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Ralf Kilian, Sara Saba, Caroline Gietz (Hrsg.)

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Fraunhofer Information-Centre for Regional Planning and Building Construction IRB
P.O. Box 80 04 69, D-70504 Stuttgart
Nobelstrasse 12, D-70569 Stuttgart
Phone +49 711 970-2500
Fax +49 711 970-2508
E-Mail irb@irb.fraunhofer.de
URL www.baufachinformation.de

Traditional and innovative materials and solutions to improve the energy efficiency of historic windows: a literature review

S. Mauri, V. Pracchi

Dept. of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, Milan, Italy. (sara.mauri@polimi.it; valeria.pracchi@polimi.it)

Abstract – During the last decades the improvement of the energy efficiency of historic built heritage has taken on increasing importance: this has led to the production of a great amount of research works within the scientific community. Among the building components, windows are commonly considered the weakest element of the envelope and, therefore, the first to be replaced in historic buildings. Contrary to what one may think, more "sustainable" solutions are possible: there are several strategies that can be applied to enhance windows thermal performance, sustainability and conservation without substituting them. Our goal is to outline the research state-of-the-art in this field through a literature review: to this purpose we collected many publications for a total of 126 documents. The result is a as complete as possible view of the research status on window interventions, with particular attention on problems and future perspectives of the high-performance materials integration in the historical context.

Keywords – Historic windows; Energy efficiency; Literature review; High-performance materials; New technological solutions

1. INTRODUCTION

Over the last decades, the enhancement of energy efficiency for historic heritage has been a widely discussed topic among the scientific community: this has led to the production of an ever-increasing amount of research works. Considering that approximately 30% of the European building stock consists of historic buildings [1], whether listed or not, any energy management and performance improvement in those buildings may lead to a significant reduction in the global energy consumption and greenhouse gas emission. As a consequence, the historic buildings' energy requalification is undergoing a strong acceleration. Unfortunately, it is widely believed that historic buildings are not energy-efficient and therefore need to be "radically upgraded". Actually, the energy performance of most historic buildings can be improved, but it is essential to find alternative and compatible energy retrofit approaches that harmonize energy efficiency needs, sustainability and conservation principles. Hence, improving the thermal performance of historic buildings is something that must be done with great care. Among the interventions on the building envelope, the solutions move from recovering or replacing parts of the building to adding high-performance elements to existing components. In this research, in particular, we want to focus the attention on windows. Historically windows configuration is linked – as for shape, size and type – to climate factors, compositional requirements and building constructive structure. Recognizing the importance of these architectural elements and the contribution they provide to the building is the first step toward deciding the proper line of action. Windows are an irreplaceable resource and should be preserved and repaired as much as possible. However, windows are commonly considered the weakest element of the envelope and, therefore, the first to be replaced in historic buildings in the name of a significant energy saving which is actually minimal compared to other interventions. As a matter of fact, in the document published by CRESME (Centre for Economic, Sociological and Market Research for Construction Industry and Environment) entitled "*Analysis of the socio-economic impact of 55% tax deductions for upgrading the energy efficiency of existing buildings*", the average annual savings achieved by type of intervention shows that the replacement of windows has the lowest saving equal to 2.6 MWh, quantifiable between 80 and 125€ with payback achieved in about 12-25 years [2]. Unfortunately, windows replacement is a widespread practice, also promoted by tax incentives, and has caused the loss of a large number of traditional windows, especially in minor historical centres. For this reason, the Italian Ministry of Economic Development and ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) have proposed a revision of the incentive's mechanism because "*it is not appropriate to demand further performance of U-values at our latitudes with risk of false or useless benefits, without paying attention to walls, floors and roofs as well*" [3]. Moreover, from the environmental point of view, the replacement of the original windows by new ones leads to a 7-fold increase in CO_2 emissions into the atmosphere, due to the whole production cycle of the new building components and to the disposal of those removed [4]. Contrary to what one may think, more "sustainable" solutions are possible: there are several strategies that can be applied to enhance windows thermal performance, sustainability and conservation without having to replace them or negatively affecting the building. This paper aims to provide a as complete as possible overview on energy retrofit interventions of historic windows, with a careful assessment of the wide range of possible solutions and a look at the problems and future prospects of the integration of new technological solutions and high-performance materials in the historical context.

