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Investigation of Partial Annealing of Acrylic Bond Joints. [1]

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Abstract

Acrylic bond joints were instrumented with strain gauges in order to measure the stress that occurs during the bonding process. Bond samples were then subject to a temperature of 60°C for extended periods and the change in stress levels compared to a reference sample at 23°C. The interpretation of the data is that the elevated temperature resulted in a decrease in the bond joint stress.

1 Introduction

The strongest acrylic bonds are made by injecting methyl methacrylate (MMA) between the pieces of acrylic that are to be joined. As the MMA cures its volume decreases by as much as 12%. Unless the pieces being bonded are

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free to move, tensile stress will occur in the joint, and could eventualy lead to crazing and possible failure of the joint.
The Sudbury Neutrino Observatory (SNO) will contain an acrylic sphere, 40 feet diameter, which will be constructed by bonding approximately 160 acrylic sheets. During the bonding process, the panels will be unable to move to accomodate the shrinkage as the bond cures. The operational life of this vessel is 10 years, during which the likelyhood of crazing must be minimized. Studies have shown that acrylic will not craze during this 10 year period if the stresses are maintained below 800 psi [1]. Other studies have shown that the stress developed in a bond joint may frequently exceed this value [2]. Since the SNO sphere will be operated in compression [3] limited crazing in the joints of the sphere is acceptable, it is desirable to reduce the possibility of crazing as much as possible.
The normal solution to this problem is to anneal the whole component, the optimum temperature profile and duration of the annealing cycle varies with the thickness of the sheet. For two inch thick sheets the cycle lasts for a period of approximately 48 hours with a peak temperature of approximately 100°C. During the annealing period the component must be supported to maintain its shape. While this is technically possible with the SNO sphere, logistic and safety considerations would mean that the cost would be prohibitive. It was decided to investigate if there was any advantage to be gained by locally heating the joint to a temperature below the annealing temperature and at which the acrylic still retains the bulk of its mechanical strength and therefore does not need supporting.

2 Experimental Technique

Three test samples, refered to as A, B, and C, were fabricated from six blocks of acrylic 6.0" wide by 2.5" thick by 4.0" deep. The 6.0" by 2.5" faces were separated by 3/16" aluminum shims which prevent the acrylic blocks moving together as the bonding material cures and shrinks. Prior to injecting the MMA bonding agent, two strain gauges [2], refered to as #1 or #2 and which had previously been bonded to thin acrylic carriers, were inserted in

[2]Gauge type CEA-06-62UW-350, gauge factor 2.115. Micro-Measurements, Raleigh, North Carolina.

the bond gap of each test specimen as shown in figure 1.

The resistance of the gauges were recorded prior to injecting the MMA into the bond gap and after the bond had cured. These resistances were then used to calculate the locked in stress. Unfortunately, strain gauge #2B suffered a broken electrical connection during the curing process and was of no further use.

Test specimens B and C were then inserted in a hermetically sealed foam box which was then placed in thermal contact with a constant temperature water bath. The foam box was provided with a thermocouple to record the temperature inside the sealed box. The remaining test specimen, A, was placed in contact with another thermocouple and left exposed to the ambient temperature of the laboratory as a reference sample.This arrangement of the test specimens is shown in figure 2.

The resistance of the strain gauges, the thermocouple outputs, the humidity of the box and laboratory were recorded on approximately a daily basis. After a period of approximately 33 days the test specimens were removed from the constant temperature enclosure and allowed to return to the same temperature as the reference sample in order to assertain if any reduction in stress remained.

3 Results

Shown in table 1 are the resistances of the strain gauges before and after encapsulation in the bond and the calculated resultant stresses due to shrinkage of the bonding material. It can be seen that all resistances are decreased indicating that the gauge is under compression since the material in which it is encapsulated has contracted. This in turn result in tension across the bond interface. In calculating the stress it was assumed that Youngs modulus for the bond material was the same as that of virgin acrylic (400,000 psi). It can be seen that these stress values are consistent with those reported earlier [2].

Test specimens B and C were then placed in the constant temperature enclosure and raised to approximately 60°C. The temperature profile and the resultant change in the resistance of the strain gauges can be seen in figure 3.

