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DILATATION MEASUREMENTS ON ARTISTIC GLASSES

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ABSTRACT

Building materials and components are often exposed to thermal stresses; in the long run this could be harmful. Effects on fragile materials such as glass could be significant, because they may break if subjected to quick or high fluctuations in temperature. It is a worrying problem if the glass is a work of art. The window surface, irradiated by sunlight, suffers different thermal stresses, depending on the color of the glass elements. Then daily thermal stresses of our typical climate have been evaluated and reproduced in a climatic room where ten glass samples, typically used for artistic window restoration, have been put inside and the thermal expansion coefficient has been evaluated.

INTRODUCTION

The conservation of artistic windows is very important due to the presence, especially in Italy, of numerous historical glasses in all the major Basilicas or Cathedrals of the world. These works of art play a dominant role in iconographical decoration. The causes of glass deterioration haven't only chemical origin; the glass is in fact subject to solar radiation, so they are subject to temperature stress on the surface, with different stress and strain in several points. Moreover the glass is embedded in its original chassis that doesn't allow for thermal expansion, causing the glass to bend until it breaks.

A quantitative evaluation of such phenomena is the aim of this paper; so measurements of thermal strain have been carried out on ten glass samples furnished by a restoration laboratory in Rome and the coefficients of linear thermal expansion have been calculated. An experimental apparatus and a measurement methodology of the deformations have been developed. The strain measurements have been carried out with electrical photoengraving strain gauges; the strain gauge is glued to the surface of a sample; when it is stressed, the correspondent strain is transmitted to the grid causing an electrical resistance variation. Two *twin* strain gauges have been employed for each measurement, one glued on to the sample, the other one on a reference material, the thermal expansion coefficient of which is known. In such a way, considering the difference between the thermal expansion of the sample and the one of the reference material, it is possible to eliminate any systematic error due to the thermal expansion of the strain gauge.

Some indications about the measurement methodology have been supplied by Technical Note TN 513-1 [1], others by ISO 7991 [2]; the measurement uncertainty evaluation conforms to UNI CEI ENV 13005 [3]. [1] has been used as a guide for the choice of the strain gauge, its connections, the preliminary operations before the strain measurements (such as the stability of the strain gauge signal, the elimination of the residual stresses, etc.); the characteristics and the precision of the measurement instrumentation, temperature uniformity in the climatic room and inside the samples have been also defined. [2] refers to the employment of the dilatometer, therefore it has been only employed to define the coefficient of the linear thermal expansion. When evaluating the measurement uncertainty [3], the *a priori* procedure calculation is employed, based on the uncertainties in the parameters measured for the calculation of the coefficient of linear thermal expansion.

NOMENCLATURE

F	gain factor of the strain gauge (-)
L	length (m)
R	electrical resistance (Ω)
T	temperature (°C, K)
T	time (s, h)

Greek Letters

α	coefficient of linear thermal expansion ($°C^{-1}$, K^{-1})
β_G	thermal coeff. of resistivity of the grid material ($°C^{-1}$, K^{-1});
ΔL	variation of length (m)
ΔR	variation of electrical resistance (Ω)
ΔT	variation of temperature (°C, K)
$\Delta\varepsilon$	strain variation between sample and reference material (-)

ε	deformation (-)

Subscripts

G	grid
R	reference
S	sample

EXPERIMENTAL METHOD

Facility

The experimental apparatus (Fig.1) is composed of a climatic room Mazzali mod. C33045, which allows control of temperature (-40 °C ÷ +150 °C) and relative humidity (15% ÷ 100%) in a volume of approximately 0.3 m^3; the glass samples with the electrical strain gauges are placed in the climatic room.

