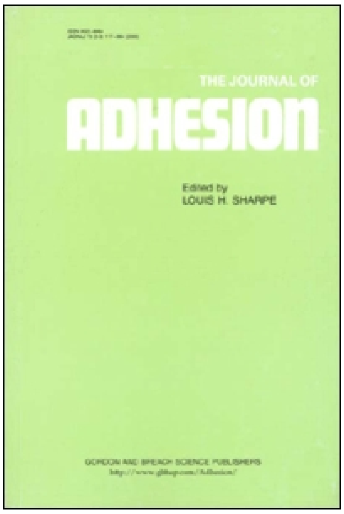

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Methodology for Determining the Durability of Sealants

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Methodology for Determining the Durability of Sealants

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This paper presents the framework for a methodology for insuring the durability of construction sealants. The basic approach involves determination of an allowable strain capacity. This is done by establishing a 5% exclusion value on the ultimate strain capacity of the unaged sealant, then modifying that by empirical reduction factors to reflect the effects of service conditions. Fatigue, heat, water, chemicals, cold, and ultraviolet light are considered, as are state of strain, joint geometry, substrate type, and a safety factor. Data taken for tests on a solvent acrylic sealant are used to illustrate application of the method. Further research needs are briefly discussed.

INTRODUCTION

The objective of this paper is to present the basis for a rational engineering approach to the use of sealants and, by extension, to suggest a procedure for the engineered design of sealant joints. Although many questions are yet to be answered, the general framework of this approach will allow new knowledge to be incorporated as it becomes available.

There are similarities between sealants, wood and adhesives. For each there exists a bewildering variety of material choices with a wide range of properties. Sealants, like wood and adhesives, are subject to various types of degradation. They are often taken for granted during design and construction.

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Sealants differ from wood and adhesives in one very important respect. Except for some glazing applications, sealants are not relied upon to carry load. Rather, they are expected to seal out the weather in joints which may be subjected to movements from various sources. Thus it is strain capacity rather than stress resistance which determines the performance capability of a sealant.

Within reason, there is no such thing as a bad sealant. But there is frequently misapplication of a given sealant. It is just as inappropriate to make a temporary, non-critical seal with an expensive elastomeric sealant as it is to seal a monumental high rise with an unidentified compound whose only known virtue is low price. The best sealant is the one which will minimize total cost over the useful life of the structure. The challenge lies in predicting long term performance so that an intelligent selection of sealant and joint design can be made. Panek[1] and Skeist[2] provide an extensive listing of sealant specifications, both domestic and foreign. In the main, these specifications establish qualitative standards which are somewhat arbitrary and do not provide the data necessary to actually design a sealed joint.

The American Society for Testing and Materials (ASTM) lists 35 tests for evaluating building sealants, caulks, and gaskets.[3] In addition, there are a number of related tests dealing with water and air transmission in windows, doors, and curtain walls. Many of the sealant tests are concerned with installation characteristics and appearance and, therefore, are not directly applicable to the durability question.

Several problems become evident when the ASTM tests are considered for possible use in a comprehensive test program. First, there is little consistency in specimen configuration or conditioning in the ASTM tests. Second, most of the tests are relatively short term and appear to be aimed at providing quality control/quality assurance data rather than design information. Finally, the tests for accelerated aging, in many cases, include a number of aging variables, making it difficult to identify relative sensitivity to the individual variables.

METHODOLOGY

The most important measure of sealant durability is strain capacity. Even in so-called non-moving joints, the sealant must withstand some movement due to thermal or moisture induced expansion and contraction. Also, sealant shrinkage and hardening with age can result in strains similar to those caused by actual joint movement. Under adverse environmental conditions, a sealant must be able to withstand movements for the life of the structure or for some acceptable period prior to replacement.

The determination of an allowable strain for a sealant joint can be treated in a manner similar to that proposed by Krueger[4] for establishing allowable stresses in adhesives. This method, in turn, is based upon an approach that has been in use for many years in the engineering design of structures and components from wood and other materials. As applied to sealants, the method involves reducing the basic ultimate strain capacity of a sealant by appropriate factors to arrive at an allowable design strain. This allowable design strain can be expressed as:

$$\begin{aligned}\varepsilon_a = {} & \pm(5\%\ \text{exclusion limit for basic strain})\\ & \times(\text{durability factors})\times(\text{state of strain factor})\\ & \times(\text{geometric shape factor})\times(\text{substrate factor})\times(\text{safety factor}).\end{aligned}$$

The basic strain value can be determined from short term tests on either shear or tension specimens. The 5% exclusion limit is a value expected, with a selected degree of confidence, to be exceeded by 95% of all future values.[5] The durability factors account for the effects of exposure to water, heat, cold, chemicals, ultraviolet radiation, fatigue, and displacement set. These factors can be obtained from accelerated or long term tests. While long term tests may be more accurate, they have obvious disadvantages. The state-of-strain factor accounts for differences in sealant joint behavior under axial and shear strain conditions. The geometric shape factor corrects for variations in strain capability that occur when the sealant is used in joint designs with width-thickness ratios or configurations that are different from that used for the basic displacement and aging tests. The substrate factor reflects the differing adhesion characteristics of the sealant on various adherends. Finally, the factor of safety accounts for uncertainties regarding actual behavior, installation, and service conditions, as well as reflecting a judgement of how critical the integrity of the joint is.

TEST PROGRAM

A testing program was developed to facilitate the determination of allowable strains for several typical sealant types. The tests used were similar in many respects to standard ASTM tests. However, specimen geometry and curing procedures were standardized so that all the specimens for a given sealant used in the various tests began with similar material properties. The specimens used are shown in Figures 1 and 2.

