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Damage Tolerance and Durability of Selectively Stitched, Stiffened Panels

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Final Report

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16. Abstract

The goal of this project was to investigate the effectiveness of selective stitching on the damage tolerance and durability of a stiffened structural element applicable to air transportation systems. Specifically, this report compares the experimental results of selectively stitched, fully stitched, and unstitched, stiffened panels. Fundamental questions concerning the effect of low-velocity impact on strength and constant-amplitude fatigue are addressed. The specific areas addressed are as follows:

- Effect of selective stitching on the manufacture of a stiffened panel
- Effect of selective stitching on static compression properties of a stiffened panel
- Effect of selective stitching on constant-amplitude fatigue properties of a stiffened panel
- Effect of selective stitching on flange and stiffener impact of a stiffened panel

A primary concern with using composite laminates is the weakness in the out-of-plane direction. A cost-effective, out-of-plane reinforcement method may be selective stitching. However, the effect of selective stitching on the manufacture and performance of a stiffened panel is uncertain. Through this investigation, the effects of selective stitching on compressive strength, manufacture, and fatigue strength are determined. It was shown that selective stitching provided an increase in compressive strength by 16.3%, whereas the flange-impacted strength increased by 15.9% compared to unstitched panels. However, selective stitching did not show improvement compared to unstitched panels for those panels with stiffener impact. Constant-amplitude fatigue strengths of stiffener-impacted panels were enhanced with stitching. The results indicate an increase in fatigue strength of selectively and fully stitched panels with stiffener damage when compared to unstitched panels, but marginal improvement, due to stitching, was seen for the flange-impacted panels.

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EXECUTIVE SUMMARY

The goal of this project was to investigate the effectiveness of selective stitching on the damage tolerance and durability of a stiffened structural element applicable to air transportation systems. Specifically, this report compares the experimental results of selectively stitched, fully stitched, and unstitched, stiffened panels. Fundamental questions concerning the effect of low-velocity impact on strength and constant-amplitude fatigue are addressed. The specific areas addressed are as follows:

- Effect of selective stitching on the manufacture of a stiffened panel.
- Effect of selective stitching on static compression properties of a stiffened panel.
- Effect of selective stitching on constant-amplitude fatigue properties of a stiffened panel.
- Effect of selective stitching on flange and stiffener impact of a stiffened panel.

A primary concern with using composite laminates is the weakness in the out-of-plane direction. A cost-effective, out-of-plane reinforcement method may be selective stitching. However, the effect of selective stitching on the manufacture and performance of a stiffened panel is uncertain. Through this investigation, the effects of selective stitching on compressive strength, manufacture, and fatigue strength are determined. It was shown that selective stitching provided an increase in compressive strength by 16.3%, whereas the flange-impacted strength increased by 15.9% compared to unstitched panels. However, selective stitching did not show improvement compared to unstitched panels for those panels with stiffener impact. Constant-amplitude fatigue strengths of stiffener-impacted panels were enhanced with stitching. The results indicate an increase in fatigue strength of selectively and fully stitched panels with stiffener damage when compared to unstitched panels, but marginal improvement, due to stitching, was seen for the flange-impacted panels.

1. INTRODUCTION.

Composite materials have been used in the aerospace industry over the past 3 decades for their strength-to-weight benefit. Based on the trend forecasted in references 1 and 2, the composite airframe progress on commercial transport was heading toward all composite wings before the year 2000, all composite fuselage after the year 2000, and the entire airframe around 2010. Unfortunately, the progress on composites usage was not so promising, even though the trend in transport aircraft size and flight range has been steadily increasing, i.e., Boeing 747-400ER and Airbus A380.

There are many factors and issues associated with the insertion of the advanced materials for primary structural applications where structural integrity is the most important factor. Especially for composites, one of the primary concerns is whether or not the material is reliable and durable for the primary structural application. Composite laminates suffer from their high sensitivity to out-of-plane failure resulting from low interlaminar fracture toughness. To alleviate this shortcoming, toughened resins have been developed to reduce the initiation and growth of delamination with limited success. However, an alternate approach to improve delamination resistance is through three-dimensional fibrous reinforcement such as through-the-thickness stitching. Recent studies by Dow, et al. [3 and 4] have shown that stitching of conventional laminates can increase damage tolerance to the level available with toughened resin systems but at a lower cost.

The main purpose of the present research was to investigate the effects of selective stitching on the damage tolerance and durability of stiffened composite panels. Stiffened panels are chosen because they are one of the most widely used structural forms. The panels used in previous phases were fabricated with a resin film infusion (RFI) process using unstitched and fully stitched plain weave fabric preforms [5]. The primary focus of this report is to summarize the experimental investigations of the selectively stitched, stiffened panels. The effect of impact damage on the selectively stitched panels is compared to the tests on the unstitched and fully stitched, stiffened panels performed in previous studies [5].

2. MANUFACTURE OF SELECTIVELY STITCHED, STIFFENED PANELS.

The panels used in this study were designed to be a two-blade stiffened panel. In addition to its overall dimensions, the panel is characterized by skin and stiffener thicknesses, stiffener spacing and height, and flange width, as listed in table 1. Because the typical stiffener spacing investigated by Starnes Jr., et al. [6], Madan [7], and Stevens, et al. [8] ranged from 12.7 to 17.8 cm, a midrange value of 15.24 cm was selected. The overall length and width of the panel were to be 25.4 cm each. The overriding constraint was that the panel should be as realistic as possible, yet could be tested in a laboratory setting.

The manufacturing of selectively stitched, stiffened panels consists of three primary steps: (1) lay-up and stitching of flanges and stiffeners, (2) preparation of resin film, and (3) resin film infusion in an autoclave.

2.1 MATERIALS.

Hexcel AS4 (3k), type 282 plain weave, and 3501-6 epoxy were selected for in-plane reinforcement and matrix in this study, as were selected in previous phases. Typical fiber and matrix properties of this material are found in references 5 and 9 through 11. Hexcel Type 282 is a plain weave fabric that has the same number of warp and fill yarns, 4.92 yarns per cm. The yarn consists of AS4-3k fiber tow. The AS4/3501-6 is a well-characterized composite and amenable to the RFI process. The AS4 fiber tows are also used as the stuffer and filler material in joining stiffeners to the skin. The thickness of the stiffened panel design uses fewer plies of plain weave than the uniweaves. The lay-up sequence used in this investigation is summarized below:

- Skin: $[0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0]_T$
- Stiffener: [45, 0, 45, 0, 45, 0]S
- Flange: [0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 0, 45, 0, 45, 0, 45]T

2.2 SELECTIVE STITCHING OF PREFORM.

Fabrication of dry preforms involves lay-up and selective stitching of fabric layers with Kevlar threads. A 1600-denier Kevlar 29 thread was selected for stitching together with a 400-denier Kevlar 29 thread for the bobbin. Their typical properties are found in references 5 and 12. Selective stitching was done on a JUKI 200 industrial sewing machine with a working platform capable of handling up to 50- x 70- x 2.5-cm preforms. The stitching speed was maintained at 18.0 cm per minute to minimize damage to the in-plane reinforcement near the stitches [13].

Fiber preforms for the selectively stitched, stiffened panels were prepared as follows. On the flange skin adjoining region, selective stitching was used to prevent stiffener separation under skin buckling and to form a near-net shape of the stiffened panel, as in the fully stitched panel. The stitch density in the selectively stitched panels was reduced to 2.48 stitches per cm^2 to investigate the effect of stitch density on the compression strength of undamaged panels and on the impact damage area. In the stiffener region, stitching was minimized for the selectively stitched panels. A minimal amount of stitch row was used for handling and to prevent edge delamination at the top of the stiffener. In addition, a stitch row near the start of the stiffener was used to investigate if the impact crack propagation could be deflected. The selectively stitched conditions are summarized in table 2, and the resulting stitched fabric preforms are shown in figure 1.

2.3 RESIN FILM INFUSION PROCESS.

A resin film was prepared using 500 grams of 3501-6 resin. This is slightly more than required for a 50% fiber volume content to ensure complete saturation of the dry preform. The refrigerated solid resin was crushed into fine particles smaller than 5 mm in diameter. The particles were spread evenly over the inside mold surface and heated to 70°C inside an autoclave for 20 minutes to form a flat film approximately 5 mm thick, as shown in figure 2.

The mold used for resin infiltration consisted of a top and a bottom platen, four side aluminum bars, and three-filleted inner aluminum bars. The inner bars determined the location and

thickness of the two stiffeners. Each of the mold parts was treated with a release agent and covered tightly with a nonporous Release Ease 234 peel ply using a high temperature adhesive tape. The mold preform assembly is shown in figure 3.

The selectively stitched preform was placed into the mold containing the resin film, pressed down using a roller, and the inner molds were put into place. Four bleeder plies approximately 8 by 15 cm were placed on center where two vacuum ports were to be located. A rectangular steel frame covered with a porous ply was inserted to keep the vacuum ports and the bleeder plies apart to avoid resin flow into the vacuum ports. Two layers of Airweave breathers were used to cover the topside, and the entire assembly was vacuum bagged using IPPLON DP-1000 and sealed around the edges with a sealant tape. After attaching two vacuum lines, a leak test was performed, as shown in figure 4.

Dimensions of the manufactured panel were 54.61 x 30.48 x 4.23 cm. Each panel was cut into two specimens using a high-pressure abrasive water jet system with a water jet pressure of 275.6 MPa. Overall dimensions of each specimen were 25.4 x 25.4 cm with two 2.54-cm stiffeners. The two specimens from the same panel were then designated with a specimen identification number and either an a or b.

3. COMPRESION BEHAVIOR OF SELECTIVELY STITCHED, STIFFENED PANELS.

The test matrix for static compression tests of selectively stitched panels is shown in table 3. The test matrices for the unstitched and fully stitched panels used in the previous phases are also included for comparison. The effects of different types of impact damage, i.e., clearly visible flange damage (CVFD) and clearly visible stiffener damage (CVSD), on the compression behavior of selectively stiffened panels were investigated. Impact damages were inflicted using drop-weight impact of 30 Joules from the skin side of the stiffened panel.

3.1 IMPACT TESTING.

Impact tests were performed according to the SACMA Recommended Test Method for Compression After Impact Properties of Oriented Fiber Resin Composites, SRM 2-88 [14]. Impact loading was applied using a drop weight on a Dynatup 8250 drop-weight impact testing machine with a 4.3-kg indenter, having a 12.7-mm-diameter tup.

For impact and subsequent compression testing, the panel was held between top and bottom end plates. The panel was inserted into the grooves of the end plates and secured using Cerrobend® alloy, having a melting temperature of 70°C. For each panel, 350 g of Cerrobend® was melted in a ceramic cup at 100°C for 15 minutes inside an oven. The top and bottom plates were also placed inside the oven, and the molten alloy was poured into the grooves of the heated plates. The plates were then removed from the oven, placed on a Plexiglas support for better alignment, and the composite panel was slipped into the grooves. The entire assembly was then allowed to cool down in ambient conditions. The panel assembly was placed on the base of the Dynatup for impact testing with the end plates providing support [15-18]. In both cases, the impact points were on the flat skin side of the panel.

3.2 COMPRESSION TESTING.

Static compression tests were performed on a 500-kN Instron test frame at a displacement rate of 1.27 mm/min. The top plate of the panel assembly was secured onto a T-shaped platen with four socket cap screws. The positions of the screws ensured alignment of the centroid of the panel with the loading axis. The T-platen was held in a hydraulic grip. Securing the assembly to the top hydraulic grip prevented the upper half of the assembly from falling on the panel when the panel failed. The bottom plate of the assembly was not secured to the T-platen. Rather, two aluminum guide rails were used to minimize lateral displacement between the bottom plate and the T-platen. The resulting gage length of the panel was approximately 25.0 cm.

Omega 900 series data acquisition modules were used to record strains, lateral displacement, top displacement, and applied load. Strain gages were placed back to back at the center of the panel to capture a bifurcation point during loading. Another strain gage was placed on the stiffener to monitor the stiffener strain. In addition to measuring the local strains, a shadow Moiré fringe technique was implemented to observe the global deformation and mode shapes during loading.

In the following sections, the effect of impact damage on the static properties of the selectively stitched panels will be discussed and compared with the unstitched and fully stitched panels.

The individual test data on the selectively stitched panels are summarized in table 4. As shown in figure 5, the average buckling strengths of selectively stitched panels for undamaged, CVFD, and CVSD are 86.0 MPa, 73.0 MPa, and 65.5 MPa, respectively. The impact damage on CVSD panel no. 7 was more than expected; this resulted in a lower buckling strength. Other than panel no. 7, a fairly consistent buckling strength was observed. A wider experimental scatter was observed for CVSD panels due to differences in stiffener damage incurred on each panel. Additional information on the manufactured panel quality for selectively stitched panels is summarized in table 5. The undamaged and CVFD results are also seen to be fairly consistent. Buckling strains measured by a center strain gage are shown in figure 6, while the elastic moduli calculated from the measured strains are shown in figure 7. On average, undamaged and CVFD panels buckled at a strain value of 2130 μstrain and 2010 μstrain, respectively, whereas CVSD panels buckled around 1720 μstrain. The initial compressive moduli remain fairly consistent with the average value of 40.3 GPa, 38.6 GPa, and 38.1 GPa for undamaged, CVFD, and CVSD, respectively. The failure strengths of the same panels are shown in figure 8. The reported values for the average failure strengths of undamaged, CVFD, and CVSD panels are 166.3 MPa, 157.7 MPa, and 132.0 MPa, respectively.

Compressive moduli of selectively stitched, stiffened panels, prior to buckling, fall between the values of the unstitched and fully stitched (9.92 stitches/cm^2) panels. From table 6, the increase in modulus of selectively stitched and stitched panels are 6.27% and 11.99%, respectively, when compared to unstitched panels. In terms of modulus, the benefit of selective stitching is marginal at best when standard deviation values are considered. It is noted that selective stitching was performed with reduced stitching density, and selected region was not stitched at all. The corresponding buckling strength increase was marginal as shown in figure 9. However, the failure strengths were shown to increase significantly with an increase in stitch density for undamaged and CVFD panels. Furthermore, the selectively stitched panel was shown

experimentally to yield the highest average strength against clearly visible stiffener impact, as shown in figure 10.

3.3 EFFECT OF STITCH DENSITY ON COMPRESSIVE PROPERTIES: UNDAMAGED STIFFENED PANELS.

In this section, the compressive properties of undamaged, selectively stitched, stiffened panels are compared to those of the unstitched and fully stitched panels. For the comparisons, tests 1 to 3 of unstitched and selectively stitched panels are used. As for the fully stitched panels, only tests 1 and 3 are used. Test 2 of the fully stitched panel was omitted since its result was considerably lower than tests 1 and 3 due to a manufactured groove defect that caused premature failure.

As summarized in tables 6 and 7, the mean values of compressive modulus and buckling strength increased with stitching, where the values of selective stitching fell in midrange of the unstitched and fully stitched panels. Compared to unstitched panels, the percent increase in compressive modulus was 2.5% and 5.8% for selectively stitched and fully stitched panels, respectively; the percent increase in buckling strength was 3.2% and 8.2% for selectively stitched and fully stitched panels, respectively. However, with such small sample sizes, one can also say that stitching has no significant effect on modulus or buckling.

As shown in figures 11 and 12, the strain plots of selectively stitched and unstitched panels closely resemble each other for both the skin (front) and stiffener (back) side strains during loading. The only difference is that the back side strain value is extended for the selectively stitched panel, hence, the failure strength increased for this panel. Prior to a failure, there is a relaxation or stagnation in the strain value for both unstitched and selectively stitched panels. As shown in figure 13, the skin side strain history for the fully stitched panel resembles those of selectively stitched and unstitched panels. However, the stiffener side strain differs in that it increases bilinearly until failure.

As summarized in table 8, the failure strengths of selectively stitched panels were on average 16.3% higher than the unstitched panels, whereas the failure strengths of fully stitched panels were on average 23.9% higher than the unstitched panels. For the selectively stitched panels, the failure to buckling strength ratio ranged from 1.83 to 2.02, and a slightly higher ratio was calculated for the fully stitched panel with a range of 2.06 to 2.21. However, the failure to buckling ratio fluctuated from 1.68 to 2.18 for the unstitched panels, and for these panels, the higher buckling strength did not necessarily translate to higher failure strength. The reason for this is due to differences in failure modes. Tests 1 and 3 of unstitched panels failed with stiffener flange separation.

With the selectively stitched panels, the stiffener flange separation was not observed. Similar to the fully stitched panels, the failure occurred with fracture of both stiffeners in the midregion and the crack line extending into the flange and skin regions as shown in figure 14. The crack line is attributed to the mode shape change prior to stiffener failure. Additional fractures at the top and bottom regions of the stiffener were experimentally observed.

As expected, the experimental results of undamaged panels indicate that the selectively stitched panels and unstitched panels were quite similar, except that the stiffener separation failure was effectively suppressed with flange region stitching. However, the selectively stitched panel did not perform at the same level as the fully stitched panel.

3.4 EFFECT OF STITCHING DENSITY ON COMPRESSIVE PROPERTIES: FLANGE-IMPACTED PANELS.

In section 3.3, the effect of stitching on the variations in compressive modulus and buckling strength was marginal as far as the standard deviation is concerned. However, the changes are noticeable in the flanged impacted panels due to the differences between the amount of damage inflicted on selectively stitched, unstitched, and stitched panels. The cause of the difference can be attributed to differing stitch densities that reduced the impact damage size. The flange-impacted stiffened panel results are summarized in this section, and tests 4 to 6 of the selectively stitched, unstitched, and fully stitched panels are compared.

The impact of 30 Joules produced clearly visible penetration through the flange thickness of selectively stitched and unstitched panels alike. However, the stitched panels sustained a lesser degree of damage around the impact area. Panels with 2.48 stitches per cm^2 (selectively stitched) typically had 20% less damage compared to unstitched panels, and panels with 9.92 stitches per cm^2 (fully stitched) had 29% less damage compared to unstitched panels.

For all stitch densities, the impacted side had a smaller damage size than the exit side. Also, as for the impact side, the damage size on the exit side decreased significantly with increasing stitch density. For example, in an unstitched panel, the impact side damage diameter was 14.85 mm, whereas on the exit side, the damage diameter was 20.85 mm. Moreover, the impact on the unstitched flange region was seen to be much more severe, as evidenced by the raised region around the damage as shown in figure 15. From the differences in impact side and exit damage diameter, the shear-out angle increased with increased stitch densities.

As shown in table 9, the compressive modulus increased noticeably with stitching due to the corresponding reduction in damage diameter. The percentage increase in compressive modulus for the flange-impacted panels with 2.48 stitches per cm^2 and 9.92 stitches per cm^2 were 11.3% and 17.3%, respectively. It is noted that the flange panel values are comparatively lower than the undamaged panels results due to presence of impact damage. A similar trend is observed for the buckling strengths with 5.8% and 8.7% for 2.48 stitches per cm^2 and 9.92 stitches per cm^2, respectively. The buckling strengths are summarized in table 10.

As shown in figures 16 through 18, the strain plots at the panel center during the loading resemble each other in that their shapes are quite similar. One obvious difference is that the failure strength increased with increased stitch density. The other difference is observed for the skin (front) side strain history. Near the 100 MPa stress level, the unstitched panel stress rises asymptotically, whereas the strain for the stitched panels continued as before. When the stiffener side (back) strain is considered, it indicates strain relaxation for all the panels alike. The source for this anomaly is uncertain. One possible explanation is that the strain relief is due to an unimpeded advancing crack in the unstitched panel. Another explanation is that the stiffener close to the impact in unstitched panel fractures ahead, leading to a different mode shape at

failure. Ultimately, the unstitched panel had the lowest compression strength as summarized in table 11.

As shown in figure 19, typical failure occurred due to a crack extension from the impact site that migrated bilaterally, and failure was imminent when the crack had extended into a stiffener. In terms of percentage increase in strength compared to the unstitched panels, the failure strength increased by 15.9% on average with 2.48 stitches per cm^2 and 18.8% with 9.92 stitches per cm^2.

3.5 EFFECT OF STITCHING DENSITY ON COMPRESSIVE PROPERTIES: STIFFENER-IMPACTED PANELS.

In this section, the stiffener impact panel results are compared using tests 7 to 9 of selectively stitched panels; tests 7, 8, and 10 of unstitched panels; and tests 8 to 10 of fully stitched panels.