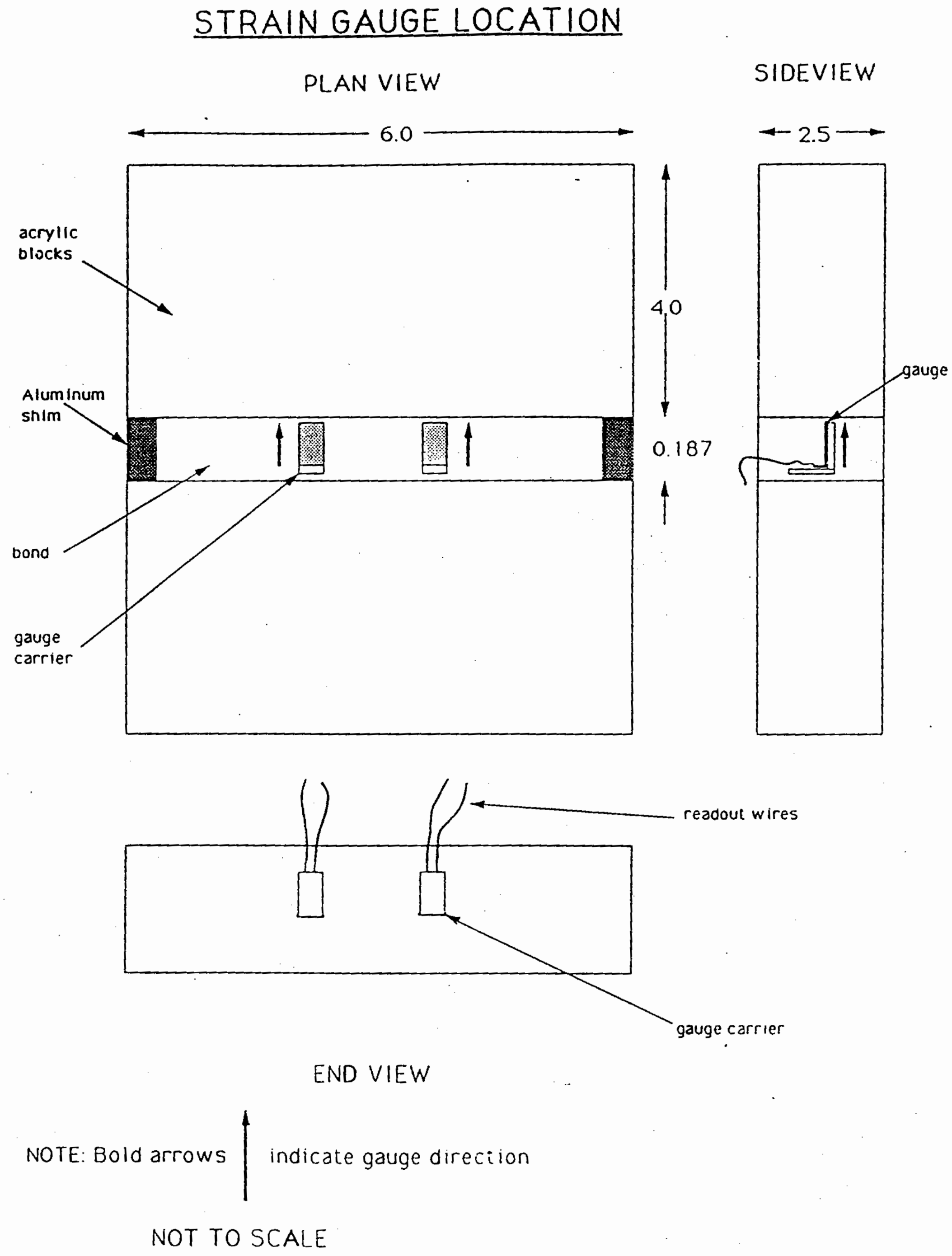

Figure 1: Schematic of the test specimens showing the location of the strain gauges in the bond gap.

