Durability of pressure sensitive adhesive joints

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Abstract

Pressure sensitive mounting tapes provide a quick and effective fastening method compared to most mechanical joining techniques. Due to the viscoelastic nature of pressure sensitive adhesives their response to mechanical and climatic stress in terms of durability is different from most structural adhesives. While the feature of compensating differences in thermal expansion of bonded members and the ability to recover during cyclic loading add to their superior properties, in specific applications their characteristic creep behavior can be detrimental in other areas. To obtain design values for adhesively bonded joints with pressure sensitive tapes, specific testing methods are required to access their long-term properties under environmental exposure. In this study standard test procedures for structural adhesives including static shear and cleavage tests have been adapted for semi structural bonds with adhesive tapes and applied to metal and glass joints under standard aging conditions. The results reveal future opportunities and limitations in using pressure sensitive tapes in demanding applications.

Introduction

Adhesive bonding has become a preferred fastening technology in applications where dissimilar materials need to be joined. In glazing applications pressure sensitive tapes have been successfully used to bond glass panels to supporting metal framework (Fig. 1). Here the adhesive fixture avoids stress concentrations in the crack-sensitive glass panel and compensates the difference in thermal expansion between glass and aluminum.

Figure 1. Bonding of laminated safety-glass panels to aluminum framework with pressure sensitive tape

Fail-safe design concepts of load bearing joints with pressure sensitive adhesives need to consider their specific mechanical long-term behavior which relates to the viscoelastic material properties of pressure sensitive polymers and blends. Prior to approval several durability tests need to be carried out to investigate and prove the durability of a specific substrates-adhesive combination against the following failure mechanisms:

- excessive long-term shear creep deformation under static and cyclic load conditions
- local cohesive failure due to crack formation and propagation in the adhesive bulk
- interfacial loss of adhesion upon exposure to damaging weather conditions

Failure Under Shear Stress

In a typical glazing application static shear deformation will occur when the adhesive layer is designed to carry the dead load of a glass panel. Additional cyclic shear deformations are usually superimposed due to the difference of thermal expansion between the glass panel and the framework. The resulting maximum stress and strain level of the adhesive tape in such situations depends on the overall length of the bonded members and the thickness of the adhesive tape. The resulting normalized shear strain tan γ can be calculated through division of the total displacement ΔL by the bond line thickness d as indicated in Fig. 2.