As shown in table 12, the fully stitched panel had the highest compressive modulus compared to the selectively stitched and unstitched panels. The percent increase in modulus calculated from the unstitched panels was 16.5% for fully stitched panels and 5.17% for selectively stitched panels. Table 13 compares the buckling strengths for the three types of stiffener-damaged panels. The buckling strength does not appear to be a function of stitching if one discards one test result, test 7, for the unstitched panel. This panel had a higher buckling strength as it sustained less damage than the other panels in this set, resulting in changes of the buckling mode. The x-ray photos in figure 20 may not show much difference between test 7 (P1b) and test 10 (P10b). However, visual inspections revealed the crack lines extending to the right side of the stiffener in panels P1b and P10b to be ~0.5 and ~1.0 cm in length, respectively. These cracks were located in the flanges between the stiffeners. Again, figures 20(b) and 20(d) appear to indicate that the stiffener cracks are through the entire stiffener height in both panels; however, the crack in panel P1b actually extended only through two-thirds of the stiffener height, whereas the stiffener in panel P10b was completely broken. In fact, the stiffener in the latter panel stayed bent as a result of the damage.

The failure strength results are summarized in table 14. The ratio of failure strength to buckling strength varied from 1.69 to 2.14 for selectively stitched panels, 1.36 to 1.61 for unstitched panels, and 1.44 to 1.96 for fully stitched panels. Similar failure strength values for fully stitched panels indicated that equivalent impact damage were inflicted on those panels. Although not readily seen from buckling strengths of the selectively stitched panels, tests 8 and 9 yielded higher failure strengths that are comparable to the discrepancy shown for the unstitched panel results. X-ray photos of tests 7 and 8 of the selectively stitched panels shown in figure 21 indicate that test 7 had damage inflicted in the flange area during impact. Moreover, test 8 had an angled crack line in the stiffener compared to the straight crack line of test 7. Although the selectively stitched panels tended to perform better than unstitched and fully stitched panels in terms of failure strengths, the test results are inconclusive. The high variation in test results, 20% coefficient of variation for selectively stitched and unstitched panels, makes the benefit of selectively stitched panels unrealizeable. The low variation of fully stitched panels indicates that stitching helps the manufacturing process to form uniform better quality panels.

Strain plots of the stiffener-damaged panels vary significantly, depending on the severity of the damage. For the selectively stitched panels, strain plot, typical of tests 8 and 9, with less severe

damage are as shown in figure 22, and is similar to those of the undamaged, figure 11, or the flange-impacted panels, figure 16. The unstitched panels show a similar trend. That is, less severe impact damage does not change the resulting strain plot to any substantial extent, as indicated by test 7 with figure 23. Note that figure 23 resembles the strain plot of unstitched, undamaged panels. All other test panels with severe impact damage, including the fully stitched panel, had strain plots similar to the one in figure 24. All the fully stitched panels suffered severe damage to the stiffener upon impact, as indicated by their strain plots.

Figure 25 shows the typical final failure for the selectively stitched, stiffener-impacted panels. The crack extended bilaterally from the stiffener impact site, and the stiffener cripples once the crack extended approximately 25.4 mm. Immediately, the load was transferred to the other stiffener and that stiffener fractured. The final failure of the other types of panels were similar.

Based on the results described in sections 2 and 3, the stitching is beneficial for both undamaged and impacted panels. However, the effect of stitching varies considerably. The undamaged panel results indicate that 2.48 stitches per cm^2 is sufficient to minimize the stiffener separation but has a lower strength (13.8% lower) compared to panels with 9.92 stitches per cm^2. However, the flange-impacted panel results indicate a marginal difference between 2.48 stitches per cm^2 and 9.92 stitches per cm^2. Moreover, the stiffener-impacted panel results indicate significant improvement in strength with decreased stitching. Hence, the stitching in the flange and skin should be 2.48 stitches per cm^2 or higher, and the stitching in the stiffener should be minimized and performed as described in section 2.

4. CONSTANT-AMPLITUDE FATIGUE BEHAVIOR OF SELECTIVELY STITCHED, STIFFENED PANELS.

The effectiveness of stitching in preventing damage growth under fatigue loading was investigated using CVFD and CVSD panels of selectively stitched, stiffened panels. The results on selectively stitched panels were then compared with unstitched and fully stitched panels. All damages were induced by 30-J impact on the skin over the stiffener. Constant-amplitude compression, load-dominated fatigue tests were conducted exclusively. In this report, the spectrum amplitude fatigue tests were omitted since the stress amplitude factors for constant-amplitude fatigue tests were extracted from the modified TWIST spectrum, as shown in table 15.

4.1 EXPERIMENTAL PROCEDURE.

Compression fatigue tests were performed on a 500-kN Instron test frame at a frequency ranging from 0.5 to 1.2 Hz, depending on the load levels, to minimize a twist during the loading cycle. The same fixtures and gripping method used in the static compression tests were used in the fatigue tests.

Constant-amplitude fatigue tests were performed at each of the five highest stress levels of the TWIST spectrum. The nominal stress levels are shown in table 16. Because of the testing difficulty, any excursion into tension regime was truncated. Hence, the resulting fatigue stress ratio was infinity on all panels, but the stress amplitude was maintained according to each load level. The flight mean level was kept at 34% of CVFD and CVSD average strength values. The

individual test results of constant-amplitude fatigue of the selectively stitched panels are summarized in tables 17 and 18.

4.2 EFFECT OF SELECTIVE STITCHING ON CONSTANT-AMPLITUDE FATIGUE OF FLANGE-IMPACTED, STIFFENED PANELS.

In this section, the constant-amplitude fatigue behavior of selectively stitched CVFD panels is summarized and compared with unstitched and fully stitched panels to quantify the effectiveness of stitching on fatigue strength for CVFD panels.

At the first stress level (135.3 MPa), two selectively stitched panels, Sep6a and Sep9a, were tested. Panel Sep6a failed at 225 cycles with the cracks extending from the impacted region, whereas panel Sep9a failed at 364 cycles due to a stiffener failure away from the impact site. The difference in the failure modes is due to the difference in the impact damage. Panel Sep6a had typical penetration damage (figure 26), whereas panel Sep9a did not have penetration damage (figure 27). The sizes of the impact damage on panels Sep6a and Sep9a were measured to be 12.7 mm and 10.0 mm, respectively. It is interesting that the differences in the number of cycles to failure are not that much different.

At the second stress level (130.1 MPa), two selectively stitched panels, Sep7a and Sep16b, were tested. Panel Sep7a failed at 4013 cycles with cracks extending from the damaged sites similar to panel Sep6a but the crack line extended across the entire panel, as shown in figure 28. The damage size of panel Sep7a was equivalent to panel Sep6a. Panel Sep16a failed at 982 cycles; figure 29 shows the failed panel.

At the third stress level (119.7 MPa), three selectively stitched panels, Sep7b, Sep9b, and Sep10b, were tested. Panel Sep7b failed at 14,164 cycles, and as shown in figure 30, its crack extension mode and damage size was similar to panel Sep7a tested at a higher stress level. Similar to test panel Sep9a, panel Sep9b failed at 2279 cycles due to a stiffener failure away from the damaged site, as shown in figure 31. Panel Sep9b also showed a nonpenetrating impact. Panel Sep10b failed at 5362 cycles similar to panel Sep7b with cracks extending from the damaged site; figure 32 shows the postfatigue photo.

At the fourth stress level (111.9 MPa), two selectively stitched panels, Sep8a and Sep10a, were tested. Panel Sep10a failed at 896 cycles, lower than panel Sep10b, tested at a higher stress level of 119.7 MPa, even though the failure mode and damage characteristics were similar, as shown in figure 33. Panel Sep8a failed at 16,126 cycles, with clean damage penetration, as shown in figure 34.

At the fifth stress level (103.6 MPa), two samples of selectively stitched panels, Sep8b and Sep11a, were tested. Figures 35 and 36 show panel Sep8b suffered visually much less impact damage than panel Sep11a. However, panel Sep11a failed at 87,934 cycles, whereas panel Sep8b failed after 6037 cycles.

To assess the effect of stitching on the fatigue lives with CVFD, the selectively stitched, unstitched, and fully stitched panel fatigue results and best-fit curves are plotted in figure 37. The best-fit parameters are shown in table 19. As shown in figure 37, the fatigue strength

improvement at 10^5 cycles is marginal for selectively stitched panels and 14% for fully stitched panels compared to unstitched panels. At transition between high to low fatigue stress levels, the best-fit curves indicate approximately 5% and 10% increase in fatigue strength for selectively stitched panels and fully stitched panels compared to the unstitched panels, respectively. However, at higher stress levels, a significant (>20%) increase in the fatigue strength is shown for the selectively stitched panel compared to unstitched panels. The selectively stitched panels perform much better at low cycle fatigue, but their performance at a high number of cycles degrades down toward the level of unstitched panels. At the lower stress levels (high cycles of fatigue) the results show that the beneficial effect with increased stitching density on fatigue strength. As expected, the fully stitched (9.92 stitches per cm^2) panels perform better than unstitched panels and selectively stitched panels at 10^5 cycles.

4.3 EFFECT OF SELECTIVE STITCHING ON CONSTANT-AMPLITUDE FATIGUE OF STIFFENER-IMPACTED, STIFFENED PANELS.

In this section, the behavior of selectively stitched CVSD panels under constant-amplitude fatigue loading is summarized and compared with unstitched and fully stitched panels to quantify the effectiveness of stitching on fatigue strength for CVSD panels.

At the first stress level (113.3MPa), two selectively stitched panels, Sep12b and Sep15b, were tested. Panel Sep12b failed at 104 cycles, and panel Sep15b failed at 6954 cycles. The failure of both panels resulted from the cracks extending from the impacted stiffener, as shown in figures 38 and 39.

At the second stress level (108.9 MPa), two selectively stitched panels, Sep14a and Sep14b, were tested at loading frequencies of 0.5 Hz. Even though these two panels were from the same batch, failure occurred at a fatigue life of 489 and 2879 cycles for panel Sep14a and Sep14b, respectively. As shown in figures 40 and 41, both panels had similar impact damage with a straight line crack through the stiffener height. Also, both panels exhibited the same failure mode with a crack line across the panel in the midsection. However, panel Sep14a had an under-infiltrated filler region that may have induced an early failure compared to panel Sep14b.

At the third stress level (100.2 MPa), two selectively stitched panels, Sep11b and Sep17b, were tested. As figure 42 shows, panel Sep11b did not have a crack line extending from the impacted stiffener. The straight line crack through the stiffener had widened upon failure at 148,489 cycles. Panel Sep17b lasted 15,916 cycles. Both panels failed due to the impacted stiffener failure. However, panel Sep11b had less impact damage than panel Sep17b, as shown in figure 43.

At the fourth stress level (93.7 MPa), two selectively stitched panels, Sep13a and Sep6b, were tested. Again, the results of the two panels were quite different. Panel Sep13a was cycled up to 270,000 and denoted as a runout. The visual inspection of panel Sep13a indicates a visible crack line through the stiffener height, as shown in figure 44. A postimpact photo indicated that panel Sep6b had an angled crack line, as shown in figure 45. Panel Sep6b failed at 68,630 cycles due to an additional twist that caused the premature failure of the panel.

At the fifth stress level (78.8 MPa), three selectively stitched panels, Sep12a, Sep15a, and Sep17a, were tested. Panel Sep12a failed at 6812 cycles. As figure 46 shows, panel Sep12a quality was particularly poor with some under-infiltrated regions on the edges of the panel. Hence, another panel was tested. Panel Sep17a failed at 58,793 cycles, and the failure originated from the damaged stiffener. Panel Sep15a lasted over 300,000 cycles and was denoted as a runout. A photo of panel Sep17a is shown in figure 47.

To assess the effect of stitching on the fatigue lives with CVSD, the selectively stitched, unstitched, and fully stitched panel results are plotted in figure 48. The best-fit parameters used are summarized in table 20. As shown in figure 48, the fatigue strength improvements at 10^5 cycles for fully stitched and selectively stitched panels are 15% and 24% compared to unstitched panels, respectively. The fatigue strength increase diminishes for fully stitched panels at higher stress levels compared to the unstitched panels. On the other hand, the selectively stitched panels perform at least 20% better than both unstitched and fully stitched panels at higher stress levels. The selectively stitched panels are more effective in preventing excessive damage in the impacted stiffener compared to the unstitched and fully stitched panels, as reported in static compression test results. At lower stress levels, both selectively and fully stitched panels are effective in preventing damage growth in the stiffener.

5. CONCLUSIONS.

The effects of selective stitching on compression behavior and constant-amplitude fatigue life of stiffened panels were investigated using two different types of impact damage: clearly visible flange damage (CVFD) and clearly visible stiffener damage (CVSD). From the experimental results, the following conclusions were obtained:

- In undamaged panels, the compressive failure strengths of the selectively stitched panels were on average 16.3% higher than the unstitched panels, whereas failure strengths of the fully stitched panel were on average 23.9% higher than the unstitched panels.

- In CVFD panels, the compressive failure strength increased by 15.9% on average with a selectively stitched density of 2.48 stitches per cm^2 and 18.8% with a fully stitched density of 9.92 stitches per cm^2 compared to the unstitched panels.

- In CVSD panels, the selectively stitched panels had an average compressive failure strength 14.4% higher than the fully stitched panels, whereas the fully stitched panels showed marginal improvements over the unstitched panels.

- In CVFD panels, a marginal fatigue limit strength increase at 10^5 cycles was found for the selectively stitched panels compared to the unstitched panels, whereas the constant-amplitude fatigue strength 10^5 cycles was shown to increase by 14% for the fully stitched (9.92 stitched per cm^2) panels compared with unstitched panels. For the selectively stitched panels, the fatigue strength increased at a higher stress level compared to fully stitched panels, while the strength decreased to the level of an unstitched panel at lower stress levels. It should be noted that the cycling stresses were much higher than one

would expect in service. The high stresses were chosen to induce failure. In practice, fatigue stresses rarely exceed 50% of static ultimate load capacity.

- In CVSD panels, the selectively stitched and fully stitched panels showed fatigue strength improvements of 24% and 15% above the unstitched panels at 10^5 cycles. The increase in fatigue strength with stitching diminished at higher stress levels for fully stitched panels but was enhanced for the selectively stitched panels.

- Both the static and constant-amplitude fatigue tests indicate that a stitching density greater than 2.48 stitches per cm^2 is needed in the flange region, but minimal stitching is sufficient in the stiffener region for similar improvement.

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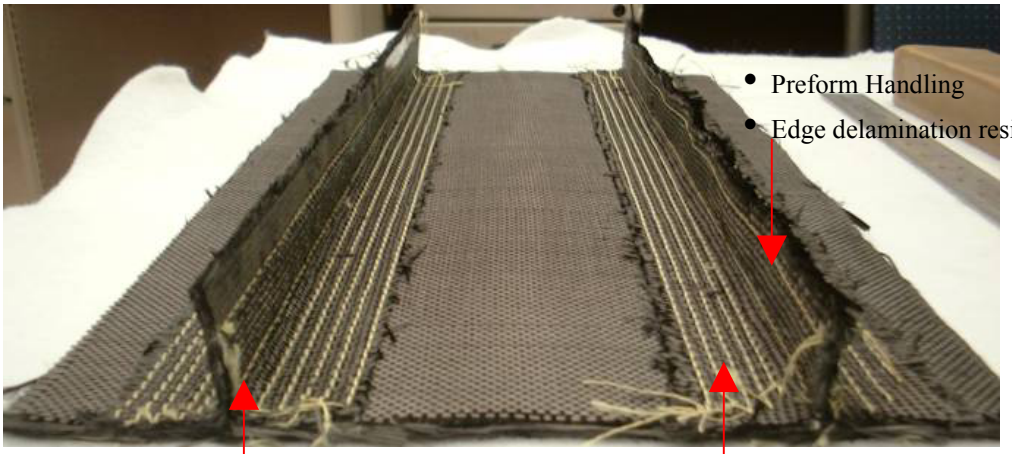