All specimens were cured one week at 23°C and 50% RH followed by another week at 40°C, 50% RH. All testing, except for low temperature testing, was done at 23°C and 50% RH. Testing was done with a universal testing machine. Specimen deformations were monitored with dial gages or electronically by the test machines. The test speed was 1.3 mm per minute except for

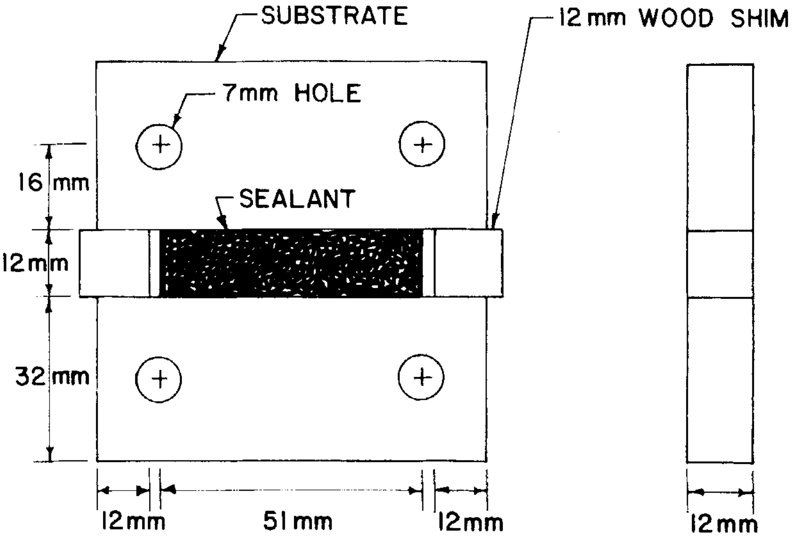

FIGURE 1 Dimensions of gunned sealant tension specimen.

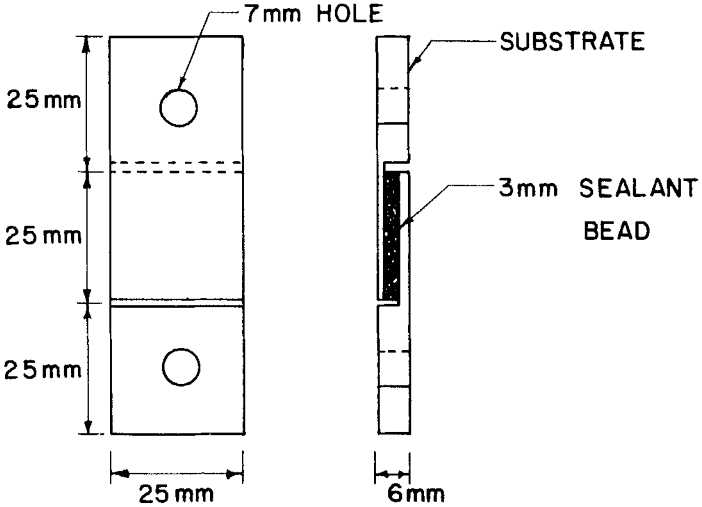

FIGURE 2 Dimensions of gunned sealant shear specimen.

fatigue tests (500 cycles/minute). The various tests used to develop the data for allowable strain determination are summarized below:

1. *Basic displacement test-tension* Specimens, as shown in Figure 1, are elongated and the ultimate strain is recorded. From these results, an estimate of the 5% exclusion value for ultimate tension strain is calculated.

2. *Basic displacement test-shear* Lap specimens (Figure 2) are pulled in shear to obtain a 5% exclusion value for ultimate shear strain.

3. *Fatigue* Tension specimens are cycled in fatigue at various peak strain levels. The tests are run at 500 cycles per minute. The data, number of cycles to failure *versus* peak strain, are fit with a hyperbolic function to estimate a strain endurance limit.

4. *Water resistance* Tension specimens are immersed in 23°C water. At various time intervals, up to 90 days, specimens are removed and tested wet to determine ultimate strain.

5. *Heat resistance* Tension specimens are placed in a 70°C ventilated oven. At various times, up to 90 days, specimens are removed and tested at room temperature to determine the effects of heat aging.

6. *Low temperature flexibility* Tension specimens are chilled in a freezer for one week and then tested cold in an insulated, cooled test chamber. The temperatures used are 0°C, −15°C, −30°C, and −45°C.

7. *Chemical resistance* This test is the same as the water resistance tests except that the water is maintained at pH of approximately 3.0 by the periodic addition of sulfuric acid.

8 *Ultraviolet exposure* Tension specimens are placed in a Q-panel exposure unit for times ranging up to 1200 hours. After exposure the specimens are tested to failure.

9. *Compression and tension set* This test measures the recovery ability of a sealant after the specimens are held in a displaced position for various time intervals. Tests are run at −30°C, 23°C, and 70°C.

10. *Substrate compatibility* The adhesion of the sealant to various substrates which might be encountered are evaluated in this test. The tension specimen of Figure 1 is used.

11. *Joint design sensitivity-tension* This test measures the effects of different width-thickness ratios on tensile strain capacity. It is used to develop the geometric shape factor.

12. *Joint design sensitivity-shear* This test is similar to the one above, except that it covers shear joints.

13. *Joint design sensitivity-special configurations* For joint geometries other than a butt tension joint or a lap shear joint, special tests must be run to determine the geometric shape factor. Fillet joints, for example, may require this additional test.

TEST RESULTS

To illustrate the application of the test data to determination of allowable strains, consider a solvent acrylic sealant on unprimed hard maple and aluminum substrates. The results from the basic tension and shear tests are shown in Table I. The strains are very large, particularly those for shear. As such, they are really nominal strains. The tension strains were obtained by dividing failure displacement by specimen width while the shear strains were calculated as failure displacement divided by specimen thickness, consistent with the usual engineering definition of shear strain. The significantly larger strain capacity in shear was expected. The state-of-strain factor for tension is 1.00 because all of the durability factors are derived from tension data. For shear, the state-of-strain factor is the 5% exclusion value for shear strain divided by the corresponding value for tension strain.

