

Experimental Investigation into the Strength of Single Sided Silicone Glazing Joints Under Blast Loading

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An experimental study has taken place to quantify the strength of single sided structural silicone glazing joints under blast loading. The structural silicone specimens in this experiment were tested using a high-speed servo-hydraulic test machine at varying rates, representative of that experienced in a blast. Tests were conducted at displacement rates of 1m/s, 2m/s and 4m/s. The load was applied at two different angles of 30° and 45°. The tests were carried out on samples with different bite depths. The load was measured and the strength of the silicone joint was calculated at different testing rates. For a given testing rate and loading angle, the strength was found to be constant for different bite depths. The strength also showed an escalation at higher displacement rates. For the loading angles tested, there was no correlation found between the angle of loading and the strength. Through the measurement of displacement during the test, the work done on the silicone joint was also calculated.

Keywords: Laminated, Glass, Silicone, Joints, Blast

1. Introduction

When an explosion occurs, a blast pulse propagates in the form of a pressure wave from the seat of the explosion. When a wave strikes a glass window the glass can fail and the pressure wave then enters the building, causing damage. Furthermore, fragmentation of the glass at high speeds can cause injuries. Laminated glass is often employed for protection against such a scenario. In protective design, two factors must be considered. Firstly, the laminated glass pane must be able to absorb the pressure pulse by its deformation. Secondly, the pane must stay in its frame and not detach from it. Both requirements are important. This paper addresses the second requirement.

Methods which exist for securing a laminated pane to its support include bolt-fixing the pane to a framework or using elastomeric gaskets in a frame. However, the most effective method is to use a structural silicone as a bonding material to the frame. Specific grades of silicone can enable reaction forces from the pane edges to be transmitted to the frame without separation if the forces are correctly quantified and the sealant is correctly chosen.

This study aims to quantify the strength of single-sided silicone joints under blast loading. From an engineering design perspective, the minimum bite depth required to resist the pane from tearing out of the frame is important. Hence, the tests are conducted at different bite depths and at different loading rates and loading angles.

2. Background

Previously, several workers have carried out research on structural silicone. Meunier et al. (2008) have carried out experimental and modelling work. They undertook tensile, compression, pure shear and bulge tests. Through the use of digital imaging correlation techniques they also took full-field strain measurements. Hyper-elastic models were fitted to their experimental data. The study also made a comparison between their experimental results and results from a finite element model.

Hautekeer et al. (2001) have conducted high speed tests. Tensile tests were conducted at displacement rates of 1.1m/s and 2.5m/s, and shear tests at 1.1m/s, which is representative of what the silicone joints would experience under blast loading. A variety of specimen sizes were tested. The length of the samples was 18mm. The depth and thickness were in the range of 6-16mm. The tests were conducted on single sided joints. The tensile strength was measured to be 1.5-2MPa and the shear strength to be 1.2-1.7MPa.

Vallabhan et al. (1997) proposed a mathematical model to be used to calculate the in-plane forces, out-of-plane forces and moments in silicone sealants used along edges of window panels. The restraining effects of the sealant were modelled through the use of three springs representative of in-plane, out-of-plane and rotational effects.

Ramesh et al. (1995) have studied how the modulus of structural silicone is affected by the time of curing of the sealant. They concluded that after 100 extra days of curing (in addition to the standard 2 weeks), a noticeable increase in modulus was observed. Keshavaraj et al. (1994) have also studied the failure mechanisms which can be due to curing of the silicone in an environment where moisture could be introduced. They stated that the modulus of the silicone can decrease if exposed to such environments.

Sandberg and Ahlborn (1989) have also conducted a study on the behavior of structural glazing joints under combined tensile and shear displacement. The tests were aimed at simulating the effect that wind loading has on the silicone joint. The testing method allowed for the loading angle to be modified. All of the tests were carried out at a low displacement rate of 2.5mm/s.

3. Method

3.1. The Test Specimen

Structural silicone is one of the crucial members of a glazing unit used for protection against blast. When a pressure wave from an explosion interacts with a laminated window system, the glass plies crack and the interlayer tolerates the tensile forces. This also puts a force, F , at an angle, θ , on the silicone joint. An illustration of this for a single sided silicone joint is shown in Fig. 1.