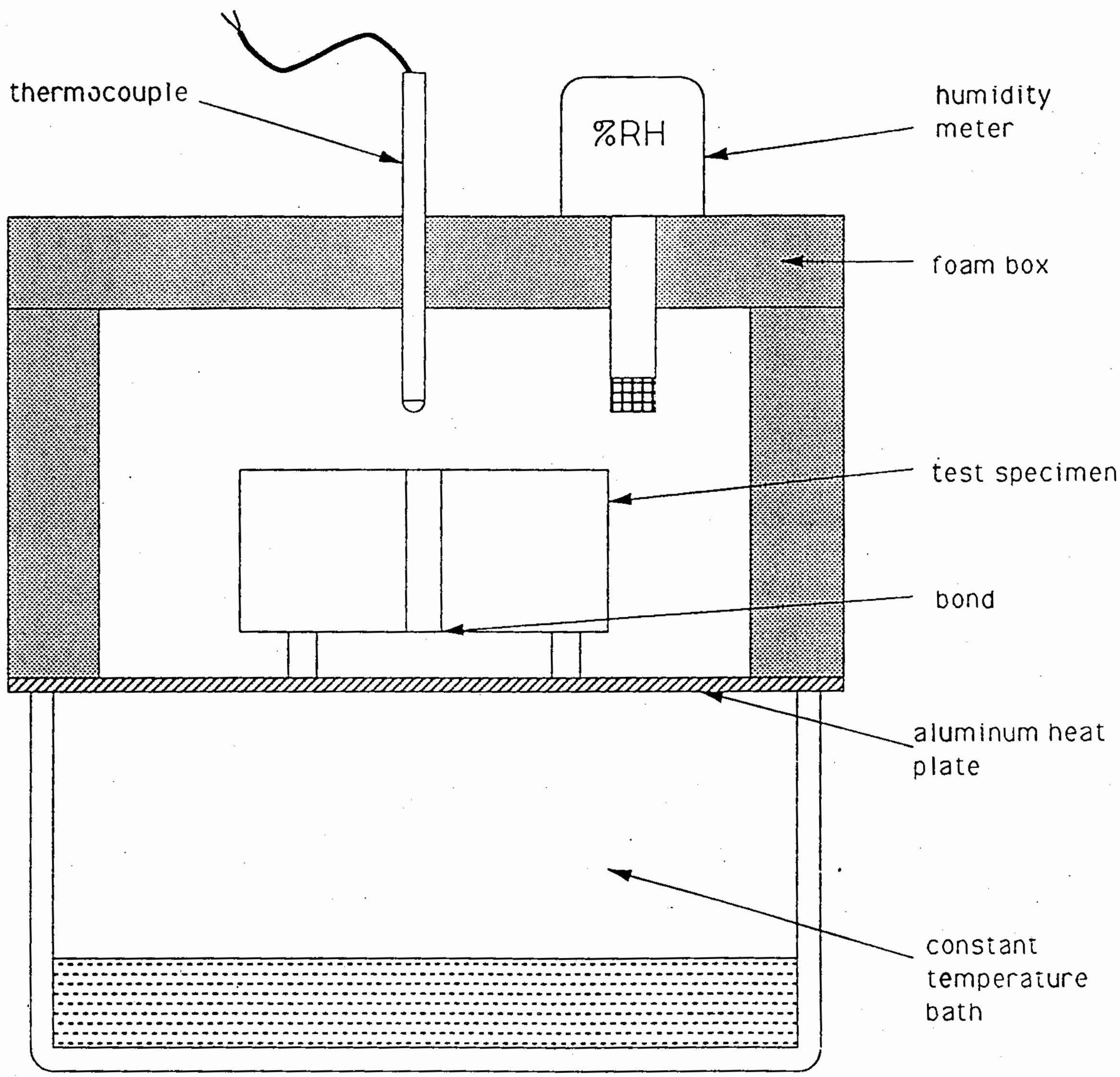

Figure 2: Schematic showing the test specimens arranged in the constant temperature enclosure.

Strain Gauge	1A	1B	2A	2B	3A	3B
Resistance (before)	0.351108	0.350668	0.351004	0.351536	0.351560	0.350691
Resistance (after)	0.349202	0.348042	0.349588	failed	0.350089	0.348877
Stress (psi)	1027	1358	741	failed	744	954

Table 1: Resistance of the strain gauges before and after encapsulation and the calculated stress.

