engineered transparency. International Conference at glasstec, Düsseldorf, Germany
21 and 22 October 2014

Experimental study of structural adhesives for a steel-glass connection

Paulo J. S. Cruz*, Raquel Pardal[a], Isabel B. Valente[b]

* ISISE, School of Architecture, University of Minho
Campus de Azurém, 4800-058 Guimarães, Portugal.
pcruz@arquitectura.uminho.pt

[a] ISISE, School of Architecture, University of Minho, Guimarães, Portugal

[b] ISISE, Department of Civil Engineering, University of Minho, Guimarães, Portugal

Abstract

This communication highlights the study of glass-steel interface behaviour where the adhesion is achieved by gluing these two materials. The investigation consists on the experimental study of externally reinforced glass specimens with steel plates, using two adhesive systems with different characteristics. The focus of this experimental study is to analyse the effects of temperature and cyclic loading on the structural response of adhesive system. To do so, all the specimens are submitted to a series of pull-out test that are performed at +23 ºC, +40 ºC, +70 ºC, and also a series of cyclic tensile loading (only at room temperature). The connection behaviour and interface failure mode are evaluated.

Keywords: structural glass, adhesives, steel, temperature, cyclic loadings, pull-out tests

1 Introduction

The use of glass as a structural material has some disadvantages compared to other traditional materials, highlighting its reduced tensile strength and brittle behaviour. One of the solutions found to increase the strength and ductility of the glass is its association with other material (Louter [1]). The adhesive bond is a solution that has been studied by several authors (Overend [2]; Nhamoinesu [3]; Carvalho [4]; Louter [5]; Machalická [6]), since it provides an adhesion with full transparency, avoiding the use of any mechanical connection, openings or application of bolted connections. In this case, the load transfer between the glass and the reinforcing material is accomplished by an adhesive layer and consequently, the post-breakage behaviour of reinforced glass is dependent of this transfer. However, the bond strength can be variable when submitted to thermal and cyclic loadings, due to the viscoelastic properties of structural adhesives.

In this sense, the experimental study allows to evaluate the behaviour of the glued interface between glass and steel when subjected to different temperatures and cyclic tensile loads. This work aims to contribute to the future study of externally reinforced glass beams with steel elements through a high performance adhesive system, taking into consideration the presence of combined bending and shear stresses.

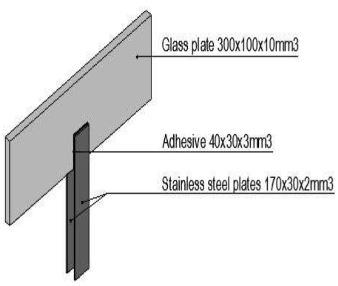
2 Selection of adhesive systems

The selection of adhesive systems was based on previous research of existing products on the market, contact with companies that produce or sell these materials and consultation of existing literature. Based on studies conducted by Louter [1] and Overend et al [2], it was possible to select the most suitable adhesives, with the following basic criteria: high shear strength; different levels of ductility; minimal loss of strength after exposure to different temperatures, ease of handling and quickly curing time. The adhesive systems selected were the 3M two-parts epoxy DP490 and the Huntsman two-part acrylate Araldite 2047.

3 Specimens description

All tested specimens are constituted by a simple rectangular plate of tempered glass with the dimensions of 300×100×10 mm^3. On each side of the glass plate were glued two AISI 304 stainless steel plates with dimensions 170×30×2 mm^3. The stainless steel plates were bonded with precision so as to be parallels. It is impossible to guarantee that an equal force is obtained in the two adhesive joints, with a symmetrical test configuration, but instead an average value of the force is divided by the two interfaces. All dimensions have a tolerance of ±1 mm. The specimen setup is shown in Figure 1a). The bonding area has 40 mm high by 30 mm width and the thickness of the adhesive has a value of 0.3mm. In order to ensure the adhesive thickness of 0.3 mm in all specimens, was placed a spacer between the two stainless steel plates during bonding and curing time, as is shown in figure 1c).

a) Specimen



b) Scheme of specimen

c) Detail of the spacer and adhesive bond

Figure 1: Specimen setup

All surfaces of steel and glass were carefully cleaned with isopropyl alcohol before applying the adhesive. In the contact zone, the stainless steel plates were sanded before applying the adhesive to allow greater adhesion between the two materials. The curing time for all specimens was 72 hours, independent of the adhesive used.

4 Test procedure

The test setup is shown in Figure 2. The tests were performed with the machine Microtest EM1/50 which has a maximum capacity of 50 kN.

