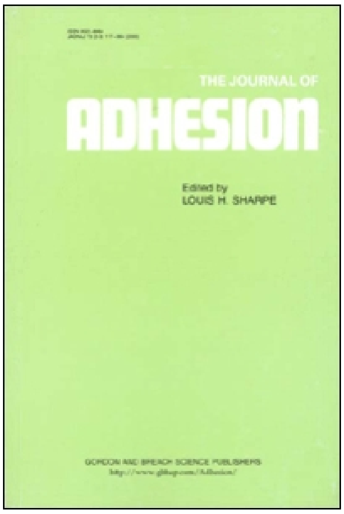


The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

The Effect of Glue-line Thickness on Bonded Steel-to-Steel Joints

R. W. Hylands[a]; E. H. Sidwell[a]
[a] Portadown Technical College, Northern Ireland Queen's University, Belfast, Craigavon, Northern Ireland

To cite this Article Hylands, R. W. and Sidwell, E. H.(1980) 'The Effect of Glue-line Thickness on Bonded Steel-to-Steel Joints', The Journal of Adhesion, 11: 3, 203 — 218
To link to this Article: DOI: 10.1080/00218468008078917
URL: http://dx.doi.org/10.1080/00218468008078917

J. Adhesion, 1980, Vol. 11, pp. 203–218
0021-8464/80/1103-0203 $06.50/0

The Effect of Glue-line Thickness on Bonded Steel-to-Steel Joints

R. W. HYLANDS AND E. H. SIDWELL

Portadown Technical College, Craigavon BT63 5BL, Northern Ireland
Queen's University, Belfast, Northern Ireland

(Received April 4, 1980; in final form, July 1, 1980)

The mono-wire joints composed of cylindrical steel to steel interfaces were used to investigate the effect of glue-line thickness with an epoxy structural adhesive. Compression and tension joints were concentrically constructed and after curing, axially loaded to failure. Nine glue-line thicknesses 0.001 to 0.100 in and five bond lengths were tested. The strongest joints were obtained with the thinnest glue-lines and increases up to 0.060 in diminished the strength by about 32% for both compression and tension specimens. From 0.60 to 0.10 in the joint strength was almost constant. Test results displayed C of V for the joint strength of between 6.89% and 13.41%. A relationship was found among mean breaking force, glue-line thickness and bond strength. In general, compression test pieces were slightly stronger than the tension ones.

INTRODUCTION

The effect of glue line thickness was investigated for mono-wire specimens as support work for a research project concerned with the prestressing (energising) of structural materials.[1–5] The main research project compared the bonding of the cables of a poststressed timber beam with a similar un-bonded beam. The cable for the poststressed timber beams consisted of Bridon prestress wire, manufactured by British Ropes Limited,[6] of 0.276 in (7 mm) diameter "patented", plain, cold drawn and produced to BS 2691.[7] Four of these were placed inside a standard square steel tube together with a central 0.1875 in (4.76 mm) diameter wire as shown in Figure 1. This arrangement prevents the four larger wires from undue warping or twisting during use.

Tests in compression and tension were made on mono-wire cylindrical joints, the range of glue line thicknesses chosen being compatible with those within the cable. This information on adhesives was helpful as the glue line thickness within the cross-section is variable.

Such results were a useful prelude to the design and analysis of the poststressed beam with bonded cables.

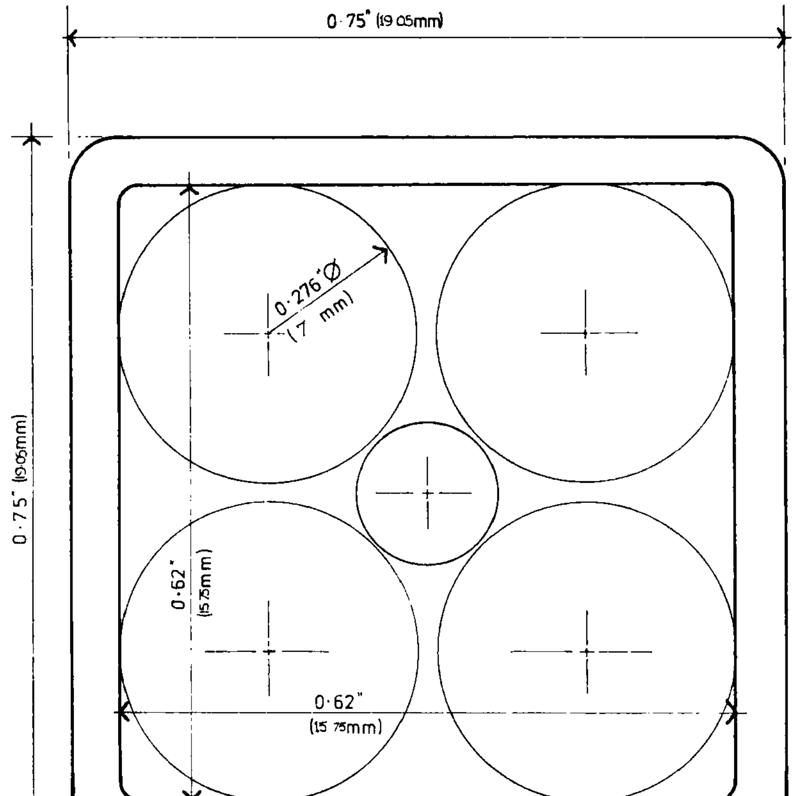


FIGURE 1 Cross-section of multiple-wire arrangement for poststressed timber beams.

