

Elevating a facade theory into practice

Mary Ben Bonham

Miami University, Oxford, Ohio

ABSTRACT: This paper draws connections between building enclosure technologies from the time of Le Corbusier's *mur neutralisant* and *respiration exacte* concepts to a present-day double-skin glass façade system, the closed cavity façade (CCF). The successes and failures of Le Corbusier's thermally controlled interior and hermetically sealed wall concepts are examined as they were applied to Villa Schwob (La Chaux-de-Fonds, Switzerland, 1916), Centrosoyuz (Moscow, Russia, 1928), and the Salvation Army Building in its originally built form (1933). Building on this historical context, the paper discusses facade technologies that emerged in 1980s and 1990s that sought to improve upon the performance of sealed glazing by eliminating condensation, improving thermal comfort and integrating solar control: the ventilated double-skin facade and the less widely discussed *façade pressurisée* (pressurized facade) and *façade respirante* (breathable facade). The facade technologies are elaborated upon in the cases of the French National Library (1989-1995) and the Grenoble Law Court (1994-2002) where facades were fabricated by French manufacturer Rinaldi-Structal. In these projects, non-standard building technologies were developed and applied through the aggregate efforts of French government research labs, manufacturers, architects, and insurers. Today, breathable facade technology is largely limited to use in France; each application receives technical review by a state agency during the design phase. On the other hand, pressurized facade technology has spread to other parts of Europe and beyond under the name CCF. Innovative forms of CCF developed by Gartner/Permasteelisa, based on initial experimentation in coordination with a German research institute, continue to push the performance envelope: CCF with facade-integrated ventilating floor slots (Roche Diagnostics, Rotreuz, Switzerland, 2011), CCF with operable windows (LEO Building, Frankfurt, Germany, 2013), CCF with wooden louvers in the cavity (EY Center, Sydney, Australia, 2014), CCF with tilted exterior faces (JTI Headquarters, Geneva, Switzerland, 2015). The built works and the threads of technological development between them are identified as applied research that bridges between theory and practice.

KEYWORDS: breathable; closed cavity; double-skin; façade

INTRODUCTION

Most, if not all technologies go through an initial phase of development in which there are competing technical ideas, which eventually resolve themselves into what is recognized as the mainstream of development (Yeomans 1998, 59).

Closed cavity facades (CCF) are presented by the industry as new, state-of-the-art glass curtainwall technology. In fact, the pressurized sealed double-wall technology was developed and applied over two dozen years ago in the final Mitterrand-era Grand Project, the French National Library in Paris (1989-1995) designed by Dominique Perrault (Fig. 2). Superior thermal performance in CCF is maintained by a steady stream of dry air supplied to a sealed air space between two glazed skins. Pressurization, which requires minimal energy to operate, prevents condensation in the glazing cavity and avoids the need to clean the interior of the window units. The desire to have a tightly sealed wall with superior thermal and operational performance is not new, and a number of insulated glazing technologies were developed and deployed before and alongside CCF. From a starting point of Le Corbusier's theories about active walls, the following sections discuss how theories about sealed walls have been elevated into current practice through applied research.

1.0 SEALED GLASS WALL CONCEPTS

1.1. *Mur neutralisant* and *respiration exacte*

Le Corbusier's Five Points for a New Architecture—*pilotis*, free plan, free façade, ribbon window, and roof garden—were theoretical principles that the architect applied and developed through experimentation with actual buildings, often in collaboration with engineers and other architects. Le Corbusier's attention to natural ventilation, light and solar control is evident in the architectural forms. Less visible perhaps is Le Corbusier's interest in combining passive and active techniques to achieve thermal comfort (Solla 2011). The successes and failures of the thermally controlled interior and hermetically sealed wall concepts can be followed in the Villa Schwob (La Chaux-de-Fonds, Switzerland, 1916), Centrosoyuz (Moscow, Russia, 1928) and the Salvation Army Building (Paris, France, 1933). Through these built works Le Corbusier learned certain boundaries that building physics placed on his theories and that glazing required ventilation and shading to avoid excessive heat build-up.