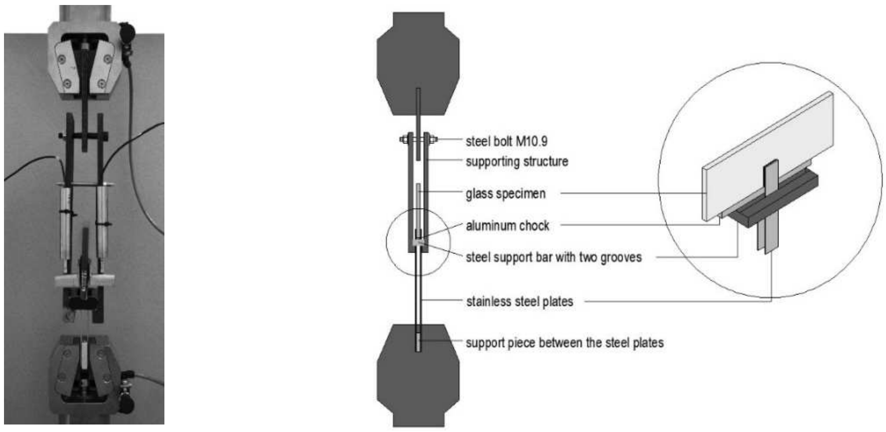


Figure 2: Test configuration

The specimen is supported on two steel pieces that are fixed to the upper of Microtest machine. A steel piece was designed with two grooves that ensure the support of the specimen at the top of machine and allow the crossing of both stainless steel to the lower part of the machine. The displacement is imposed on the lower part of machine where the two stainless steel plates are fixed. Therefore, it was possible to impose equal values of slip between the steel plates and glass in both adhesive joints. Among the steel piece with two grooves and the specimen is placed an aluminium wedge which has a modulus of elasticity equal to the glass, preventing the occurrence of stress concentration in the contact zone and the consequent premature failure of the glass. In order to measure the slipping between steel plates and glass in the adhesive bond, were design two additional steel pieces that were glued on each stainless steel plate.

Monotonic tests were displacement controlled and a displacement rate of 0.2 mm/min was applied for all specimens. At the beginning of each test, was applied a pre-load of 0.5 kN with a displacement rate of 5 mm/min. The tests were divided into three series for the three levels of temperature: 23 ºC, 40 ºC and 70 ºC. In each test series were tested at least three specimens for each type of adhesive. The specimens tested at 40 ºC and 70 ºC were previously heated for 24 h in the Fitoclima 300 climate chamber with a constant temperature and relative humidity of 50 %.

Cyclic tests were divided into three series. In each series of tests were performed eight cycles and controlled with loading rate of 2 kN/s. After end of cycles, all specimens achieved failure with displacement control and rate of 2 mm/s. At the beginning of each test, was applied a pre-load of 0.5 kN with a displacement rate of 5 mm/min. The tested adhesive was the Huntsman Araldite 2047. The definition of minimum and maximum limits for each series of cycles had as a benchmark, the maximum capacity obtained by the adhesive Araldite 2047 in the monotonic pull-out test at temperature of 23 ºC. In the Table 3 are presented the parameters for each series of cyclic tests.

Series	Specimens	Cycles	Lower limit [% P_{max}]	Upper limit [% P_{max}]	Loading rate (cycle) [kN/s]	Displacement rate up to failure [mm/min]
I	3	8	25	50	2	2
II	3	8	50	75	2	2
III	3	8	65	90	2	2

Table 3: Parameters for the cyclic tests

The average temperature measured in the test room was 23 ºC with an average relative humidity of 55 %.

5 Results of monotonic pull-out tests

The results achieved by monotonic tests at different temperatures are presented in Figure 4. In the force-displacement diagrams are represented one of three tested specimens for each series of temperature: 23ºC, 40ºC and 70ºC.

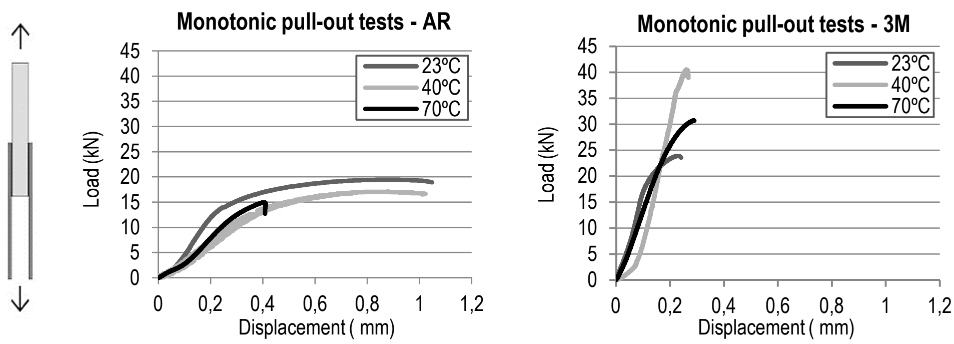


Figure 4: Force-displacement diagrams for the monotonic tests for different temperatures

5.1 Temperature of 23 ºC

All Araldite 2047 specimens experienced plastic deformation before failure and exhibited a lower load capacity in comparison with 3M DP490 adhesive. The mean load capacity of the three tested specimens was approximately 20.39 kN. In all specimens was observed failure at the steel/adhesive interface. The 3M DP490 specimens showed brittle behaviour, although they presented a higher mean load capacity. Failure at the steel/adhesive interface at relatively low values of slip was observed in all specimens. The mean load capacity of the three tested specimens was approximately 24.37 kN.

