I03 – NATIONAL ADAPTATION AND TRANSLATION OF THE CURRICULA

AdTech
European Harmonized Training for Adhesive Bonding Technology

EUROPEAN ADHESIVE ENGINEER

MODULE 4.8

DURABILITY- COMBINED TEMPERATURE-MOISTURE-MECHANICAL STRESS EFFECTS ON ADHESIVE JOINTS

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4.8 Combined Temperature – Moisture - Mechanical Stress Effects on Adhesive Joints

Scope:

- ✓ Thermal effects
- ✓ Combined effects
- ✓ Evaluation parameters
- ✓ Accelerated service life testing

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Thermal effects [1]

Key problems caused by high and low temperature conditions

One of the main advantages of using adhesive bonding is the possibility of bonding dissimilar materials, such as carbon fibre reinforced plastics (CFRP) to aluminium alloys.

Dissimilar adherends may have very different coefficients of thermal expansion (CTE). Temperature changes may introduce thermal stresses in addition to the externally applied loads. Adhesive curing and the resulting thermal shrinkage may also introduce internal stresses. Deformations or even cracks can appear.

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Thermal effects [1]

A full study of the effects of temperature on joints must cover the three following aspects:

1. shrinkage of the adhesive,
2. differential thermal expansion (different CTE),
3. variation of adhesive mechanical properties with temperature.

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Thermal effects [1]

Shrinkage of the Adhesive

During curing process, volume shrinkage of the adhesive occures. The magnitude of shrinkage can be 3 - 5 %. If the shrinkage is 0,5 %, shrinkage stresses are not important as their effect is less than 10 % comparing to the imposed mechanical stress.

For adhesive joints in CFRP/aluminium alloy single lap joints, which are typical in the aircraft structures, thermal stresses are caused by different coefficients of thermal expansion (CTE) of two different adherends. Adhesive shrinkage stresses have much less effect than adherend mismatch.

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Thermal effects [1]

Effect of differential thermal expansion

As an example, the residual stresses in an adhesive bonded joint between aluminium alloy and CFPR will be presented. Typical coefficients of thermal expansion (CTE) are:

- aluminium alloy adherend: CTE = 24×10^{-6} K^{-1}
- CFRP adherend (longitudinal): CTE = $-0{,}1 \times 10^{-6}$ K^{-1}
- CFRP adherend (transverse): CTE = 30×10^{-6} K^{-1}
- epoxy adhesive: CTE = 60×10^{-6} K^{-1} (below T_g); CTE = 180×10^{-6} K^{-1} (above T_g).

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Thermal effects [1]

With a negative thermal load, that is with a decrease in temperature from the stress-free temperature *(*T_{SF}*)*, and a compliant adhesive, the aluminium and the CFRP adherends can contract freely. Length of the CFRP adherend does not change because its longitudinal CTE is close to zero.

For a stiff adhesive in its glassy region, the adherends cannot contract freely so that the CFRP is subjected to a compressive axial load and the aluminium adherend is under tension. The axial load causes bending of the joint. The resultant stress will then be the sum of the uniform component caused by the axial load plus the linearly varying (through the thickness) contribution caused by bending.

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Thermal effects [1]

More important than the thermal stresses in the adherends are the stresses in the adhesive. For metal /CFRP joints for example, the metal tends to shrink as the temperature is decreased from the cure value (generally a high temperature) and this is partially resisted by the composite (lower CTE), thereby inducing residual bond stresses especially at the ends of the joint. One end has positive residual shear stresses and the other end has negative residual shear stresses. The thermal stresses are beneficial at one end of the joint but have the reverse effect on the other side of the joint.

The thermal load ΔT is: $\Delta T = T_0 - T_{SF}$

T_0 …operating temperature

Thermal effects [1]

It is reasonable to consider the stress-free temperature as the normal cure temperature of the adhesive. However, this is valid only if the adhesive always operates below its glass transition temperature (T_g). When the adhesive is heated above its T_g, thermal stresses are relaxed because the adhesive is very compliant.

Upon subsequent cooling, once the adhesive becomes hard again, below its T_g, thermal stresses start to build up, so that the stress-free temperature is no longer its cure temperature but its T_g. This was proved experimentally by the measurement of the thermal strains, and hence stresses, of aluminium alloy-adhesive-CFRP sandwich specimens with strain gauges.

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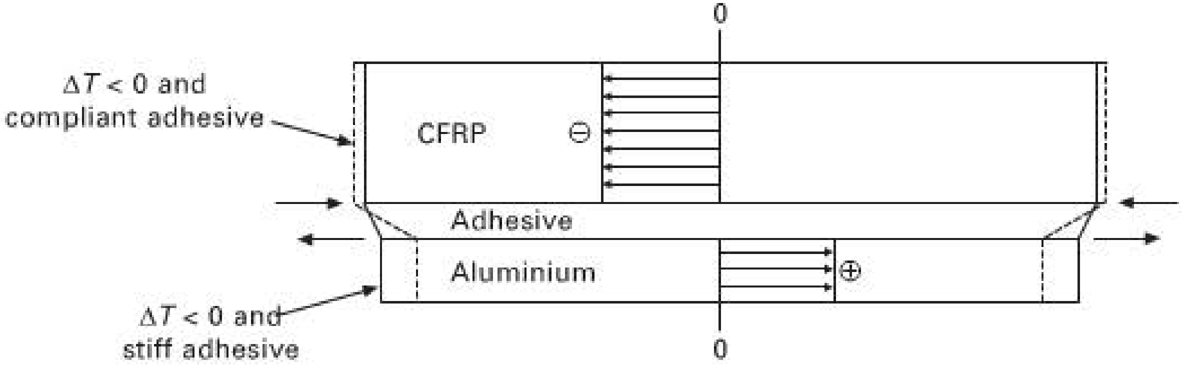
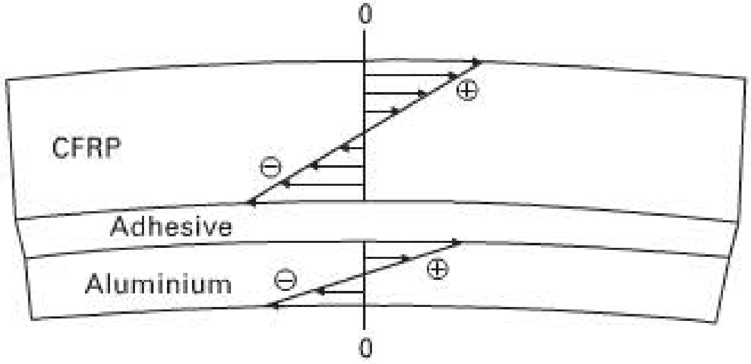
Thermal effects [1]