Glass facades have always been a source of light to interiors, and only sometimes a source of natural ventilation. In the first decades of the 20th century, glass architecture grappled with the new possibilities and technical challenges offered by mechanical central cooling. The idea of hermetically sealed interiors that would keep out noise and air pollution of industrialized cities competed with recognition that natural ventilation has energy-free practicality and capability to overcome stuffy and potentially unhealthy interior air. For a time, Le Corbusier promoted sealed walls alongside the active concepts of *mur neutralisant*, thermally conditioned air cavities between sealed glass or opaque wall construction, and *respiration exacte*, mechanical air conditioning capable of controlling both temperature and humidity.

In an early experiment at Villa Schwob, Le Corbusier placed heating elements between two fixed glass layers in a large multistory window of the residence (Solla 2011). Later at Centrosoyuz, a social housing project designed with Russian architect Nikolai Kolli, Le Corbusier intended for a thermally conditioned air cavity to be used in both opaque and glazed wall areas. The interwall air spaces were to be served by a secondary mechanical system, separate from the building mechanical air conditioning system. This time the experimental 'hermetically sealed' proposal was tested before construction by the glass manufacturer St. Gobain and the American Blower company, who found the wall concept to be impractical and consume excessive amounts of energy (Wigginton 2000). In the adapted design, stone walls were built as a single layer with no air space. Ribbon windows were built as two glass layers with an unconditioned air cavity and sliding windows; solar control remained an unsolved problem for Centrosoyuz residents (Fig. 1).

Le Corbusier proposed the *mur neutralisant* idea again at the Salvation Army Building. The south-facing facade of the building was to have a closed-loop air conditioning system dedicated to conditioning the air space between two all-glass wall layers. The system was again deleted due to uncertainty and cost. The facade was constructed as a single, sealed glass wall. In the first summer, overheating proved intolerable for the occupants, and Le Corbusier was forced to have a series of sliding windows installed in the upper third of each window area as a retrofit. Shortly after these experiences, and inspired by travel and commissions in hot climates, Le Corbusier is observed to make a transition from active to passive wall concepts in order to avoid the solar overheating and glare problems associated with large expanses of glass (Taylor 1987).



Figure 1: Centrosoyuz, 1928. Source: (CC-BY-SA: Digr)

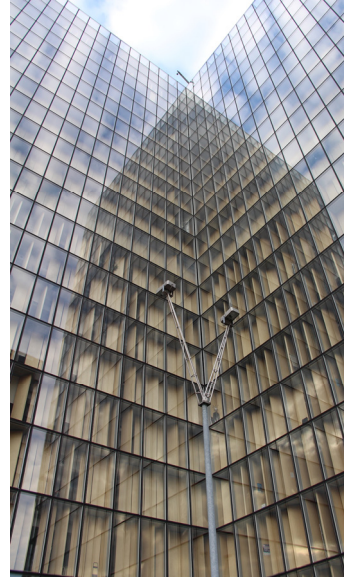


Figure 2: French National Library, 1995. Source: (CC-BY: Fred Romero)

1.2 Insulating glazing units

Even while Le Corbusier's own work evolved to include solar control and ventilation as necessary accompaniments to glazed walls (consider the *brise soleil* and *aérateurs* of the Carpenter Center, for example), the theory of the 'hermetically sealed' glazed wall remained a compelling concept. From the mid-century emergence of Thermopane, the sealed glass wall concept has been under continuous development. Insulated glazing units (IGU) and manufacturers' proprietary curtainwall framing systems are produced with ever-improving thermal performance and durability. Material technologies continually improve the performance of windows and curtainwalls. In the areas of glazing: plate glass, tighter and more durable seals, tints and reflective coatings, low-emissivity coatings and films, gases in the sealed cavity. In the areas of framing: thermally broken frames and factory-sealed unitized construction. With the advent of low-iron content glass and frameless, structural glass technologies, it is now possible to specify ultra-transparent walls with high thermal resistance and high visible light transmittance.

