Protective Glazing: The Conflict Between Energy-Saving and Conservation Requirements

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Keywords
stained glass; conservation; protective glazing; energy efficiency; heat loss

Abstract
Heating a historic church is expensive. To improve the energy efficiency of such churches, their windows are increasingly fitted with protective glazing using a double-glazed unit. This applies particularly to the great number of parish churches in Switzerland with post-mediaeval stained-glass windows. The added glazing is intended to protect the stained glass from weathering and to provide thermal insulation. In a collaborative research project, we are exploring whether, or to what extent, protective-glazing systems that are primarily fitted for insulation purposes fulfil energy-saving and conservation requirements. Among other issues, we are investigating the thermal efficiency and condensation behaviour of various protective-glazing systems. The aim of this study is to assist church authorities, architects, and monument conservators to evaluate energy-saving options.

Context and Aims of the Project

Switzerland has approximately 5,000 parish churches. About 80% of these churches were built before 1850 and have historic stained-glass windows that, with the exception of a comparatively small number of mediaeval windows, date mostly from the nineteenth and twentieth century. However, these churches also feature some restored Renaissance and Baroque glazing. Although originally constructed without heating systems, today the great majority of these buildings are heated (Giezendanner 2009, p. 24). Heating such large and mostly non-insulated buildings is usually very costly. The annual heating costs for a parish church in Switzerland lie between 5,000 and 40,000 CHF, depending on the heating system and the energy source used (Bickel and others 2009, p. 9). The average cost is 9,600 CHF (€ 8,000) per year. Two-thirds of the churches are heated electrically, with average annual heating costs of 7,200 CHF (€ 6,000) (Aufdereggen 2012). Because of rising energy costs, and encouraged by the current energy debate, church authorities are trying to lower the energy consumption of their buildings.

Numerous guidelines have been published that provide advice on how to improve the energy efficiency of churches (for example Dahm 2010). Measures to improve the windows are usually outlined among options to reduce heat loss in buildings and lower heating costs (Bickel and others 2009, p. 19). When considering energy-saving options, there is a tendency to assume that windows represent a determining factor in reducing energy consumption. This has already led church authorities to install protective glazing on a large scale. In the canton of Zurich alone, an estimated 50% of its nearly 300 churches have been fitted with protective glazing in the past 30 years, and the trend to install protective glazing for 'energy-saving' reasons continues. However, protective-glazing systems not only are intended to improve the thermal properties of churches, but also have to fulfil a number of other requirements: to protect the stained glass from environmental impact and vandalism, to reduce condensation on the historic windows and surrounding structures, to be aesthetically in keeping with the rest of the building, and to reduce the number of interventions (restoration, conservation, maintenance) on the stained glass.

The question as to whether thermally efficient protective glazing (e.g. protective-glazing systems glazed with a double-glazed unit) also represent an effective solution in terms of conservation has become fundamental to the preservation of the large body of post-mediaeval stained glass in Switzerland. The question becomes even more critical in the long-term if one considers the high cost of fitting protective glazing, the low durability of polymer materials often used in such glazing (e.g. silicone sealants), and the risk of subsequent damage to the stained glass and building structures adjacent to the windows (see, for example, Baumann, Zehnder, and Rüegg 1998).

In the process of planning for the renovation and thermal retrofitting of churches, architects and building owners in Switzerland are advised to follow the guidelines of the Swiss Federal Office of Energy and the Federal Commission of Monument Preservation, according to which the effects of measures to improve the thermal properties of a historic building have to be quantified (Furrer and others 2009). However, appropriate methods and techniques to quantify measures and evaluate requirements (conservation, aesthetic considerations, energy saving, comfort, etc.) have yet to be defined. There is a general lack of experience when it comes to understanding the effects of certain types of protective glazing on stained-glass windows; further, there is an inadequate understanding of the thermal losses and climatic impacts (condensation on the stained glass in particular). In order to close this gap, the Vitrocentre Romont initiated an interdisciplinary research project in 2012. The aims of the project are twofold:

1. To determine the overall heat transfer coefficient of historic windows fitted with protective glazing based on calculations and measurements in a climate chamber, the so-called ‘hot box’.
2. To investigate the climatic effects of protective glazing, particularly condensation, on stained-glass windows, by initiating a survey in situ of post-mediaeval stained-glass windows with protective glazing, and by recording measurements in a weathering chamber.

