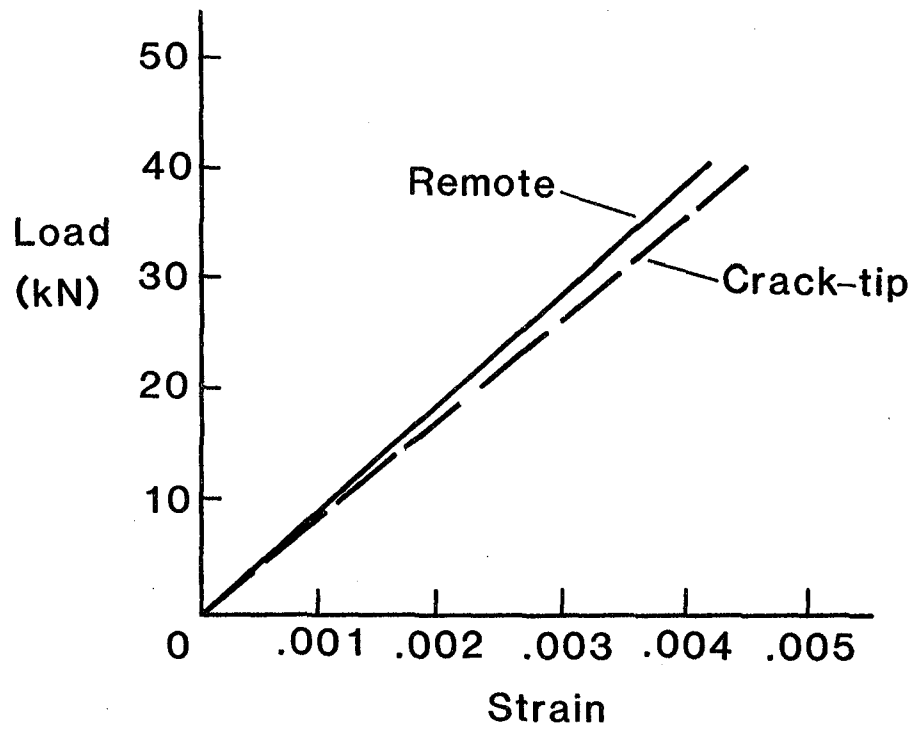


(c) After 2 repetitions.

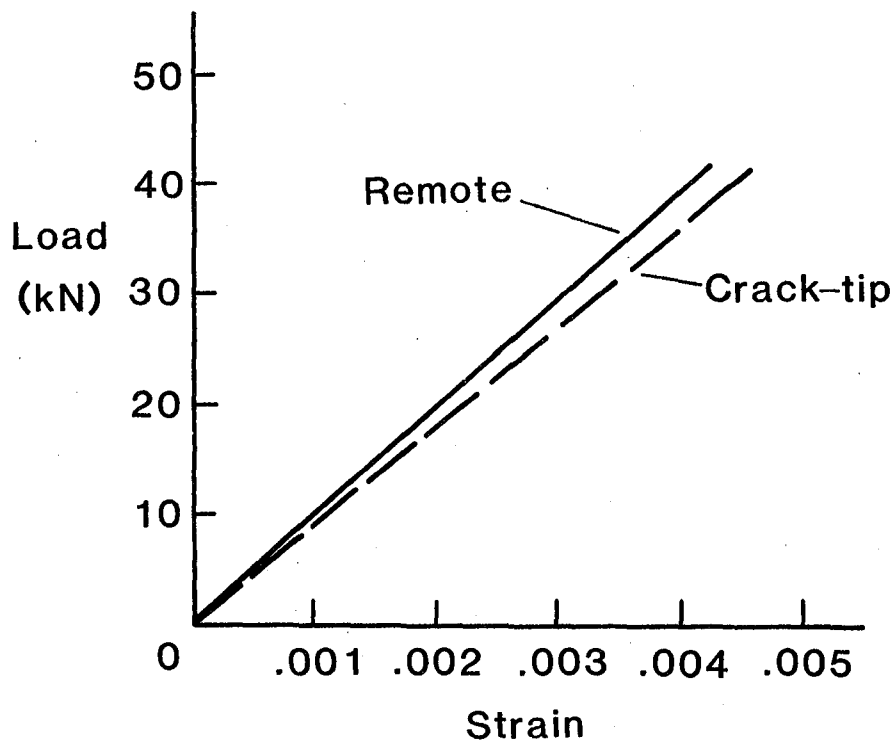


(d) After 2 1/2 repetitions.

Figure 6. Continued.



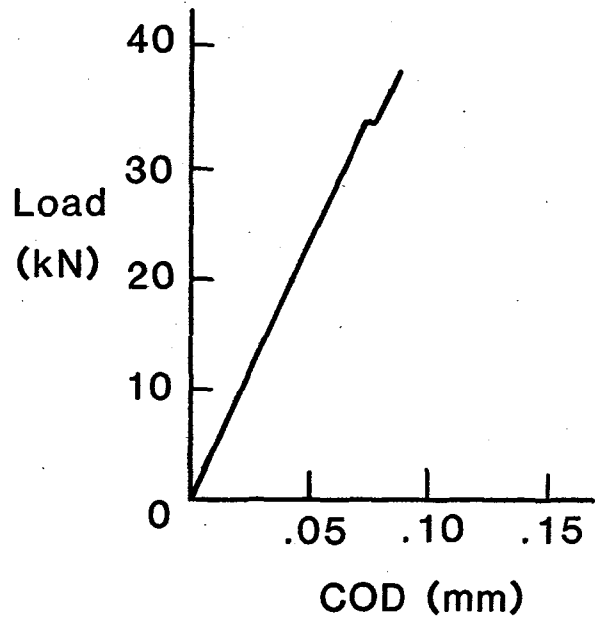
(e) After 2 3/4 repetitions.



