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REVIEW

SHORT COMMUNICATION

EVALUATION OF PROTECTIVE GLAZING SYSTEMS

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Abstract

Protective glazing systems are widely accepted as a preventive conservation method for stained glass windows in Germany and other European countries. However, the ventilation of the interspace between the original and the protective glass has to be well adapted for each object since the intrusion of air pollutants and the occurrence of condensation can still cause damage. The efficiency of protective glazing systems can be evaluated by glass sensors, which consist of highly sensitive model glasses, reacting to the local corrosive impact within one year of exposure. This paper concentrates on the comparison of case studies in Gloucester (UK) and León (Spain), to include the environmental impact measured on unprotected windows.

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glass, protective glazing, weathering

1. Weathering of glass

The initial step of glass weathering can be described as the attack of humidity on the surface[1]. The basic reaction is an ion exchange process, which leads to the formation of a gel layer, low in alkaline ions and calcium ions but rich in protons and water. If this layer, which differs chemically and structurally from the bulk glass, reaches a certain thickness, thermal and hygric stresses will cause micro-cracks, thus allowing increased access for harmful substances to penetrate deeper into the material (Figure 1). Air pollutants, dust and micro-organisms accelerate this process.

Medieval glass, containing a rather high percentage of potassium and calcium, has developed a variety of corrosion phenomena over the centuries[1]. The degree of decay varies from one window to the next, depending on the local conditions the glass was exposed to and depending on the restoration techniques applied during the window's history. The weathering of glass may lead to phenomena such as pitting or to the development of a dense crust of corrosion products (see Figure 2). For more stable glass from the 19th century, the loss of paint represents the major degradation phenomenon, mainly caused by condensation (Figure 3).

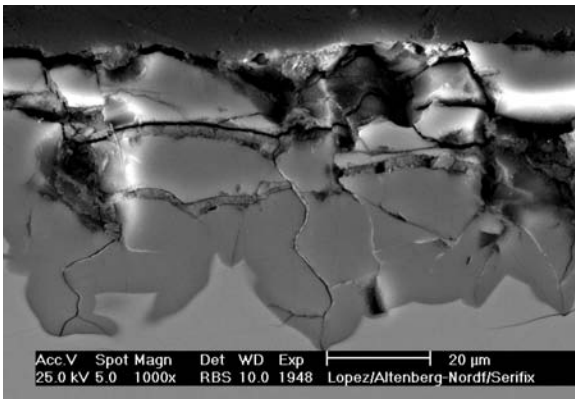

Figure 1: Glass fragment from the Dome in Altenberg, Germany; investigation of a cross section by scanning electron microscopy (SEM): unaltered bulk glass at the bottom, gel layer with micro-cracks in the middle, embedding material for stabilising the cross section at the top

Figure 2: Detail of a stained glass panel from the Dome in Altenberg, Germany; the density of the corrosion crust depends on the composition of the glass and thus varies within one panel (photograph provided by the Dombauhütte Köln, Germany)

Figure 3: Detail of a 19th century panel from Langenstrasse, Germany; the damage on the paint is caused by condensation effects (photograph provided by Glasmalerei Peters, Paderborn, Germany)

2. Protective glazing: history, parameters, systems

In his first experimental study on protective glazing, Roy Newton recommended a terminology to describe the different systems available. "External protective glazing" should be employed exclusively where an external shield of glass or plastic material is attached to protect the medieval glass against weather. The term "isothermal glazing" should be used if the ancient glass is placed in a "museum-type atmosphere" by re-hanging it inside the building, whereas a modern glass is installed in the glazing grooves[2,3]. Later on, the type of ventilation of the interspace - "internally" or "externally" ventilated - became the characteristic terms to describe the type of protective glazing installed in a given building[4-8].

Depending on the experience of workshops and decision-makers in a certain region, the construction of a protective glazing varies both in the type of materials applied for the metal framework and in the design of the glazing (plain glass sheets, with anti-reflective coatings, clear leaded lights copying the original etc.) (see Figure 4). The distance of the stained glass to the protective glass and the size of the ventilation slots (top and bottom, but sealed on the verticals) has to be adapted to minimise condensation effects[9].