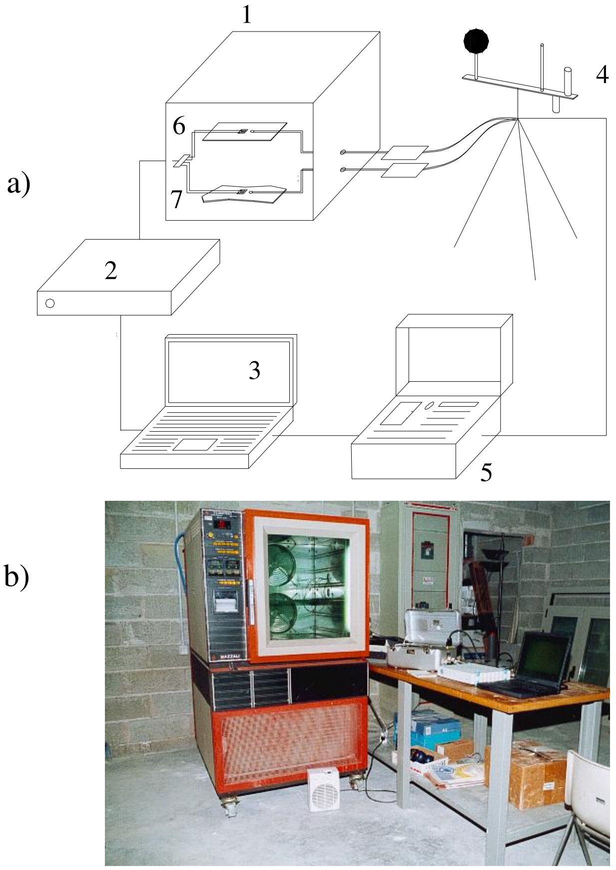

Figure 1: Measurement facility: (a) scheme, (b) view. *1) Climatic room; 2) Multichannel Transducer Spider 8; 3) PC; 4 and 5) Microclimate acquisition system TCR Tecora; 6) Reference bar with strain gauge and surface temperature probe; 7) glass sample with strain gauge and surface temperature probe.*

The strain-gauges are the Micro-Measurements type, series EA-06-125MG-120, produced by Measurements Group (Fig. 2). They are made up of a grid of laminated metal glued onto a support of plastic material; they are sensitive and precise in the temperature range -75°C ÷ +175°C. The number of fatigue cycles depends on the effort value that has been reached when measuring the deformation: 10^8 cycles at 1200 μm/m; 10^6 cycles at 1500 μm/m; 10^5 cycles at 1800 μm/m; 10^4 cycles at 2800 μm/mm for unidirectional solicitations of compression or traction. The gain factor, defined as the ratio between the electrical resistance variation $\Delta R/R$ and the correspondent variation of length $\Delta L/L$, is 2,045 ± 0.5% at 24°C; the cross-sectional sensitivity considers the lateral contraction of the grid and it is about +0,9 ± 0.2% at 24 °C.

In order to eliminate the error due to the thermal expansion of the strain gauge grid we employ two of them, one glued on to the sample, the other is glued on a reference material with a low value of α: a silica-titanium bar has been employed, with $\alpha = 0.03 \times 10^{-6}$ °C^{-1}. The two strain gauges are of the same type and are made by the same manufacturing processes. If high accuracy is required, *twin* strain gauges EA-06-125MG-120 are employed; they are sold coupled and are separated when employed (Fig. 2).