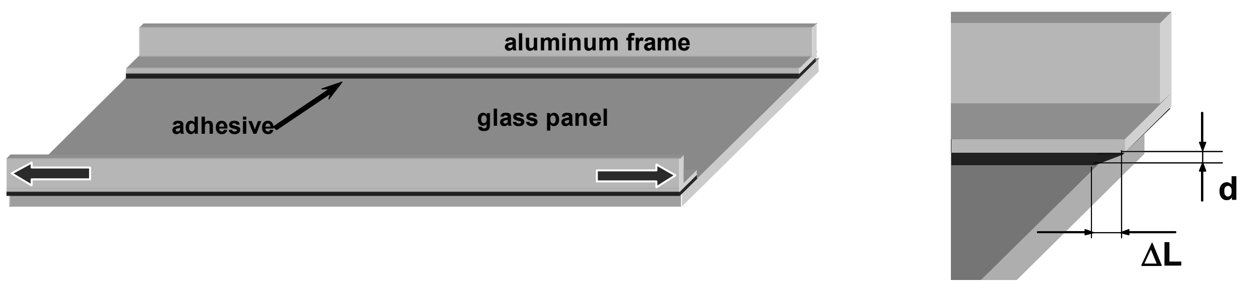

Figure 2. Shear strain at the edge of a bonded assembly due to thermal movement

The relaxation of stress is e.g. a desired feature in hybrid joints combining different materials with different coefficients of thermal expansion (α, CTE). If the adhesive layer is not able to compensate for the difference in thermal strain, the assembly will be deformed or the adhesive joint may fail. This needs to be considered for example when aluminum frame profiles are to be bonded to glass panels. With values of α-aluminum = $23{,}8 \cdot 10^{-6}$ 1/K and α-glass = $8{,}1 \cdot 10^{-6}$ 1/K and a total bond length at room temperature of L0 = 2500 mm for a change in temperature of ΔT= 40 K a difference in length at both ends of $\Delta L = \Delta T \cdot L0 / 2 \cdot (\alpha Al - \alpha Gl) = 0{,}785$ mm will occur in a stress-free assembly. A pressure sensitive mounting tape with a thickness of d_{min} = 0,8 mm therefore should be suitable to compensate $\Delta\alpha$-induced strain in this configuration.

On the basis of this calculation together with experimental data of stress relaxation as a function of time (Fig. 3) for a high performance double face acrylic pressure sensitive tape an estimation of thermal stress can be made. While creep experiments apply a constant load to the sample and follow the increase of strain over time the relaxation technique applies a fixed strain to the specimen at the beginning of the test and records the decrease in stress over time caused by the plastic deformation of the adhesive polymer /1/.

The experimental data were obtained from single overlap shear tests on a high precision testing machine with non-contact video extensometry and closed-loop control to keep the true shear strain in the bond area on a constant level throughout the test.

The expected residual load for strain-inducing temperature events on a ten hours timescale in the described situation of a hybrid joint under thermal movement can be estimated from the data in Fig. 3 at 0,04 N/mm² and then used for the further analytical prediction of mechanical deformations of the assembly.

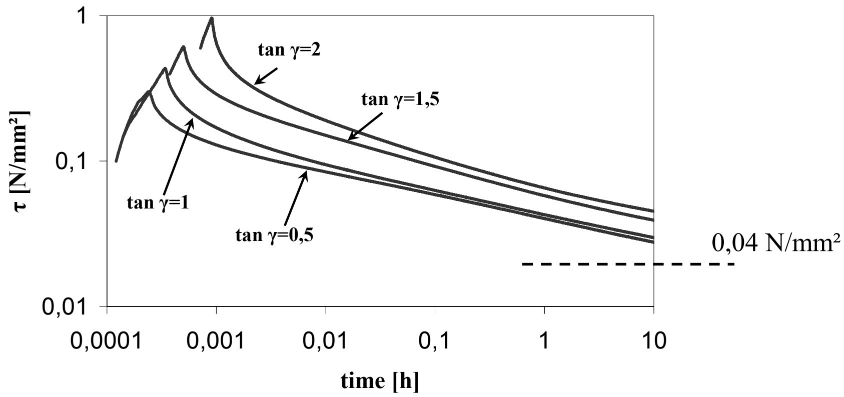

Figure 3. Stress relaxation from different initial strain values, acrylic pressure sensitive tape, d=1,1 mm

The data from relaxation tests can also be used to predict the maximum level of a static load keeping the pressure sensitive bond from exceeding a certain strain-limit after a given period of time. The experimental data for time dependent stress from relaxation tests can be converted to estimate maximum load values under creep conditions based on the assumption that the declined value of shear stress after a specific time in the relaxation experiment will cause less deformation when this level of stress is constantly applied in a corresponding creep experiment /2/. To check this concept experimentally single overlap shear specimen were prepared by bonding aluminum specimen after ultrasonic degreasing in acetone with acrylic pressure sensitive tape. The thickness of the tape was chosen as 1.1 mm and the size of the bonded area was 25 mm by 25 mm. Stress relaxation at room temperature after initial strain of tan γ = 1 was recorded for 24 hours and stress values determined for 0.5, 2, 8 and 16 hours (Fig. 4).