But even the highest performing systems have limitations. Heat build-up in sealed glass units, especially those with blinds integrated into the cavity, limits the durability of gaskets, reradiates heat to the interior and creates risk of condensation. Double wall technologies were developed that sought to improve upon the performance of single-skin sealed glazing. A variety of construction strategies, including both ventilated and unventilated designs, aim to eliminate condensation and improve thermal performance while still integrating solar control.

2.0. VENTILATED DOUBLE-SKIN GLASS FACADES

In addition to seeking daylight and transparency with thermal comfort, double-skin glass facades were developed in response to factors such as acoustic buffering and energy conservation. These criteria motivated the construction of early double-skin architecture including the Cattle Dealers Savings Bank by Behnisch and Partner in Stuttgart, Germany (1969), the Occidental Chemical Center by Cannon Design, Niagara Falls, New York (1981), and Briarcliff House by Arup Associates, Farnborough, England (1983). In each of these buildings, facades were externally ventilated. The introduction of an outside air stream passing between the two glazed skins serves a critical role of evacuating excess heat and humidity and reduces the chance for condensation forming on any of the surfaces. Externally ventilated

facades are found with a wide variety of details regarding glazing, ventilation openings and cavity depth profiles. Many have openings in the inner skin that permit natural ventilation of interior spaces; some have provisions to draw warm air from the cavity to supplement building heating. The general principle of an externally ventilated double-skin is shown in Figure 3a.

Early double-skin facades were also developed with internal ventilation. The air space between two glazed skins serves as a return air plenum integrated with building mechanical systems. Conditioned room air is drawn between the two skins where it creates a constantly refreshed thermal buffer against heat gain and losses through the facade. Cavity air is returned to the building services for energy recovery. Typical airflow in an internally-ventilated facade is upward (Fig. 3b), however, in one of the earliest versions of this technology, Lloyd's of London by Richard Rogers, London, England (1986), airflow is downward (Fig. 3c).

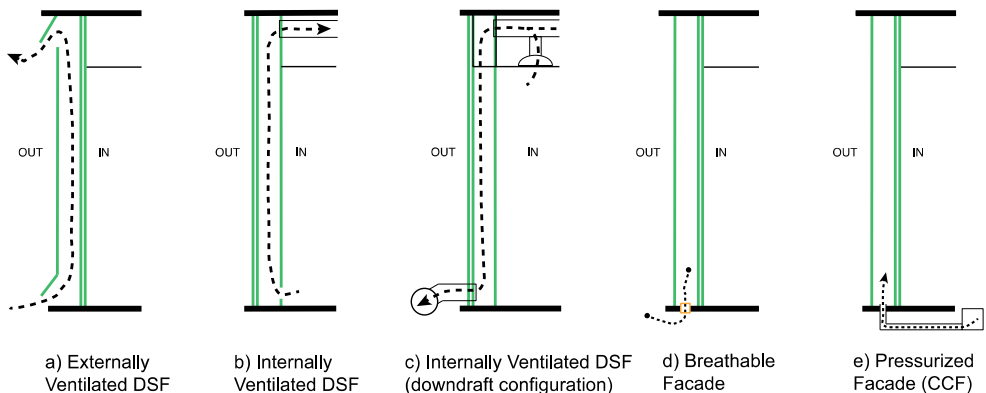


Figure 3: Ventilating and unventilated double-skin glass facade schematic configurations. Source: (Author)

3.0 UNVENTILATED DOUBLE-SKIN GLASS FACADES

Less widely discussed are early double wall innovations that do not feature pass-through cavity ventilation: *façade respirante* (breathable facade) and *façade pressurisée* (pressurized facade). These unventilated facade technologies will be elaborated upon in the cases of the Grenoble Courthouse (1994-2002) and French National Library (1989-1995).

3.1. *Facade respirante* (breathable facade)

The courthouse in Grenoble, France designed by Claude Vasconi employs both ventilated and unventilated double-skin facades in its enclosure. Glass, daylight, and transparency in the architecture are intended to convey the “light of justice” in France’s modern judicial system (APIJ 2003). A multistory ventilated double-skin facade clads an eight-story office block, and an unglazed box-window breathable facade forms the backdrop to a large public atrium space (Fig. 4). Opaque facades are clad with lacquered steel panels.

