

Premature Failure in UV-Cured Adhesive Joints

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1. Abstract

In the field of structural glass adhesives, the current emphasis is to find solutions which can support high loads. A potential solution to this problem is UV-cured acrylics. While it has been shown that bonds with these adhesives are indeed capable of carrying structural loads; few investigations have focused on the influence of adhesive stiffness and load duration on the performance of the UV-cured adhesive joint.

Excessively stiff adhesives are unable to accommodate the required amount of movement and do not evenly distribute the differential shear stresses along the bond length, thereby giving rise to high stress peaks in the glass elements. In addition, a key performance requirement of structural adhesives is the ability of the adhesive to sustain loading over significant periods of time without degrading.

This paper reports on research into the effects of stiffness and sustained loading on the performance of UV-cured acrylic adhesives. The research consists of experimental investigations on a range of different UV-curing acrylics under short-term and sustained loading for glass-glass and glass-steel joints. The experimental results are accompanied by analytical and numerical modelling of the adhesive connections. The principal conclusion of this research is that short term strength is not always a good measure of the long term performance of adhesive joints and in the adhesive selection process, short-term strength should often be secondary to factors such as gap filling properties and adhesive stiffness.

Keywords: UV-Curing Acrylics, Structural Glass, Adhesive Joints

2. Introduction

Since the invention of the Float Process in 1959 the use of glass in buildings has increased steadily. Over the long term, the glass market is growing in volume terms at around 4-5% a year [1]. Architecturally it is an extremely popular material due its transparency, durability, low cost and high quality finish. Also, with the heat treatment processes available a much higher tensile strength can be achieved and glass is now being used for primary load bearing elements such as beams and floors. However, there has been little development in joining techniques. Until recently the only option for high stress applications was to use bolted connections and fully toughened glass. This is surprising, in that bolted connections in glass are inherently inefficient due to stress concentrations around the bolt holes and flaws induced during the drilling process. There are also unknowns associated with heat treatment processes, such as the degree of toughening around bolt holes [2]. This means that design values must be conservative due to this uncertainty, but also inefficient due to highest stress in low strength regions.

From here a logical step was to investigate the potential of adhesive technology for glass. This conceptually seems a good choice as it evenly distributes the load and reduces stress concentrations. There is now a plethora of new adhesives on the market of which the most popular are acrylics. To-date these have been used in the field of furniture design and are generally relatively stiff, colourless, transparent, water resistant and, as most of these adhesives are cured using UV radiation, they are completely resistant to UV damage/ageing. A downside of several of these adhesives is that they cannot be used for thick joints as the UV radiation would not penetrate fully to the centre of the adhesive. A comparison of the tensile and shear strengths of three different acrylics before and after an artificial ageing process has been carried out [3] and shows great potential. UV curing acrylics have also been used in several feasibility case studies so far, such as a new transparent room system aimed at offices [4], an 8m long aquarium [5], a transparent pavilion, an all glass staircase and square glass columns [6].

However, adhesives of this type are brittle and do not have the gap-filling properties such as those of traditional silicone adhesives. Yet perhaps more worryingly the performance of acrylic adhesives under sustained loading is unknown. It is expected that due to the stiffness of these adhesives large stress peaks occur at the edges of the joint, causing deterioration of the bond. This theory is supported by several research efforts such as those of Bigwood and Crocombe [7]. In addition, it is thought that if too large an area of adhesive is used these same stress peaks may be sufficiently large to cause failure of fully toughened glass. Hence the purpose of this work is to experimentally and numerically verify these hypotheses.

3. Experimental Work

The test methodology included short-term and long-term tests to examine the behaviour of both glass-glass and glass-steel joints.