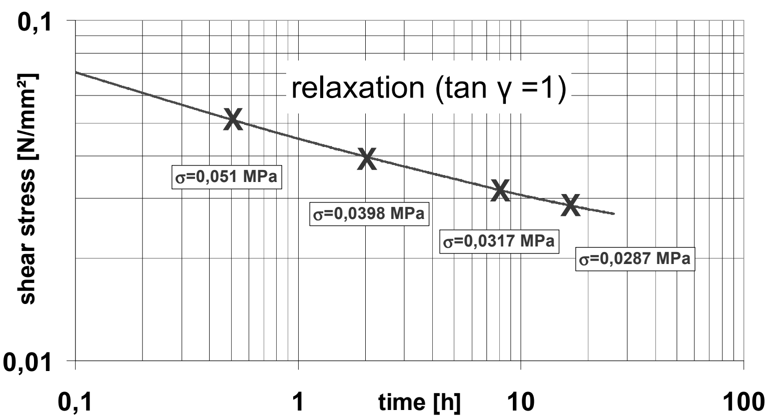

Figure 4. Relaxation data for aluminum lap shear specimens bonded with a 1.1 mm acrylic tape, 23 °C

The results of four corresponding creep experiments applying the time dependent load values from Fig. 4 prove that the predicted strain limit of tan γ = 1 was not exceeded in either one of the creep tests

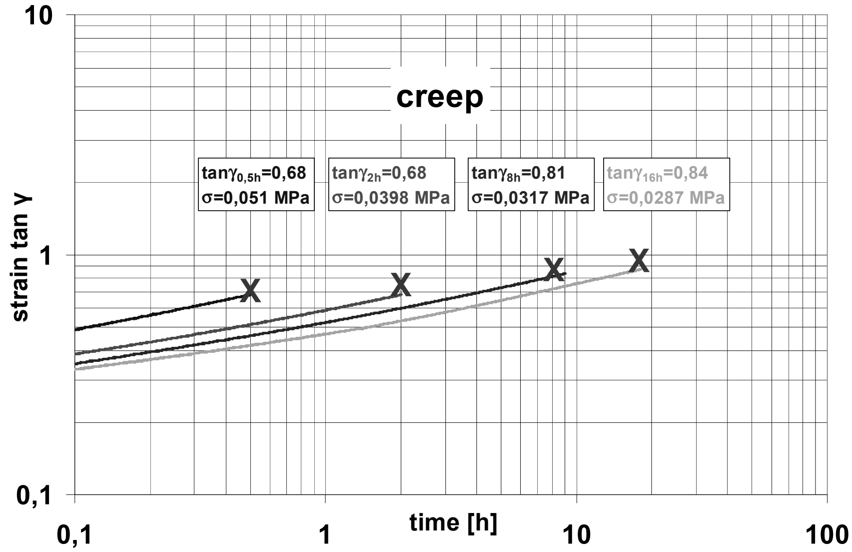

Figure 5. Results of creep experiments under static stress at ambient temperature corresponding to load values extracted from Fig. 4

It is important to avoid excessive shear strain of the pressure sensitive tape because cohesive failure is likely to occur if the shear deformation leads to a build up of tensile stress in the adhesive at both ends of the bonded area. The state of stress set up in a long rubber block under various shear deformations nes been found to depend on the shapes of the end surfaces, even when the block is quite long. This phenomenon is attributed to the absence of compressive stress on the end surfaces that is needed in order to maintain a state of simple shear in a block element of adhesive polymer /3/. At an imposed normalized shear strain of tan $\gamma = 3$ the hydrostatic tension in a soft rubbery solid has been predicted by GENT et al to be about three times the shear modulus which is sufficiently high enough to cause internal fracture /4/. This mode of failure especially tends to occur in pressure sensitive tapes with particles in the bulk material acting as crack initiators for cohesive failure under local tensile stress condition. Fig. 6 illustrates this failure mechanism and the resulting fracture surface of the separated polymer wedges after the test.