Other parameters, such as the size of the window and of the lights, the indoor climate (heating system, visitor numbers) the outdoor climate (pollutants, exposure to rain and wind etc.) and the condition of the stonework as such cannot be modified. From this follows that there is no "one size fits all" solution and that a protective glazing has to be adapted to the local situation. The International Technical Committee of the Corpus Vitrearum Medii Aevi (CVMA) intends to provide support in this field with the publication of guidelines on how to find the optimum compromise for any given case[10].

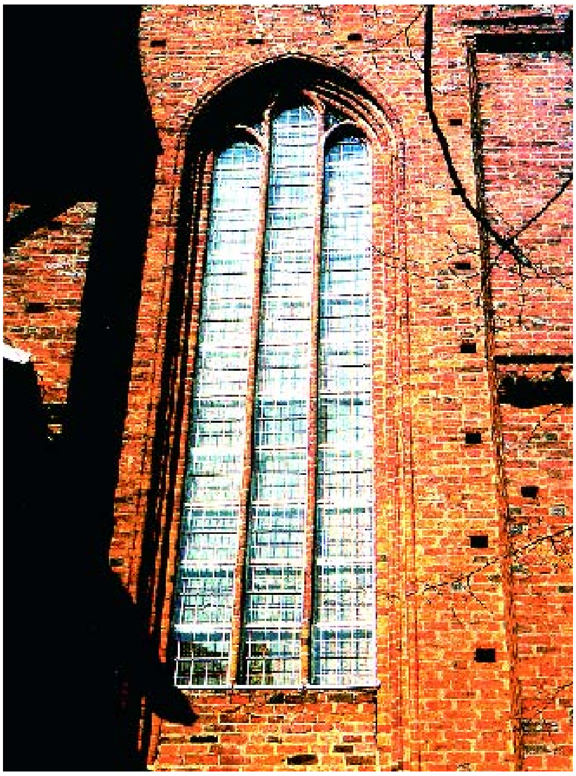

Figure 4: Protective glazing in Stendal, Germany[8].

3. Evaluation of protective glazing systems

3.1 General aspects

The residual risk for stained glass windows after installation of a protective glazing has always been of concern for conservators and scientists. Already the first prototypes had been monitored for temperature and humidity. Based on these results, external ventilation was recommended for protective glazings in the UK[4] whereas internal ventilation has proved to be advantageous for the climate in Austria and other countries[7]. Examinations of the microclimate in the interspace can provide an important screening of the environmental situation and have been carried out on many churches and cathedrals during the past decades[9].

For the interpretation of temperature and humidity readings, not only the absolute values but the cycles of change and the frequency of condensation have to be considered. Since no general damage function for glass is available, microclimatic investigations need to be interpreted by experienced experts. It should never be neglected that the environmental impact is also governed by the immission rate of gaseous pollutants, the air flow close to the sensitive glass surfaces, the deposition of particles and the potential of a microbiological attack.

3.2 The glass sensor method

The environmental impact on glass can be assessed by using standardised, highly sensitive test glasses as dosimeter-material, called "Glass Sensors"(see Figure 5). This method, developed at the Fraunhofer-Institut für Silicatforschung (ISC), Würzburg, for environmental stress monitoring, indoor and outdoor, has been widely used in many European countries for the evaluation of the efficiency of protective glazing systems[9-11].

Damage processes, which in historic glasses occur over decades or centuries, can be studied on the surface of glass sensors within months. The sensitivity of the sensor glass is increased by the appropriate choice of glass composition and surface treatment. Glass sensors allow the evaluation of long term risks, integrating environmental influence as well as synergetic interactions. In order to cover a full year's cycle with warm and cold periods, an exposure of 12 months is recommended.

The measurement of the corrosion process, i. e. the glass sensor's response to the environmental stress on site, is carried out by infrared (IR)-spectroscopy. The absorption by a suitable OH band at 3300 cm^{-1} correlates with the thickness of the sensor glass weathering layer. The extinction difference (ΔE) represents a direct measurement of the "damage effect" integrated by the sensor, compared with the initial spectrum of the freshly prepared sensor Please note: a low ΔE-value corresponds to a low corrosion rate and thus to a low environmental stress situation[11,12]. In general, the IR data give reliable results for ΔE-values in the range from 0.01 to about 0.60.