The fatigue data for the acrylic is shown in Figure 3. The test was run at 500 cycles per minute and was a non-reversing (tension only) cycle from zero displacement to some peak displacement. A reversing cycle may be more appropriate in general, but was not used because of the particular application

TABLE I

Basic tension and shear

Strain/ substrate	Mean strain %	Std. dev. strain %	5% excl. strain %	State of strain factor
Tension/W	205	49	117	1.00
Tension/Al	220	24	176	1.00
Shear/W	837	100	655	5.60
Shear/Al	880	43	803	4.56

W = Maple substrate Al = Aluminum substrate

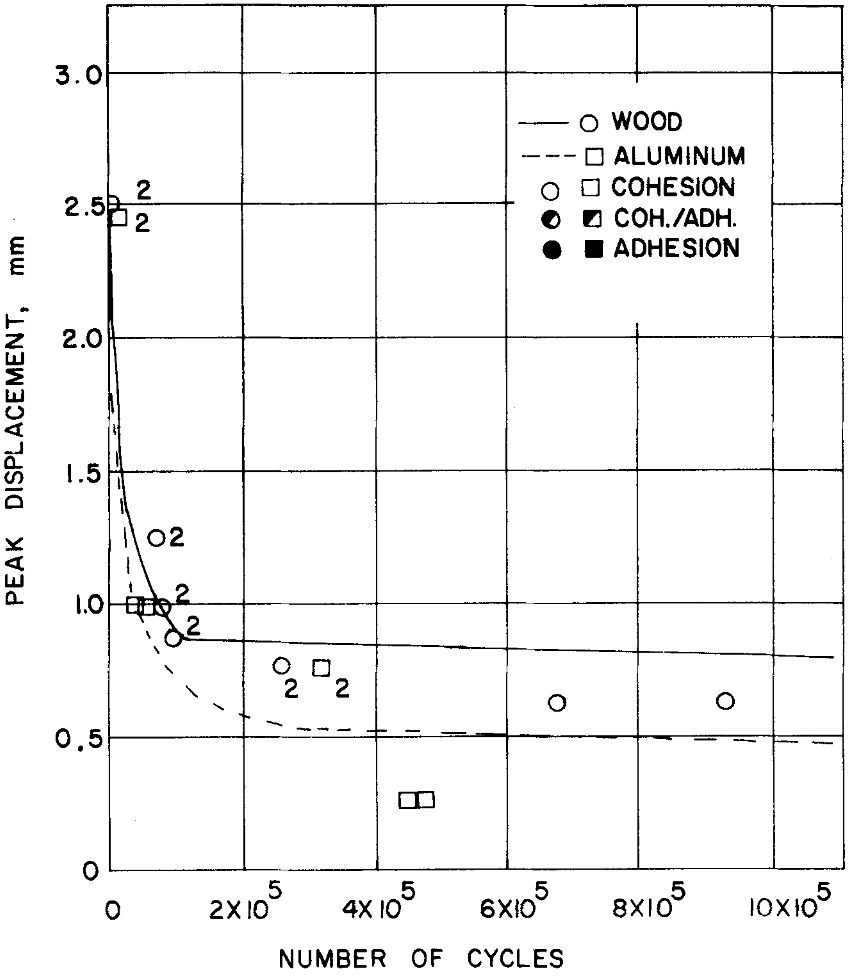

FIGURE 3 Fatigue test data, acrylic sealant.

that was considered in the study. All of the acrylic specimens failed cohesively. A hyperbolic equation was fit to the data and the results are shown in Table II.

The 2500 cycle limit is intended to account for thermal expansion cycling. Assuming three months of severe winter exposure per year results in 2500 of these cycles (at near peak amplitude) over a 30-year life. Other numbers of cycles could be used depending on the desired life and on availability of data for actual movements in buildings.

The one million cycle limit is suggested for cases, such as mobile homes,

TABLE II

Fatigue results for acrylic

Substrate	Equation	Std. dev. (mm)	2500 cycle factor	1 million cycle factor
Wood	$Y = 9800/x + 0.828$	0.183	0.172	0.0329
Aluminum	$Y = 20900/x + 0.513$	0.246	0.316	0.0210

Y = Peak displacement (mm)
x = Number of cycles to failure

where the structure will be subjected to transportation-induced dynamic loadings.

To obtain the durability factors for fatigue, the 2500 cycle and one million cycle limits were divided by the appropriate mean strain from the basic tension test. The results are shown in Table II.

Since the tests for water, heat, and chemical resistance were conducted in much the same fashion, they can be discussed together. The data are shown respectively in Figures 4, 5 and 6. Exponential decay curves were fitted to these points, but only a few of the curves were statistically significant. To obtain some estimate of the degradation, the data for 50, 70, and 90 days of exposure were averaged for each exposure type and divided by the mean strain from the basic tension test. The resulting durability factors are given in Table III.

The results of the cold temperature flexibility test are shown in Figure 7. A near total loss of displacement capacity occurred at −45°C. Calculation of a durability factor for cold must reflect actual expected conditions. For illustration, the data at −30°C was averaged and divided by the mean tension strain to get the factors given in Table IV.

TABLE III

Water, heat and chemical factors

Substrate	Water	Heat	Chemical
Wood	0.02	1.00	0.07
Aluminum	0.22	1.00	0.26

TABLE IV

Low temperature factors, −30°C

Substrate	Factor
Wood	0.63
Aluminum	0.32

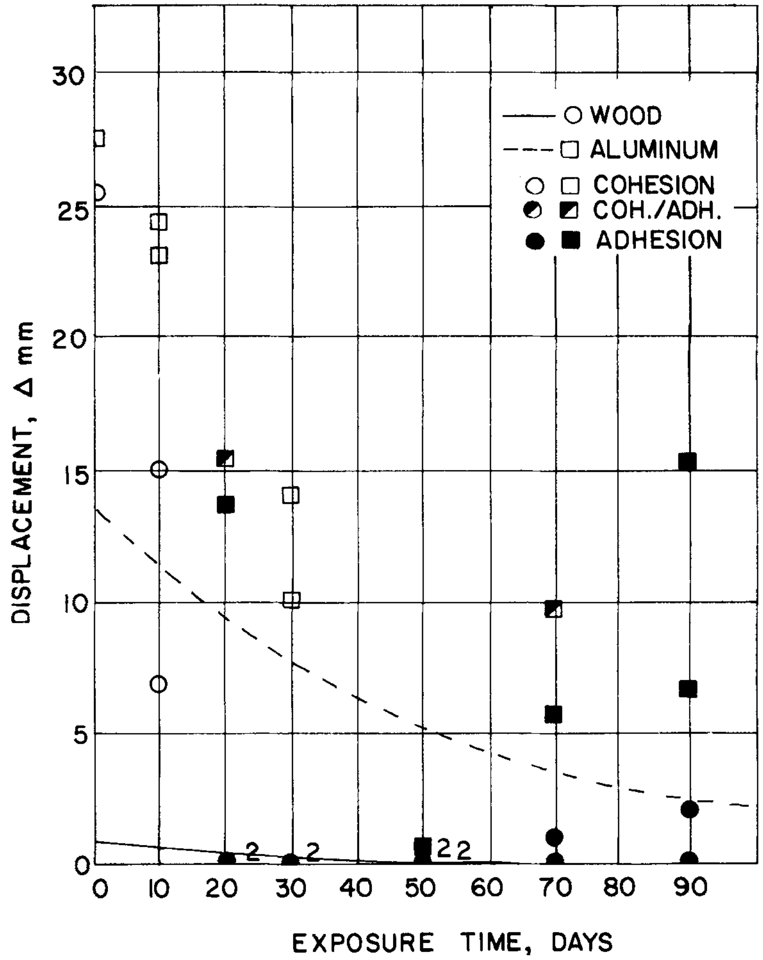

FIGURE 4 Water immersion test data, acrylic sealant.