5.2 Temperature of 40 ºC

There is a significant difference between the behaviour of the two structural adhesive systems. In the Araldite 2047 tests, was observed a mean load capacity loss of approximately 15 % compared with the results obtained at ambient temperature. The mean load capacity of the three tested specimens was approximately 17.26 kN. However, all specimens showed failure at the steel/adhesive interface with plastic deformation prior to failure. In the 3M DP490 tests, glass failure was observed at relatively low values of slip. It was only possible to obtain the load capacity of the adhesive until the glass failure. It was concluded that the adhesive showed higher load capacity in comparison with the results obtained at ambient temperature, since no failure occurred at the adhesive/glass interface. The mean load capacity of the three tested specimens was approximately 39.82 kN, corresponding to the glass failure.

5.3 Temperature of 70 ºC

In the Araldite 2047 tests was observed a mean load capacity loss of approximately 27 % in comparison with the results obtained at ambient temperature and 13 % compared to the results obtained at 40 ºC. The mean load capacity of three tested specimens was approximately 14.94 kN. Failure at the glass/adhesive interface was observed in all specimens. The 3M DP490 specimens showed a brittle failure without plastic deformation prior to failure. Glass failure at relatively low values of slip was observed in all specimens. It was only possible to obtain the load capacity of the adhesive until the glass failure. It was concluded that the adhesive showed higher load capacity in comparison with the results obtained at ambient temperature, since no failure occurred at the adhesive or steel/glass interface for higher load values. The mean load capacity of three tested specimens was approximately 27.80 kN when glass failure occurred.

In all monotonic pull-out type tests wasn't observed failure modes associated with glass embedment by compression or associated with stainless steel plates. Failure modes are represented in Figure 5.

Figure 5: Failure modes for the monotonic tests: Adhesive failure (left); failure at the steel/adhesive interface (center); glass failure (right)

6 Results of cyclic pull-out tests

The achieved results by three series of cyclic tests are presented in Figure 6. In the force-displacement diagrams are represented one of three tested specimens for each series.

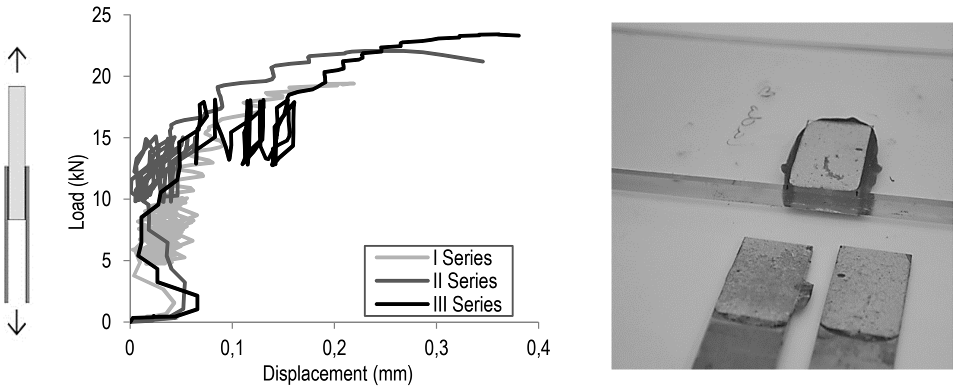


Figure 6: Force-displacement diagrams for the cyclic tests at 23ºC (left); Adhesive Failure (right)

6.1 I Series

In the first series of tests, the adhesive exhibited a mean load capacity of approximately 21 kN. Adhesive failure at very low slip values was observed in all specimens.

6.2 II Series

In the second series of tests, the mean load capacity was approximately equal to that obtained in the first series of cyclic tests (21 kN). However, all specimens showed adhesive failure with plastic deformation prior to failure.

6.3 III Series

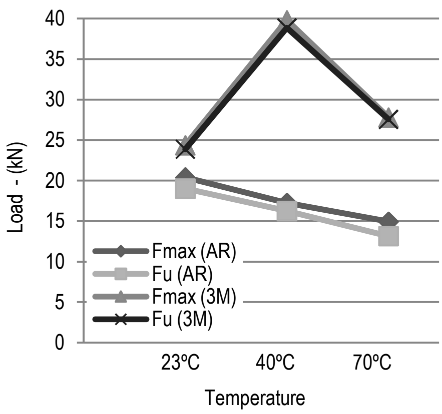
In the third series of tests, the mean load capacity was approximately 26 kN. However, all specimens showed failure at the glass/adhesive interface with plastic deformation prior to failure.