MILD STEEL SPECIMENS USED IN MONO-WIRE TESTS

The glued joint which was constructed consisted essentially of a steel rod placed concentrically inside a hole which was drilled along the centroidal axis of a circular steel bar. The steel rod had part of its length geometrically similar to the 0.276 in dia. prestress wire and had a polished bright surface finish. A hole was drilled and reamed at the centroid of the bar cross-section along the length of the specimen. These specimens were used to enable accurate control of the bond length and glue line thickness of each joint. Nine different hole diameters were selected to give glue line thicknesses ranging from approximately 0.001 in (0.0254 mm) to 0.100 in (2.54 mm) and five different bond lengths, *viz.*, 0.5 in (12.7 mm), 1.0 in (25.4 mm), 1.5 in (38.1 mm), 2.0 in (50.8 mm) and 2.5 in (63.5 mm) used to increase test data. Figure 2 shows the test specimens.

DESIGN OF JIGS FOR ALIGNMENT OF MONO-WIRE JOINTS

It was necessary to design jigs which would enable both proper alignment and a concentric joint of uniform thickness to be maintained. Two types of jigs were designed and manufactured to accommodate compression and tension specimens. Five complete sets of jigs for each type of test were made so that the testing programme period could be shortened. Figure 3 shows typical alignment jigs for compression and tension test specimens.

To ensure easy separation of the jigs after the adhesive joint had been cured a film of grease was smeared on the portion of the test specimens adjacent to the jigs. Great care was taken to ensure that no grease came into contact with the surfaces being bonded or indeed with the adhesive. When assembled, both parts of the jig and joint specimen were held firmly in position using hexagon screws as indicated in Figure 3.

The jigs for the compression joint specimens were made to receive the complete range of bond lengths, the bond length being determined in each case by the length of circular steel bar with the concentric hole along its length. The length of these bars was cut to agree with the correct length of bond. For the compression tests a special gripping device was designed and manufactured to fit the top jaws of the Avery testing machine and also the steel specimen which was to be tested. A circular steel block was made to receive the lower portion of the jointed specimen being tested and to maintain an axially applied load during testing.

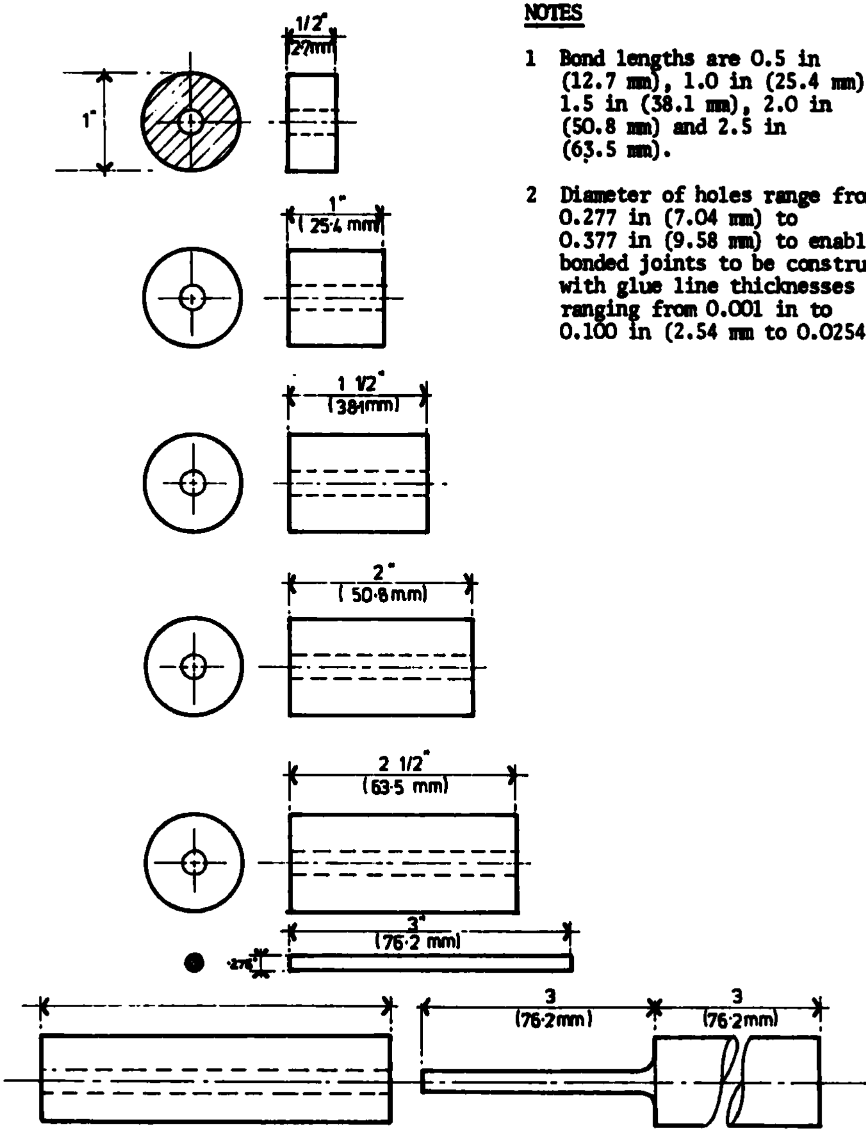
The jigs for the tension joint specimens were so designed to facilitate the assembly of the five different bond lengths. This was achieved by means of a small grub screw attached to the female portion of the jig which allowed the joint specimen to be positioned at the desired bond length.

REQUIREMENTS OF TESTING APPARATUS

The main objects of this part of research were to determine:

The strength characteristics of a selected adhesive for the monowire tests (compression and tension), steel-to-steel.