The project has focused on two particular protective-glazing systems: (1) protective glazing fitted in a metal frame and glazed with a single glass sheet, and (2) protective glazing fitted in a metal frame and glazed with a double-glazed unit. Both systems have been evaluated with and without external ventilation. Despite being widespread in Swiss parish churches with stained glass from the nineteenth and twentieth century, these protective-glazing systems have hitherto received insufficient attention. Isothermal glazing, a system more commonly used in the preservation of mediaeval stained glass, has been excluded from this study.

The results of this investigation should enable the following questions to be answered. To what extent do the above-mentioned glazing systems improve the thermal efficiency of historic windows? Do they meet preservation requirements (by, for example, preventing condensation on the stained glass)? It is also hoped, that this study goes some way towards identifying appropriate solutions for the comprehensive, long-term preservation of post-mediaeval stained-glass windows in Switzerland.

Efficiency of Protective Glazing: Current State of Research

Condensation problems related to protective glazing have been reported from various places all over Europe (see, for example, Bacher 1988; Trümpler 1988; Berkenkopf 2005). The observations prompted research on the effectiveness of protective-glazing systems (see the overview in Oidtmann, Leissner, and Römich 2000; Römich 2004; Hör and Seele 2005). Among the first researchers to study systematically the effects of internally and externally ventilated as well as unventilated protective-glazing systems under variable climatic conditions was Stefan Oidtman, who carried out simulations in a hot box and compared them to in situ measurements (Oidtmann 1994). Many studies have followed since, including the European research project VIDRIO, which aimed to monitor the climatic conditions of stained-glass windows with internally ventilated protective-glazing systems, and to develop methods to detect condensation in the interspace between the historic window and the protective glazing (Bernardi and others 2012). Researchers from the Federal Institute for Materials Research and Testing in Berlin have looked at, among other things, the problem of dust deposition in the interspace in isothermal glazing (Torge and Müller 2011; Torge, Bücker, and Feldmann, 2013). To date, however, research has concentrated mostly on the conservation aspects of protective-glazing systems in general, and isothermal glazing in particular. To our knowledge, the only investigation focussing on the thermal effectiveness of protective glazing was published by researchers from Eindhoven Technical University (Neilen, Schellen, and van Aarle 2003).

Fig. 1. Unventilated protective glazing fitted in a metal or wood frame: 'Église des Capucins' in Romont, installed around 1950 (left); Parish church of Frauenfeld-Oberkirch, installed probably before or around 1900 (right). Photos: authors.

Those authors provide interesting insights into the energy efficiency of various insulation measures (including double glazing) in churches. They also point out that, among the various options to improve energy efficiency, the thermal insulation of a church's roof and floors, as well as well the replacement of old heating systems, usually provides much more potential for energy saving than the installation of protective glazing. Their conclusions draw on the evaluation (from a conservation as well as an energy perspective) of heating systems in churches (see, for example, Schellen 2004; Limpens-Neilen 2006). They also draw on the development of sustainable heating concepts such as 'friendly heating' (Camuffo and others 2010), which have found their way into various guidelines, textbooks, and standards on how to heat historic buildings appropriately (for example DIN EN 15757). Yet, despite these findings, church owners in Switzerland are reluctant to review the options to reduce heating costs (for example, by reducing temperature set points for heating). The fact that the Vitrocentre Romont continues to be consulted on the choice of thermally effective protective-glazing systems seems to justify further investigations into the efficiency of such systems, both in terms of energy and conservation.

Results

Efficiency of Protective Glazing in Swiss Parish Churches

One type of protective glazing with which the Vitrocentre Romont has been confronted in recent years (in connection with restoration and monitoring projects) is a system that was prevalent in the 1950s or even earlier. This type of protective glazing is fitted in a metal or wood frame to the window's reveal (i.e. the masonry adjoining the window) and is not connected structurally to the historic window (figure 1).

Fig. 2. 'Bonded' protective-glazing system: stained glass fitted in a metal frame together with the protective glazing, installed around 1970. Photo: authors.