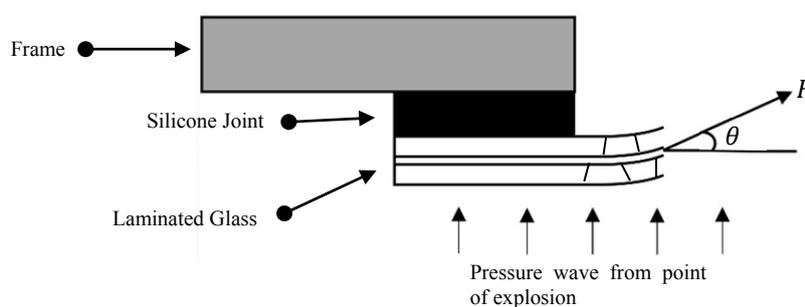


Fig. 1 A simplified illustration of the application of structural silicone.

Based on this, a sample was prepared, details of which are shown in Fig. 2. The structural silicone used was the Sikasil SG-500 from Sika. After the preparation of the silicone joint, the samples were allowed to cure a further month in addition to the minimum cure time, so that the mechanical properties could be fully developed. The silicone joint had a length, b , of 50mm. Sandberg and Ahlborn (1989) and Sandberg et al. (1989) have suggested that according to their experimental research, the length of the silicone joints, has no significant impact on the strength of the joint. The thickness, t , was approximately 5.5mm. The bite depth, d_b , was variable in different samples ranging from 10mm to 40mm in increments of 5mm.

3.2. Test Rig Setup

This testing method was originally developed at Imperial College by Hooper (2011) based on observations from blast tests. The test setup is shown in Fig. 3. The rig was connected to a high rate servo-hydraulic test machine. The samples were tested at an angle relative to the actuator of the testing machine. The sample was bolted and secured to an adjustable base, on which the angle of the base relative to the platform where the samples is secured can be varied by 0° to 90° .

The load was measured through the use of a piezoelectric load cell. The extension was taken as that of the actuator. This is because the compliance of the test rig was deemed negligible compared to that of the silicone joint. A high speed camera was also employed to record the test. This allowed for visual observations to be made during the failure of the joint.

A total number of 29 samples were tested; 14 samples at 30° and 15 at 45° . Tests were carried out at displacement rates of 1m/s, 2m/s and 4m/s. The tests were conducted on samples with bite depths varying between 10mm and 40mm in steps of 5mm. Table 1 shows the test matrix.

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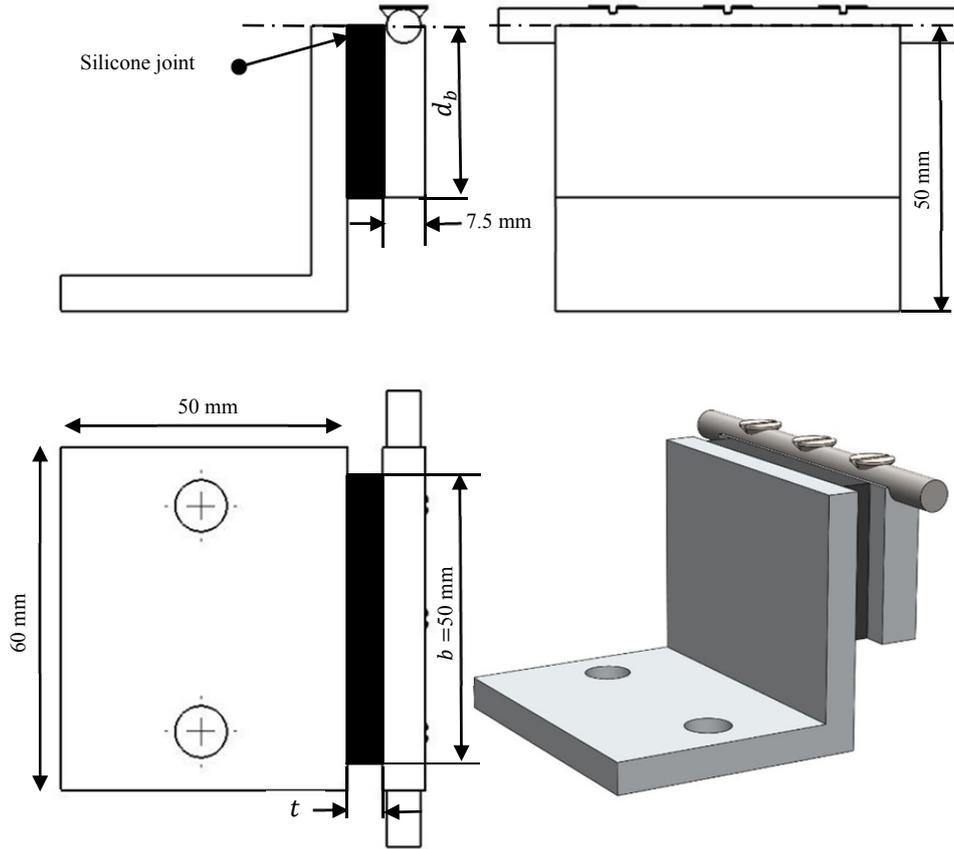