In all cyclic pull-out tests wasn't observed failure modes associated with glass embedment by compression or associated with stainless steel plates.

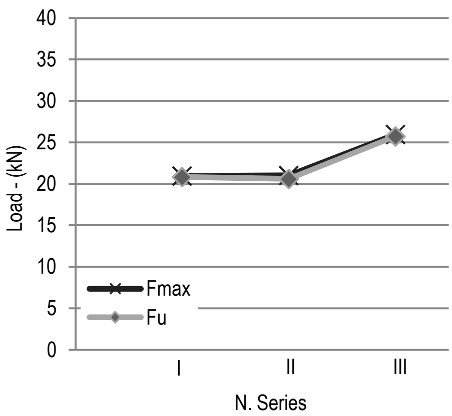
7 Conclusions

The main purpose of this paper was to identify and compare the behaviour of the glued interface between glass and steel when subjected to different temperatures and cyclic tensile loads at 23ºC.

In Figure 7 and Table 8 are presented the comparative results of the mean load capacity of the monotonic and cyclic tests.



a) Monotonic test with different temperature



b) Cyclic tests at 23ºC

Figure 7: Comparative graphs between monotonic and cyclic tests

	Mean maximum load	Mean failure load	Mean extension at maximum load	Mean extension at failure load
	[kN]	[kN]	[mm]	[mm]
Monotonic pull-out tests				
Araldite 2047				
23ºC	20.39	19.01	0.69	0.81
40ºC	17.26	16.26	1.05	1.17
70ºC	14.94	13.16	0.44	0.49
3M DP490				
23ºC	24.37	23.89	0.21	0.21
40ºC*	39.82	38.86	0.28	0.29
70ºC*	27.80	27.57	0.30	0.30
*glass failure: load capacity of adhesive before glass failure.				
Cyclic pull-out tests				
Araldite 2047				
I	20.96	20.84	0.32	0.33
II	21.03	20.61	0.27	0.35
III	25.98	25.74	0.41	0.44

Table 8: Numerical results of monotonic and cyclic pull-out tests

Based on the results achieved by monotonic and cyclic pull-out tests, it can be concluded:

- The Araldite 2047 adhesive has a good structural performance for the type of connection studied; in the specimens were observed adhesive failure or failure at the adhesive/glass interface and showed good shear strength; the percentage maximum loss of load capacity was only 27 %; the adhesive exhibited significant plastic deformation; easy handling; the effect of the cyclic loading does not significantly affect the load capacity of the adhesive Araldite 2047, having been observed a decrease of plastic deformation when compared to the results obtained in monotonic tests at ambient temperature.
- The 3M DP490 adhesive showed higher load capacity in all monotonic tests; the adhesive exhibited lower values of load capacity in the tests at 23ºC; brittle failure at very low slip values was observed; glass failure in tests at 40ºC and 70ºC: it was only possible to obtain the load capacity of the adhesive until to glass failure; easy handling.

8 Acknowledgement

This work is funded by FEDER Funds, through the Operational Programme Competitiveness Factors – COMPETE, and Portuguese Funds, through FCT - Foundation for Science and Technology, under the project PTDC/ECM/116609/2010, S-GLASS – Structural Performance and Design Rules of Glass Beams Externally Reinforced.

9 References

[1] Louter C.: Adhesively bonded reinforced glass beams. In: *Heron*, 52 (1/2), 2007, pp 31-58.

[2] Overend M.; Jin Q, Watson J.: The selection and performance of adhesives for steel-glass connection. In: *International Journal of Adhesion & Adhesives*, doi:10.1016/j.ijadhad.2011.06.001, 2011, pp 587–597.

[3] Nhamoinesu S.; Overend M.: The mechanical performance of adhesives for steel-glass composite façade system, In: *Proceedings of Challenging Glass 3*, Delft, Holland, 2012, pp 293-306.

[4] Carvalho P.; Cruz P.; Veer F.: Perforated steel plate to laminated glass adhesive properties, In: *Glass Performance days*, Tampere, Finland, 2011, pp 219-223.

[5] Louter C; Fred Veer.: Redundancy of reinforced glass beams, temperature, moisture and time dependent behaviour of the adhesive bond, In: *Proceedings of Challenging Glass 2*, Delft, Holland, 2010, pp 479-490.

[6] Machalická K.; Eliášová M.: Influence of various factors to mechanical properties of glued joint in glass, In: *Proceedings of the second international conference on structures and architecture*, Guimarães, Portugal, 2013, pp 321-328.