Results for the ultraviolet resistance test are given for the acrylic in Figure 8. Note that displacement capacity actually increased with exposure. This was probably due to the effect on curing from the gentle heat (45°C) associated with the test. Ultraviolet light had little effect on any of the sealants tested, but it must be emphasized that these were opaque sealants and substrates. In situations where light can reach the sealant-substrate interface the results would probably be very different. For this test the durability factors for the acrylic were set at 1.00.

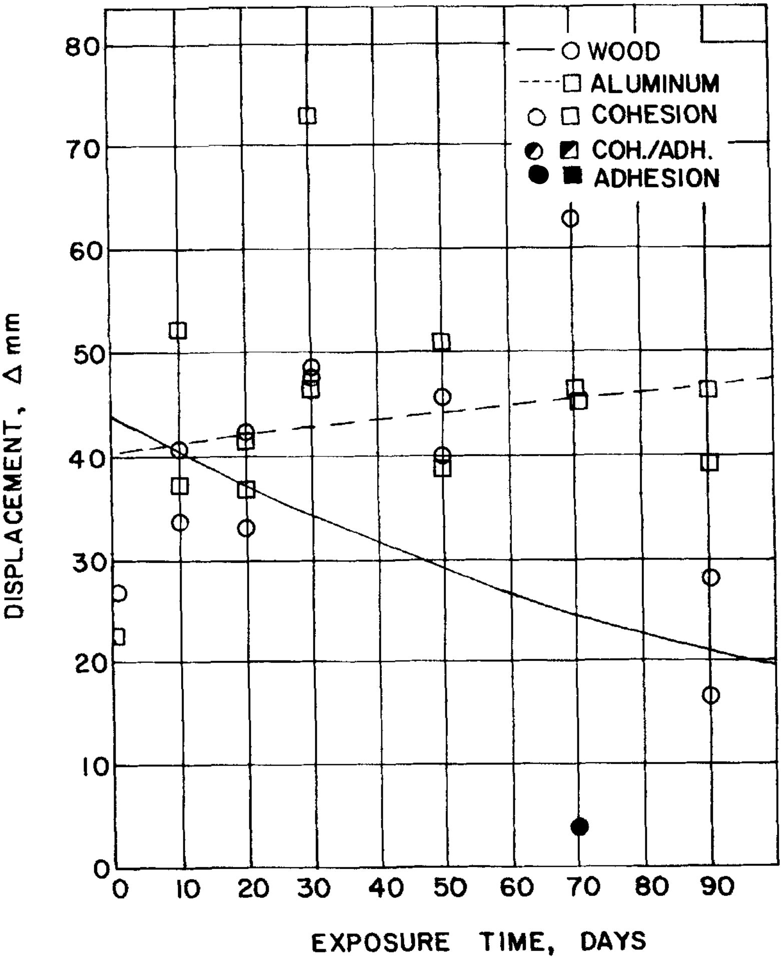

FIGURE 5 Heat resistance test data, acrylic sealant.

The results for the compression and tension set tests for the acrylic are shown in Figures 9 and 10. The initial strain was 15%. The most important data are those at 70°C since compression of a sealant joint is most likely to occur from expansion of adjacent substrate at high temperature. At the same time, irrecoverable creep deformations are most likely to occur at higher temperatures. Since the greatest movements generally would occur from daily thermal cycles, the six to twelve hour recovery, approximately 5%, was used to calculate the compression set factor. Compression set has the effect of increasing the total strain during subsequent extension. To account for this, the compression set factor is taken to be

$$C_{cs} = R/200 + 0.5$$

where R is the recovery in percent. Note that a perfectly elastic sealant has a compression set factor of 1.00 while a sealant with no recovery has a factor of

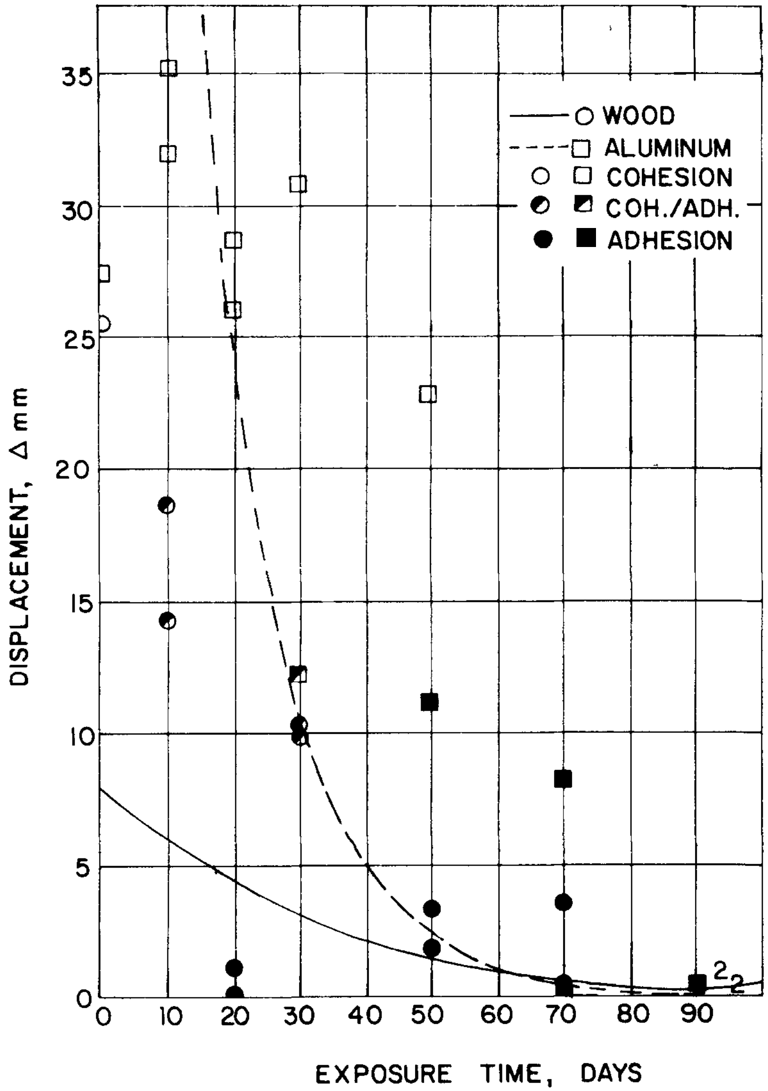

FIGURE 6 Chemical resistance test data, acrylic sealant.