Since the material in which the gauges are encapsulated expands when heated, the resistance of the gauge will increase as it is stretched. The change in gauge resistance and the change in temperature allows a simple check of the operation of the gauges. The average change in the specimen length calculated from the change in resistance is 0.22% while the average change in length calculated from the change in temperature is 0.33%. (Since the coefficient of thermal expansion of the aluminum shims ($25x10^{-6}$ per °C) is less than that of acrylic ($60x10^{-6}$ per °C) it is not neccessary to consider the expansion of the shims). This agreement is felt to be reasonably good and also gives an indication of the errors associated with the technique of embedding strain gauges in acrylic.

Once maintained at a constant high temperature it is seen that the stress appears to increase (i.e. gauge resistance decreases) at a rate which is higher than that of the reference sample. Initialy, this appears contary to expectation, however, the material under stress will creep in a direction that reduces the stress, i.e. they will move together. The strain gauge which is embedded in the bond responds as if it is being compressed and therefore the resistance decreases. The difference in the stress before and after the heating cycle therefore represents the stress relieved due to creep of the material. The residual stress in the bond is therefore the original stress minus the reduction due to creep.

The change in the stress as recorded by the strain gauges in the test specimens while at elevated temperature and the reference specimens over the same period of time is given in table 2. The residual stress calculated in the manner described above is also given. It can be seen that the specimens at elevated temperature undergo a significant decrease in resistance (stress)