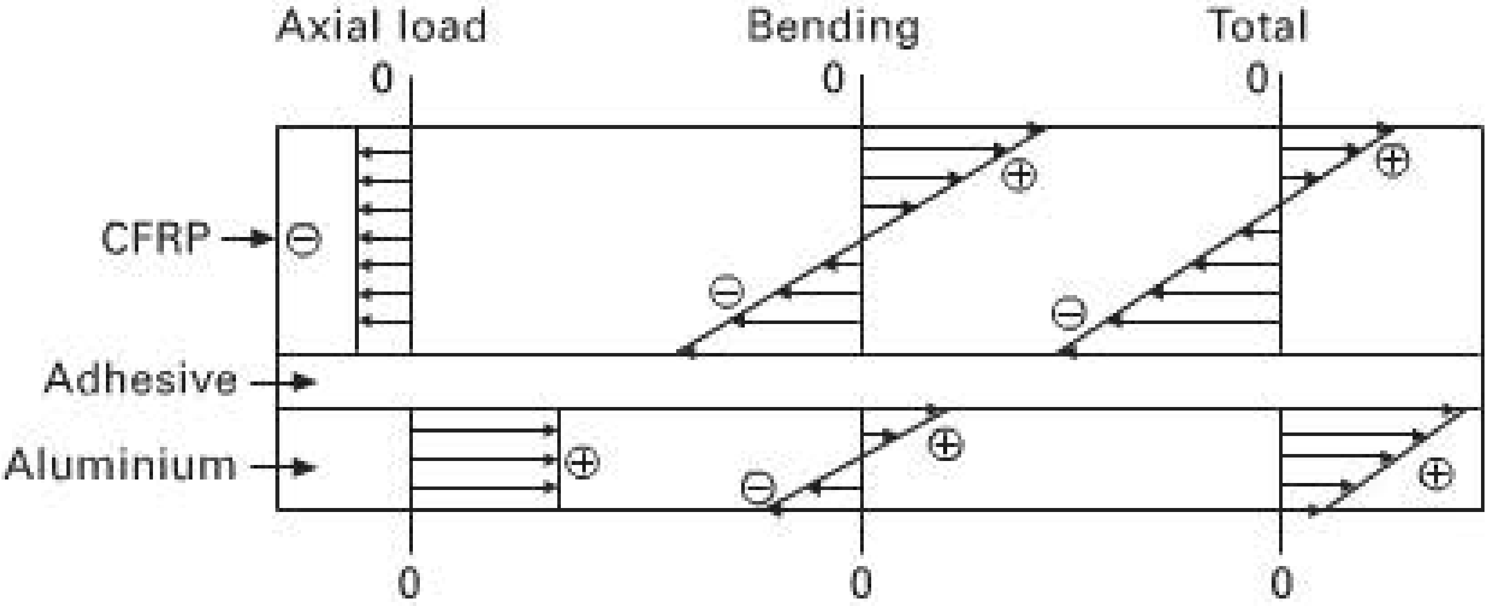
Axial stress



Bending stress

Stresses in adherend for negative thermal load *ΔT < 0* and stiff adhesive

Thermal effects [1]



Total stress in stiff adhesive for negative thermal load $\Delta T < 0$

Combined effects [2]

Effects of stress, moisture and temperature

Mechanical stress accelerates the effect of the environment on the adhesive joint. A great amount of data is not available on this phenomenon for specific adhesive systems because of the time and expense associated with stress-aging tests.

But moisture markedly decreases the ability of certain adhesive to bear prolonged stress especially at slightly elevated temperatures. The interaction of temperature and moisture causes greater degradation than can be attributed to either environment by itself.

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Combined effects [2]

This effect was noted in the 1960s, when stressed and non-stressed aluminum lap shear joints were aged in a natural weathering environment in Florida, USA. Stress was applied by flexural bending of lap shear samples and keeping them in that state during the aging period.

Depending on the type of adhesive, there was a significant degradation after 1–2 years due to stress-weathering, whereas the joints that were aged in the non-stressed condition showed little degradation. In high humidity environments stressed joints weaken more rapidly than unstressed joints. Joints made with a flexible adhesive having low glass transition temperature failed by creep of the adhesive at relatively short service times.

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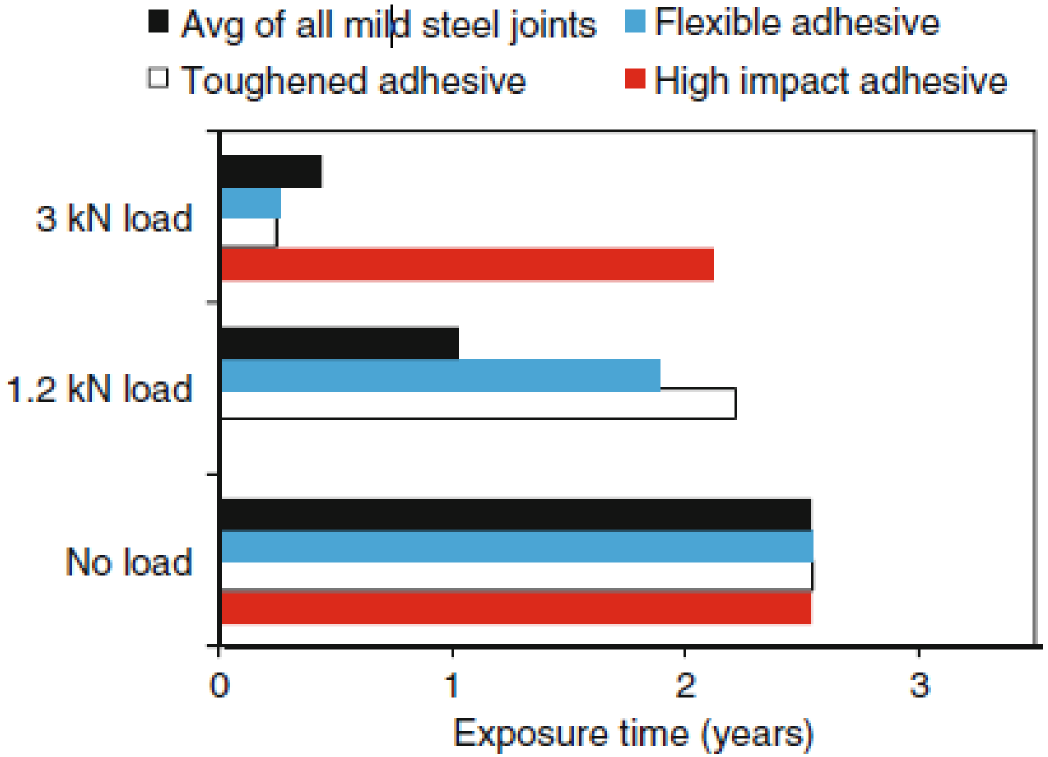
Combined effects [2]



Average failure times for stressed and unstressed Zn-Ni coated steel joints in tropical environment

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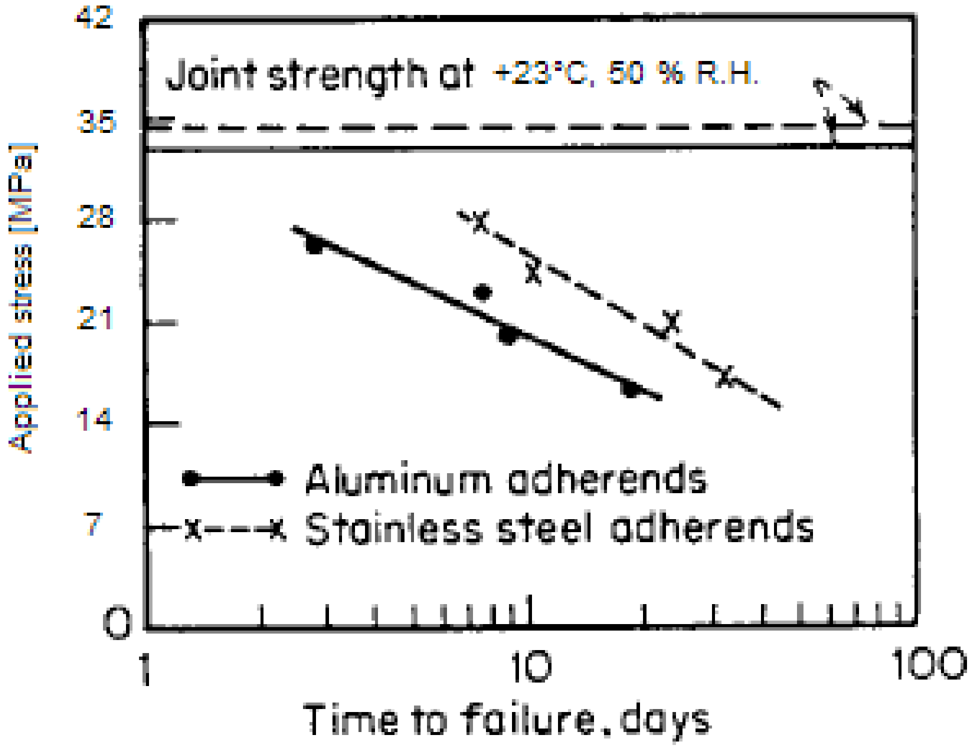
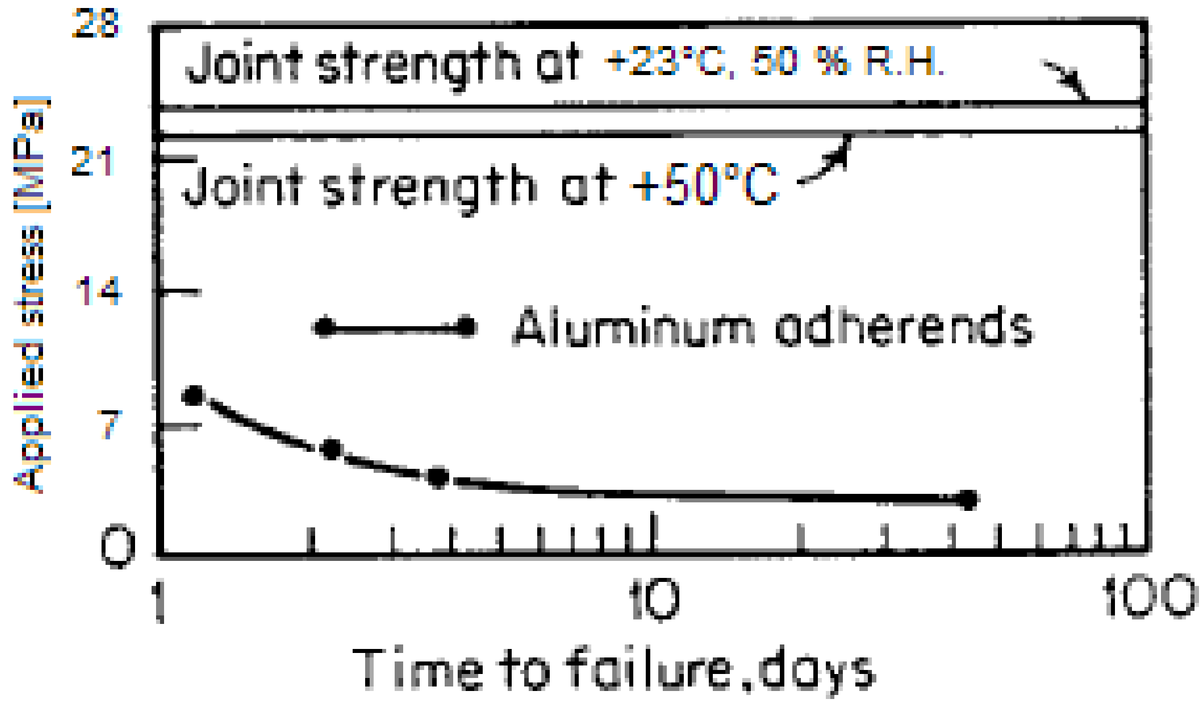
Combined effects [2]