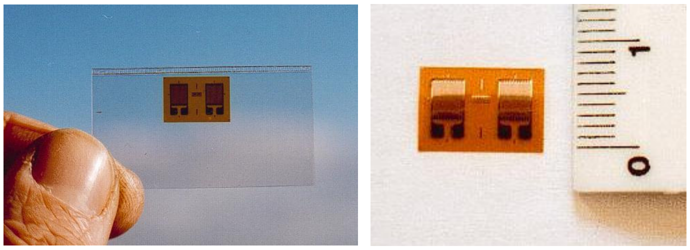

Figure 2: Strain gauge Micro Measurement, series EA-06-125MG-120

The strain gauge signal yields the value of $\Delta\varepsilon$; it is recorded by a multichannel transducer SPIDER 8, equipped with 8 channels for the acquisition of electrical resistance, current, voltage. It is connected to a Personal Computer for data storage and analysis by means of software Catman 2.1. At the same time, the surface temperatures of the sample and of the silica-titanium bar are measured by two NTC (Negative Temperature Coefficient) sensors (accuracy ± 0.04 °C); each one has a purposely realized electronic interface card and transmits the signal to a microclimate data acquisition system TCR Tecora, with optional channels for electrical signals (voltage up to 2500 mV). A tarature curve has been evaluated to transform the electrical voltage in the corresponding value of temperature. The sensors are connected to the sample and to the reference bar by a heat conducting paste. The data of surface temperature are stored and analysed by a PC.

Experimental Procedure

The first step of the experimental procedure is to verify the stability of the strain gauge signal. In the climatic room the temperature is kept constant (24 °C) for three hours, to promote thermal equilibrium between the sample and the air temperature; during the next three hours, the strain and the surface temperature of a glass sample and of the silica-titanium bar are recorded. In one of the first tests, the surface temperature of the reference bar varied between 23.7 °C and

23.8 °C; the surface temperature of the sample glass varied between 24.2 °C and 24.3 °C. The corresponding strains were in the range $-0{,}444 \cdot 10^{-6}$ and $+0.444 \cdot 10^{-6}$, with maximum instantaneous variations of $\pm\ 0{,}222 \cdot 10^{-6}$ (Fig. 3), so the strain gauge stability is verified. Such verification was periodically carried out during all the measurements.

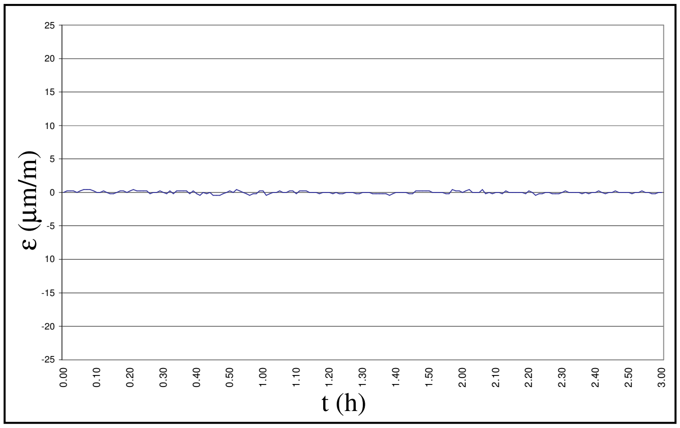

Figure 3: Strain of the glass sample vs. time during the test of strain gauge signal stability.

Temperature cycles, before the onset of the strain measurements have been executed to eliminate the residual stresses in all the components of the measurement system (glass samples, reference bar, strain gauges, wires, etc.); three cycles of temperature at least 5 °C above the maximum value and below the minimal value of the measure cycles have been realized, so the residual stress is eliminated and the possibility of repeating the test is guaranteed (normally this happens after the second or the third cycle). Three thermal cycles between 5 °C and 55 °C have been set, with a temperature gradient of 12,5 °C/h. The periods at T = constant = 5 °C and T = constant = 55 °C continue for 40 minutes; the periods with temperature gradient of 12,5 °C/h continue for 4 hours; so the total time of the three cycles is 28 hours. This temperature variation ($\Delta T = 50$ °C) is similar to the one to which glass in churches is subject; in fact the strain measurements have been carried out in the 10 ÷ 50 °C temperature range. In the system calibration, the surface temperature of the silica-titanium bar varied within these ranges (Fig. 4):

I cycle: 5,1 °C - 54,5 °C ($\Delta T = 49{,}4$ °C)
II cycle: 5,1 °C - 54,0 °C ($\Delta T = 48{,}9$ °C)
III cycle: 5,2 °C - 53,6 °C ($\Delta T = 48{,}4$ °C)

The surface temperature of the glass sample varied within these ranges:

I cycle: 5,6 °C - 55,1 °C ($\Delta T = 49{,}5$ °C)
II cycle: 5,6 °C - 54,6 °C ($\Delta T = 49{,}0$ °C)
III cycle: 5,6 °C - 54,2 °C ($\Delta T = 48{,}6$ °C)

A comparison between the surface temperature of the samples and the air temperature in the climatic room shows a delay of some minutes of the sample temperatures: it is necessary for the samples to reach the thermal equilibrium with the air temperature.