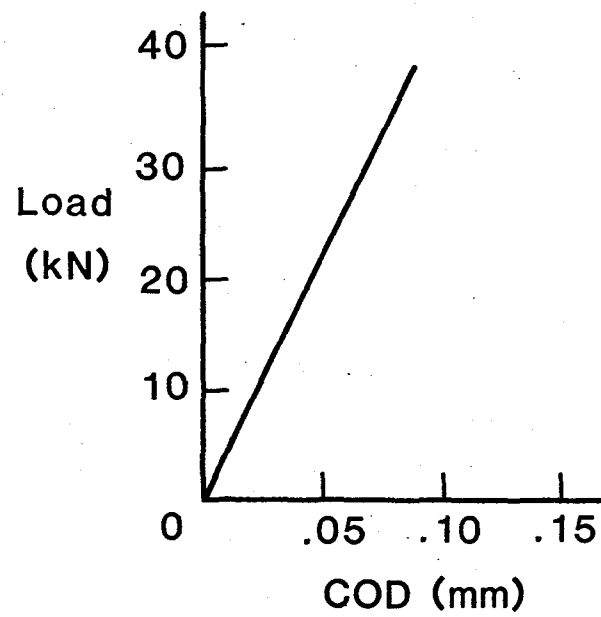
(f) After 3 repetitions.

Figure 6. Concluded.

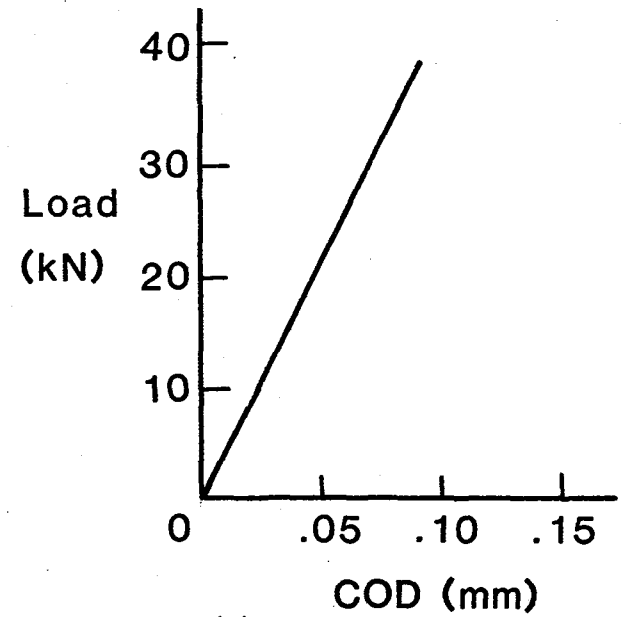




(a) Initial load, 50% of failure.

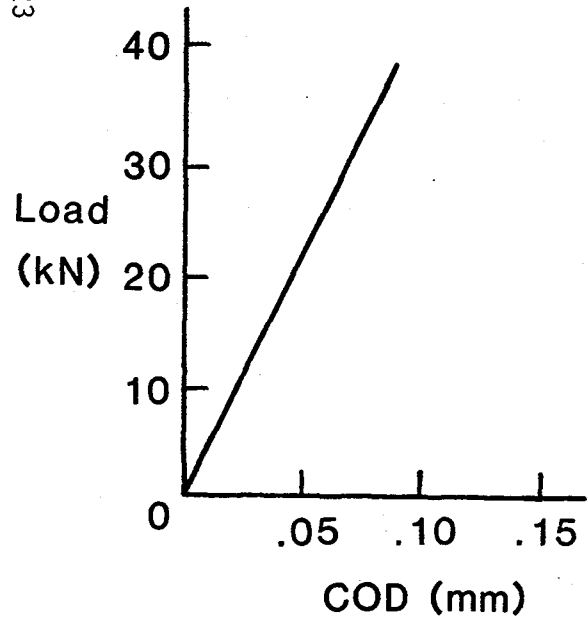


(b) After 1 repetition.

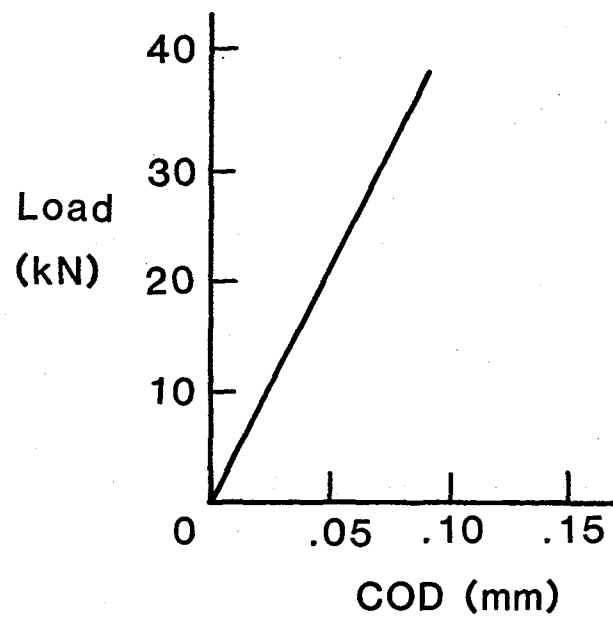


(c) After 2 repetitions.

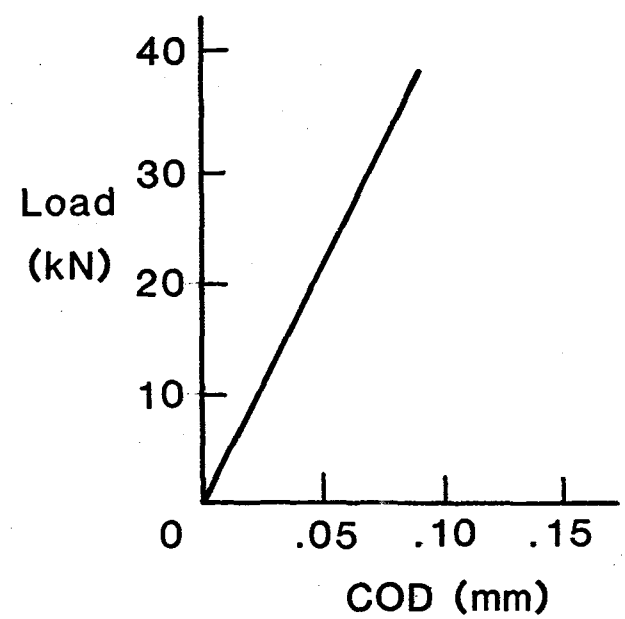
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(d) After 2 1/2 repetitions.