The thermal performance of the southwest-facing office block facade relies on external ventilation of a 692 mm (27 in) wide, multistory airspace. Motorized dampers at the base and the top of the facade control airflow between the two glass skins. Clear low-iron glass is single-glazed in the outer skin and double-glazed in the inner skin. Motorized louver blinds for solar control are protected from weather inside the cavity. Catwalks are integrated into the structure so that the facade interior surfaces are accessible for maintenance. Although still considered innovative at the time the courthouse was built, this climate-adaptable type of ventilated double-skin had been in use in Europe since the 1980s.

In a contrasting design solution, the double-skin in the courthouse’s west-facing atrium consists of tightly sealed modular facade units fitted with fine mesh filters permeable only to vapor. Small oblong filtered openings in the lower frame area link the double-skin air space with the exterior environment, a technique that allows vapor pressures to balance between the

air space and the exterior, thus preventing condensation in the cavity (Fig. 5). Glazing here is also clear low-iron. Solar control is provided by fixed external metal louvers. As discussed in Section 4 below, application of breathable facade technology required (and still requires today) technical review by an agency that works on behalf of the French government to support the emergence, development and safe use of innovative building technologies.



Figure 4: Grenoble Courthouse, 1994-2002. Breathable facade. Single-glazed outer skin, 40 mm (1.5 in) wide air space, double-glazed IGU inner skin. Source: (Author)



Figure 5: Grenoble Courthouse. Breathable facade. Small dust-filtering breathing holes in the bottom portion of the unitized aluminium frame. Source: (Author)

3.2. *Façade pressurisée* (pressurized facade / closed cavity facade)

The French National Library in Paris, France designed by Dominique Perrault also aimed for utmost transparency with the highest level of thermal control. The performance challenge of cladding the iconic book-shaped glass towers was met with an innovative new pressurized facade double-skin technology (Fig. 6). Called closed cavity facade (CCF) outside of France, the application at the French National Library is likely the first in France and possibly first in Europe.

In the French National Library facade, a pressurized supply of filtered and dehumidified air is continuously fed through tiny tubes in the modular unit frames to a sealed air space (Van Santen 2001). The dry air, supplied in minute quantities based on external climate conditions, prevents condensation in the air space and, because dust and other contaminants are not brought into the airspace, eliminates the need to clean the cavity. Pivoting wooden panels set back from the glazing provide solar control (Fig. 7). The extra-clear glazed outer skin is structurally glazed to the frame using a silicone sealant specially engineered for the application (Dow Corning).

4.0. APPLIED RESEARCH MECHANISMS

Some details about how the facades for the Grenoble Courthouse and the French National Library came into being give a glimpse into the workings and drivers of innovation. In these buildings, experimentation with non-standard techniques occurs on a grand scale with the cooperation of client, architect, façade manufacturer, government research lab, and insuring bodies who shared the common goal of developing and applying new building technologies while managing the risks of innovation (Bonham, 2012). French facade manufacturer Rinaldi-

Structural fabricated the facades for both landmark buildings, working in close collaboration with the buildings' respective architects and project teams to realize ambitious design visions.



Figure 6: French National Library. Double-skin pressurized facade (CCF). Single-glazed outer skin, 90 mm (3.5 in) wide pressurized air space, double-glazed IGU inner skin. Source: (CC-BY: Fred Romero)



Figure 7: French National Library. Floor-to-ceiling wooden panels pivot to control light. Source: (Author)

4.1 Progression of breathable wall technology

The theory of *respiration* that led to breathable facades was first studied by the French Scientific and Technical Centre for Building (CSTB) in the late 1980s as a solution to the problem of condensation forming in standard insulating glazing units in which seals would typically fail after years in use. The experimentation developed into the present day double-skin configurations with vapor permeable filters. Air space widths can range from 40 mm (1.5 in) to 500 mm (19 in). The wider versions can accommodate architectural elements such as operable louver blinds in the cavity (CSTB Dec 2007; Keinlin 1994).

