ADHESIVELY BONDED AND BOLTED STEEL JOINTS

P. Albrecht, A. Sahli and D. Crute, University of Maryland
College Park, Maryland, U.S.A.
J.G. Cheng, Nanking Institute of Chemical Technology, P.R.C.

INTRODUCTION

The results of a recently completed study showed that attaching a cover plate to the tension flange of a steel beam with longitudinal welds along the central region, and with friction-type high-strength bolted connections at the nonwelded ends, increased the fatigue life by a factor of 16 over that of conventionally end-welded cover plates.[1] Accordingly, end-bolted cover plates have the fatigue strength of Category B, in the American specifications for civil engineering structures, rather than that of Category E for long attachments. See for example Ref. 2. The large increase in life is possible because friction-type bolted connections can transfer force from one plate to another with much less stress concentration than would occur in rigid welded connections.

Similarly, one would expect an increase in the strength of structural details when adhesives help to distribute and to transfer the load over a larger area, thus preventing severe stress concentrations. Two main applications come to mind. One deals with load-carrying bolted joints, such as splices, and consists of reinforcing the joint with adhesives applied on the plate contact surfaces. In doing so, the force is transmitted over the full contact surface rather than only at the clamped regions surrounding the bolts. This could increase the mean fatigue life by a factor of at most three, from Category B for bolted joints to Category A for base metal; and the static strength by a factor of at most 1.00/0.85 = 1.18, corresponding to the strength ratio of a member without bolt holes to that of a member with bolt holes.[2]

The other main application deals with the fatigue strength of attachments that are presently welded. The severity of the stress concentration

and, hence, the fatigue strength depend on the length of an attachment. For example, the mean fatigue life of a Category B welded plate girder without attachments drops to Category C (factor of 2.5) for 50-mm attachments, to Category D (factor of 7) for 100-mm attachments, and to Category E (factor of 16) for 200-mm and longer attachments. Since end-bolting cover plates raised the fatigue strength from Category E to Category B, one may expect similar improvements when attachments are adhesively bonded.

The combined use of bolts and adhesives, and the replacement of welds by adhesives, go beyond increasing, for example, the fatigue strength of details in new construction. The bolt-and-adhesive combination can also be effectively used to repair cracked members and to upgrade the strength of structural details in existing bridges.

These are times of aging bridges, increasing traffic volume, pressure to increase the legal truck weight limits, and lack of funds to replace many old bridges that have reached their service life. In addition, new details with higher fatigue strength are needed. One must, therefore, find economic ways of retrofitting bridges and increasing the fatigue and static strength of structural details. The use of adhesives, either in combination with bolts or alone, appears to have an excellent potential for success. This paper describes the preliminary findings of an ongoing testing program that explores these objectives.

EXPERIMENTAL WORK

1. Testing Program

The feasibility of adhesively bonding structural details for highway bridge applications was examined with five series of tests. In two series of tests, labeled A and C, tensile specimens were subjected to cyclic and static loading, respectively. Two types of specimens were used. One type, shown in Fig. 1, consisted of 16 x 64 x 305 mm long plates that were spliced with two 8 x 64 x 254 mm long plates and two 16-mm (5/8-inch) diameter ASTM A325 high-strength bolts on either side of the splice. The ratio of 1.24 between the ultimate shear strength of the two bolts and the ultimate tensile strength of the plates at the net section is typical of that found in structures. The other type of specimens was identical to that shown in Fig. 1, except that it had only one bolt on either side of the splice. One-half of the Series A and C specimens were tested without adhesive, for control purposes, and the other half with adhesive applied on the contact surfaces between the main and splice plates.

In the third and fourth series of tests, labeled B and D, beam specimens were subjected to cyclic and static loading, respectively. The basic specimen consisted of a wide flange W 14x30 beam tested on a 4572-mm span under four-point loading. The flanges of the Series B fatigue test beams were spliced at midspan with two 13 x 171 x 381 mm long plates attached to the flanges with either six or four 19-mm (3/4-inch) diameter A325 high-strength bolts on either side of the splice. Six bolts are needed to fully develop the beam moment. Since the splice was located in the constant bending moment region, the web splice did not carry any shear. The 6-bolt splices were tested without and with adhesive, the 4-bolt splices only with adhesive. In addition, all Series B beams had two 13 x 171 x 1143 mm cover plates adhesively bonded to the tension flange. After three beams had been tested, the cover plate ends were clamped with two 19-mm (3/4-inch) diameter A325 bolts to prevent debonding at the ends.