Fig. 3. Protective glazing fitted with a double glazing unit: outside view (above) and inside view showing fungal growth on the walls surrounding the stained-glass window (below). Photos: authors.

It is usually unventilated, although such protective glazing is rarely perfectly airtight. The interspace between the stained-glass window and the protective glazing normally ranges between 10 and 30 cm, depending on the width of the window reveal. The framing is usually delicate. Occasionally, the drawn glass has been preserved, and the stained glass has remained untouched in its original place. Our observations show that this type of protective glazing is still effective in protecting the stained glass. Because of the limited extent of external ventilation, these systems have created very good climatic and conservation conditions for (at least certain types of) stained glass.

Another type of protective glazing became common in the second half of the twentieth century. Here, the stained glass is fitted in a metal frame together with the protective glazing to form a new type of 'bonded' glazing; the interspace between the stained glass and the protective glazing glazed with a single glass sheet is usually less than 4 cm and normally unventilated. This leads to condensation on cold surfaces in the interspace: in winter on the inner side of the protective glazing, and in summer on the outside of the stained glass and the lead cames (figure 2). Another problem associated with these 'bonded' systems is that structural changes have to be made to the historic windows. For example, the stained glass has to be trimmed to fit the new frame, and historic armouring usually has to be removed.

Finally, a type of protective glazing that has found increasing use since the 1980s consists of unventilated systems that combine the stained glass with double-glazed units (figure 3). Practical experience shows that the fitting of such systems does not solve but only shifts the problem of condensation. Under certain climatic conditions, water condenses not on the glass surfaces but on the frames and cold wall surfaces adjacent to the windows. If the water is not properly drained, it can lead to damage and fungal growth (figure 3, bottom picture). In some cases, the double glazing creates quasi 'hermetic' conditions, which, in contrast to the originally permeable stained-glass windows (which often included little vent windows), can lead to climatic conditions that are detrimental to the interior of the church (affecting woodwork, wall paintings, organ, etc.). One variant of such a double-glazed protective glazing is the so-called 'sandwich glazing', which involves the stained glass being fitted between the two panes of a double-glazed unit (figure 4). The main problem with this system is the limited durability of the materials used in the double glazing.

Fig. 4. Type of double-glazed protective glazing known as 'sandwich glazing', installed around 1990. Photo: authors.

Over the years, the silicone sealing begins to leak, leading to condensation on the stained glass.

The durability of double-glazing systems has been shown to be relatively short compared with the lifetime of historic stained-glass windows with 'low-tech' protective glazing, which – if properly maintained – can span a century. The short lifespan of double glazing (with replacement likely to be necessary every 20 to 30 years) presents additional risks for the historic windows as well as additional costs, which are usually not included in the original cost calculations for improving the thermal efficiency of the church. Considering the risks and the costs of repair or replacement, double-glazing systems seem to be less sustainable than, for example, the 'simpler' protective-glazing systems that use a single glass sheet. One might also add that the possibilities of an aesthetic integration of a protective glazing using double-glazed units into church façades are limited in comparison with (to give an example) a frameless protective-glazing system or single-pane protective glazing framed in thin wooden or metallic frames.