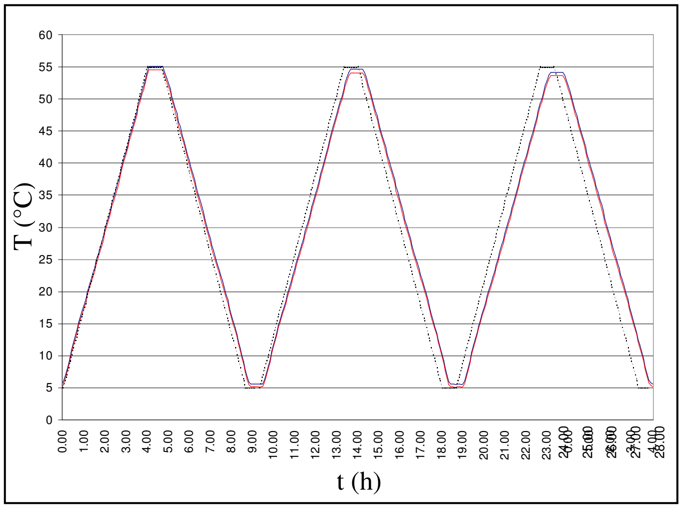

Figure 4: Surface temperature of the glass sample, of the reference bar (continuous lines) and of the air temperature in climatic room (dotted line) vs time, during the test of elimination of the residual stresses.

After verifying the strain gauge signal stability and the residual stress elimination, the measurements can begin.

A thermal cycle for the strain measurement has been chosen. It begins by maintaining the temperature at 10 °C, for 4 hours; then the temperature increases with a thermal gradient of 6,66 °C/hour, corresponding to 40 °C in 6 hours; another maintenance of the temperature at 50 °C, for 4 hours, and a decrease in temperature with a gradient of 6,66 °C/hour for 6 hours are then realized, until the temperature becomes 10 °C; finally a temperature maintainance at 10 °C for 4 hours is carried out. The cycle lasts 24 hours.

The measurement system has been tested measuring the strain of a *Saint Gobain* glass sample, with a known coefficient of thermal linear expansion (9.0×10^{-6} °C^{-1}). After eliminating the residual stresses, the strains were measured by setting up the described thermal cycle in the climatic room. Fig. 5 shows the Saint Gobain glass surface temperature vs. time; the temperature varies between 10,4 °C and 49,9 °C, so $\Delta T = 39{,}1$ °C. Fig. 6 shows the relative strain vs. time; the recorded data are:

$\Delta\varepsilon_{min} = -0{,}243 \times 10^{-6}$;
$\Delta\varepsilon_{max} = 352{,}798 \times 10^{-6}$;
$\Delta\varepsilon_{tot} = 353{,}041 \times 10^{-6}$.

The calculation procedure of the coefficient of thermal expansion of the Saint Gobain glass is carried out, by the procedure described in Data Elaboration, and a value of $9{,}054 \times 10^{-6}$ °C^{-1} is found. It coincides perfectly with the data given by the company.