The flanges of the Series D static test beams were spliced with either six, four or two bolts layed out as shown in Fig. 2. One-half of the beams were assembled without adhesive, for control purposes, and the other half with adhesive applied on the contact surfaces. The intent of reducing the number of bolts per splice was to determine to what degree the adhesive would help transfer the load.

In the fifth series of tests, labeled E, double strap tensile specimens were subjected to sustained loads to determine the creep strength of the adhesive bond. The main adherends were 13 x 25 x 108 mm long. The straps were 6 x 25 x 29 mm or 6 x 25 x 53 mm long and overlapped each adherend by 13 mm or 25 mm, respectively. All contact surfaces were adhesively bonded.

The Series A 1-bolt specimens and the Series D beams had not been tested at the time this paper was written. The data are, therefore, not included.

2. Materials

The plates and beams were fabricated from steel that conformed to the requirements of the American Society for Testing and Materials (ASTM) A588

Specification for High-Strength Low-Alloy Steel with 345 MPa Minimum Yield Point to 100 mm thick. The minimum tensile requirements for this steel are 345 yield point, 485 MPa tensile strength and 21% elongation.

The bolts conformed to the requirements of the ASTM A325 Specification for High-Strength Bolts for Structural Steel Joints. The minimum tensile requirements are 635 MPa yield strength and 825 MPa tensile strength for bolts up to 25-mm diameter.

The adhesive consisted of two parts, a modified acrylic adhesive and either one of two accelerators. One type of accelerator had to be mixed directly with the adhesive in fixed proportions. Because of its short pot life, it was used for bonding the small surfaces of the creep specimens alone. The second type of accelerator could be applied on the contact surfaces after the adhesive. It was used for the Series A to D specimens. The mean shear strength of the adhesive, measured in the laboratory under monotonically increasing load, was 27.4 MPa, with 2.1 MPa standard deviation.

3. Specimen Fabrication

All plates and beams were fabricated by a structural steel fabricator to standards typical of bridge construction, shotblasted to a near-white condition, and assembled for shipment with the bolts hand tightened. The specimens were disassembled in the laboratory. Thereafter, those that needed to be bonded were cleaned, if needed, and received one coat of adhesive and one coat of accelerator. Glass beads of 0.25-mm diameter were sprayed on the surfaces to help attain the recommended bond line thickness of 0.25 mm. The bolts were then tightened. The bonded surfaces of the cover plates and the creep specimens were clamped. All specimens were cured prior to testing at least twice as long as the 24 hours recommended by the adhesive supplier.

The control specimens were high-strength bolted in the laboratory in the as-received condition. All bolts were tightened with a calibrated wrench to an initial tension corresponding to 70% of the 825 MPa minimum specified tensile strength for A325 bolts.

4. Testing Procedure

The Series A to D tensile and beam specimens were tested indoors at room temperature and humidity. The Series A tensile specimens were stress cycled until they broke in two parts. The Series B beam specimens had several details. When a fatigue crack caused failure at one detail, the beam was repaired by bridging the crack with thick plates that were fastened with high-strength bolts and C-clamps. The test was then continued to permit collection of data at the other details on the same beam.

The Series E creep specimens were set up in portable spring-loaded frames that maintained a constant load during the length of the test.

FATIGUE STRENGTH OF TENSILE SPECIMENS

A total of 20 Series A specimens with 2-bolt splices shown in Fig. 1 were tested; 12 of them control specimens without adhesive, and 8 with adhesive. The four control specimens tested at 124 and 145-MPa stress range did not fail. Based on those results, higher stress ranges of 159 and 207 MPa were chosen for the remaining tests to ensure that the specimens would fail. The minimum stress was 7 MPa in all tests.

Six control specimens and six bonded specimens failed from cracks that initiated in the main plate, at the first bolt hole closest to the specimen ends. They propagated at first as corner or bore hole cracks and then as through cracks across the plate width. The other three failures initiated at the second hole in the splice plates. These cracks propagated in the same manner as the main plate cracks.