With roles somewhat akin to the National Institute of Standards and Technology (NIST) and national labs like the National Renewable Energy Laboratory (NREL) in the United States, scientists and engineers in CSTB labs test and develop technical innovations. Manufacturers may come to the CSTB requesting preliminary assessment of new products; design teams in collaboration with builders and fabricators may request assessment in order to apply unproven building techniques. After technical evaluation, products and techniques can seek acceptance by a technical committee of French insurers with the goal to earn normal cover status in damage and responsibility insurance (Atkinson 1995).

Breathable facades are manufactured by a number of companies who are allowed to commercialize their product lines referencing a technical appraisal by CSTB called an *avis technique*. Based on lengthy analysis and tests of products in their first years of existence, this technical notice denotes a level of security and quality comparable to traditional products and processes (CSTB 2009). Technical review of a breathable facade includes a project-specific study of the proposed application's climatic conditions, materials and dimensional configuration, after which recommendations are made for details such as the number and size of the filter openings (CSTB 2009).

Rinaldi-Structal fabricated all the facade types for the Grenoble Courthouse (APIJ 2003). Though largely constrained to distribution in France, breathable facades are presently being

manufactured by a number of fabricators, including Arcora, Kalory'R, and Wicono, each of whom is competing to add value and performance to their version of the technology. For example, Kalory'R promotes a breathable window unit with operable vents and integrated blinds as the "new generation of breathable windows." Like other breathable facades in France, the window meets stringent thermal and airtightness regulations and is marketed under a CSTB technical document specific to that product (Cyberarchi 2014).

Breathable facade technology is employed throughout France in projects such as the 28-story Oxygène Tower in Lyon by Arte Charpentier and the Louis Dreyfus Building, a renovation in Paris with a retrofit facade fabricated by Groupe Goyer (Hespel 2011). Rinaldi-Structal was again the fabricator for the breathable facades of a new hospital in Douai, France designed by Brunet and Saunier (CSTB May 2007).

4.2. Progression of CCF technology

The pressurized facade concept first employed in the French National Library is now being widely marketed under the name CCF by European façade manufacturers. CCF can be seen as an evolution and a hybrid of preceding strategies. Designers and manufacturers sought the thin profile, thermal performance, and maintenance benefits of double or triple glazing with blinds sealed in the IGU cavity, but wished to avoid the problems associated with blind controls passing through the unit seal and the increased levels of trapped heat created due to the thermal mass of the blinds. They sought the ability to expel heated air from the cavity as could be done with internally or externally ventilated double-skin facades, but wished to avoid condensation on the glass and eliminate the cleaning cycles necessitated by air passing through the cavity. With units as thin as 40 mm (1.5 in), CCF and other double-skins with thin-profile air spaces have a reduced facade zone compared to earlier-developed thick-profile double-skin facade options.

In comparison to ventilated thin-profile double-skin facades, CCF have comparable thermal, visual and acoustic performance without the disturbance to occupants those systems require when the facade units must be accessed for periodic cleaning of the glass and the blinds. According to a leading manufacturer, U value of CCF glazing is 0.89 W/m²/°K (0.16 Btu/h/ft²/°F), g value is .55 (0.15 w/blinds), and light transmission = 69% (De Bleecker 2012).

CCF performance comes with a cost that currently limits applications to high-end properties. According to an account of the London market, CCF installation costs are in the same range as an all-glass thin-profile ventilated double-skin facade, costing 30 or 50% more than a base case of single-skin curtainwall with 50% solid panels. The cost premium allows projects to have a conventional facade zone depth, larger window-to-wall ratio, and an improved thermal, visual and acoustic environment while still meeting strict European energy codes. The expectation is that life-cycle costs support the investment, however, data on maintenance and operating costs is lacking (Mudie, Coleman and Watts 2017).