Compression tests



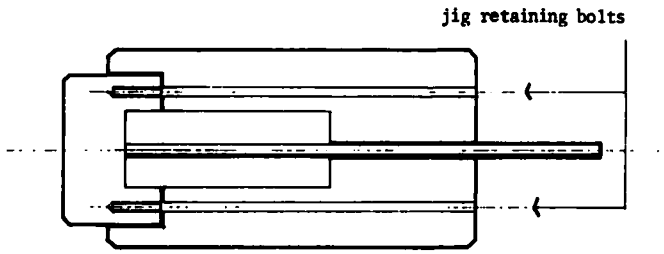
NOTES

1 Bond lengths are 0.5 in (12.7 mm), 1.0 in (25.4 mm), 1.5 in (38.1 mm), 2.0 in (50.8 mm) and 2.5 in (63.5 mm).

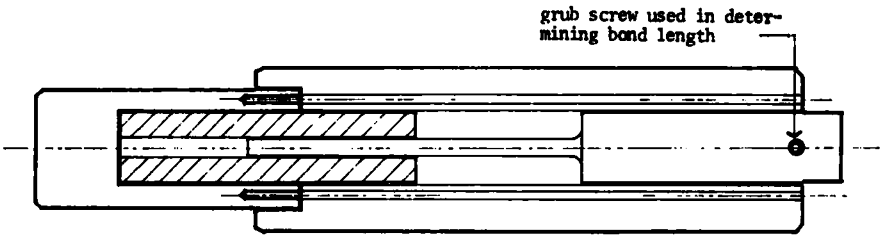
2 Diameter of holes range from 0.277 in (7.04 mm) to 0.377 in (9.58 mm) to enable bonded joints to be constructe with glue line thicknesses ranging from 0.001 in to 0.100 in (2.54 mm to 0.0254 mm

Typical arrangement for tension tests

FIGURE 2 Compression and tension specimens for adhesive tests.



Typical alignment jig for compression test specimens (mono-wire)



Typical alignment jig for tension test specimens (mono-wire)

FIGURE 3 Typical alignment jigs for compression and tension test specimens.

How the strength of a joint varies with glue line thickness.

How the strength varies with bond length.

The mode of failure for the adhesive tests.

The testing machine satisfied the following requirements:

Accuracy. The test machine shall be verified according to the requirements of Grade A, BS 1610, Verification of testing machines, Part 1, Methods of load verification requirements for elastic proving devices and verification of machines for tension and compression testing.[8]

Rate of loading. With the test piece in position and under load. The rate of increase in load shall be between 300 and 600 lbf/minute, according to BS 1203: 1963 Appendix B.[9]

Type of jaw assembly. The jaws shall grip the test piece with a wedge action. Each pair of jaws shall be attached by loose fitting pin joints which in turn are fitted by ball-and-socket joint to the straining heads. In a machine mounted horizontally the dead weight of the jaw assembly shall be carried by freely moving cross-members. This shall not affect the freedom of rotation of the jaws.

Alternatively, one of the pair of jaws shall be attached rigidly to the tensile machine and the other jaws shall be suspended from a ball-and-socket joint allowing sufficient sideways movement of the jaw to permit self-alignment of this jaw while the test pieces are being pulled.

Axial load for compression testing. The machine will require adaptability for the addition of suitably designed portions of apparatus to facilitate proper compression tests to be executed.

Additionally, the machine must be capable of adjustment to operate with a scale not exceeding 20 kN and of producing a graphical recording of load against change in length to enable observation of the mode of failure for a particular test.

The machine used for the adhesive tests was the Avery-Denison Universal Testing Machine.

An equal number of tests was carried out for the compression and tension specimens for all adhesive test series, all test specimens being subjected to axial loading.

The number of tests to be repeated for each joint specimen was another important consideration. BS 1203:1963, Appendix B[9] specifies that five tests should be carried out for each specimen and the mean of the results reported for the failing load. It was also decided to consider five different bond lengths so that such things as edge effects, Poisson's effect, *etc.*, could be considered.

TEST PROCEDURE

The following is a generalised procedure for carrying out adhesive tests.

All steel specimens were thoroughly degreased using carbon tetrachloride on a fluff-free cloth. A close inspection of the surfaces to be bonded was carried out to check the presence of any undesirable foreign particles that would interfere with the glue line of the joint. The surfaces were also checked to ensure that they were free from damage.

The adhesive was prepared in accordance with the manufacturers instructions and due regard given to handling precautions for Araldite epoxy resin materials.[10] Araldite AY 103, a plasticised liquid epoxy resin was mixed with Hardener HY 991, a light-brown liquid in the recommended mix proportions of 100 parts Araldite to 40 parts Hardener by weight or 100 parts Araldite to 50 parts Hardener by volume. The adhesive was prepared at room temperature, *i.e.* 20°C (68°F) using volumetric proportioning and was thoroughly stirred to give a uniform liquid of low viscosity. The mixed adhesive was then poured into the female specimen and the male portion inserted to form the required joint. The excess glue displaced was removed from the joint.

The jointed samples were placed in the Standards Laboratory and left for twenty-four hours to cure in a controlled room temperature of 20°C (±1°C) *i.e.* 68°F (±1.8°F).

After curing, each joint specimen was carefully assembled between the jaws of the Avery-Denison Universal Testing Machine. The specimens had been identified by letter or number and were tested at approximately ten minute intervals to agree with the twenty-four hour curing period. An axial load was applied to the jointed specimen, the rate of increase in load being kept within the limits of 300 and 600 lbf/minute as stated in BS 1203:1963 Appendix B.[9] The rate of loading was controlled using the load pacer on the testing machine. Careful records were kept of the quality of the joint specimen, mode of failure, *etc.*, for each test sample.