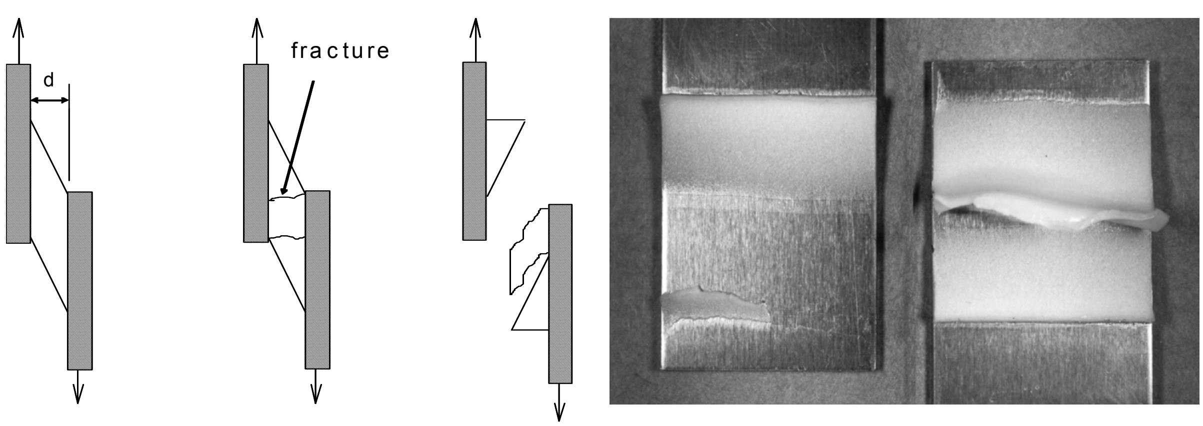

Figure 6. Bond failure under excessive shear due to cohesive fracture of the adhesive

In practice it has been found that strain in assemblies with such pressure sensitive tapes should not exceed values of tan γ beyond 2 whereas in comparison design rules for rubbery moisture curing one component polyurethane adhesives recommend to limit repeatedly occurring shear deformation to values of tan γ below 0.5.

The relaxation test method can be used as an effective method to obtain data for the prediction of long-term shear since the long-term part of the time dependent decrease in stress is governed by the viscous flow of the polymer leading to a linear time dependant stress-strain relation in the logarithmic plot /5/.

Interfacial Debonding

It is self understood that the design rules for mechanical durability under shear stress that have been discussed above are only valid as long as the adhesive strength at the substrate surface exceeds the shear resistance of the adhesive bulk. The adhesion of pressure sensitive tapes especially to the surface of untreated glass has shown to be quite sensitive to degradation in presence of moisture in combination with mechanical stress. Fig. 7 illustrates the typical failure mode of single lap shear joints bonded with acrylic pressure sensitive adhesives after accelerated aging in an environment with increase temperature and humidity.

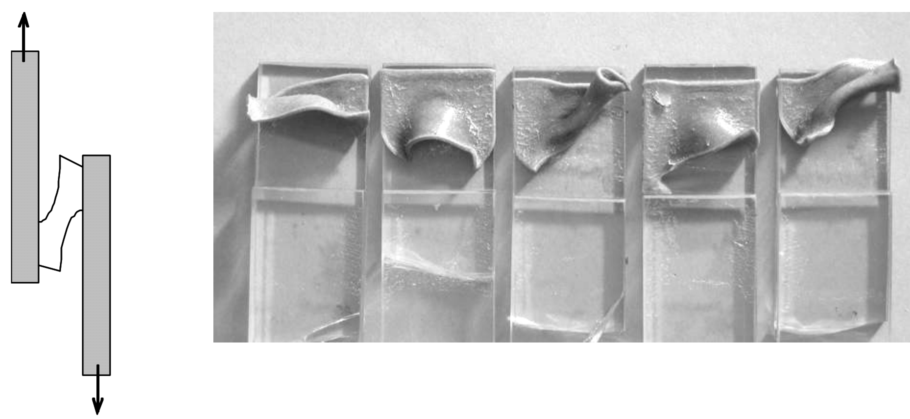

Figure 7. Failure of single lap shear specimen due to interfacial debonding after two weeks exposure to 60° C / 90% relative humidity, float glass samples bonded with acrylic pressure sensitive tape

The single lap shear test only provides limited insight into the time dependant mechanisms of this failure mode. For the assessment of surface pretreatments for structural aluminum bonds the Boeing wedge test is widely used in the adhesive industry and is standardized according to ASTM D 3762. For the testing of glass specimen bonded with pressure sensitive adhesive tapes the test procedure had to be modified to be applicable for the significantly different material and adhesive.

