Technical Abstract

Glass is one of the most prolific materials in contemporary construction, used in the outer façade of many buildings. It is also a material that is easily damaged due to its brittle nature, with a strength that is a function of the properties of surface and edge flaws. When glass is damaged it loses strength and is visually spoilt, so is often replaced. However, repairs could form a cheaper and reliable alternative to replacement, which is done at great cost in both monetary and energy terms.

This investigation focuses on the quantification of strength increase due to repair and the durability of repairs in a harsh water environment, both areas in which there is little academic knowledge. The aim was to provide confidence in repair performance, giving scientific backing to industry practices.

Glass can be damaged in many different ways, causing different flaw geometries. Three different types of initial flaw have been investigated to test the repair process on different geometries. The chosen flaws were indentations, made using a Vicker's Indentation Machine; naturally weathered glass, which had been exposed to the external environment for 20 years, and scratches, applied using a specially manufactured scratching device.

The repairs themselves were carried out using two types of resin, an epoxy and an acrylic using a repair process that has been derived from the industry standard repair method. Each flaw and resin combination has been tested with a batch of 16 identical samples from which a mean strength was found. There was a need for the application of the initial flaws to be a repeatable process to obtain near identical flaws so a reliable average strength could be measured.

To investigate durability, for each flaw and resin combination there were two batches of repaired specimens, with one batch being placed in laboratory conditions for a week and one batch being stored in a pool of water for a week. The strengths of the two batches were compared to assess the impact of the water environment.

The results of the investigation showed that repairs with resin do not cause a significant increase in strength, but the results suggest a slight increase in strength in all flaw types. The mechanism for strength increase was hypothesised to be bridging of resin over the flaw. The repairs improve the glass visually, with the flaw becoming almost invisible post repair. The acrylic resin returned a slightly higher strength increase than the epoxy resin, and this was determined to be because the acrylic penetrated further into the flaw, due to its lower contact angle.

The results suggested water had a detrimental effect on the strength of the flawed glass, whether or not the flaw had been repaired. It seems odd that the resin did not seem to prevent this strength reduction; one would expect it to inhibit the waters ingress into the flaw. However, the results were not statistically significant and the spread of strengths within each batch may have caused the mean measured values to be slightly erroneous.

The large spread of strengths within each batch across the entire test series, but especially in naturally weathered glass, have made significant conclusions hard to draw. However constant trends over all the batches enabled sensible evaluations and deductions to be made. Fractographic analysis was also used extensively in aiding and providing evidence for conclusions.

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1. Introduction

Glass is the material of the moment in the Structural Engineering world. It is used ever more widely in construction and in the automotive industry, with developments in Engineering technology enabling glass to be used as a load bearing component. Even as further developments increase the strength and durability of glass, its inherent brittle nature persists. Mechanical surface flaws cause this brittleness [1] and as such when glass becomes damaged, significant flaws are produced which become initiation points for crack growth, providing an origin for catastrophic failure.

At present, when glass is damaged in the construction industry components are often replaced rather than repaired to ensure the safety of the structure. There is no precise knowledge of the quantification of strength increase due to a repair or the durability of glass repair. These are the areas in which this project aims to provide insight.

There are two main repair techniques used in industry: repair using resins, and repair through polishing. There is little research of polishing as a technique to strengthen glass, however the aim of polishing glass is to decrease the size of the flaw and effectively eliminate the flaw entirely, by removing the material layer containing the flaw. However it can be argued that by making the glass thinner the strength will decrease, so there may be a delicate balance between removing glass material and removing the flaw.

There have been a number of research papers written on the area of strengthening glass using resins. Among the different types of resins used, Epoxy Resins and Sol Gels are discussed most widely and in all academic papers an increase in strength has been observed when a filler resin has been used. El-Sayed and Hand [2] found that the strength increase from an indented state to a repaired state using Epoxy was from 30.4±1.8MPa to 108±10MPa. With the glass having an initial as received strength of 123±13MPa. This equates to increasing the strength of the glass from 25% of the as received strength to 89%. However, because the test was done using a four-point bend test, edge effects could have played a part, meaning the failure could have originated at the edge of the specimen, with the strength of the flaw in the centre not being tested. It would be preferable to use a ring on ring bend test where edge effects are not encountered as has been done in this investigation; this is discussed later.

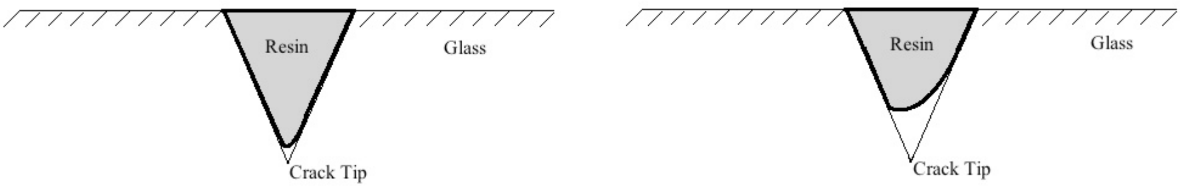


Figure 1: Simplified images of differing resin penetration into a flaw

There have been suggestions on what causes the increase in strength in the repaired glass but there has been no evidence to shown one model is better than another. One suggestion is flaw penetration [2], whereby the further the resin penetrates into the crack the higher the increase in strength due to the larger surface area contact with the glass. This is shown in Figure 1, where the left hand flaw would theoretically have a higher increase in strength compared to the right hand flaw. It is suggested the depth of resin penetration into the flaw can be linked to the resin contact angle made with the glass surface, with suggestions that the lower the contact angle the less viscous the resin and the further it will penetrate. Another suggestion on the cause of strength increase is that the prevention of moisture reaching the crack tip [3], whereby moisture acts to reduce the failure strength of glass. A final suggestion is that closure stresses in the flaw are generated by a thermal expansion mismatch of the coating [4], and this can account for the observed strengthening.

The glass repair industry itself consists of a few small firms that offer a choice of repair services. The services they offer are mainly polishing and resin repair but the systems and technologies they use, whilst achieving visual results, claims of performance are not backed up by published scientific research.

2. Design of Experiment & Theory

2.1. Opportunities

There has been a lack of research on the comparison between repairs on different types of flaw. Flaws in glass can be categorised, as has been done in BSAU251: 1994 [5]. In this British Standard document flaws are separated into six types of chips and cracks. As such, there is a need to compare strengthening between different flaw types.

Another area that has thus far received little attention in academic studies is the comparison of different repair techniques, such as resin repair and polishing repair. Polishing was initially to form part of the investigation but unfortunately it was not possible. It is a repair technique requiring specialist equipment and involvement was sought from Chicago Glass, one of the largest glass repair companies in the UK to assist in providing polishing capabilities. During the course of the project it became apparent that it would not be possible due to the industry's reluctance to assist in providing specialist capabilities. Therefore the decision was taken to investigate repairs using resin only.

Three different types of flaw were investigated, repaired with two different resins and the effect on the strength of the glass was observed. Different types of initial flaw were investigated as the initial flaw is thought to have a significant impact of the scope of the repair. Testing multiple flaw types will highlight the differing repair needs for different types and levels of severity of the initial flaw. Furthermore, it was intended to contact glass repair companies such as Autoglass and request their assistance in the tests using resin. They would have used industry standard equipment to carry out some repairs and strength tests would then have been performed in the laboratory. However, attempts to gain industry insight again proved fruitless.

Durability is another aspect of repair that has had little research done. This investigation observes the ability of repairs to withstand storage in an adverse, humid environment, and as such the effect of moisture on the repair can be determined.

2.2. Objectives

The aim of the experimental testing was to quantify the strength increase in glass due to repair. The durability of repair techniques was also assessed through measuring the change in strength after specimens have been repaired and stored for a period of time in a harsh environment. It was aimed to test different types of flaws and repair techniques and hoped the project as a whole will instil confidence in different repair processes, enabling glass repair to become a viable option in dealing with damaged glass.

2.3. Experimental Description

There are three main parts of the experimental process, which have been designed to test the strength of repaired glass.

- Create initial flaw to be repaired. Three initial flaws that have been tested are:
    - Indentations created using the Vickers Hardness Indentation Machine.
    - Glass with a surface that has been naturally weathered for 20 years.
    - Scratches created with a glass-scratching tool.
- Repair the initial flaw using resin one week after the initial flaw has been created.
- Strength-test to failure one week after the repair.

All of the glass used in the investigation was annealed glass, which is standard float glass and has not been tempered or hardened. Annealed glass was chosen as a testing material as it is the most basic form of glass with some small residual stresses in the surface in the order of 4-10 MPa, (much smaller than the residual stresses in thermally treated glass). The simplicity of the glass composition means more effective comparisons can be drawn between sample batches: Annealed glass is the weakest form of glass so when repaired, the repair will give a larger percentage increase in the strength making the effects more obvious.

A time of one week was set for the samples to sit before they were repaired to allow for slow crack growth to take place after the initial flaw has been created. A similar time of one week was allowed after the repair until testing to allow for the repair to set properly and the effect of the environment in which the sample is placed to take effect.

A total of 304 samples have been prepared with initial flaws, repaired, and strength tested.

The 304 samples were split into 19 batches of 16 specimens, as described in Table 1 and Figure 3. There are a large number of specimens, which is necessary in order for a reliable average failure stress to be determined. Of the 19 batches one batch was undamaged and used as a control; six were indented; six were naturally weathered; and six were scratched. Of each of the six batches in each category, two were unrepaired; two were repaired using resin A, an acrylic; and two were repaired using resin B, an epoxy resin. Then one batch in each of these pairs of batches was stored in water for a week prior to strength testing.

Resin A is manufactured by GT Glass [6] and is stated as being an acid free, acrylic resin, specifically made for windscreen repair and is quoted to have passed BSAU251 [5] which is a British Standards Document setting standards of performance for windscreen repairs.
Resin B is an epoxy resin called HXTAL NYL-1.

Contact angle measurements of the two resins have been made to determine the wettability (ability of the resin to maintain contact with the glass) of the glass with each resin to determine any correlation with an increase in strength. A low contact angle between the glass and resin enables the resin to create a larger surface contact with the glass, and it is thought the resin with a low contact angle will be more likely to penetrate any flaws or cracks, shown in Figure 1. The definition of the contact angle ϕ is shown in Figure 2.

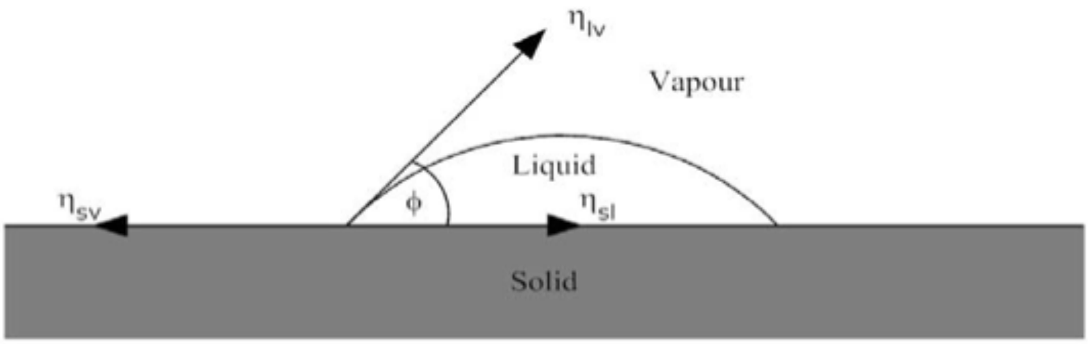


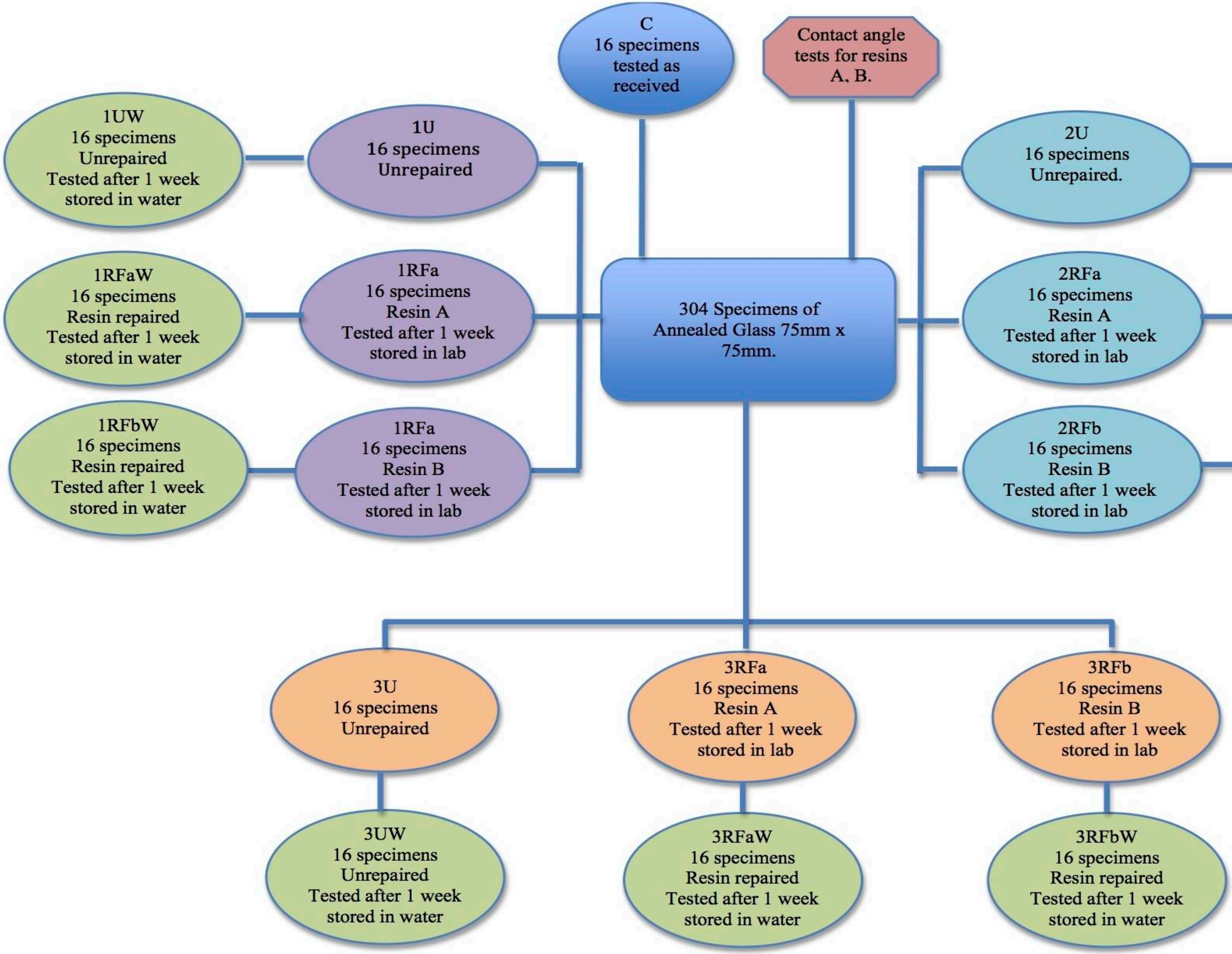
Figure 2:Schematic showing contact angle [7]

2.3.1. Testing Map

For clarity a testing map has been produced and is shown in Figure 3 to depict the testing procedure. The abbreviations given to each batch of tests, which were written on the specimens to identify them are defined in Table 1.