Time to failure vs. stress for one part cured modified epoxy adhesive

Combined effects [2]



Time to failure vs. stress for flexibilized amine cured epoxy adhesive

Combined effects [2]

Several sources seem to come to general agreement as to the relative durabilities of structural adhesives. Results of sustained load durability testing and outdoor weathering studies provide the same order for the relative durabilities of different adhesive classes.

Such a ranking of performance should only be taken as an approximate guide, since it is difficult to make reliable predictions about the performance of an adhesive in any general way.

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Combined effects [2]

Relative durabilities of structural adhesives

Most durable adhesives:

- 180°C cure film: nitrile-phenolic, vinyl-phenolic, novolac-epoxy
- 120°C cure film: modified epoxy, nitrile-epoxy, nylon-epoxy
- heat-cure paste: nitrile epoxy, nylon-epoxy, vinyl-epoxy

Least durable adhesives:

- room temperature cure paste: epoxy/PA, epoxy/anhydride

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Combined effects [3]

Effects of Moisture and Stress on Bonded Joints

Environmental degradation modeling of bonded joints involves three main steps:

- The first step is modeling moisture transport through the joint in order to determine the moisture concentration distribution through the joint as a function of time.

- The second step involves evaluation of the transient mechanical-hygro-thermal stress–strain state resulting from the combined effects of hygro-thermal effects and applied loads.

- The final step involves incorporation of damage processes in order to model the progressive failure of the joint and hence enable the residual strength or lifetime of a joint to be predicted.

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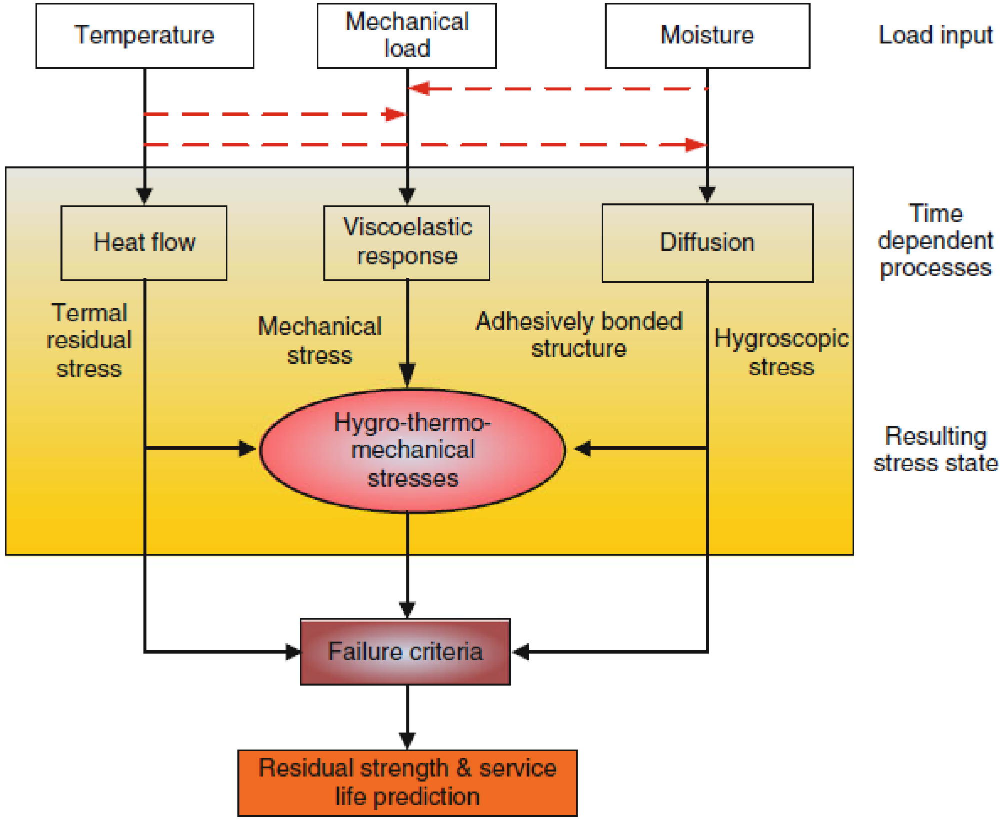
Combined effects [3]



Framework for modelling the environmental ageing of adhesively bonded joint

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Evaluation parameters [3]

It must further be pointed out that such predictive methods based on numerical evaluation can only be applied under the premise that no mechanisms of aging, being either independent or related to the presence of mechanical load, are superimposing the long-term behavior, and thus the durability.

Common detrimental environmental influences on the static load bearing capacity of adhesive joints include an increase of compliance and reduction of the glass transition temperature due to absorption of humidity or water or swelling under the influence of other media.

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Evaluation parameters [3]

Other ageing effects may include corrosive attack starting at the bondline, debonding at or close to the interface between adhesive and adherend or chemical ageing of the adhesive polymer under the influence of temperature, oxygen, or ultraviolet or other ionizing radiation.

Methods of evaluation of durability and test regimes including exposure to elevated and reduced temperatures, UV radiation, moisture, saline solutions, mechanical stress and fatigue, both individually and combined in cycles.

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Evaluation parameters [2]

Since nearly every adhesive application is unique, the adhesive manufacturers often do not have data concerning the aging characteristics of their adhesives in specific environments. Thus, before any adhesive is established in production, a thorough evaluation should be made in either a real or a simulated operating environment.

With most structural adhesives, strength is more directional than with mechanical fasteners. Generally, adhesives perform better when stressed in shear or tension than when exposed to cleavage or peel forces. Residual stresses inside the joint can also present serious problems. Such stresses arise from shrinkage due to cure or aging, from different coefficients of thermal expansion between substrates, and from other circumstances.

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Evaluation parameters [2]

The methodology of the test and evaluation program requires careful thought. A critical feature is that the tests must have a known relationship to the final product. Often this requires either developing creative, non-standard tests that stress the part in a mode that is more indicative of its service load, or producing actual prototype specimens with the adhesives and bonding conditions that are intended to be used in production.

These prototype specimens then would be subjected to simulated service environments. The environmental exposure can be accelerated to reduce testing time. Caution needs to be exerted so that the acceleration does not cause reactions or mechanisms within the materials or bond-line that would not actually be present in the intended real environment.

Evaluation parameters [2]

These ‘‘non-standard’’ test methods should be controlled so that the tests are repeatable and the variability is low. Among the obvious variables that need to be controlled are surface cleaning, joint geometries, method and extent of material mixing, method of application, fixtures utilized and cure conditions.

To develop a joint with an adequate service life and with a realistic design margin, the use of a ‘‘Mathes ladder’’ is suggested to establish a testing hierarchy. In this process testing proceeds from simple, standard tests of basic materials where well defined test specifications are available to increasingly complex tests. Depending on the application and the type of information available from the lower rungs of the ladder, the need for more complex testing may be reduced or even eliminated.