Best results in the double cantilever wedge test geometry could be obtained by using standard microscope glass slides with a size of 76 mm by 26 mm and a thickness of 1 mm (Fig 8). An alternative test geometry with better handling properties especially for the testing of larger parameter series is based on a single cantilever geometry using a rigid glass panel to support a set of six specimen to be mounted on top of it (Fig 9). Upon introduction of the wedge the crack will start to propagate after some time if the energy stored in the deflected beam is higher than the fracture energy of the adhesive bond. The driving force for the propagation of crack thus comes from the stiffness of the beams separated by the wedge. This driving force decreases as the crack propagates. The length of the debonded area serves as an indicator of the debonding resistance as a function of time and environmental exposure. Since no further apparatus is needed to keep the individual specimens under mechanical stress it is easy to store the wedge test samples under accelerated aging conditions including elevated temperature and humidity.

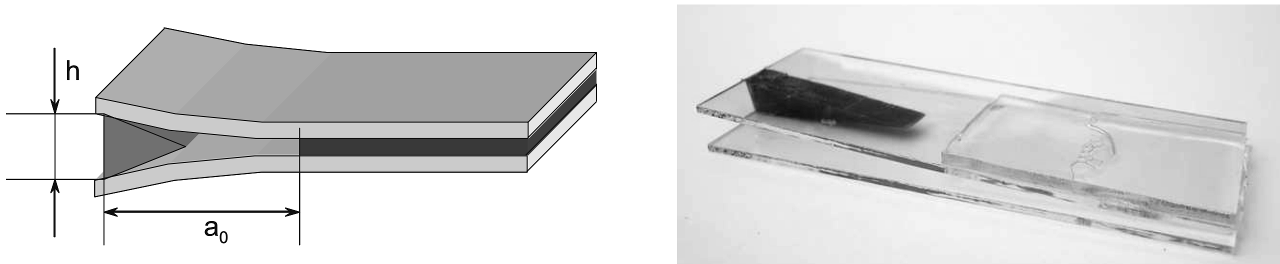

Figure 8. Double cantilever wedge test specimen, glass slides bonded with acrylic pressure sensitive adhesive

