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Fatigue and Creep Behaviour of Stainless Steel / Glass / SentryGlas® Joints

F.A. Veer [a], A.C. Riemslag [a], P. Cruz [b] & P. Carvalho [b]
[a] *Delft University of Technology, f.a.veer@tudelft.nl*
[b] *University of Minho*

Abstract: SentryGlas® foil has been used for over a decade as a laminating foil but also to bond metal inserts to glass. Most famously in the Apple cube and other Apple buildings and staircases. Although the joint is transparent and statically strong, little is known about the long term behaviour. Specimens were prepared of perforated stainless steel and glass. These were laminated using SentryGlas® foil. Tensile tests, fatigue tests and creep tests were conducted at room temperature and additional creep/fatigue tests at 40°C. The results are analysed and conclusions about the mechanisms involved and the safety are drawn.

Keywords: SentryGlas® , glass stainless steel connection

1. Introduction

The SentryGlas® laminating foil has been used for some 20 years. It is widely recognized as the best interlayer for safety glass. It has also been increasingly used to make connections of glass to metal. In fact SentryGlas® is the connecting medium that keeps the apple cube together.

Google scholar finds some 249 papers referring to SentryGlas® at February 1th 2016. Most of these do not deal with creep and fatigue behaviour. Callewaert et al. demonstrate the temperature effect of the mechanical properties. Louter et al. show there are effects of humidity and thermal cycling on SentryGlas® joints. Di Carvalho shows that the SentryGlas® stainless steel connection can debond under the influence of humidity if not sealed.

However most papers only focus on the good properties of SentryGlas® laminates. There is however thus an open question if a structural joint of stainless steel/ SentryGlas® / float glass is safe under long duration loading.

Thus a testing program to look at creep, fatigue and creep/fatigue problems was initiated.

2. Experimental method

Specimens were made of perforated stainless steel embedded in annealed float glass using two layers of SentryGlas® foil. These specimens were tested in a Zwick z100 and Zwick z10 testing machine using the Zwick 2015 software for cyclic and creep loading. The setup is shown in figure 1. The perforated stainless steel of thickness 1 mm, had a width of 36 mm. One side had an embedded length of 57 mm, the other of 120 mm. In tension the glass is the weakest point although the stainless steel deforms before the glass breaks. The SentryGlas® is not the weakest link at room temperature as is shown in figure 2. As shear stresses for the perforated steel cannot be exactly calculated only the applied loads are given.

Using these specimens a series of creep and fatigue tests were conducted at room temperature, which were followed by a series of fatigue tests at 40°C with different hold times to look at the creep fatigue interaction.

Fig. 1 Test setup

Fig. 2 Specimen after tensile test

3. Room temperature creep test results

Test were conducted at 4000 N and 6000 N. At 4000 N a deformation from 1.0 to 1.23 mm was obtained after 3600 seconds. At 6000 N the deformation increased rapidly due to deformation of the SentryGlas® from an initial 3.8 mm to 6.6 mm in 150 seconds after which the test was stopped. No elongation of the stainless steel or damage was visible.

It was concluded that at 4000 N load there is some creep effect but that this slows down significantly in time. At 6000 N the initial creep rate is high and there is some slowing but the creep rate remains significant and does not stabilize.

Figure 3 shows the creep at 4000 N load and figure 4 at 6000 N load.

