REVIEW OF VENTILATED FAÇADE SYSTEM WITH FOCUS ON BASIC REQUIREMENTS

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Abstract

Considerable attention is currently focused on the building envelope, in particular from an architectural and aesthetic point of view. The design and execution of the façade has a significant influence on the perception of a building within its surroundings. The main factors influencing the selection of a façade system include the view from the building, the extent and type of interior daylighting, the method of ventilation of the building, the challenges of building maintenance, and finally the load imposed by the façade system. Perhaps this is why the so-called ventilated façade system has become very popular in the last decade. The presented paper reviews the basic design requirements and principles. The secondary aim of this article is to describe the less common application of ventilated façade with bonded joints as well as the main advantages and disadvantages of such a fastening method.

Keywords

Adhesive, bond. façade, joint

1 INTRODUCTION

Considerable attention is currently focused on the building envelope, in particular from an architectural and aesthetic point of view. The design and execution of a façade has a significant influence on the perception of a building within its surroundings. Some authors like to state that the façade shapes *"the face"* of the building [1]-[7] and they are not far from the truth, since the term façade is based on the French word for face or appearance [8], [9]. Although the façade is a key element when looking at a building from the outside, its design and execution also affects its internal environment and user comfort [1]. The main factors influencing the selection of a façade system include such factors as the view from the building, the extent and type of interior daylighting, the method of ventilation of the building, the challenges of building maintenance, and finally the load imposed by the façade system. Perhaps this is why the so-called ventilated façade system has become very popular in the last decade.

The term ventilated façade refers to the so-called cold façades which work on the principle of a continuous air gap between the façade cladding and the load-bearing wall of the building. It is a multi-layered wall system in which the rain protection layer is separated from the wind protection layer by a ventilated gap [1]. The inner skin of the façade, the building wall, has the task of fulfilling static, thermal and acoustic requirements. The outer skin then creates a protective barrier against the effects of weather conditions, but mainly fulfils an aesthetic function [8], [9]. The high variability in cladding design allows for use in both, new buildings and reconstruction and repair of existing buildings.

2 THE CONCEPT OF VENTILATED FACADE SYSTEMS

It may seem that the ventilated façade system is a relatively new concept of the 20th century. However, according to historical records, it is a technology that has evolved alongside the construction industry, with its roots stretching back several centuries [2],[4],[10]-[13]. The attributed place of origin points mainly to Norway, where a façade system called the open-jointed barn technique was used. As the name suggests, the system was installed predominantly on farm buildings. Timber cladding was attached to a load-bearing grid, also made of timber, which allowed an open gap between the cladding itself and the building wall facilitating the escape of vapours and possibly rainwater.

Scientific research, in the current sense of the word, aimed at studying the behaviour and determining the basic characteristics of ventilated facades began in the 1940s. It was quickly realised that this technique (concept) was in many respects superior to previously known methods. The first modern building with a ventilated façade is considered to be the Regional Enterprise Tower located in Pittsburgh, better known as the Alcoa Building, until 2001. The building, designed by architects Harrison and Abramovitz in 1951 and completed in 1953, features a shell that consists of identical large-scale aluminium panels [14]. By the end of the 1950s, the ventilated façade system had fully penetrated the wider building industry and the scientific world, [10]-[13] becoming a widely used facade cladding option by the end of the 1980s. The benefits of this system are highlighted in relation to climate change, global warming and its positive impact on the indoor well-being [11], [12], [15]-[17]. There is a plethora of studies and scientific publications related to this issue [18], [19]. They often focus on very narrowly defined research areas such as ventilated double façades, photovoltaic façades, the implementation of so-called smart façades with solar walls and façade solar collectors or the so-called green façades.

Basic design principles

As previously mentioned, the ventilated façade system is a multi-layered structure, consisting of several individual layers, each serving a unique function, see the diagram in Fig. 1.