After testing the specimens were soaked in chloroform for twenty-four hours to break down the epoxy resin on the specimen. The specimens were then cleaned and stored in methylated spirit preparatory to further testing.

MONO-WIRE TESTS

The steel specimens to be jointed were designed to give nine glue line thicknesses: 0.001, 0.004, 0.012, 0.020, 0.035, 0.040, 0.060, 0.080 and 0.100 in, *i.e.*, 0.0254 to 2.54 mm.

Provision was also made to test each glue line thickness over five different bond lengths, *viz*; 0.5, 1.0, 1.50, 2.0 and 2.5 in. The order of carrying out the tests on the specimens was as follows: Day No. 1, all 0.5 in bond lengths (nine tension and nine compression tests), day No. 2, all 1.0 in bond lengths, *etc.* This testing procedure was adopted to retain consistency within each group of results.

In the compression tests, the male specimens were designed to ensure that there would be no buckling of the member when the joint was being loaded to failure.

The length of specimen between the upper jaws of the testing machine and the glued joint was calculated to be 1.875 in, this value being the greatest possible load anticipated, *viz.*, 6,000 lbf (26.7 kN). In the tension specimen the length of member was not a ruling factor.

The specimens whose glue line thickness was 0.001 in provided some difficulty in ensuring that the adhesive completely covered all parts of the joint. As previously stated alignment jigs were used to assemble the concentrically jointed specimens. A film of grease was smeared around the surfaces of the parts of the jointed specimen not being bonded and also on the adjacent surfaces of the alignment jigs. This facilitated easy removal of the jointed specimen from the steel jigs after the twenty-four hour curing period.

The analysis of tests results show an approximate spread of 12% between the lowest and highest readings after five repeated tests for a particular joint. This spread is satisfactory for adhesive tests. In general, it was found that the tension joint specimens were slightly weaker than the corresponding compression joint specimens. It is believed that this is because of the Poisson's ratio effect when the jointed specimen is under axial load. The compression male member is obviously subjected to a small lateral increase in dimension whereas with the tension arrangement the member is subjected to a small contraction. This is a possible reason for both types of tests having differing results. Compression and tension specimens failed with a marked explosive bang with a well defined reading being recorded on the testing machine. The results of 450 tests using the mono-wire arrangement revealed information regarding varying glue line thickness and bond length for both compression and tension test specimens.

Graphs of mean breaking force *versus* glue line thickness were plotted for both compression and tension experiments using a mean of five readings for each point plotted and are as shown in Figures 4 and 5. Additional graphs of mean breaking force *versus* bond length were plotted to check if there was a linear relationship between breaking force and each equal increment of bond length. An approximate linear relationship was found to exist for test specimens having a similar glue line thickness. Figures 6 and 7 show graphs of breaking force *versus* glue line thickness with all results plotted.

These give a pictorial representation of the spread of results for each bond length. Calculations for the coefficient of variation indicate a spread of values ranging from 6.89% to 13.41%.

From the graphs of mean breaking force versus glue line thickness, Figures 4 and 5, it can be seen that the strongest joint is obtained with a thin glue line. As the glue line becomes thicker, up to about 0.060 in, the joint strength diminishes for both compression and tension tests, and for glue line thicknesses in the range 0.060 in to 0.100 in the joint strength is approximately constant.

A probable reason for the diminution in strength with the thicker glue line joints is the slight shrinkage of the adhesive from the interfaces during curing. The shrinkage property for the adhesive under consideration is approximately $1\frac{1}{2}$%. Self straining in the adhesive is more likely during shrinkage in a thick glue line than a thin one; in a very thin one it would be negligible. From test results in would appear that the shrinkage of adhesive during curing period affects the joint strength to varying degrees up to a glue line thickness of approximately 0.060 in; beyond this joint thickness the adhesive shrinkage does not significantly diminish the strength of the jointed steel specimen.