3.3 Glass sensor study in Gloucester (UK)

The Great East Window of Gloucester Cathedral is recognised as an outstanding example of medieval stained glass in the UK and in Europe. When urgent repairs to the masonry became necessary, the overall condition of the window was

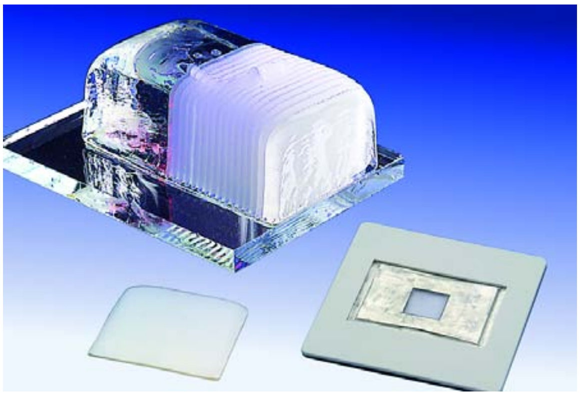

Figure 5: Preparation of a glass sensor: glass block, partially cut into slices, slice of sensitive glass, glass sensor with frame (ready for exposure)

discussed by the surveyor of the cathedral, local authorities, English Heritage and the Dean & Chapter.

After several restoration campaigns in the 19th and 20th century, S. Strobl was the first one to examine the window in 1998[13]. He described the general condition of the glass as "surprisingly good". However, for the internal side he noted excessive signs of condensation and of dampness, resulting in biological growth as well as localised soiling and damage to the paint layers. On the external side corrosion affects the glass, but only occasionally has led to the formation of corrosion crusts.

Based on the report, the cathedral's Fabric Advisory Committee considered the installation of an isothermal-glazing system for the window. As a first step the environmental conditions within the Cathedral had to be evaluated.

Within this context, Stainburn Taylor Architects commissioned the Fraunhofer-Institut für Silicatforschung (ISC) to carry out a glass sensor study at Gloucester.

The sensor study was conceived with the following objectives:
- to provide data on the environmental impact and stress-level inside the church, focussing on possible damage caused by condensation
- to compare environmental stress in different heights of the window
- to evaluate the difference in potential damage inside / outside the church
- to interpret this data in context with other sensor studies in Europe.

The glass sensor study was carried out at the Great East Window of Gloucester Cathedral from July 2000 to July 2001[14]. Figure 6 illustrates the installation of the sensors in Gloucester. A total number of 11 sensors were available for exposure. 10 sensors were placed on the internal side of the window, one on the external side. The exact position of the sensors and the corresponding ΔE are indicated in a sketch of the window (Figure 7).

Figure 6: Installation of glass sensors in Gloucester (photograph provided by S. Strobl)

The corrosion rate measured on the glass sensors reflect the environmental risk for the window:
- the corrosivity at the interior side is not homogeneously distributed (tendency: higher values on the left and towards the top; the masonry is not particularly endangered)
- compared to similar studies at windows without protective glazing in several European countries, the values detected at the interior side in Gloucester are extremely high
- the sensor exposed outdoor was only slightly corroded, less than most sensors form indoor positions, which underlines the potential for damage at the interior side.

The glass sensor study demonstrates the high environmental risk to which the window is exposed. Most probably this is caused by condensation effects, rather than by specific indoor pollutants. Humid surfaces are subject to biological contamination, which may lead to additional deterioration of the glass and of the paint layers. It is recommended to discuss urgently possible countermeasures, such as the introduction of a protective glazing or the installation of a new heating system.

3.4 Glass sensor study in Leon (Spain)

The Cathedral in León belongs to the most remarkable Gothic monuments in Spain. The stained glass windows, dating from the 13th century onwards, have been heavily restored last time at the end of the 19th century[10].