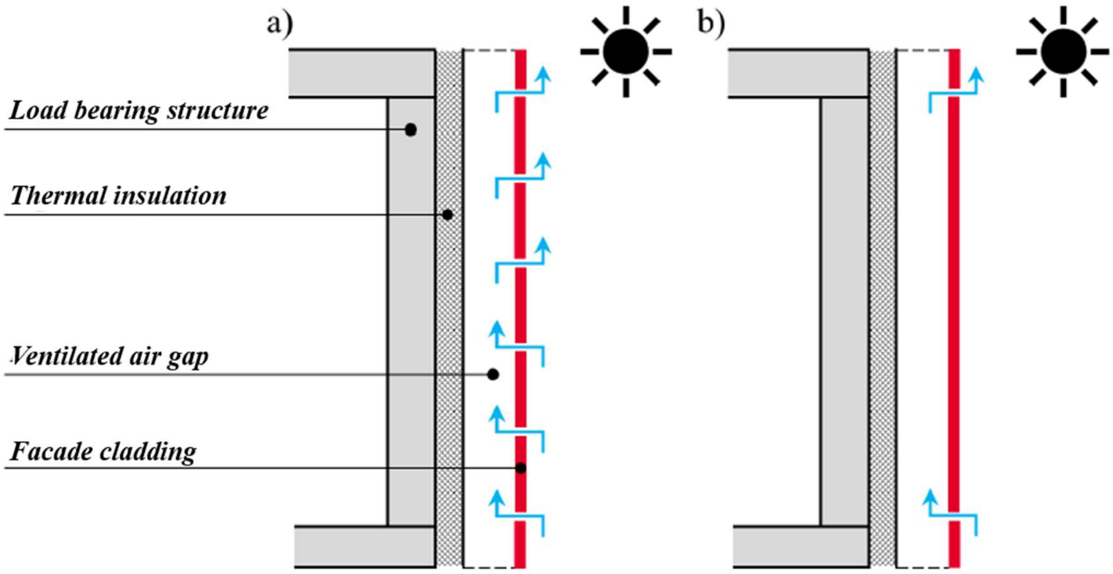

Fig. 1 External cladding: a) open system – noncontinuous façade area; b) closed system – continuous façade area [1], [18].

Moving from the interior of the building outward, the supporting structure of the façade cladding is mounted on a load bearing substrate, for example a masonry wall of the building. This supporting structure of the façade cladding is often referred to as the façade grid. This grid, typically constructed from materials like steel, aluminium, or wood, prioritizes lightweight elements. The grid can be unidirectional or bi-directional, and made of profiles of different cross-sectional characteristics and lengths. The support grid can be fixed directly to the subfloor or raised using system brackets. Thermal insulation is inserted between the support profiles with emphasis on dimensional stability and fire resistance during material selection. This is followed by a layer of continuous ventilated air gap, which is the core of the system. Its design, performance and functionality are essential for the entire façade system. It is recommended a minimum gap of at least 40 mm wide for the cladding of houses. For high-rise buildings, an individual assessment is necessary [16]. It is advisable to insert a windproof layer between the ventilated and the insulation layer to prevent possible degradation of the thermal insulation. The final layer is the outer skin of the façade, consisting of the façade cladding. This layer offers a wide range of materials with diverse properties, and a wide range of colours. The choice is most often made by the architect. The appropriate use of materials significantly influences performance characteristics – weather resistance, impact resistance, etc. [20]. Cladding attachment methods vary, with mechanical options including rivets, screws, staples, anchors and other anchoring elements, in which case the anchoring elements will usually be admitted. Another method is the invisible anchoring method, such as a bonded structural joint.

Basic design requirements

As stated by Puskar et al. [1], the requirements imposed on the envelope are an integral part of the requirements imposed on the architectural work. These include mainly legal, social, financial and technical requirements. The

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different areas are intertwined. It is not possible to fulfil the essence of one group without considering the requirements of the other groups. Without realising it, some architects and planners very often incorporate these aspects into their designs automatically.

Legal requirements

The legal and normative requirements for façade cladding are primarily related to the constraints that must govern each design. The most common requirements are thermal, energy, hygiene, acoustic and fire safety.