The fatigue test data are plotted in Fig. 4 with open triangles for the control specimens and solid triangles for the bonded specimens. The runouts are identified with arrows. Also shown for comparison are the mean S-N line of the Category B data base and the allowable S-N line for Category B details located two standard deviations to the left of the mean.[2] The fatigue lives of bolted bearing-type connections are normally plotted against the net area stress range, and those of friction-type connections against the gross area stress range. On that basis, all data are expected to fall above the allowable Category B line.

The control specimens slipped into bearing, whereas the adhesively bonded specimens behaved as friction-type connections. For ease of comparing the fatigue lives, all data were plotted in Fig. 4 in terms of the gross area stress range. All control specimen data would fall above the allowable Category B line, had they been plotted against the net area

stress range. As Fig. 4 shows, adhesively bonding, in addition to bolting, increased the fatigue life of the Series A specimens, on average, by a factor of 1.7, from 1,899,000 to 3,264,000 cycles at 159-MPa stress range, and from 446,000 to 775,000 cycles at 207-MPa stress range. The increase is attributed to a change in connection behavior, from bearing-type to friction-type, and a distribution of force transfer from the main plate to the splice plates over a larger area, with less concentration.

FATIGUE STRENGTH OF BEAM SPLICES

A total of 18 Series B beam specimens shown in Fig. 2 were tested; six control beams with 6-bolt splices without adhesive, six 6-bolt splices with adhesive, and six 4-bolt splices with adhesive. Since each half of the symmetrical splice was repaired when it failed, and the test continued, the number of details is twice the number of splices. Some details were not repairable, or the repair did not last long enough. In these cases the test had to be discontinued. The details were cycled at 158 and 207 MPa bending stress range calculated with the equation $f_r = M/S$, where M = constant bending moment between loading points, and S = section modulus of W 14x30 without deducting the area lost to bolt holes. The minimum stress was set at 7 MPa.

Nine 6-bolt control details, eight 6-bolt bonded details, and eight 4-bolt bonded details failed from cracks that initiated in the flange at the first row of bolt holes closest to the supports. Two 6-bolt control details failed from cracks in the splice plate at the third row of holes, and two 4-bolt details at the second row. The tests of the remaining seven details were ended after 10,000,000 cycles produced no cracking or when the repair failed at other details on the same beam. The cracks propagated in the same manner as those in the tensile specimens.

The fatigue test data for the 6-bolt details are plotted in Fig. 5 with open triangles for the control details and with solid triangles for the bonded details. The former behaved as bearing-type connections and the latter as friction-type connections. All points were plotted in terms of the gross area stress range, as was done with the tensile test data. As Fig. 5 shows, adhesively bonding the contact surfaces increased the fatigue life of the bolted splices, on average, by a factor of 1.4 at 207-MPa stress range, from 474,000 to 686,000 cycles, and by a factor of more than 5.2 at 158-MPa stress range from 1,335,000 to 6,950,000 cycles. In the latter case, adding adhesive to details tested near the fatigue limit pushed several to runout.

The data for the 4-bolt splices are plotted in Fig. 6. Their mean fatigue lives were comparable to those of the 6-bolt control details without adhesive, that is 375,000 versus 474,000 cycles at 207-MPa stress range, and 1,464,000 versus 1,335,000 cycles at 158 MPa stress range. The bonded details tested at the higher stress range gradually slipped into bearing under cyclic loading, whereas those tested at the lower stress range behaved as friction-type connection throughout the fatigue life. The test data suggest that the number of bolts in the splice could be reduced by one third, without a loss in life if the contact surfaces were adhesively bonded. But there appears to be a limit on stress range, or maximum stress, above which the connections would no longer act as friction-type.

Figures 5 and 6 also compare the data with the allowable Category B line. If the data were plotted against the net area stress range for bearing-type behavior and gross area stress range for friction-type, all points would fall above the Category B allowable line. Two-thirds of the data points for 6-bolt bonded details (see Fig. 5) tested at 158-MPa stress range were runouts, meaning that the fatigue limit for this detail is closer to the 165-MPa limit for Category A base metal than to the 110-MPa limit for Category B.

FATIGUE STRENGTH OF COVER PLATES

Thirty-three 14 x 229 x 1220 mm long cover plates were adhesively bonded to the tension flange of W 14x30 beams, as shown in Fig. 2. Six cover plate ends were left nonbolted, and 27 ends were clamped to the flange with two 19-mm (3/4-inch) diameter A325 bolts.