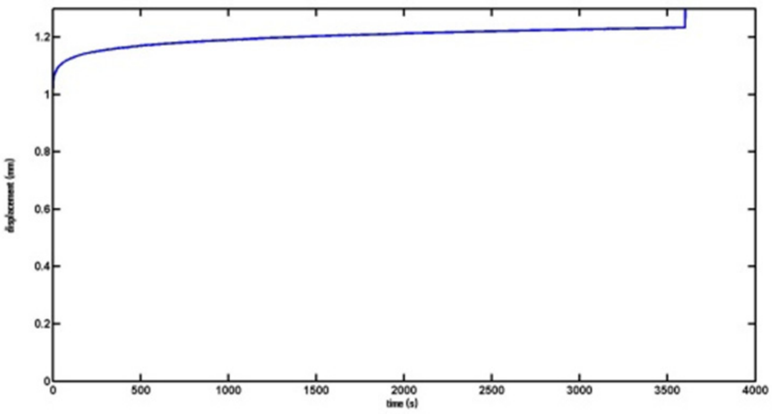

Fig. 3 Creep at 4000 N load

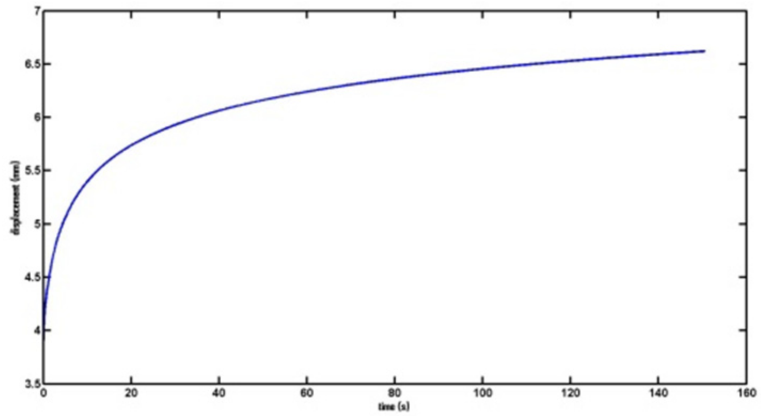

Fig. 4 Creep at 6000N load

4. Room temperature fatigue

As 4000 N seems to be close to the maximum load allowable from a creep perspective, this was also chosen as the maximum load in fatigue. A series of test were started with the load cycling from 4000 N to 400 N (load ratio of 0.1) with variable hold times at maximum and minimum. The tests are summarized in table 1.

Table 1: fatigue tests conducted

Test number	Maximum load (N)	Minimum load (N)	Hold time at maximum load (s)	Hold time at minimum load (s)
1	4000	400	0.1	0.1
2	4000	400	1	1
3	4000	400	5	5
4	4000	400	5	20

Some tests were interrupted and allowed to recover for 24 hours to see if fatigue properties recover. All test were done at least twice. The tests were found to be very reproducible. Figure 5 shows the results of two identical test using a hold time of 0.1 s with an interruption of 24 hours. Figure 6 shows the initial cycles of the test with an hold time of 5 seconds at maximum and 20 seconds at minimum. Figure 7 shows the full test.

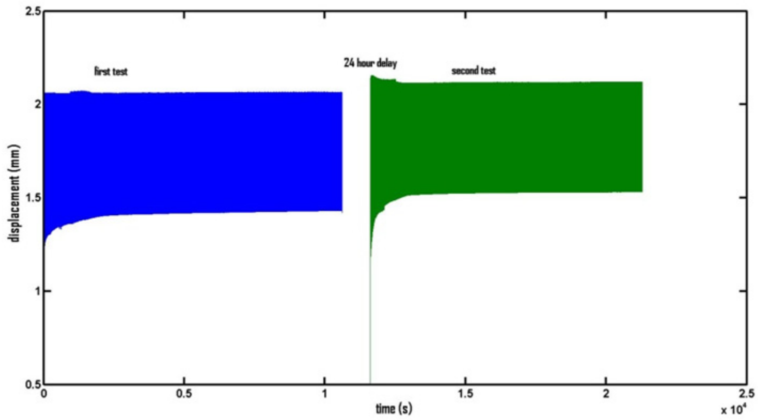

Fig. 5 Results of test with a hold time of 0.1 s and interruption of 24 hours in the middle of the test.

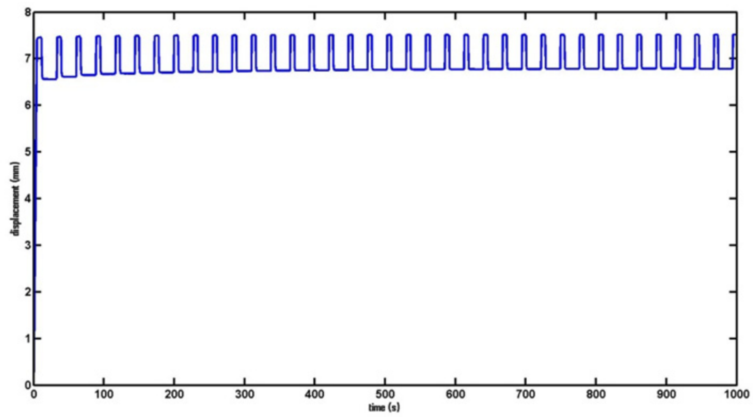

Fig. 6 Initial cycles of test with a hold time of 5 seconds at maximum and 20s at minimum load.