(e) After 2 3/4 repetitions.



(f) After 3 repetitions.

Figure 7. Periodic plots of load versus crack-opening-displacements (COD) for three repetitions of MINITWIST.  $\epsilon_m = 0.0042$ .

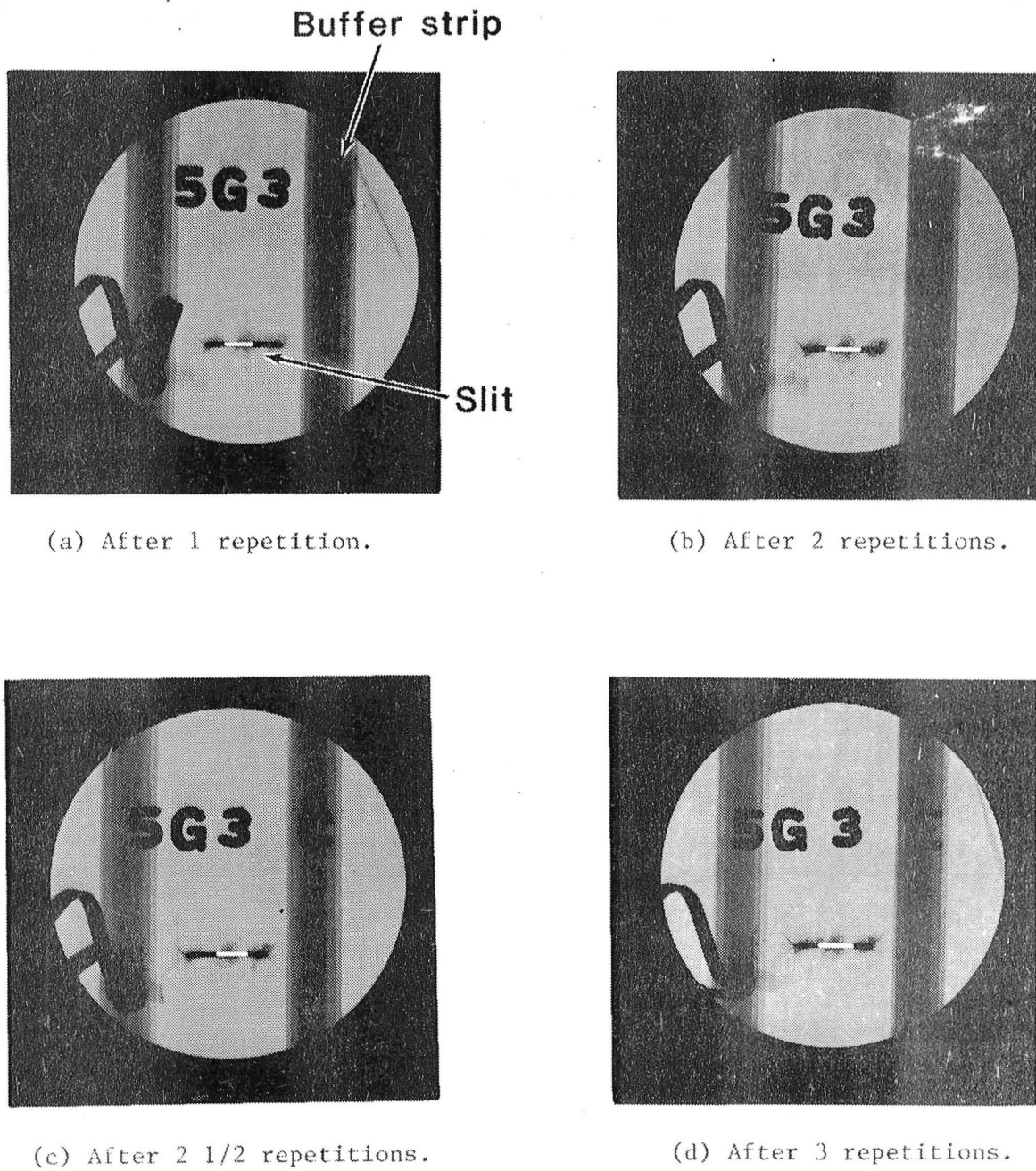