The six nonbolted ends, identified with open triangles in Fig. 7, gradually debonded with stress cycling. For example, an ultrasonic compression-wave scan of one nonbolted end showed that a 100-mm length had debonded after 2,000,000 cycles of 145-MPa stress range. See the shaded areas in Fig. 8. These progressive separations are caused by high shear and tension (cleavage) stresses in the adhesive. To avoid them, the cover plate ends were bolted in subsequent tests.

The bonded and end-bolted cover plates failed from cracks that initiated in the flange at the bolt holes. In no detail did cracks initiate in the cover plate, nor did the flange cracks cross the bond line. The fatigue test data, plotted in Fig. 7 with solid triangles, show that the detail exhibited Category B strength. The mean factor increase in life over conventionally end-welded cover plates, classified under Category E, was at least 20 for the data at the three highest stress ranges, and over 35 at 145-MPa stress range. Since six of eight details tested at the lowest stress range were runouts, the fatigue limit may be about half-way between the limits for Category A (165 MPa) and Category B (110 MPa). Bonding and end-bolting has the potential of making cover plate ends of typical highway bridge girders fatigue proof.[3]

STATIC STRENGTH OF TENSILE SPECIMENS

The 16 Series C specimens were arranged in a two-way factorial with the following variables: two-bolt versus one-bolt splices, and control versus bonded specimens. Four specimens were tested at each combination of the variables, for a total of 16 specimens.

Figure 9 shows the applied load versus elongation of the 2-bolt control specimen C2 and the 2-bolt bonded specimen C5. Specimen C2 exhibited major slip at a load of 113 kN and a slip coefficient k_s = 0.33. The slip coefficient was calculated from

$$k_s = \frac{P_s}{n\ m\ T_i}$$

where: P_s = slip load, n = number of bolts, m = number of shearing planes, $T_i = 0.70\ F_u A_b$ = initial tension corresponding to 70% of the ultimate stress of the bolt. The connection went into full bearing at 196 kN. Thereafter, the load rose again linearly. The nonlinear behavior began with net area yielding of the splice plate at 304 kN and net area yielding of the main plate at 330 kN. The net area of the splice plate approached the ultimate load at 408 kN, the gross area of the splice plate yielded at 420 kN, and the bolts sheared at 425 kN. The yield and ultimate loads were calculated using the tensile properties reported by the mill. The shearing deformation of the bolts contributed to the nonlinear behavior.

The load-elongation curve of the 2-bolt bonded specimen C5, also shown in Fig. 9, rose almost linearly to 425 kN at which load the adhesive bond failed and the joint slipped. The corresponding slip coefficient,

$k_s = 1.26$, was 3.8 times higher than that for the control specimen C2. The load dropped to 340 kN by the time the bolt went into full bearing. Thereafter, it rose again, and the plates sheared the bolts at 410 kN. Yielding of the gross area of the splice plate at 420-kN load caused large strains at the mid-length of the splice plates. This in turn broke the bond beginning at the interior ends of the laps and led to the sudden failure of the adhesive.

The behaviors of the 1-bolt control specimen C10 and 1-bolt bonded specimen C14 were qualitatively similar to those of their 2-bolt counterparts. Their load-deflection curves are shown in Fig. 10. The control specimen C10 exhibited the first major slip at a load of 101 kN and a slip coefficient $k_s = 0.59$. The connection went into full bearing at 131 kN. Thereafter, the load-elongation curve began to deviate from linearity as the shearing deformations of the bolts increased. The bolts sheared at 215 kN, well below the yield loads of the plates.

The load-elongation curve of the 1-bolt bonded specimen C14 is also shown in Fig. 10. It rose linearly to 220 kN. At this load, the adhesive bond failed at a corresponding slip coefficient of $k_s = 1.31$. The plates slipped into bearing and immediately sheared the bolt because the slip load was greater than the ultimate capacity of one bolt in double shear.

The following main conclusions can be reached from an analysis of the 16 Series C specimens tested in this study:

1. Adhesively bonding the 2-bolt specimens increased the mean Slip coefficient from $\bar{k}_s = 0.36$ ($s = 0.05$) to $\bar{k}_s = 1.23$ ($s = 0.03$). But it did not increase the ultimate load capacity over that of the control specimens.

2. The slip coefficient of the 1-bolt specimens correspondingly increased from $\bar{k}_s = 0.61$ ($s = 0.05$) to $\bar{k}_s = 1.46$ ($s = 0.16$). Again, bonding did not increase the ultimate load capacity.