FIGURE 1. SELECTIVELY STITCHED PREFORM WITH STIFFENERS

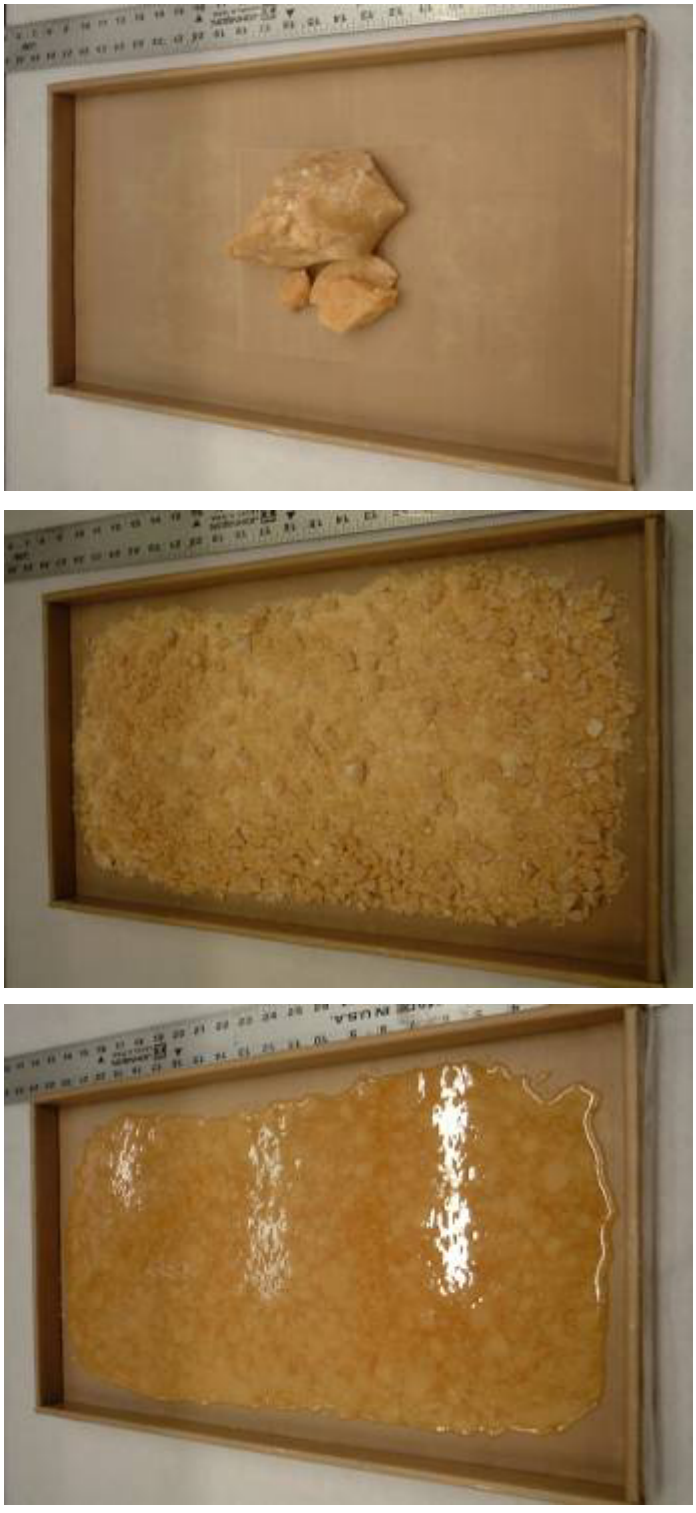


FIGURE 2. RESIN FILM PREPARATION



FIGURE 3. MOLD PREFORM ASSEMBLY

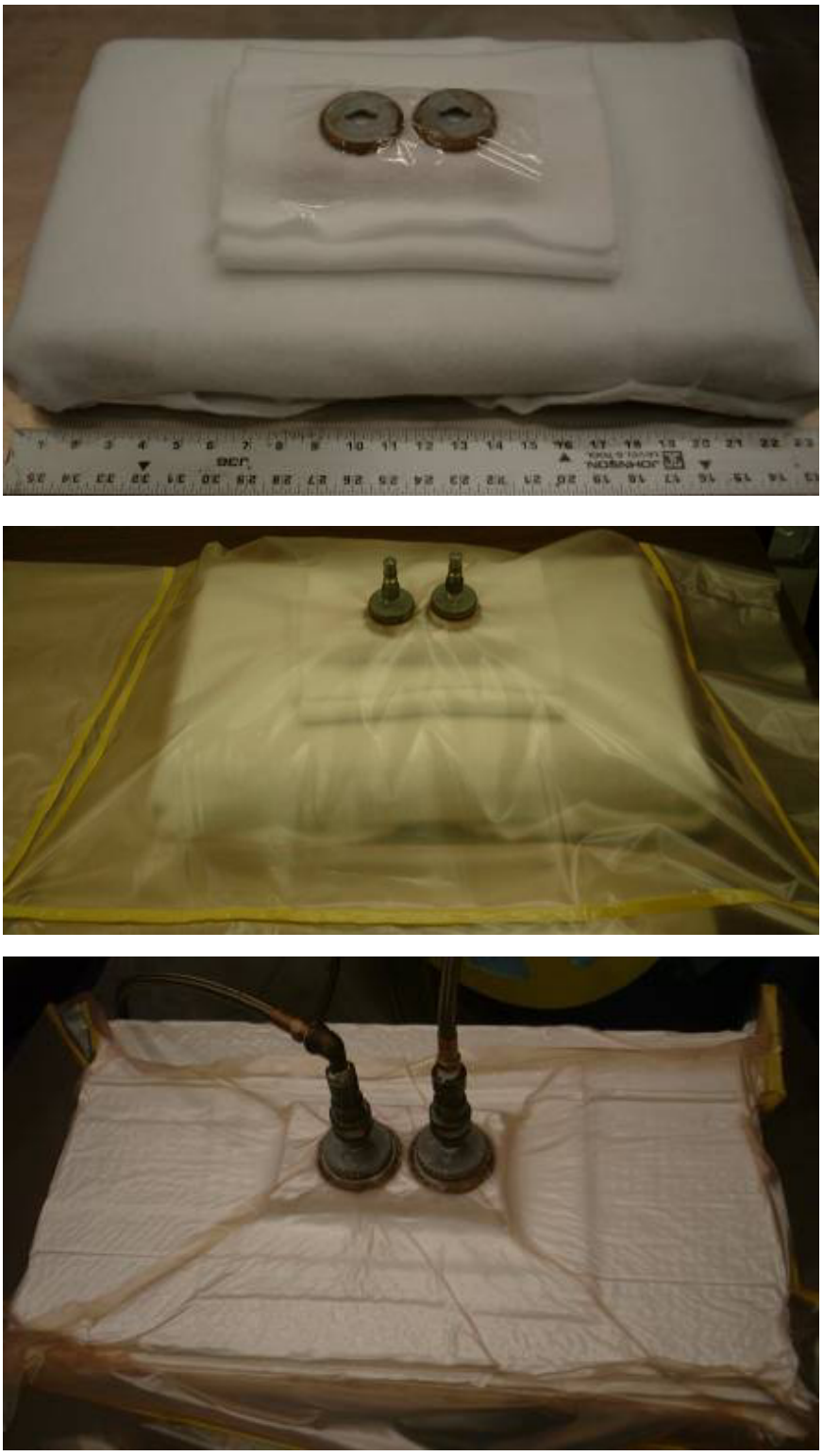


FIGURE 4. VACUUM BAGGING AND LEAK TEST

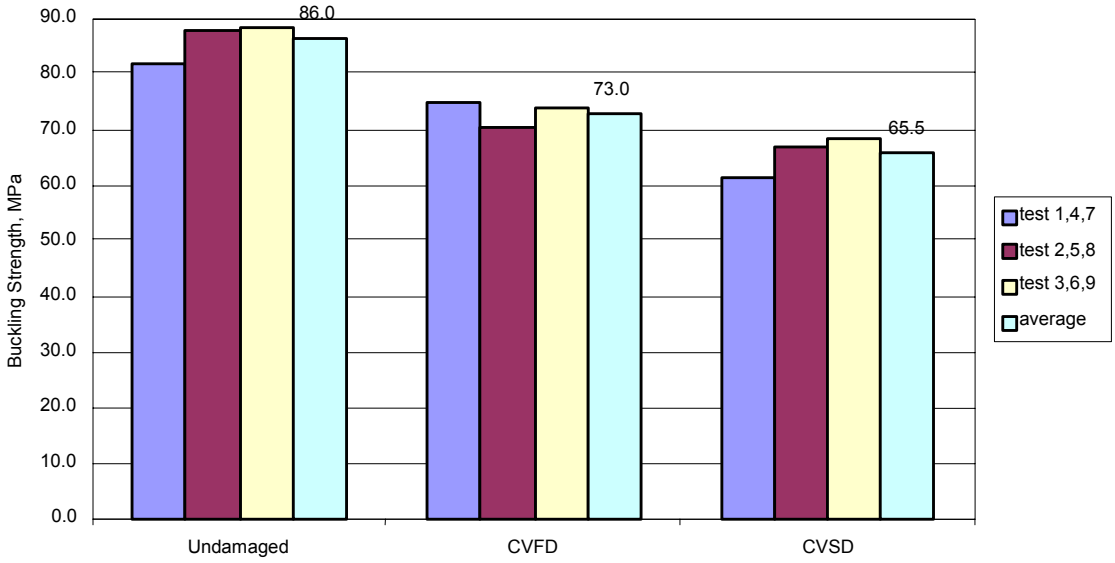


FIGURE 5. BUCKLING STRENGTHS OF SELECTIVELY STITCHED PANELS

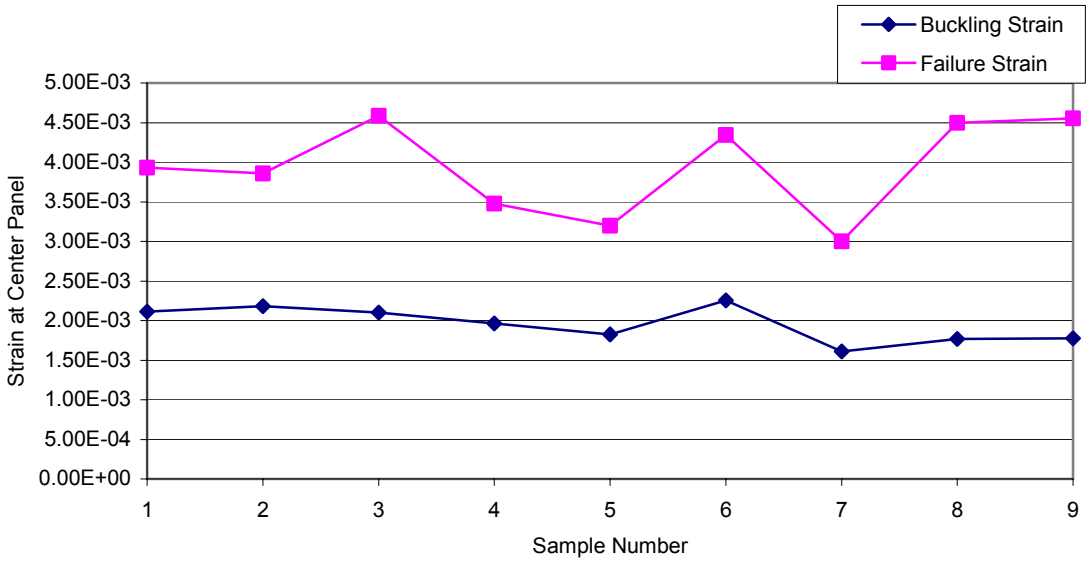


FIGURE 6. BUCKLING AND FAILURE STRAINS OF SELECTIVELY STITCHED PANELS

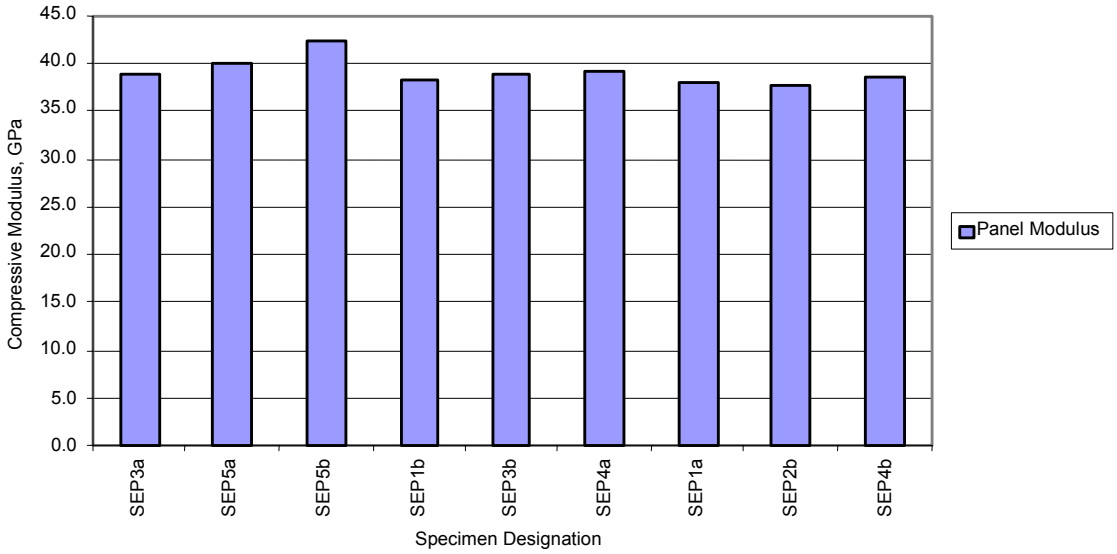


FIGURE 7. COMPRESSIVE MODULI OF SELECTIVELY STITCHED PANELS

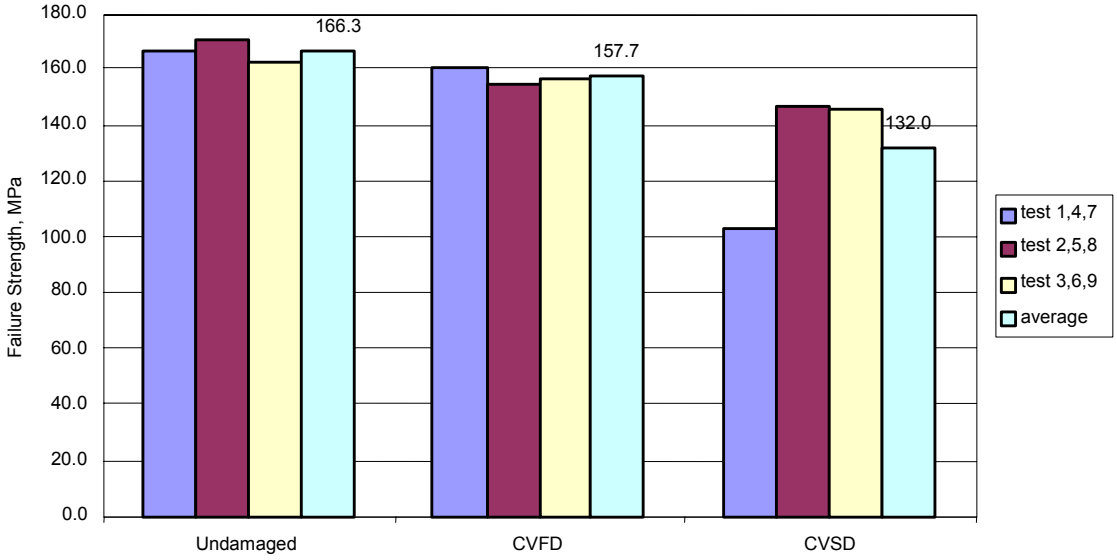


FIGURE 8. FAILURE STRENGTHS OF SELECTIVELY STITCHED PANELS

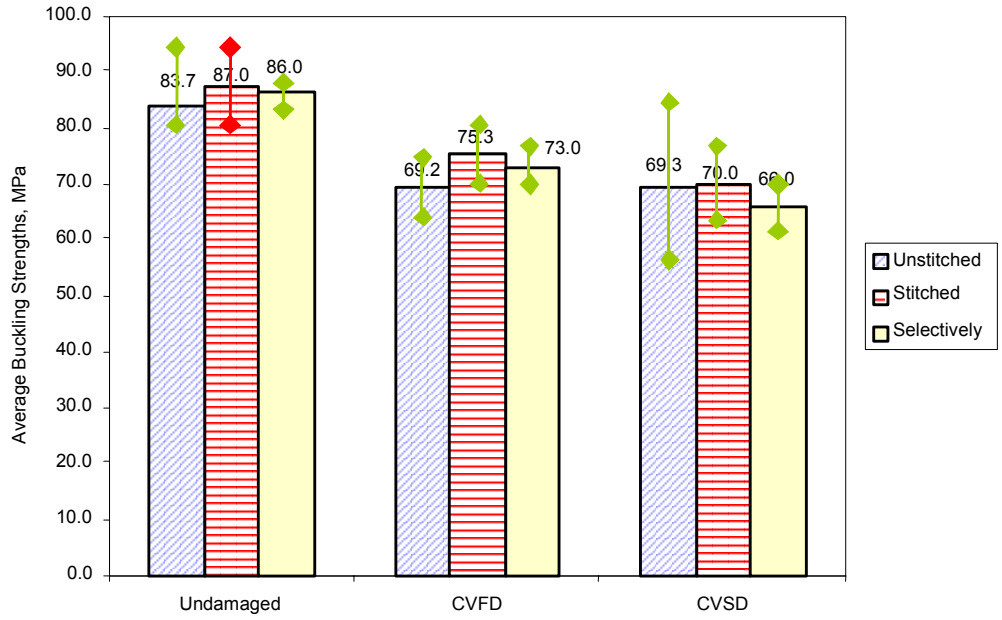


FIGURE 9. AVERAGE BUCKLING STRENGTHS OF SELECTIVELY STITCHED, UNSTITCHED, AND FULLY STITCHED, STIFFENED PANELS

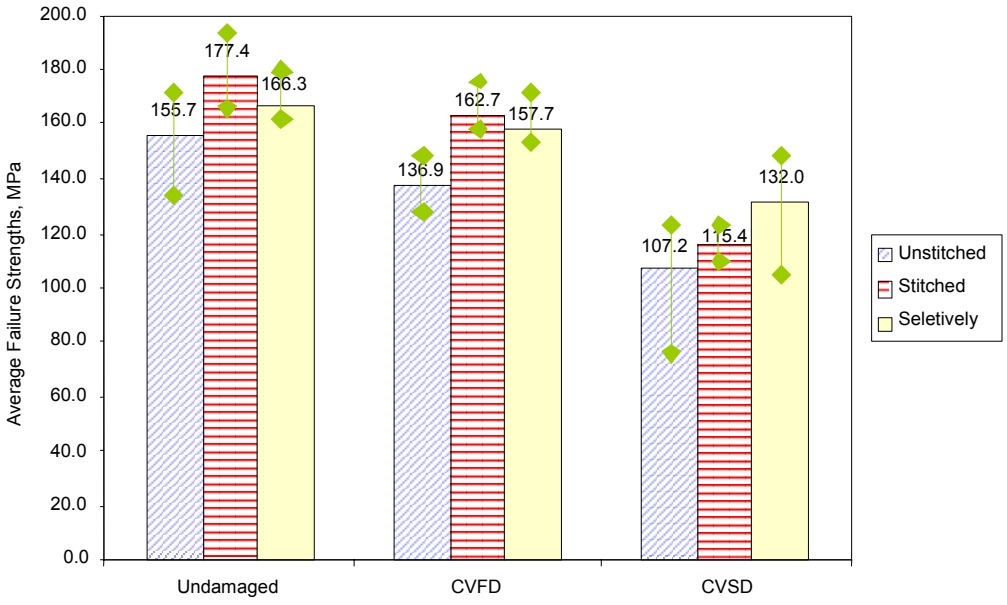


FIGURE 10. AVERAGE COMPRESSION STRENGTHS OF SELECTIVELY STITCHED, UNSTITCHED, AND FULLY STITCHED, STIFFENED PANELS

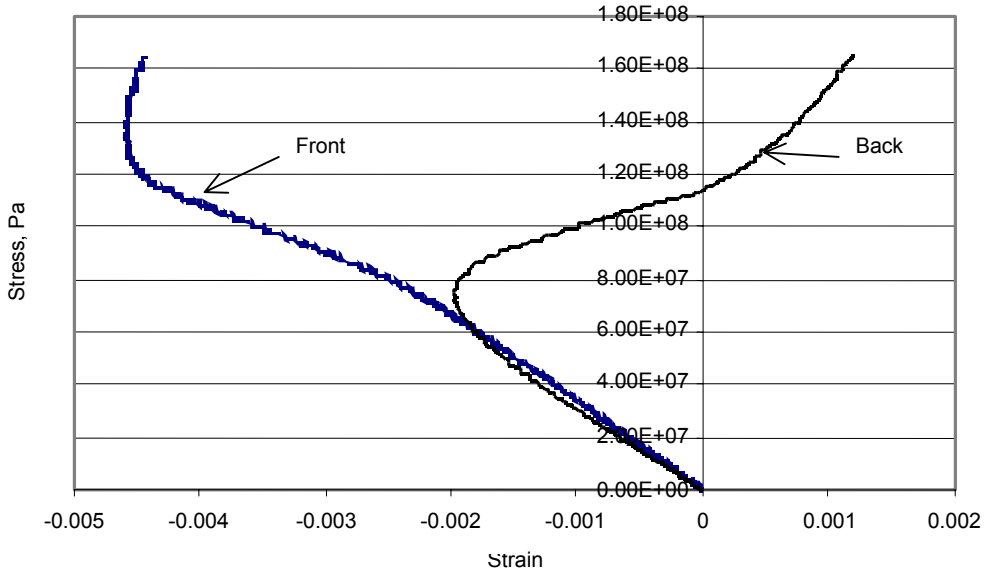


FIGURE 11. LOAD-STRAIN PLOT OF SELECTIVELY STITCHED, STIFFENED PANEL: UNDAMAGED

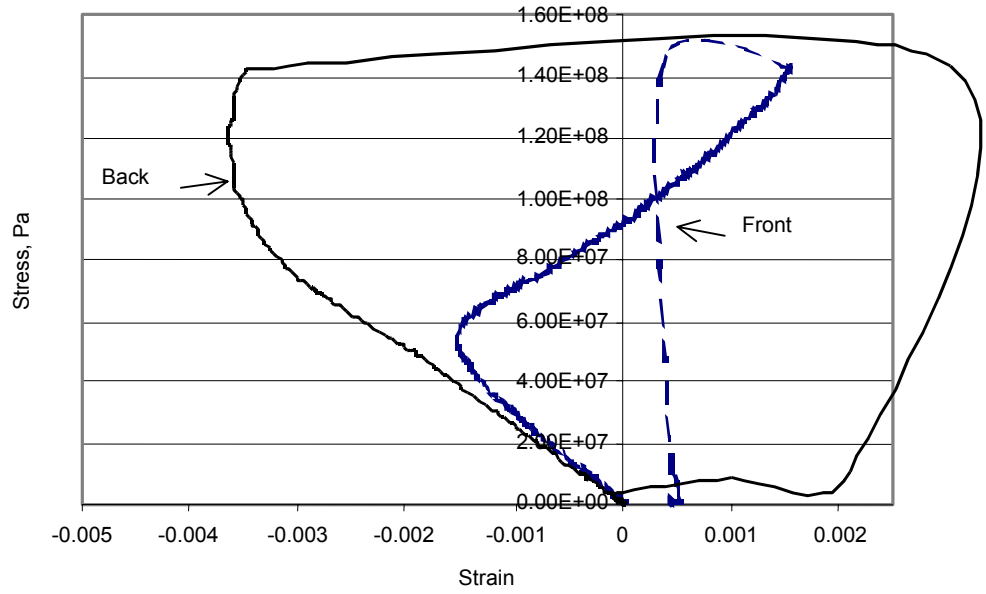


FIGURE 12. LOAD-STRAIN PLOT OF UNSTITCHED, STIFFENED PANEL: UNDAMAGED

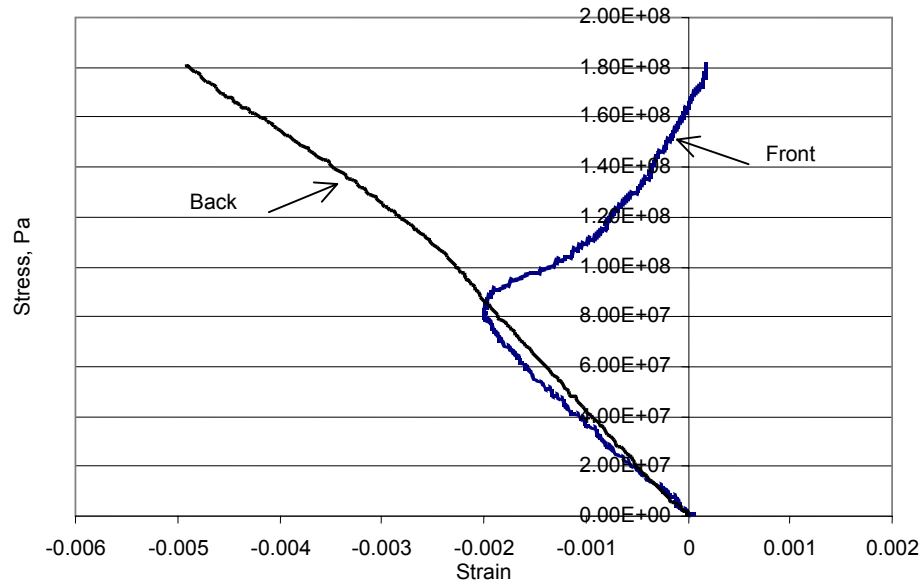