Working both inside and outside of France, facade manufacturer Josef Gartner, a subsidiary of Permasteelisa, is known for progressing a number of developments in CCF technology beginning with the in-Haus2 project in Duisburg, Germany (2008-2009). The building for the Fraunhofer Society is a research facility for the study and promotion of intelligent facades, room and building systems. It features five types of experimental curtainwalls including a closed cavity facade prototype for Gartner/Permasteelisa (Rudolf 2012). Permasteelisa quickly brought CCF technology into serial production with their MFree-S (moisture/ maintenance-free sustainable) line. Press releases for subsequent projects celebrate one 'first' after another:

Roche Diagnostics, Rotkreuz, Switzerland (2011): First CCF application in Switzerland, and first ever integration of CCF with fresh air preconditioning ventilation slots. LEO building, Frankfurt, Germany (2013): First full-scale CCF application in Germany (after in-Haus2), and first ever CCF with operable windows. The major refurbishment project replaced the existing Poseidon House building facade with CCF, glass fiber reinforced concrete facade panels, and BMS-controlled parallel-opening windows. EY Centre / 200 George St., Sydney, Australia (2014): First CCF application in Australia, and first ever integration of wood solar protection in the CCF air space (Permasteelisa).

CCF modules create a unique quilted appearance for the facade of the JTI Building in Geneva, Switzerland (2015) designed by SOM (Fig. 8). The design takes advantage of a feature that all double-skin facades have when the inner skin forms the primary thermal and air control layer for the interior: because the inner skin is constructed with thermally broken frames and tight seals, the outer skin can be designed with more freedom. In the JTI facade, the triple-glazed inner skin of each sealed unit is vertical and flush to abutted modules. The outer skin is diagonally split into panels that tilt alternately inward or outward such that projections shade alternate panels (Ijeh 2014).

With innovative high-profile building applications and widely-distributed press releases, Gartner/ Permasteelisa's leadership in the CCF market is unmistakable, but they are only one of the companies that offer the high performance facades. Wicona and Rinaldi-Structal are among the list of manufacturers who have developed CCF systems.

4.3. Disappearance or diffusion

CCF technology appears to be spreading globally. But breathable facade technology, which offers a completely passive configuration without the integration of the air supply system, does not appear to have the same momentum. A breathable facade was applied for the first time outside of France in the European Court of Justice of Luxembourg (2007). Designed by architect Dominique Perrault (of French National Library fame) with facade planning specialist Ralf Rache Engineering, the court's breathable facade was fabricated by Gartner/Permasteelisa (Fig. 9). This latest first had potential to be a harbinger of more widespread use of breathable facades. CSTB engineer Jean-Louis Galea says about the Luxembourg project:

For this project, CSTB has made a provision of a rather special kind. On one side, there was no question of applying the French legislation; on the other hand, it was normal to benefit companies of our expertise... We hope the use of this French technique on a landmark building is only a first step that will help other developments abroad (CSTB Dec 2007).

Subsequent news of breathable facade export outside of France is not readily found, however. The barrier to technology transfer could perhaps be related to intellectual property or other legal or political boundaries.

While there are no completed CCF projects in the United States known to the author at this writing, the increasing practicality of unitized, thin-profile high performance facade systems is beginning to be recognized in this market. The National Institute of Building Sciences (NIBS) awarded Permasteelisa North America with a 2017 'Beyond Green' Honor Award for company's propriety CCF system. The "writing is on the wall" that CCF will soon be a first in North America.



Figure 8: JTI Headquarters, 2015. Geneva, Switzerland. CCF facade. Single-glazed outer skin with tilted planes, variable depth air space, triple-glazed IGU inner skin. Overall unit depth 400 mm (16 in). Fabric roller blinds in the cavity. (CC-BY: Guilhem Vellut)



Figure 9: European Court of Justice, 2007. Kirchberg, Luxembourg. Breathable facade. Architectural metal elements within 150 mm (6 in) wide air space. Source: (CC-BY-SA: sprklg)

CONCLUSION

CCF manage to merge the seemingly incompatible strategies of ventilation and hermetic seal. The space-saving sealed units perform on par with externally ventilated double-skin facades and have the added benefits of minimal maintenance and avoidance of visible ventilation openings on the façade exterior. The tiny flexible air tube infrastructure is easily integrated into perimeter floor edges, and the air handling system required to pressurize the supply of dry and filtered air requires minimal energy. If power goes out, the facade units are tested to remain condensation-free for up to twelve hours. Both *mur neutralisant* and *respiration exacte* concepts are present. With CCF, have we finally realized the perfect marriage of Le Corbusier's passive and active principles? Or will all-passive solutions like breathable facades prevail in the long run?