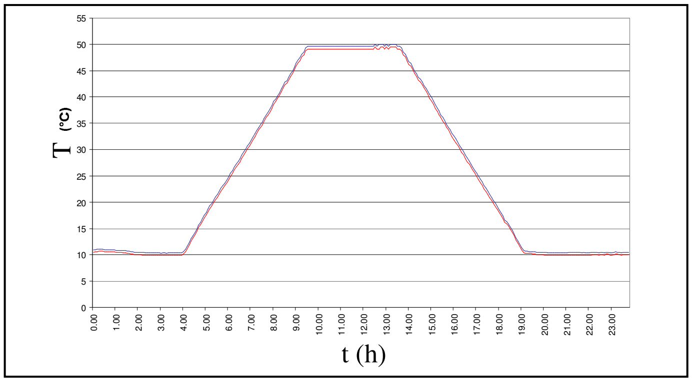

Figure 5: Surface temperature of the Saint Gobain glass (dotted line) and of the reference bar (continuous line) vs time during the strain measurements.

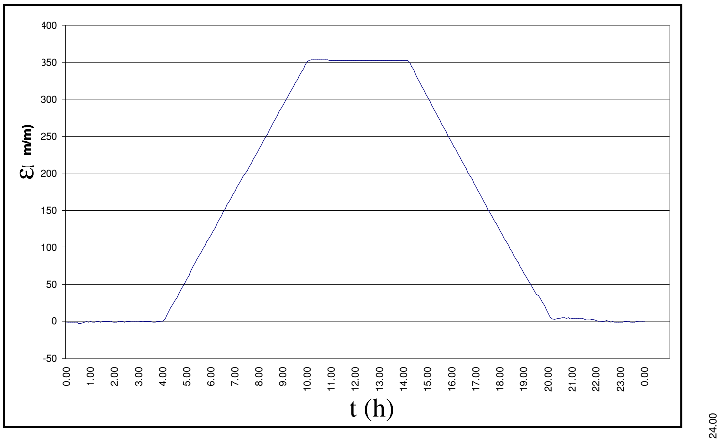

Figure 6: Saint Gobain glass strain vs time.

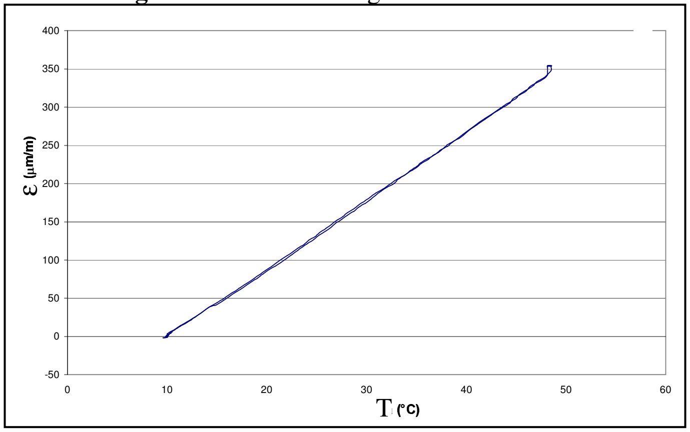

Figure 7: Thermal output vs surface temperature of the Saint Gobain glass, with increasing and decreasing temperature.

One final consideration has been made; in order to avoid measurements errors, the glass temperature must be uniform throughout the thickness of the sample or, at least, in the region where the strain gauge is glued. In order to control this temperature uniformity, the diagram of the stress vs temperature is sketched out for increasing and decreasing temperatures. The heating and cooling curves have to coincide; if the two parts of the curve are meaningfully separated to form a hysteresis loop, the temperature is not uniform in the sample thickness: in this case, two strain values correspond to the same temperature variation. Fig. 7 shows the results obtained for the Saint Gobain sample: it presents very good temperature uniformity in the thickness of the glass.

The choice of the temperature gradient in the measurement cycle is suggested by the ISO 7991: the maximum values are 300 ± 60 °C/h for increasing temperature and 120 ± 12 °C/h for decreasing temperature. A series of preliminary tests has been carried out, setting up various gradients, to evaluate the maximum gradient necessary to avoid the formation of hysteresis loops: 6.66 °C/h, 13.33 °C/h, 40 °C/h, 80 °C/h, all inferiors to those suggested by ISO 7991. Results show that with gradients over 6,66 °C/h there is a hysteresis loop between strain in the heating and the cooling; so this value of the temperature gradient has been chosen.