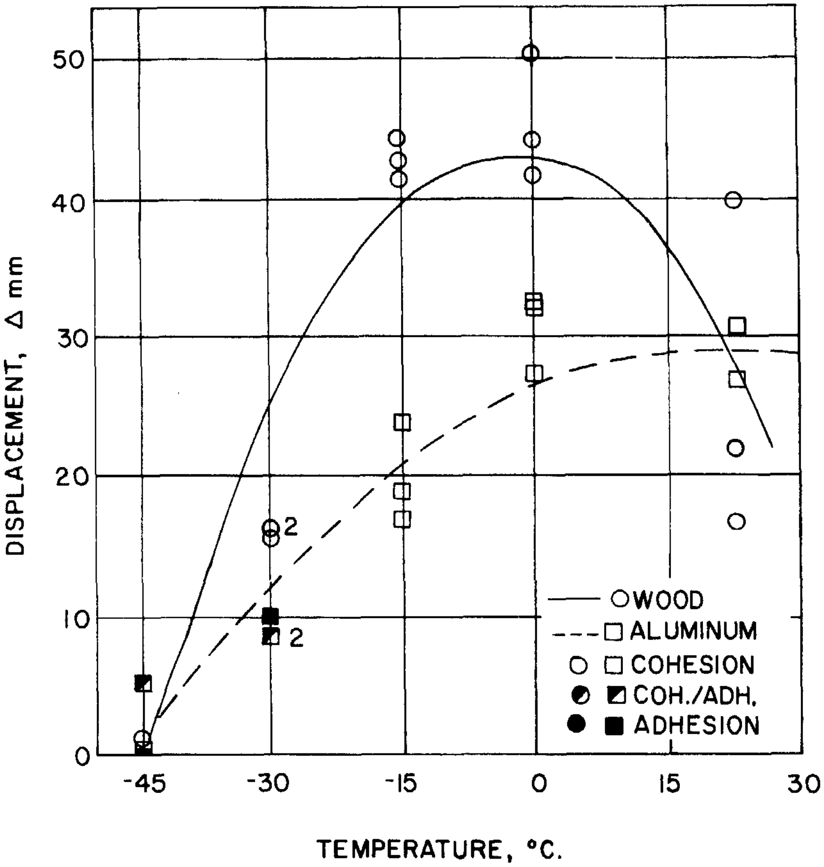

FIGURE 7 Cold temperature flexibility test data, acrylic sealant.

0.50. For this latter case, the sealant is assumed to go into tension as soon as movement reverses from compression to extension. Thus for movement about the mean daily joint width, usable tensile strain capacity is one-half of the total capacity. For the acrylic sealant, C_{cs} equals 0.52.

The test for the effect of width-thickness ratio on tensile strain capacity was conducted with specimens with widths and thicknesses of 6.4 × 12.7, 9.5 × 12.7, 3.2 × 12.7, 12.7 × 9.5, and 12.7 × 6.4 mm. The resulting data is shown in Figure 11. Neither a first order (shown) or second order polynomial fitted to the acrylic data proved statistically significant. Therefore, the geometric shape factor was taken as 1.00. Other sealants did show significant effects.

The width-thickness results for shear, shown in Figure 12, show a definite second order relation between ultimate strain and width-thickness ratio. The widths used were 1.6, 3.2, 4.8, 6.4, and 7.9 mm, with the corresponding shape factors given in Table V.

Geometric shape factors may also be derived for other joint geometries, such as for the fillet joint specimen shown in Figure 13. Here, the parts of the joint which are parallel to the displacement are primarily in shear and the part perpendicular to the displacement is under tension along with some shear. Failure occurred in the latter part of the joint for all sealant types.

The nominal strain in the critical area was calculated as simply the failure

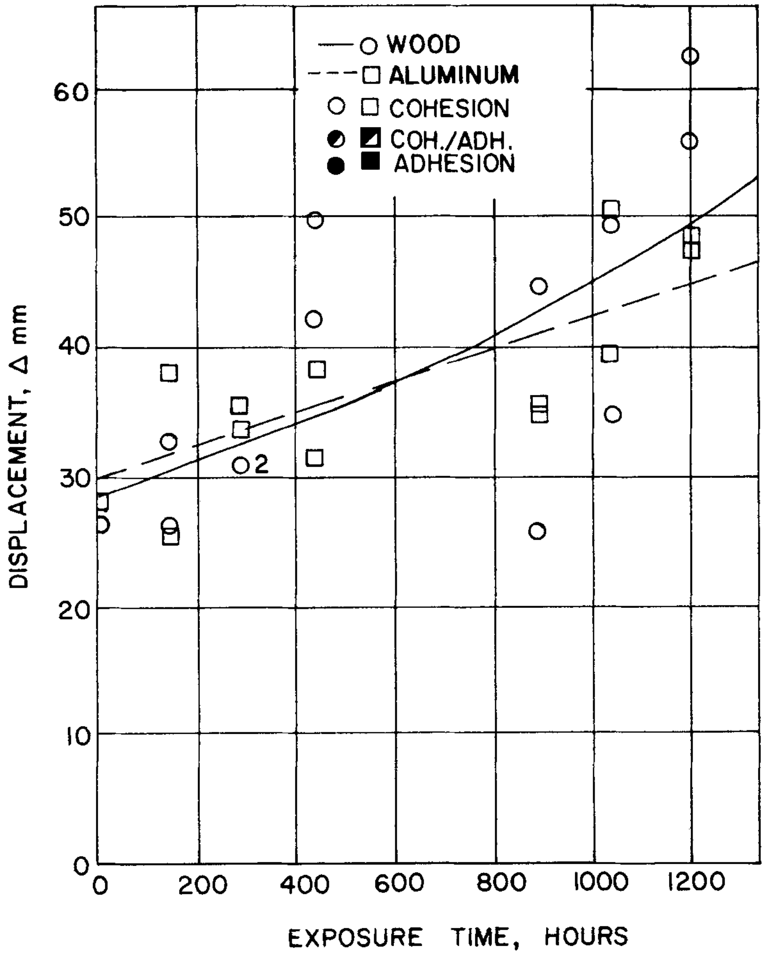

FIGURE 8 Ultraviolet exposure test data, acrylic sealant.