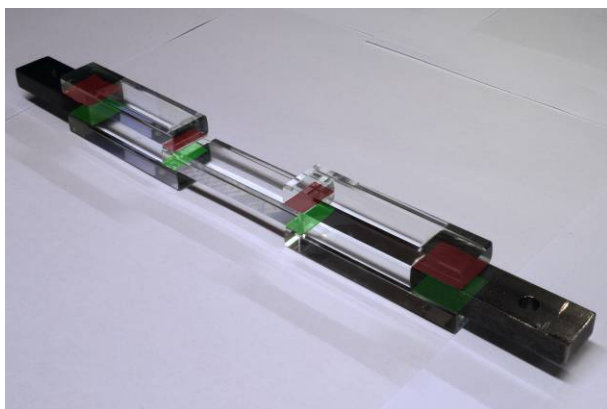


Figure 1 – A Typical Glass-Glass Specimen, with Adhesive Lap Areas Highlighted

3.1 Experimental Setup

3.1.1 Glass-Glass

Double lap shear tests were chosen as a compromise between theoretical and practical simplicity. The testing was carried out using an Instron 5500R electromechanical testing machine. However, direct mounting of glass specimens would inevitably cause stress concentrations in the glass which would in turn influence the outcome of the tests - so steel end pieces were used (but to avoid influencing the results the glass-steel lap length was double that of the glass-glass

lap). Hence the specimens were made up of 5 identical annealed glass and 2 bright mild steel pieces (80x20x10mm) and had lap lengths of 10mm (glass-glass) and 20mm (glass-steel). The glass edges were arrised and the cut faces were highly polished to reduce the influence of cutting induced flaws on the strength of the glass. The steel conformed to BS EN 10277-2:2008. A typical specimen is shown in Figure 1.

3.1.2 Glass-Steel

For these tests it was decided that it would most suitable to use single lap shear geometry as again this would be the most practical whilst providing a challenging and interesting joint geometry.

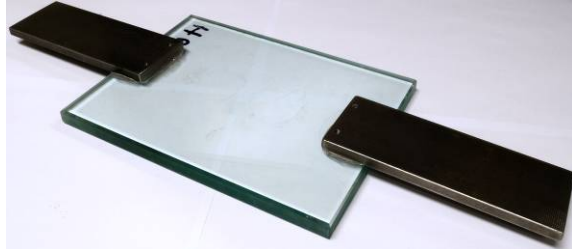


Figure 2 - Typical Glass-Steel Specimen

The tests were again carried out with an Instron 5500R electromechanical testing machine. The specimens (see Figure 2) were made up of 2 in number 140x50x6.35mm bright mild steel pieces conforming to BS EN 10277-2:2008 and 1 fully toughened glass piece measuring 200x150x10mm with an adhesive lap area of 27x50mm. Load and extension were recorded.

3.1.3 Assembly

Controlling the thickness of the adhesive joint to the 0.1mm optimum specified by the manufacturers was challenging. This was controlled by adding a small quantity (<5%) of glass microspheres of diameter 0.106mm were added to the adhesive. Hence when pressure was applied to the joint the desired thickness was obtained. The steel had a polished finish to ensure the joint thickness remained well controlled. Each specimen received 90 seconds of UVA radiation from a 300W wide spectrum UV-lamp at a distance of 10cm; due to the double bond geometry of the glass-glass specimens the exposure was repeated on both sides.

3.2 Glass-Glass Experimental Results

3.2.1 Short-Term Strength Tests

Four acrylic adhesives were tested – Delo 4468, Delo GB485, Delo adve56903 and Bohle 682-T. The purpose of the short term tests was twofold: Firstly to determine the performance of the adhesive joints under short term loading and secondly to identify a characteristic load for the long-term tests. Five samples of each adhesive were therefore tested so that a statistical model could be established. A summary of the short-term tests is shown in Table 1.

Table 1 - Summary of Short Term Strength Tests

Adhesive	Mean Failure Stress (MPa)	Standard Deviation (MPa)	Characteristic Stress (MPa)	Characteristic Load (kN)
Delo 4468	22.18	3.13	12.52	1.80
Bohle 682-T	25.30	10.26	-6.42	-0.92
Delo adve56903	17.07	4.03	4.62	0.66
Delo GB485	21.82	2.22	14.95	2.15

For each of the Delo adhesives failure initially occurred in the adhesive, in some samples glass failure followed initial adhesive failure. However, for the Bohle 682-T failure always occurred in the glass element first. This is because the Bohle 682-T is the stiffest adhesive and hence will have the largest stress peaks, causing failure in the glass element earlier than for the Delo adhesives. To get a more accurate value for the Bohle 682-T, we would need to avoid glass failure, which could be done using toughened glass.