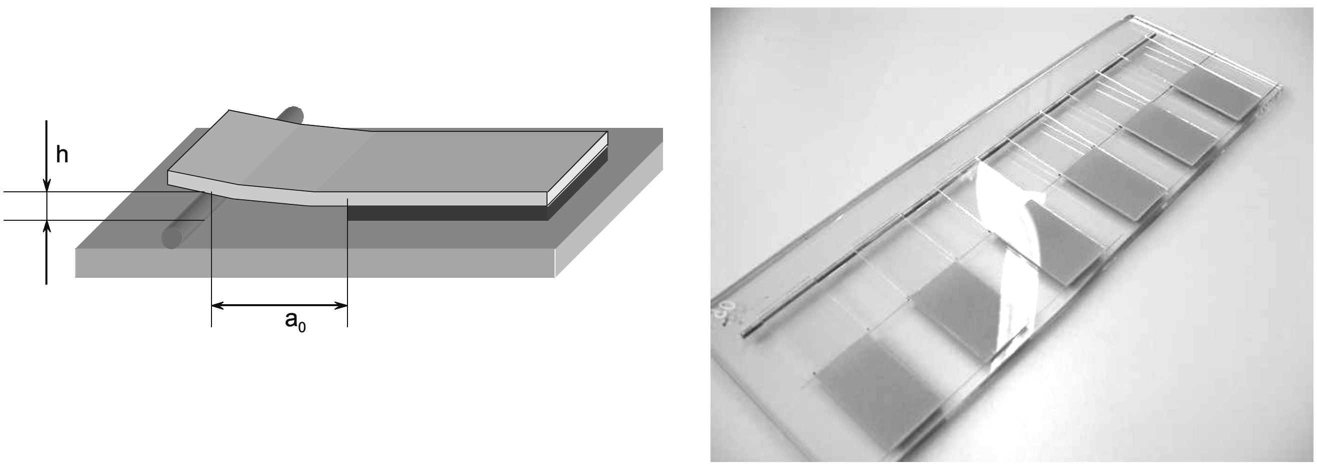

Figure 9. Single cantilever wedge test specimen, glass slides bonded with acrylic pressure sensitive adhesive

The test geometry in Fig. 9 was used to investigate the effect of silane treatment on the durability of specimens bonded with an acrylic pressure sensitive tape. All glass specimens were initially solvent wiped with acetone. The commercial silane prime was applied by first wetting the surface with a soaked cloth and then wiping dry. The acrylic tape had a thickness of 1.1 mm and was applied in an area of 40 mm by 25 mm to the rigid glass panel. After bonding a rod with a diameter of 3 mm was introduced allowing the glass slide to be bent on an open length of 30 mm.

The test panels were then subjected to different aging conditions including storage at standard laboratory condition, outside weathering at average temperatures around 8 °C with occasional rain and under constant climate conditions at 23°C with 80 % relative humidity and 60°C with 95% relative humidity. The test panels that had been prepared without silane primer initiated debonding cracks at the interphase within the first 12 hours after exposure to outside weathering as well as under climate conditions with enhanced humidity. Within one week in average more than half of the area was debonded and after two more weeks the test had come to an end due to the complete decline of the wedge force. The panels without primer which were stored under standard laboratory conditions showed first signs of interfacial debonding with an average length of 2 mm after three weeks of monitoring.

In Fig. 10 images at different states of debonding are shown. Fig. 11 illustrates the time dependent average crack propagation length for test panels without primer.