Data Elaboration

When a strain gauge is installed on the surface of a non stressed structure and the temperature of the material varies, the strain is transmitted to the grid of the sensor causing a variation in electrical resistance, proportional to the same deformation:

$$\frac{\Delta R}{R}=\frac{\Delta L}{L}F=\varepsilon F \tag{1}$$

If the solicitation transmitted to the structure is a temperature variation ΔT, we can write:

$$\Delta L=\alpha L\Delta T \tag{2}$$

From the previous two equations the following is obtained:

$$\frac{\Delta R}{R}=\alpha F\Delta T \tag{3}$$

So the coefficient of thermal expansion of a sample (S) can be calculated simply by measuring the variation of specific electrical resistance ΔR/R and the difference of temperature ΔT, knowing the gain factor F of the strain gauge; this is due to the combination of two factors: the expansion of the glass sample and of the grid; therefore it is necessary to consider α_S, α_G, and the variation of resistivity of the grid material, by means of the term β_G. So:

$$\frac{\Delta R}{R}=\left[\beta_G+\left(\alpha_S-\alpha_G\right)F\right]\Delta T \tag{4}$$

Combining equations (1) and (4) the following is obtained:

$$\varepsilon_{(G/S)}=\left[\beta_G/F+\left(\alpha_S-\alpha_G\right)\right]\Delta T \tag{5}$$

in which $\varepsilon_{(G/S)}$ is the thermal output of the strain gauge glued over the sample. Using a second strain gauge glued to a reference bar, (5) can be rewritten:

$$\varepsilon_{(G/R)}=\left[\beta_G/F+\left(\alpha_R-\alpha_G\right)\right]\Delta T \tag{6}$$

Subtracting member to member equation (6) from equation (5):

$$\alpha_S=\alpha_R+\Delta\varepsilon/\Delta T \tag{7}$$

In equation (7) α_R is the coefficient of thermal expansion of the material that constitutes the silica - titanium bar, supplied by the Corning Glass Company (Corning NY 14831); in the range of temperatures -45 °C + 175 °C it is $0.03 \times 10^{-6} \pm 0.03 \times 10^{-6}$ °C^{-1}. ΔT is the measured value by surface temperature probes on the samples. The value of $\Delta\varepsilon$ is supplied directly by the acquisition system, which gives the electrical resistance variation as a strain; the measurement of the electrical resistance variation is carried out by a Wheatstone bridge electrical circuit, where two branches are constituted by the two *twin* strain gauges, whereas the others are simulated by the Spider 8.

RESULTS

The glass samples have been classified according to their surface characteristics; they are described in Tab. 1. Two of the samples (n. 9 and n.10) have been subjected to chemical analysis; the results show that, except for the calcium oxide absence, they can be considered sodium - calcium glasses. As an example, in Fig. 8 (a, b, c) the results related to the glass sample n. 4 are shown. In particular, in Fig. 8a) the surface temperature trend, in function of time, is shown: variation ΔT is about 38.1 °C. In Fig. 8b) the relative strain is reported: 381.6 µm/m. In Fig. 8c), finally, the strain trend vs the increasing and decreasing temperature are shown; there is no hysteresis loop, so the hypothesis of temperature uniformity throughout the thickness of the sample is verified. The calculation carried out with these data gives $\alpha_4 = 10{,}05 \times 10^{-6}$ °C^{-1}.