The characteristic stress in Table 1 refers to the stress which will statistically cause 0.1% of the specimens to fail and was calculated using a normal distribution. The use of a normal distribution for these values was verified using an Anderson-Darling goodness of fit test. This raises questions about the validity of the goodness of fit test as the Bohle data is clearly not a

normal distribution as the characteristic stress for the Bohle adhesive is negative. The 2 adhesives that were carried forward to the next stage of the testing were Delo 4468 and Delo GB485 as they had the largest characteristic load.

3.2.2 Failure Modes

The mode of failure is very interesting as it reveals hidden information about the adhesive joint e.g. stress concentrations/stiffness. The samples from the short-term tests failed through 3 distinct modes (as shown from left to right in Figure 3):

1. Glass failure across the central member – smooth curved fracture surface perpendicular to principal stress vectors
2. Adhesive cohesion failure in one lap area followed by glass failure (the latter is caused by load shedding)
3. Adhesive adhesion failure followed by adhesive adhesion failure – results in two failed bonds and two halves with undamaged glass



Figure 3 - Failure Modes

The Delo 4468 samples all failed through mode 3, which illustrates that this adhesive is not as stiff as the others and was unable to generate the stress peaks required to cause the glass to fail. In contrast all of the Bohle 682-T samples failed through mode 1 due to the larger stiffness of the adhesive. While the Delo Adve56903 and Delo GB485 failed through mode 2 placing them between the other adhesives in terms of stiffness.

3.2.3 Long-Term Resistance Tests

The specimen assembly for these tests was identical to that of the short-term strength tests. The loading however, was applied by suspending weights from the samples; provision was made to record extension over time. The intention was to leave the samples under this sustained loading for 6 weeks before repeating the same short-term testing and comparing the performances. However, none of the samples could carry the constant loading with all of the samples failing within 5 hours. A single Bohle 682-T sample was tested to see if there was any improvement. While the sample nearly lasted 11 hours this was well short of the proposed 6 weeks. The time to failure for each of the specimens is shown in Table 2.

Table 2 - Failure Times of Long-Term Specimens

Sample No.	Adhesive	Time until failure (hr:min:sec)
1	Delo 4468	02:32:15
2	Delo 4468	02:56:15
3	Delo 4468	01:05:30
4	Delo 4468	00:56:45
5	Delo 4468	04:40:15
6	Delo 4468	03:27:15
7	Delo GB485	00:46:50
8	Delo GB485	00:55:50
9	Delo GB485	00:06:25
10	Delo GB485	00:09:25
11	Bohle 682-T	10:57:10

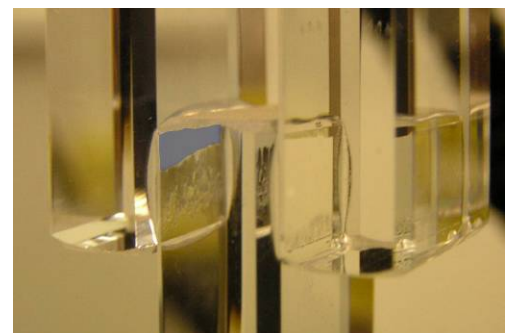


Figure 4 - Progressive Bond Damage (highlighted in image) During Long-Term Testing [14]

Needless to say, the fact that these adhesives cannot carry a small load (relative to their short-term strength) for more than 12 hours brings their use as structural adhesives into question.

It was observed during the tests that progressive failure was occurring along the bond length (see Figure 4). This is due to the fact that the stress peaks at the edge of the joint cause viscoplastic deformation. The reason the Bohle 682-T outperformed the other adhesives in this test is because its tensile strength (25MPa) is larger than both the Delo 4468 (22MPa) and the Delo GB485 (19MPa) enabling it to resist failure due to the stress peaks. As the Bohle is stiffer as well it would probably suffer less from creep (but this is little more than speculation and requires further research).

3.3 Glass-Steel Experimental Results

3.3.1 Short-Term Strength Tests

It was decided to use the Bohle 682-T adhesive for these tests. This was because it outperformed the other adhesives in the long-term tests and had the highest tensile strength.