FIGURE 13. LOAD-STRAIN PLOT OF FULLY STITCHED, STIFFENED PANEL: UNDAMAGED

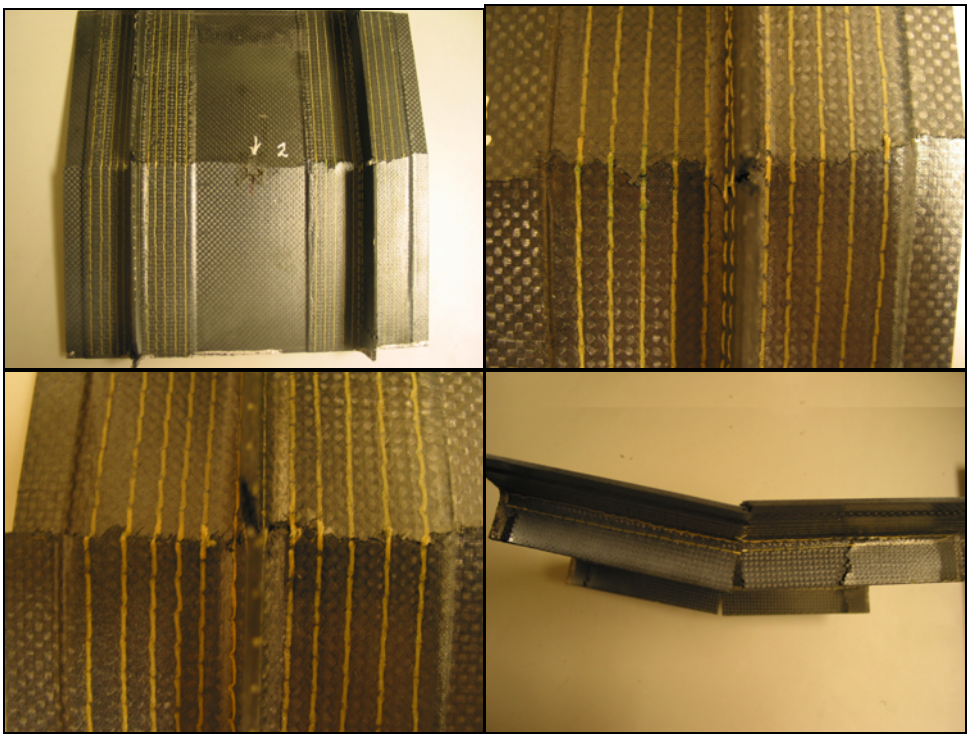


FIGURE 14. FAILED SPECIMEN (SEP3a): UNDAMAGED, SELECTIVELY STITCHED

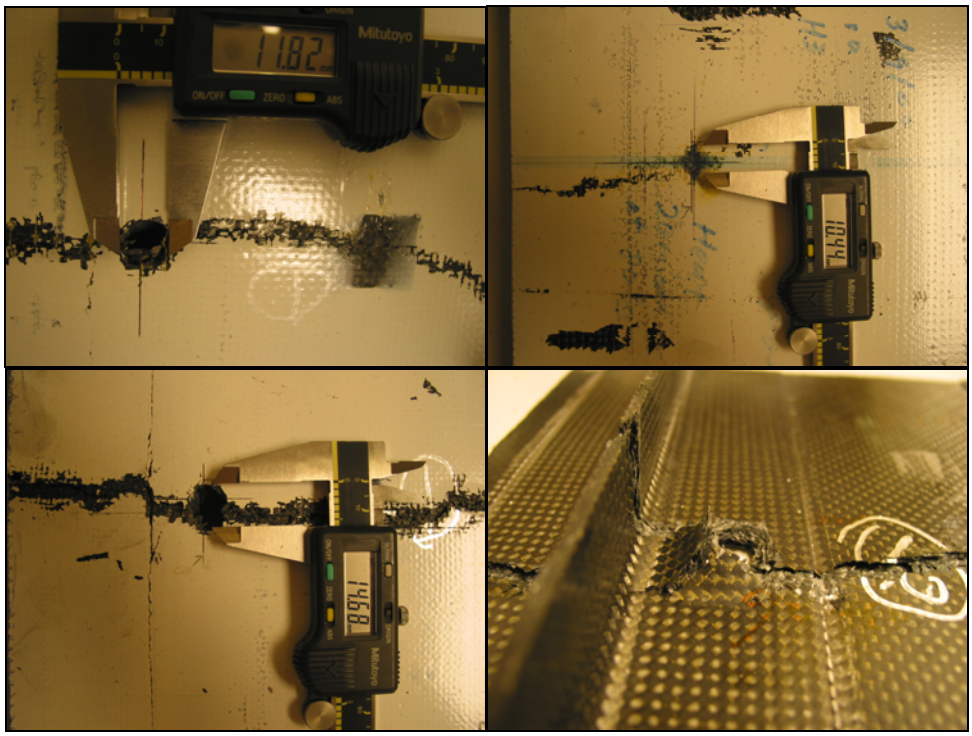


FIGURE 15. FLANGE IMPACT DAMAGES: 2.48 STITCHES PER cm^2 (TOP LEFT), 9.92 STITCHES PER cm^2 (TOP RIGHT), UNSTITCHED (BOTTOM LEFT), AND UNSTITCHED STIFFENER SIDE VIEW (BOTTOM RIGHT)

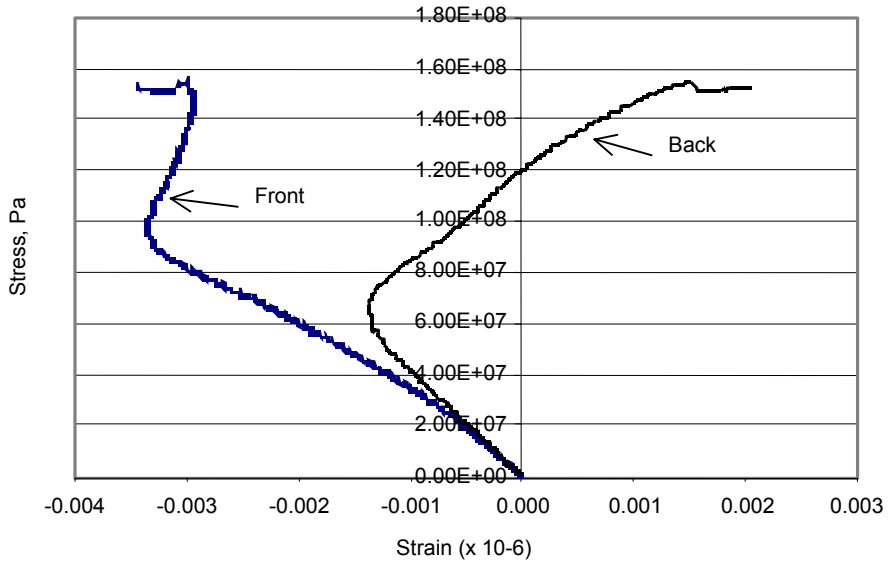


FIGURE 16. LOAD-STRAIN PLOT OF SELECTIVELY STITCHED, STIFFENED PANEL: FLANGE DAMAGED

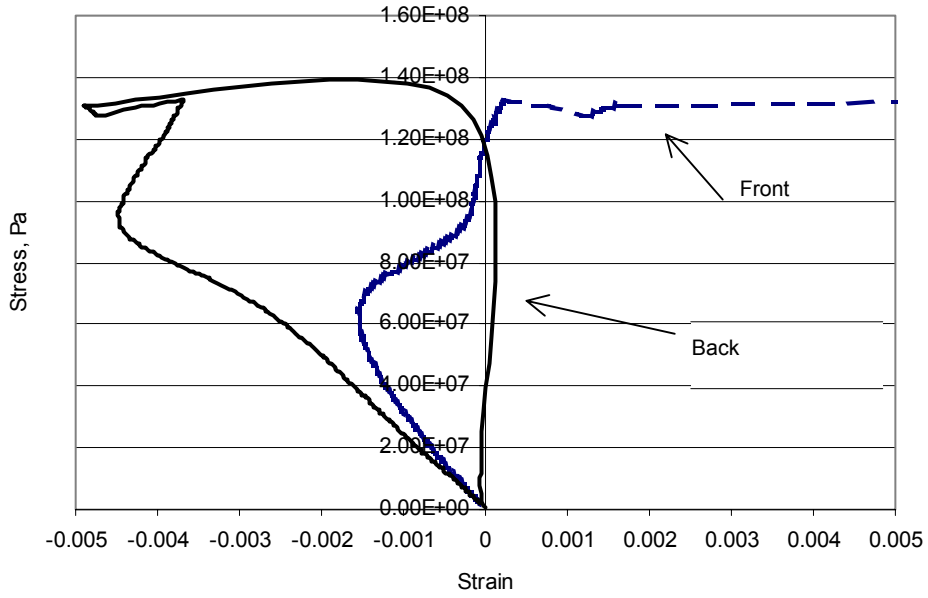


FIGURE 17. LOAD-STRAIN PLOT OF UNSTITCHED, STIFFENED PANEL: FLANGE DAMAGED

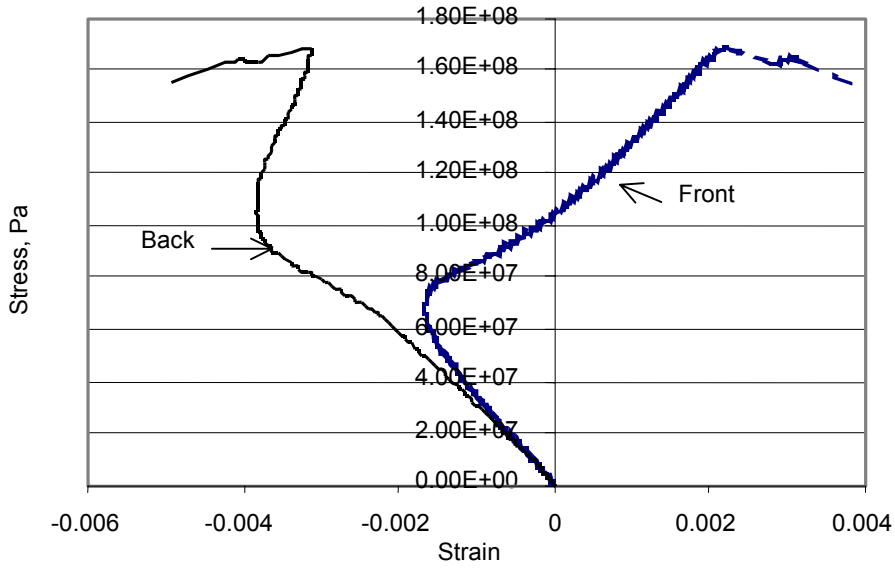


FIGURE 18. LOAD-STRAIN PLOT OF FULLY STITCHED, STIFFENED PANEL: FLANGE DAMAGED

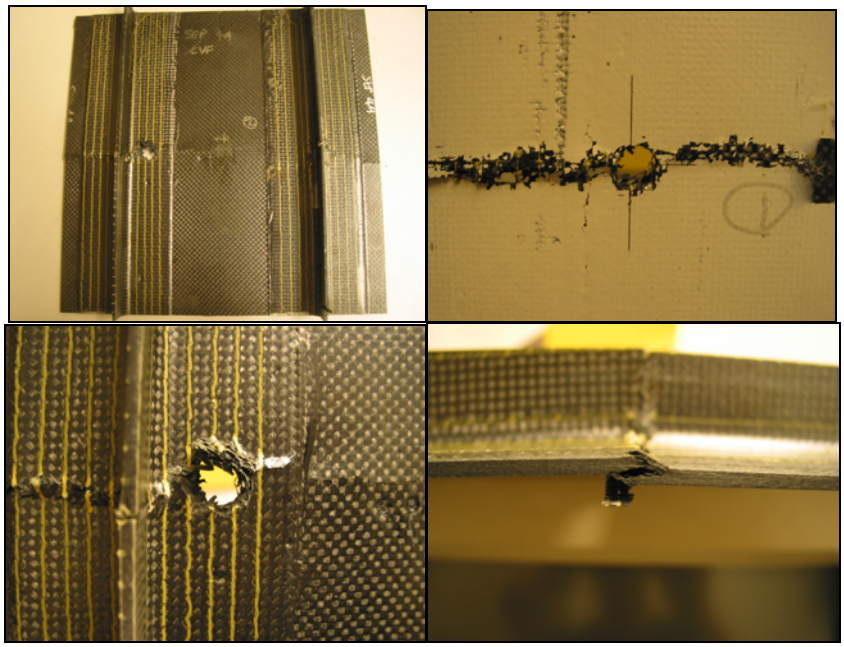


FIGURE 19. FAILED SPECIMEN (SEP4a): FLANGE-IMPACTED, SELECTIVELY STITCHED

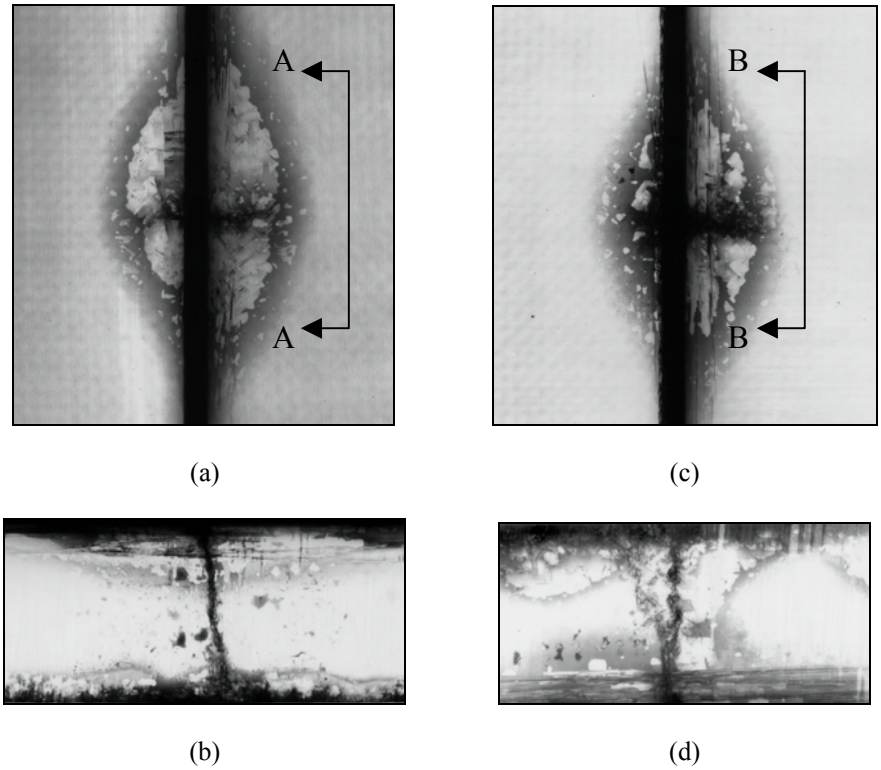


FIGURE 20. X-RAY PHOTO OF UNSTITCHED CVSD (a) PLAN VIEW OF P1b, (b) STIFFENER VIEW OF P1b (A-A), (c) PLAN VIEW OF P10b, AND (d) STIFFENER VIEW OF P10b (B-B)

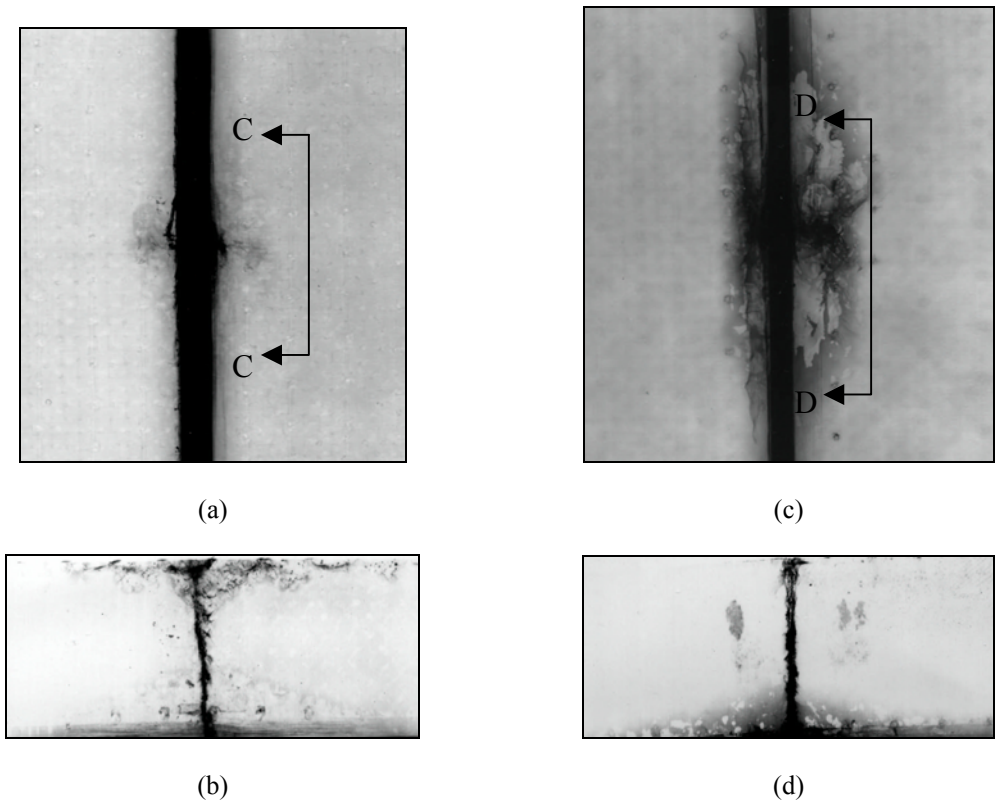


FIGURE 21. X-RAY PHOTO OF SELECTIVELY STITCHED CVSD (a) PLAN VIEW OF SEP2b, (b) STIFFENER VIEW OF SEP2b (C-C), (c) PLAN VIEW OF SEP1a, AND (d) STIFFENER VIEW OF SEP1a (D-D)