In response to global efforts to reduce CO2 production and the implementation of laws and regulations aimed at energy efficiency, certain restrictions have been adopted in the building sector which are mandatory for every proposal. These include, in particular, the thermal-technical assessment of all proposed constructions for the so-called heat transfer coefficient, the assessment of the formation of thermal bridges and their elimination, the assessment of water vapour condensation in the structures or on their surfaces, etc. Furthermore, it is an energy assessment of the building related to the obligation to draw up the so-called energy performance certificate of the building, which is part of the energy assessment. In connection with these restrictions and limits, it is very often necessary to combine the ventilation system with other energy-saving measures.

Last but not least, it is important to assess acoustic and fire safety. National technical standards set specific limits for the acoustic insulation of building envelopes, which is influenced by parameters such as ambient noise, traffic noise, building use, etc. The limits may differ for renovated and new buildings, and for buildings in urban and rural areas. The wind flow around the building, its direction and magnitude (speed) also play an important role. The acoustic properties of the envelope can be modified by an appropriate design of the materials used, as recommended, for example, by Fišarová [21], [22].

The building envelope must be approached in the same way from a fire safety standpoint. By determining the fire resistance of the individual façade components and the fire reaction class, it is possible to assess and eliminate potential risks. Again, this is subject to the constraints and requirements given by national regulations and technical standards. In general, the use of non-combustible materials is emphasised in order to eliminate the possibility of flame spread through the façade cladding [23], [24], [25].

In addition to the legal requirements related primarily to the characteristics of the building envelope, which can be positively influenced by the design and choice of materials, it is necessary to take into account other legislative constraints in relation to local site-specific planning, and architectural and morphological planning. For example, the use of a ventilated façade on historic and cultural monuments during their reconstruction is almost impossible, and aesthetically and morally inappropriate.

Social requirements

Social requirements can be classified according to two target groups: the general public (i.e. potential customers) and the professional public (i.e. architects, designers, contractors, etc.). The main difference between these groups is the level of knowledge and experience required to select the appropriate type of ventilated façade system. The most common decision criteria for the general public are financial and aesthetic. While the second group, the professionally knowledgeable, must incorporate not only these basic aspects but also technical requirements into their designs, always following the applicable legal requirements. I believe that fostering close cooperation between the two groups is essential for the smooth implementation of their ideas.

Financial requirements

The financial requirements are based on the chosen envelope type, regardless of whether the ventilated façade is installed on a new or existing building. The requirements are mainly influenced by material choices and maintenance considerations, often far exceeding the initial implementation costs. At present, financial constraints are often linked to the availability of subsidies, which not always cover the entire proposed investment, making in certain cases the implementation of a new envelope economically unacceptable.

Technical requirements

The technical requirements are mainly related to the problems associated with implementing a ventilated façade in existing buildings. Most often they relate to structural, functional and architectural-aesthetic areas.

Structurally, a thorough analysis of the supporting structure is always necessary, whether installing the envelope in a new building or an existing building. It is advisable to assess whether the structure will be able to carry the additional loads imposed by the ventilated façade alongside the primary loads acting on the building, e.g. dead weight, wind loads, seismic activity, thermal expansion, etc. It is also necessary to assess whether the material of choice for the supporting structure is suitable for the installation of the ventilated façade system to prevent issues like cracks, disintegration of the supporting material, etc., as cases of collapse of a newly installed envelope on an existing structure have been reported [26].

From a functional point of view, potential alterations relate to cable or pipe installations, air-conditioning installations, etc. Installing a ventilated façade in existing buildings will also largely affect the level of daylight (natural) lighting in the interior of the building.