2. LITERATURE REVIEW METHODOLOGY

In order to outline the research status on window interventions, a literature review was carried out: studies on windows energy retrofit strategies and on the development and application of new technological solutions, also with the use of high-performance materials, have been collected. The search for articles published in scientific journals and conference proceedings took place through three electronic databases of peer-reviewed literature (Scopus, Web of Science and Google Scholar). After analysing all these publications, 63 were picked. To these should be added guidance instruments such as handbooks, guidance, booklets and so on published on the websites of associations as well as governmental and non-profit organizations from all over the world. They are addressed to architects, building contractors, owners and users with the intention to explain the most appropriate conservation practices, heritage management and energy improvement solutions for historic buildings. Finally, there are many Research Institutes and Centres that have developed long-term research programs and projects which significantly contributed to the production of study reports. In addition to the previous documents, other 43 handbooks, booklets etc. and 20 study reports were taken into consideration, for a total of 126 documents. The literature review process was then summarized in three research fields: retrofit solutions; new technological experimentation and perspectives; high-performance materials and solutions applied to existing buildings.

2.1 RETROFIT SOLUTIONS

The starting point of the literature review is a research carried out a few years ago in which 21 study reports, published in Europe and America, were examined in order to understand how the interventions on windows in historic buildings are dealt with in the current debate [5]. These reports take into account different parameters to evaluate the performance of historical windows: transmittance is the most recurrent value (it is present in 13 reports), but parameters such as air leakage, saved energy, costs, payback and LCA are also reported. What has emerged from the comparison of results is that although single-glazed windows have a U-value of about 5,18 W/m^{2}K, significant performance improvements can be achieved through a series of measures that gradually balance energy performance with preservation of historical material consistency, without having to replace the original window.

	2 English Heritage	3 Historic Scotland	4 Ireland	5 Norwegian Institute	6 Grand Poitiers	7 Berner Fachhochschule	8 ReHab	13 US Department	15 Iowa	16 Vermont	17 Victoria	18 Winsconsin	20 NCPTT	Average [W/m2K]
Unimproved single glazing	4,3	4,5	5,4	4,7	4,4	4,5	4,9	4,9	6,2	5,2	6,8	5,6	5,9	5,18
Heavy curtains	2,5	3,2	3,2										3,2	3,03
Closing shutters	1,8	2,2	2,2											2,07
Insulated shutters	1,7													1,70
Internal window film	1,9-2,3										3,2	2,8	3,1	2,66
Secondary glazing system	1,8	1,7	1,7		2,5	2,6			2,8		3,6		2,3	2,38
Secondary glazing and shutters	1,6	1,1	1,1											1,27
Insulating glazing							1,4 (vi)							1,4 (vi)
Double glazing		1,9	1,9	2,8	1,4	1,9		2,8		2,8		1,4		2,11
Polycarbonate panel		2,4												2,4
Internal storm window				2,6 (vs) 2,0 (vd)	1,1 (vi)	2,3 (vs) 1,3 (vd) 1,0 (vi)	2,3 (vs) 1,1 (vi)							2,40(vs) 1,65 (vd) 1,06 (vi)
Internal and external storm windows				2,7 (vs)		2,6 (vs)	2,3 (vs) 1,1 (vi)							2,5 (vs) 1,1 (vi)
External storm window						2,2 (vs)		2,7 (vs) 2,2 (vi)	3,3 (vs) 1,9 (vi)	2,9 (vs)		2,8 (vs) 2,1 (vi) 1,8 (vd)	2,1 (vi)	2,78 (vs) 2,07 (vi) 1,8 (vd)