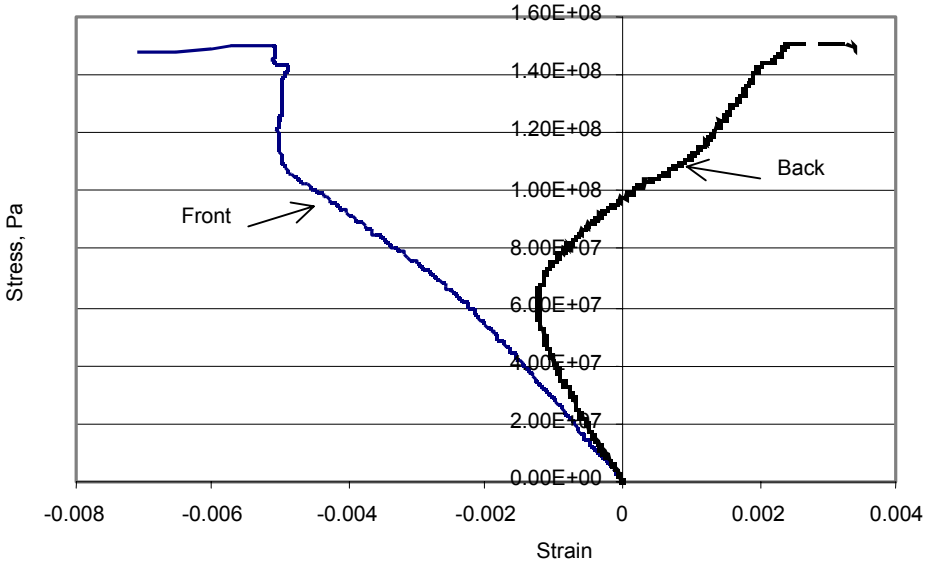


FIGURE 22. LOAD-STRAIN PLOT OF SELECTIVELY STITCHED, STIFFENED PANEL: STIFFENER DAMAGED

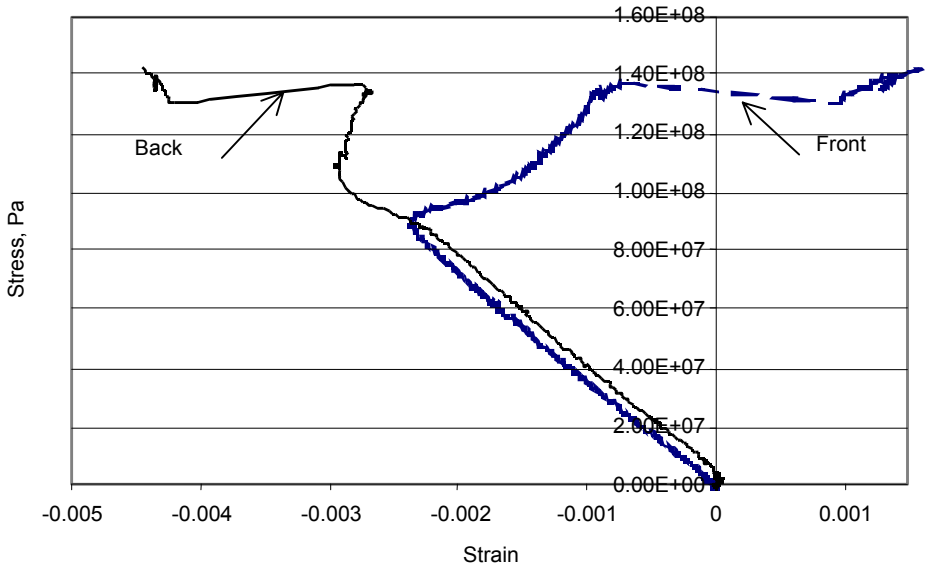


FIGURE 23. LOAD-STRAIN PLOT OF UNSTITCHED, STIFFENED PANEL: STIFFENER DAMAGED

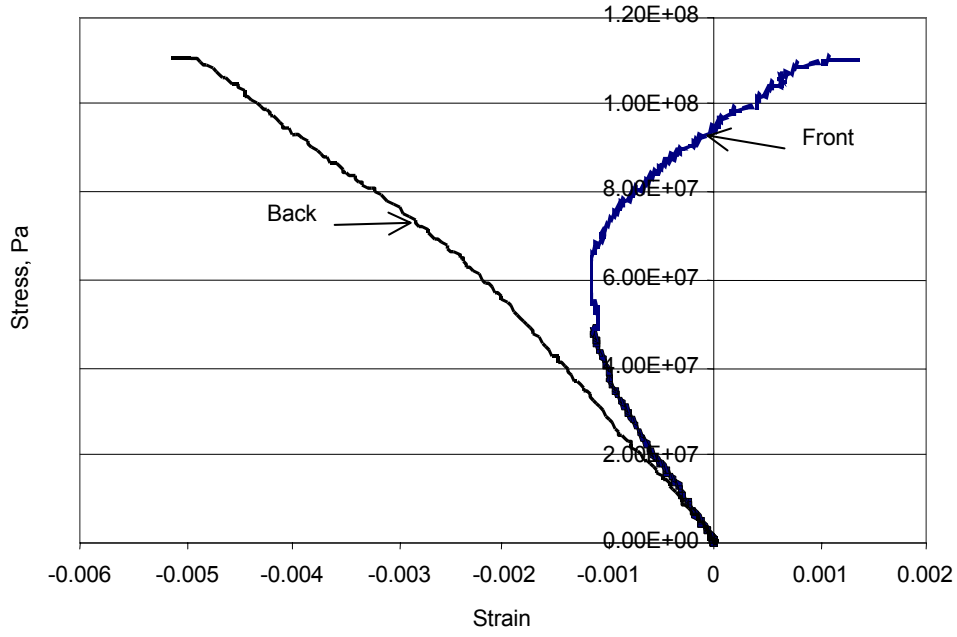


FIGURE 24. LOAD-STRAIN PLOT OF FULLY STITCHED, STIFFENED PANEL: STIFFENER DAMAGED

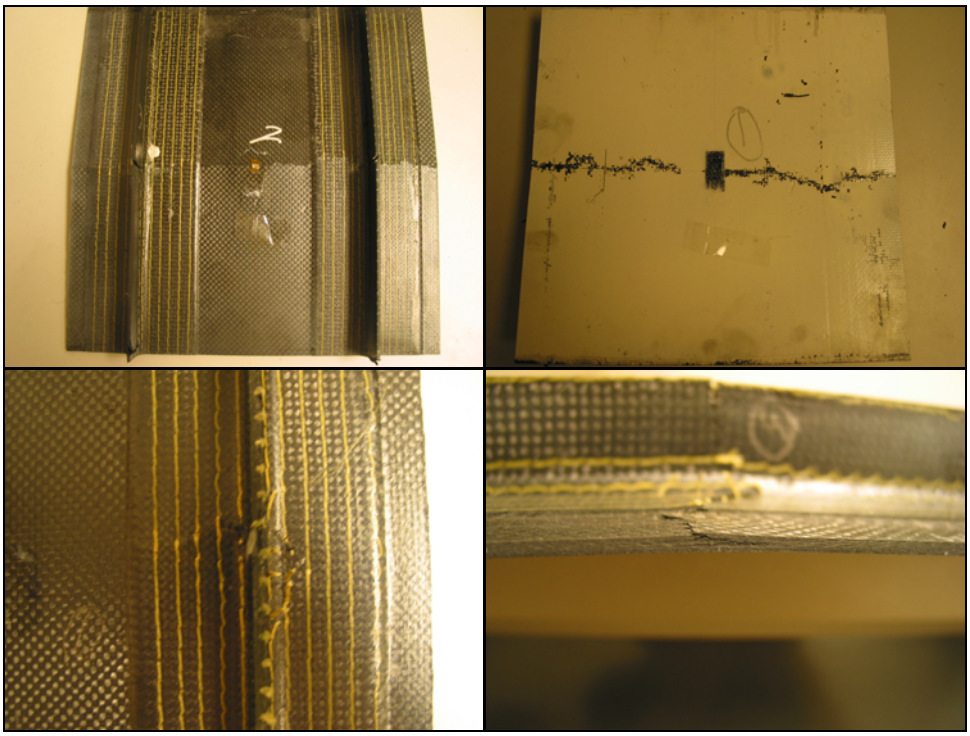


FIGURE 25. FAILED SPECIMEN (SEP1a): STIFFENER-IMPACTED, SELECTIVELY STITCHED

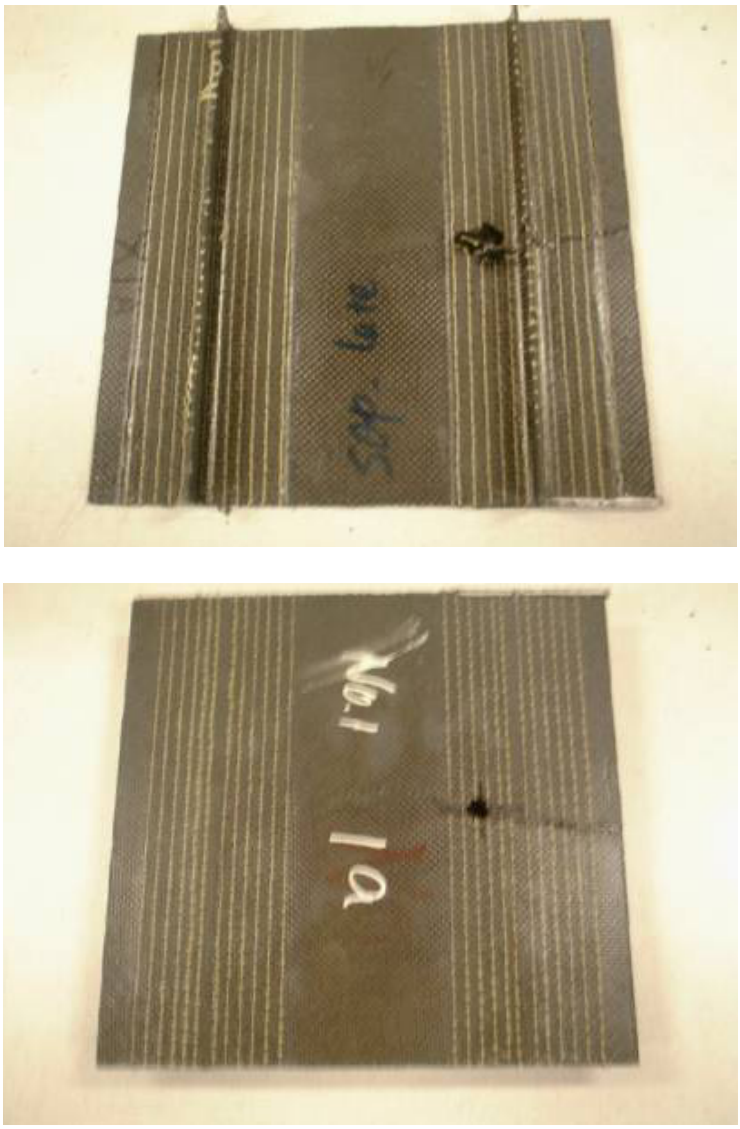


FIGURE 26. PANEL SEP6a POSTFATIGUE





FIGURE 27. PANEL SEP9a POSTFATIGUE

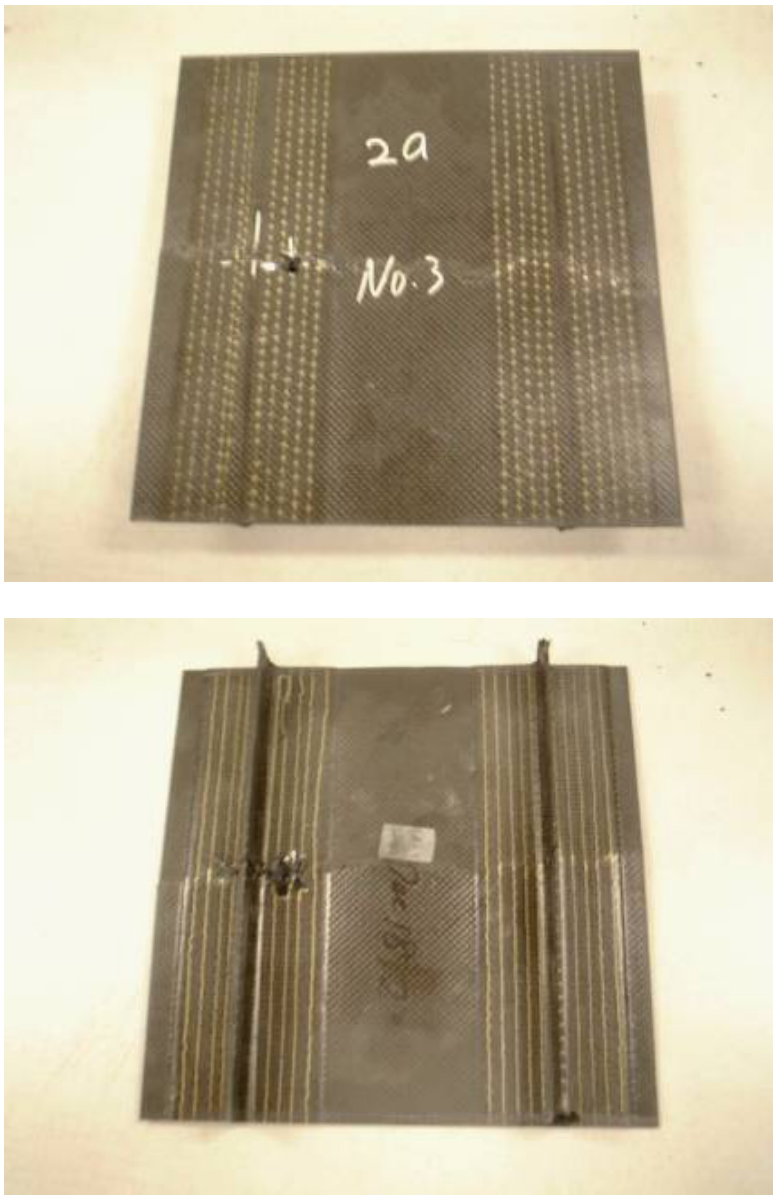


FIGURE 28. PANEL SEP7a POSTFATIGUE

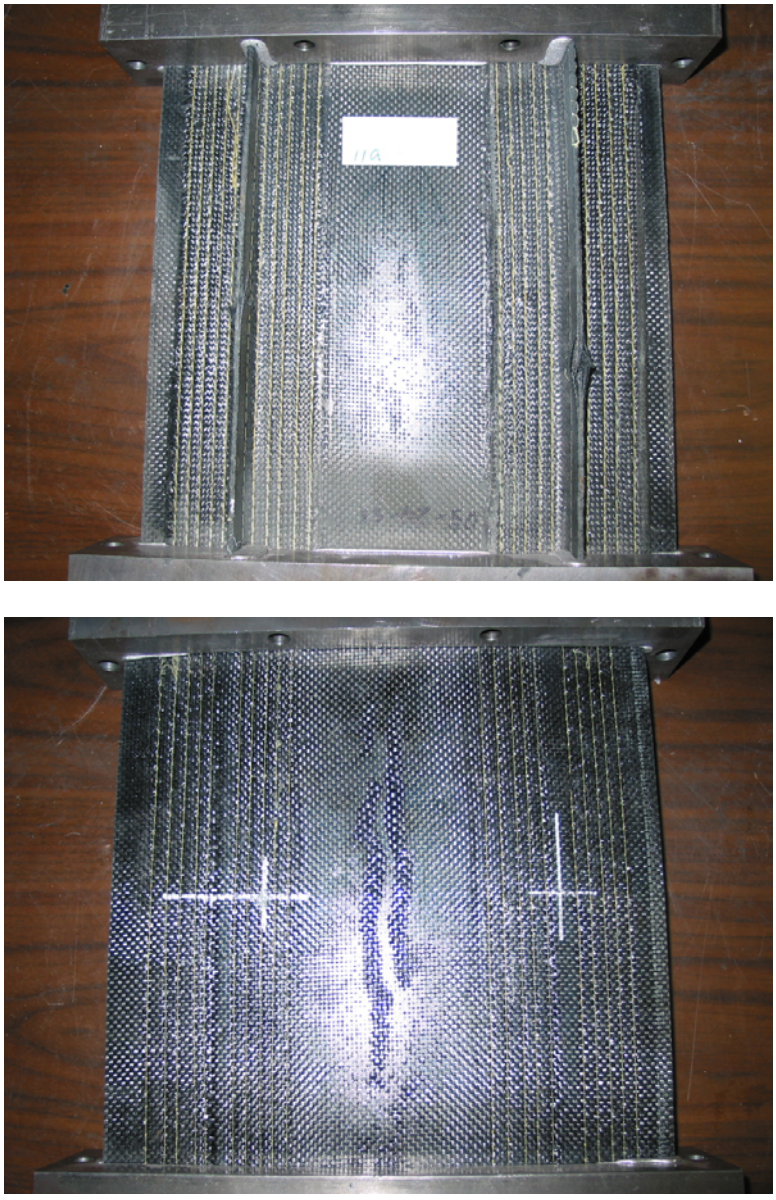


FIGURE 29. PANEL SEP16a POSTFATIGUE

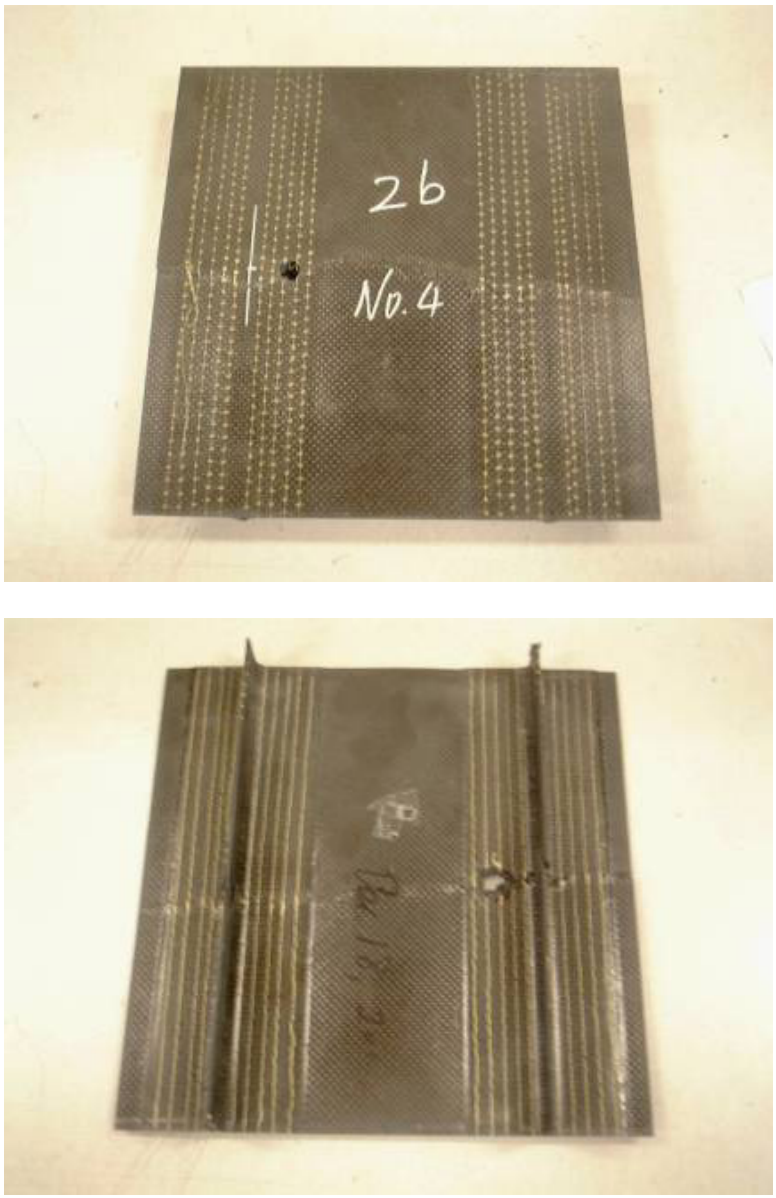


FIGURE 30. PANEL SEP7b POSTFATIGUE

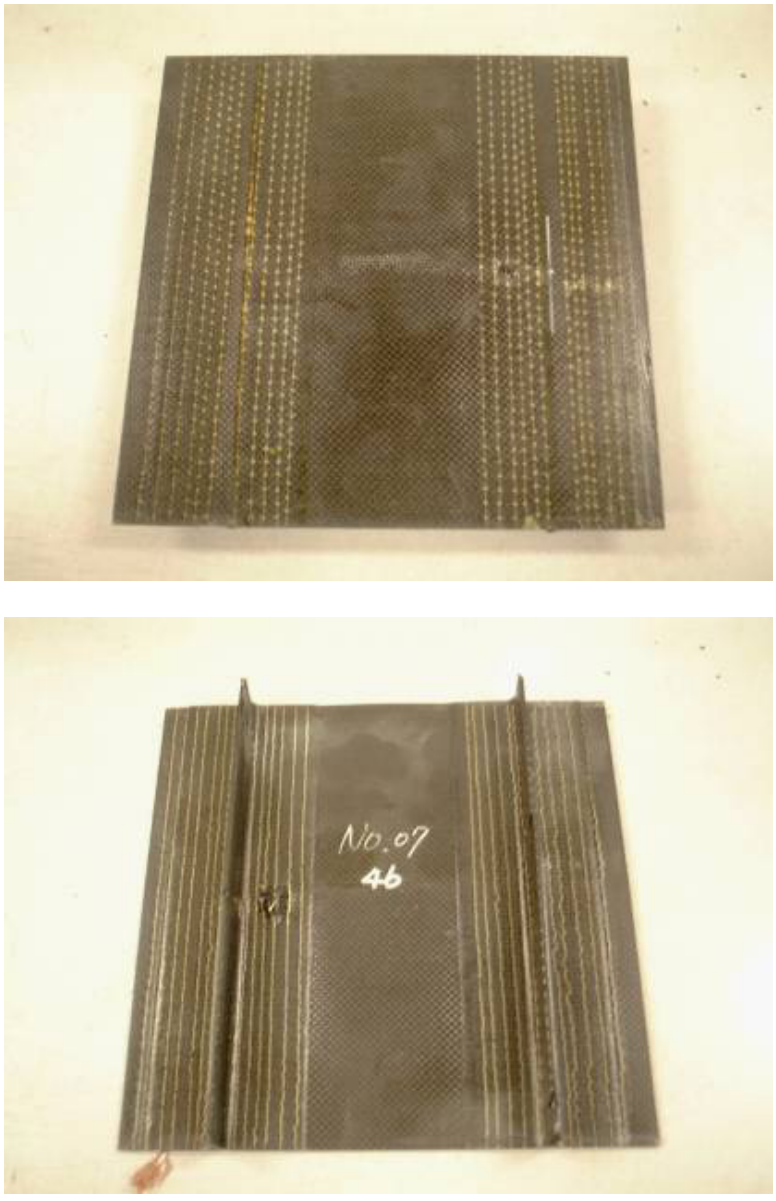


FIGURE 31. PANEL SEP9b POSTFATIGUE

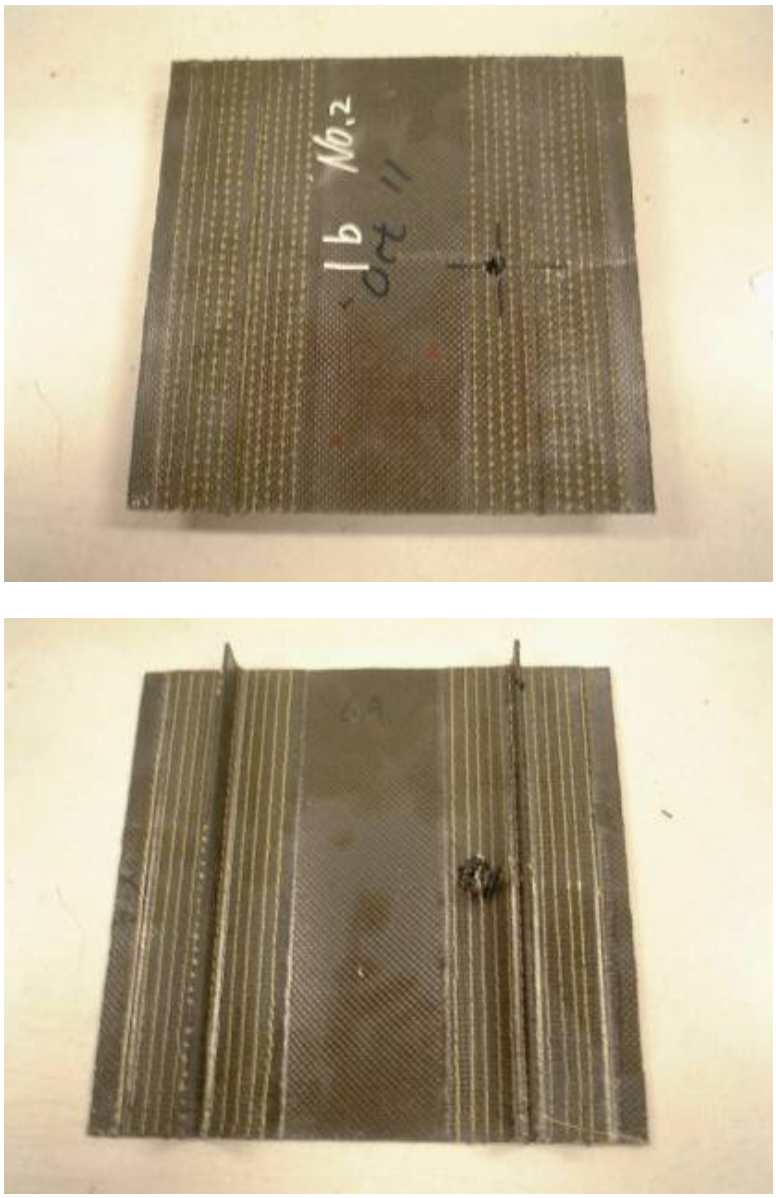


FIGURE 32. PANEL SEP10b POSTFATIGUE

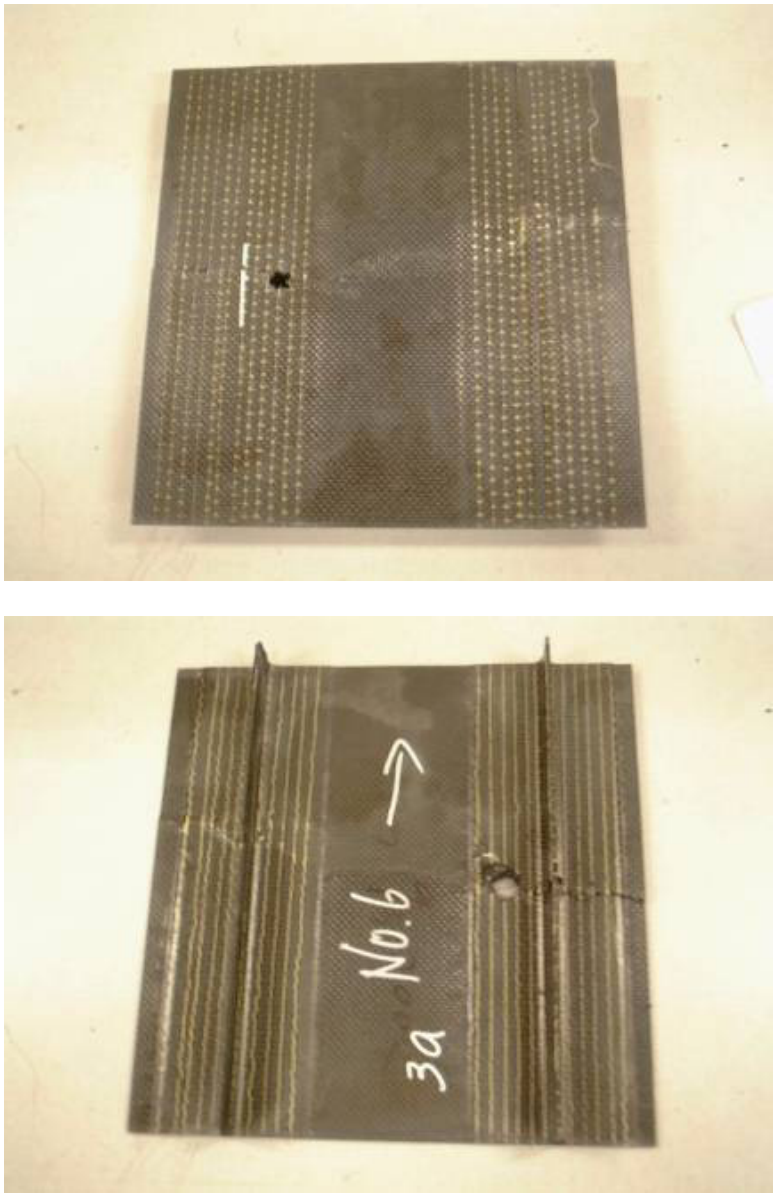


FIGURE 33. PANEL SEP10a POSTFATIGUE

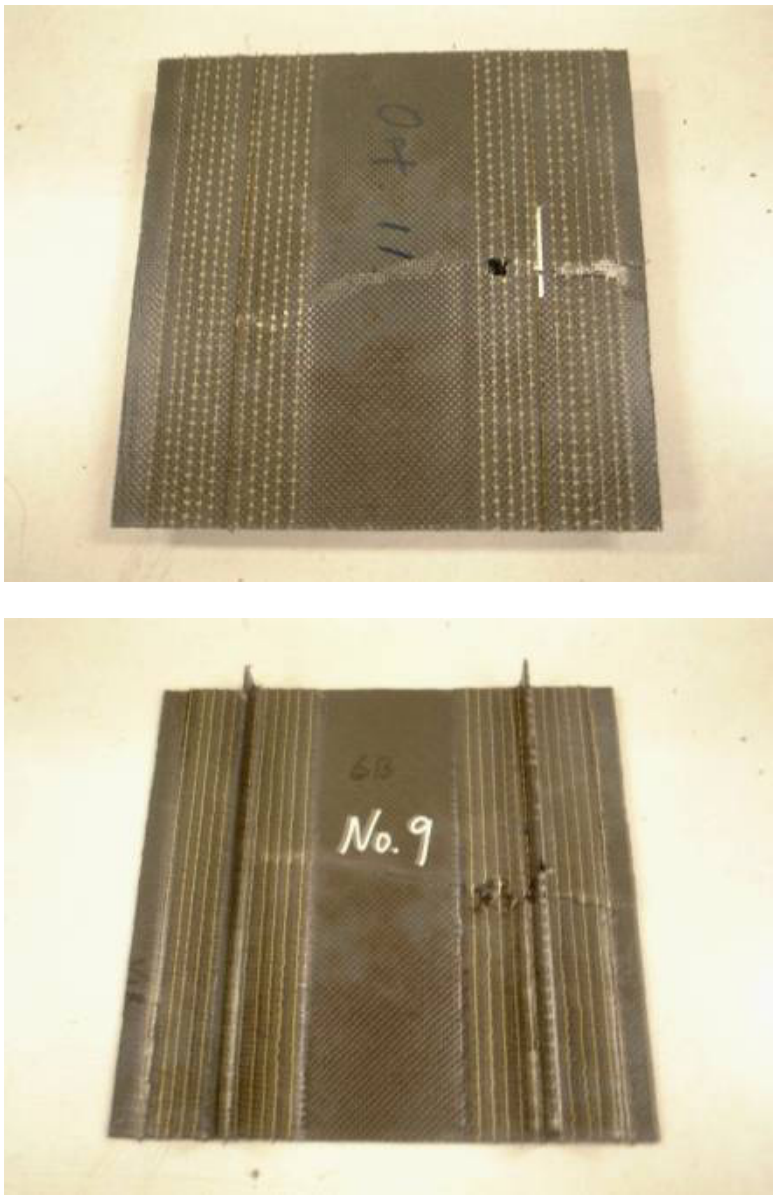


FIGURE 34. PANEL SEP8a POSTFATIGUE

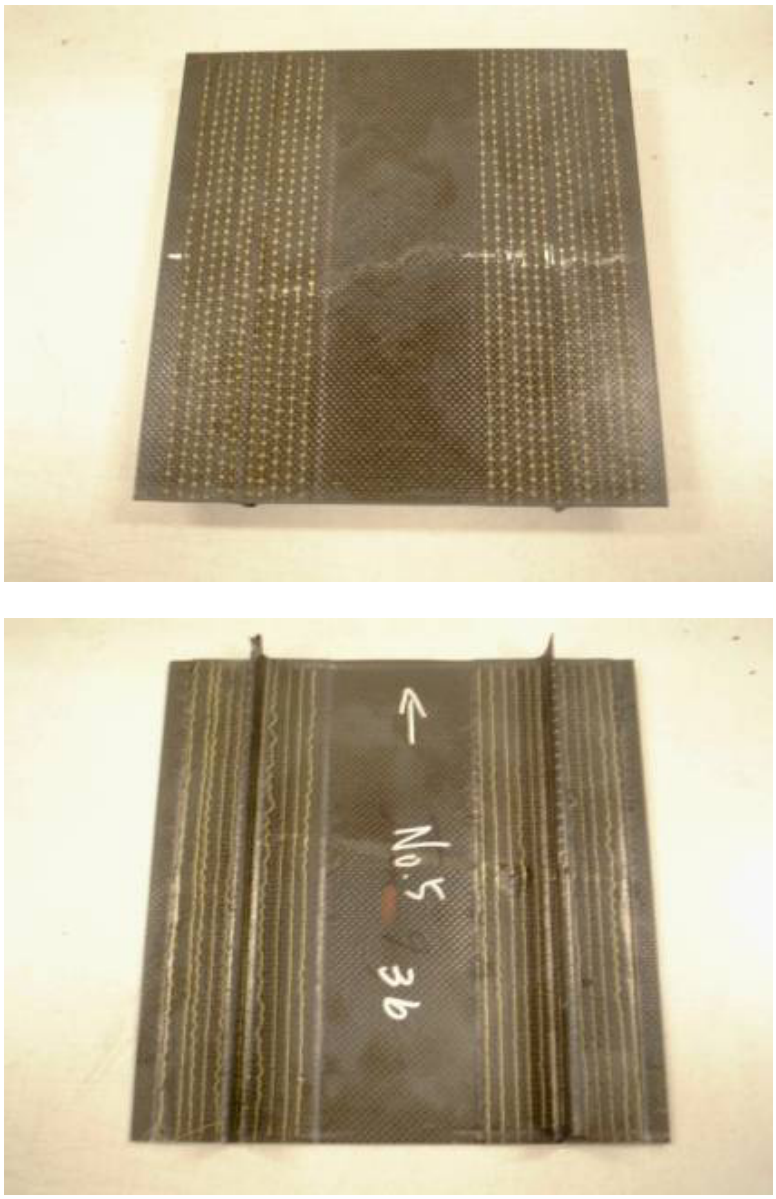


FIGURE 35. PANEL SEP8b POSTFATIGUE

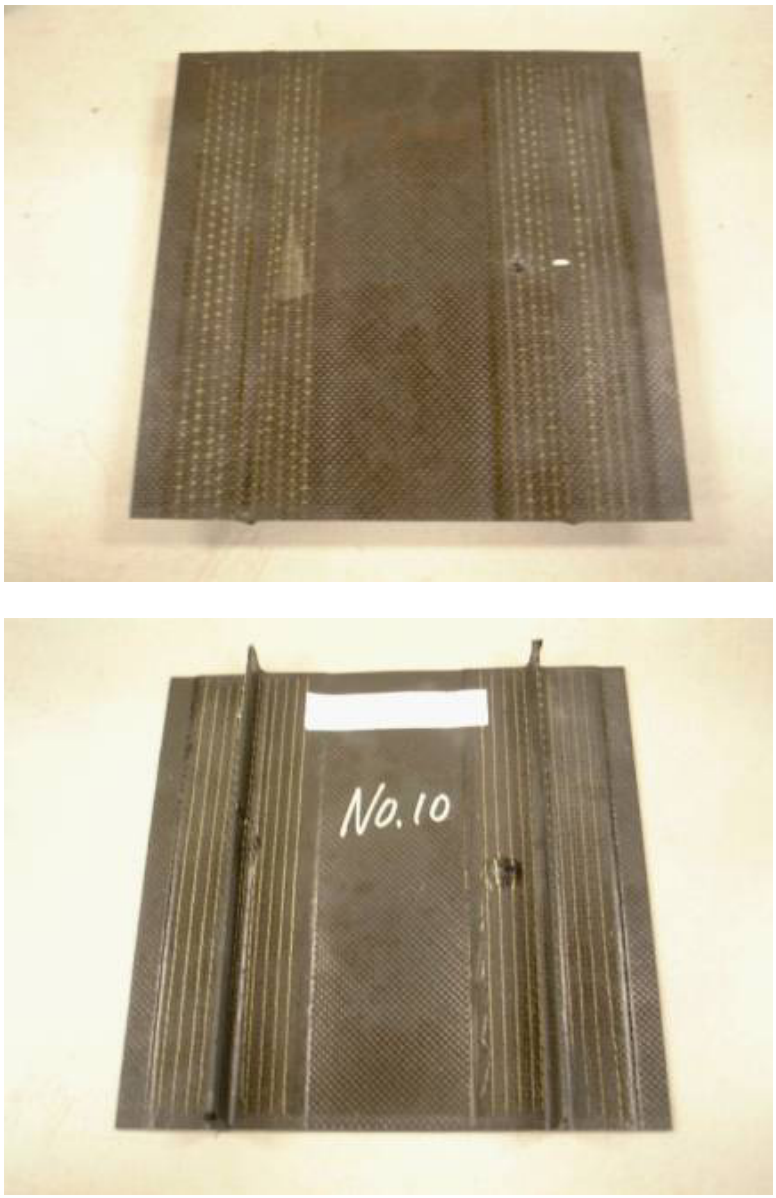


FIGURE 36. PANEL SEP11a POSTFATIGUE

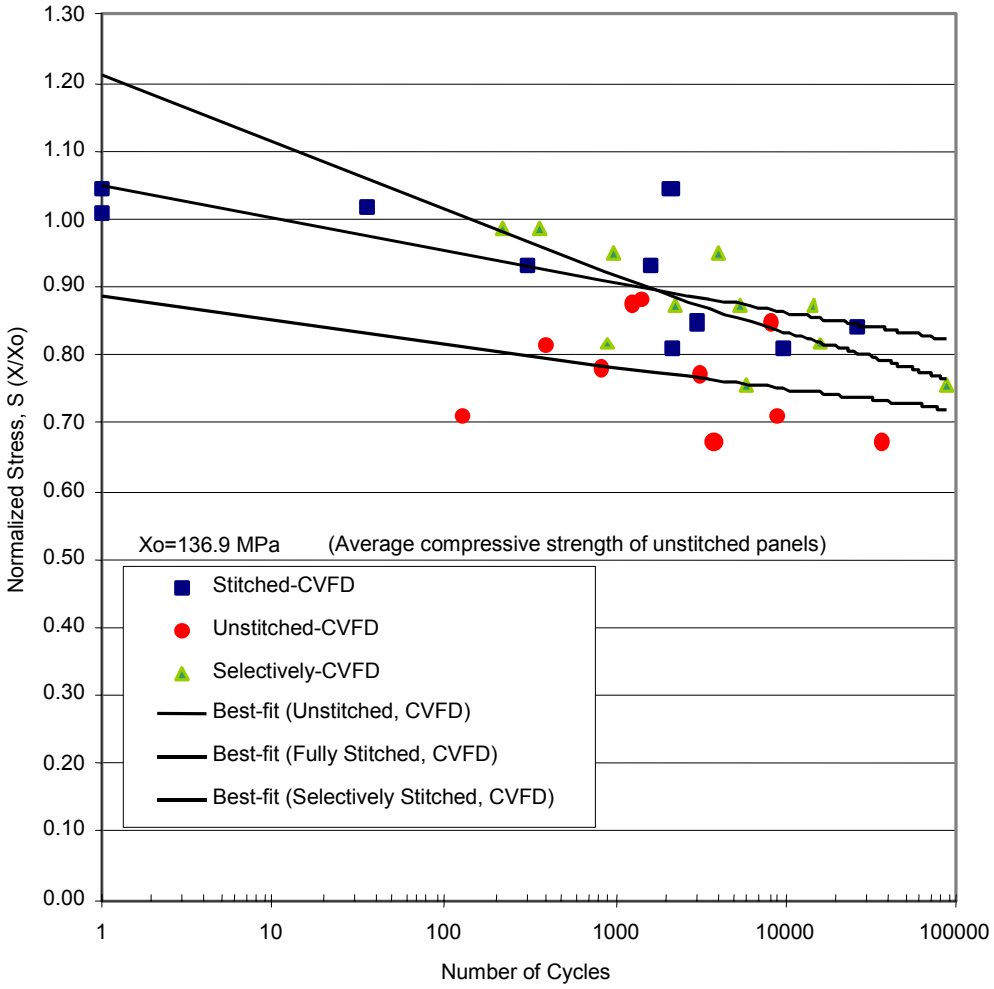


FIGURE 37. CLEARLY VISIBLE FLANGE DAMAGE PANEL FATIGUE S-N CURVE

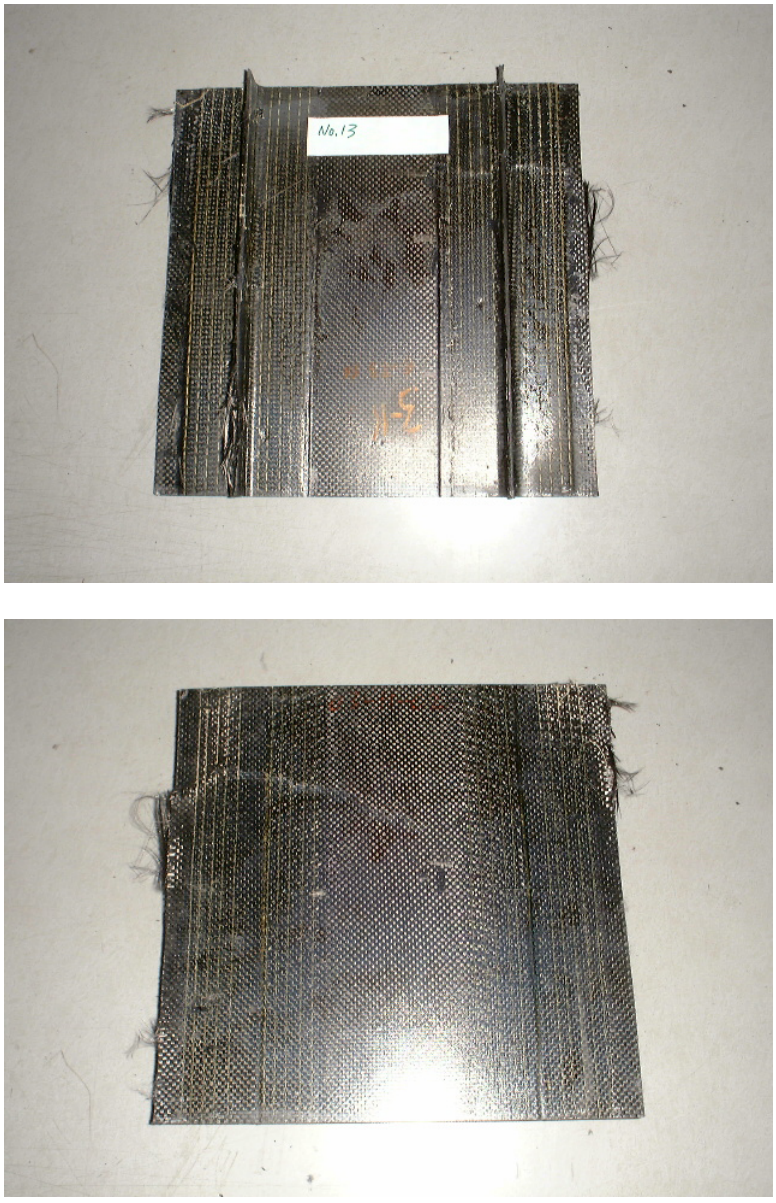


FIGURE 38. PANEL SEP12b POSTFATIGUE

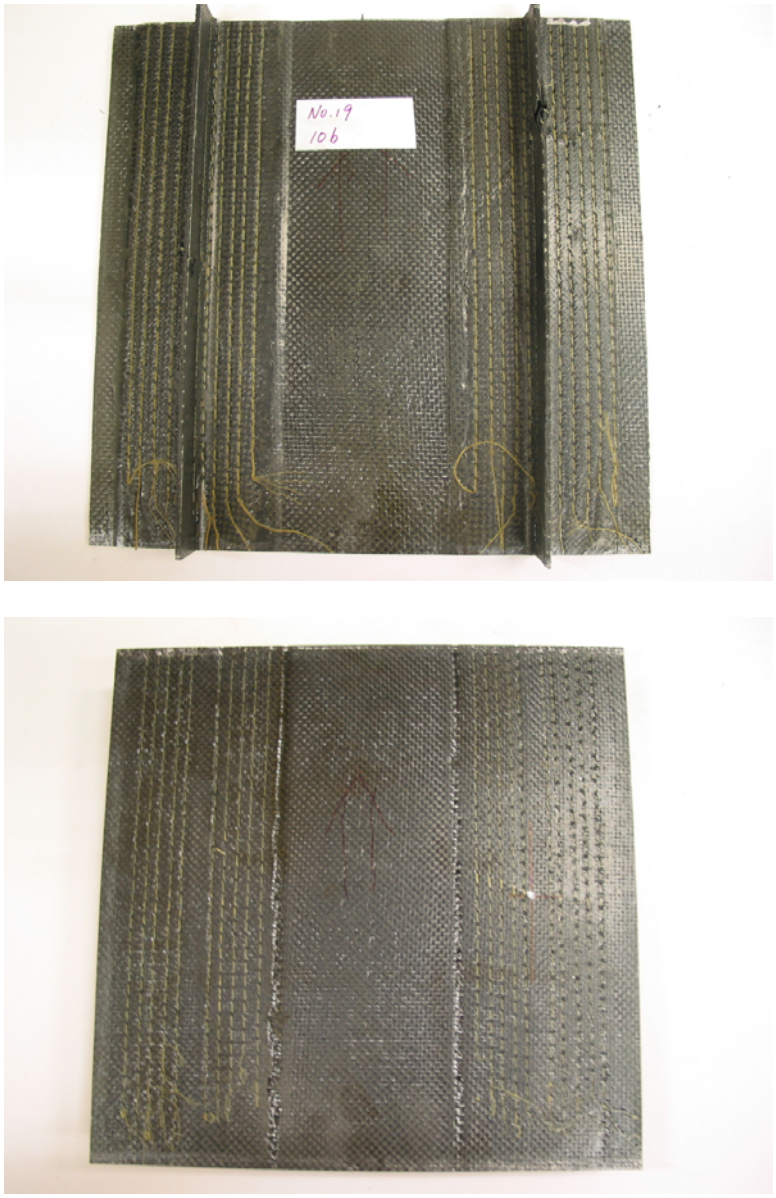


FIGURE 39. PANEL SEP15b POSTFATIGUE



FIGURE 40. PANEL SEP14a POSTFATIGUE

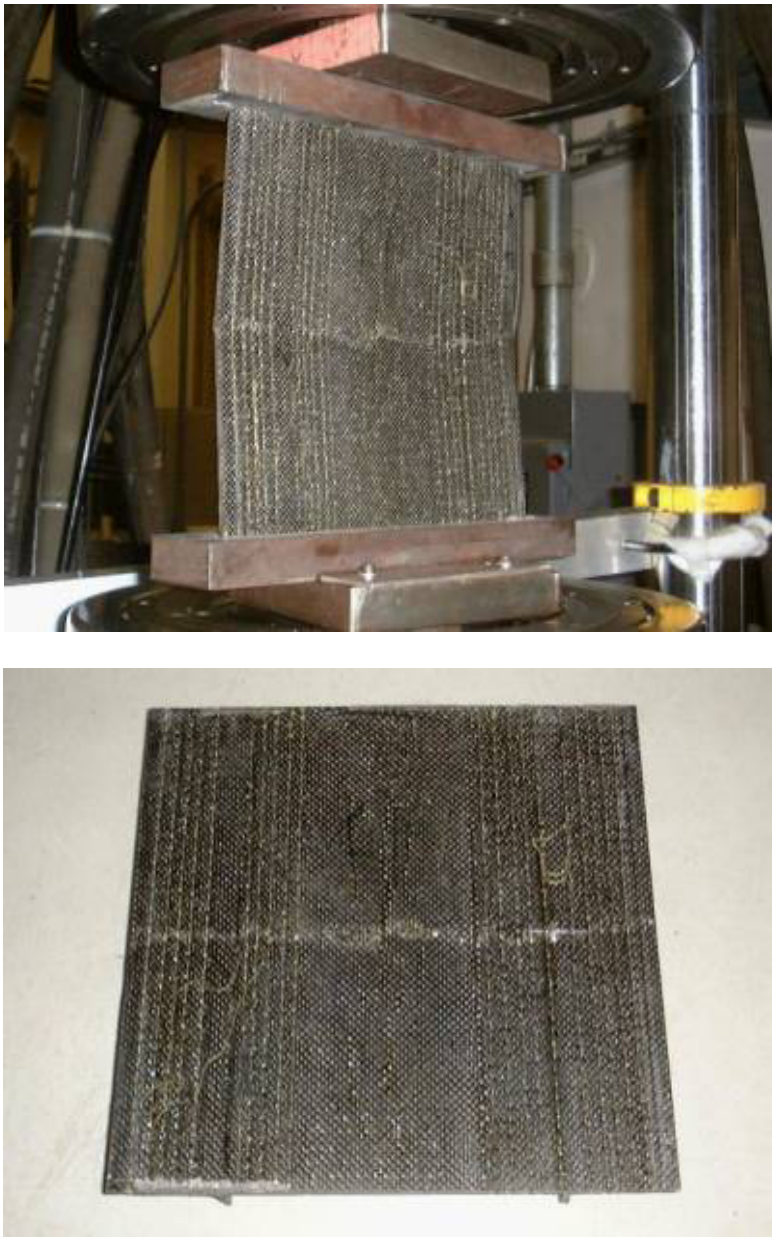


FIGURE 41. PANEL SEP14b POSTFATIGUE

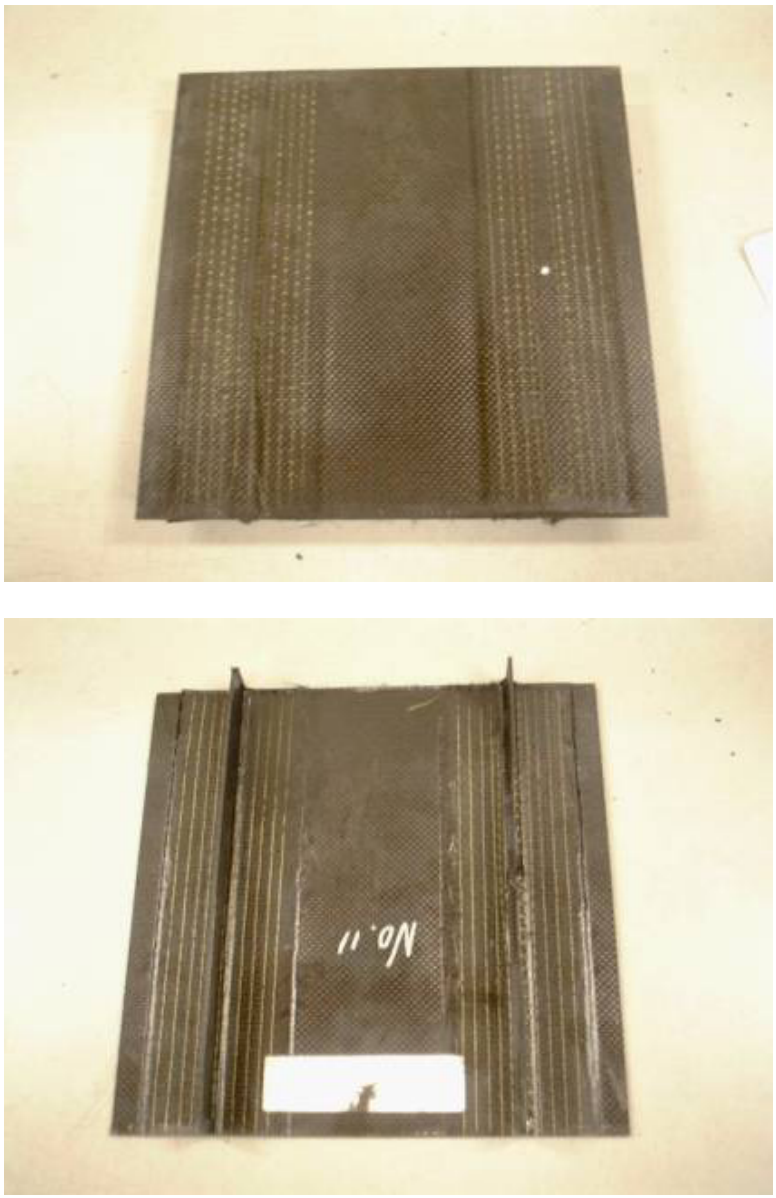


FIGURE 42. PANEL SEP11b POSTFATIGUE

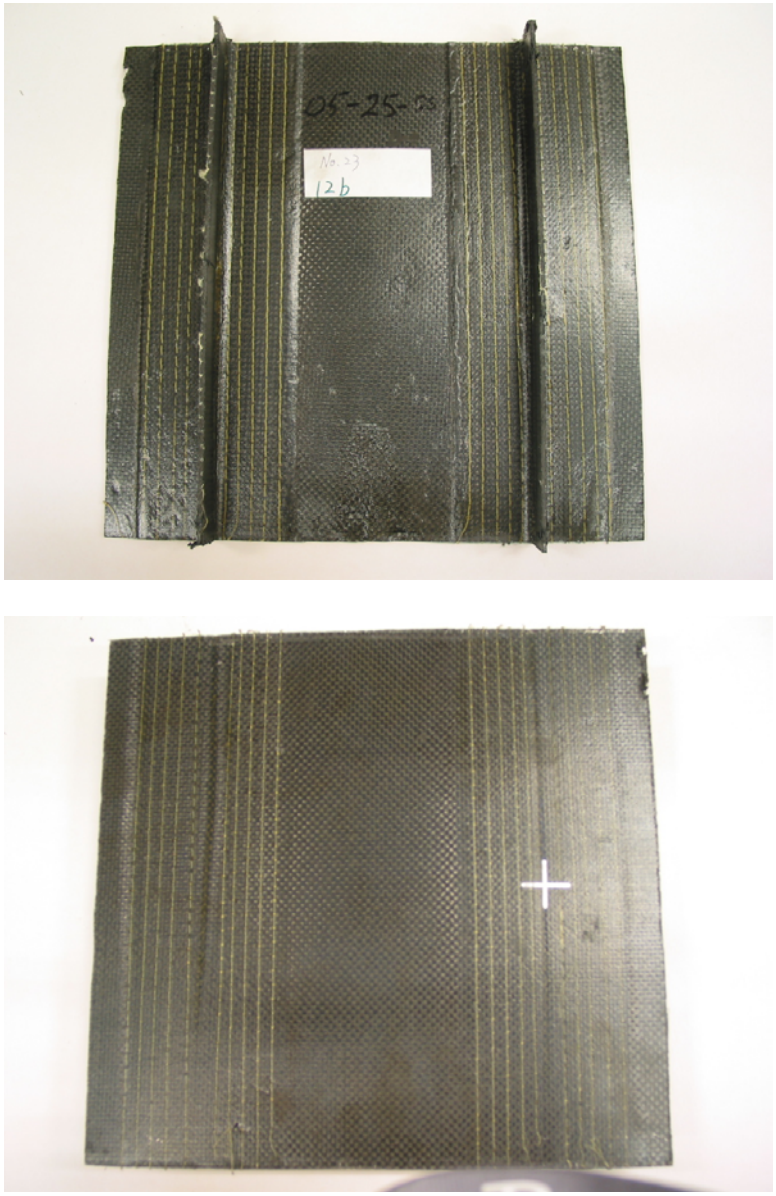


FIGURE 43. PANEL SEP17b POSTFATIGUE

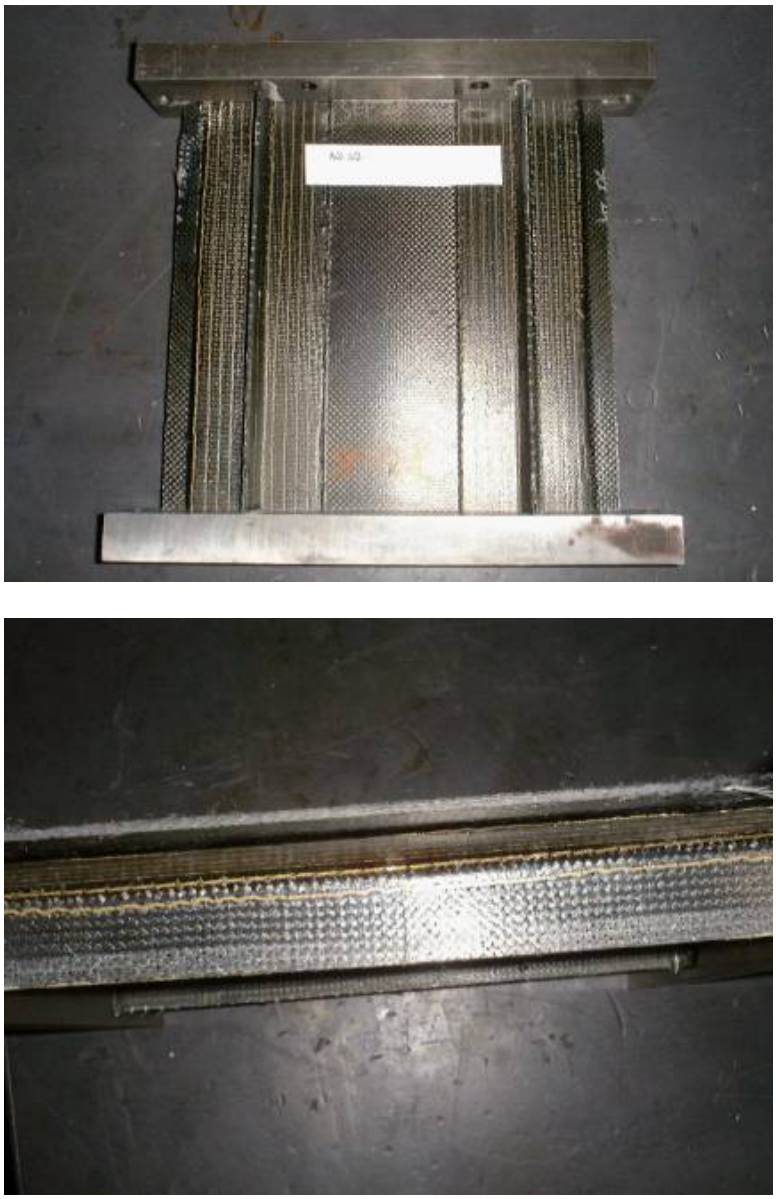


FIGURE 44. PANEL SEP13a POSTFATIGUE

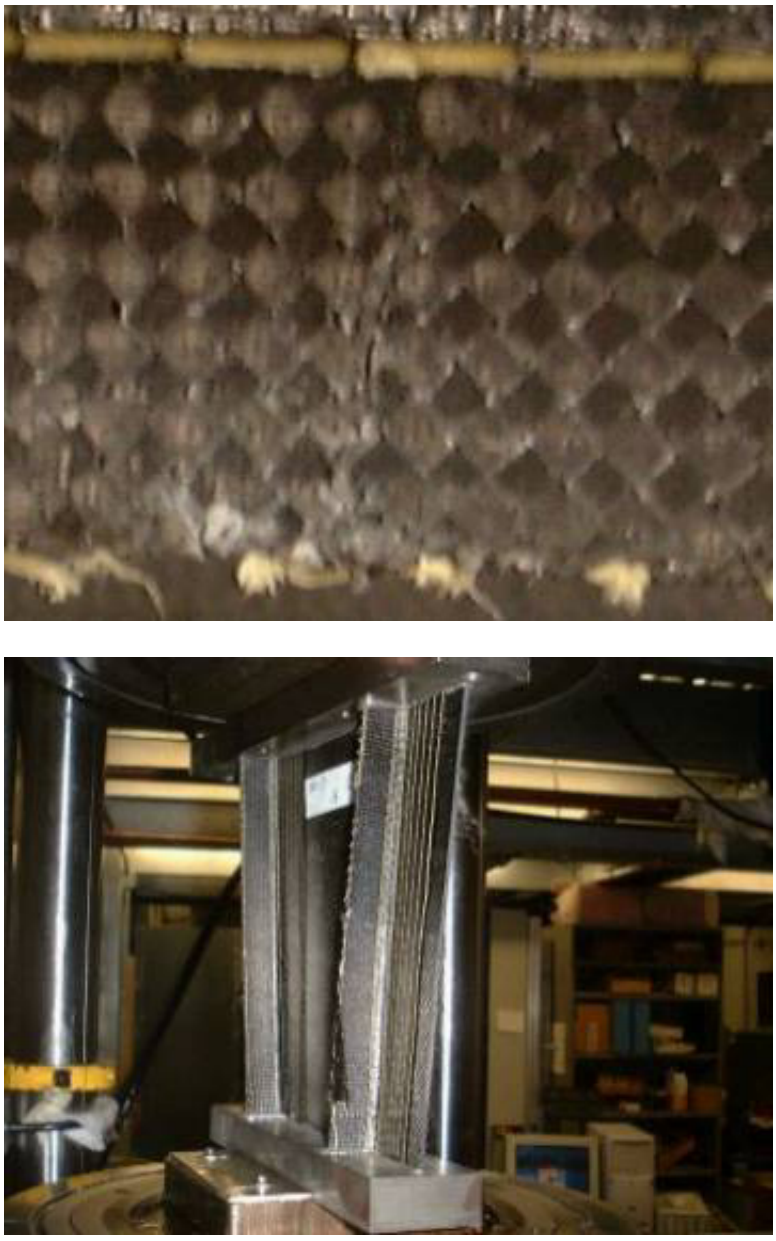


FIGURE 45. PANEL SEP6b POSTFATIGUE

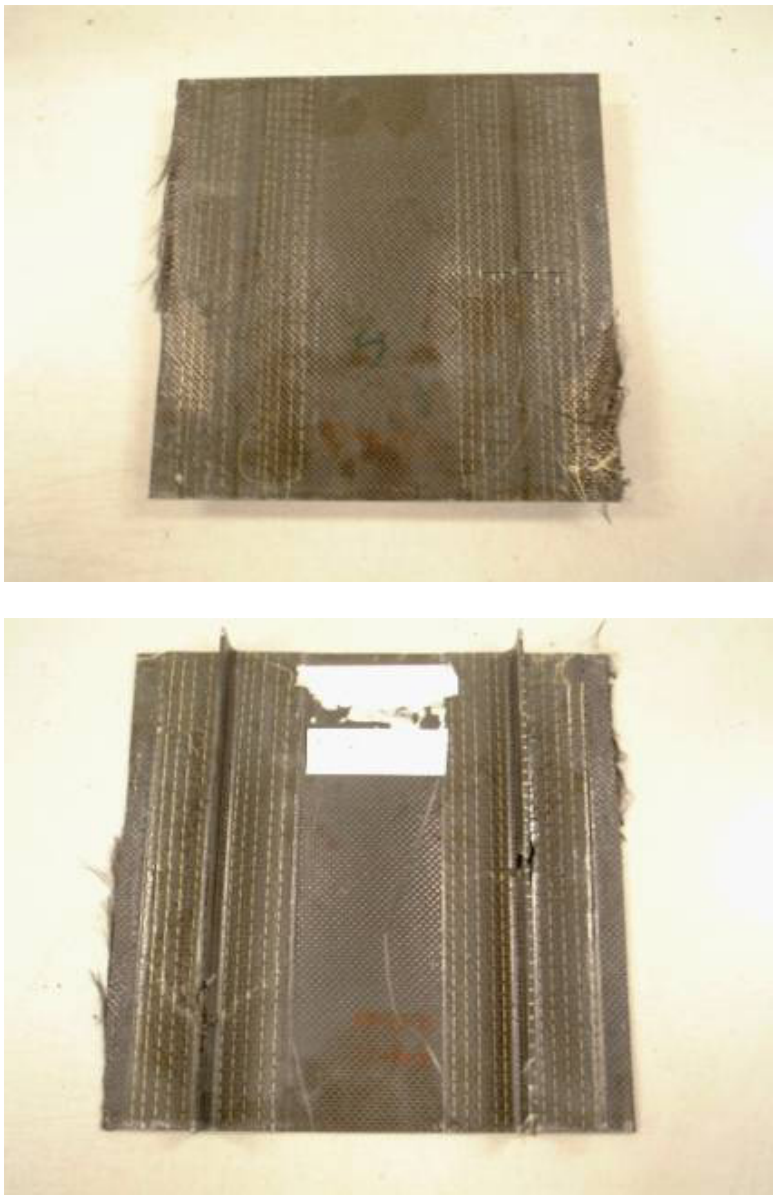


FIGURE 46. PANEL SEP12a POSTFATIGUE

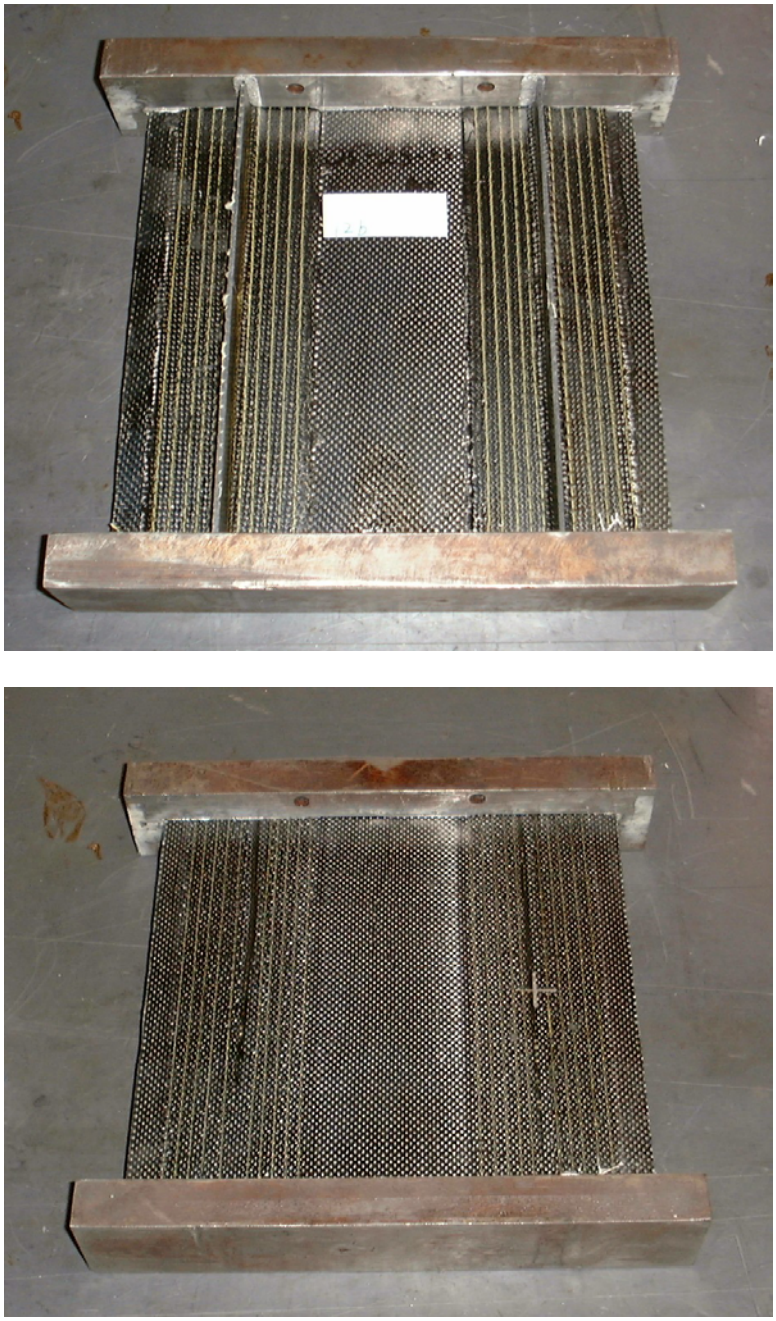


FIGURE 47. PANEL SEP17a POSTFATIGUE

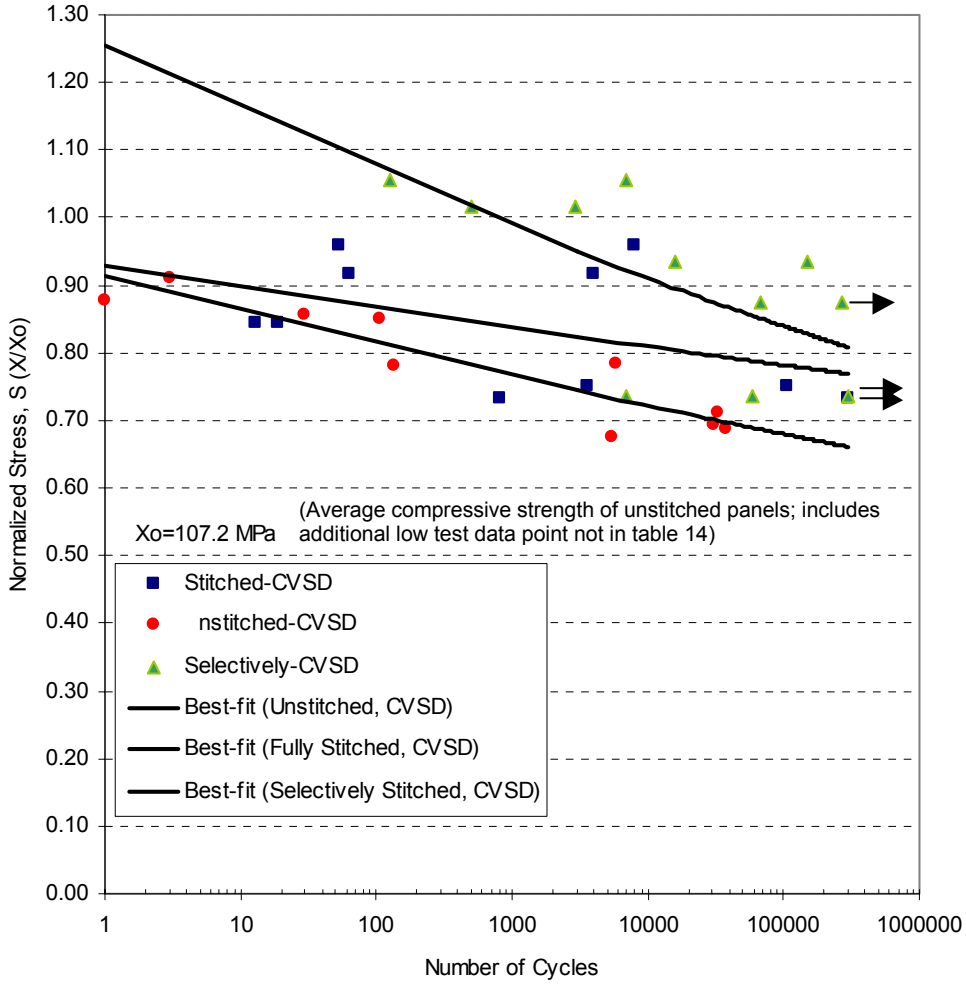


FIGURE 48. CLEARLY VISIBLE STIFFENER DAMAGE PANEL FATIGUE S-N CURVE

TABLE 1. NOMINAL DIMENSIONS OF STIFFENED PANELS

Dimension	Unit, mm
Lpanel	254.0
Ls	247.7
Le	3.18
Wpanel	254.0
Ws	152.4
Tskin	2.86
Triser	2.64
Hs	25.4
We	76.2
Wt	4.18

TABLE 2. FABRIC LAY-UP SEQUENCE AND STITCH DENSITY FOR SELECTIVELY STITCHED, STIFFENED PANELS

Region	Fabric Ply Lay-Up Sequence	Stitch Density
Skin	$[0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0]_T$	None