Fig. 2 Joint sample specifications.

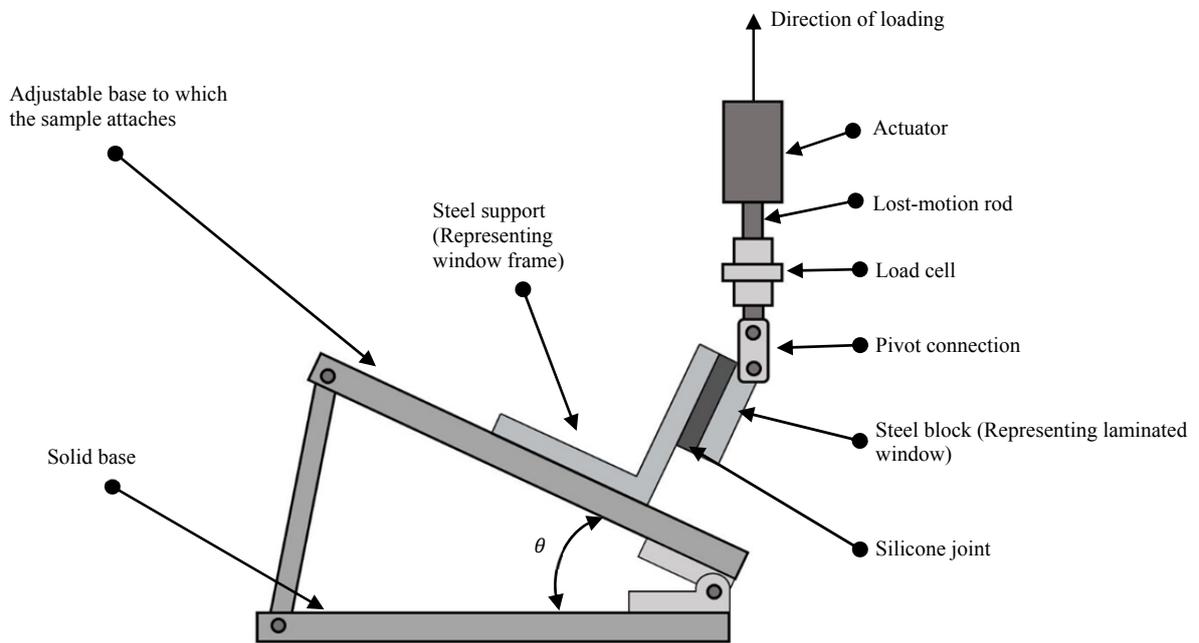


Fig. 3 Joint test setup.

Table 1: Test matrix showing the angle and speeds at which the different bite depths were tested.