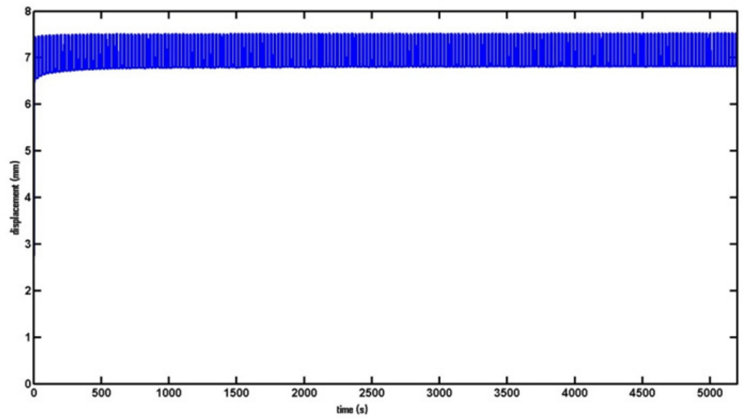

Fig. 7 Full test with a hold time of 5 seconds at maximum and 20s at minimum load.

The results show that at this load and temperature the displacement stabilizes within 50 cycles and does not change. If the specimen is allowed to relax, the properties recover and a second test has identical results to the first test. There is no significant effect of hold time on displacement. There is no evidence of damage accumulation during cycles.

5. Fatigue tests at 40°C

As the room temperature tests were very positive, additional tests were conducted at 40ºC. This because facades, and thus the connections, can easily reach 40ºC in summer even in a moderate climate. The tests are summarized in table 2.

Table 2: Fatigue tests conducted at 40ºC

Test number	Maximum load (N)	Minimum Load (N)	Hold time at maximum load (s)	Hold time at minimum load (s)
1	4000	400	1	1
2	4000	400	2	2
3	4000	400	5	5
4	4000	400	5	5

The initial cycles of tests 1 and 3 are given in figures 8 and 9. The full results of tests 2 and 3 are given in figures 10 and 11.

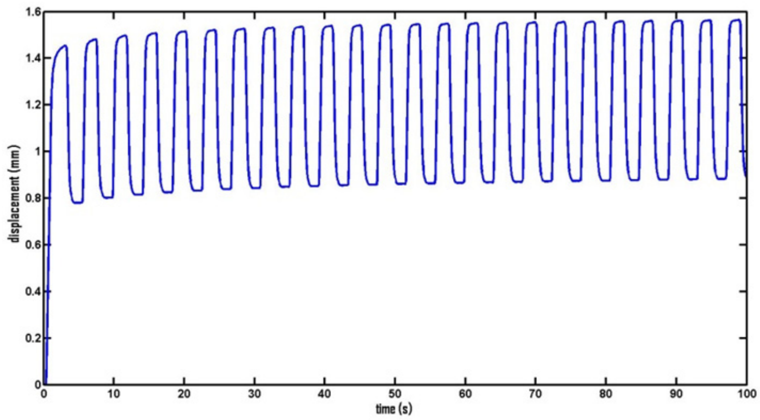

Fig. 8 Initial cycles of test at 40ºC with a hold time of 1s.

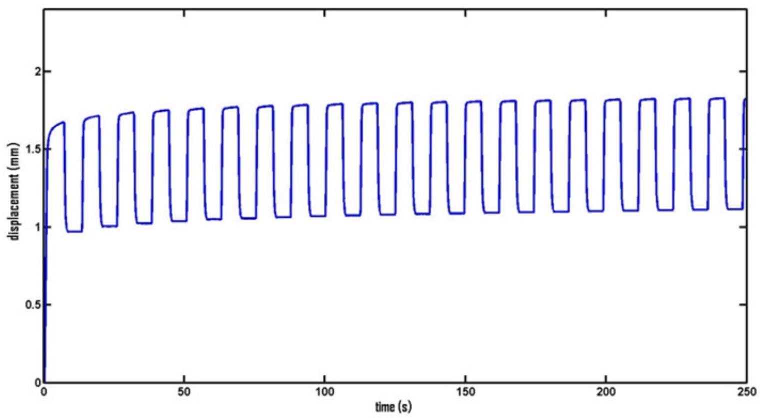

Fig. 9 Initial cycles of test at 40ºC with a hold time of 5s.