Series Abbreviation		Definition
C		Control. Specimens were strength tested in their undamaged, as-received state.
Series 1 – Indented	1U	Specimens were indented and strength tested in their un-repaired state.
	1UW	As 1U but stored in water for 1 week prior to testing.
	1RFa	Specimens were indented and repaired with resin A, before strength testing.
	1RFaW	As 1RFa but stored in water for a week prior to testing.
	1RFb	Specimens were indented and repaired with resin B, before strength testing.
	1RFbW	As 1RFB but stored in water for a week prior to testing.
Series 2 – Naturally Weathered	2U	Nat. weathered specimens were strength tested in their un-repaired state.
	2UW	As 2U but stored in water for 1 week prior to testing.
	2RFa	Specimens were repaired with resin A, before strength testing.
	2RFaW	As 2RFa but stored in water for a week prior to testing.
	2RFb	Specimens were repaired with resin B, before strength testing.
	2RFbW	As 2RFB but stored in water for a week prior to testing.
Series 3 - Scratched	3U	Scratched specimens were strength tested in their un-repaired state.
	3UW	As 3U but stored in water for 1 week prior to testing.
	3RFa	Specimens were scratched and repaired with resin A, before strength testing.
	3RFaW	As 3RFa but stored in water for a week prior to testing.
	3RFb	Specimens were scratched and repaired with resin B, before strength testing.
	3RFbW	As 3RFB but stored in water for a week prior to testing.

Table 1: Abbreviation Definitions



Prefixes:
1 = Series 1: Indented glass. (Vicker's Hardness Indentation Machine)
2= Series 2: Naturally weathered glass.
3 = Series 3: Scratched glass

Suffixes:
C: Control
U: Unrepaired
RF: Repaired, Filler
RFW: Repaired, Filler, Water
A/B: Acrylic and Epoxy resins

Figure 3: Test map

2.3.2. Test Comparisons

The multiple tests that have been undertaken mean there have been many comparisons between test results. The comparisons that have been undertaken are detailed in Table 1. Further to these comparisons, there have been comparisons of strength increase made between different series to judge how repairs on different flaws compare to each other, and to establish whether a particular repair technique lends itself to a particular flaw type.

	Test comparison		Outcome of comparisons	Further comparisons
Indented Glass	C	1U	Decrease in failure strength due to flaw	-
	C	1RFa	Effectiveness of repair of two different resins	Compare two results to show which resin performs best repair
	C	1RFb		
	1RFa	1U	Strength increases due to repair using 2 different resins	Compare to see which resin offers highest strength increase
	1RFb	1U		
	1RFa	1RFaW	Significance of environment on durability of repair	-
	1U	1UW	Significance of environment on durability of flaw alone	-
Naturally Weathered Glass	C	2U	Decrease in failure strength due to flaw	-
	C	2RFa	Effectiveness of repair of two different resins	Compare two results to show which resin performs best repair
	C	2RFb		
	2RFa	2U	Strength increases due to repair using 2 different resins	Compare to see which resin offers highest strength increase
	2RFb	2U		
	2RFa	2RFaW	Significance of environment on durability of repair	-
	2U	2UW	Significance of environment on durability of flaw alone	-
Scratched Glass	C	3U	Decrease in failure strength due to flaw	-
	C	3RFa	Effectiveness of repair of two different resins	Compare two results to show which resin performs best repair
	C	3RFb		
	3RFa	3U	Strength increases due to repair using 2 different resins	Compare to see which resin offers highest strength increase
	3RFb	3U		
	3RFa	3RFaW	Significance of environment on durability of repair	-
	3U	3UW	Significance of environment on durability of flaw alone	-

Table 2: Test Comparisons

2.4. Theory

2.4.1. Determining the Failure Stress

For Ring-on Ring load testing, the failure stress can be calculated via finite elements but in this investigation the failure stress in the sample has been calculated. The ASTM International Standards [8] for ring on ring testing give the failure stress to be:

$$\sigma_f = \frac{3F}{2\pi h^2}\left[(1-\nu)\frac{D_s^2 - D_l^2}{2D^2} + (1+\nu)\ln\left(\frac{D_s}{D_L}\right)\right] \tag{1}$$

where:

F = Failure Load in N

h = Glass specimen thickness

D_s = Support ring diameter

D_L = Load ring diameter

v = Poisson's ratio

For a square, D is the diameter of a circle that expresses the characteristic size of the plate:

$$D = \frac{L}{0.90961 + 0.12652\dfrac{h}{D_S} + 0.00168 ln\left(\dfrac{l - D_S}{h}\right)} \tag{2}$$

Where L is the side length of the square specimen.

2.4.2. Equivalent Failure Stress

All glass specimens have been tested at a constant stress rate to failure, therefore failure occurred after slightly differing loading times within batches. As the strength of glass is a function of the stress history, the failure stresses should be converted to a time invariant equivalent stress. This ensures comparisons between failure stresses are 'like for like' and ensures mean strengths of samples are reliable. The equivalent stress applied for a period of time will have the same effect as the actual stress applied over the actual time to failure in the test. 30 seconds has been chosen as an appropriate time t_e to calculate the equivalent stress:

$$\int_0^{t_e} \sigma_e^n(t)dt = \int_0^{t_f} \sigma^n(t)dt \tag{3}$$

where n ≈16 [1]

σ_e = 30 second equivalent stress

σ = stress in test

t_f = the time to failure

By writing $\sigma = \frac{\sigma_f}{t_f} t$ the equivalent stress can be found to be:

$$\sigma_e = \sigma_f \left[\frac{t_f}{t_e(n+1)} \right]^{1/n} \tag{4}$$

The equivalent stress has been used in all calculations and comparisons in the investigation.

2.4.3. Linear Elastic Fracture Mechanics

Irwin [9] postulated that fracture occurs when the stress intensity factor, K is equal to a material specific value, K_{IC} called the fracture toughness. Irwin's expression for the stress intensity factor is:

$$K = Y\sigma\sqrt{\pi a}. \tag{5}$$

where $K = K_{IC}$ at failure.

For soda-lime-silica glass $K_{IC} \approx 0.75$MPa $m^{1/2}$

Y = geometry factor

σ = tensile stress normal to the crack

a = Crack depth

The geometry factor, Y, is hard to find but for a straight front plane edge crack, Y=1.12 which may be appropriate for the scratched specimens. However, all flaws in glass are unique so the geometry factor will be unique for every flaw, meaning the use of Irwin's relationship can be questioned when dealing with glass.

2.4.4. Sub-critical Crack Growth and Inert Testing

Sub-critical crack growth is the mechanism by which a material can fail below the true failure strength when loaded for a period of time, enabling the flaw to grow until critical flaw size has been obtained, at which point fast fracture occurs. The loading environment can have a significant effect on sub-critical crack growth.

To negate the effects of sub-critical crack growth a number of methods of testing may be adopted [10]:

- Testing in a vacuum
- Testing in a dry environment
- Testing at a rapid stress rate
- Testing at a very low temperature

To achieve the true full failure strength, the chosen method in this case was to perform the tests in an inert environment using an atmosphere of dry nitrogen, which as well as being un-reactive is very cheap. The dry nitrogen atmosphere also creates an atmosphere without humidity, which is another contributor to sub-critical cracking. This is also useful to test the validity of the strength hypothesis mentioned in Section 1: The prevention of moisture reaching the crack tip [3]. The apparatus used to create the inert atmosphere can be seen in Section 3.9.

2.4.5. Effects of Humidity

A humid environment can cause a crack to grow sub-critically. Wiederhorn [11] showed that crack velocity (as a function of stress intensity) was related to the quantity of water present. He showed that the crack growth curve could be divided in to three regions. Region I represents the crack growth governed by the reaction between glass and water in the environment. Region II is governed by the rate of transport of water to the crack tip; in region III, the crack growth is independent of water. These regions can be translated into regions on a Failure Stress versus Humidity plot and the general relationship of failure strength due to subcritical crack growth in a humid environment can be seen in Figure 4. Note that the x-axis can be interchanged with time to show general sub-critical crack growth.

As discussed in Section 2.4.4 the strength tests carried out were perfromed in an inert atmosphere without humidity, meaning tests were carried out in region III, in order to test the true failure stress of the glass.

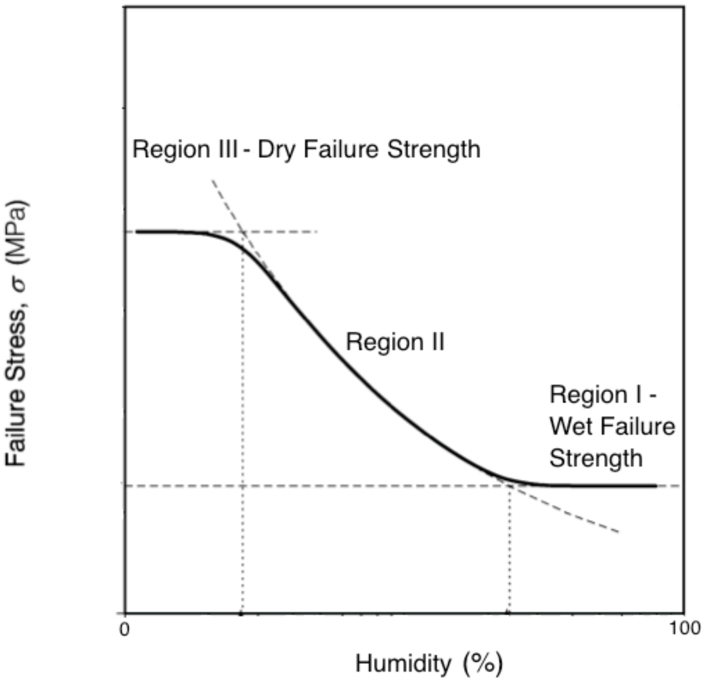


Figure 4: General shape of relationship between failure stress and humidity [12]

2.4.6. Residual Stresses

Annealed glass was used for all of the glass specimens in this investigation. Although annealed glass is designed to have no residual stress, there may still be some leftover residual stresses within the glass as a by-product of the manufacture process. To reduce these small residual stresses the specimens could be further annealed in a furnace. However readings of the residual stress using a Scattered Light Polariscope (SCALP) showed they were in the order of 4MPa and would not be significant in altering the failure stress in testing. Therefore surface residual stresses were assumed to be negligible in this investigation and no extra annealing is needed.

3. Apparatus and Experimental Techniques

3.1. Sample Preparation

All the samples were handled carefully to avoid inadvertently scratching them and creating further flaws other than those intended. Float glass is manufactured by pouring molten glass onto molten tin, on which the glass floats, hence the name. Some tin atoms diffuse into the tin side of the glass and that side of the glass is slightly mechanically weaker than the non-tin side [1]. This is not due to the presence of tin atoms but due to the small flaws induced by rollers (which pull the glass along the production line) on that side. The tin side is the side that was tested in this investigation, primarily to ensure consistency in the experimental work. Testing the weaker side ensures the failure strength measured is representative of the first failure that could occur in practice. To determine the tin side, a UV light was shone on the glass surface; the tin side responds to this by reflecting with a white fluorescence as shown in and Figure 5 and not in Figure 6. It was very hard to determine the tin side for naturally weathered glass due to the dull surface. However every effort was made to determine it, wherever possible.

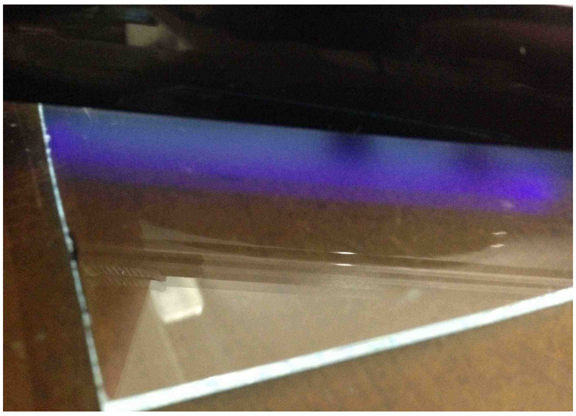


Figure 5: Tin side showing white fluorescence

Figure 6: Non tin side

All of the glass was cleaned using glass cleaner prior to testing to remove dust or any particles, which may have had a bearing on the failure strength.

A clear plastic adhesive film was applied to compression side of specimens during strength testing to keep the pieces of glass together after testing, enabling visual analysis of the fracture to be undertaken. Further, in keeping the glass fragments together, it means the glass is much safer to handle. The adhesive was placed on the compression side only, so that its presence has no bearing on failure stress, as failure is caused by fast fracture on the tension side.

The thickness of the glass was measured using a micrometer at 2 points diagonally opposite (points furthest apart) on each glass specimen and the thickness was recorded. Where the two thicknesses were different an average thickness was taken.

3.2. Vicker’s Indentations

The first initial flaw that was investigated was an indentation made using a Vicker’s Hardness Indentation Machine, which simulated the repair of a chip.

The machine uses a diamond square shaped pyramid indenter, which was loaded with 30kg. This was found to produce a suitable and repeatable indentation size that could be repaired using resin. Examples of the indentations produced can be seen in Figure 7 and Figure 8.

The indentation machine was first tested to investigate whether the machine could produce near identical flaws between samples so returning a repeatable flaw and thus similar failure strength in each sample enabling a reliable average to be found. After this had been verified, the actual samples were indented.

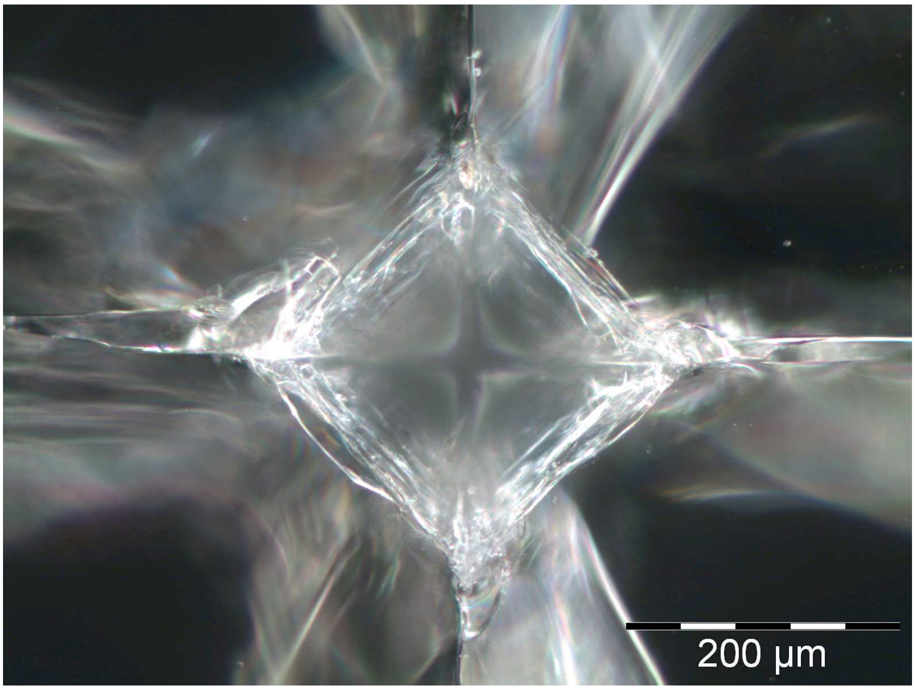


Figure 7: Magnification of an indentation made using Vicker’s Indentation Machine.