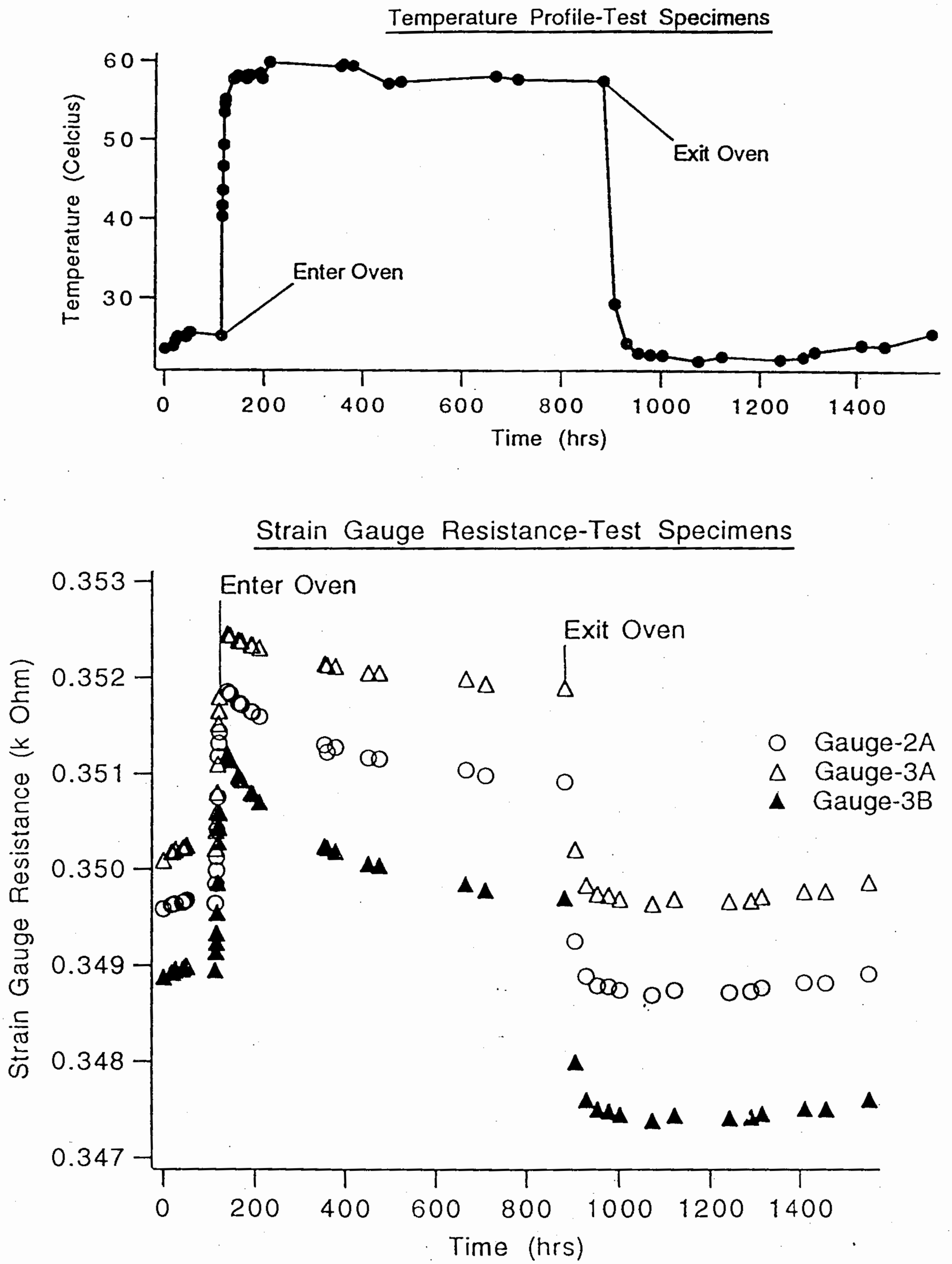

Figure 3: Variation in the temperature and resistance of the test specimen strain gauges throughout the duration of the tests.

Strain Gauge	1A	1B	2A	2B	3A	3B
Stress before heating	1027	1358	741	failed	744	954
Stress after heating	1131	1570	1179	failed	965	1718
Residual stress	1023	1146	303	failed	523	190
Percentage reduction	0.4	16	59	failed	30	81

Table 2: Stress (psi) in bond joints before and after the period of elevated temperature and the resultant residual stress.

compared to the specimens at ambient temperature.

Shown in figure 4 is the temperature profile and the change in gauge resistance of the reference specimen. It can be seen that the gross changes in resistance are correlated to changes in temperature and that the percentage reduction of the stress is significantly less than that in the higher temperature specimens.

4 conclusions and Discussion

Based on the interpretation of the data it is concluded that slight elevation of the temperature of the acrylic bond can result in considerable reduction of the locked in stress. The shape of the curve suggests that the bond material is undergoing second and third stage creep deformation. If so, this is encouraging, since these deformations are non-recoverable the stress will be premanently relieved.

The results and the above interpretation must be treated with caution. The interpretation was driven by what one would simplistically expect to happen to stress when raising the temperature of a plastic material. However, the behaviour of encapsulated strain gauges is not well understood and there are many alternative interpretations of what may cause the response reported. For example, although the strain gauges were chosen for use with high thermal expansion coefficient plastics, it is not known how well the gauge remains embedded in the bond material at elevated temperatures. The decrease in the resistance of the gauge could be due solely to the gauge slipping within the bond and attempting to return to its original dimensions.