Figure 1. U-value results for window retrofit interventions: vs means single glazing, vi insulating glazing and vd double glazing. All the options have previously undergone draught-proofing operations. Source: [5]

Thanks to the above-mentioned study reports and the analysis of further documents for a total of 93, it was therefore possible to provide a complete overview of the window retrofit options. These were then grouped into three levels of increasing impact on the heritage, in the perspective of a step-by-step approach to energy efficiency improvements. The first level concerns low-impact interventions, i.e. conservative options potentially applicable to any building, such as repairing windows, improving their airtightness, recovering shutters and adding curtains. The second level regards medium-impact interventions: in this case the sustainability of the intervention depends on the characteristics of the building and the climatic zone in which it is located. It includes strategies such as installing a secondary glazing, inserting an external or internal storm window, adding window film and replacing existing glass. Finally, the third level has the greatest impact and correspond to the window replacement: this needs careful reflection because it is aimed at achieving high performances while taking little account of the values of the historic buildings. These strategies cannot be applied automatically to the building, but a case-by-case evaluation is needed. Moreover, the building components are connected to each other and in the assessment of the window retrofit interventions it is necessary to adopt a global vision of the building. As a matter of fact, the performance of historical windows can be improved by working not only on glass, frames and shading systems, but also on the connections with the walls. This is a weak point because thermal bridges and air infiltrations are concentrated here. To cope with these problems, a very common solution in current practice is to insulate the interior side of the wall by turning the insulation over the reveals and windowsill. This kind of intervention can be greatly simplified by the use of high-performance materials such as aerogel which, thanks to its low thickness, limit the narrowing of the opening compartment allowing the original window to be maintained [6]. Another aspect of utmost importance is the climate context in which the building is placed. This is proved in a study published by the National Trust for Historic Preservation Green Lab [7] that examines multiple window improvement options, comparing their energy, carbon and cost saving in five cities representing various climate types of the continental U.S. The results of this analysis demonstrate that the best retrofit options for a heating-dominated climates may not be right for a cooling-dominated climates. However, for all cities at least one and often two of the selected retrofit options can achieve energy savings within the range of savings expected from new high-performance windows (at a fraction of the cost). Finally, a study carried out in "La Specola" museum of Florence shows that even in the same climate context, windows with different solar exposures need tailor-made solutions [8]. Generally speaking, it is better to follow the historic buildings characteristics and take inspiration from the solutions used in the past. Strategies such as inserting or recovering indoor and outdoor curtains and shutters are widespread in hot climates where the biggest problem is preventing the entrance of solar radiation. On the contrary, in cold climate measures that limit air infiltration and heat loss through the glass, like the installation of a secondary glazing, are more commonly used.

Figure 2. Example of installation of a secondary external glazing in Villa Piazzi in Nerviano (MI) by the restorer Ercole Livio Rini. (a, b) View of the external side. (c) Inside view of the closed window.

As we have seen, in the assessment of possible interventions we must not only consider quantitative criteria, referred to comfort and thermal properties, but also qualitative criteria, linked to the restoration's principles (compatibility, reversibility, invasiveness, etc.). Only a clear methodology based on a multidisciplinary and integrated approach allows to make informed decisions directed towards balancing all the aspects at stake.