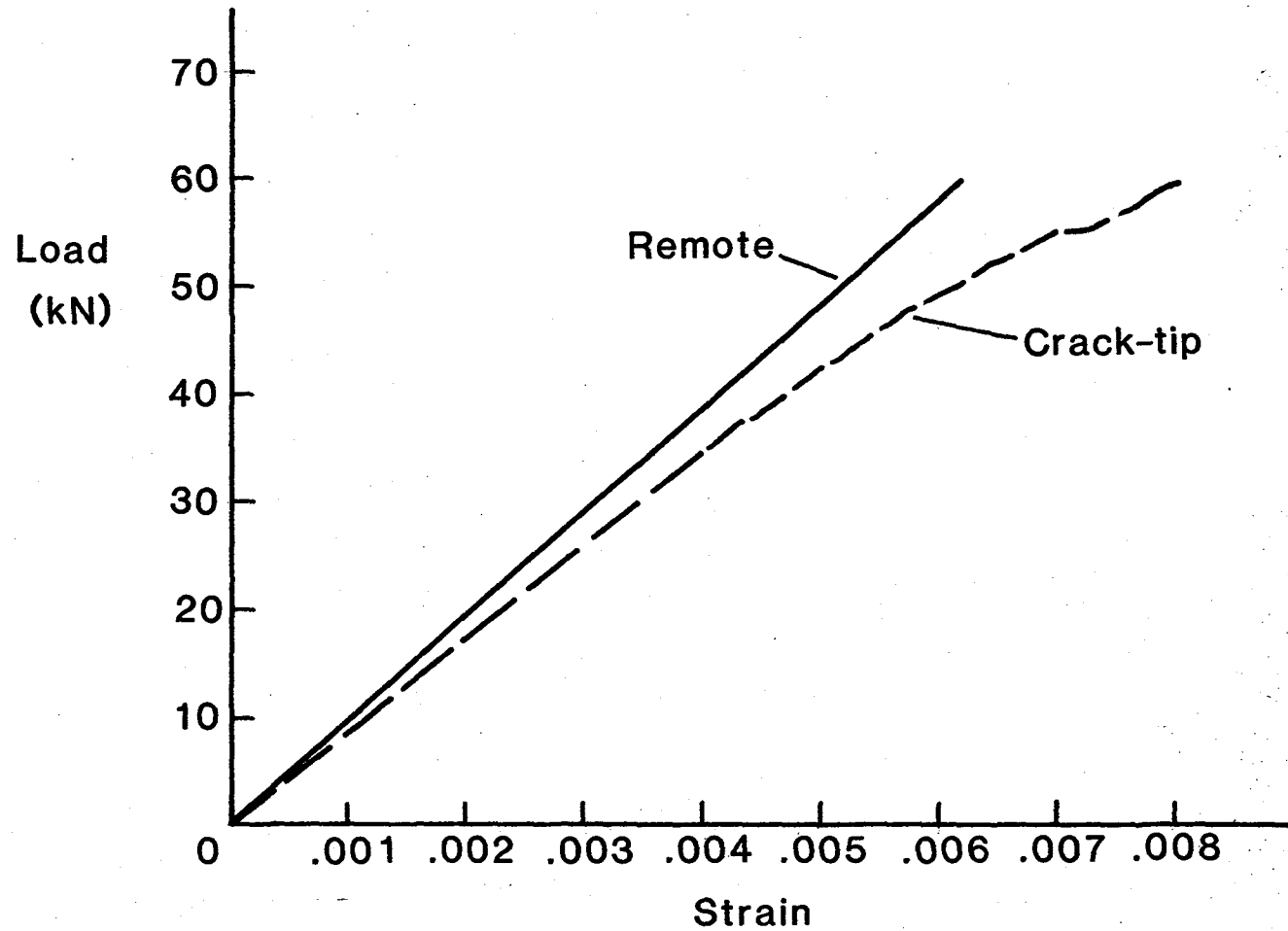
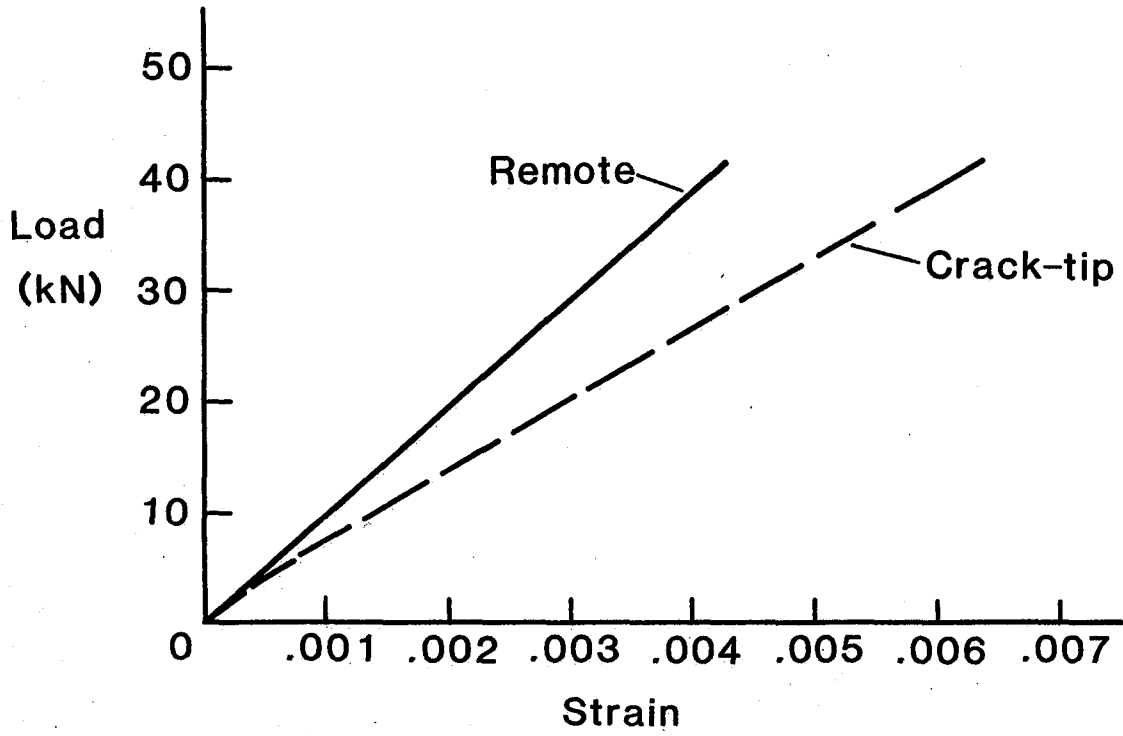


Figure 8. Radiographs of S-Glass buffer strip panel subjected to three repetitions of MINITWIST spectrum.  $\epsilon_m = 0.0042$ .