Figure 7 is the same indent as shown in Figure 8, however Figure 7 was taken using a dark field setting on the microscope highlighting aspects on the flaw not visible in Figure 8.

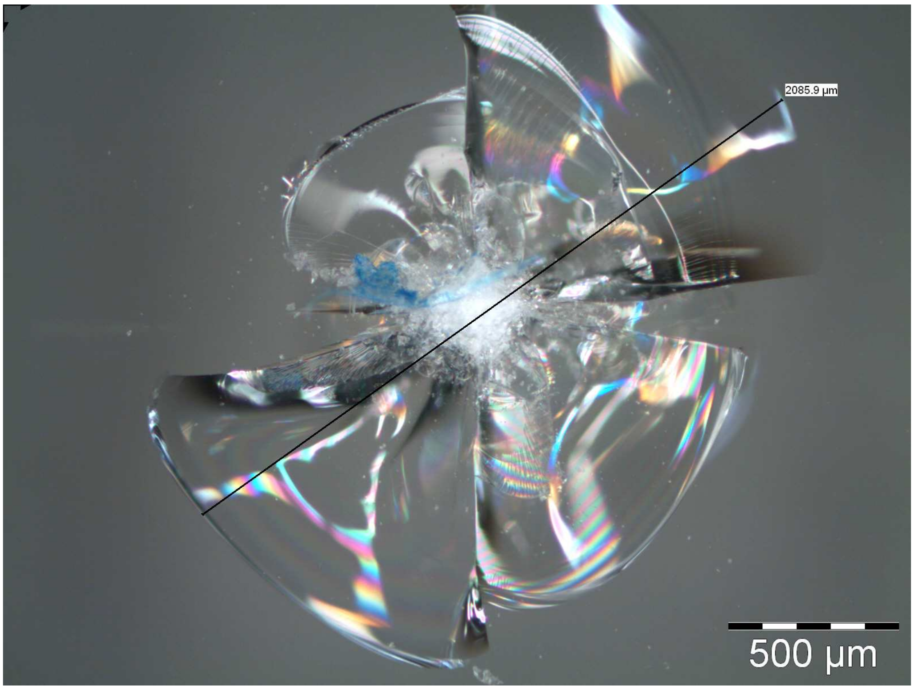


Figure 8: Magnification of indentation showing full extent of outer crack.

3.3. Naturally Weathered Glass

Naturally weathered glass was the second initial flaw type tested. The glass is 20 years old and has been open to the outside environment and undergone some biological degradation. The surface is dull to the naked eye and when magnified, the surface is pitted and scratched as can be seen in Figure 9.

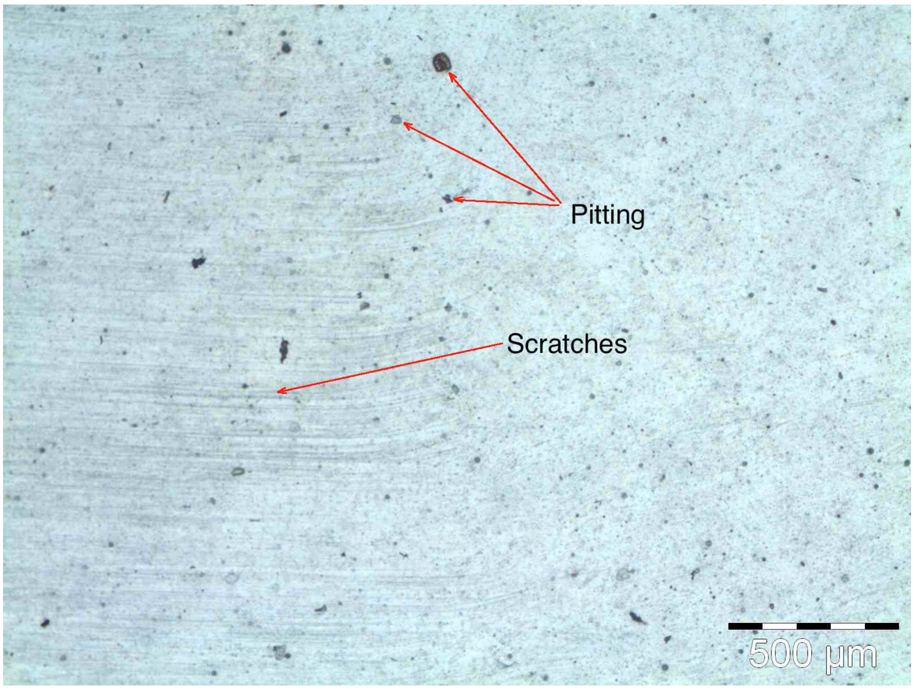


Figure 9: Surface of Naturally weathered glass

3.4. Scratching Device

The third group of flaws tested were scratches, a common type of flaw often caused by vandals. For the purposes of the investigation it was a necessity to produce a repeatable scratch to enable comparisons between batches and retain similarity in the same batch. To create a repeatable scratch with the same length and depth using a hand held scriber would be almost impossible, so a scratching device has been manufactured to create the repeatable scratches necessary for the investigation.

The created device uses a vertical tungsten carbide scratching nib to scratch the surface. Tungsten Carbide is much harder than glass, with a Young's Modulus of 550GPa compared to 70GPa for glass. The nib is attached to a free sliding vertical stem, above which a platen allows mass to be added to the nib. Inside the stem a variable mass damper controls the bouncing motion of the nib across the surface. The device is shown in Figure 10 and Figure 11.

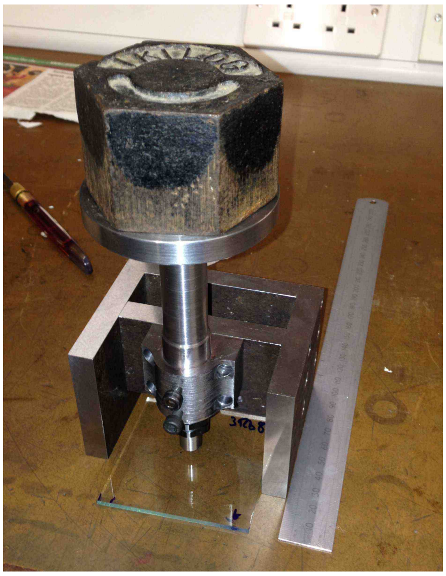


Figure 10: Glass scratching device

Figure 11: Tungsten carbide nib

Trial scratches were made with different masses added to the platen and the variable mass damper at different stiffness settings. The platen and stem alone have a mass of 0.4kg. The first trail comprised of an extra 2kg added to the platen and the resulting scratch can be seen in Figure 12. Figure 13 shows a scratch with an extra mass of 1kg and Figure 14 shows a scratch caused by the mass of the stem and platen alone. The 2.4kg scratch has many unpredictable secondary lateral flaws extending out from the main scratch as a result of the extra mass. The 0.4kg scratch was not visible with the naked eye suggesting it would be unrealistic and insignificant as a test of a real life scenario, although every scratch produced was very similar. The scratches produced by the 2.4kg mass were deemed too dissimilar to one another for comprehensive testing. The 1.4kg mass scratch was chosen as the configuration to use in the main investigation as a sensible trade off between the repeatability of the flaw and similarity to flaws, which would be repaired in reality.

The scratches were all straight with the same length of 8mm. The scratches were kept straight by resting the edge of the specimen against the device the length was measured by pushing the scratching device over the glass next to a ruler fixed to the desk. The configuration is shown in Figure 10.

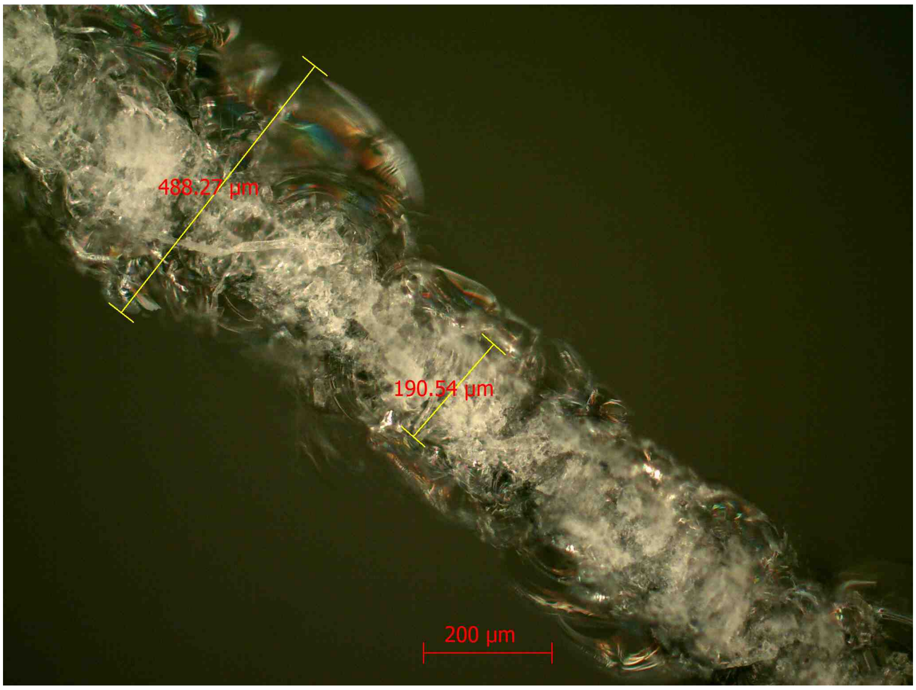


Figure 12: Resulting scratch from nib loaded with 2.4kg

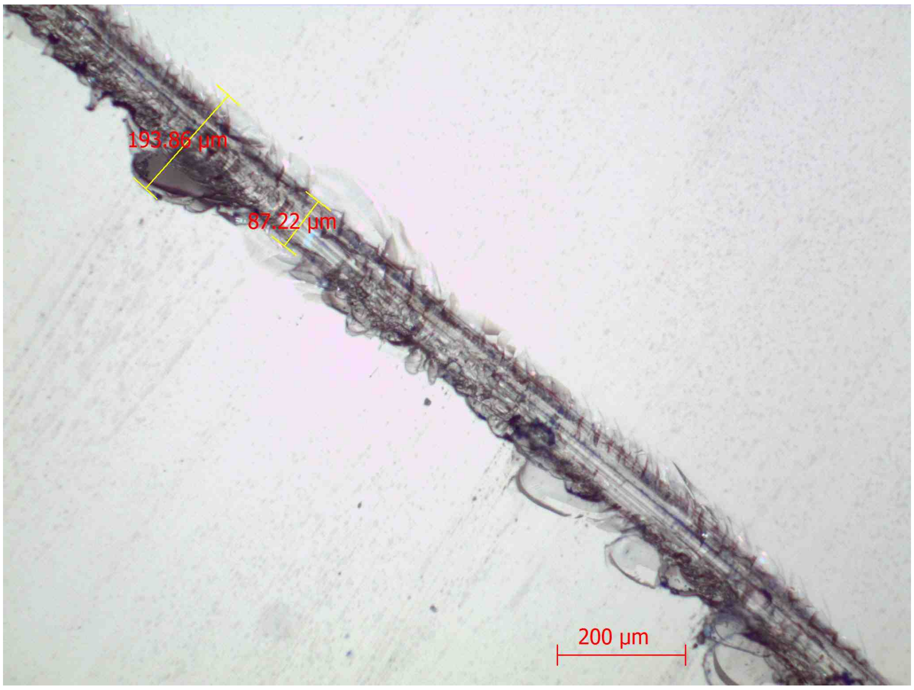


Figure 13: Resulting scratch from nib loaded with 1.4kg

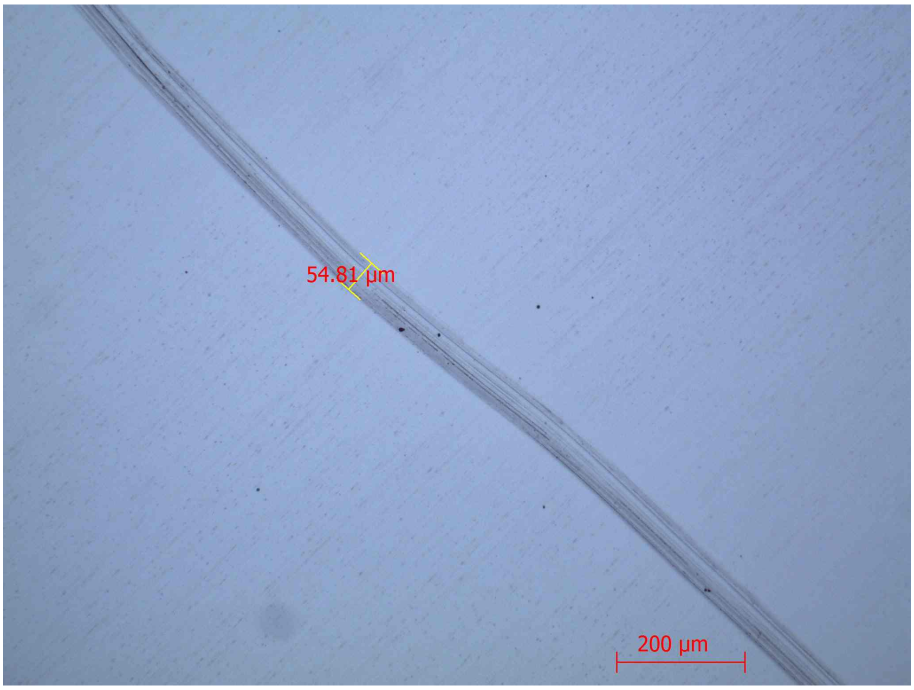


Figure 14: Resulting scratch from nib loaded with 0.4kg

3.5. Repair Technique

After the initial flaws had been applied to the glass specimens, and the specimens had sat for a week to allow for environmental effects, the specimens were repaired. The repair technique is critical to create a repair that is as strong and robust as possible. The technique was derived from researching how glass repair companies carry out their repairs. Chicago Glass use GlasWeld [13] systems for their repairs. The idea is to seal off the flaw, apply the resin, remove the air around the flaw, and insert the resin. Their repair equipment has been designed to specifically carry out this task. The repair process developed for this investigation has tried to mimic the industry standard repairs as far as possible. The developed repair process is as follows:

- The resin is applied to the flaw.
- A 1mm thick double-sided adhesive foam is applied around the flaw.
- A plastic covering and clamp is applied over the foam and pressure is applied. This creates a sealed chamber over the flaw with the only opening in the plastic covering.
- A syringe is inserted into the plastic covering and the plunger pulled upwards to create a vacuum over the resin and draw trapped air out of the resin. The syringe is held in this position for 2 minutes to allow enough for the air to be released.
- The syringe is removed to allow air into the chamber and then the syringe is reinserted and pressed down to force the resin into the flaw.
- The foam, covering and syringe are then removed and the resin placed under a UV light for 5 minutes.

The repair process is depicted from Figure 15 to Figure 19.