Preliminary Experiments and Calculations

Preliminary measurements in a hot box, as well as thermal calculations, have been carried out in order to determine the overall heat transfer through various glazing systems in steady-state conditions (i.e. at constant internal and external air temperatures). The measurements provide the thermal transmission coefficients, called *U*-factor, for the tested glazing systems and allow verification of the thermal calculations. The *U*-factor is expressed in W/m^2 K and represents the amount of heat transfer per square metre and per degree of temperature difference between the warm side and the cold side of the tested element. The rule is that the higher the *U*-factor, the higher the heat loss of the tested element. Three hot-box experiments have been carried out so far. In the first one, a stained-glass window (146 x 71.5 x 2.5 cm) fitted with a double-glazed protective glazing was tested. The stained glass was taken from Vitromusée Romont's depository and dates from around 1910. The dimensions of the unventilated interspace between the stained glass and the protective glazing were as follows: height 146 cm, length 71 cm, and width 0.39 cm. In the second experiment, the same assembly was used but was ventilated to the exterior and the interspace was slightly enlarged (gap width 0.44 cm) to allow for natural convection by four openings in the protective-element. A third experiment was conducted with the double glazing alone to get the precise *U*-factor of the unit. This last test also represents the reference measurement when comparing calculations to measurements. Figure 5 shows the stained-glass window and the double-glazed unit as well as a model cross-section of the tested glazing systems. In all three cases, the assembly was surrounded by insulating material with a known thermal conductivity in order to evaluate the thermal performance of the window only. The temperatures chosen in the measurements were 17°C for the room side and 2°C as the outdoor temperature. For the ventilated assembly, thermal conductivities of the air cavities were chosen according to the European standard EN ISO 10077-2. The *U*-factor of the stained-glass window alone and the sandstone wall were determined by calculation only, because they represent very simple cases and need not to be confirmed by hot-box measurements: for the existing stained-glass window, a *U*-factor of $U_{\text{stained glass}} = 5.78$ W/m^2 K was calculated; the *U*-factor of the sandstone wall with a thickness of 0.5 m was $U_{\text{wall}} = 2.38$ W/m^2 K. The calculated and measured *U*-factors for the three different glazing systems range between 1.56 W/m^2 K for the stained glass with unventilated double-glazed protective glazing and 2.1 W/m^2 K for the double glazing alone. That the double-glazed unit is composed of three fields fitted in a metal frame explains its relatively high *U*-factor (which is usually found to be less than 1 W/m^2 K for modern double glazing). The ventilation seems to have a negligible effect on the thermal conductivity of the window element: the *U*-factor for the unventilated system is 1.56 W/m^2 K, while that of the ventilated system is 1.68 W/m^2 K.

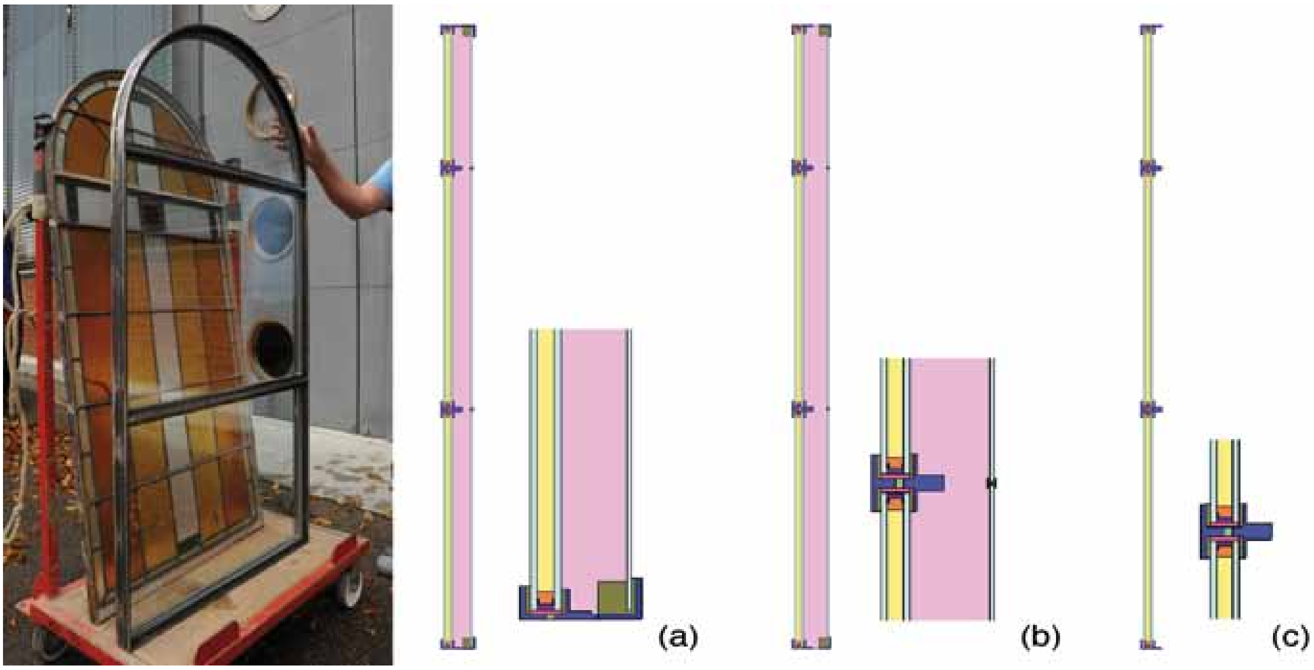

Fig. 5. Stained-glass window and double glazing used in the hot-box measurements (left) and model cross-section of the three window assemblies tested in the hot box (right): (a) unventilated assembly, (b) ventilated assembly, (c) double-glazed unit alone. Photo: authors.