Loading angle [degrees]	Bite depth [mm] tested at following speeds:		
	1m/s	2m/s	4m/s
30	10,15,20,25,30,40	10,15,20,25,30	15,20,25
45	10,15,20,25,30,35,40	10,15,20,25,30	15,20,25

3.3. Data Analysis

Displacement and force against time for each test were obtained. The start time, t_{start} , and end time, t_{end} , were chosen at times corresponding to a force value of approximately 1% of the maximum force value. This is shown in Fig. 4. The displacement at the start and end were then known, such that they corresponded to the start and end time selected. The actual speed of the actuator was then calculated from the displacement and time data.

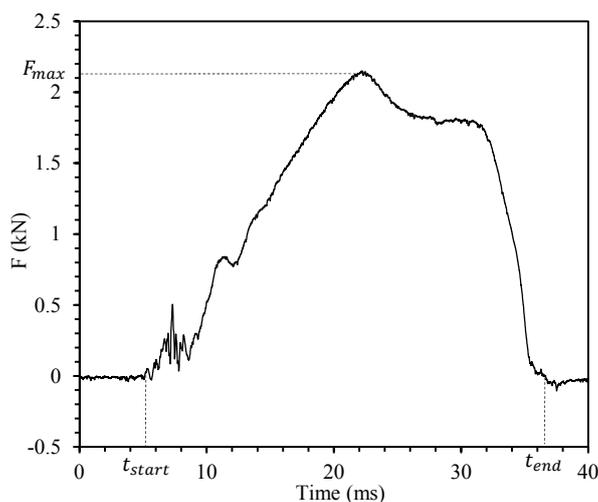


Fig. 4 The data extracted from a common force against time graph.

Force was also plotted against displacement and the energy absorbed during the experiment was calculated. This was done by using the trapezoidal numerical integration method. The maximum force, F_{max} , was extracted from the force against time trace (see Fig. 4). This was then divided by the bite depth, d_b , and the joint length, b , to define a joint strength, σ_{joint} . This is shown in equation (1).

$$\sigma_{joint} = \frac{F_{max}}{bd_b} \quad (1)$$

This means that with the condition that the relationship between force and bite depth is linear, the joint strength should be a constant for any bite depth. From a design perspective, when the joint strength is known, for a maximum tolerable force, the bite depth of the silicone joint can be calculated. Following this argument, for a given angle and speed, the strength was calculated for each bite depth and the mean value obtained with a corresponding standard deviation.

4. Results and Discussion

4.1. Failure Strength

The maximum force over the joint length was plotted against bite depth. Fig. 5 displays a sample plot for the experiments undertaken at 1m/s at a 45° pulling angle. Similar plots were obtained at other testing conditions. As it can be seen, the relationship between force and bite depth is linear.

The mean strength values were calculated at both pulling angles (30° and 45°) and at every test rate. This is shown in table 2. The mean displacement rate was also calculated; this is the mean value of the actuator velocity measured during the test for every bite depth. The standard deviation values for the test rate and joint strength were also calculated. From the results, it is clear that the joint strength increases with increasing displacement rate. No significant trend was observed between the test angle and the joint strength.

The joint strength was plotted against displacement rate. Fig. 6 illustrates this graph for a loading angle of 30°. A similar trend was also observed for 45°. From the graph it can be implied that at higher displacement rates, the joint strength is increased. Taking the silicone joints tested at 30° as an example, the mean joint strength and standard deviation for a mean displacement rate of 1.10m/s was 1.26±0.15. Whereas at a mean displacement rate of 4.45m/s, the strength was 2.33±0.08. This suggests that the silicone joint can take higher stresses at increased displacement rates. From an engineering design perspective, it is more conservative to use the strength values at 1m/s, with a suitable safety factor. Furthermore, this illustrates that the strength of the structural silicone is rate dependent. Similar conclusions have been made on other rubbers, an example being the work of Greensmith (1960). This is thought to be because of the viscoelastic properties of the material.