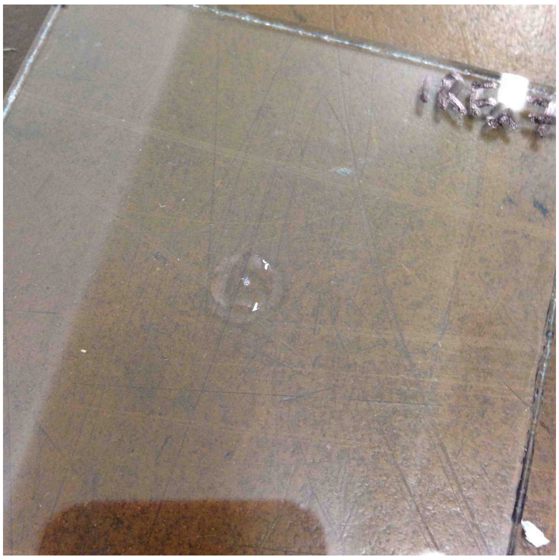


Figure 15: Resin is applied to the flaw.

Figure 16: Adhesive foam is applied around the flaw.

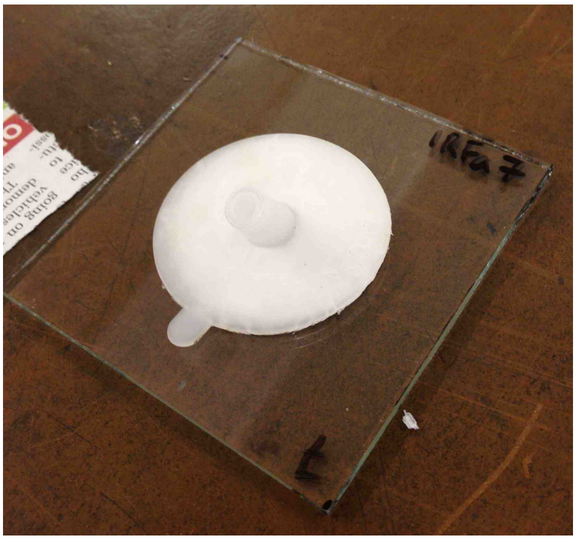


Figure 17: A plastic covering is applied over the foam.

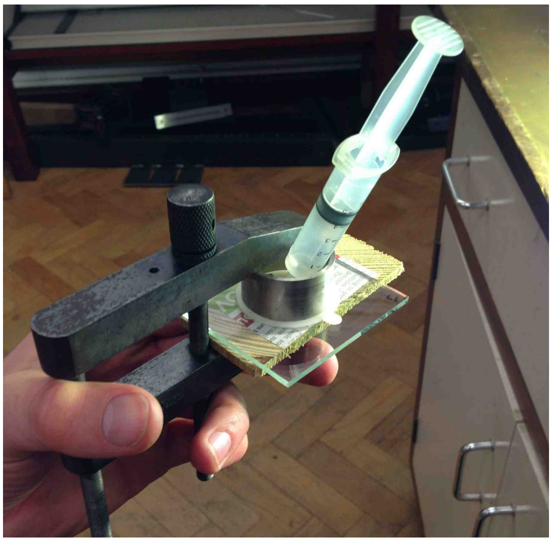


Figure 18: A clamp is applied over the plastic cover and a syringe is used to apply pressure to the resin in the flaw.

Figure 19: The covering is peeled off, leaving the resin in the flaw

3.6. Durability of Repair

To test the durability of the repairs, for each combination of flaw type and resin there were two batches of repairs. One of these batches was stored in water with a head of 50mm for a week prior to strength testing and the other was left in laboratory conditions for a week. The comparison of the two assessed the water's effect on the strength of the repair. The ability of the resin to prevent water reaching the crack tip is thought to be the critical factor in determining the durability. One of the two unrepaired batches for each flaw type was also left in a pool of water to observe the effect on the flaw without a repair. As discussed in Section 2.4.5 the humidity promotes crack tip advancement so one would expect the results of failure strength of samples stored underwater to have a lower strength.

3.7. Ring-on-Ring Testing

The strength tests have been undertaken using a co-axial ring-on-ring setup on a 2kN Instron Machine. The ASTM International Standards [8] dictate the specifications for loading setup and have been adhered to here. A schematic of the test setup is shown in Figure 20.

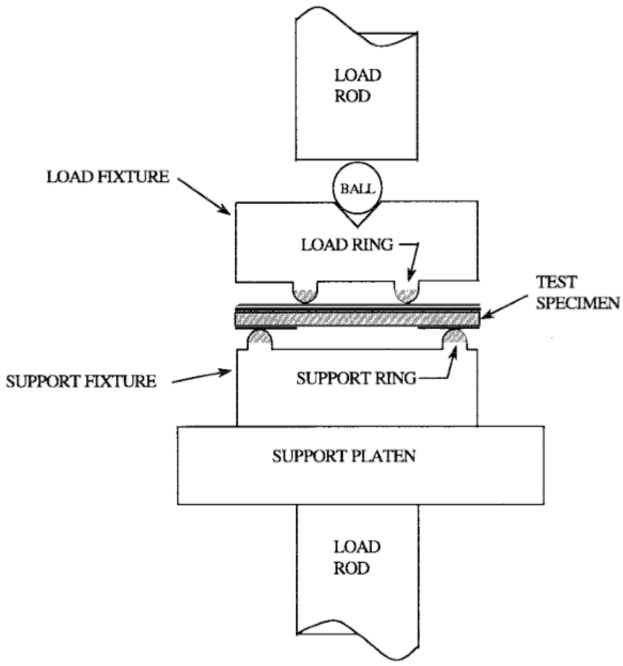


Figure 20: Schematic of ring on ring set up [8]

In the test the ring diameters were:

$D_{support} = 48\text{mm}$ $\qquad\qquad$ $D_{loading} = 15\text{mm}$

This adheres to the ASTM standards recommendation of $0.2 \le \frac{D_L}{D_S} \le 0.5$

The Standards also recommend these inequalities for plate and ring dimensions:

$$\frac{D_S}{10} \ge h \ge \sqrt{\frac{2\sigma_f D_S^2}{3E}} \qquad (6)$$

$$2 \le \frac{D - D_S}{h} \le 12 \qquad (7)$$

where $D = 0.54(l_1 + l_2)$ and l_1 and l_2 are the side lengths of the specimen.

The loading rate is recommended to be:

$$\dot{\delta} \cong \left(\frac{D_S{}^2}{6Eh}\right)\dot{\sigma} \qquad (8)$$

where, $\dot{\delta}$ is the displacement rate in mm/s

$\dot{\sigma}$ is the maximum value of nominal stress rate occurring in the specimen.

and $\left(\frac{\dot{\sigma}}{E}\right) = 10^{-4}/s$ which gives a minimum displacement rate of 0.0128mm/s. A rate of 0.05mm/s was used in the tests mainly for practical purposes so the tests did not take an excessive amount of time.

After the tests, the specimens were photographed and handled carefully.

3.8. Area of Repair

It is important to ensure the flaws and repairs were small enough to be contained within the central loading ring (15mm diameter). This was possible with the indented glass and scratched glass and for these cases a repair area of 10mm was chosen as seen in Figure 19. However, the naturally weathered glass has a surface covered in flaws. Ensuring the flaws were contained within the central ring for naturally weathered glass was clearly not possible. In this case the repair area was widened to a diameter of 20mm, and in this way it was ensured there was no part of the surface in the central ring area that was unrepaired. Fractographic analysis was used to ensure specimens were removed from the data if the failure origin was outside the central load ring, because in this case it is not the repaired flaw that has failed, but another area of glass.

3.9. Inert Testing Apparatus

The inert conditions discussed in Section 2.4.4 were created using a Perspex box. The lid was greased and able to able to slide up and down, attached to the loading ring. The box had a gas inlet and an exhaust on opposite sides to accommodate the nitrogen piping. The set up is shown in Figure 21 and Figure 22.

Figure 21: Inert testing set up

Figure 22: Nitrogen chamber

3.10. Instron Machine Data Collection

All of the tests were performed on an Instron Machine, which recorded the data via a data logger on a PC. An example of the data plot received from the Instron Machine is shown in Figure 23.

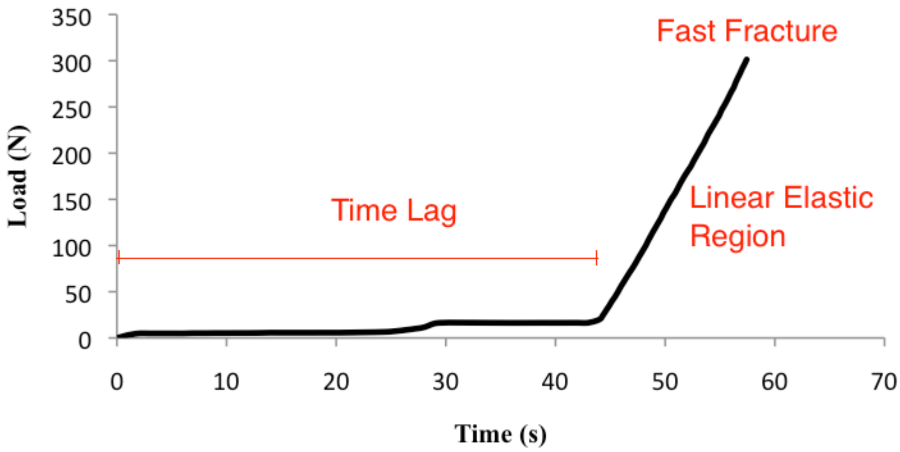


Figure 23: Example of plot received from Instron Machine

As the Instron machine starts a test, there is a significant lag between the machine initiating the test and the start of the elastic deformation of the sample. This lag is due to the time for the loading ring to reach the sample surface from its starting position and the time for the loading rig to compress together, taking the play out of the system. In analysing the data in this investigation, the lag time has been subtracted from the time of the test, so the time to reach brittle failure is only the time taken to reach failure in the elastic region.

All of the results have been depicted with Stress against Time; but as displacement was set to increase linearly with time on the Instron, the plots are equivalent to Stess-Displacement plots.

3.11. Fractographic Analysis

After failure, the specimen fragments were examined by eye and under an optical microscope. As discussed in Section 3.8, if a specimen's failure origin was outside the central loading ring, the specimen was removed from the data.

By examining the failed specimens with repairs it is possible to determine how far the resin has penetrated into the flaws, and determine the relationship with any strength increase.

By measuring the flaw depth of the scratched series, the expected failure strength can be calculated using Irwin's relationship as discussed in Section 2.4.3, however it is difficult to know what value Y factor to use and how relevant the relationship is. A straight front plane edge crack has Y=1.12; scratches are similar to this value so for scratched specimens it may be possible to compare the expected failure strength with the actual failure strength.

4. Results and Discussion

4.1. Repairs

If the quality and strength of a repair is dependent on the penetration into the flaw as suggested in Section 1, the penetration should be examined at a microscopic level. Figure 24, Figure 25 and Figure 26 depict the three flaws after having been repaired with resin. These figures provide evidence to validate the repair technique showing the flaws can be satisfactorily filled.

Figure 24: Resin shown penetrating into an indentation.

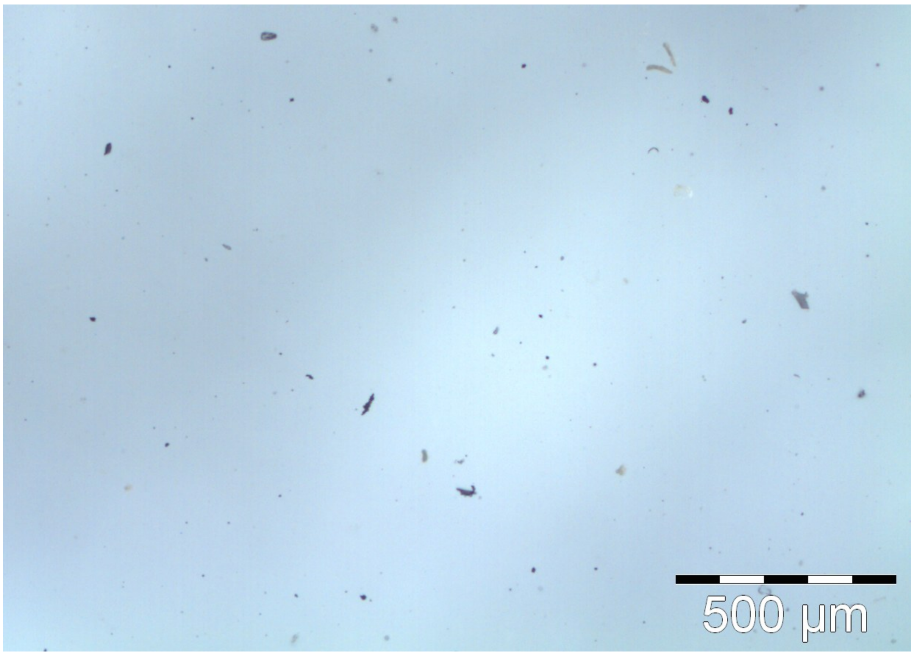


Figure 25: Resin on the naturally weathered surface – flaws are no longer seen.

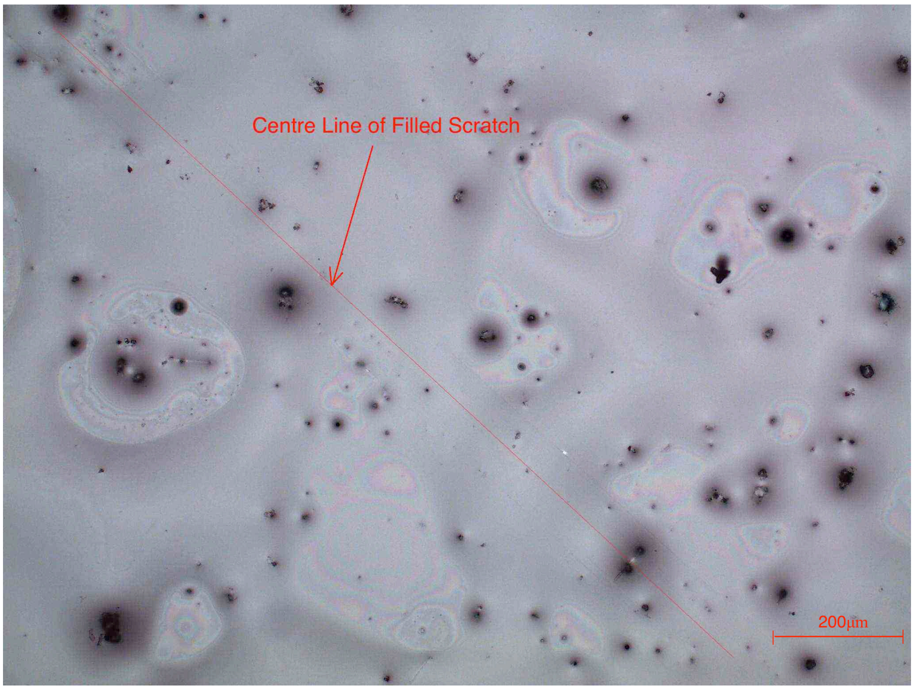


Figure 26: Resin shown penetrating into a scratch.

The flaws are barely visible showing that the resin has indeed penetrated into the flaws. The weathered glass shown in Figure 25 is the same specimen as shown in Figure 9. The black marks are dust and dirt, which have caught on the surface of the resin after having been stored in the lab for a week.