TABLE V

Acrylic geometric shape factor—shear

Substrate	Width-thickness ratio 0.6	0.13	0.19	0.25	0.31
Wood	1.59	1.00	0.62	0.44	0.48
Aluminum	1.66	1.00	0.59	0.44	0.54

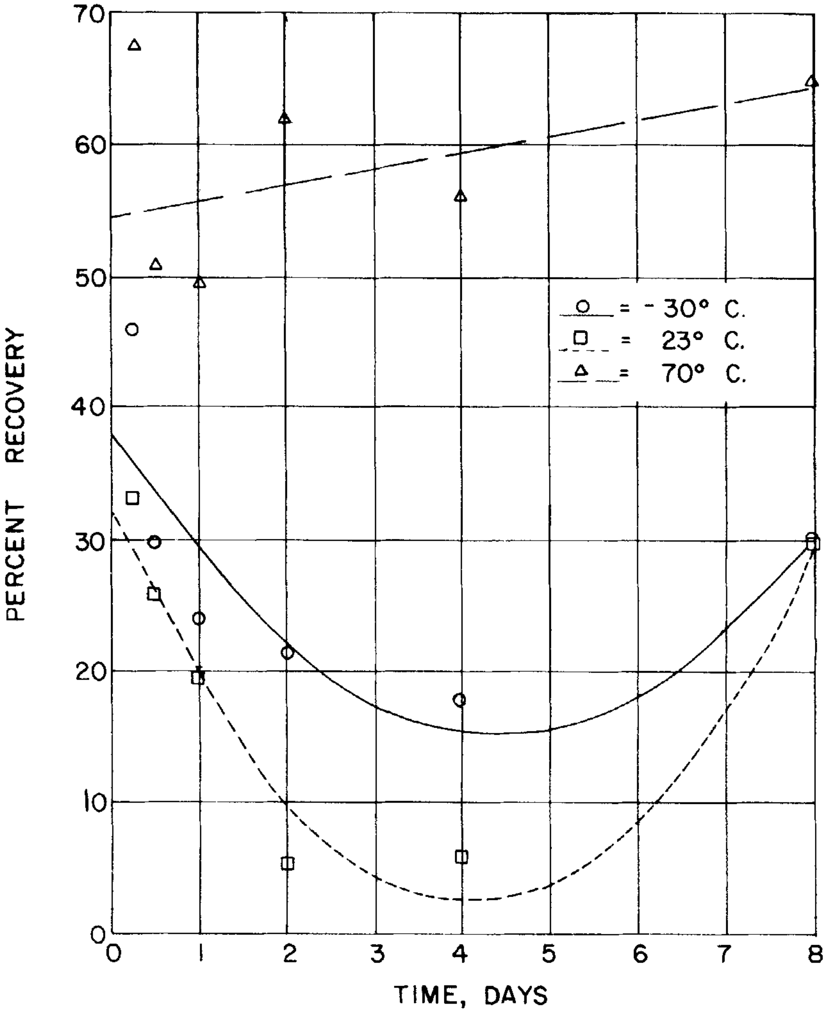

FIGURE 9 Extension set test data, acrylic sealant.

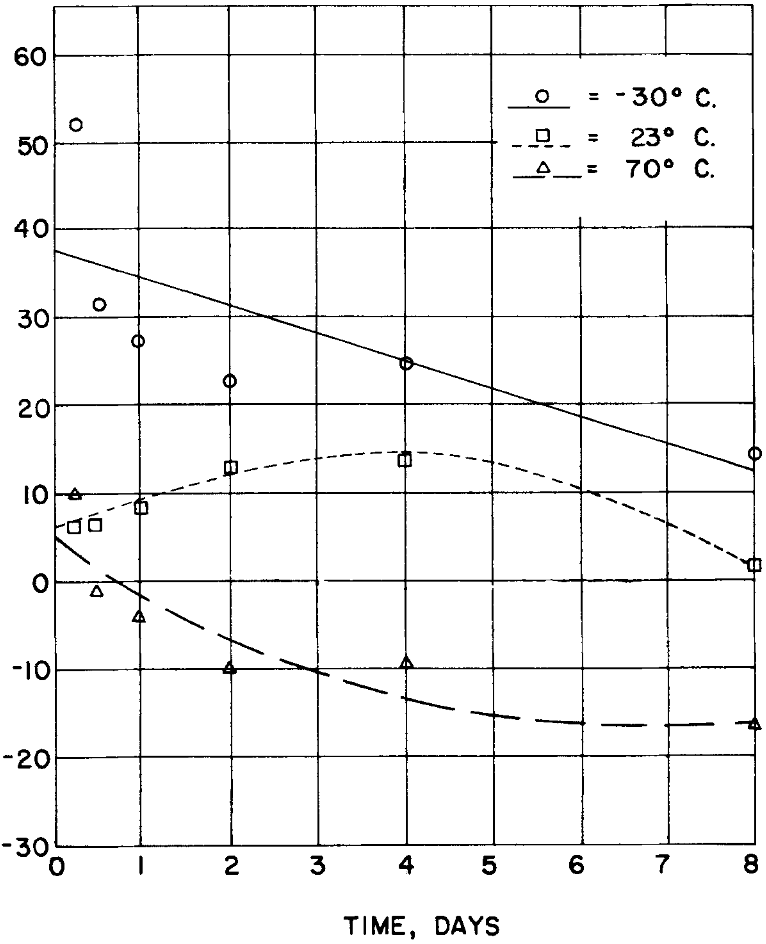

FIGURE 10 Compression set test data, acrylic sealant.

displacement divided by the leg size of the fillet (9.5 mm). The resulting mean strain divided by the mean basic tension strain yields the special geometric shape factor shown in Table VI.