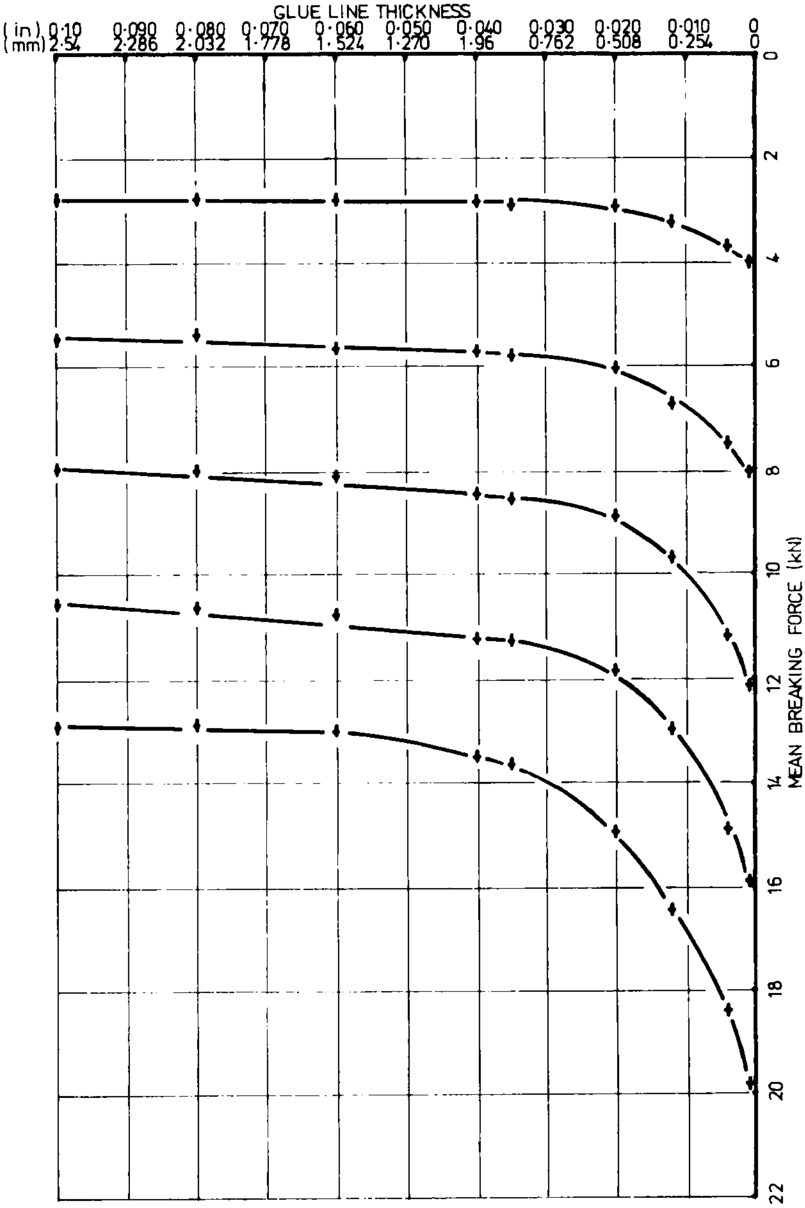


FIGURE 4 Mean breaking force versus glue line thickness for mono-wire tests on compression specimens, steel to steel.

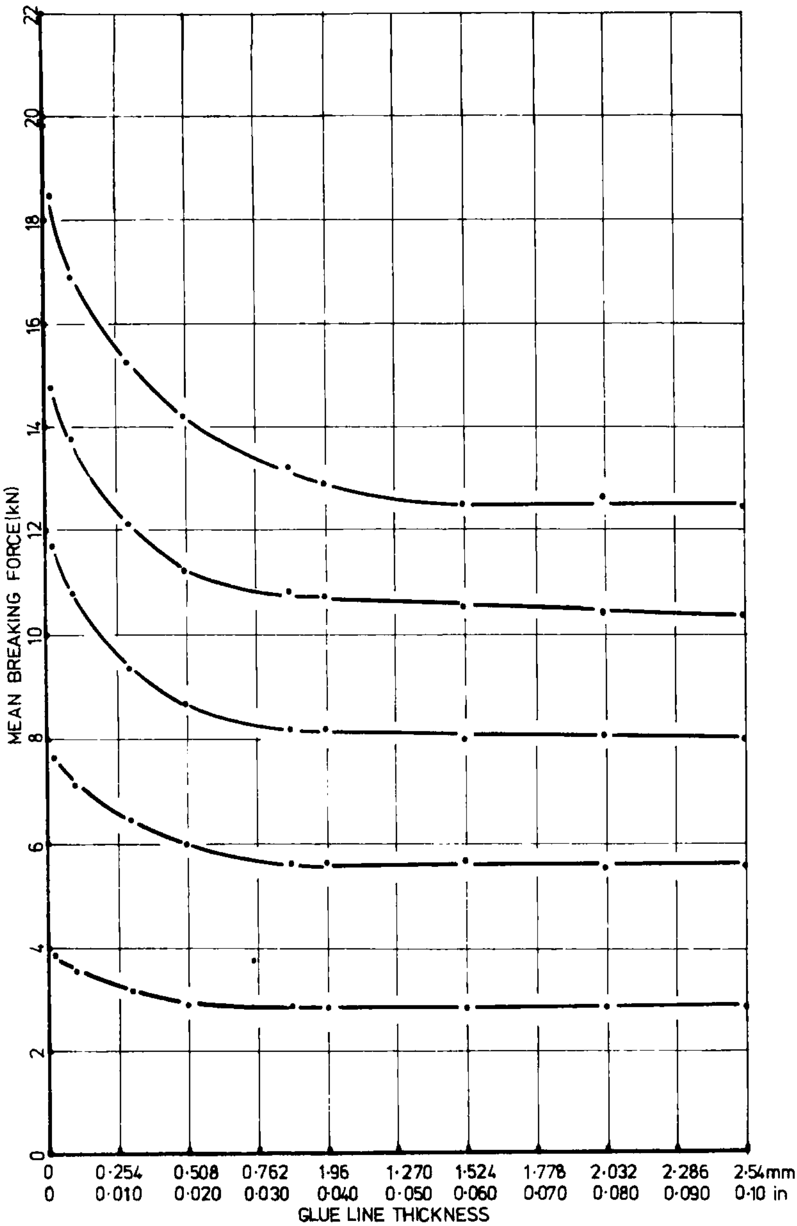


FIGURE 5 Mean breaking force versus glue line thickness for mono-wire tests on tension specimens, steel to steel.