The examination of glass fragments indicate that the medieval glass is heavily corroded, mainly due to its low durable chemical composition and the local environmental conditions. The general climatic situation in León is characterised by hot summers and quite strong winters. The pollution level in León is estimated to be rather high, as most of the buildings are still heated with coal. In addition, there is heavy traffic circulation around the cathedral[14].

A new restoration campaign was started in 1993, when a protective glazing was installed at some of the windows. In this instance, a special glass was chosen, slightly etched on the outside to reduce reflection of light. In addition, a wire netting was placed outside to avoid damage by vandalism. The original panels were transferred to the interior of the church, leaving a distance between the protective glazing and the originals of about 4-6 cm. The interior ventilation of the

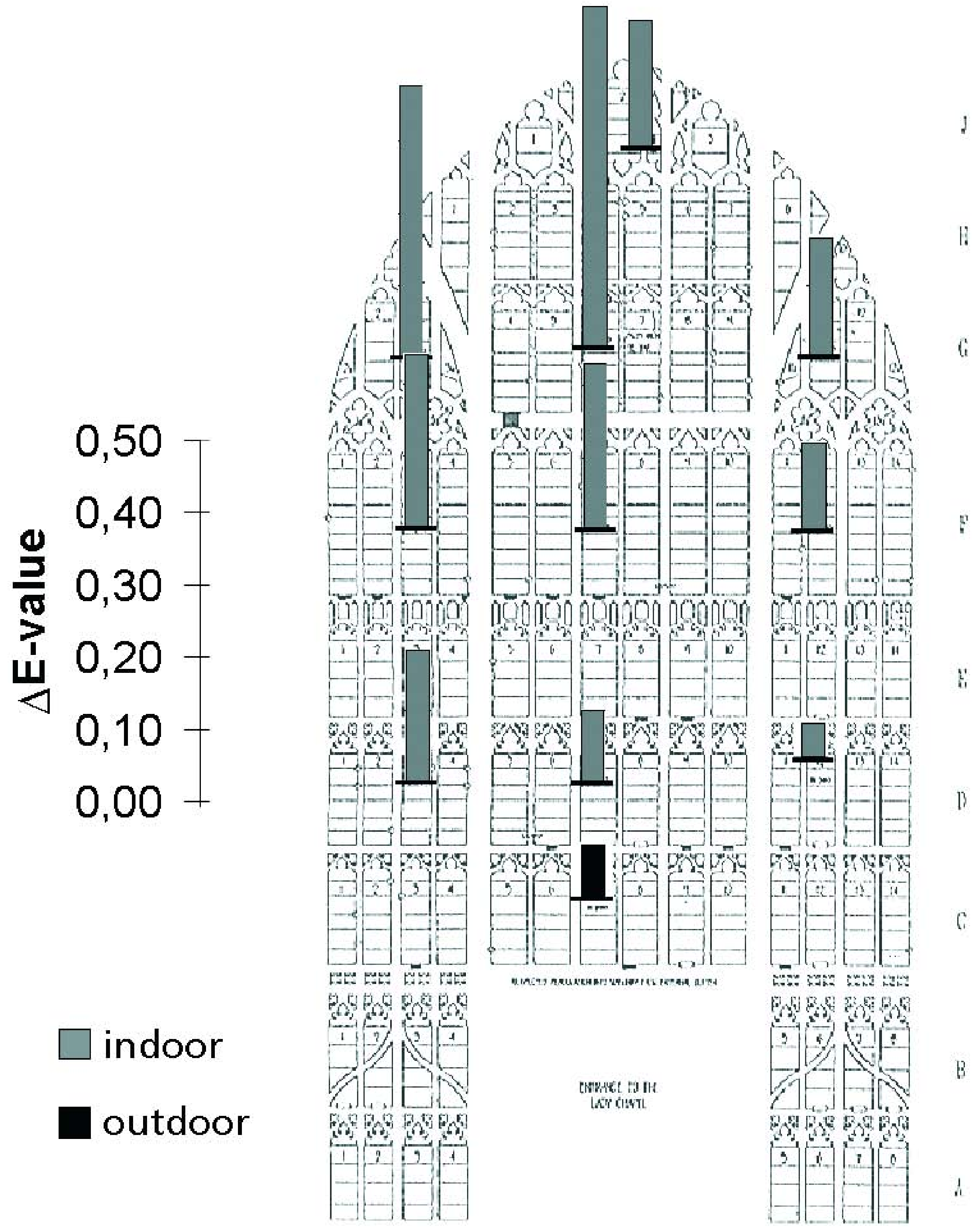

Figure 7: Sketch of the Great East Window in Gloucester, sensor positions and corresponding stress levels detected on glass sensors (ΔE-values)