Table 3 - Summary of Short-Term Steel-Glass Tests

Sample	Failure Load (kN)	Failure Mechanism
1	11.045	Glass Failure
2	20.382	Glass Failure
3	17.921	Adhesive Failure
4	8.341	Glass Failure
5	9.721	Glass Failure

The failures in the short-term tests were due to glass element failure and did not show the true potential of the adhesive. Therefore in an attempt to induce adhesive failure fully toughened glass was used in these tests. The results are shown in Table 3.



Figure 5 - Glass Failure in Glass-Steel tests

The mean failure load was 13.482kN with a standard deviation of 5.335kN. However, as with the glass-glass tests the majority of the failures were in the glass element. This explains the large variation in failure load. The origin of failure occurred close to edges of the adhesive area (see Figure 5), agreeing with the premise that stress concentrations at the adhesive edges are causing these failures.

4. Analytical Analysis

A review of analytical methods for adhesive joints was undertaken to identify a means of producing quick and accurate initial adhesive joint designs and for checking any numerical models.

The geometry most commonly considered analytically is single lap symmetric joints i.e. adherends of the same thickness and material. Due to the intricacy of the problem all analyses make simplifications to eliminate some variables. As a result of this complexity nearly all the work reviewed uses computational methods rather than providing simple equations. A good overview of the development of stress analysis in lap joints is described by Adams [8].

The single lap geometry was investigated initially to assess its usefulness as a technique. This was chosen as it provides a greater academic challenge compared with double lap designs due to the element of bending inherent with single lap configurations.

While there is plenty of work available that focuses on symmetric joints there are very few that adherend materials and thicknesses. In fact only 2 sources could be found, Her [9] & Tsai et al [10], that give approximate equations to describe the shear stress distribution in the adhesive layer.

However, these two methods ignore the eccentricity-induced bending which is perhaps a simplification too far. Yet, there are some more complete works which can be implemented using a spreadsheet. One such example is the analysis carried out by Bigwood and Crocombe [7] which gives the shear and peel stresses in the adhesive. A drawback of this method is that

the loading conditions at the ends of the overlap region are required, which requires the adherend deflection and rotation to be quantified.

A comparison of these 3 models with the numerical results is shown in Section 5 in Figure 9.

5. Numerical Analysis

In order to model the adhesives accurately it was important to determine the effect of both strain magnitude and strain rate on the shear modulus of the material. So preliminary experiments were performed using adhesive dumbbells in order to independently determine the visco-elastic and elasto-plastic properties of the adhesive. The dumbbells were cured in silicone rubber moulds and conformed to BS EN ISO 527:1996 [11][12].

The numerical modelling was carried out using LUSAS v14.3, in which Equation 1 is used to describe the visco-elastic adhesive.

$$G(t) = G_v e^{-\beta t} \quad (1)$$

Where G_v = visco-elastic shear modulus and β = decay constant.