It is not clear from these results to what degree the conclusions would hold for connections with more than two bolt rows and for different ratios of bonded area to cross sectional area of bolts.

CREEP STRENGTH

A total of 79 double-strap specimens, shown in Fig. 3, were tested to determine the creep strength of the adhesive. Of these, 55 were set up indoors in spring-loaded frames and 24 outdoors. The indoor specimens were

subjected to nominal load levels varying from 80% to 30% of the 27.4 MPa mean shear strength under monotonically increasing load. The outdoor specimens were subjected to nominal load levels varying from 50% to 20%. The lap lengths were 13 mm or 25 mm. Longer lap lengths could not be tested because the spring capacity limited the load that could be applied to 21.4 kN.

The creep shear stress data were plotted in Fig. 11 against the logarithm of the time to failure. Comparing the triangular and square data points for specimens with 13-mm and 25-mm lap length reveals no significant difference. The specimens tested outdoors (solid symbols) failed after a significantly shorter time than the specimens tested indoors (open symbols). Still in progress are the indoor and outdoor tests at 30% and 20% load level, respectively. They are identified in Fig. 11 with arrows. These tests suggest that the load levels may be close to the creep thresholds for the two environments.

The loss in creep strength with outdoor exposure is attributed to the effect of temperature. The outdoor tests at 50% to 30% load levels were performed during the hot summer days, with temperatures reaching as high as 41°C on the roof of the building where the outdoor specimens were placed. Creep displacements, temperature and relative humidity were periodically measured. The creep rates were found to increase during high-temperature day time hours and to decrease during low-temperature night time hours. Relative humidity had no significant effect on creep strength.

In a previous study, 39 manufacturers had submitted information on their adhesives.[4] After a preliminary evaluation, 11 were selected for testing and, of those, three were then recommended for possible use in civil engineering structures. The modified acrylic adhesive, used in the present study, was one of the three. It had been recommended for its high shear and tensile strength, short curing time at room temperature, and minimal requirements for surface preparation. It may have, however, a creep strength lower than would be desirable for applications at high ambient temperatures.

SUMMARY

Adhesively bonding and high-strength bolting offers a significant potential for increasing fatigue life and resistance to slip of structural steel members. There are ways of designing bonded splices so that they will not fail in creep.[5] With further studies focusing on adhesive characterization and design rules development, the eventual application of adhesives to steel structures on a large scale appears to be only a matter of time.

REFERENCES

[1] Albrecht, P., Wattar, F., Sahli, A., and Vannoy, D.W., "End-Bolted Cover Plates", Report No. FHWA/MD-82/01, Department of Civil Engineering, University of Maryland, College Park, Maryland, July 1982.

[2] "Specifications for Highway Bridges", American Association of State Highway and Transportation Officials, Washington, D.C., 1977.

[3] Albrecht, P., Wattar, F., and Sahli, A., "Towards Fatigue-Proofing Cover Plate Ends", Proceedings of W.H. Munse Symposium on Metal Structures, Convention, American Society of Civil Engineering, Philadelphia, Pennsylvania, May 1983.

[4] Tara, H. and Gasparini, D., "Fatigue Resistance of Adhesively Bonded Structural Connections", Report No. 45K1-114, Department of Civil Engineering, Case Institute of Technology, Cleveland, Ohio, September 1981.

[5] Hart-Smith, L.J., "Adhesive Bonded Joints for Composites - Phenomenological Considerations", Report No. 6707, Douglas Aircraft Company, 1978.