4.2. Control Series

The control series provides a benchmark to compare all other samples to. The plot in Figure 27 shows the failure points of the undamaged glass. Only the point of failure has been depicted for clarity (if all lines were shown, it would not be possible to see the failure points). All of the plots are linear with their origins at zero, as suggested by the layout of the failure points.

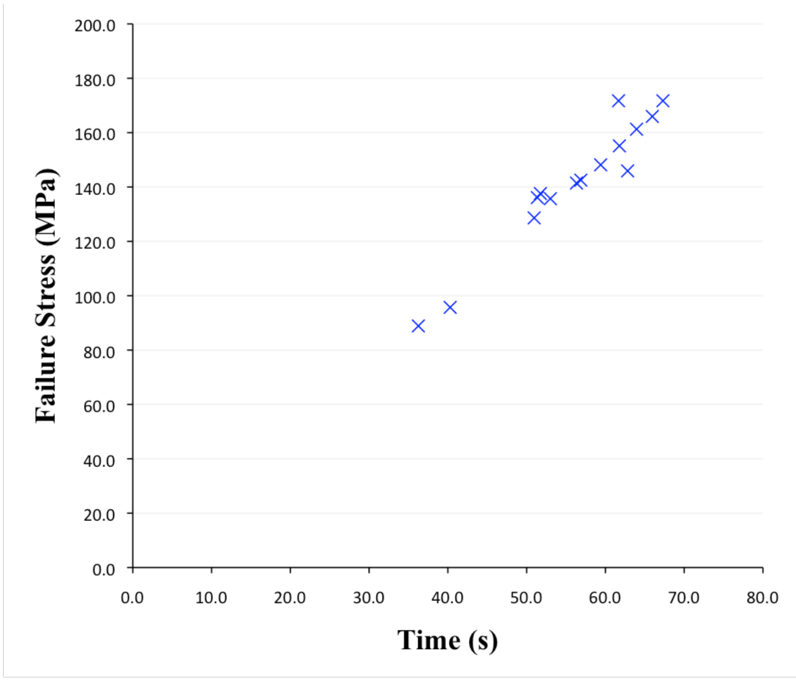


Figure 27: Undamaged glass failure strength points

Specimen	Time to Failure (s)	Displacement at Failure (mm)	Failure stress (MPa)	30 Second Equivalent Failure Stress (MPa)
C2	51.4	0.41	136.1	117.9
C3	61.7	0.53	171.7	150.5
C4	51.7	0.41	137.6	119.3
C5	53.0	0.44	135.7	117.8
C6	40.3	0.34	95.7	81.7
C7	67.3	0.54	171.7	151.3
C8	62.8	0.47	145.9	128.0
C9	36.3	0.32	88.9	75.3
C10	51.0	0.43	128.6	111.4
C11	61.8	0.51	155.1	136.0
C12	59.4	0.49	148.2	129.5
C13	66.0	0.54	166.0	146.1
C14	64.0	0.53	161.3	141.6
C15	56.9	0.47	142.5	124.3
C16	56.3	0.47	141.4	123.2
MEAN	**56.0**	**0.46**	**-**	**123.6**

Table 3: Specimen strengths of un-damaged annealed glass

The failure points show linear plots of stress increasing with time, which is well documented for soda lime silica glass. Table 3 shows the equivalent stresses, which has been calculated as in Section 2.4.2; from this the mean strength of the series has been calculated.

There is evidently some scatter in the strength of the glass, with the standard deviation being calculated as 22.12MPa, which constitutes a 17.90% coefficient of variation from the mean. This variation is expected by the nature of glass failure due to the critical flaw model.

4.3. Overview of All Results

After all the failure stresses were converted to 30 second equivalent stresses an overview of the failure stresses can be plotted, and is shown in Figure 28.

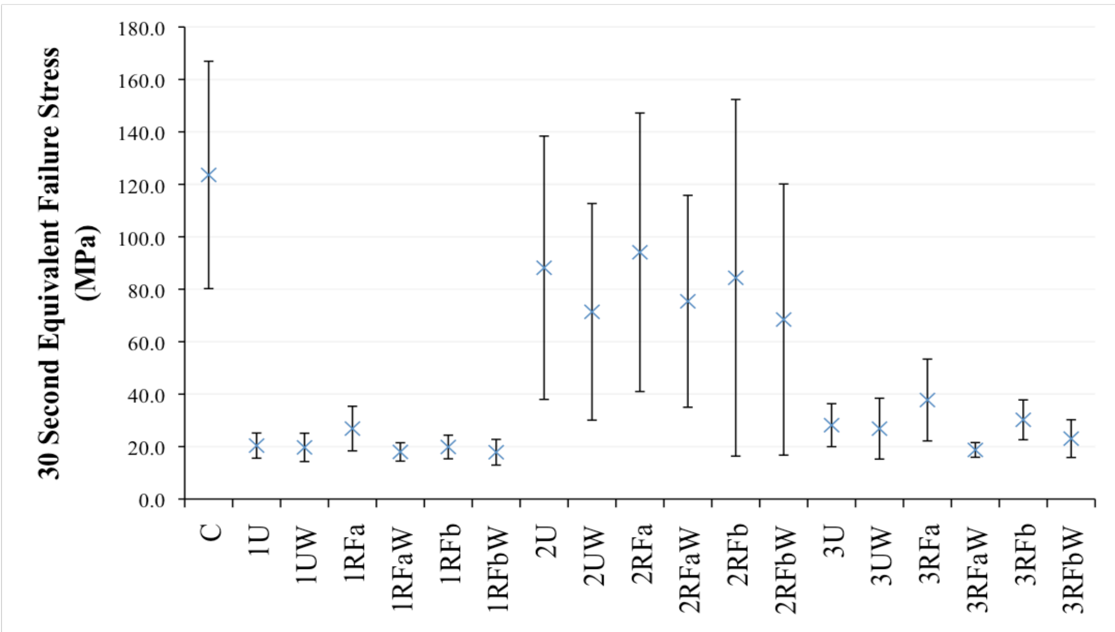


Figure 28: Overview of results

4.4. Indented Glass Repair

Series	Mean Time to failure (s)	Mean Displacement at Failure (mm)	Mean 30 Second Equivalent Strength (MPa)	Standard Deviation (MPa)	Percentage coefficient of variation (%)
1U	13.1	0.10	20.4	2.5	12.1
1UW	11.3	0.10	19.7	2.7	13.9
1RFa	16.1	0.13	26.9	4.4	16.2
1RFaW	12.3	0.09	18.0	1.8	9.9
1RFb	12.7	0.11	19.9	2.3	11.5
1RFbW	10.5	0.09	17.9	2.5	14.1

Table 4: Series 1- Results

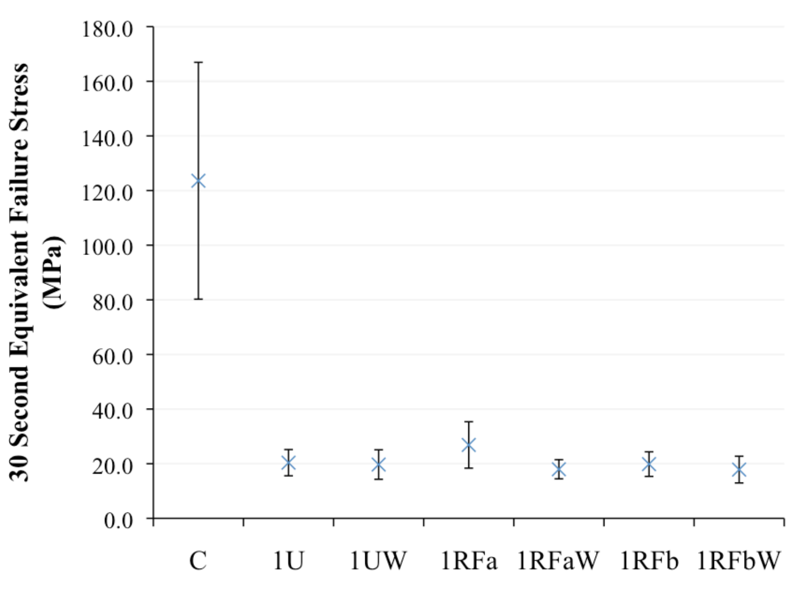


Figure 29:Mean Strengths of Indented Specimens

The points in Figure 29 show the mean strength of each of the batches of indented glass. The error bars show 1.96 standard deviations from the mean, which would be equivalent to 95% confidence intervals, assuming the failure stress is normally distributed. This seems a reasonable assumption and it is intuitively what one would expect dealing with glass strength. However, the sample size of 16 is small in statistical terms, meaning it is not possible to say whether the results are definitely normally distributed. The error bars will therefore be approximately equivalent to 95% confidence intervals and for this reason 1.96 standard deviations has been chosen as the given error. The scatter of strengths of the indented glass can be more accurately seen via a ranked plot of the failure strengths in each individual batch.

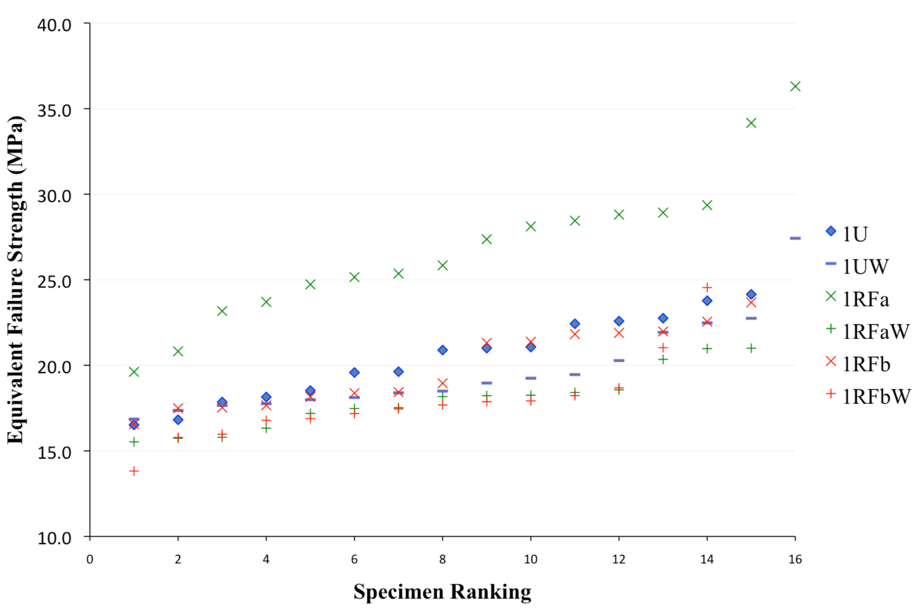


Figure 30: Scatter of Failure Strengths of Indented Glass

Comparisons can be made as explained in Table 2 that show the effectiveness of the different repairs:

Test comparison		Outcome	Strength Decrease/ Increase (MPa) Errors based on 95% confidence (± 1.96s)	Analysis for indented glass
C	1U	Decrease in failure strength due to flaw	123.6 -20.4 = **103.2** ± 55	Indented glass has 17% of original strength
C	1RFa	Effectiveness of repair of two different resins	123.6 – 26.9 = **96.7** ± 52	Glass repaired with resin A has 22% of original strength
C	1RFb		123.6 –19.9 =**104** ± 48	Glass repaired with resin B has 16% of original strength
C	1RFaW	Effectiveness of the repair with the two resins after being stored in water for a week	123.6 – 18 = **106** ± 47	Glass repaired with resin A and then stored in water for a week has 15% of the original strength of the glass
C	1RFbW		123.6 –17.9= **106** ± 48	Glass repaired with resin B and then stored in water for a week has 14% of the original strength of the glass
1RFa	1U	Strength increases due to repair using 2 different resins	26.9 – 20.4 = **6.5** ± 13.5	Glass repaired with resin A is 32% stronger than unrepaired glass
1RFb	1U		19.9-20.4 = **-0.5** ± 9.4	Glass repaired with resin B is 2% weaker than unrepaired glass
1RFa	1RFaW	Decrease in strength post repair, due to storage in harsh environment	26.9 – 18 = **8.9** ± 12	Glass repaired with resin A and stored in water for a week is 33% weaker than if it were stored in air
1RFb	1RFbW		19.9 - 17.9 = **2** ± 9.4	Glass repaired with resin B and stored in water for a week is 10% weaker than if it were stored in air
1U	1UW	Decrease in strength due to harsh environment without repair	20.4 – 19.7 = **0.7** ± 10	Unrepaired glass loses 3% of its strength due to exposure to water for a week

Table 5: Analysis of effect of repairs in Series 1.

The above analysis firstly shows that the indentation reduces the strength of the glass by 83%. The repairs do not increase the strength anywhere near to the undamaged strength, however, it is clear that the repairs do have some effect in increasing the strength. Repairs with resin A, the acrylic, increasing the strength by 32% from the indented state, with Figure 30 showing how the strengths are consistently above the unrepaired strength when ranked. Another point of analysis is the effect of storing the repaired specimens in water. The results suggest this has a detrimental effect on the strength, which is in agreement with Wiederhorn

[11]. Water seems to have the most effect on repairs with resin A, with the mean strength reduction of 33%.

All of the comparisons have been made using mean strengths, which all have independent variances which are large as seen in Figure 29 and Table 5. The overlapping of error bars in Figure 29 imply that statistically, there are no significant results (at the approximate 5% level), however the values of mean strengths allow some discussion to be made about the influence of the repairs. The large errors are down to the nature of glass and the nature of the indentations, which are all unique.