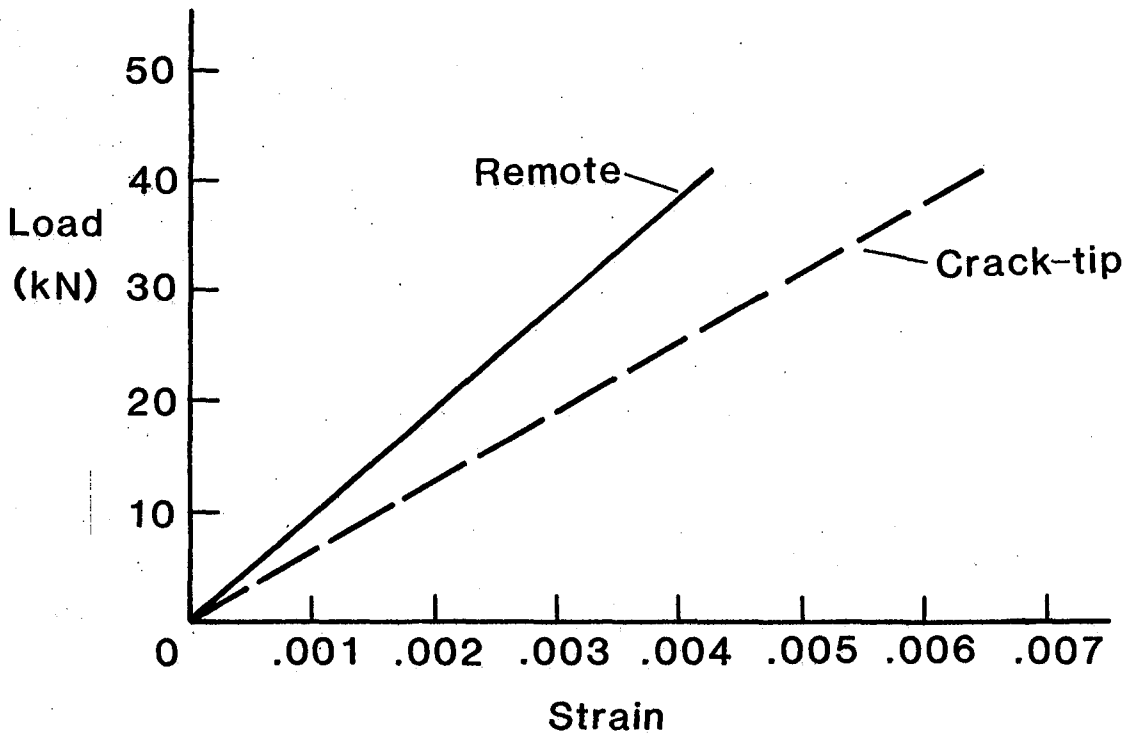


(a) Preload, 80% of failure.

Figure 9. Periodic plots of load versus strain for two repetitions of MINITWIST spectrum.  $\epsilon_m = 0.0042$ .

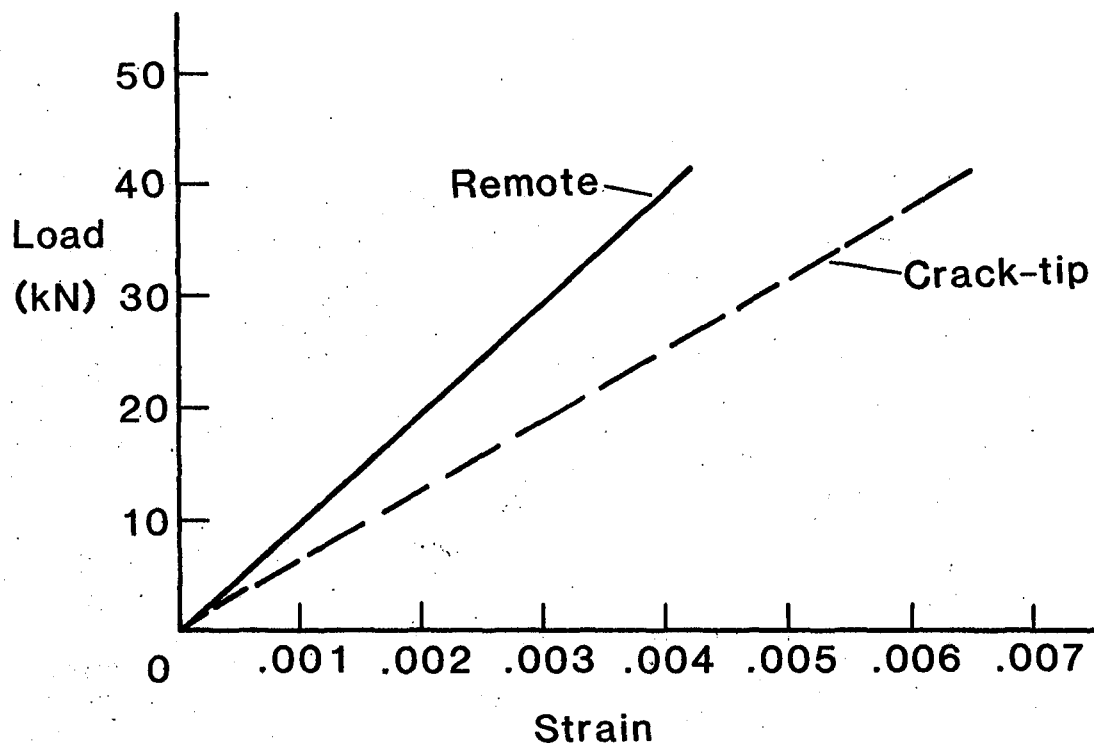


(b) After preload.