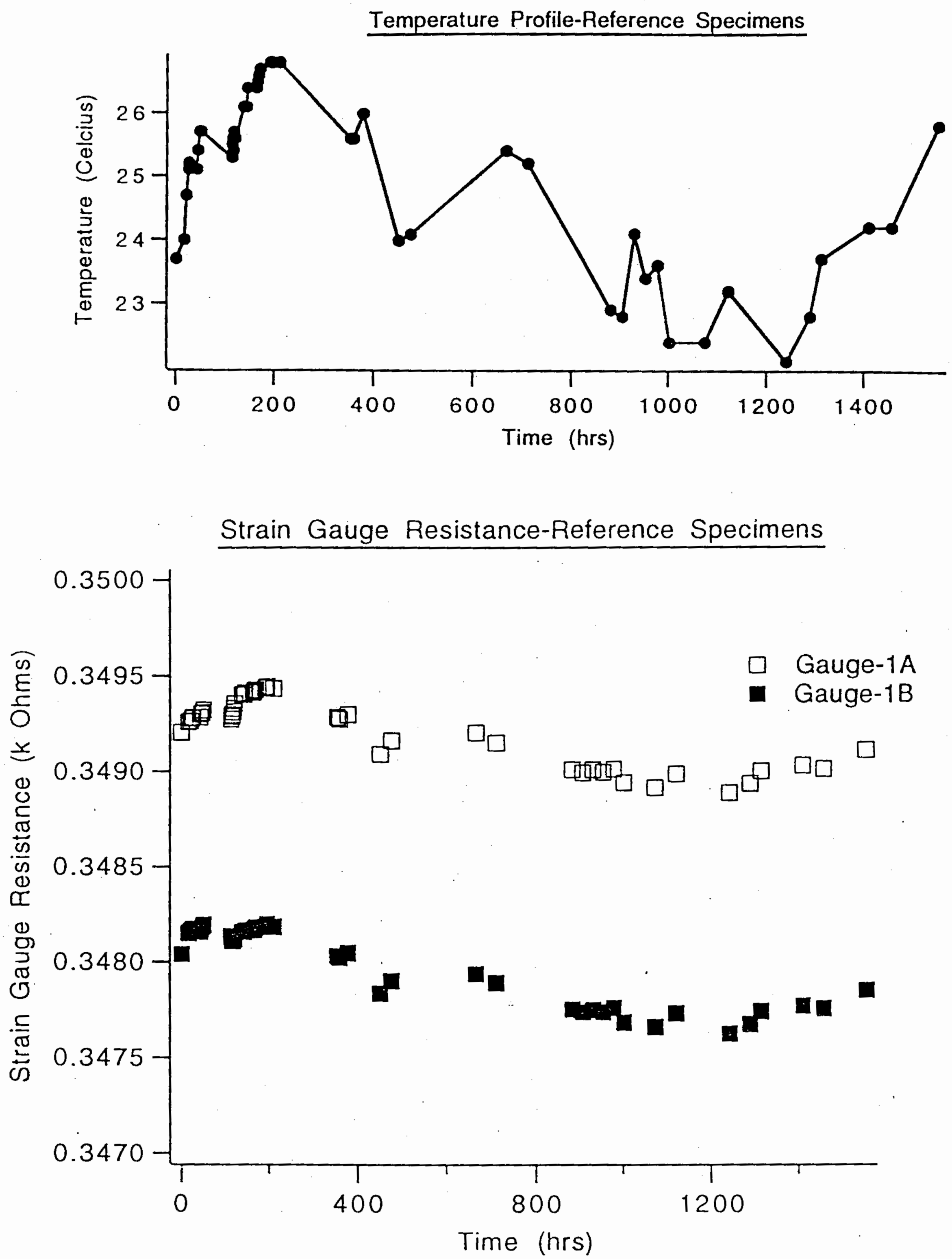

Figure 4: Variation in the temperature and resistance of the reference specimen strain gauges throughout the duration of the tests.

If the shape of the curve really reflects second and third stage deformation, then most of the stress relief will occur in the second stage during the first few 10's of hours, which is compatable with the logistics of the bonding operations. Perhaps the most encouraging aspect of these results is that it may offer an alternative to scraping a bond which has unacceptably high stresses.

A Raw data.

Table 3 shows the raw data obtained in the experiment.

References

[1] "Crazing and Degredation of Flexure Strength in Acrylic Plates as a function of Time", J.D. Stachiw and J.L. Stachiw, Technical Report 1303, Naval Ocean Systems Center, San Diego, CA 92152-5000, June 1989.

[2] "Stress in Acrylic Bond Joints", P. Doe, SNO-STR-91-59, September, 1991.

[3] " technical Position on Selection of Engineering Concept for the SNO Sphere", J.D. Stachiw, Memo, August 9, 1990.