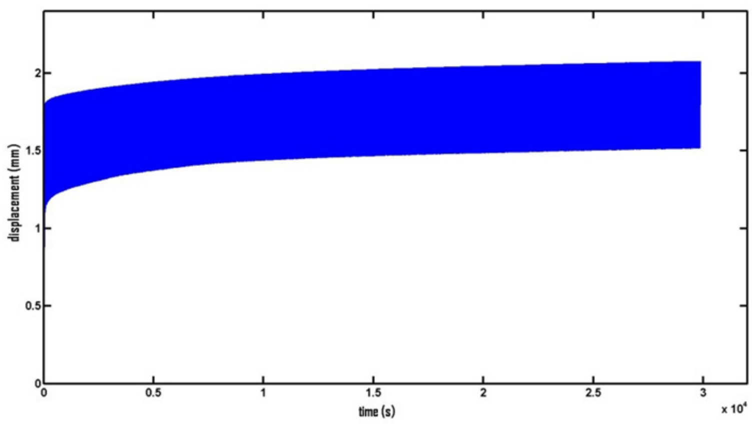

Fig. 10 Results of full test at 40°C with a hold time of 2s

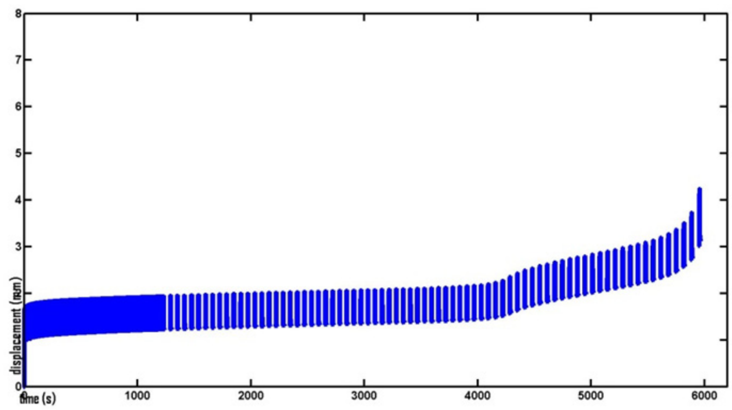

Fig. 11 Results of full test at 40°C with a hold time of 5s at maximum and minimum load.

6. Discussion

Thermoplastic polymers have according to van der Vegt three types of deformation under stress.

- Elastic deformation that is immediately recovered when the stress is released.
- A time dependent elastic deformation that builds up under stress and slowly recovers when the stress is released.
- Non-elastic deformation that slowly forms under tension and is not recovered when the stress is released.

The proportions of these three are according to van der Vegt heavily dependent on temperature and molecular weight. The results can be explained using these three deformation mechanisms. At room temperature there is initial elastic deformation and a time dependent elastic deformation. At the applied load level this saturates after a number of cycles and the deformation does not increase. If the test is stopped, the elastic and time dependent elastic deformation are recovered. If the test is restarted the specimen effectively behaves as if it was never tested at all, as is seen in figure 5. At 40°C this changes as the non-elastic deformation plays a role. As can be seen in figure 9, each cycle at maximum load the displacement increases slightly while this is not recovered at minimum load. The deformation which at room temperature is independent of the hold time, at 40°C is highly dependent on the hold time as is seen in figure 12. The test with a hold time of 2s having a greater displacement than the test with a hold time of 1s. The hold time of 5s gives initially a higher displacement but this increases at a given point, presumably because the cumulative deformation has eliminated the reserve capacity of the SentryGlas® and then rapidly accelerates to failure. One of the glass panels then falling of the specimen as is seen in figure 13. The stainless steel is pulled out and is no longer anchored in the SentryGlas® foil.

As the area of perforated steel is some 36×57 mm, allowing for a 50% perforation the shear stress is around 2 MPa. At room temperature this does not cause fatigue, at 40ºC this can cause total delamination if enough time for creep exists at the top of the fatigue cycle. Presumably higher loads at room temperature and higher temperatures with low hold times will have similar behaviour. This will be an object of future research.

From an engineering safety point of view test results at room temperature clearly do not have to be representative of test results at higher temperatures, which however can still occur in the construction. The focus on the static behaviour of SentryGlas® connections thus neglects the serious risk of fatigue of these connections.