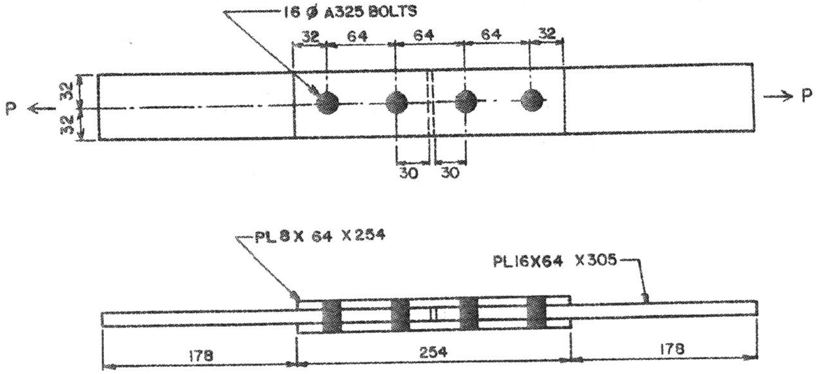


Fig. 1 Series A and C tensile specimens with 2-bolt splices

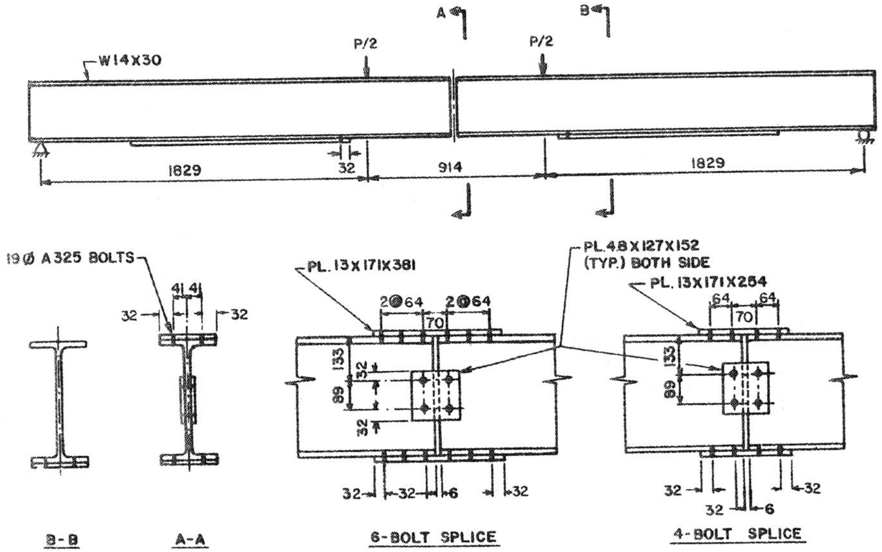


Fig. 2 Series B beam specimen with splices and cover plates

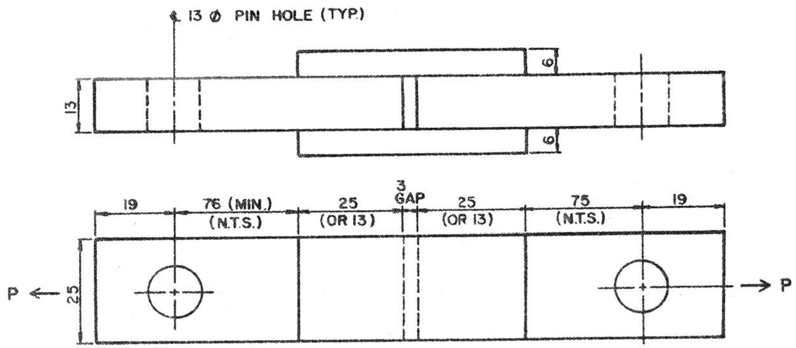


Fig. 3 Series E double strap specimen

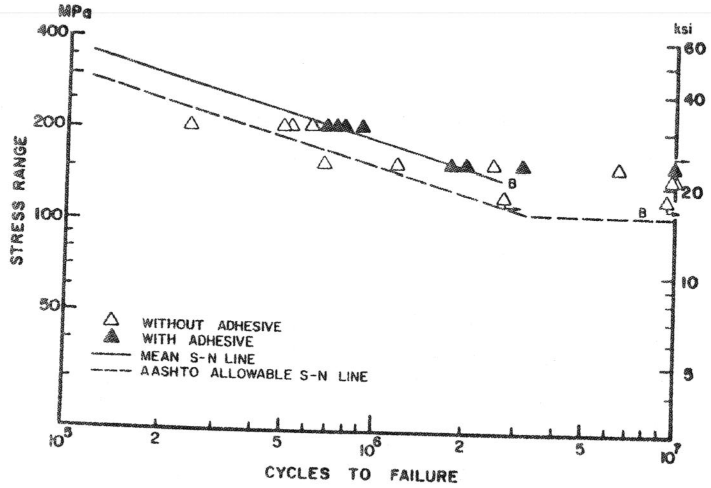


Fig. 4 Fatigue test data for series A tensile specimens with 2-bolt splices