Stiffener	$[45, 0, 45, 0, 45, 0, 0, 45, 0, 45, 0, 45]_T$	1.24 stitches/cm^2
Flange	$[0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 45, 0, 0, 45, 0, 45, 0, 45]_T$	2.48 stitches/cm^2

TABLE 3. TEST MATRICES FOR STATIC COMPRESSION TESTS

	Selectively Stitched Panel		Unstitched Panel		Fully Stitched Panel	
Test No.	Designation	Impact	Designation	Impact	Designation	Impact
1	SEP3a	None	P1a	None	SP2b	None
2	SEP5a	None	P2a	None	SP5a	None
3	SEP5b	None	P3b	None	SP3a	None
4	SEP1b	CVFD	P4a	CVFD	SP4a	CVFD
5	SEP3b	CVFD	P5b	CVFD	SP5b	CVFD
6	SEP4a	CVFD	P18b	CVFD	SP12b	CVFD
7	SEP1a	CVSD	P1b	CVSD	SP3b	BVFD
8	SEP2b	CVSD	P3a	CVSD	SP1a	CVSD
9	SEP4b	CVSD	P5a	CVSD	SP15a	CVSD
10			P10b	CVSD	SP11b	CVSD

TABLE 4. STATIC COMPRESSION TEST RESULTS OF SELECTIVELY STITCHED PANELS

Specimen Designation	Modulus (GPa)	Buckling Strength (MPa)	Buckling Strain (E-6)	Impact Damage	Failure Strength (MPa)
SEP3a	38.71	81.9	2115	Undamaged	166
SEP5a	40.11	87.6	2183	Undamaged	170
SEP5b	42.15	88.5	2100	Undamaged	163
SEP1b	38.06	74.7	1962	CVFD	164
SEP3b	38.68	70.6	1825	CVFD	155
SEP4a	39.03	73.7	2255	CVFD	157
SEP1a	37.97	61.3	1613	CVSD	103
SEP2b	37.82	66.9	1770	CVSD	147
SEP4b	38.51	68.4	1776	CVSD	146
Average Standard Deviation	39.00 1.366				

TABLE 5. MANUFACTURING DEFECTS, IMPACT DAMAGES, AND FAILURE MODES OF SELECTIVELY STITCHED PANELS

Test No.	Specimen Designation	Impact Location	Impact Damage	Manufacturing Defect	Failure Mode
1	SEP3a	None	None	No groove	Stiffeners broken at failure
2	SEP5a	None	None	No groove	Stiffeners broken at failure
3	SEP5b	None	None	Rough skin texture	Stiffeners broken at failure
4	SEP1b	Right side of left stiffener	Dent, broken fiber	No groove	Impacted region stiffener broken
5	SEP3b	Right side of left stiffener	Dent, broken fiber	No groove	Impacted region stiffener broken
6	SEP4a	Right side of left stiffener	Dent, broken fiber	No groove	Impacted region stiffener broken
7	SEP1a	On right side stiffener	Stiffener damage	No groove	Crack extended from impacted stiffener
8	SEP2b	On right side stiffener	Stiffener damage	No groove	Crack extended from impacted stiffener
9	SEP4b	On right side stiffener	Stiffener damage	No groove	Crack extended from impacted stiffener

TABLE 6. MEASURED COMPRESSIVE MODULUS OF UNDAMAGED COMPOSITE PANELS

Test No.	Compressive Modulus Selectively Stitched Panel (GPa)	Test No.	Compressive Modulus Unstitched Panel (GPa)	Test No.	Compressive Modulus Fully Stitched Panel (GPa)
1	38.7	1	42.5	1	41.3
2	40.1	2	40.0	3	41.9
3	42.2	3	35.5		
Mean	40.3		39.3		41.6
Standard Deviation	1.76		3.55		0.42

TABLE 7. MEASURED BUCKLING STRENGTH OF UNDAMAGED COMPOSITE PANELS