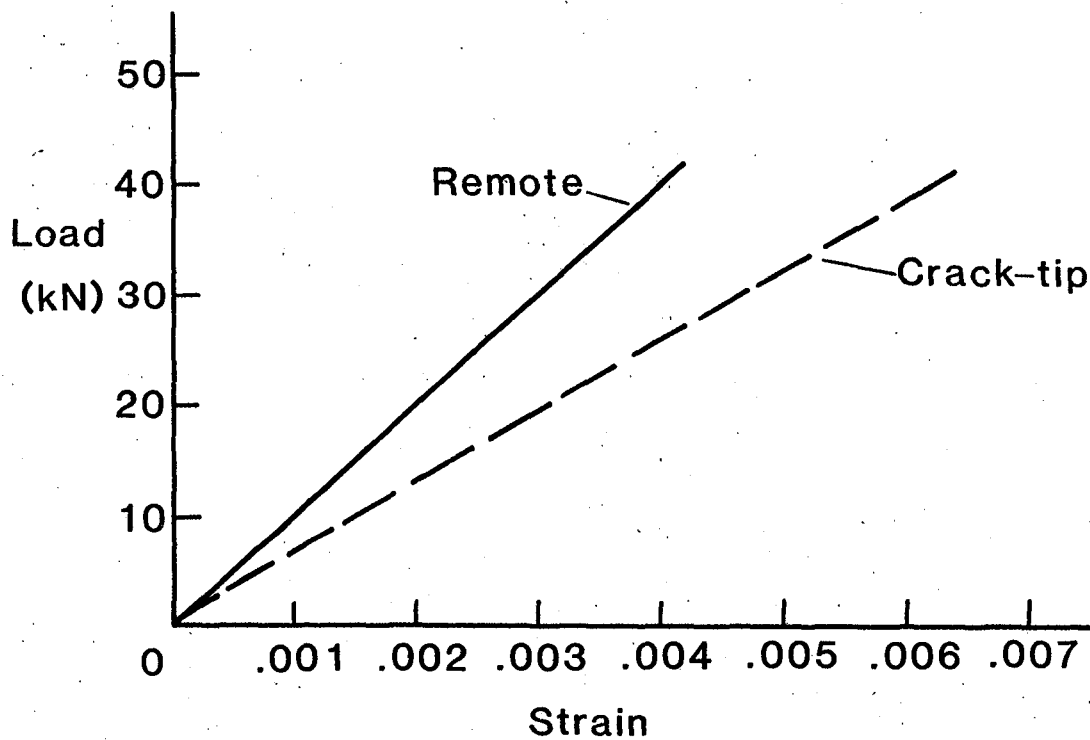


(c) After 1 repetition.

Figure 9. Continued.

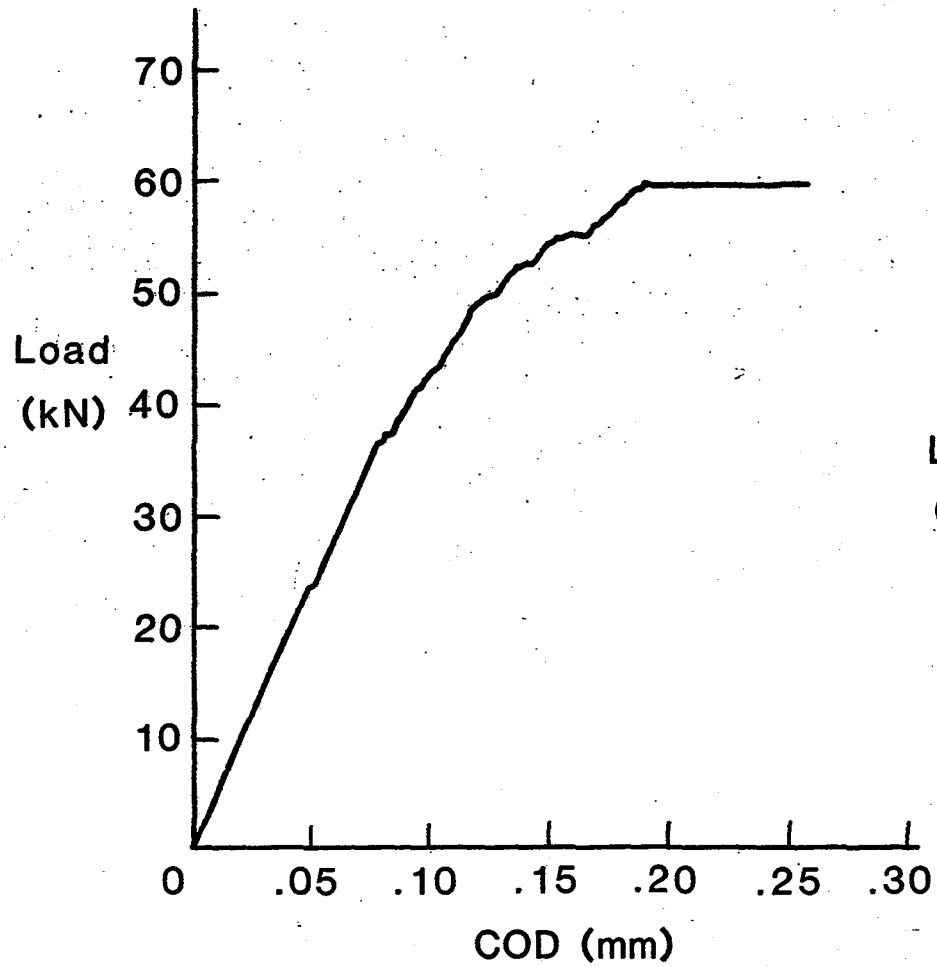


(d) After 1 1/2 repetitions.