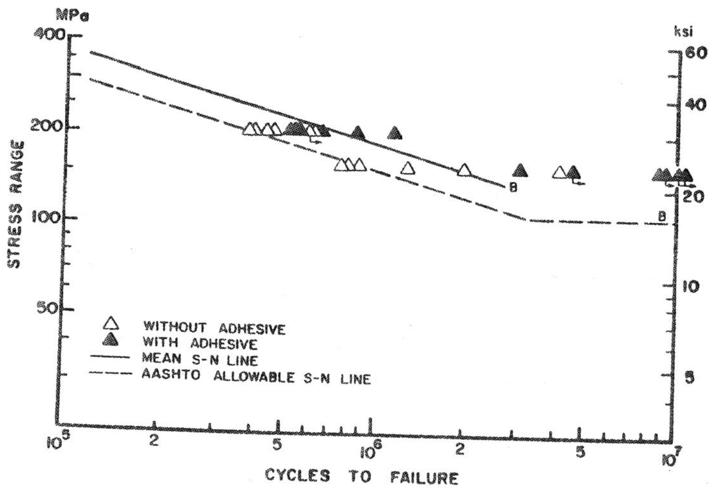


Fig. 5 Fatigue test data for series B specimens with 6-bolt splices

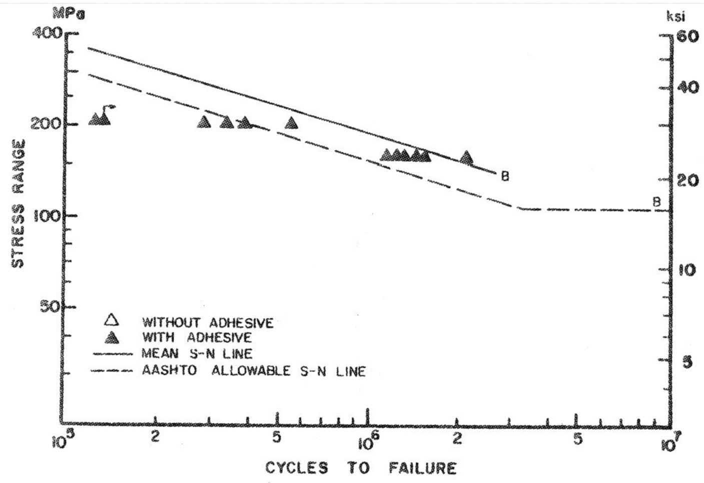


Fig. 6 Fatigue test data for series B specimens with 4-bolt splices

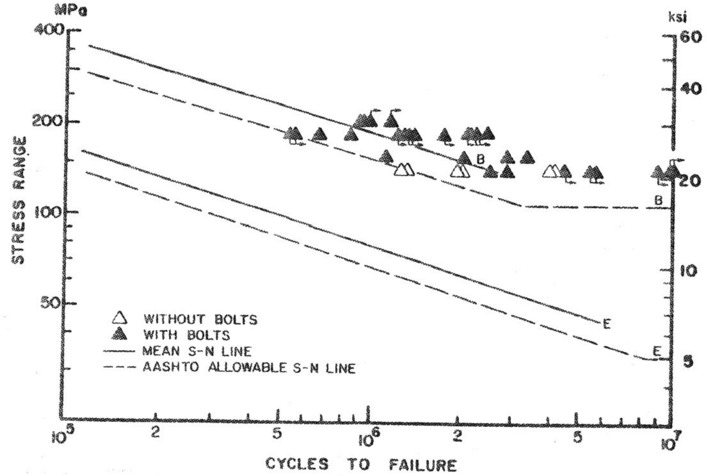


Fig. 7 Fatigue test data for series B specimens with cover plates

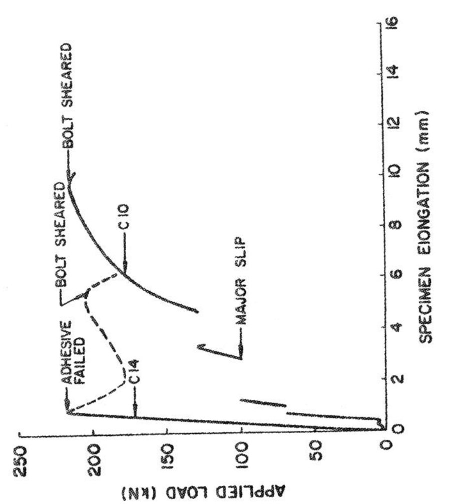
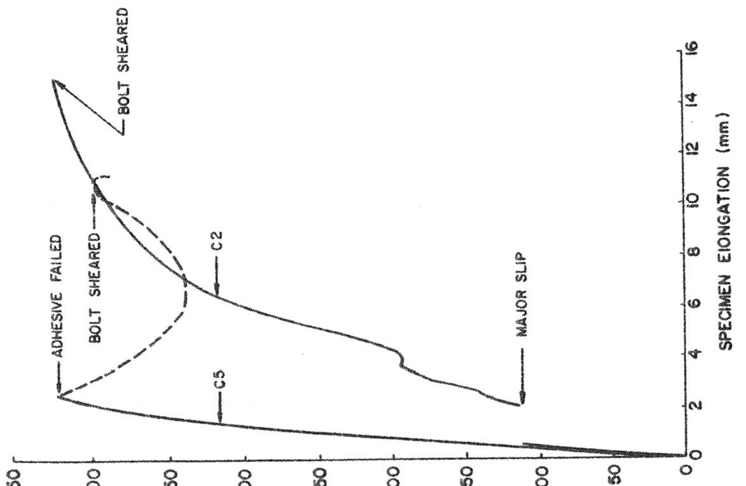