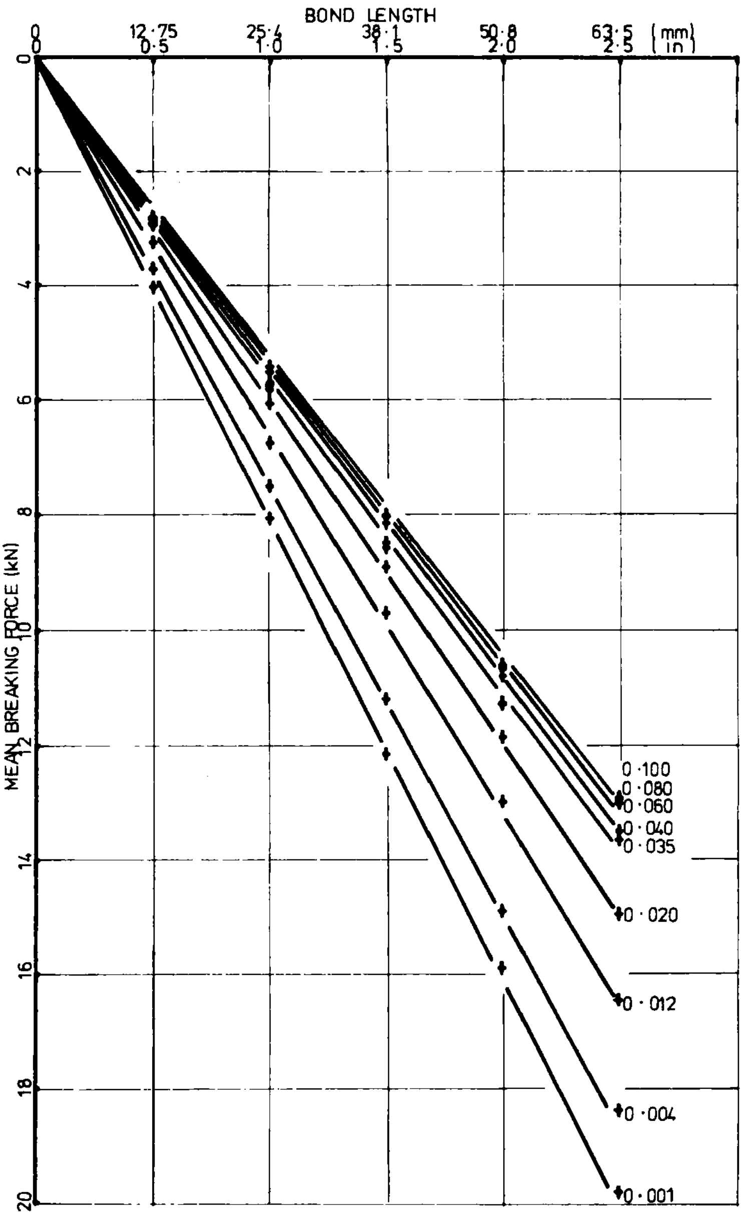


FIGURE 6 Mean breaking force versus bond length for mono-wire tests on compression specimens, steel to steel.

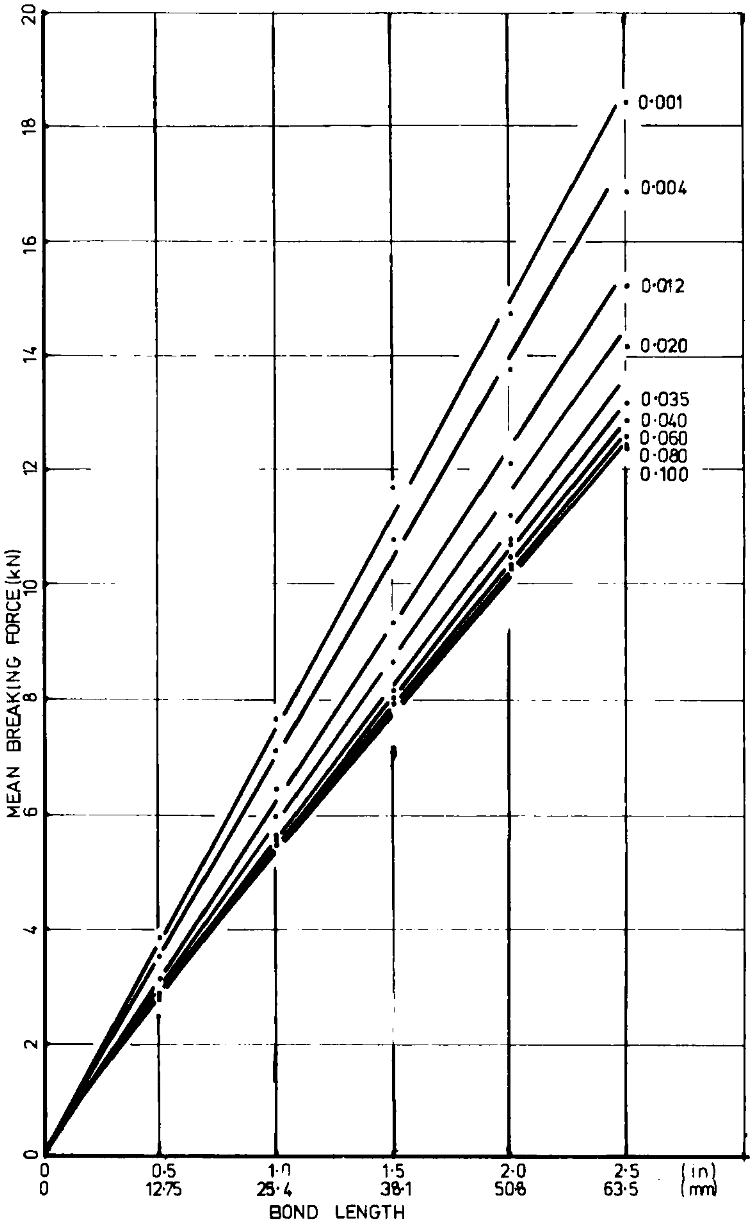


FIGURE 7 Mean breaking force versus bond length for mono-wire tests on tension specimens, steel to steel.