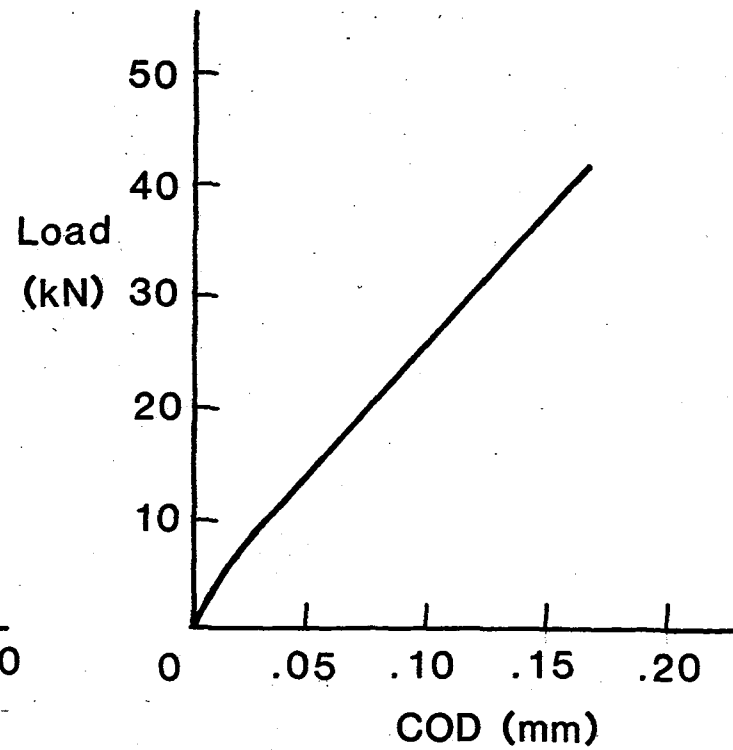


(e) After 2 repetitions.

Figure 9. Concluded.

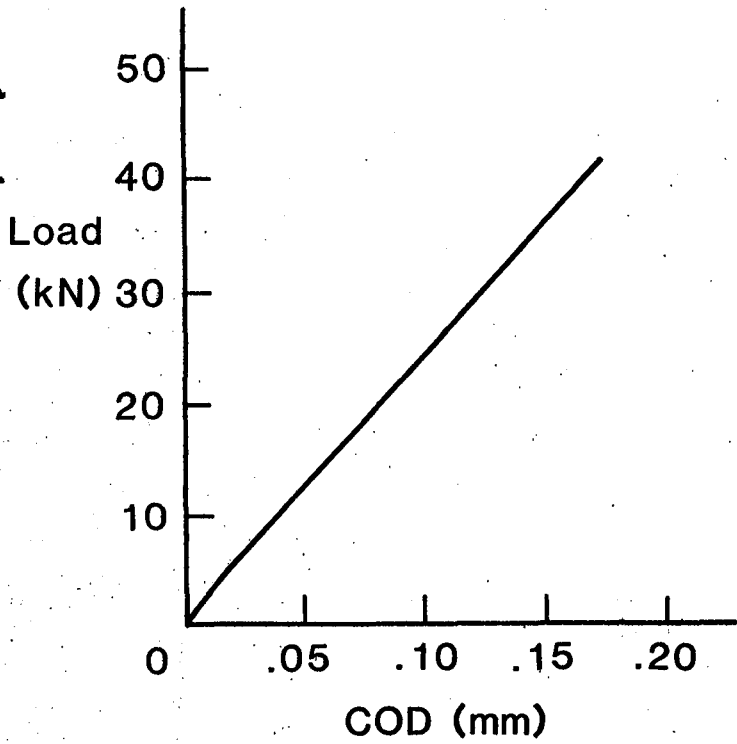


(a) Preload, 80% of failure.

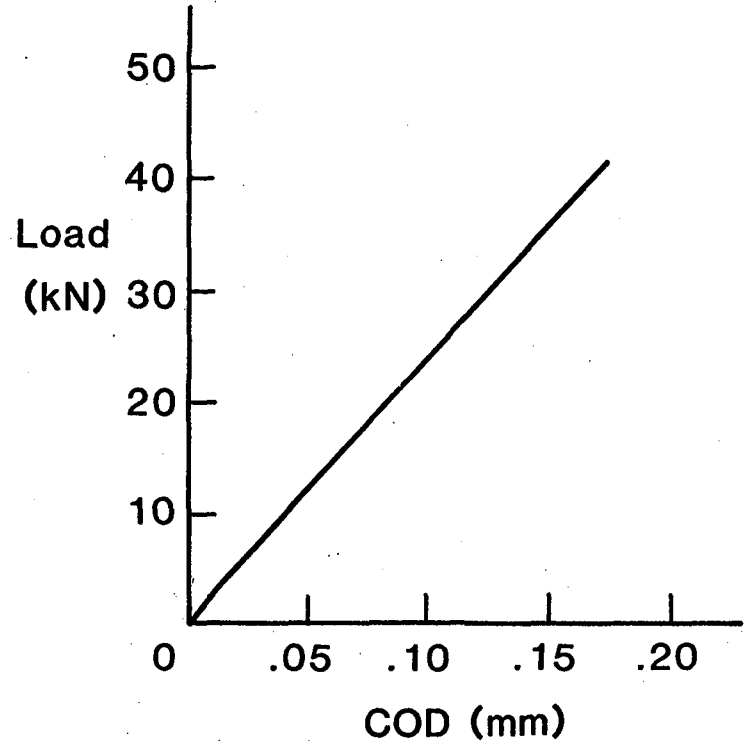


(b) After preload.

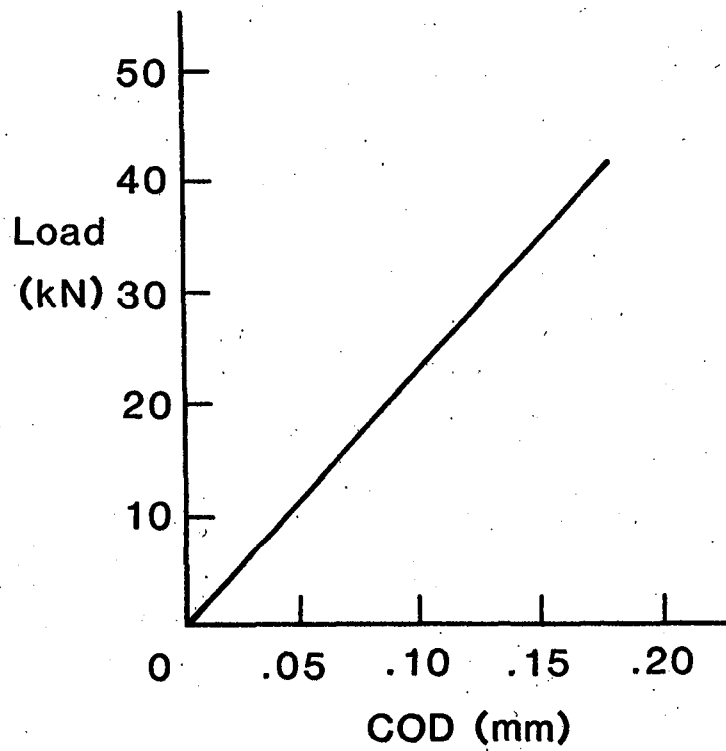
Figure 10. Periodic plots of load versus crack-opening-displacements (COD) for two repetitions of MINITWIST with preload.  $\epsilon_m = 0.0042$ .