Substrate compatibility requires very careful consideration. Obviously, the ideal approach would be to run a full battery of tests on each sealant-substrate combination that might be used. This would be prohibitive in cost. To explore a compromise approach, the following procedure was adopted. First, all tests of a sealant were run with two substrates, wood and aluminum. These represent porous and nonporous materials, respectively, in terms of volatile

TABLE VI

Fillet joint data

Mean failure strain (%)	Std. dev. (%)	Geometric shape factor
168	6	0.82

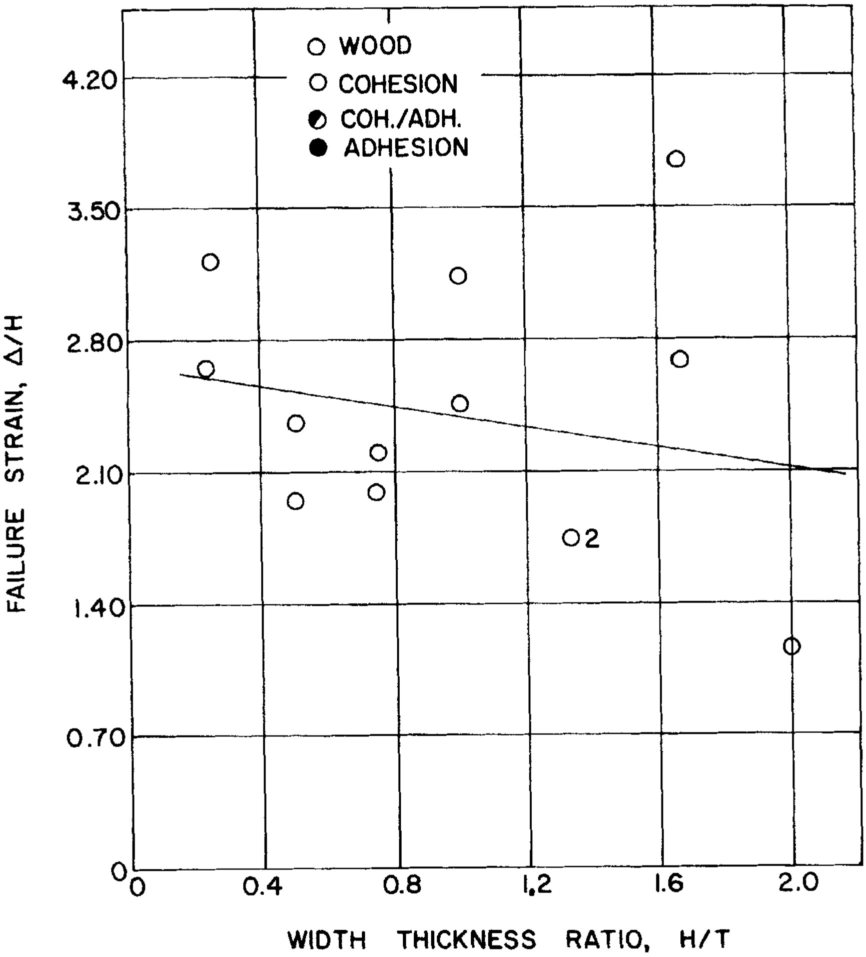

FIGURE 11 Width-thickness in tension test data, acrylic sealant.

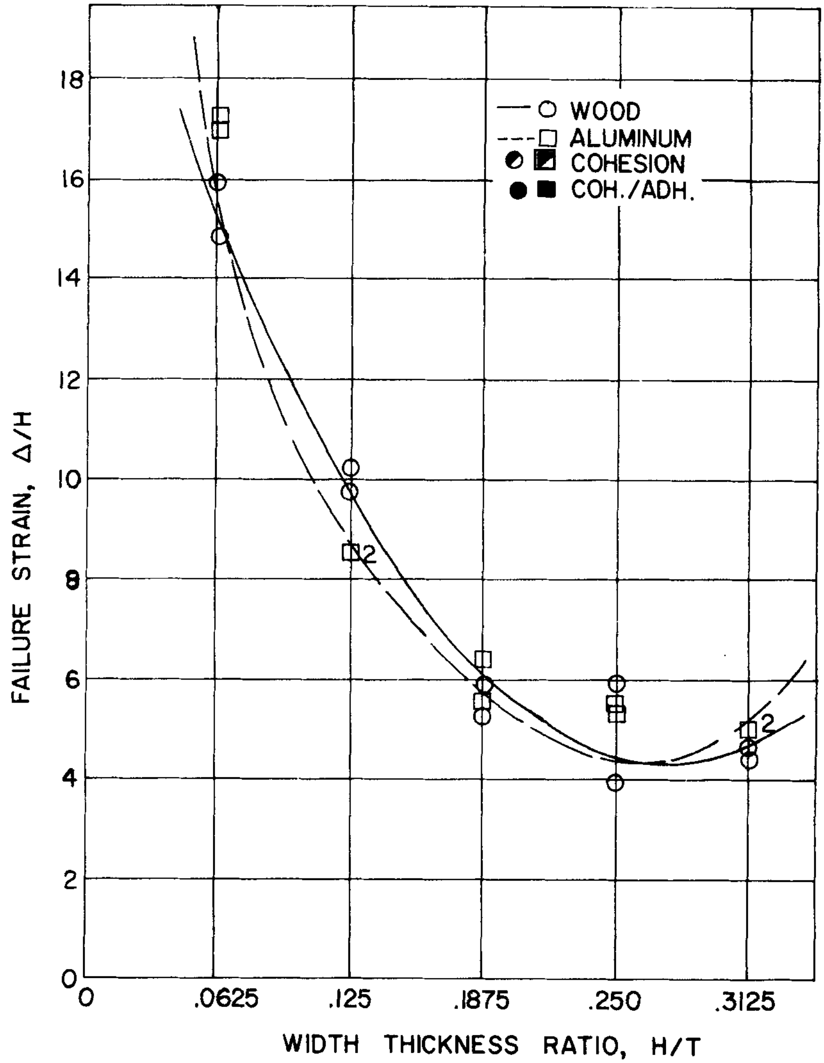

FIGURE 12 Width-thickness in shear test data, acrylic sealant.