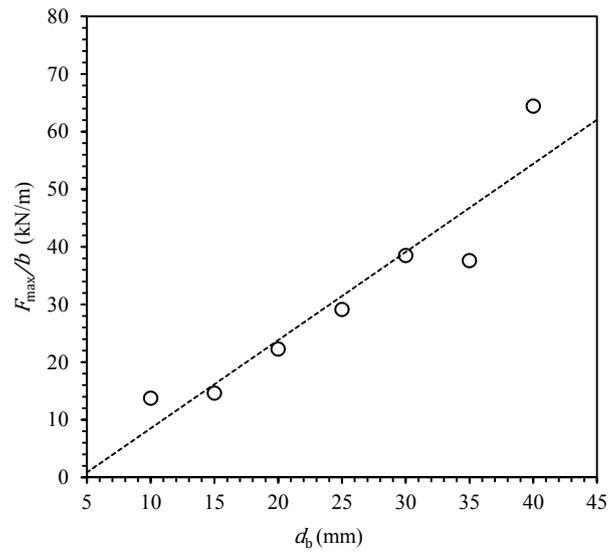


Fig. 5 The maximum force over joint length against the bite depth for a 45° pulling angle and a speed of 1m/s.

Table 2: Joint strength for a given angle and test rate.

Angle [degrees]	Mean Measured Test Rate [m/s]	Standard Deviation of Test Rate	Mean Joint Strength [MPa]	Standard Deviation of Joint Strength
30	1.10	0.04	1.26	0.15
30	2.16	0.09	1.54	0.16
30	4.45	0.05	2.33	0.08
45	1.11	0.09	1.23	0.20
45	2.01	0.09	1.49	0.24
45	4.11	0.06	2.84	0.43

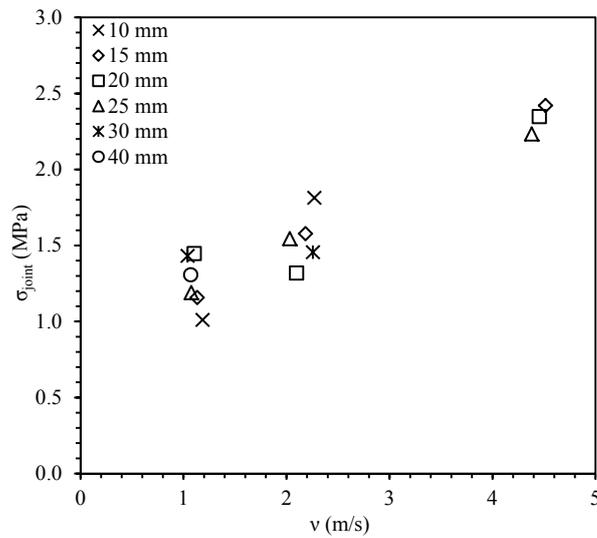


Fig. 6 Joint strength against displacement rate at a 30° pulling angle.

4.2. Effect of Angle of Pull on Joint Strength

In order to identify the effect that the pulling angle has on the joint strength, the joint strength was plotted against loading angle for a given displacement rate. Fig. 7 illustrates this for a displacement rate of 1m/s. As it is evident, no significant trend was observed between the joint strength and the loading angle. This could be because the difference between the two testing angles was only 15°, which is not significant enough to show any changes. Future tests will need to be carried out at a wider range of testing angles, allowing potential trends to be identified clearly. Similar patterns were observed at 2m/s and 4m/s.

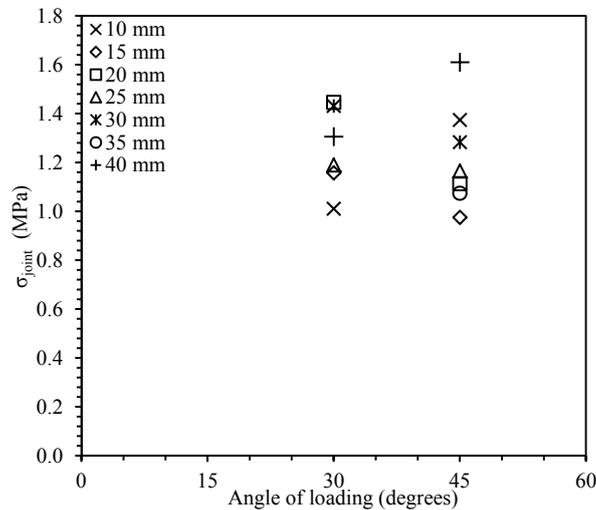


Fig. 7 Joint strength against loading angle at 1m/s.