Point	Time.y	Gauge_1A.y	Gauge_1B.y	Gauge_2A.y	Gauge_3A.y	Gauge_3B.y	Temp.y	RH.y	Temp_oven.y
0	0	0.349202	0.348042	0.349588	0.350089	0.348877	23.7	17	23.7
1	17	0.349258	0.348149	0.349629	0.350177	0.348922	24	16	24
2	21	0.349264	0.348158	0.349632	0.350183	0.348927	24.7	15	24.7
3	25	0.349276	0.348168	0.349646	0.350201	0.34895	25.1	14	25.1
4	27	0.349283	0.348173	0.34964	0.35021	0.34896	25.2	13	25.2
5	42	0.349281	0.348158	0.349647	0.350218	0.348958	25.1	15	25.1
6	45	0.349298	0.348173	0.349663	0.350225	0.348974	25.4	20	25.4
7	49	0.349307	0.348185	0.349672	0.350243	0.34899	25.7	19	25.7
8	51	0.34932	0.348195	0.349681	0.350249	0.348988	25.7	15	25.7
9	113.5	0.349272	0.348134	0.349644	0.350217	0.348948	25.3	28	25.3
10	114.25	0.349284	0.348132	0.349846	0.350399	0.34914	25.3	28	40.3
11	114.75	0.349285	0.348122	0.349989	0.350499	0.349237	25.5	29	41.7
12	115	0.349297	0.348116	0.35013	0.350598	0.349334	25.6	29	43.6
13	116	0.349288	0.348112	0.350404	0.350804	0.349545	25.4	29	46.7
14	117	0.349293	0.348107	0.350752	0.351095	0.349855	25.7	27	49.4
15	119	0.34931	0.348118	0.351177	0.351516	0.350283	25.6	26	53.6
16	120	0.349327	0.348117	0.351316	0.35165	0.350435	25.6	25	54.7
17	121	0.349352	0.34812	0.351428	0.3518	0.350585	25.6	22	55.3
18	138	0.3494	0.348157	0.35185	0.35245	0.351199	26.1	17	57.8
19	143	0.3494	0.348155	0.351831	0.352439	0.351157	26.1	16	58
20	145	0.349409	0.348164	0.351824	0.352436	0.351135	26.4	16	58.2
21	163	0.349409	0.348163	0.351735	0.352384	0.350976	26.4	20	57.9
22	165	0.349414	0.348166	0.351731	0.35238	0.350962	26.5	21	58.3
23	167	0.349422	0.348171	0.35172	0.352375	0.350942	26.6	20	58.3
24	170	0.349425	0.34818	0.351714	0.352376	0.350926	26.7	18	58.3
25	191	0.349437	0.348183	0.351645	0.352335	0.350797	26.8	17	58.5
26	195	0.349443	0.348196	0.351638	0.352333	0.350784	26.8	12	57.9
27	210	0.349431	0.348184	0.351589	0.352303	0.350699	26.8	17	59.9
28	354	0.349281	0.348031	0.351299	0.352136	0.350235	25.6	27	59.3
29	359	0.34927	0.348022	0.351221	0.352126	0.350221	25.6	28	59.6
30	378	0.349296	0.348046	0.35127	0.352111	0.350184	26	26	59.4
31	450	0.34909	0.347836	0.35116	0.352044	0.350052	24	22	57.1
32	474	0.34916	0.347901	0.35115	0.352043	0.350036	24.1	23	57.3
33	666	0.349201	0.347938	0.351039	0.351981	0.349845	25.4	32	57.9
34	710	0.34915	0.347889	0.35098	0.35193	0.349781	25.2	29	57.5
35	882	0.349008	0.347751	0.350912	0.351883	0.3497	22.9	32	57.2
36	906	0.348992	0.347736	0.349253	0.350205	0.347997	22.8	37	29.3
37	930	0.349007	0.347749	0.348888	0.349834	0.347598	24.1	28	24.4
38	954	0.348993	0.347737	0.348791	0.34974	0.347499	23.4	28	23.2
39	978	0.34901	0.347758	0.348777	0.349725	0.34748	23.6	36	23
40	1002	0.348939	0.347683	0.348743	0.349688	0.347445	22.4	38	22.9
41	1074	0.348911	0.347661	0.348693	0.349638	0.347388	22.4	35	22.2
42	1122	0.348986	0.347732	0.34874	0.349687	0.347439	23.2	46	22.8
43	1242	0.348886	0.347626	0.348718	0.349666	0.347416	22.1	34	22.4
44	1290	0.348934	0.347675	0.348728	0.349669	0.347418	22.8	34	22.7
45	1314	0.349	0.347743	0.348769	0.349716	0.347459	23.7	26	23.4
46	1410	0.349029	0.34777	0.348822	0.34977	0.347512	24.2	14	24.2
47	1458	0.349009	0.347756	0.348816	0.349766	0.347505	24.2	18	24.1
48	1554	0.349109	0.34785	0.348908	0.349861	0.347601	25.8	31	25.7

Table 3: Raw data.