Architectural and aesthetic criteria are essential for ventilated facades. As Pushkar et al. state*, "Man in all epochs and cultures has devoted inexhaustible energy to creating something beautiful"* [1]. Nevertheless, if the installation of a ventilated façade is carried out on existing buildings with interesting architectural details, the design of this type of envelope will certainly not increase the aesthetic value of the building, quite the contrary. As already mentioned in the introduction, the architectural design of the façade not only influences how the building is perceived within its surroundings but should also how it aligns with the functional design of the interior, ensuring. usable comfort. The most important design features are colour and geometry which is in close relation to the nature of the use of the building. For residential buildings the choice is natural and less clear [16], in the case of commercial buildings it is appropriate to use contrasting colours and materials with high gloss or transparent elements [1]. The choice of colour and material of the cladding is also closely related to the finish of the elements. Equally important is the spatial form, i.e. the shape and size of the façade cladding. Large-format cladding has a unifying effect and can create the illusion of a less massive building, whereas small formats visually enlarge the area [16], [27].

Basic classification of materials suitable for façade cladding

At present, the selection of suitable façade cladding materials is a challenging task. The range is very wide, almost inexhaustible, in an attempt to satisfy the financial and social requirements of all investors. Tab. 1 gives a brief overview of the basic materials most commonly used.

Tab. 1 Overview of basic material variants of facade cladding [15], [27].

Material	Representatives	Example
Steel	Galvanized, stainless, coated or powder-coated steel; Natural, coated or anodised aluminium; aluminium alloys; Copper; Titanium zinc, natural or pre-weathered (less commonly titanium for special composite panels – see composite cladding);	Thin-walled moulded or bent cassette profile or slat; Low trapezoidal, pillared or corrugated sheets; Weathering steel – large format panel cladding;
Stone	Natural stone slabs - granite, sandstone, marble, slate, etc; Technical (artificial) stone;	Small-format and large-format panel tiles;
Ceramics	Sintered ceramics glossy, semi-glossy, matt or with a roughened surface variant; Traditional brick partitions;	Small-format and large-format panel tiles; Brick strips;
Wood	Natural wood (untreated): Coniferous trees – pine (*Pinus spp.*), spruce (*Picea spp.*), larch (*Larix spp.*), cedar (*Cedrus*), meranti (*Shorea*), bangkirai (*Shorea spp.*), ipe (*Tabebuia spp.*), etc; Deciduous trees – oak (*Quercus*), teak (*Tectona gradis*), etc; Modified wood: Pressure impregnated – with oil or resin; thermally treated (thermowood); varnished or brushed, etc; Composite wood (see composite cladding); Overlaid and multi-layered wood cladding;	Planks and boards with different cross-sections – e.g. conically bevelled, tongue and groove, Tatra profile, log profile, planed straight boards, etc. Shingles; Small-format and large-format board tiles;
Plastic	Hardened polyvinyl chloride (PVC); Polyester laminates; High Pressure Laminate (HPL);	Decks, small-format and large-format board tiles;

Material	Representatives	Example
Glass	Contact or Continuous Pressed Laminate (CPL); Polycarbonate systems; Transparent and non-transparent elements; Safety glass; Tempered glass; Printed glass, enamel glass; Solar facade cladding;	Decks, small-format and large-format board tiles;
Composite	Silicate tiles (e.g. fibre cement and cement-bonded tiles); Composite wood (e.g. wood-plastic composite);	Decks, small-format and large-format board tiles;

Basic fastening methods for façade cladding

As with the various material options for façade cladding, the choice of fixing elements for cladding goes beyond the appropriate technical solution; it also involves a focus on aesthetic requirements. Fixing elements can be divided into exposed or concealed, mechanical or glued.

Mechanical bonding, is a centuries-old tested method for anchoring façade cladding where the most common elements such as nails, screws, bolts, rivets, hooks, etc., are visible. Recently, concealed mechanical anchoring elements have also become popular, operating on the principle of tongue and groove combinations, where the façade panels are fitted with grooves on the reverse side into which staples are inserted firmly connecting them to the supporting grid.

On the other hand, bonded joints always involve hidden anchoring systems applied from the reverse side of the cladding. The appropriate choice of mounting systems (facade adhesives) is rather limited. The adhesive properties of the bonded surfaces, i.e. the substructure and the façade cladding, play an important role and directly influence the quality and durability of the structural joint.