Fig. 9 Static test of nonbonded 2-bolt specimen C2 and bonded 2-bolt specimen C5 (left)

Fig. 10 Static test of nonbonded 1-bolt specimen C10 and bonded 1-bolt specimen C14 (below)



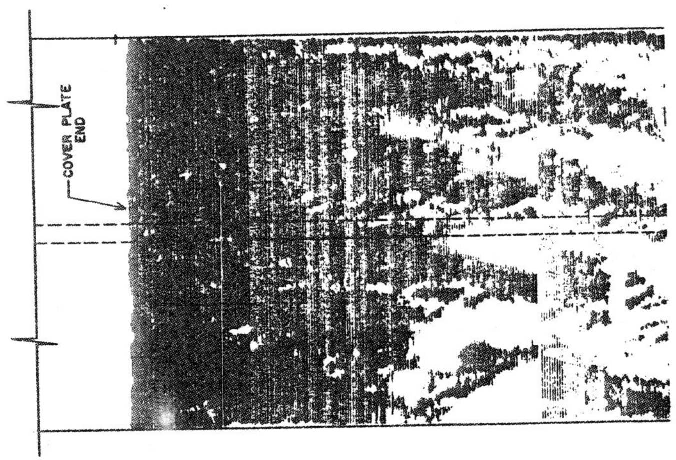


Fig. 8 Compression-wave scan of nonbolted cover plate end (debonded area is shaded)

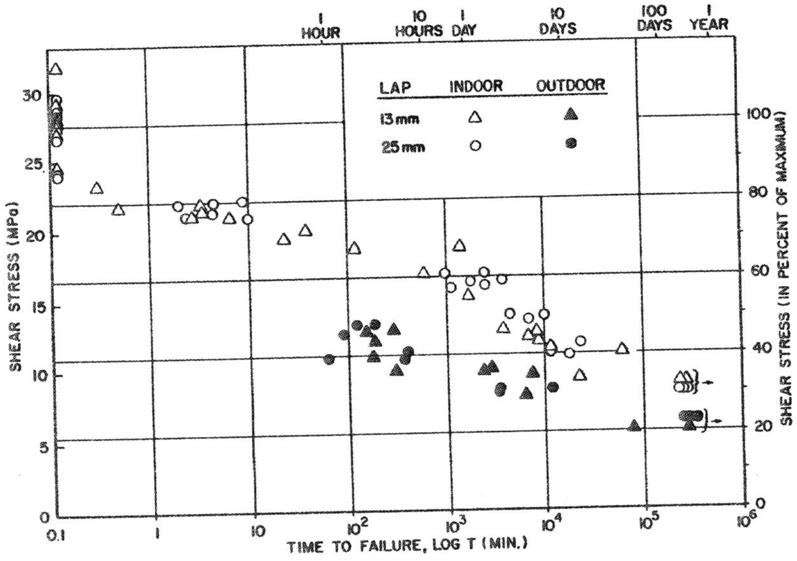


Fig. 11 Creep data for series E specimens