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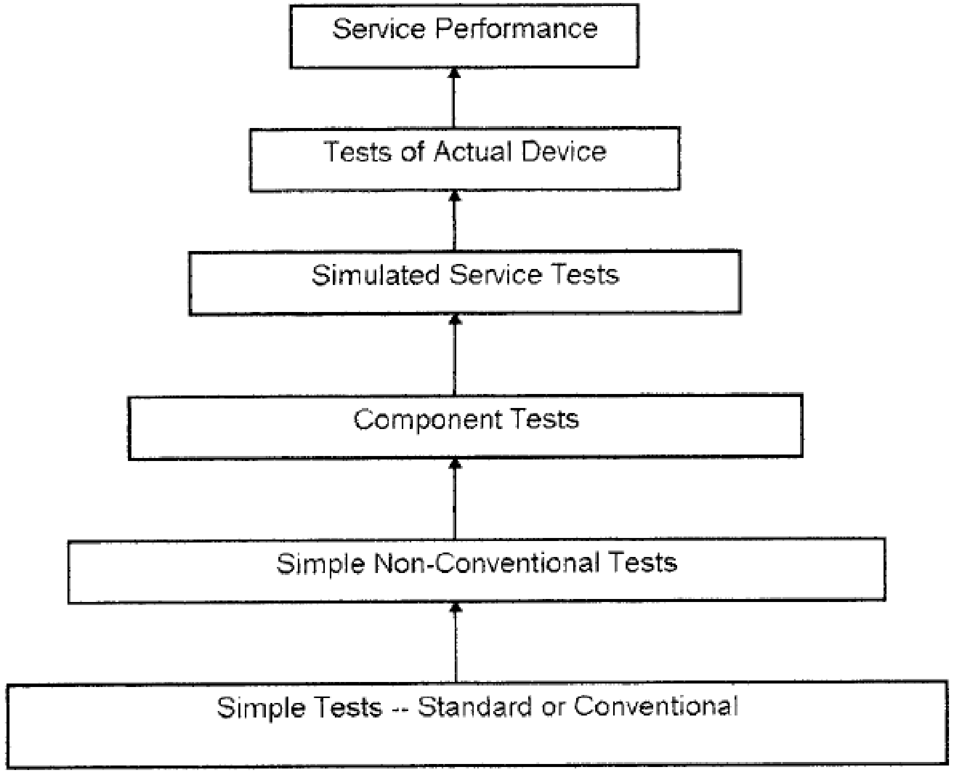
Evaluation parameters [2]



Testing hierarchy as
illustrated by the ‘‘Mathes ladder’’

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Evaluation parameters [2]

The most difficult failure situations to predict are those that result from interactive effects. Thus, it is important to consider and evaluate the adhesive joint as a ‘‘system’’. There is a thought processes which will help to guide the engineer toward systematically getting the information required:

1. Define extent of service condition variables (upper limits of conditions to be encountered).
2. Identify specific failure mode(s).
3. Determine rate of damage for each failure mode at the extreme service conditions.
4. Define critical failure mode.
5. Establish endurance limit of the system.
6. Determine reliability of endurance limit value(s).
7. Plan margin of safety for engineering design from established endurance limit.

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Accelerated service life testing [1]

The aim of any accelerated test must be to simulate the same mechanism(s) of failure as seen in normal usage hut cause them to occur more rapidly; not to introduce different mechanisms which may lead to completely misleading conclusions being reached.

The durability of adhesive joints may be assessed using long-term field exposure and this is likely to decrease the risk of introducing poorly performing joints into the marketplace. However, the cost of developing new adhesive materials and systems is directly related to the time-to-market, which strongly correlates with research and development time.

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Accelerated service life testing [1]

Accelerated tests must be employed to assess the durability within reasonable time scales, particularly in an era where there is an increasing demand for shorter research and development cycle.

A number of approaches have been used to accelerate such tests:

- increasing the temperature
- applying increased mechanical loading

With any such approach there are two important questions:

'Does the acceleration alter the failure mechanism?

'How much is the ageing accelerated?'

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Accelerated service life testing [1]

For qualitative and ranking experiments, the second question may not be important, but if any behavioral predictions are desired, the amount of acceleration needs to be determined. The usual ways of addressing these questions are to characterize the failure mode and to test at intermediate values of the accelerating parameters to see if the process follows the same kinetics at all times.

A popular form of accelerated aging for load-bearing structural joints involves the use of static or dynamic stress, particularly at or near adhesive/ adherend interfaces and simultaneous exposure to hostile environments, such as high humidity, elevated temperature or corrosive conditions.

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Accelerated service life testing [1]

The ready ingress of water molecules into bonds near the propagating crack tip, coupled with the high stress concentration which is present at the crack tip, leads to an easily observable acceleration factor. Thus, this test method circumvents a problem associated with accelerating environmental attack through the use of unrealistically high temperatures.

Some well-known methods are: the wedge test, constant displacement rate test, peel test, cyclic fatigue test, pull-off test, blister test and so on. In recent years, the constant displacement rate test method has been used extensively .

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Accelerated service life testing [1]

Constant displacement rate test method

Since the displacement rate strongly influences crack growth rate, the displacement rate can be selected to drive the crack at a velocity that is either faster or s lower than the degradation rate of bonds ahead of the crack tip. Dependence of adhesive fracture energy on the crack velocity exhibits distinct regions.

Of particular interest in the study of durability is the lowest crack velocity region, which is associated with water molecule diiffusion to the propagating crack tip at a rate faster than the crack velocity, thus allowing water molecules to reach and weaken the crack tip.

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Accelerated service life testing [1]

The durability of adhesive joints is readily discernable in this low crack velocity region. On the other hand, when joints are loaded at a fast displacement rate, crack extension may occur at a rate faster than the diffusion rate of water molecules, suppressing any potential effect of water attack.

It was found that adhesive fracture energy recorded at 21°C ± 1°C for 55% relative humidity (RH) was greater than that recorded for 21°C ± 1°C liquid water tests, but the values of adhesive fracture energy were of statistically the same magnitude for both the environments if relatively fast rates were employed. Thus the durability ranking obtained from high displacement rate tests can be misleading.

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Accelerated service life testing [1]

Data collection to establish the dependence of adhesive fracture energy G_C upon the crack velocity as illustrated in Slide 35 is usually time consuming, as each data point is obtained from a single displacement rate for each specimen. To accelerate the rate of experimentation it was proposed that multiple different displacement rates may be applied to a single specimen. The researchers then constructed a plot of adhesive fracture energy versus crack velocity within eight days.

This plot was found to be statistically identical to those obtained previously on other specimens using a single displacement rate for each specimen which took three months to complete. This method can reduce experimental time, but it also can enable a reduction in variations introduced by using different specimens. However, it should be noted that a relatively simple fracture-mechanics relation was used.