(c) After 1 repetition.

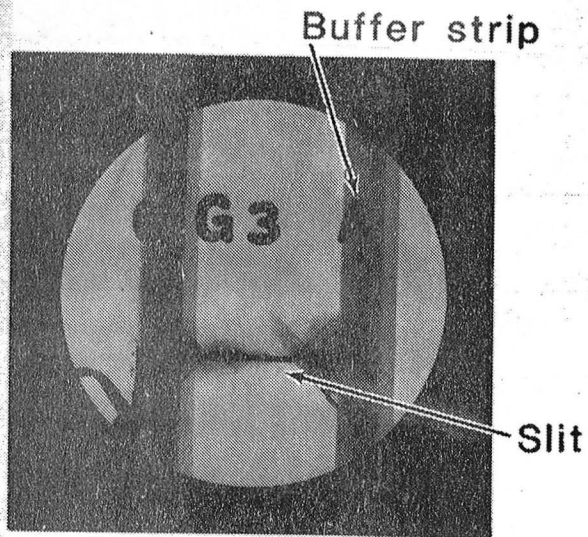


(d) After 1 1/2 repetitions.

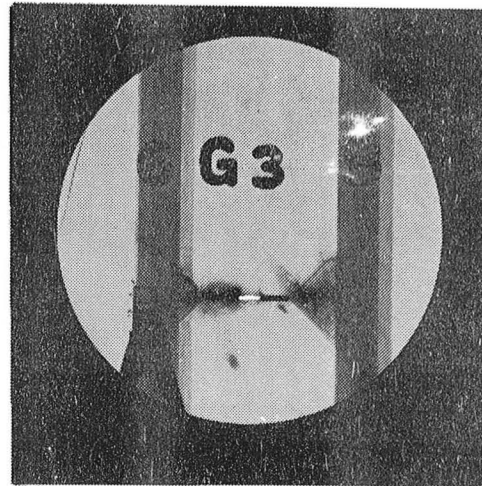


(e) After 2 repetitions.

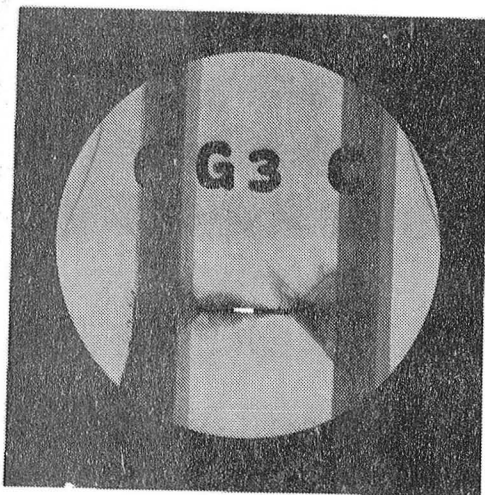
Figure 10. Concluded.



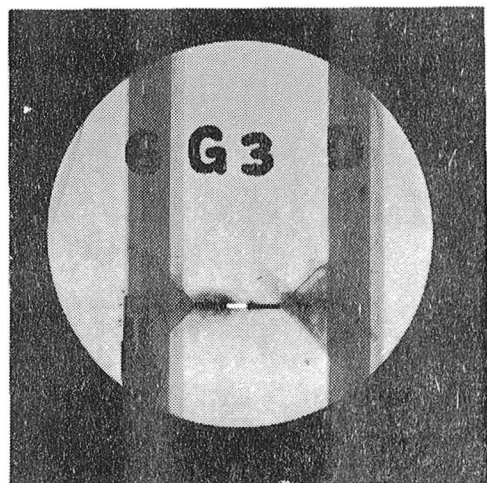
(a) Preload, 80% of failure.



(b) After 1 repetition.



(c) After 1 1/2 repetitions.



(d) After 2 repetitions.

Figure 11. Radiographs of S-Glass buffer strip panels subjected to preload and two repetitions of MINITWIST.  $\epsilon_m = 0.0042$ .





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16. Abstract <p>The effects of fatigue loading on the behavior of graphite/epoxy panels with either S-Glass or Kevlar-49 buffer strips were studied. Buffer strip panels were fatigued and tested in tension to measure their residual strength with crack-like damage. Panels were made with [45/0/-45/90]<sub>2s</sub> layup with either S-Glass or Kevlar-49 buffer strip material. The buffer strips were parallel to the loading direction and were made by replacing narrow strips of the 0-degree graphite plies with strips of either 0-degree S-Glass/epoxy or Kevlar-49/epoxy on a one-for-one basis.</p> <p>The panels were subjected to a fatigue loading spectrum MINITWIST, the shortened version of the standardized load program for the wing lower surface of a transport aircraft. Two levels of maximum strain were used in the spectrum with three durations of the fatigue spectrum. One group of panels were preloaded prior to the application of the fatigue cycling. The preload consisted of statically loading the specimen in tension until the crack-tip damage zone reached the adjacent buffer strips. After fatigue loading, all specimens were statically loaded in tension to failure to determine their residual strengths.</p> <p>The residual strengths of the panels were not affected by the fatigue loading, with or without preload. The stiffnesses of the specimens were not significantly changed by the fatigue loading. Also, the buffer strips arrested the cracks and increased the residual strengths significantly over those of plain laminates without buffer strips.</p>					
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