2.2 NEW TECHNOLOGICAL EXPERIMENTATION AND PERSPECTIVES

An interesting field of research concerns the future prospects of the technological evolution of windows and their shading systems. The literature review highlights 33 documents that focus on building components, devices and products made with high-performance materials and technologies resulting from universities experimental research and never applied to new or existing buildings because they are not yet available on the market. Aerogel, phase-change materials (PCMs) and advanced and smart glazing systems are the materials and technologies most frequently applied to experimental solutions for the high performance they can provide. Studies on PCMs account for 79% of the analysed documents. PCMs are characterized by a melting point near the comfort temperature and they accumulate and release latent heat during the transition phase from the solid to the liquid state, without changing their surface temperature. During the day, when the temperature increases, PCMs absorb heat and as a consequence liquefy, cooling the room; when the temperature decreases, the material returns solid and releases heat that can be dissipated by ventilation [9]. Thanks to the possibility of integration in limited thickness components, they are often used for shutters and glass prototypes. In this regard, following research works provide valuable insight: the studies carried out by the University of Aveiro in Portugal on a shutters system with aluminium blades filled with PCM[1] [10] and the studies carried out by the Politecnico di Torino in Italy on a cutting-edge system with PCM inserted between the glass panes[2] [11]. Glass is also the element on which some research works on aerogel are focused. They account for 12% of the analysed studies. Aerogel is a light, highly porous material produced from silicon dioxide and is composed of approximately 96% of air and the remaining 4% of open-pores structure of silica which gives great lightness to the system thanks to its small specific weight. Aerogel has the lowest thermal conductivity among solid materials, even lower than that of the air, thus making it an excellent thermal insulation product. The introduction of aerogel in glazing systems occurs both using monolithic and granular aerogels in the glazing interspace[3] [12]. The University of Perugia is particularly active in aerogel experimentation and boasts a series of studies conducted in laboratory on glass and polycarbonate systems with granular aerogel [13]. Finally, 9% of the analysed documents present a complete overview of the latest developments in the world of high-performance glass [14]: intelligent, vacuum, photovoltaic and photochromic glazing are just some examples of the products designed for new buildings that can have interesting applications also in the historical context. In this regard, it should be pointed out that in the last few years a real breakthrough has taken place in the field of photovoltaic glazing: in 2018 the University of Milano-Bicocca developed a patent of a transparent photovoltaic window that uses LSC (Luminescent Solar Concentrator) technology, integrated in the transparent component, to convert sunlight into infrared rays. These are then reflected inside the panel up to the edge where a strip of silicon photovoltaic cells converts it into electrical current. Unfortunately, at the moment there are no experimentations in historic buildings, but it would be interesting in the near future to test the prototypes in traditional windows to verify their actual efficiency [15].

Despite the strong limitations due to the experimental character of these technologies, some of them are quite interesting and could lead to the development of new products for historic buildings, obviously to be tailored, in terms of compatibility and sustainability, to the specific needs of the built cultural heritage. On the other hand, others are still too “embryonic” to be used in the historical context (this is the case of the PCMs).

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[1] The research presents the results of an experimental campaign of a full-scale outdoor test cell, composed by two side-by-side compartments with and without PCMs. The results reveal the PCM potential for the thermal regulation of indoor spaces during winter and summer periods. In the cold season, the compartment equipped with PCM shutters reached a maximum internal temperature of 37.2°C compared to 53.8°C detected in the sector taken as reference (16.6°C less). During the summer season, the compartment with PCM shutters reduced the indoor temperature from roughly 22% to 18% and decreased the maximum and minimum temperature peaks by 6% and 11% respectively.

[2] The performances of the prototype were monitored in an experimental campaign and compared with those of a conventional double glass unit. It was found that PCM glazing is able to contribute to a better indoor thermal environment for most of the time during the various season compared to the reference glazing.

[3] The monolithic aerogel is more suitable for use in glazing systems because it offers the best compromise between light transmission and thermal insulation. Due to its fragility, excessively high cost and difficulties linked to production processes, it is not yet widely marketed. The use of granular aerogel in glazing therefore offers an alternative solution to the monolithic version because it is cheaper, more robust and easier to produce on a commercial scale. However, it is characterised by poor transparency and a translucent aspect, which strongly limits the view towards outside with hazily deformation of optical images.

2.3 HIGH-PERFORMANCE MATERIALS AND SOLUTIONS APPLIED TO HISTORIC BUILDINGS

The last field of research investigates the use of retrofit solutions with high-performance materials and technologies in historic buildings: in particular, 8 documents out of 93 (referred to "Retrofit solutions" paragraph) are related to the built cultural heritage. The results of the literature review show that two are the most practiced research lines: working on the glazing systems or on shading systems like shutters.