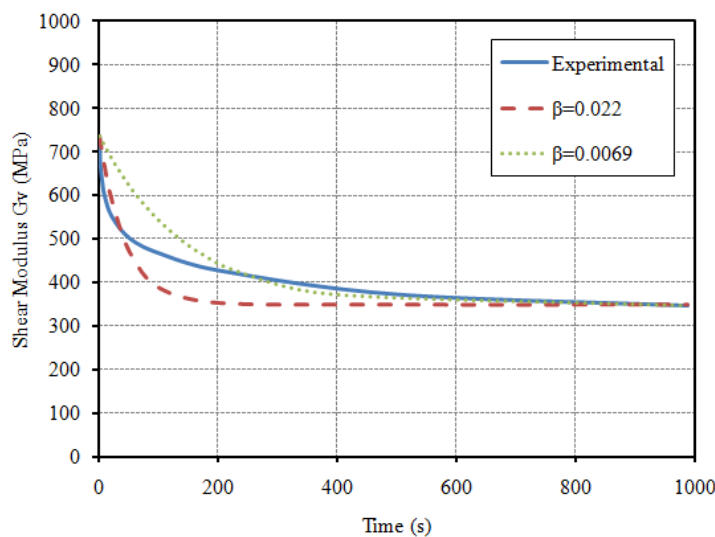


Figure 6 - Visco-Elastic Parameters

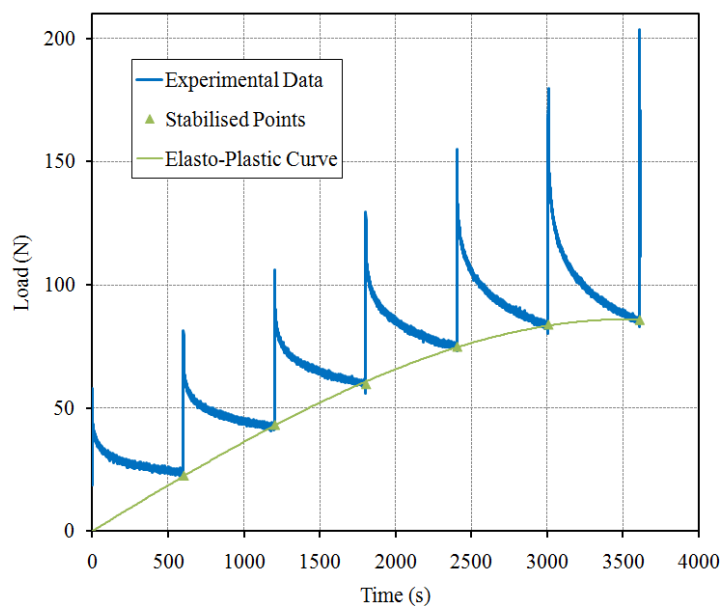


Figure 7 - Elasto-Plastic Adhesive Testing

To determine the visco-elastic characteristics, G_v and β , of the adhesive a rapid uniform extension was applied to the specimen, then the stress decay was recorded. To calculate the decay constant two different methods were used – minimising the sum of square differences between experimental and calculated values for shear modulus or time. Both methods are plotted against the dumbbell results in Figure 6 and are expected to define the theoretical upper and lower limits.

To determine the elasto-plastic behaviour of the adhesive the samples were loaded in steps and the load was held constant until 98% of the decay was complete – to speed up the testing (see Figure 7). This was repeated until the dumbbell had failed and the stabilised points represent the elasto-plastic nature of the adhesive. These points were converted into stress and strain and a curve was fitted to them, which was entered into LUSAS as the elasto-plastic constitutive model for the adhesive.

The system was then modelled in LUSAS v14.3. The outcome was compared with the experimental results and is shown in Figure 8. Further details on the numerical modelling are available in [13].

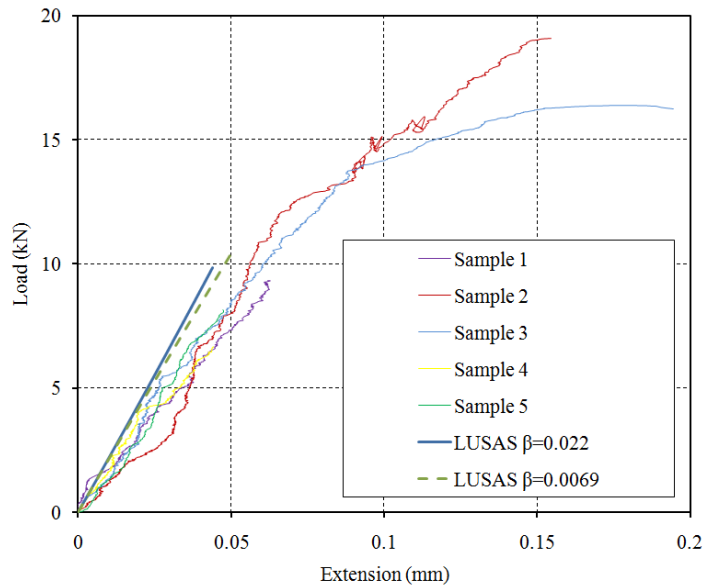


Figure 8 - Numerical and Experimental Results

This unfortunately means that they do not pick up the peak stress and hence are not useful as design tools where brittle failure occurs (they probably are adequate for ductile failures).