From the graphs of mean breaking force *versus* bond length, Figures 6 and 7, it is seen that there is an approximate linear relationship in both compression and tension tests. There is however a tendency for the joint strength to deviate from this linear relationship and diminish slightly in strength as the bond length increases; it is believed that if the bond length range was substantially extended this linear relationship would not necessarily prevail.

A comparison of compression and tension test results for *mean breaking* force *versus* glue line thickness is shown in Figure 8 and it may be generally seen that the compression tests are slightly stronger than the corresponding tension tests. The following may provide a possible explanation. When the 0.276 in diameter steel bar is loaded there is a change in its lateral dimension which would tend to be more significant in the higher load range and almost negligible in the lower load range. In both compression and tension tests the shrinkage of the adhesive during curing and Poisson's effect must contribute to the joint strength of corresponding test specimens. It is reasonable to argue that the shrinkage is the same for both compression and tension tests and hence the difference in joint strength in the corresponding tests is caused by the Poisson's effect alone. The Poisson's effect in the compression tests would tend to make the joint stronger because of the additional frictional force developed by the increased lateral spread of the 0.276 in diameter bar. In the tension tests the bar would contract a small amount laterally and tend to pull away from the joint interface thus reducing the strength of the joint. The graphs in Figure 8 support this reasoning.

From the results of the test series a relationship was derived between the three variables mean breaking force (Y) kN, glue line thickness (X_1) mm and bond length (X_2) mm, a separate equation being determined for compression and tension test situations. Using a computer program obtained from the University of Kansas,[11] a facility exists to express a dependent variable Y in terms of two independent variables X_1 and X_2 using a polynominal equation up to the power of 7. However, a polynominal equation of degree 4 gave sufficient accuracy for adhesive test results, *viz.*,

$$
\begin{aligned}
Y = {} & C_1 + C_2X_1 + C_3X_2 + C_4X_1^2 + C_5X_1X_2 + C_6X_2^2 + C_7X_1^3 + C_8X_1^2X_2 \\
& + C_9X_1X_2^2 + C_{10}X_2^3 + C_{11}X_1^4 + C_{12}X_1^3X_2 + C_{13}X_1X_2^3 + C_{14}X_2^4 \\
& + C_{15}X_1^2X_2^2
\end{aligned}
$$

This program is an outgrowth of research in geological trend analysis. The method consists of expanding the desired linear regression into a matrix of normal equations, which is then solved by inversion, giving coefficients of the regression. A simple Gaussian elimination is used for inverting the matrix.

The coefficients of the equations for compression and tension specimens are as follows:

Compression joints (maximum error = 3%)

$C_1 = -0.8156$	$C_6 = -0.7032 \times 10^{-2}$	$C_{11} = 0.7864$
$C_2 = -3.5370$	$C_7 = -4.1023$	$C_{12} = -0.2121 \times 10^{-1}$
$C_3 = 0.4710$	$C_8 = 0.1010$	$C_{13} = -0.7808 \times 10^{-5}$
$C_4 = 6.8191$	$C_9 = 0.3828 \times 10^{-3}$	$C_{14} = -0.7563 \times 10^{-6}$
$C_5 = -0.1873$	$C_{10} = 0.1236 \times 10^{-3}$	$C_{15} = 0.1673 \times 10^{-3}$

Tension joints (maximum error = 6%)

$C_1 = 0.4274 \times 10^{-1}$	$C_6 = 0.6253 \times 10^{-3}$	$C_{11} = 0.6724$
$C_2 = -2.7993$	$C_7 = -3.5703$	$C_{12} = -0.1933 \times 10^{-1}$
$C_3 = 0.3185$	$C_8 = 0.1060$	$C_{13} = 0.7919 \times 10^{-5}$
$C_4 = 5.9071$	$C_9 = 0.1014 \times 10^{-2}$	$C_{14} = 0.3780 \times 10^{-6}$
$C_5 = -0.2065$	$C_{10} = -0.4092 \times 10^{-4}$	$C_{15} = -0.7295 \times 10^{-4}$

CONCLUSIONS

The following conclusions are indicated from results of tests employing an epoxy resin adhesive (Araldite AY 103 with Hardener HY 991).

i) The strongest joints are obtained using thin glue lines.

ii) The strength of a bonded joint diminishes as the glue line increases in thickness up to about 0.060 in; the joint strength being approximately constant for thicker glue lines in the range 0.060 in to 0.100 in.

iii) Jointed specimens subjected to compression loads tend to be slightly stronger than corresponding joints subjected to tension, due to Poisson's ratio effect when load is applied to the joint.

iv) A relationship does exist between mean breaking force, glue line thickness and bond length for the mono-wire joints; a separate equation being necessary for compression and tension joints.

RECOMMENDATIONS FOR FURTHER RESEARCH

The range of glue line thicknesses in this research project has been confined to 0.001 in to 0.100 in. From test results associated with the mono-wire arrangement it would appear that the ultimate strength of a bonded joint is approximately constant for glue line thicknesses between 0.060 in and 0.100 in. However, it would be a useful exercise to extend this range to check if this constant relationship still exists for thicknesses beyond 0.100 in.