4.5. Naturally Weathered Glass Repair

Series	Mean Time to failure (s)	Mean Displacement at Failure (mm)	Mean 30 Second Equivalent Strength (MPa)	Standard Deviation (MPa)	Percentage coefficient of variation (%)
2U	37.7	0.33	88.2	25.6	44.5
2UW	36.3	0.31	71.4	21.1	29.5
2RFa	41.2	0.34	94.1	27.1	36.5
2RFaW	32.4	0.28	75.4	20.6	27.3
2RFb	38.7	0.31	84.4	34.7	41.1
2RFbW	35.3	0.29	68.4	26.4	38.6

Table 6: Series 2 – Results

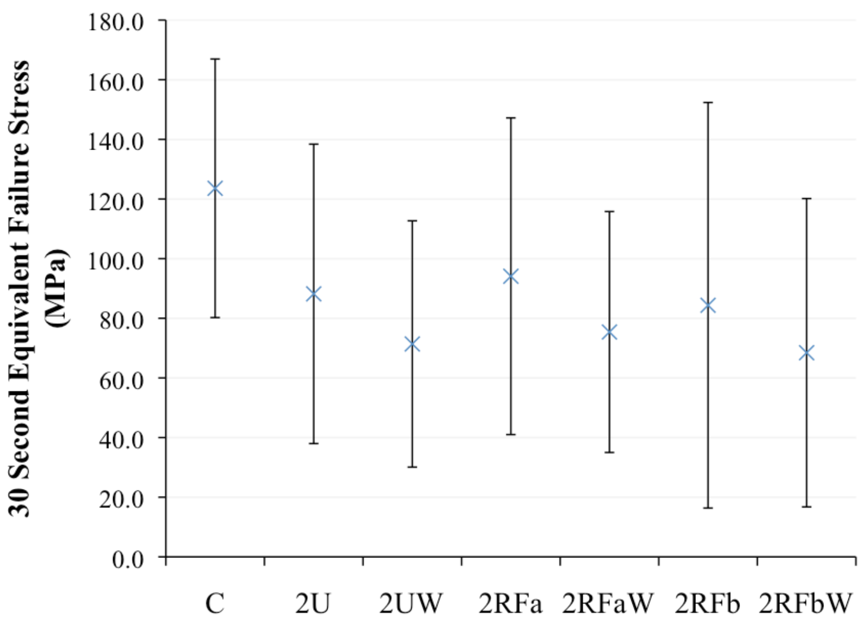


Figure 31: Mean Strengths of Naturally Weathered Specimens

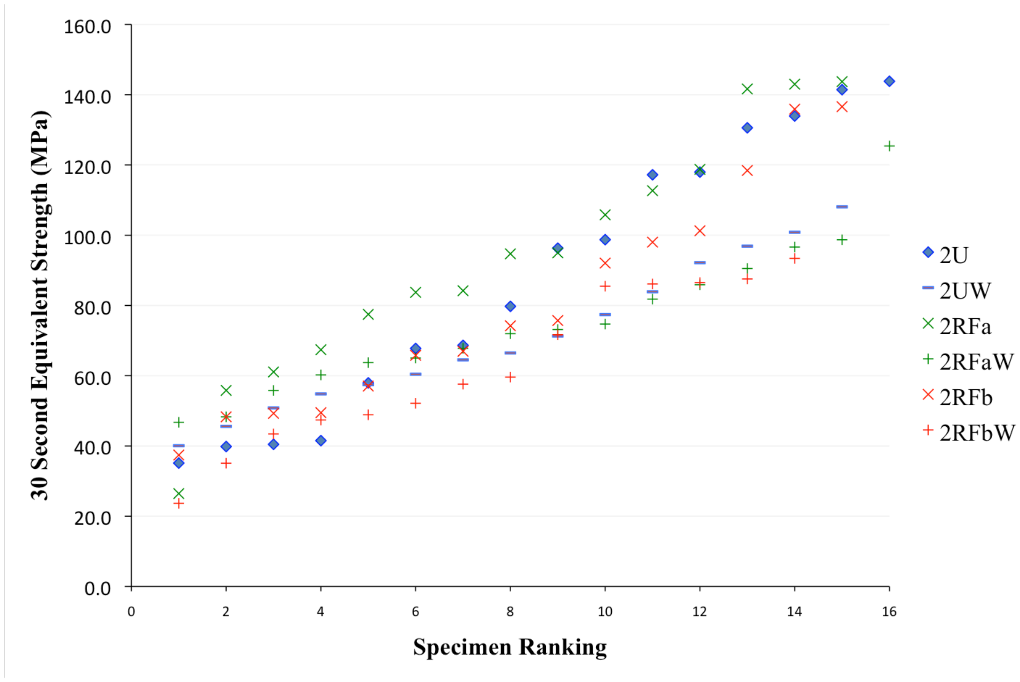


Figure 32: Scatter of Failure Strengths of Naturally Weathered Glass

The points in Figure 31 show the mean strength of each of the batches of naturally weathered glass. The error bars again show error bars of 1.96 standard deviations from the mean, which approximately depict 95% confidence intervals. The scatter of strengths of the naturally weathered glass has again been shown in a ranked plot shown in Figure 32.

It is immediately clear the strengths for the naturally weathered specimens have a far larger spread of strengths than the indented glass. However, from looking at the mean strengths alone in Figure 31 it looks as if resin A again out performs resin B and it again looks like the water has a detrimental effect on strength which is consistent with the indented batch.

Quantitative analysis can be performed again by looking at the comparisons from 2.3.2.

Test comparison		Outcome	Strength Decrease/ Increase (MPa) Errors based on 95% confidence (± 1.96s)	Analysis for Naturally weathered glass
C	2U	Decrease in failure strength due to flaw	123.6 -88.2 = **35** ± 93	Naturally weathered glass has 71% of original strength
C	2RFa	Effectiveness of repair of two different resins	123.6 – 94.1 = **30** ± 96	Naturally weathered glass repaired with resin A has 76% of original strength
C	2RFb		123.6 –84.4 =**39** ± 110	Glass repaired with resin B has 68% of original strength
C	2RFaW	Effectiveness of the repair with the two resins after being stored in water for a week	123.6 – 75.4 = **48** ± 83	Glass repaired with resin A and then stored in water for a week has 61% of the original strength of the glass
C	2RFbW		123.6 – 68.4 = **55** ± 95	Glass repaired with resin B and then stored in water for a week has 55% of the original strength of the glass
2RFa	2U	Strength increases due to repair using 2 different resins	94.1 – 88.2 = **5.9** ± 103	Glass repaired with resin A is 7% stronger than unrepaired glass
2RFb	2U		84.4 – 88.2 = **-3.8** ± 118	Glass repaired with resin B is 4% weaker than unrepaired glass
2RFa	2RFaW	Decrease in strength post repair, due to storage in harsh environment	94.1 – 75.4 = **19** ± 93	Glass repaired with resin A and stored in water for a week is 20% weaker than if it were stored in air
2RFb	2RFbW		84.4 – 68.4 = **16** ± 120	Glass repaired with resin B and stored in water for a week is 19% weaker than if it were stored in air
2U	2UW	Decrease in strength due to harsh environment without repair	88.2 – 71.4 = **17** ± 118	Unrepaired glass loses 19% of its strength due to exposure to water for a week

Table 7: Analysis of effect of repairs in Series 2.

In the discussion of the naturally weathered samples it would be foolish to draw hard quantitative outcomes from the results, due to the large spread of strengths within batches. The spread is caused by the nature of the naturally weathered specimens; unlike the indented and scratched specimens they have not been treated identically. The specimens have been naturally weathered over the course of 20 years, and clearly some specimens had larger critical flaws and whereas other specimens the surface was almost undamaged meaning their strength was greater. The spread may also be widened due to the inability to determine the tin side for naturally weathered glass.

However if the mean strengths are taken into consideration, we see again that resin A gives the largest increase in strength increasing the strength by 7%. This is less than for indented glass (which was 32%) but in its unrepaired state the weathered glass is much stronger than the indented glass: 71% of original strength, so there is less scope for strength improvement.

The effect of water can also be seen by looking at the means, with the water negating the effect of the repair, reducing strength by about 20% in each case.

4.6. Scratched Glass Repair

Series	Mean Time to failure (s)	Mean Displacement at Failure (mm)	Mean 30 Second Equivalent Strength (MPa)	Standard Deviation (MPa)	Percentage coefficient of variation (%)
3U	15.1	0.13	28.2	4.2	24.7
3UW	15.5	0.12	26.8	5.9	22.1
3RFa	19.5	0.17	37.8	8.0	21.1
3RFaW	10.9	0.09	18.7	1.5	7.7
3RFb	16.0	0.14	30.2	3.9	31.9
3RFbW	13.9	0.11	23.0	3.7	16.0

Table 8: Series 3 – Results

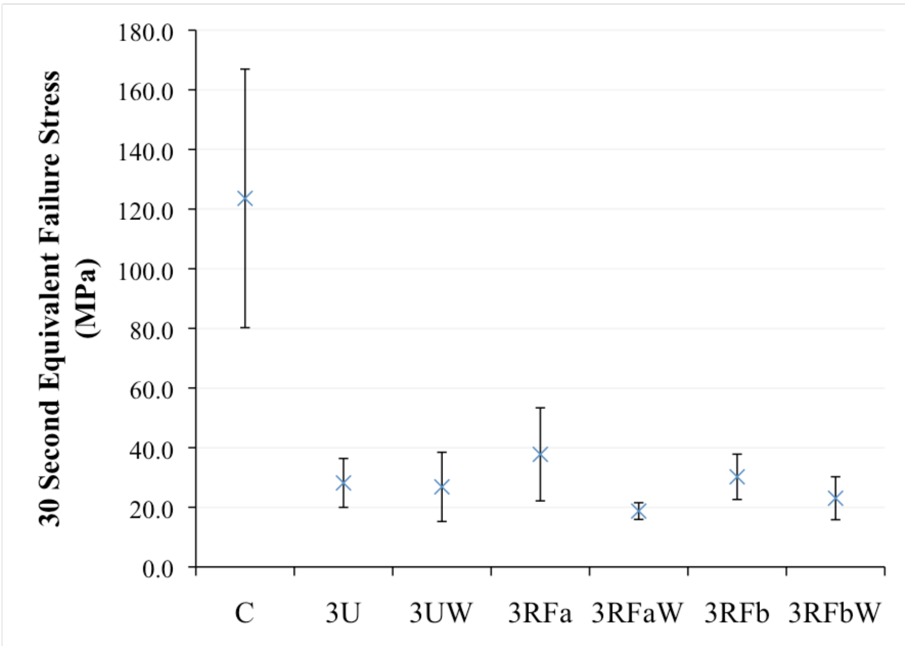


Figure 33: Mean Strengths of Scratched Specimens.

The points in Figure 33 show the mean strength of each of the batches of scratched glass. The error bars are again 1.96 standard deviations from the mean, showing approximate 95%

confidence intervals. The scatter of strengths of the naturally weathered glass has again been shown in a ranked plot, shown in Figure 34.

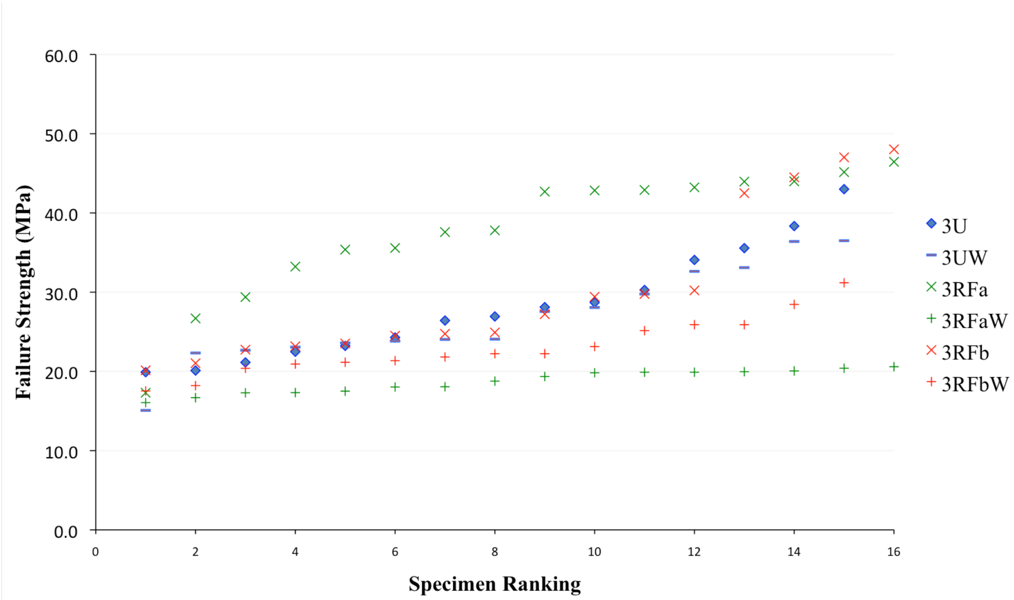


Figure 34: Scatter of Failure Strengths of Scratched Glass

The result that stands out in the scratched testing batch is the strength of the glass with the repair using resin A and the comparative strength of resin A when exposed to water for a week. The strength over this comparison drops a significant amount and the error bars do not overlap, meaning the introduction of water to the flaw has a significant detrimental effect on the strength in this case.

From Table 9, scratched glass has an average strength, which is about 23% of the strength of undamaged, meaning the initial flaw causes a loss of about 77% strength. This is marginally stronger than the indented samples, and much weaker than the weathered glass. Again, as is the case with the other batches, the spread of strengths is significant and allows limited concrete conclusions to be drawn. The general trend is similar to the other two series however, with resin A increasing the strength, again by about 34% compared to unrepaired which is similar to the figure found for indented glass, with resin B having little to no effect. The continuation of the trend of water having a detrimental effect on the strength is seen in this series too.

Quantitative analysis can be performed again by looking at the comparisons from Section 2.3.2.

Test comparison		Outcome	Strength Decrease/ Increase (MPa) Errors based on 95% confidence (± 1.96s)	Analysis for scratched glass
C	3U	Decrease in failure strength due to flaw	123.6 -28.2 = **95.4** ± 51	Scratched glass has 23% of original strength.
C	3RFa	Effectiveness of repair of two different resins	123.6 – 37.8 = **36** ± 59	Scratched glass repaired with resin A has 31% of original strength
C	3RFb		123.6 –30.2 =**93** ± 51	Glass repaired with resin B has 24% of original strength
C	3RFaW	Effectiveness of the repair with the two resins after being stored in water for a week	123.6 – 18.7 = **105** ± 46	Glass repaired with resin A and then stored in water for a week has 15% of the original strength of the glass
C	3RFbW		123.6 – 23 =**101** ± 95	Glass repaired with resin B and then stored in water for a week has 19% of the original strength of the glass
3RFa	3U	Strength increases due to repair using 2 different resins	37.8 – 28.2 = **9.6** ± 24	Glass repaired with resin A is 34% stronger than unrepaired glass
3RFb	3U		30.2 – 28.2 = **2** ± 16	Glass repaired with resin B is 7% stronger than unrepaired glass
3RFa	3RFaW	Decrease in strength post repair, due to storage in harsh environment	37.8 – 18.7 = **19.1** ± 18	Glass repaired with resin A and stored in water for a week is 49% weaker than if it were stored in air
3RFb	3RFbW		30.2 – 23 = **7.2** ± 15	Glass repaired with resin B and stored in water for a week is 24% weaker than if it were stored in air
3U	3UW	Decrease in strength due to harsh environment without repair	28.2 – 26.8 = **1.4** ± 20	Unrepaired glass loses 5% of its strength due to exposure to water for a week

Table 9: Analysis of effect of repairs in Series 3.

4.7. Resin A – Acrylic

Across all series of tests where resin A has been used there is an increase in strength compared to the untreated flaw. This is shown in Figure 35 and although none of the results are significant when presented at the approximate 95% confidence level the fact that all mean strengths across all three series shows a strength increase suggests there is a relationship between repairing with resin A and a slight increase in strength. From looking at the mean values it seems like resin A has the largest impact on scratched glass, with a mean strength increase of 34% compared to its unrepaired state.