With regard to glazing, the Italian guideline includes a collection of sheets on available materials and types of intervention in which high-performance technologies play a leading role: insulating glazing with TIM (Transparent Insulating Materials) and aerogels, chromogenic glazing and photovoltaic glazing are just some examples of the systems considered [16]. However, in the section dedicated to the case studies, these types of glazing are never present: on the contrary, there is a considerable preference for the replacement of the whole window. In general, a wide range of high-performance glazing is available today, but the choice depends on the window state of conservation, its material and dimensional characteristics, the strength of the existing frames and the weight of the new glazing system. A remarkable study entirely dedicated to the replacement of the existing single glass unit with a variety of high-performance double-glazing products (retaining their original frame in 6 cases out of 10) is that carried out by Changeworks in some listed buildings located in Edinburgh [17]. Conventional double glazing consists of two layers of glass up to 25 mm apart with dry air or inert gas in the cavity. Most traditional windows, however, have a glazing bar with a shallow rebate, designed to take a single sheet of glass of about 3 mm: this means it is usually impracticable to replace old glass with standard double-glazed units. For this reason, the focus of this study is the installation and on-site monitoring of slim-profile double glazing, characterised by a significantly smaller cavity and lower weight compared to conventional double glazing (from 8.2 to 16 mm), but with a similar thermal transmittance (ranging between 1 W/m^2K to 2.8 W/m^2K) [17]. Different types of this kind of glazing were investigated by the authors, but the most innovative is certainly the vacuum glazing, consisting of two glass panes with a vacuum-filled space between them. Although the cavity thickness of the vacuum glazing was only 0.2 mm, it proved to be the best from the U-value point of view, reaching a value of 1 W/m^2K compared to the others that reached values always amounting to 2 W/m^2K or more [17]. Even though vacuum glazing is a valuable resource for the thermal performance improvement of historic windows, it is necessary to take into account some drawbacks related to the choice of these products: they employ metal pillars between glass panes, to prevent glass breakage (due to the pressure gradient), that are visible from a close distance; they can be produced only in limited sizes and their cost is still very high [18]. Despite these limitations, in recent years, the installation of vacuum glazing has been fostered by the institutions involved in preservation. Another interesting innovation in the field of glazing concerns the use of aerogel: 3 are the studies, collected during the literature review process, that simulate the insertion of a new glazing system with monolithic aerogel in the cavity of a double-glazing units of two historic buildings (one of which is listed). Both projects assume to upgrade only a glazed portion of the window, alternating aerogel-enhanced glazing and traditional transparent ones: several alternative configurations were therefore considered (40, 60, 80 and 100% of aerogel). The results of the simulation showed that heating energy consumption decreased by increasing the aerogel proportion in the windows and that cooling energy consumption kept stable with percentages of aerogel above 60%: the greater the quantity of aerogel the lower the window SHGC and U-value (it ranges from 1.2 W/m^2K for 40% of aerogel to 0.6 W/m^2K for 100% of aerogel) [18]. In the review, the only real application example of panels filled with aerogel in a listed building is the Alte Börse in Zürich

(Switzerland), where the existing roof was substituted with aerogel elements with an improvement in the U-value from 2 W/m^{2}K to 0.6 W/m^{2}K [19]. Aerogel glazing show significant energy savings which, however, is still burdened with high costs of materials and long payback times: on top of that, they are characterised by a translucent aspect that is an unacceptable alteration for a historic building. Moreover, given the lack of case studies in built cultural heritage, the application conditions and compatibility of the aerogel glazing have not yet defined comprehensively.