4.3. Energy Absorbed

The total work done during the test was calculated by finding area under the graph of force against displacement. The total work done on the sample is the sum of the energy used in tearing the silicone, strain energy, viscoelastic losses and kinetic energy. Fig. 8 is a plot of total work done against bite depth at different displacement rates and pulling angles. As it can be observed, there is a linear trend between the energy absorbed and the bite depth. This is expected, as for greater bite depths, a higher amount of work has to be done on the silicone joint to extend the tear through the additional bite depth.

In Fig. 8 it is evident that for a given bite depth, as the displacement rate increases, the energy absorbed during the test also increases. However this increase was very insignificant in most cases. The effect of loading angle on the energy absorbed was also studied. From Fig. 8 there is no evidence to suggest that the loading angle has an effect on the energy absorbed. This could be due to the fact that the difference in pulling angles is very small (15°), thus further tests in the future on a wider range of pulling angles, would allow better conclusions to be made on the effect of pulling angle on the energy absorbed.

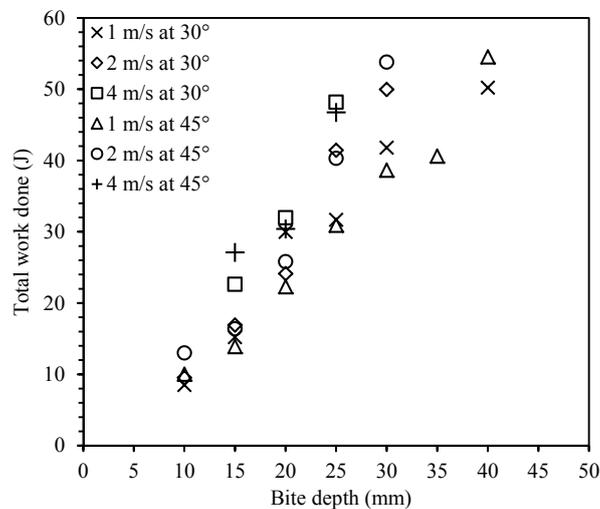


Fig. 8 Energy absorbed against bite depth.

5. Conclusion

This work has experimentally investigated the strength of single sided silicone joints that are commonly used where protection against blast is required. Experiments were conducted at loading angles of 30° and 45°, and displacement rates of 1m/s, 2m/s and 4m/s, which are representative of that encountered when a laminated glass panel undergoes blast loading. The tests were carried out on samples with bite depths in the range of 10mm-40mm, in increments of 5mm. A total of 29 samples were tested. The load, displacement and time were measured during the experiment. From this, the strength and the total work done in the experiment were calculated.

The failure force showed a linear escalation with increasing bite depth. However for a given loading angle and test speed, the strength of the joint was constant, independent of the bite depth. The strength showed to be greater, at higher displacement rates. Depending on the testing rate, the strength varied between 1.26MPa and 2.33MPa at 30°, and between 1.23MPa and 2.84MPa at 45°. For engineering design purposes, it is recommended that a strength of 1.2MPa is taken with a suitable safety factor.

The total work done on the silicone joint was also calculated. At a specific pulling angle and displacement rate, the energy absorbed showed an increase at increasing bite depth. This was expected, as further energy is required to tear through the additional bite depth of silicone. The increase in energy absorbed at greater displacement rates was found to be trivial. The effects of loading angle on energy absorbed during the experiment was also identified to be negligible.

The strength was plotted against testing angle and it was concluded that there was no correlation between the loading angle and joint strength for the range of angles tested. This could be because the difference in loading angle was only 15°. It was concluded that future tests will need to be carried out at a wider range of loading angles, so that trends could be identified more clearly.

Acknowledgements

The authors acknowledge the Engineering and Physical Sciences Research Council (EPSRC) and Arup Resilience, Security and Risk for financially supporting Mohammad Amin Samieian since the beginning of his PhD. The authors also thank Sika Services AG Building Systems & Industry for preparing, manufacturing and providing the test specimens.

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