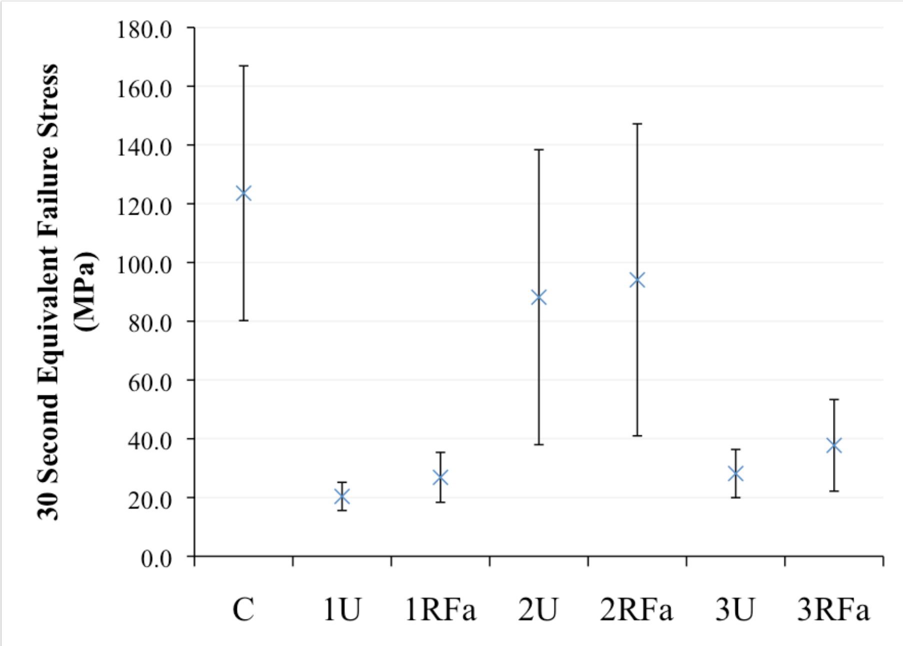


Figure 35: Failure Strengths with Resin A

4.8. Resin B – Epoxy

Resin B is an epoxy resin, with a viscosity of 1.8 times that of water. From Figure 36 it is hard to be convinced that the epoxy resin impacts on the failure strength at all.

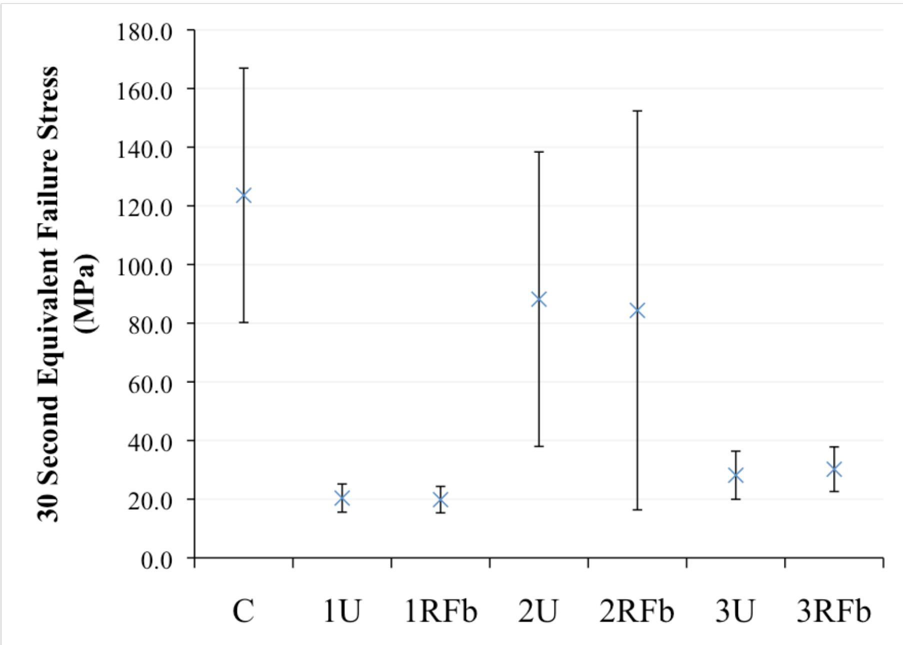


Figure 36: Failure Strengths with Resin B

Repairs with resin B on indented and weathered show no improvement in mean strength compared to the unrepaired state, whereas in the scratched series the mean strength increases by 7%. Whilst unlikely to reduce the strength of the glass, the results suggest resin B has very little or no effect on the strength of the flawed specimens. This may be due to the lack of flaw penetration as discussed in Section 4.9.

4.9. Contact Angles & Wettability of Resins

One of the reasons why resin A is returning a slight increase in mean strength and resin B is not seen increasing the strength is thought to be the ability of the resins to make contact with the glass surface. The wettability of the glass by the two resins can be determined by measuring the contact angle, as discussed in Section 2.3. The contact angle of water of glass will be used as a reference for comparison purposes.

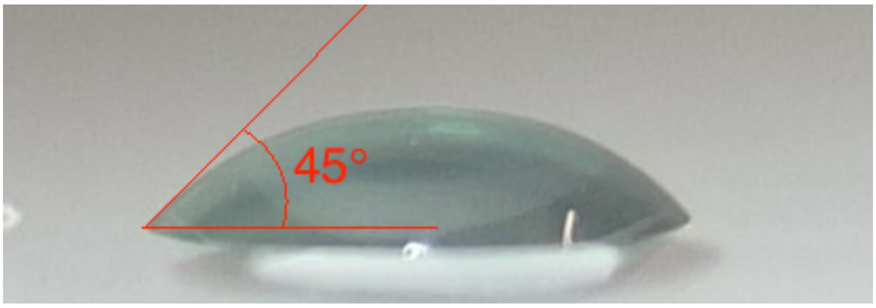


Figure 37: Contact angle of water.

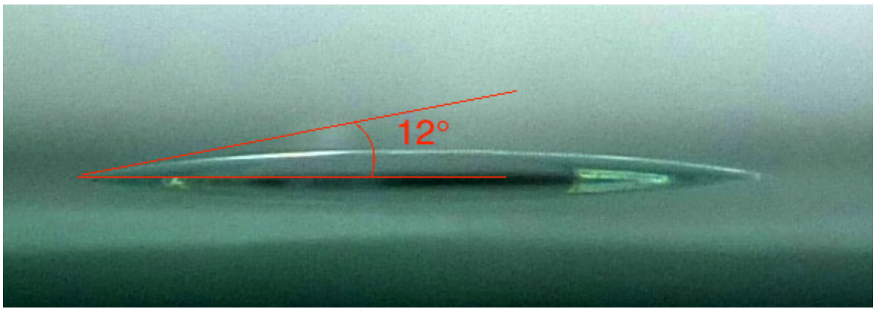


Figure 38: Contact angle of acrylic, resin A.

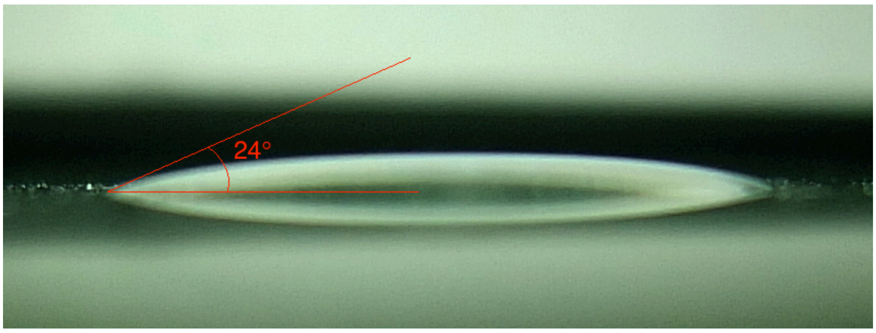


Figure 39: Contact angle of epoxy, resin B.

As can be seen in Figure 37, Figure 38 and Figure 39 the contact angle of water was measured to be 45° ± 3°, the contact angle for resin A is 12° ± 3°, and the contact angle of resin B is 24° ± 3°. This shows that both resins are more prone than water to wetting the surface of the glass due to their lower contact angles. Further, resin A has a greater ability to wet the surface of glass than resin B; this is consistent with the strength results recorded in Sections 4.4, 4.5 and 4.6.

This makes a strong case for the suggestion that the lower the contact angle the higher the flaw penetration and the higher the strength increase due to the repair. This hypothesis is backed further by fractographic analysis, examining the flaws that have been repaired to determine whether the resin has penetrated into the flaw. These are shown in Figure 40, Figure 41, Figure 42 and Figure 43.

Figure 40 shows an indentation repaired with resin A and it is clear to see the resin residue in the indentation, showing that resin A, with the lower contact angle has penetrated further into the indented flaws further than resin B, of which an example is shown in Figure 41, where there is no residue left in the indented flaw.

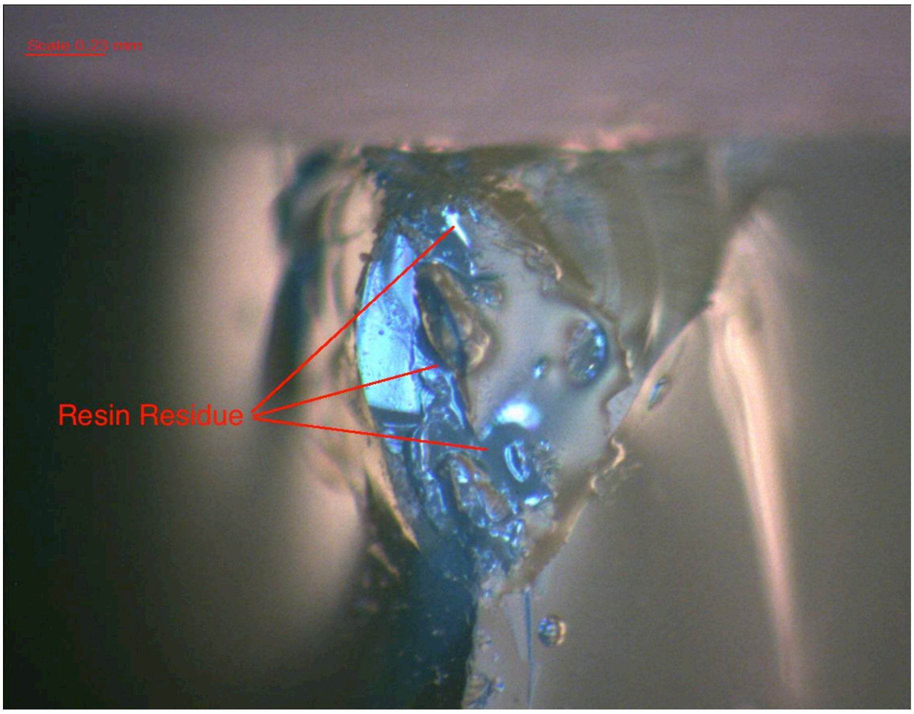


Figure 40: Indentation failure, with resin A residue in the flaw

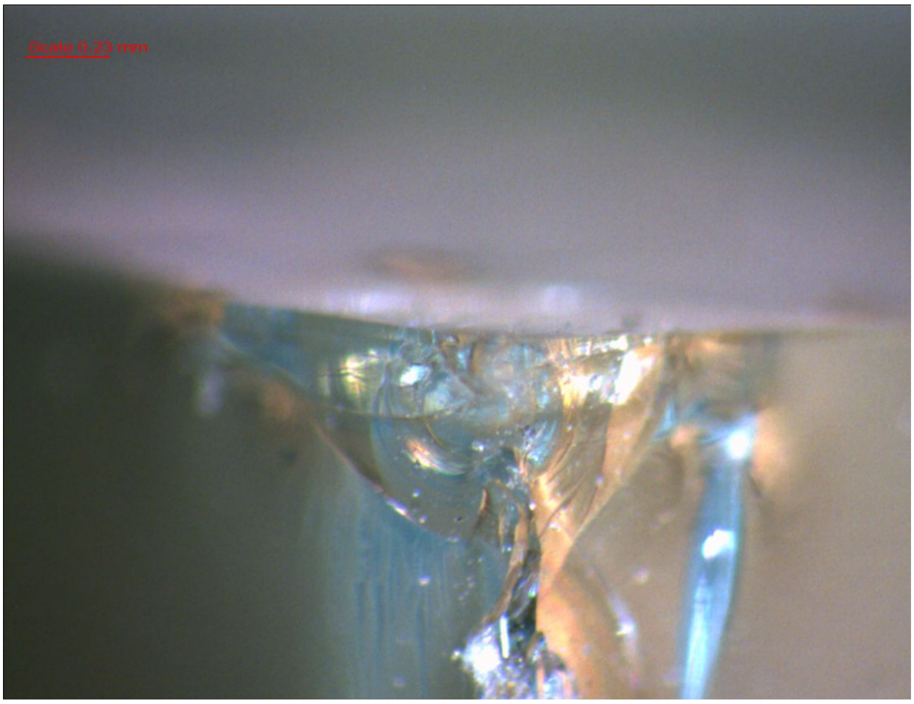


Figure 41: Indentation of a repair using resin B, with no residue

In Figure 42 and Figure 43 the same trend is seen, with scratches repaired with resin A, failing at a higher stress, where resin A has penetrated further into the flaws than resin B. The observations suggest the slight extra strength seen with resin A is due to its lower contact angle, and consequently its greater flaw penetration.

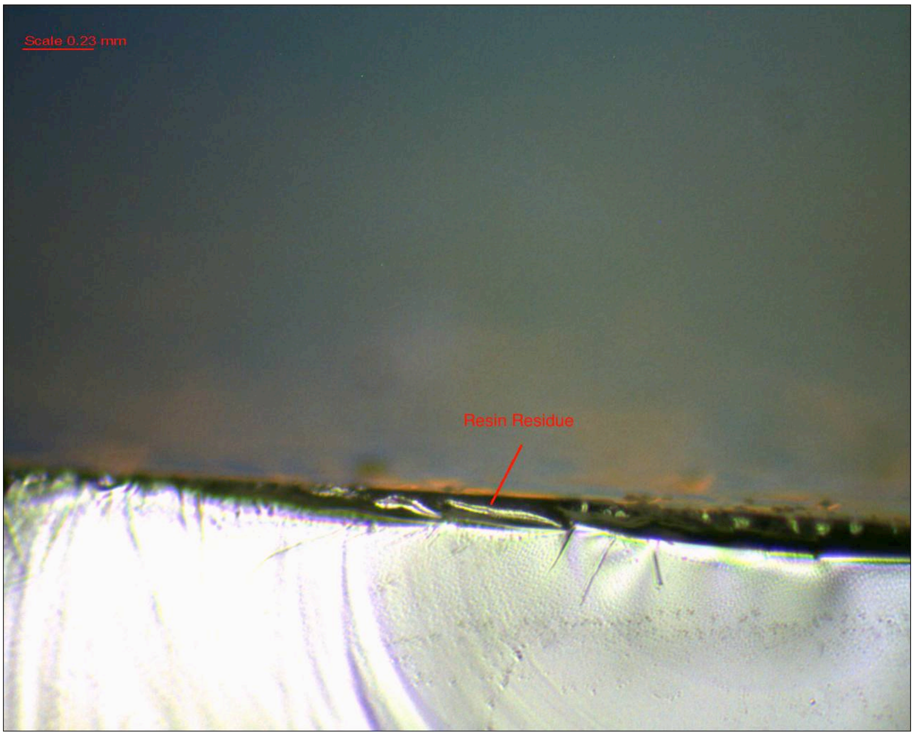


Figure 42: Scratch repaired with resin A, showing residue

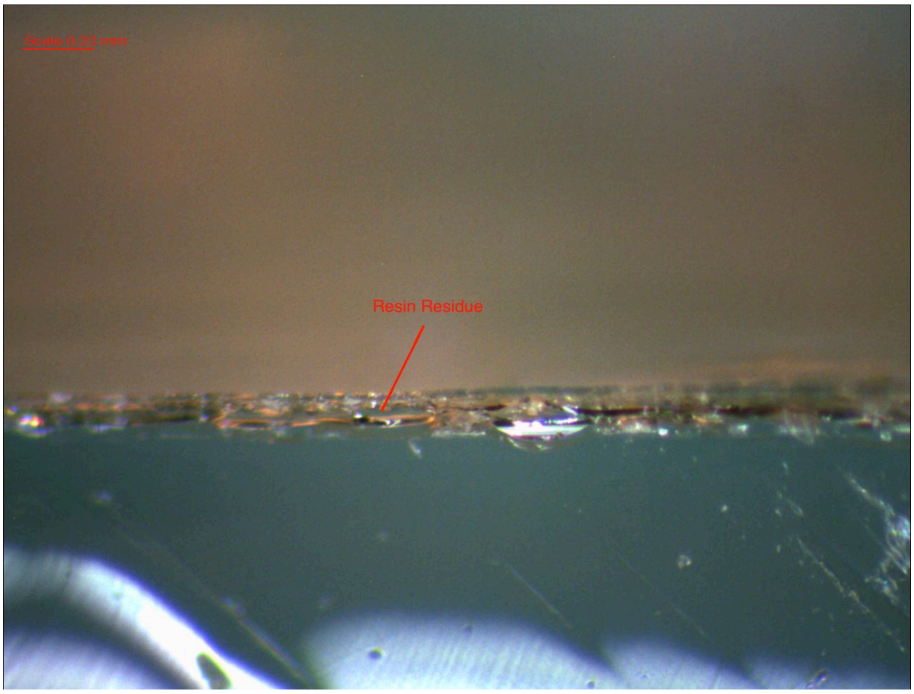


Figure 43: Scratch repaired with resin B, showing less residue in the flaw than resin A.