Figure 3 (a, b). Vacuum glazing installed in a historic building located in Edinburgh. Source: [17]
Figure 4. The roof of the Alte Börse in Zürich after the renovation with the aerogel glazing. Source: [19]

Finally, regarding shutters interventions, 2 are the studies that must be mentioned: an in-lab testing carried out by the Historic Scotland, followed by a practical application in one of their case studies. The first study measured in laboratory the performance of a traditional shutter and a modified shutter with a 9 mm thick aerogel insulation blanket inserted into panels and covered with plywood (the insulated area was 55%). The traditional shutter showed a U-value of 2.2 W/m^{2}K, while the insulated shutter led to a U-value of 1.6 W/m^2, equivalent to low-E double glazing [20]. A similar type of shutter, upgraded using a 10 mm aerogel quilt, was used in a tenement flat in Edinburgh a few years later. Here, starting from a U-value of 2.2 W/m^{2}K the shutters reached a value down to 0.4 W/m^{2}K, with an 82% improvement [21]. Although promising, this type of intervention cannot be applied to all types of shutters: they must have enough internal space to house the insulation, so if they consist of a single piece of wood, alternative tailor-made measures are required.

3. CONCLUSIONS

In many countries, historical windows are disappearing at an alarming rate, replaced by highly efficient windows with a great environmental impact. Three are the main reasons: disregarding their importance in representing the material culture of the craftsmanship, tax incentives and misunderstanding about sustainability. Despite this, nowadays it is possible to prove that many alternative retrofit solutions are available for improving the performances of ancient windows. In this paper we tried to define a picture of the research state-of-the-art on window interventions though a literature review. This showed that managing several quantitative and qualitative criteria is crucial in selecting the best intervention and, therefore, a multidisciplinary approach is required in order to balance energy efficiency and sustainability needs with conservation aspects. High-performance materials and technologies can help in this regard: in recent years, the growing interest in this field has led to a strong acceleration in the technological development of new efficient products. However, as pointed out by Milone et al. [23] "*the Best Available Technologies for building components characterized by high level of thermal performances show, not rarely, a limited compatibility with the architectural integrity of the building […] to which a certain artistic, historic and/or architectural merit is recognized*". Hence, the delicate relationship between building protection and energy efficiency cannot be solved through the uncritical application of the best technologies from a performance profile, but through a good balance between advanced technologies and the conservation of the identity of the historic buildings. Unfortunately, at the moment, although the first results from the thermal point of view are encouraging, there is not enough research works investigating in detail the application conditions (including climatic aspects) and compatibility of these technologies in heritage buildings. Our purpose is therefore to implement our knowledge and experience in this field through the assessment of a wide range of case studies.

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Ralf Kilian, Sara Saba, Caroline Gietz (Hrsg.)

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The 4th International Conference on Energy Efficiency in Historic Buildings

In order to achieve the ambitious governmental and societal goals in CO_2 reduction that are needed to mitigate global climate change, the contribution of all sectors including buildings and the construction industry is required. Historic and traditional buildings compose a considerable part of the worldwide building stock. In this context solutions are needed that respect the historic fabric of these buildings and yet contribute to energy efficiency improvements and CO_2 reduction.

This volume collects papers given at the 4th International Conference on Energy Efficiency in Historic Buildings EEHB2022 at the Fraunhofer Centre for Conservation and Energy Performance of Historic Buildings at Benediktbeuern Monastery, Germany, from May 2nd to 5th 2022. Scholars presented new research and best practices on a wide range of topics relating to energy efficiency in historic buildings.

The EEHB2022 conference especially addressed issues related to the role digital technologies can play in improving the energy performance of historic buildings, whilst respecting the principles of conservation. In this context, the aim was and is to take a closer look at the interfaces between digital building models and the building simulation and the question of the necessary accuracy of both 3D digitisation and hygrothermal or building energy performance simulation tools. Both technologies – 3D scans and building simulation – have been available for a long time, but so far there are no automated processes for converting 3D scans into the energetic building simulation, also concerning the degree of accuracy of the building survey using digital methods in order to represent a historical building accurately. This volume provides an insight on current themes and scholarly efforts around the world. These topics were also treated during the two-day-long workshop entitled »Recording historic buildings using digital workflows – Designing the intersection from 3D model to building simulation« that preceded the EEHB2022 conference. This volume provides an insight into current research efforts around the world.

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