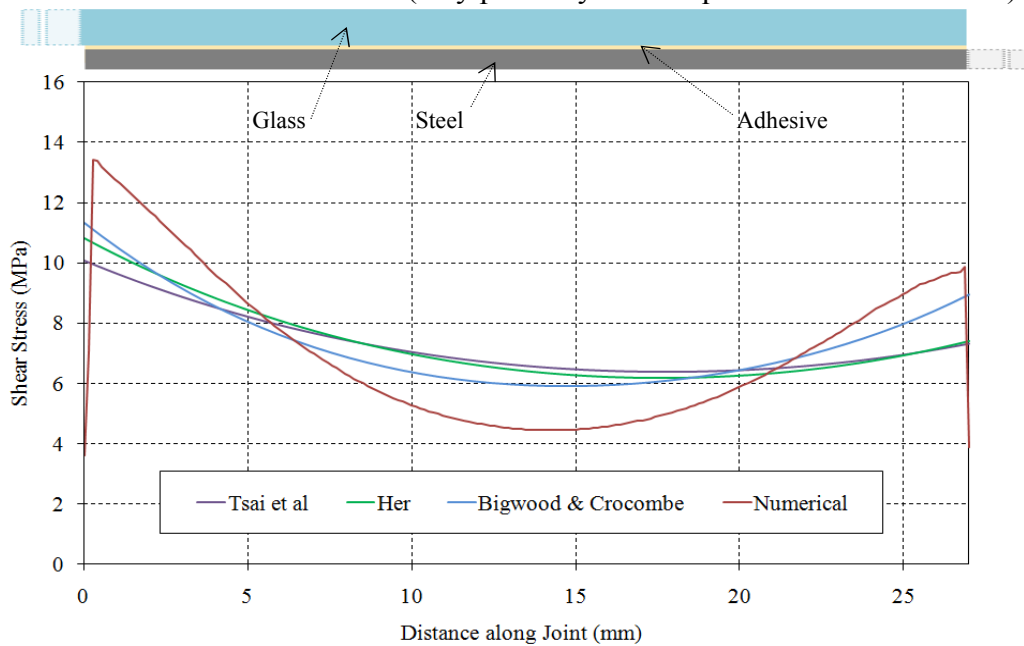


Figure 9 - Comparison of Analytical and Numerical Predicted Shear Stresses across Joint

However, they are still useful as a check for numerical models. The numerical model also confirms that the loads applied are of the right order to cause glass failure; it predicts a maximum principal stress of 92.6MPa near the joint at a load of 9.82kN. Another shortcoming in the analytical models is they do not predict the maximum principal stress only the shear or peel stresses, which are a well below the maximum principal stress.

6. Conclusions and Future Work

While there are benefits of UV-curing adhesives (high stiffness, strength and transparency) at the moment the long-term behaviour of these adhesives must be improved if they are to be seriously considered for structural purposes. Another consideration is that while high stiffness is necessary, care must be taken during the design process to check that the dangerous stress peaks do not cause premature failure of the glass elements. Furthermore, apparent high strength in short-term is not necessarily an indication of long-term performance and the

While the fit of stiffness between the numerical and experimental results is promising the analysis did not complete due to a lack of convergence and so plastic failure was not accurately predicted.

A comparison of the stresses predicted along the joint at mid height by the analytical and numerical models at a load of 9.82kN is also shown in Figure 9. While the analytical methods do give a reasonable estimate of the stress distribution along the joint, there are some shortcomings. The stress peaks at the edges of the joint are underestimated by these analytical methods, probably because of the stress boundary condition for the edges of the joint.

failure mode must be considered as this provides important information on long-term performance. In addition, the use of a normal distribution for determining a characteristic load merits further scrutiny. The long-term resistance tests for steel-glass samples have not yet been completed.

At the moment analytical techniques are not sufficient to complete adhesive joint designs in glass, as they underestimate the stress concentrations and numerical models are still required. However, to construct accurate numerical and analytical models the bulk material properties must be determined; which is a non-trivial task.

7. Acknowledgments

We would like to thank Prof. Crocombe for his help and input into the joint analysis. We would also like to thank Hourglass Ltd. for the free supply of the glass samples, DELO for the free supply of their adhesives and EPSRC and Hourglass Ltd. for their financial support.

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