Test No.	Buckling Strength Selectively Stitched Panel (MPa)	Test No.	Buckling Strength Unstitched Panel (MPa)	Test No.	Buckling Strength Fully Stitched Panel (MPa)
1	82	1	93	1	93
2	88	2	80	3	88
3	89	3	78		
Mean	86.3		83.7		90.5
Standard Deviation	3.79		8.14		3.54

TABLE 8. MEASURED FAILURE STRENGTH OF UNDAMAGED COMPOSITE PANELS

Test No.	Failure Strength Selectively Stitched Panel (MPa)	Test No.	Failure Strength Unstitched Panel (MPa)	Test No.	Failure Strength Fully Stitched Panel (MPa)
1	166.0	1	155.9	1	191.3
2	170.0	2	174.6	3	194.7
3	163.0	3	136.7		
Mean	166.3		155.7		193.0
Standard Deviation	3.51		18.95		2.40

TABLE 9. MEASURED COMPRESSIVE MODULUS OF FLANGE-DAMAGED COMPOSITE PANELS

Test No.	Compressive Modulus Selectively Stitched Panel (GPa)	Test No.	Compressive Modulus Unstitched Panel (GPa)	Test No.	Compressive Modulus Fully Stitched Panel (GPa)
4	38.1	4	34.0	4	42.0
5	38.7	5	34.0	5	40.0
6	39.0	6	36.0	6	40.0
Mean	38.6		34.7		40.7
Standard Deviation	0.46		1.15		1.15

TABLE 10. MEASURED BUCKLING STRENGTH OF FLANGE-DAMAGED COMPOSITE PANELS

Test No.	Buckling Strength Selectively Stitched Panel (MPa)	Test No.	Buckling Strength Unstitched Panel (MPa)	Test No.	Buckling Strength Fully Stitched Panel (MPa)
4	75	4	72	4	79
5	71	5	65	5	67
6	74	6	71	6	80
Mean	73.3		69.3		75.3
Standard Deviation	2.08		3.79		7.23

TABLE 11. MEASURED FAILURE STRENGTH OF FLANGE-DAMAGED COMPOSITE PANELS

Test No.	Failure Strength Selectively Stitched Panel (MPa)	Test No.	Failure Strength Unstitched Panel (MPa)	Test No.	Failure Strength Fully Stitched Panel (MPa)
4	164.0	4	142.9	4	171.2
5	155.0	5	124.7	5	159.4
6	157.0	6	143.2	6	157.6
Mean	158.7		136.9		162.7
Standard Deviation	4.73		10.60		7.39

TABLE 12. MEASURED COMPRESSIVE MODULUS OF STIFFENER-DAMAGED COMPOSITE PANELS

Test No.	Compressive Modulus Selectively Stitched Panel (GPa)	Test No.	Compressive Modulus Unstitched Panel (GPa)	Test No.	Compressive Modulus Fully Stitched Panel (GPa)
7	38.0	7	38.0	8	41.0
8	37.8	8	34.5	9	43.0
9	38.5	10	37.5	10	42.5
Mean	38.1		36.7		42.2
Standard Deviation	0.36		1.89		1.04

TABLE 13. MEASURED BUCKLING STRENGTH OF STIFFENER-DAMAGED COMPOSITE PANELS

Test No.	Buckling Strength Selectively Stitched Panel (MPa)	Test No.	Buckling Strength Unstitched Panel (MPa)	Test No.	Buckling Strength Fully Stitched Panel (MPa)
7	61	7	89	8	58
8	71	8	71	9	78
9	68	10	75	10	74
Mean	66.7		78.3		70.0
Standard Deviation	5.13		9.45		10.58

TABLE 14. MEASURED FAILURE STRENGTH OF STIFFENER-DAMAGED COMPOSITE PANELS

Test No.	Failure Strength Selectively Stitched Panel (MPa)	Test No.	Failure Strength Unstitched Panel (MPa)	Test No.	Failure Strength Fully Stitched Panel (MPa)
7	103.0	7	142.9	8	113.5
8	147.0	8	96.9	9	112.7