In order to get an impression of the thermal efficiency of a stained-glass window protected with double glazing in an 'average' parish church, the following simple calculation was done using the calculated U-factors for the ventilated and the unventilated glazing systems as well as for the stained-glass window alone: $U_{total} = U_{window} \times A_{window}/A_{total} + U_{wall} \times A_{wall}/A_{total} + PSI \times P_{wall}$, where U is the thermal transmittance of the window or wall, respectively, A is their area, and P_{wall} is the circumference (perimeter) of the window. The total U-factor ranges between 2.6 W/m^2 K (stained-glass window without protective glazing) and 2.4 W/m^2 K (with double glazing). The results illustrate that, regardless of the type of glazing system present, the thermal loss through the windows, which in our example make up 5% of the total wall area, is very small compared with the loss through the walls. Figure 6 shows the calculated temperature distribution through a cross-section of each of the tested assemblies. The temperatures in the interspace are to be regarded as average temperatures, because the model does not include computational fluid dynamics to model real air flow. The calculated temperatures on the surfaces of the stained-glass window and the protective glazing will be relevant in our further investigations regarding condensation in the interspace between stained glass and protective glazing. In a further step to investigate condensation, water vapour transmission through

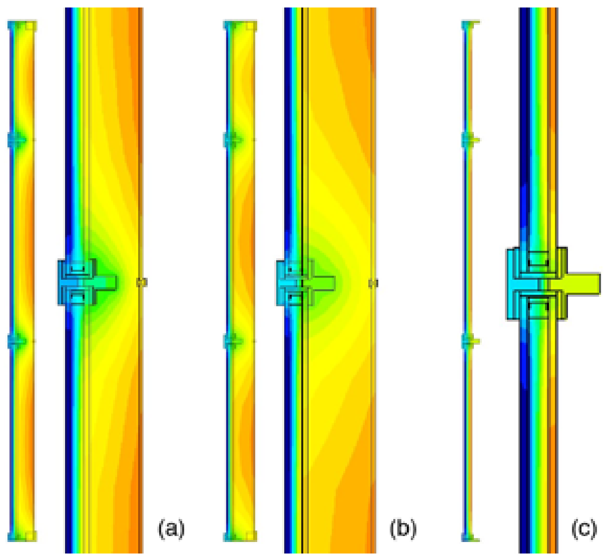

Fig. 6. Calculated temperature distribution in the three investigated assemblies for indoor temperature and external temperature of 17°C and 2°C, respectively. False colour images: the temperatures range between 0°C (dark blue) and 18°C (dark orange). Images: authors.

stained glass was measured. Two identical panes of stained glass measuring approximately 30 x 40 cm and dating from the mid-twentieth century were used in these tests: one test panel had naturally aged putty, while the other had freshly applied putty. The measurements were carried out according to the European Standard EN 12086. The test results show a clear reduction of water vapour transmission by a factor of approximately 1.6 for the stained glass with freshly applied putty. Additional measurements on older stained glass (nineteenth and early twentieth century) with naturally aged putty are planned. These supplementary measurements should provide an indication of the range of water vapour transmission values for stained glass in various states of preservation.