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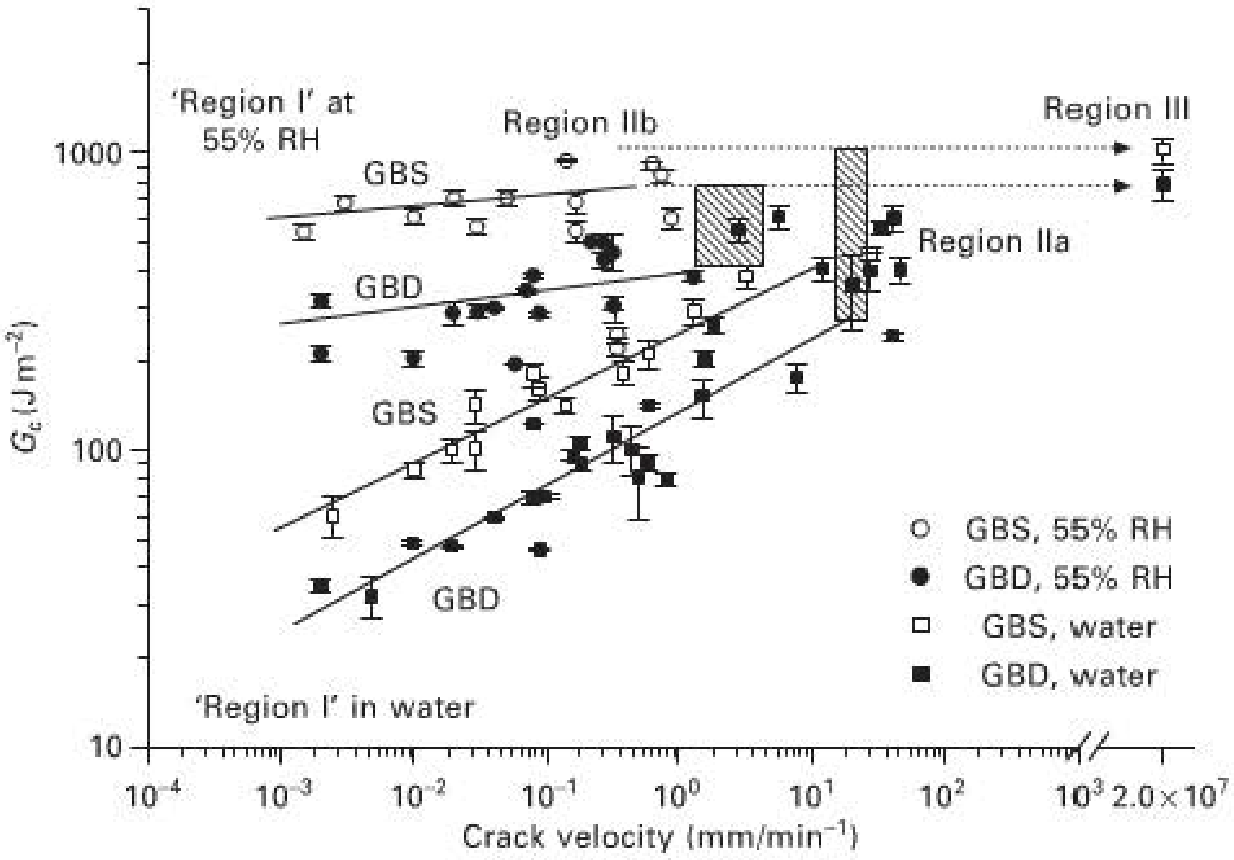
Accelerated service life testing [1]



Relationship between adhesive fracture energy G_C and the crack velocity for aluminium alloy/epoxy joints recoreded at 55 % R.H. and in liquid water at +21°C ± 1°C.

GBD…grit blasted and degreased adherend
GBS…grit blasted, degreased and silane pretreated adherend

Accelerated service life testing [1]

The adhesive fracture energy mechanical relation depends only on load and displacement and is independent of crack length. The adhesive fracture energy may be calculated readily from the load-displacement data. It is important when conducting these tests to ensure that each successive step has a fracture energy that is equal to or higher than that for the previous step.

The growing crack will have a crack-tip deformation zone whose size depends on fracture energy. If the next step normally would have lower fracture energy, the measurement may be influenced by the larger deformation zone generated in the previous step. This is particularly important for tough materials in which the zone size may not be small compared to 1 mm.

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Accelerated service life testing [1]

It remains to be demonstrated whether such an approach provides a sound basis for an accelerated test if more complex fracture-mechanics relations, such as those whose equations explicitly include crack length, are required. In such cases, the lack of data points for determining adhesive fracture energy at each displacement rate may well compromise both the accuracy and reliability of results.

The fluctuating loads used in cyclic fatigue tests always lead to much lower resistance to crack growth than those seen under monotonic loads. Thus, the combination of a hostile environment and cyclic fatigue loading constitute a very severe test environment.

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Accelerated service life testing [1]

Cyclic fatigue loading represents an accelerated test method extensively used to increase the rate of water attack on the joints without the detrimental effects associated with the common practice of raising the test temperature or crack blunting caused by water plasticization occurring in specimens subjected to monotonic loading.

However, most cyclic-fatigue tests commonly are undertaken using expensive servo-hydraulic test machines. The disadvantage of these machines is that usually only one specimen can be tested at a time, leading to both extended testing and extensive financial outlay.

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Accelerated service life testing [1]

The ingress of water into full adhesive joints usually takes a relatively long time, in the region of years, to reach saturated conditions. Modifications to test geometries have been proposed to accelerate water uptake. Specimens are made by coating a thin layer of adhesive over the adherends which are then placed in environments with different levels of relative humidity and temperature.

Owing to a larger exposed surface area for water ingress and shorter diffusion path, equilibrium is achieved very quickly, usually within days. Adhesion loss is then measured using the notched coating test, shaft-loaded blister test or scrape test.

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Accelerated service life testing [4]

Adhesives are often used in applications where they are exposed to continuous or intermittent loads over long periods. It is difficult to duplicate such conditions in the laboratory. Neither is adhesive testing and/or observation under actual service conditions a very feasible alternative.

The designer is not usually able or willing to await the results of years of testing before using the adhesive, and to tie up testing equipment and space for such long periods would be prohibitively expensive. There are companies, universities, and other industry groups that have loading racks or other test systems where samples are exposed to dead weight or other loadings while exposed to ‘‘natural-weathering’’ conditions. It is advantageous, however, to have these backed up with accelerated tests.

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Accelerated service life testing [4]

These accelerated tests are generally experiments in which extreme conditions are used to increase the rate of degradation and deterioration of the adhesive joint. Although it is seldom possible to establish a one-to-one correlation between the rate of deterioration in the accelerated test and actual weather-aging conditions, it is hoped that the short-term tests will, at the very least, provide a relative ranking of adhesive–adherend pairs, surface preparation, bonding conditions, and so on, and/or provide some insight into relative expected lifetimes.

Some accelerated tests are surprisingly simple and intended to give only highly qualitative information, while others have been formulated into standard tests intended to yield more quantitative results. Since heat and moisture to which adhesive joints are commonly exposed are environmental factors known to greatly influence adhesive durability, most accelerated tests involve these two agents.

Accelerated service life testing [5]

It is possible to obtain information about the longer-term performance of an adhesive joint by exposing the joint to a controlled environment, where factors such as temperature and humidity can be defined or varied according to the end-needs of the assembly/joint under test. Such an environment would be more extreme than that normally seen by the assembly in its standard operating condition. The higher temperature and humidity increases the rate at which the joint degrades and ages, and hence the testing is 'accelerated'.

The user must be aware of two potential problems with accelerated ageing. The first is that it can be difficult to relate the length of time that the joint survives in its accelerated ageing environment to the length of time that the joint would survive in-service.

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Accelerated service life testing [5]

For example, an accelerated ageing test at +85°C and 85 % relative humidity might cause failure in 3 months, but it is then difficult to predict how long the joint will survive at +25°C and 50 % relative humidity - probably longer than 3 months is the only real certainty.

The second problem is that if the temperature and humidity of the accelerated process are very different from that experienced in-service, the type of failure may be changed, i.e. the failure mechanism will not be the same. This means that the information obtained from accelerated ageing is not relevant to how the joint may fail in-service.

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Accelerated service life testing [5]

There are five general factors that will affect how durable an adhesive joint system is. These factors are listed below, along with some of the more specific issues covered by each factor:

- Environment - temperature, humidity, water and other liquids (chemicals), salt, radiation, vacuum
- Loads and stresses - strength, creep and fatigue
- Adhesive type - epoxy, acrylic, polyurethane, toughened, and others
- Adherend material - steel, aluminium, titanium, polymers, composites
- Surface preparation - interface creation, adhesion theory, degrease, abrasion, etch, anodise, primers

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Accelerated service life testing [6],[7]

By far the most detrimental factors influencing adhesives aged outdoors are heat and humidity. Thermal cycling, ultraviolet radiation and low temperatures are relatively minor factors.

When exposed to weather, structural adhesives rapidly lose strength during the first 6 months to 1 year. After 2 - 3 years, the rate of decline usually levels off at 25 - 30% of the initial joint strength, depending on the climate zone, adherend, adhesive and stress level.

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Accelerated service life testing [6],[7]

The following generalizations are important in designing a joint for outdoor service:

- The most severe locations are those with high humidity and warm temperatures
- Stressed panels deteriorate more rapidly than unstressed panels
- Stainless steel adherends are more resistant than aluminium adherends
- Heat-cured adhesive systems are generally more resistant to severe outdoor weathering than room-temperature-cured systems
- Using the better adhesives, unstressed adhesive bonds are relatively resistant to severe outdoor weathering, although all joints will axhibit some shear strength loss.