9	146.0	10	119.4	10	120.0
Mean	132.0		119.7		115.4
Standard Deviation	25.12		23.00		4.00

TABLE 15. MODIFIED TWIST SPECTRUM

	Alternating Load, X Flight Mean Load									
	1.6	1.5	1.3	1.1	0.99	0.84	0.68	0.53	0.37	0.22
Number of Cycles	1	2	5	18	52	152	800	4170	34800	358665

TABLE 16. NOMINAL MAXIMUM COMPRESSIVE STRESS LEVELS FOR CONSTANT-AMPLITUDE FATIGUE TESTS

	Clearly Visible Flange Damaged		
Load Level	Selectively Stitched (MPa)	Unstitched (MPa)	Fully Stitched (MPa)
1	135.3	120.9	144.1
2	130.1	116.3	138.5
3	119.7	107.0	127.4
4	111.9	97.7	116.3
5	103.6	92.5	110.2
	Clearly Visible Stiffener Damaged		
Load Level	Selectively Stitched (MPa)	Unstitched (MPa)	Fully Stitched (MPa)
1	113.3	94.6	102.2
2	108.9	91.0	98.3
3	100.2	83.7	90.4
4	93.7	76.4	80.5
5	78.8	72.4	78.2

TABLE 17. CONSTANT-AMPLITUDE FATIGUE RESULTS: SELECTIVELY STITCHED CVFD PANELS

Specimen ID	Max. Comp. Stress (MPa)	Loading Frequency (Hz)	Number of Cycles to Failure	Causes of Failure
SEP6a	135.3	0.5	225	Damage-induced stiffener failure
SEP9a	135.3	0.5	364	Stiffener failure
SEP7a	130.1	1.0	4013	Damage-induced stiffener failure
SEP16a	130.1	0.5	982	Damage-induced stiffener failure
SEP7b	119.7	1.0	14164	Damage-induced stiffener failure
SEP9b	119.7	0.5	2279	Stiffener failure
SEP10b	119.7	1.0	5362	Damage-induced stiffener failure
SEP8a	111.9	1.0	16126	Damage-induced stiffener failure
SEP10a	111.9	0.5	896	Damage-induced stiffener failure
SEP8b	103.6	0.5	6037	Stiffener failure
SEP11a	103.6	1.0	87934	Stiffener failure

TABLE 18. CONSTANT-AMPLITUDE FATIGUE RESULTS: SELECTIVELY STITCHED CVSD PANELS

Specimen ID	Max. Comp. Stress (MPa)	Loading Frequency (Hz)	Number of Cycles to Failure	Causes of Failure
SEP12b	113.3	0.5	124	Damaged stiffener failure
SEP15b	113.3	0.5	6954	Damaged stiffener failure
SEP14a	108.9	0.5	509	Damaged stiffener failure
SEP14b	108.9	0.5	2899	Damaged stiffener failure
SEP11b	100.2	1.0	148489	Damaged stiffener failure
SEP17b	100.2	0.5	15916	Damaged stiffener failure
SEP13a	93.7	1.0	270000	Run-out
SEP6b	93.7	1.0	68630	Damaged stiffener failure
SEP12a	78.8	0.5	6812	Damaged stiffener failure
SEP15a	78.8	1.0	300000	Run-out
SEP17a	78.8	1.0	58793	Damaged stiffener failure

TABLE 19. BEST-FIT PARAMETERS FOR SELECTIVELY STITCHED, UNSTITCHED, AND FULLY STITCHED PANELS WITH CVFD

	α^*	β
Selectively Stitched	1.2092	-0.0402
Unstitched	0.8863	-0.0180
Fully Stitched	1.0504	-0.0213

*Normalized value using unstitched CSAI

TABLE 20. BEST-FIT PARAMETERS FOR SELECTIVELY STITCHED, UNSTITCHED, AND FULLY STITCHED PANELS WITH CVSD

	α^*	β
Selectively Stitched	1.2537	-0.0348
Unstitched	0.9146	-0.0257
Fully Stitched	0.9281	-0.0149

*Normalized value using unstitched CSAI