Summary and Conclusions

The calculations and measurements in this study represent preliminary results on the thermal efficiency of stained-glass windows protected by double-glazed units. The results have shown that the addition of protective glazing with a double-glazed unit improves the thermal conductivity of a stained-glass window by a factor of approximately 3 as compared to the stained-glass window alone. The experiments have also demonstrated that the *U*-factor for a double-glazed unit that is designed to protect stained glass and to fulfil aesthetic requirements does not achieve the thermal efficiency values of modern double glazing. Additional experiments on protective-glazing systems glazed with a single glass sheet will follow. They will include the thermal simulation of ventilated and unventilated systems with interspace widths varying between 3 and 12 cm. In a further step, the efficiency of the glazing systems investigated will also be compared under transient (i.e. varying) temperature conditions. These calculations will be verified by measurements in a weathering test chamber. The aim of the research is to compare the thermal performance of single-pane and double-glazed protective-glazing systems, while taking into consideration the specific characteristics of the different systems, for example the large insulating interspace of early protective-glazing systems and the divided metal frames in double-glazed protective glazing. The results of these experiments should enable us to discuss the pros and cons of the glazing systems studied, regarding both thermal loss and (more importantly in conservation terms) the frequency of condensation on the stained glass and in the interspace. They should also allow us to identify the systems that are most appropriate in terms of energy saving, stained-glass preservation, and aesthetic result. At this point in the study, the results already corroborate the hypothesis that, regardless of the glazing system chosen, the amount of heat loss through church windows is minimal compared to the loss through the walls. The effects of double-glazed units are negligible when considering that, in historic churches, the thermal loss through stained-glass windows without protective glazing is estimated to be less than 10% (Neilen, Schellen, and van Aarle 2003) and that the heat loss normally accounts for only between 10% and 20% of the total energy consumption (Baumann 2004).

With regard to appropriate solutions for the comprehensive and long-term protection of post-mediaeval stained-glass windows, our empirical survey has provided valuable information on the environmental impact (the risk of condensation on the stained glass in particular) of certain types of protective glazing. One major outcome of the study is the observation that the early protective-glazing systems dating from the first half of the twentieth century have created surprisingly good conditions for the conservation of at least some of the post-mediaeval stained glass in Switzerland. However, so far we only have a limited understanding of the efficiency of these systems, which is why they remain one of the focal points of the project. The aim of further research will be not only to establish whether there are additional arguments to preserve these early protective-glazing systems, but also to understand how these systems function and to apply the principles in the design of new protective-glazing systems. Notwithstanding the advantages of the systems outlined here (or any other protective-glazing system), alternative approaches to the conservation of stained glass should always be considered. Even from an energy-saving point of view, the conservation of stained glass without protective glazing must remain an option, at least for windows dating from the nineteenth and twentieth century.

Acknowledgements

The authors would like to thank the *Stiftung zur Förderung der Denkmalpflege* Zürich for supporting the project. The authors are also very grateful to Urs Rickenbach of *Mäder Glas*, Zurich, and the *Association professionnelle suisse du vitrail* for supplying materials and for sharing their expertise on various glazing systems. Hannelore Römich, Sebastian Strobl, and an anonymous reviewer are thanked for their helpful comments and advice on correct terminology. A special thank you also to Bill Gilonis for proofreading the text.

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EDITED BY
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Spa Uitgevers

ISBN number:	978-90-8932-113-8
Publisher:	SPA Uitgevers Assendorperstraat 174-4 8012 CE Zwolle, the Netherlands www. spa-uitgevers.nl
Layout:	Hidde Heikamp, SPA publishers
Graphic design:	Erica Dooijes-Hoogwijk
Proofreading:	Gary Anderton (Anderton Editing), Hoorn, the Netherlands
Editors:	Hannelore Roemich and Kate van Lookeren Campagne
Scientific Committee:	Joost Caen, Antwerp, Belgium Renske Dooijes, Leiden, the Netherlands Gerhard Eggert, Stuttgart, Germany N. Astrid van Giffen, Corning, NY, USA Ineke Joosten, Amsterdam, the Netherlands Kate van Lookeren Campagne, Amsterdam, the Netherlands Luc Megens, Amsterdam, the Netherlands Isabelle Pallot-Frossard, Champs-sur-Marne, France Lisa Pilosi, New York, NY, USA Hannelore Roemich, New York, NY, USA Sebastian Strobl, Erfurt, Germany Norman H. Tennent, Amsterdam, the Netherlands
Conference sponsors:	Rijksmuseum, Amsterdam (RMA) University of Amsterdam (UvA) Cultural Heritage Agency of the Netherlands, Amsterdam (RCE) National Museum of Antiquities, Leiden (RMO)
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