There is also lack of information regarding the behaviour of joints having a wide variety of bond lengths and consequently more work requires to be done to obtain strength characteristics of the adhesive when subjected to an extended range of bond lengths. For example, results of tests for bond lengths

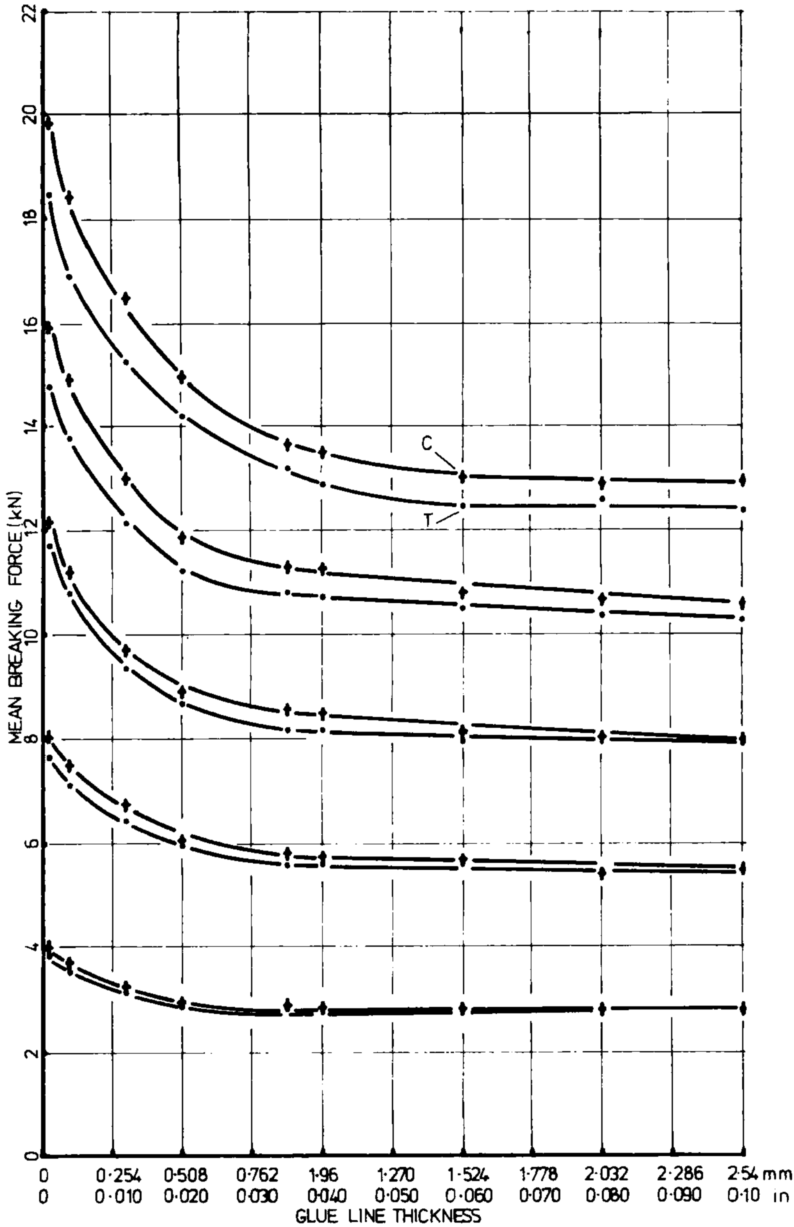


FIGURE 8 Mean breaking force versus glue line thickness for mono-wire tests on compression and tension specimens, steel to steel.

varying from 100 mm to say 1 m in 100 mm increments of bond length would be invaluable. From these results graphs may be plotted and an appropriate law developed related to strength and bond length which could be used by designers whose work involves a detailed knowledge of epoxy resin adhesives.

The information derived relating to mono-wire bonded joint situations was concerned with concentrically formed joints giving a uniform glue line thickness throughout the joint. Test results data related to a similar joint having variable glue line thickness within the mono-wire arrangement would prove beneficial.

A detailed study as to the surface preparation and finish of the adherend would be useful. For example, polished bright surfaces compared with sand blasted chemically etched and other surface finishes could be compared from the point of view of strength variation. To ensure consistency it is suggested that the tests be carried out using the mono-wire arrangement and a glue line thickness kept within the constant portion of the graphs of Figures 4 and 5; the only variable would then be surface preparation and finish. From the results of this work the designer could be given positive direction as to the choice and standard of finish for a particular practical situation.

All of the tests reported are associated with one epoxy resin adhesive. The authors believe that similar tests should be carried out on a number of different epoxy resins and a comparison made of their structural inter-relationships.

Notation

$C_{1,2,3-}$ coefficients of the equations for compression and tension specimens.
X_1 glue line thickness in mm.
X_2 bond length in mm.
Y mean breaking force in kN.

References

1. E. H. Sidwell, *Civil Engineering* **64**, (751) 120 (1969).
2. S. R. Port and E. H. Sidwell, *ibid.* **64**, (752), 226 (1969).
3. E. H. Sidwell and B. C. Carroll, *ibid.* **66**, (774/5), 47 (1971).
4. E. H. Sidwell and F. F. Keatley, *ibid.* **69**, 28 (1974) and **70**, 50 (1975).
5. R. W. Hylands, *The bonding of the cables of a poststressed timber beam and a comparison of its performance with a similar unbonded beam.* PhD Thesis, CNAA (1978).
6. British Ropes Limited, Doncaster, England. *Bridon wire and strand for prestressed concrete* (1962).
7. British Standards Institution, B.S. 2691, *Specification for steel wire for prestressed concrete* (London, 1969).
8. British Standards Institution, B.S. 1610 Grade A. *Verification of testing machines. Part 1. Methods of load verification of machines for tension and compression testing* (London, 1964).
9. British Standards Institution, B.S. 1203, *Synthetic resin adhesives for plywood* (London, 1963).
10. Ciba-Geigy (UK) Ltd., Plastics Division. *Handling precautions for Araldite epoxy resin materials* (Duxford, Cambridge, 1974).
11. The University of Kansas State Geological Survey. *Computer contributions No. 28 KWIKR8 —A FORTRAN IV program for multiple regression and geological trend analysis.*