release and soaking of the sealant substrate interface. To evaluate the effects of substrate on strain capacity, the following common construction materials were used: ABS plastic, galvanized steel, particleboard, polyester enamel coated steel, and PVC. None of these were primed, only carefully cleaned before sealant application. The specimens were given the standard cure and no

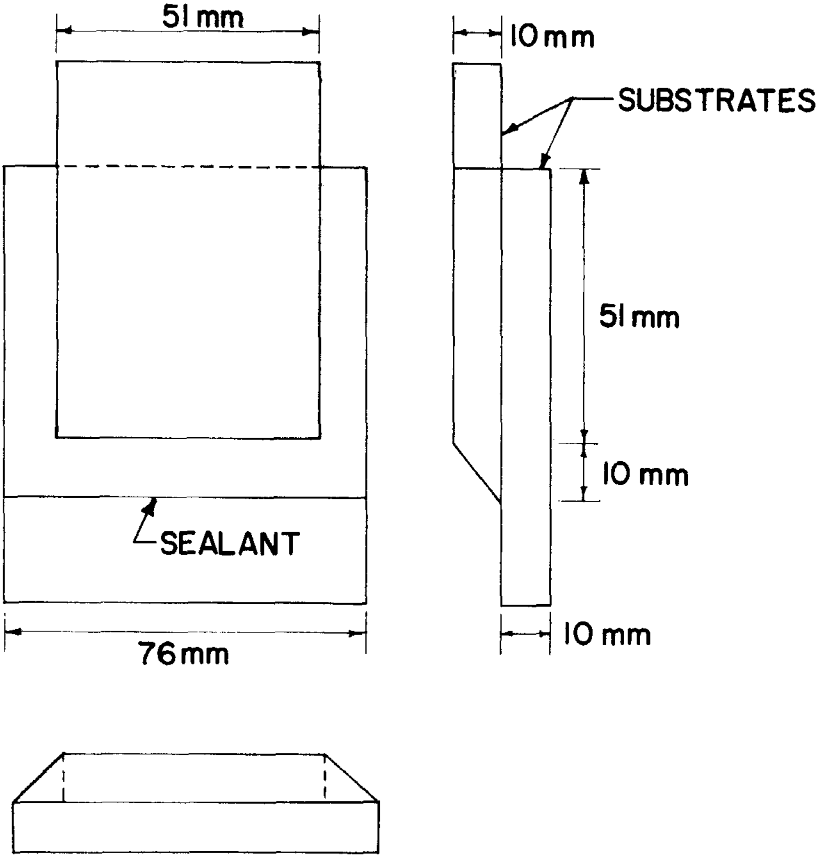

FIGURE 13 Dimensions of fillet joint.

other form of aging exposure. The one porous substrate, particleboard, was compared to wood, while the others were compared to aluminum to obtain substrate factors shown in Table VII. The acrylic sealant used for illustration is of a type which is well known for its excellent adhesion characteristics.[6] Some of the other sealants showed more significant adhesion dependence on substrate type.

Any attempt to simplify the problem of sealant-substrate interactions, including this one, must be approached with caution. Heat aging might have a significant impact on bonds to some plastics. Water will certainly affect bonds to various porous substrates in different ways. And high modulus elastomeric sealants may produce failure of an aged substrate. Thus, judgement is required, with selected aging tests being employed where the need may exist.

TABLE VII

Effect of substrate

Substrate	5% excl. value % strain	% adhesion failure	Substrate factor
Wood	117	0	1.00
Particle board	139	0	1.00
Aluminum	176	0	1.00
A.B.S.	139	0	0.79
Galvanized steel	179	0	1.00
Polyester enamel	61	5	0.35
PVC	138	0	0.78

The final term in the allowable sealant strain equation is a safety factor, representing a reduction in strain from a level at or near ultimate to a level that will provide consistently acceptable performance in service. Several things influence the selection of the safety factor. First, there is the nature of the application. The considerations here include consequences of failure and cost of replacement. Second, there is the degree of uncertainty involved in the design. Thermal movements in buildings are not always easily predicted. The procedures for establishing allowable strains in the sealant and then allowable joint displacements are certainly approximations. And installation conditions may be less than ideal. Finally, the safety factor must be based on past experience with the sealant, where data are available. If the calculated allowable strain for a given sealant proves to be over- or under-conservative in light of field experiences, the safety factor provides a convenient means of adjustment. This may not be entirely satisfactory from a purely scientific viewpoint, but such adjustments to reality are not uncommon and merely recognize the limitations of applying simplified analytical or empirical models to extremely complex phenomena.

APPLICATION OF THE ALLOWABLE STRAIN EQUATION

A good deal of engineering judgement is required to apply the procedure for calculating an allowable sealant strain. Not all modification factors should be included in every case. In the case of an acrylic tension joint on aluminum in a building wall for example:

basic tension strain = 176%
state-of-strain factor = 1.00
2500 cycle fatigue factor = 0.32

water immersion = N/A†
heat aging = 1.00
chemical aging = N/A†
cold flexibility (−30°C) = 0.49
ultraviolet = 1.00
compression set = 0.52
shape factor (W/T = 1.00) = 1.00
safety factor = 0.67
allowable strain = ±6.3%

This is in close agreement with the recommended values for solvent based acrylics.[1,2]

CONCLUSIONS

It is possible to treat sealants as full fledged engineering materials. The general methodology for this has been presented. While there are a number of refinements which are needed to effectively implement the procedure, it is a flexible procedure which can readily accommodate improvements as they become available.

A major need exists for reliable accelerated aging techniques which allow prediction of long term strain capacities with satisfactory confidence. Two approaches to this problem should be explored. First, the continuous rate process method may be adaptable to predicting sealant aging characteristics on an accelerated basis. This method has been applied to adhesives in the past[4,7,8] and has potential for providing a rational measure of the long term effects of heat, water, chemicals, and ultraviolet light from accelerated laboratory tests. Second, correlations between field performance and allowable strains predicted in the laboratory are vitally important. This is undoubtedly the surest means of calibrating the proposed procedure for determining allowable strains.

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† These immersion factors are not considered necessary unless there is the possibility of prolonged immersion or soaking.

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