glazing was achieved by ventilation slots of about 1-2 cm on the bottom and the top of the window. Lead strips pressed against the stone rebate avoid additional ventilation from the sides and prevent any distracting light effects. Any condensation occurring in the interspace is led to the outside via a small tube at the bottom of the window[10].

Before completing the installation of the protection, the system just installed had to be evaluated. From February 1996 to February 1997 a total number of 21 glass sensors were placed at 7 windows with different orientation, in different heights, with and without protection[15].

The sensor study, commissioned by the "Asociación Cultural Conservación Catedral de León" was conceived with the following objectives:
- to compare the environmental stress on windows with and without protection
- to compare environmental stress in different heights of the window (inside / outside the church)
- to interpret this data in context with other sensor studies in Europe.

From the results (shown in Figures 8 and 9) the following conclusions can be drawn for this study:
- for windows with a protective glazing the residual stress in the interspace is much lower than the potential for damage outside the building; this proves that the system applied in León (internally ventilated, slots at the top and the bottom) is appropriate for the objects and the environmental conditions in León
- for windows with protection there are no significant differences in stress level for the inside of the window and the interspace
- the environmental situation outside the building is characterised by very high corrosion rates on glass sensors (even higher in upper positions)
- the stress levels inside the cathedral are very low, for windows with and without protection.

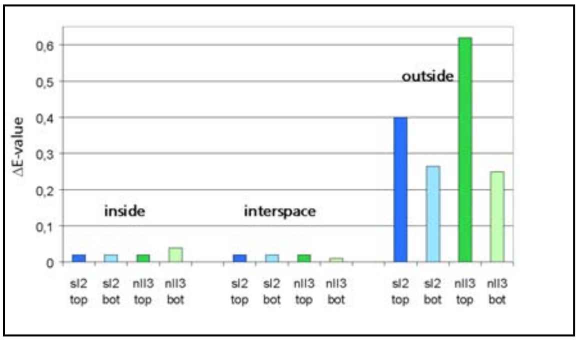

Figure 8: Glass sensor study in León (Spain): sensor positions (different windows, top and bottom) and corresponding stress levels detected on glass sensors (ΔE-values) for protected windows

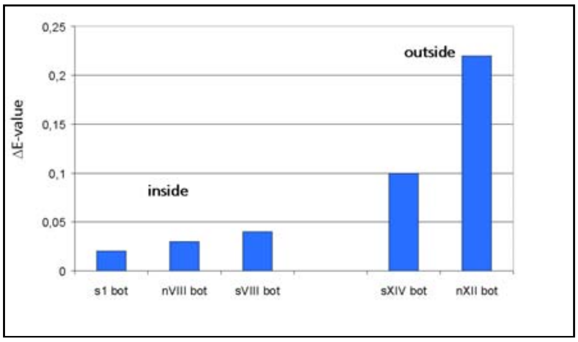

Figure 9: Glass sensor study in León (Spain): sensor positions (different windows, only bottom position) and corresponding stress levels detected on glass sensors (ΔE-values) for unprotected windows

The sensor study in León demonstrates that a protective glazing can improve significantly the environmental conditions for stained glass windows. This is of special importance for León, where the local environment outside the building reflects high corrosion levels, probably due to a high level of pollutants and the aggressive local climate.