In order to verify the reliability and the possibility of repeating the results, two or three tests in the same conditions have been carried out; for every sample the final value of α is the average value of the different tests. For the sake of brevity, the extensive results relate to the other samples are not reported; a synthesis of all the measurements is reported in Tab. 1. The results show that the values of α vary between $8{,}4 \times 10^{-6}$ °C^{-1} and $10{,}3 \times 10^{-6}$ °C^{-1}. The higher values relate to glasses 5 and 6 (10.21×10^{-6} °C^{-1} and 10.29×10^{-6} °C^{-1}); it is due to the particularitity of the two glasses: the red coloration of glass sample 5 is obtained in bath and not by adding metallic oxides in the paste; the brown color of glass sample 6 is due to a coloration only on one surface, realized with the technique called *grisaglia*.

The measurement uncertainty has been finally evaluated [3]; the measurement uncertainty of the different parameters has been estimated and the law of propagation of the uncertainty has been applied to equation (7). The uncertainty on α_R is equal to $\pm 0.03 \times 10^{-6}$ °C^{-1}, the one of ΔT is ± 0.84 °C, the one of $\Delta\varepsilon$ is approximately 0.08×10^{-6}. The measurement uncertainty obtained for α_s varies between 0.17 and 0.21×10^{-6} °C^{-1} for the different samples; it is in any case about 2% (Tab. 2). As regards the deformation measurements, the uncertainty is 0.02%.

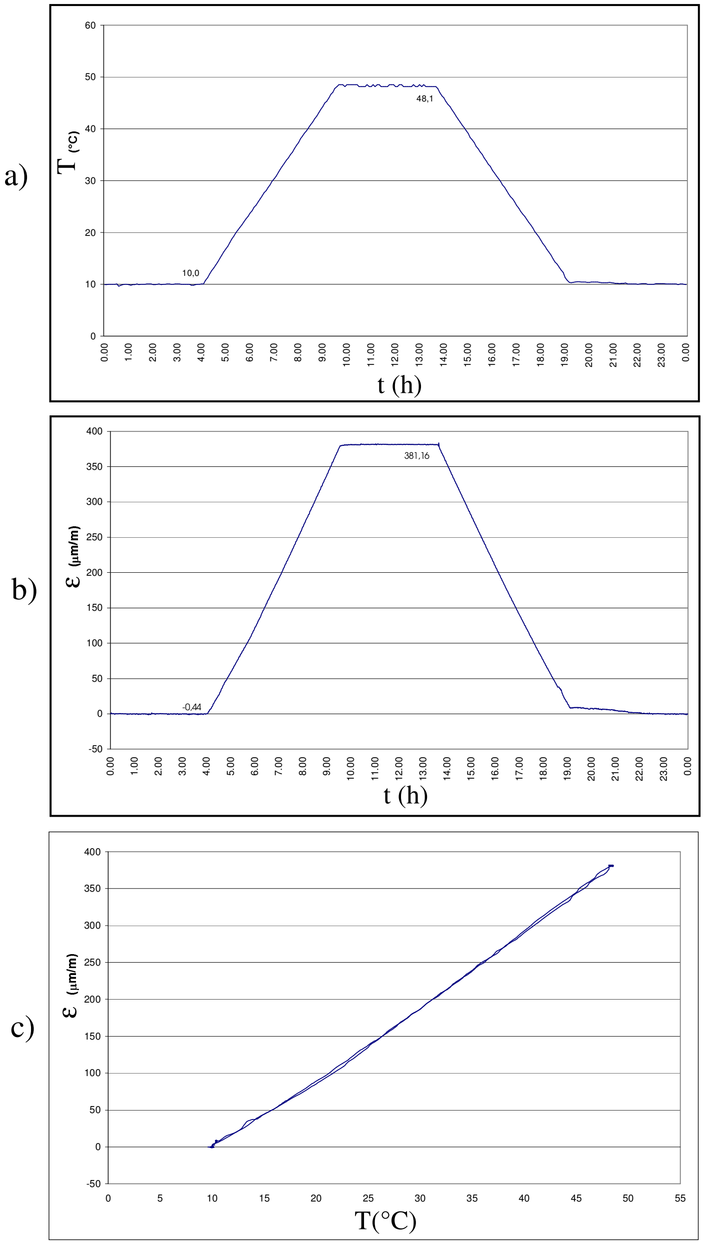

Figure 8: Surface temperature (a) and strain (b) vs time and strain vs temperature (c) of the glass sample n. 4.