In the North American market, answers to such questions will likely be pinned on practicalities such as the development of regional manufacturing, design, and construction expertise related to the new technologies. To become mainstream practice, these high performance facade solutions will need to meet cost and procurement criteria as well as support project goals for energy conservation and architectural intent.

REFERENCES

- Atkinson, G. A. 1995. Construction Quality and Quality Standards, The European Perspective. London: E & FN Spon, 61-65.
- APIJ (l'Agence publique pour l'immobilier de la justice). 2003. Palais de Justice de Grenoble, <http://www.apij.justice.fr/nos-projets/les-operations-judiciaires/palais-de-justice-de-grenoble/>.
- Bonham, M. B. 2012. New French Judicial Architecture. Proceedings of the Solar 2011 Conference of the American Solar Energy Society. Raleigh, NC: ASES.
- CSTB. Dec 2007. La technique du vitrage respirant s'exporte au Luxembourg. <http://www.cstb.fr/archives/webzines/editions/decembre-2007>.
- CSTB. May 2007. Du verre, rien que du verre pour la façade du Centre Hospitalier de Douai. <http://www.cstb.fr/archives/webzines/editions/mai-2007>.
- CSTB. 2009. Avis Technique, Appréciation Technique d'Expérimentation, Pass' Innovation : les clés pour comprendre. <http://www.cstb.fr/archives/webzines/editions/edition-de-fevrier-2009>.
- Cyberarchi. 2014. Kalory'R: Nouvelle génération de fenêtre respirante. February 26, 2014. <http://www.cyberarchi.com>.
- Ijeh, I. 2014. Skin deep: SOM's JTI Building in Geneva. Building.co.uk, October 22, 2014.
- Mudie, S. 2011. Specialist Costs: Curtain Walling. Building.co.uk, May 20, 2011.
- Mudie, S., Coleman, R. and Watts, S. 2017. Facades: Do all-glass buildings make financial sense? Building.co.uk, July 12, 2017.
- De Bleecker, H. 2012. Permasteelisa MFree-S Closed Cavity Façade: Cost-effective, Clean and Environmental, presented at the Council on Tall Buildings and Urban Habitat (CTBUH) 9th World Congress.
- Dow Corning. N.d. Case Study: Bibliothèque Nationale de France, Paris. <https://consumer.dow.com/documents/en-us/case-study/>.
- Keinlin, D. 1994. Insulated pressurized glazing. European Patent EP0620354, filed March 30, 1994, published October 19, 1994.
- Martin, P. 2012. Façades Légères en Detail. Paris: Le Moniteur.
- Mudie, S., Coleman, R. and Watts, S. 2017. Facades: Do all-glass buildings make financial sense? Building. July 12, 2017. <http://www.building.co.uk/>.
- NIBS. 2018. Institute Recognizes 2017 Beyond Green Award Winners. National Institute of Building Sciences. January 18, 2018.
- Permasteelisa. N.d. Press Releases. <https://www.permasteelisagroup.com/news-media/press-releases/>.
- Rudolf, B. 2012. Breathing Facades: Facade Technology toward Decentralised, Natural Ventilation. Detail 5.
- Solla, I.F. 2011. The Steiff factory and the birth of curtain walling. Facades Confidential. November 27, 2011. <http://facadesconfidential.blogspot.com>.

- Taylor, B. B. 1997. *Le Corbusier, the City of Refuge, Paris 1929-33*. Chicago and London: The University of Chicago Press.
- Van Santen, R.-J. 2001. *Façades complexes*. *Architecture Intérieure-Créé* 298: 128-131.
- Wigginton, M. and Battle McCarthy. 2000. *Environmental Second Skin Systems*. Battle McCarthy Consulting Engineers and Landscape Architects. www.battlemccarthy.com.
- Yeomans, D. 1998. *The Prehistory of the Curtainwall*. *Construction History* 14.