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Experimental example #1 [6],[7]

One particular accelerated test in laboratory condition is so called „JAN cycle test“ according to ex USA military standard MIL-STD-304. Duration of test is 30 days, all three conditions are alternating:

- cold (–54 ° C),
- dry heat (+71 ° C),
- heat and humidity (+71°C, 95 % RH)

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Experimental example #1 [6],[7]

After the exposure period of 30 days, the aluminum alloy panels used in the studies (AW-2024-T3) were cut into individual specimens and tested at – 55° C, +23° C and +71° C. Eleven types of adhesives were tested. Only one adhesive actually failed. Only one adhesive actually failed.

The results are shown in Slides 49 and 50. Virtually all the adhesives showed a loss in strength when tested at +71 ° C, some being more affected than others. One adhesive (No. 7), the epoxy-anhydride room temperature-cured system, lost approximately 70 % of its joint strength at +23 ° C after cycling. The room temperature-cured epoxy-polyamide systems (No. 1) seemed to be the least affected of the adhesive types tested.

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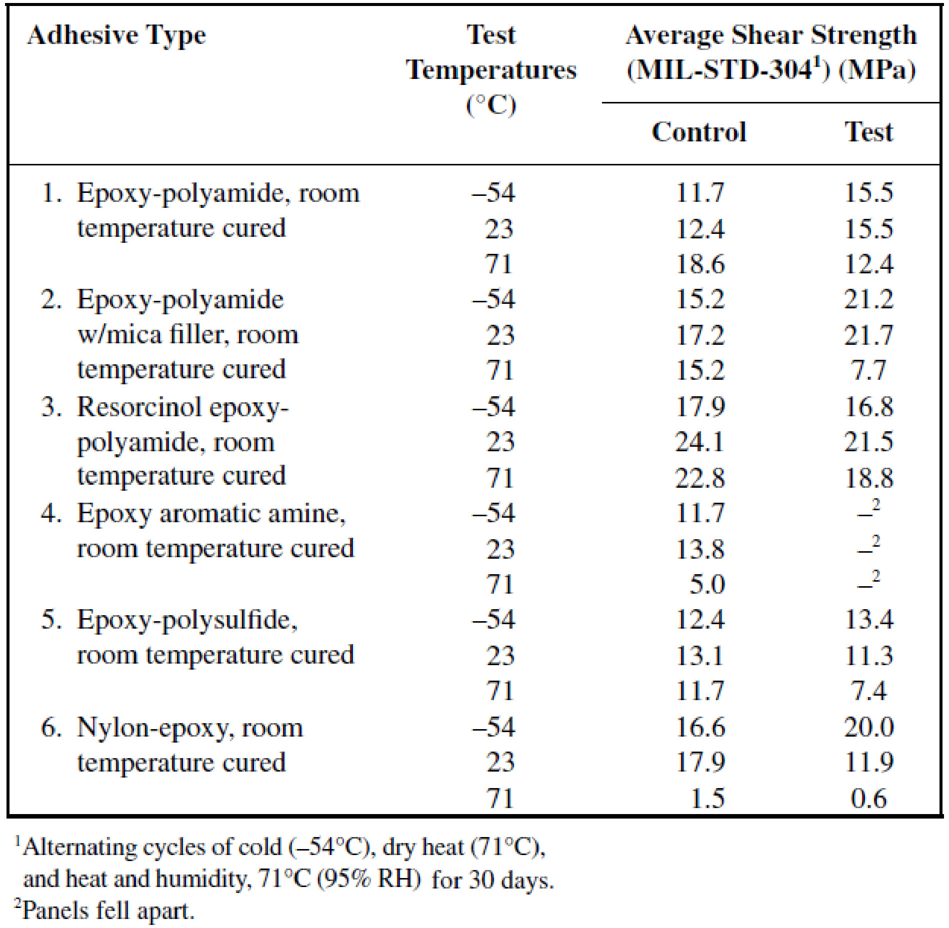
Experimental example #1 [6], [7]

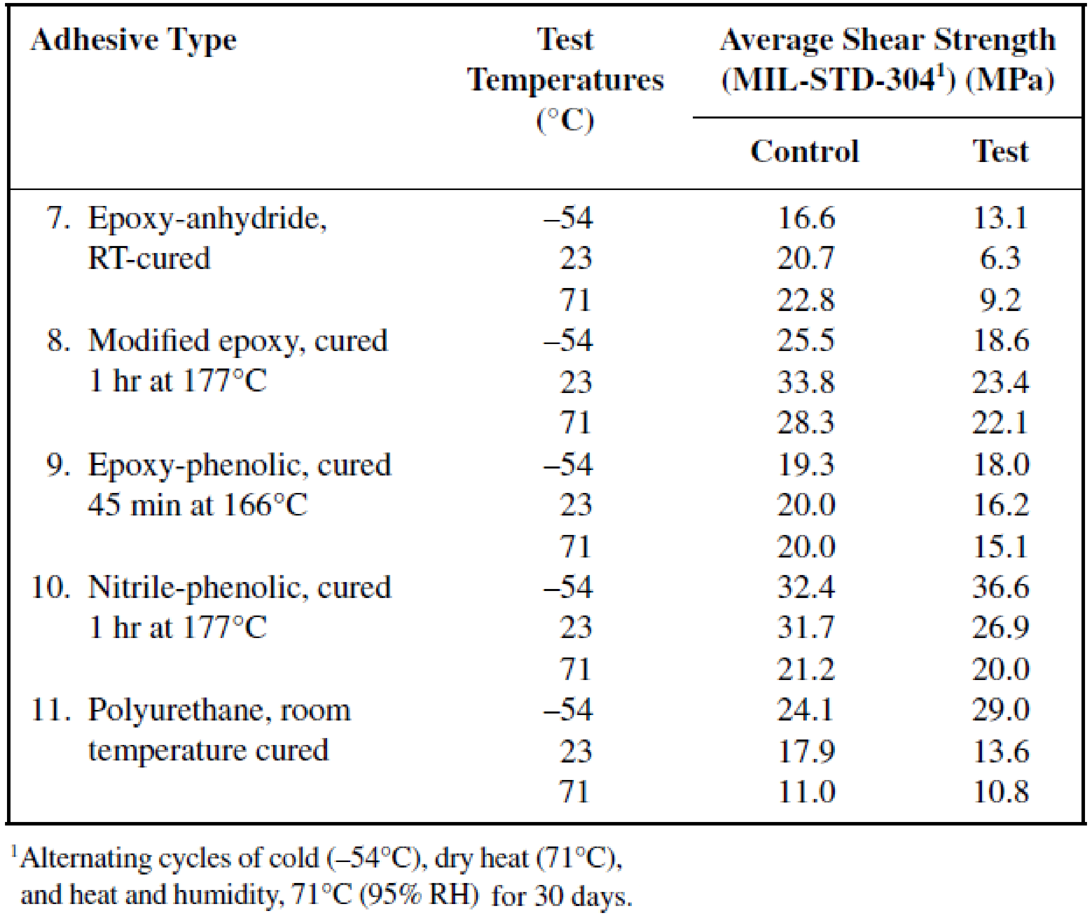


Adhesive Type	Test Temperatures (°C)	Average Shear Strength (MIL-STD-304[1]) (MPa)	
		Control	Test
1. Epoxy-polyamide, room temperature cured	–54	11.7	15.5
	23	12.4	15.5
	71	18.6	12.4
2. Epoxy-polyamide w/mica filler, room temperature cured	–54	15.2	21.2
	23	17.2	21.7
	71	15.2	7.7
3. Resorcinol epoxy-polyamide, room temperature cured	–54	17.9	16.8
	23	24.1	21.5
	71	22.8	18.8
4. Epoxy aromatic amine, room temperature cured	–54	11.7	–[2]
	23	13.8	–[2]
	71	5.0	–[2]
5. Epoxy-polysulfide, room temperature cured	–54	12.4	13.4
	23	13.1	11.3
	71	11.7	7.4
6. Nylon-epoxy, room temperature cured	–54	16.6	20.0
	23	17.9	11.9
	71	1.5	0.6

[1] Alternating cycles of cold (–54°C), dry heat (71°C), and heat and humidity, 71°C (95% RH) for 30 days.

[2] Panels fell apart.