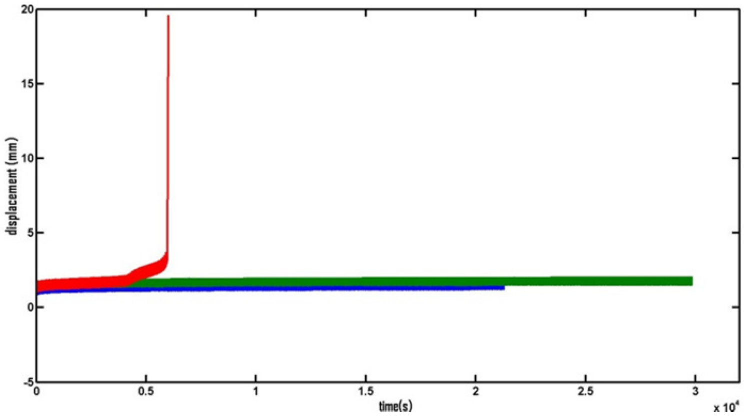

Fig. 12 All tests at 40ºC

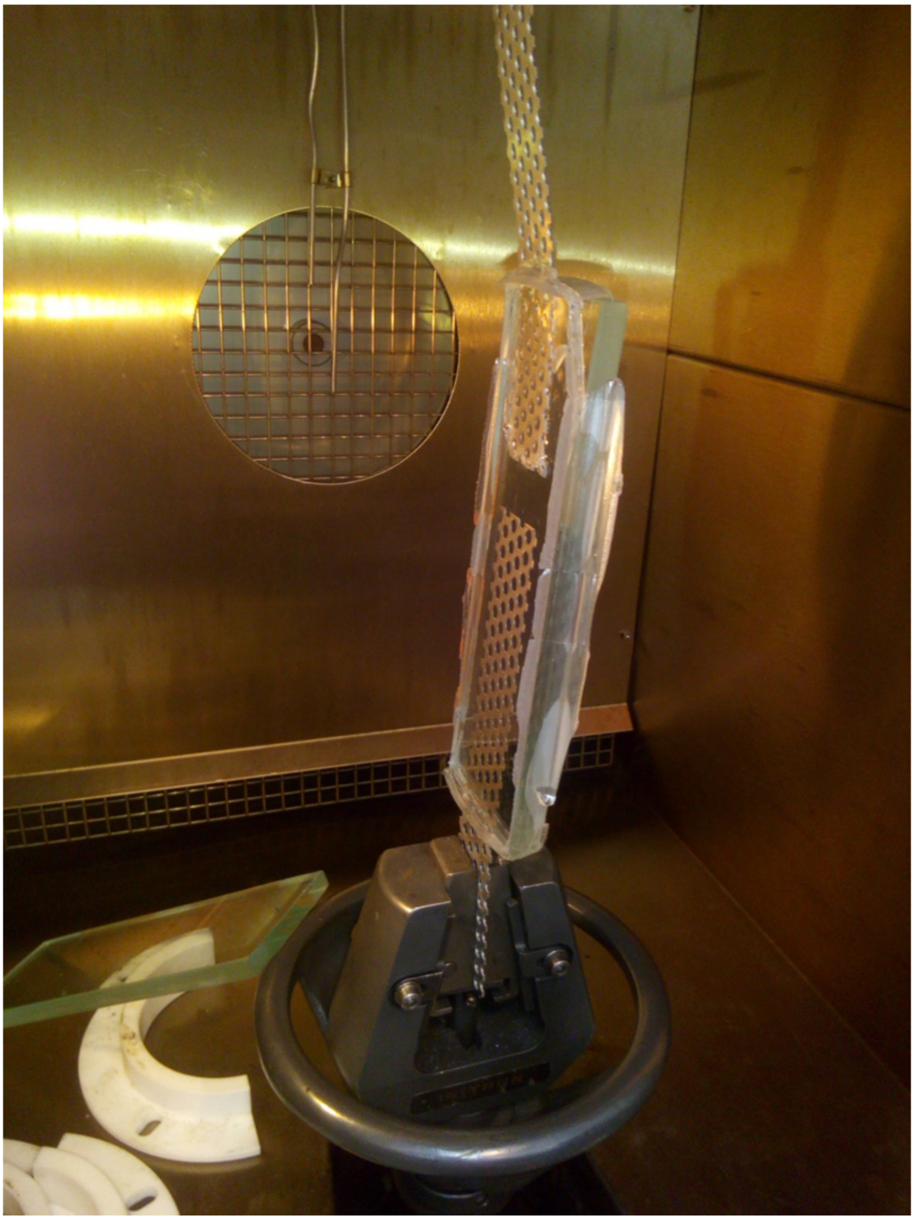

Fig. 13 Specimen 4 after testing at 40°C

Fig. 14 Pulled out stainless steel of specimen 3 tested at 40^{0}C

7. Conclusions

From the results the authors conclude that the fatigue behaviour of glass/ SentryGlas® / stainless steel connections follows from the elastic/time dependent elastic/ non elastic stress/strain behaviour of the SentryGlas® foil. In situations where the non-elastic stress/strain behaviour is not involved the combination essentially shows no fatigue behaviour. Where the non-elastic stress/strain behaviour however occurs due to higher temperatures/hold times/stresses there is a serious risk of cumulative creep-fatigue damage leading to delamination.

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