4.10. Effect of Storage in water

Storage of specimens after repair in an environment of water simulates the impact of a humid environment on glass repair. The addition of water to the unrepaired specimens saw the strengths decrease by: 3%, 19% and 5% for indented, naturally weathered and scratched glass respectively. The fact that the 19% strength decrease is wildly different to the 3% and 5% decrease in strength of indented and scratched glass seems to suggest the figure found for weathered glass is erroneously high. One would assume water would have the same level of impact on each type of flaw so it may be the result of the large errors encountered with naturally weathered glass. The results suggest the average decrease in strength should be about the 4% mark, an average of the effect on indented and scratched glass, discounting the weathered specimens.

The repaired specimens, after having been stored in water for a week showed strength decreases compared to the unrepaired, dry specimens. Furthermore, the strengths of the specimens that were repaired and exposed to water are all less than the unrepaired state with water, suggesting that repair plus water has a more detrimental effect than water alone. This seems counterintuitive; as it seems unlikely the repair would make the strength worse. The errors in the mean strengths of the tests could be playing some part here, but what is clear is the repairs do not prevent the decrease in strength caused by the water. This suggests water is able to penetrate to the flaw under the resin. Perhaps the resin was not completely set upon exposing the repair to water; although the specified set time of the resins was adhered to allow the resin to set as well as curing with a UV lamp. A plot showing effects of the water is shown in Figure 44 below. More investigation is needed in this area to draw strong conclusions.

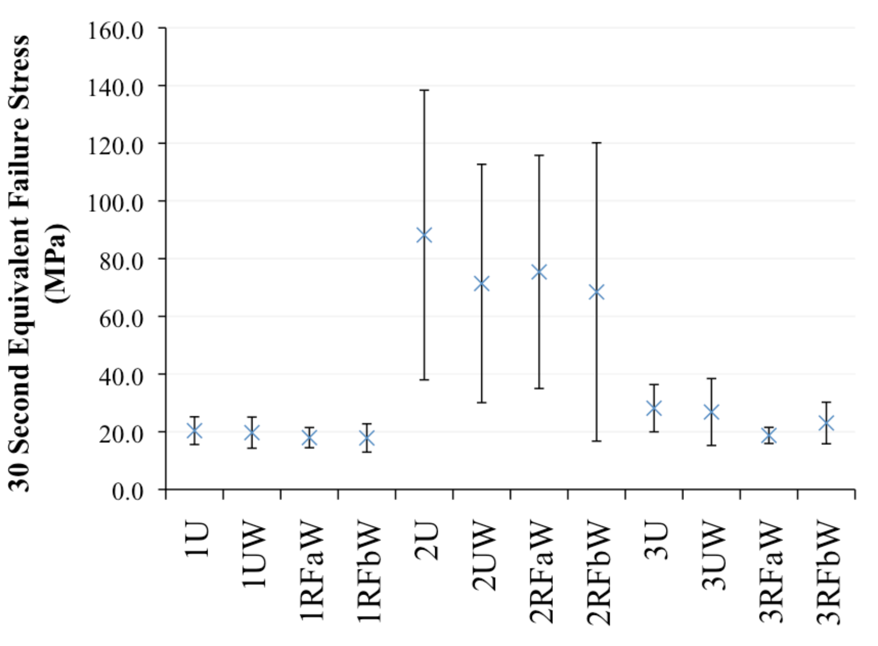


Figure 44: Effect of water on repaired strength

4.11. Secondary Strength

Some of the failures of the specimens did not have single failures but failed once and continued to take load until their ultimate failure. An example of such a load vs time plot is shown in Figure 45. The continuation of the ability to withstand load is possibly due to the geometry of the crack, which first forms with the fragmented pieces still bridging the loading ring. In any case, the failure load taken into consideration for all calculations and analysis in this investigation is the first load at which the glass fails, as this is the point at which the glass would no longer be deemed fit for purpose. However it is worth pointing out that some samples exhibited this "extra strength" after the first failure, which lead to an ultimate failure strength of almost twice the initial failure.

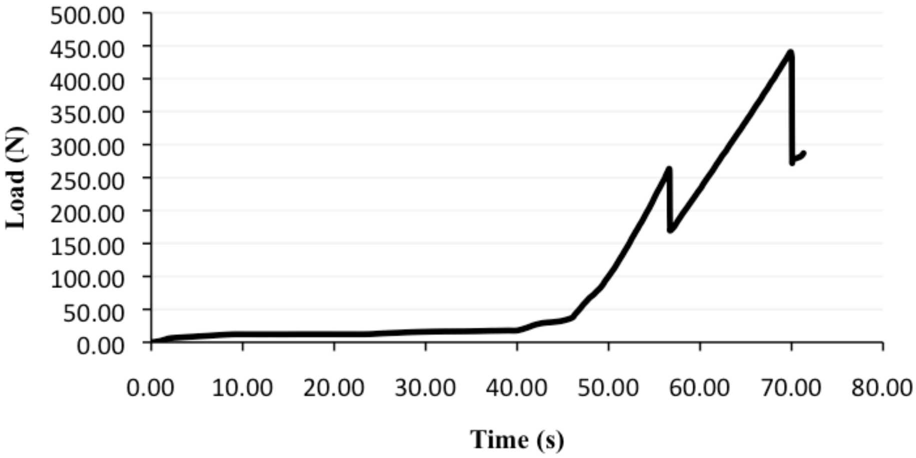


Figure 45: Example of a Load vs Time plot showing first and second failure

4.12. Fractographic Analysis

Specimens were examined after failure and if the failure origin was found to be outside the loading ring then the specimen was discounted from the investigation as discussed in Section 3.8. An example of this is shown in Figure 46.

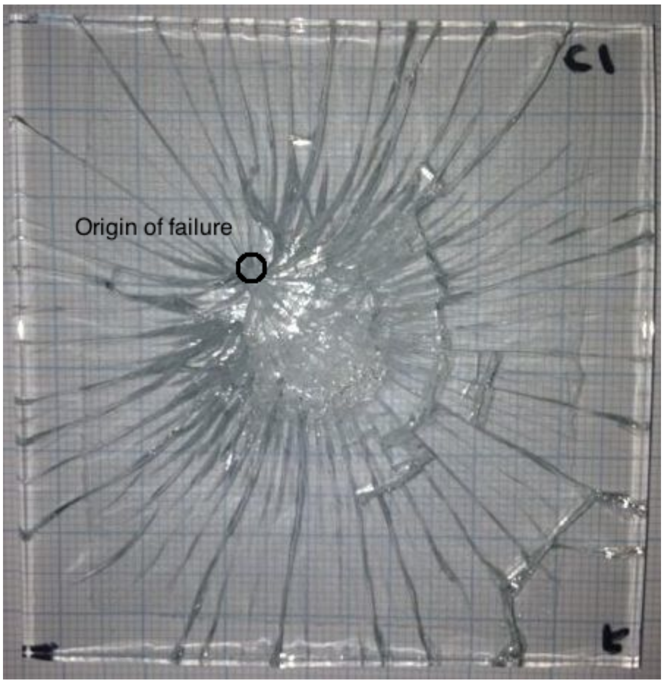


Figure 46:Discounted specimen with failure origin outside the central loading ring

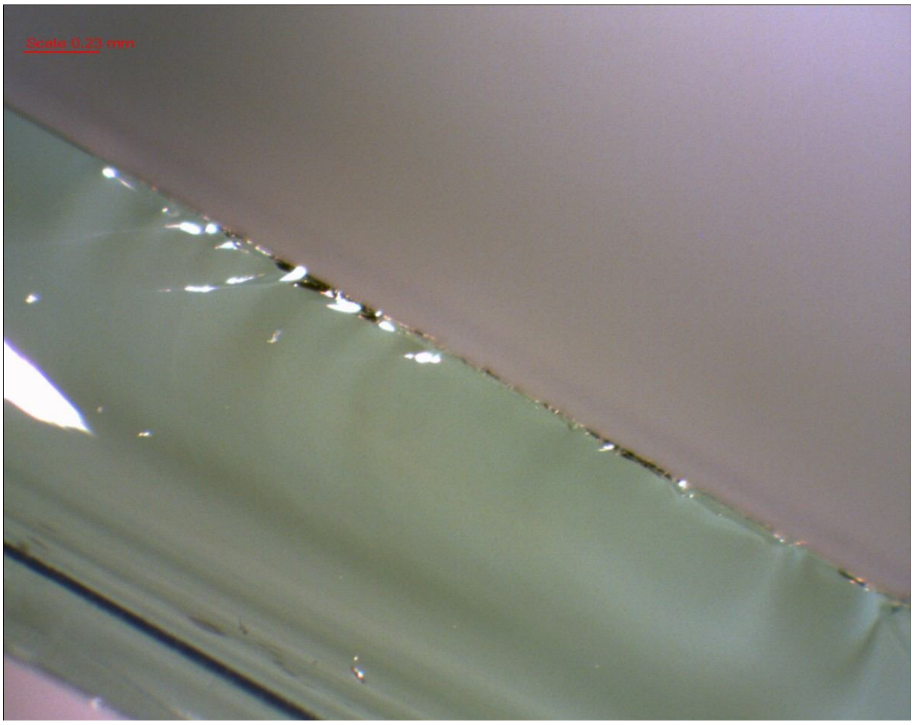


Figure 47: Edge view of scratch on surface of glass specimen

As discussed in Section 3.11, due to the similarity between the scratches on the glass specimens and a straight front plane edge crack for which $Y = 1.12$ in Irwin's relationship it may be possible to use the relationship to estimate the stress at failure in hindsight by measuring the scratch depth. With a measured scratch depth of 0.1mm from Figure 47 the expected failure stress from Irwin's relationship is:

$$K_{IC} = 0.75 = Y\sigma_f\sqrt{\pi a}$$
$$0.75 = 1.12\sigma_f\sqrt{\pi 0.001}$$
$$\sigma_f = 27MPa$$

The actual mean failure stress that was recorded for the scratched specimens was 35MPa ±8.2MPa. The comparison of these two values means Irwin's relationship gives a correct 'ball park' figure for failure stress. The Y geometry factor was not known for the other flaws so this could not be calculated for them.

5. Conclusions

In this investigation, extensive testing has been undertaken to determine the effect of repairs with resin on the strength of glass. 304 individual specimens have been tested in 19 series of tests. Two different resins have been used to undertake repairs on three types of initial flaw: indentations, natural weathering and scratches. The effect of the environment in which the repair is stored was observed as well, with one half of all repaired specimens stored in water and half stored under lab conditions.

The results of the investigation suggested:

- Flaws in annealed glass such as indentations and scratches can lower the failure strength of the glass to 17%-23% of its original undamaged strength.

- Repairing flawed glass with resin has a has a very small impact on the strength of the glass when compared to the undamaged strength, with observed increases the mean strength of about 30% taking the strength up to about 22% to 30% of the undamaged strength.

- The strength increase has been hypothesised in past studies to have a relationship with the penetration of the resin into the flaw [2]; this has also been observed to be the case here. Repairs with resin A provided on average a greater strength gain than resin B. Resin A was observed to leave residue in the flaw whereas Resin B left little or no residue, showing resin A penetrated deeper, consistent with the suggestion of extra strength originating from the depth of flaw penetration. The contact angle of the resins were measured and it was observed that resin A with the lower contact angle has a greater ability to wet the surface than resin B, suggesting a reason for the deeper flaw penetration.

- As the strength benefit from the resin's presence is small, it seems as if the mechanism of extra strength is due to the resin bridging the flaw.

- The results suggest the presence of water reduces the strength of glass with a flaw regardless of the repair. Although the reduction of strength of a flaw due to water is well known, the fact the strength loss is not mitigated by the repair seems odd, as one would expect the repair to block ingress of water to the flaw. Further investigation into this area could alleviate this confusion.

- The large uncertainties in the mean values of strength are due to the nature of glass. The largest uncertainties came with naturally weathered specimens, which may not have been treated identically. Most of the results are not significant at the statistical 95% level, however conclusions can be drawn due to trends across all of the tests.

- The main benefit to repairing glass seems to be superficial. The visual impact of the flaw was reduced with the flaws becoming almost invisible post repair.

5.1. Further work

To reduce the uncertainties in the mean strengths of the specimens, more tests would need to be undertaken in larger batches. This would reduce scatter in order to obtain more reliable means.

To ascertain the mechanism of strength increase, further investigation is needed to confirm the strength increase is indeed caused by the bridging of the resin over the flaw, as suspected.

To investigate further the effect of water on the repairs, tests could be carried out with repairs exposed to water after different time periods after the repair. This would test if the resin needs a longer time to set, and harden to block the ingress of water. The resins could also be placed at different depths in water to test whether the water pressure is a factor.

It would be interesting to run tests using industry standard repair equipment and ascertain if it is of any added benefit.

For a comprehensive investigation into glass repair, polishing would also be examined as a repair technique and compared to the use of resins.

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7. Appendix

7.1. Risk Assessment - Retrospective

A general risk assessment was handed in at the beginning of Michaelmas term, which examined the general risks involved with the project, these were:

- Working with glass, and broken fragments of glass.
- Working on the Instron Machine.

This initial risk assessment whilst grasping the overall risks did not cover the specific risks in testing, which were not determined until the final testing programme had been finalised. At this point in early December 2013, another risk assessment was produced, which analysed the more specific risks involved with the testing procedure. This involved analysing the testing with an inert atmosphere, and using a compressed gas cylinder. This second risk assessment also gave a more detailed assessment of exactly what work was being undertaken on the Instron machine, how it was to be used. It would not have been possible to know the exact testing programme at the beginning of the project so a second risk assessment was always needed. In retrospect there was no other way of dealing with these specific later risks other than to deal with them as they arose, so it would not be beneficial to change the way the initial risk assessment was approached.