CONCLUSION

The degradation of the artistic glass depends not only on the chemical actions due to air pollution and atmospheric agents, but is also due to the temperature stresses caused by solar radiation; they can be different from point to point of the glass, because of the

Table 1: Glass samples characteristics and experimental results.

Sample n.	*Colour*	*Thickness (mm)*	*ΔT (°C)*	*Δε*	*α (°C^{-1})*
1	violet	2,71	38,1	337,99 x 10^{-6}	8,90 x 10^{-6}
2	transparent	2,71	38,1	343,87 x 10^{-6}	9,05 x 10^{-6}
3	violet	3,74	38,5	326,92 x 10^{-6}	8,50 x 10^{-6}
4	green	2,84	38,1	381,60 x 10^{-6}	10,05 x 10^{-6}
5	red	2,65	36,7	373,50 x 10^{-6}	10,21 x 10^{-6}
6	brown	1,96	36,7	376,71 x 10^{-6}	10,29 x 10^{-6}
7	blue	3,96	37,2	322,67 x 10^{-6}	8,70 x 10^{-6}
8	blue	3,39	37,4	316,41 x 10^{-6}	8,49 x 10^{-6}
9	yellow	3,52	36,7	374,28 x 10^{-6}	9,86 x 10^{-6}
10	violet	2,38	35,6	348,85 x 10^{-6}	9,84 x 10^{-6}

Table 2: Mean strain measurements, coefficients of thermal expansion and measurement uncertainties.

α (10^{-6}°C^{-1})	*Sample n.*	*Δε(10^{-6}m/m)*	*ΔT (°C)*	*Uncertainty*	
				(10^{-6}°C^{-1})	*(%)*
8	8	320	40	0.17	2
9	1, 2, 3, 7	360	40	0.19	2
10	4, 5, 6, 9, 10	400	40	0.21	2

glass colours and the relative absorption coefficients for solar radiation. The Laboratories of Thermotechnical and Environmental Controls of the Department of Industrial Engineering of the University of Perugia have been involved in the preservation of works of art for a long time. In a recent work [4] an analysis of the distribution of the surface temperature and of the relative thermal stress on an stained glass window in the Cathedral of Perugia has been carried out by means of a calculation program (Ansys 5.3); results show that the thermal stresses can cause a cracking of the glass.

In the present paper a methodology to measure the deformations due to temperature stresses and to calculate the coefficient of linear thermal expansion have been developed. Ten glass samples, employed in artistic glass restoration, have been subjected to thermal stress in a climatic room; the strains have been measured and the coefficients of thermal linear expansion have been calculated. The results of the measurements, carried out by means of electrical strain gauges, show values of the coefficients of thermal expansion within 8.4 x 10^{-6} °C^{-1} and 10.3 x 10^{-6} °C^{-1}. The measurement uncertainity has been estimated following the indications reported in [3]; it is 2% circa.

The obtained values are of the same order of magnitude of those classified in Literature as sodium - calcium glass; a chemical analysis, made on two of the ten samples, shows they can be considered sodium - calcium glass, a part a few chemical components. The higher values of the coefficients of thermal expansion have been obtained for the samples number 5 and number 6 (10,2 ÷ 10,3 x 10^{-6} °C^{-1}); their coloration is in fact obtained differently than in the other samples.

This methodology could be employed for the measurement of the thermal expansion of any kind of material. The obtained results can be employed for the simulation of the conditions of thermal stress on artistic windows with different geometrical configurations and spectral characteristics of the glasses, by means of adeguate calculation programs. The same measurements, finally, can be repeated after having subjected the samples to accelerated aging in a climatic room, to estimate the influence of aging on the properties of thermal expansion of this kind of glasses.

ACKNOWLEDGEMENTS

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