Experimental example #1 [6], [7]



Adhesive Type	Test Temperatures (°C)	Average Shear Strength (MIL-STD-304[1]) (MPa)	
		Control	Test
7. Epoxy-anhydride, RT-cured	–54	16.6	13.1
	23	20.7	6.3
	71	22.8	9.2
8. Modified epoxy, cured 1 hr at 177°C	–54	25.5	18.6
	23	33.8	23.4
	71	28.3	22.1
9. Epoxy-phenolic, cured 45 min at 166°C	–54	19.3	18.0
	23	20.0	16.2
	71	20.0	15.1
10. Nitrile-phenolic, cured 1 hr at 177°C	–54	32.4	36.6
	23	31.7	26.9
	71	21.2	20.0
11. Polyurethane, room temperature cured	–54	24.1	29.0
	23	17.9	13.6
	71	11.0	10.8

[1] Alternating cycles of cold (–54°C), dry heat (71°C), and heat and humidity, 71°C (95% RH) for 30 days.

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Experimental example #2 [8]

The test results (load per unit width) for adhesive bonded joints in titanium alloy TiA6V4, bonded with modified epoxy adhesive AF126-2 (3M), show that there is a synergistic effect between temperature and humidity. Results represent the average effects of temperature, relative humidity and exposure time on joint strength. No noticeable changes were observed for those specimens stored for 2-3 weeks under standard laboratory conditions.

As with the immersion tests, the joint strength exponentially declines to a non-zero limiting value, which is dependent upon the relative humidity and temperature of the conditioning environment. It has been observed that the diffusion coefficient and the saturation moisture contents for AF126-2 adhesive increases with temperature and relative humidity. The glass-transition temperature of the adhesive is sensitive to moisture.

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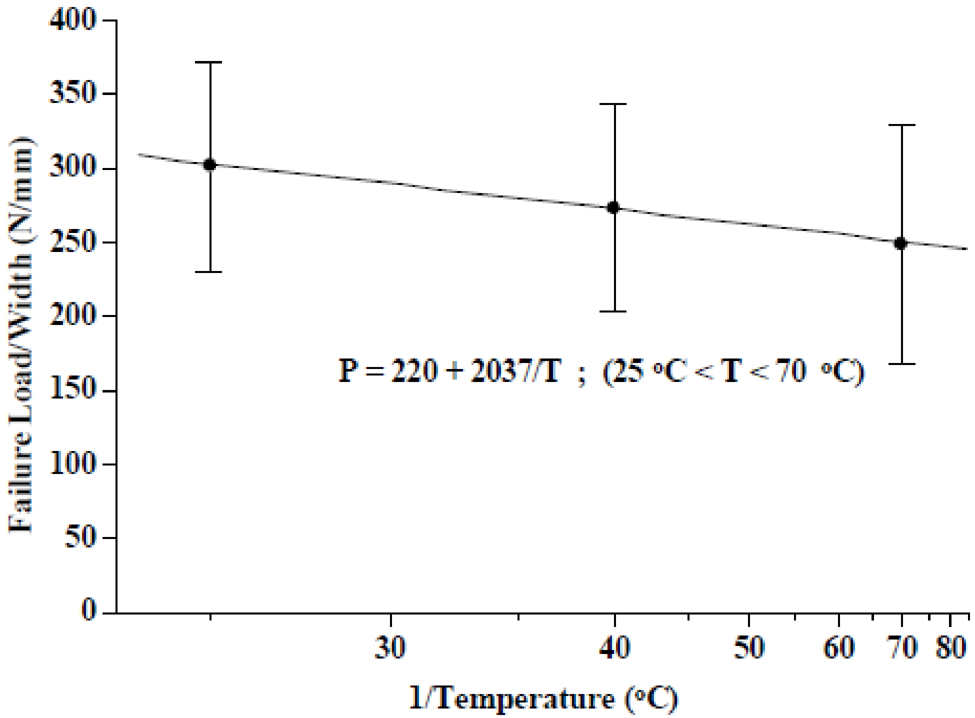
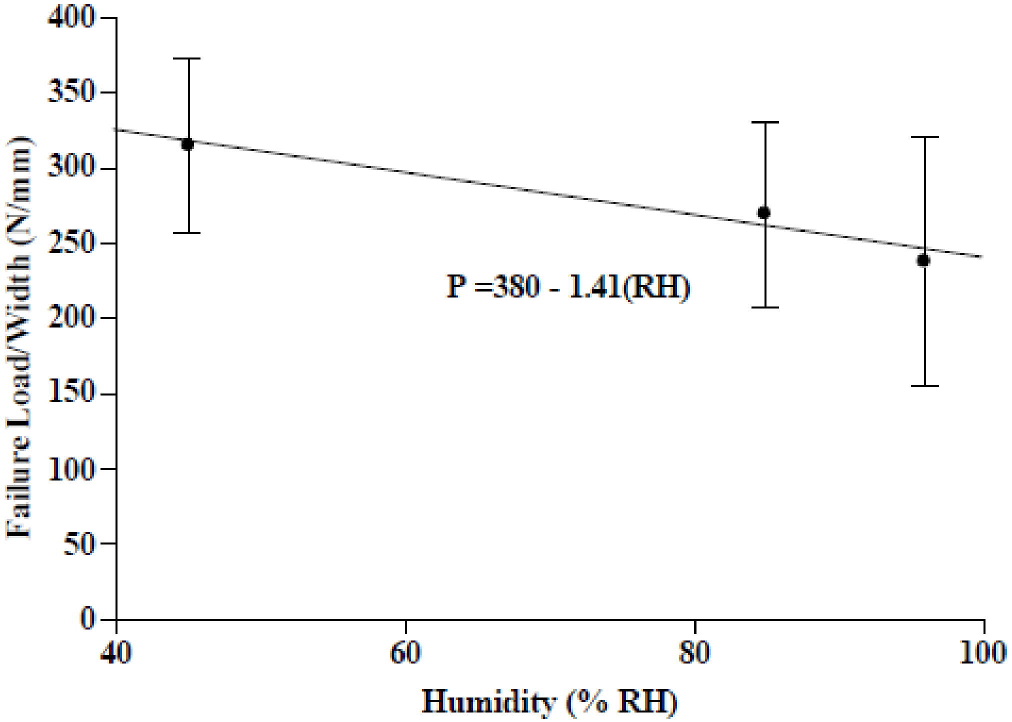
Experimental example #2 [8]



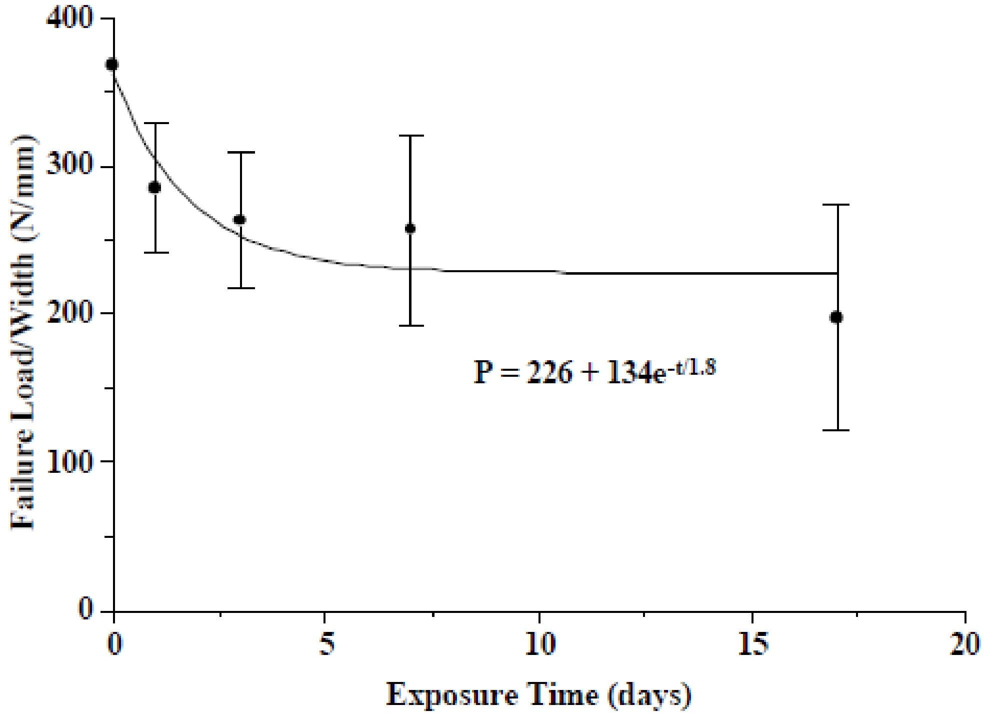
Effect of temperature on failure load for TiAl6V4 alloy /AF126-2 single lap joint

Experimental example #2 [8]