3.5 Conclusions about the evaluation of protective glazing systems

Investigations of temperature and humidity in the interspace of a protective glazing give an indication on the residual risk for the object. However, also other parameters (such as pollutants, particles, frequency of condensation) have to be considered before concluding about the overall protective effect of the construction on site. A European project is currently dealing with chemical, physical and biological degradation of stained glass windows (www.isac.cnr.it/~vidrio/). The investigations carried out in Troyes and Paris (France) and Cologne (Germany) may result in the improvement of protective glazing systems and also for other objects.

Since the environmental situation outdoors and indoors changes in daily and yearly cycles, the evaluation of the environment in the interspace should be based on a continuous survey lasting one year. Depending on the climate and especially on the size of the window, more than one measurement should be taken[9].

Glass sensor studies, carried out by the Fraunhofer ISC as contract research, provide the possibility to evaluate the impact of the environment (as an alternative or in addition to the registration of single parameters).

The results presented in this paper from the studies in Gloucester and León can be interpreted in comparison with similar studies carried out in Europe[11,16,17].

Extremely high ΔE-values on the outside of a building indicate high corrosive attack, mostly caused by high concentrations of gaseous pollutants, mainly SO_2. The maximum values measured on the exterior side of stained glass windows have been found in Erfurt (former East Germany) in the years 1989 / 1990 (ΔE between 0.6 and 1.0). In León the values ranged between 0.4 and 0.6, which is also considered as high. The lower end of the scale is represented by Assisi, with values around 0.05 to 0.1. According to these comparisons the ΔE-value from Gloucester can be rated as low, even if it has to be considered that only one sensor was placed and that also on the outside of the window we find a distribution of stress levels, mostly higher in the upper regions of the window.

If high ΔE-values are found outdoor, also the internal side of the window can be endangered by the intrusion of pollutants into the building. For León the low corrosive effects detected in the interspace compared with the high values outdoor, prove that the protective glazing is highly efficient.

The range of ΔE-values registered in Gloucester for the interior of the stained glass lies far higher (from 0.05 to 0.5) than any value measured in the other studies for this position. In Langenstraße (Germany) several 19th century windows without protective glazing were found to be around 0.18, which was significantly higher than the values from the interior side of protected windows (0.04) in the same church[18]. Most investigations for the interior side of windows have been carried out on protected windows. The maximum value for Assisi[17] was registered at 0.030, for Canterbury[11] 0.035. Within a sensor study in Germany, 17 churches and cathedrals have been compared[9]. Here, the maximum value found for the interior position was obtained in Keyenberg (0.07). All these examples demonstrate that the situation in Gloucester has to be considered as an extreme case, with ΔE-values ranging 10 times higher than in other studies.

As demonstrated with these examples, the database on sensor studies available at Fraunhofer ISC, allows comparisons of the environmental impact of a variety of protective glazing systems in Europe. Especially if accompanied by microclimatic measurements on site, the evaluation of the environmental situation of a stained glass window can be interpreted and appropriate action can be taken.

4. Protective glazing: pros and cons

Protective glazing systems are a widely accepted preventive conservation measure in countries such as Germany, Switzerland, Austria, Netherlands and Belgium. This does not only apply to medieval windows, but also 19th century windows, which have gained increased appreciation towards the end of the last century. Paint loss can only be avoided if condensation is minimised on the interior side of the window, which is important for all objects, regardless the durability of the glass as such.

The lack of funding and the negative aesthetic appearance are the main reasons for decision-makers to reject the installation of protective glazing systems. Besides, the impact of the new glazing on the stonework and the building in general might be considered as disadvantageous. However, the long-term improvement of the environmental situation for the glass should be regarded as an appropriate counterbalance. The reduction of condensation effects on the interior and exterior side of a historic window will avoid damage to the glass and the paint and will thus prolong the intervals between restorations and save money in the long run.

In order to achieve the best performance, architects should co-operate with scientists, art historians and experienced practicioneers. The situation on site has to be investigated carefully to explore the best compromise for the conservation of the glass window and the stonework. Monitoring of the environment may assist in the optimisation of the system for a specific case. And finally, maintenance of the glazing is essential to keep the efficiency of the ventilation.

From a scientist's point of view, protective glazing systems provide an appropriate preventive measure, acceptable with all the pros and cons, if the stained glass windows was to remain in their original architectural setting.

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