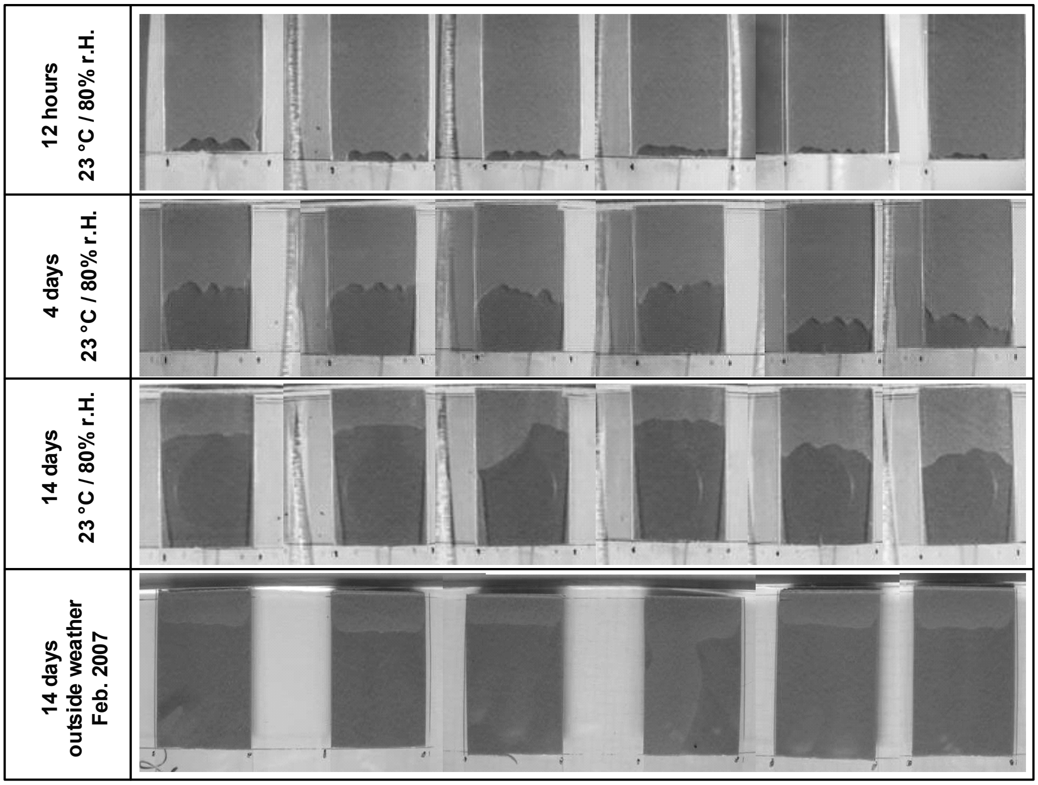

Figure 10. Test panels without primer, progress of debonding for different aging times and conditions

The debonding of the wedge specimens usually starts in the mid section with a peninsular type of propagation. The crack line straightens out as the stress caused by the bending of the glass slides decreases towards the end of the test.

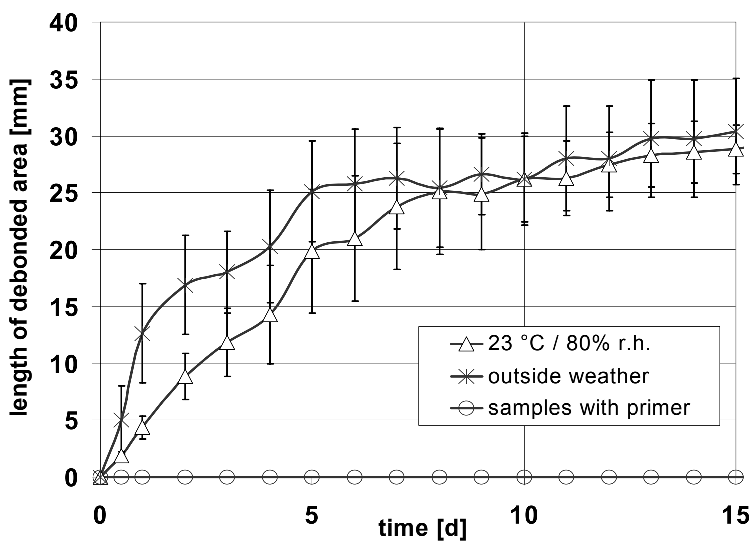

Figure 11. Time dependent average crack propagation length, average of six specimens

In the case of the specimens without primer the initial propagation of the debonded area is faster under outside weathering than under controlled climate conditions. This effect relates to occasional rain wetting the samples at the time of season when the tests were carried out.

The circled data points in Fig. 11 indicate the significant increase in durability for the specimens which were prepared with silane primer. During the test period no signs of debonding even under conditions of 60 °C and 95% relative humidity could be observed.

Summary

Today's standards for the testing of pressure sensitive adhesive tapes are focused on non-structural applications. For the purpose of design and durability assessment of high performance mounting tapes in semistructural applications test procedures are needed which specifically take into account the viscoelastic nature of pressure sensitive adhesives. The long-term shear behavior can be investigated and predicted on the basis of rheological models. A major design criterion is to limit the total shear deformation to a maximum of $\tan \gamma = 2$ since load conditions with high shear strain carry the risk of inducing cohesive failure due to hydrostatic tension at the edge of the bondline.

The durability of interfacial adhesion is sensitive to climatic exposure under mechanical stress. A modified single cantilever wedge test with glass slides has been used to investigate the durability of pressure sensitive joints under climatic exposure. The results indicate a pronounced moisture sensitivity of the interfacial pressure sensitive adhesion to glass, which could be significantly improved in these tests by applying a commercial silane primer before bonding of the glass specimens. The use of primers and adhesion promoters opens a promising opportunity to increase the durability of load bearing pressure sensitive joints and to encourage their use in semistructural application.

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