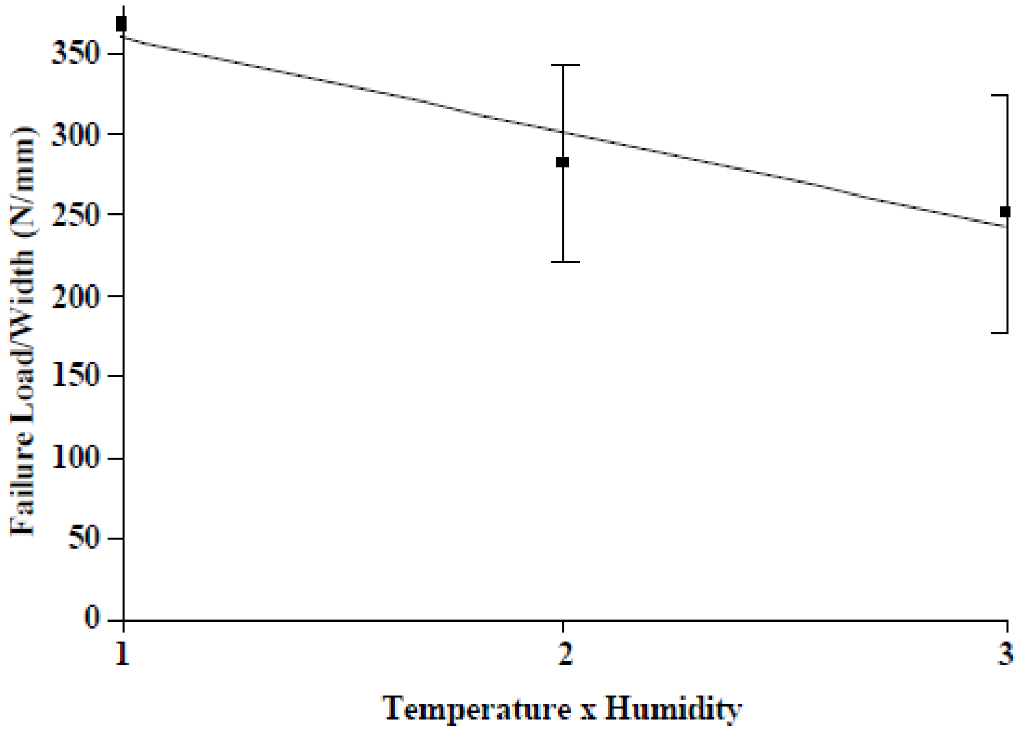
Effect of humidity on failure load for TiAl6V4 alloy /AF126-2 single lap joint

Experimental example #2 [8]



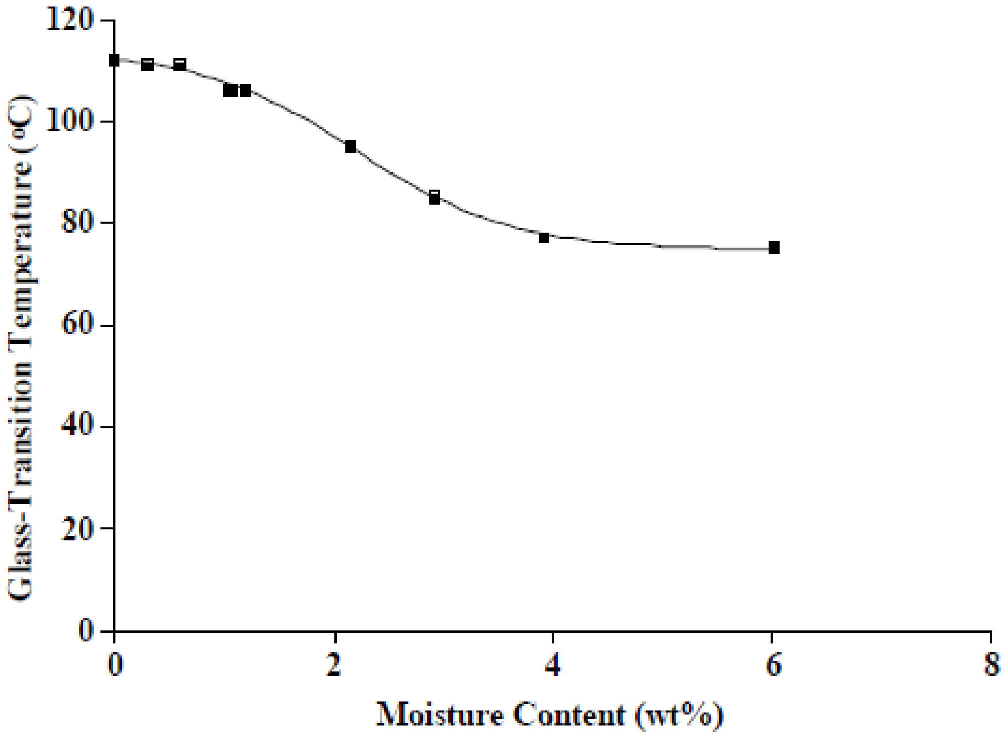
Effect of time on failure load for TiAl6V4 alloy /AF126-2 single lap joint

Experimental example #2 [8]



Interaction between temperature, humidity and their relative effect on the failure load

Experimental example #2 [8]



Glass transition temperature T_g of modified epoxy adhesive AF126-2 as a function of moisture content

Experimental example #2 [8]

The results presented in this example show that for this particular system and joint configuration simple algebraic relationships can be used to estimate the effects of temperature and humidity, and their interactions, on joint strength. Unfortunately, there is no universal formulation that can be applied to all adhesive systems or adhesive types.

The chemical and physical complexity of adhesive materials, adherend surfaces, and the multifaceted nature of degradation mechanism(s) prevents the formulation of simple solutions.

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Experimental example #2 [8]

The results indicate that for moisture sensitive adhesives it is possible to relate the strength reduction of single-lap joints with changes in both *Tg* and the conditioning temperature, thus enabling strength values to be determined at intermediate temperatures. This applies equally to water immersion and exposure to hot humid environments.

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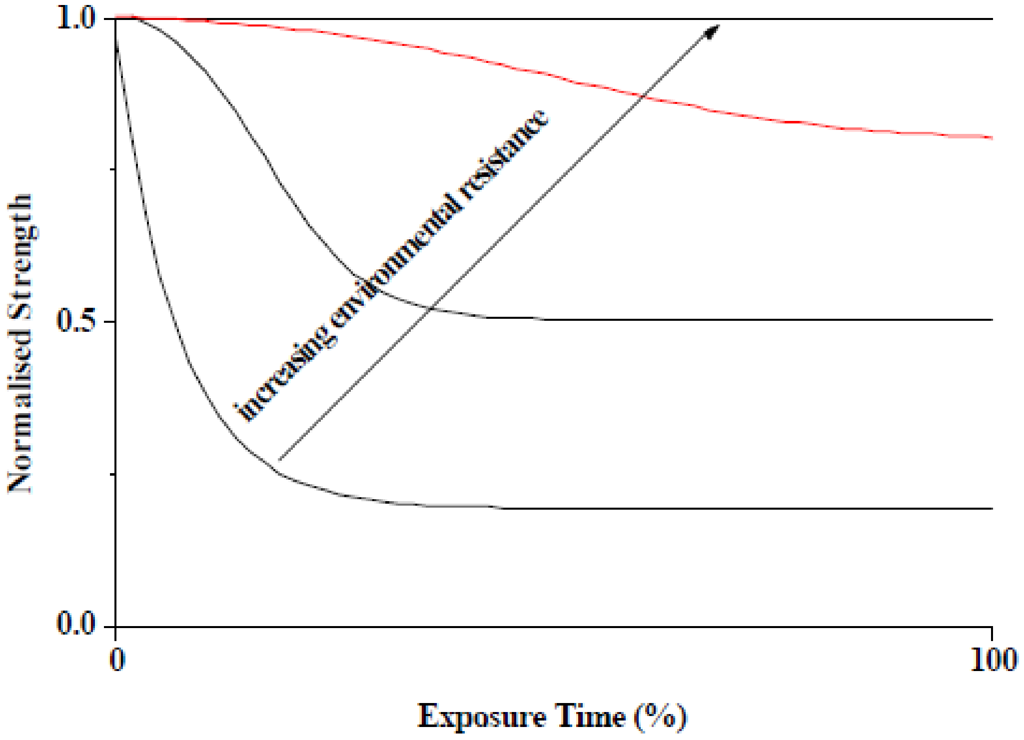
Experimental example #2 [8]



Typical strength reduction with exposure time curves showing resistance to environment effects

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