3 BONDED JOINTS IN FAÇADE APPLICATIONS

The concept of bonding has been an integral part of human history. The greatest development in this field occurred in the second half of the 20th century. With the development of research and production of polymer-based adhesives, the fields of their application have expanded. Today, bonded joints are an increasingly common alternative to mechanical joints in many industries. Their advantages are mainly speed and ease of installation, enhanced durability, resistance and reduced demands on machinery. Bonded joints provide a solution with uniform stress distribution in the joint [28]-[37], increasing the stiffness of the structure and the capability to transfer even large loads. This is illustrated as an example in Fig. 2.

A very positive benefit of bonded joints is the reduction of the weight of the entire façade cladding structure, while at the same time enabling a reduction in financial costs. The polymeric nature of the adhesives used also provides some degree of vibration and shock absorption, positively impacting the durability and fatigue strength of the joints. Furthermore, bonded joints have a high degree of flexibility, allowing the elimination of deformations caused by joining materials with different thermal properties or due to moisture expansion.

There are a number of adhesives produced by different manufacturers that can potentially be used for structural facade joints. The best known are silicone sealants, which are most commonly used when a flexible structural joint is required between glass and aluminium or steel, or between glass and glass [38]. Compared to other types of adhesives, the behaviour of silicones and the understanding of changes in their mechanical properties or durability due to ageing has been well documented in several technical standards and codes [39], [40]. Structural silicone joints are relatively strong (thick) and flexible, which allows them to adapt to different thermal stresses between glass and metal. However, with tensile strengths ranging from 0.8 to 1.8 MPa [41], structural silicones are not suitable for transferring the higher shear loads as required in other types of materials such as ceramic and composite cladding. Therefore, polymer-based structural adhesives are currently used in this area. Specifically, these are polyurethanes and modified polymers, which have similar tensile properties to silicones, but can withstand significantly higher loads.

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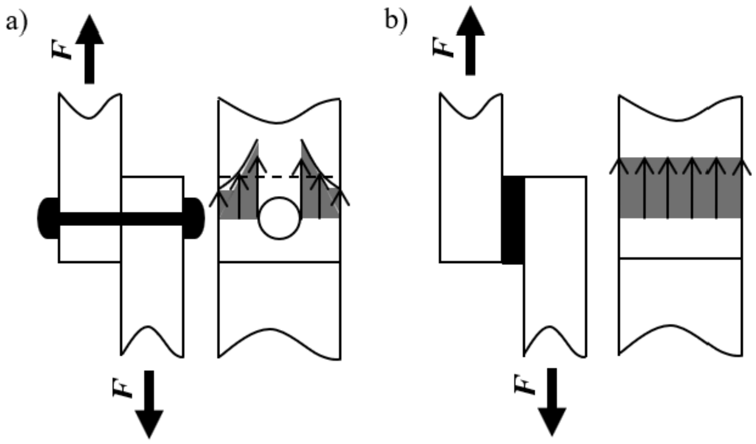

Fig. 2 Comparison of stress distribution in the joint: a) mechanical joint; b) bonded joint [29],[37].

Polyurethane adhesives

Polyurethane adhesives belong to the urethane polymer group, with chemical constituents from the diisocyanate or isocyanate group. Polyurethane adhesives are flexible, with exceptional elastic properties, with an average elongation at failure of up to about 600% [28], [29], [30],[32],[34]. Similar to epoxy adhesives, polyurethane adhesives are available in solid form, characterized by very high damage resistance, reaching up to about 25 MPa. Polyurethane adhesives can be divided into three basic groups:

- Two-component.
- One-component heat curing (rigid adhesives).
- One-component moisture curing (flexible adhesives).

The last mentioned group of adhesives is also used in the field of facade joints. Their excellent surface wettability allows the adhesive to penetrate into the pores of the adherend, where it can react with moisture to form a very strong, non-breakable bond.

Modified silane adhesives

Modified silane adhesives, commonly referred to as MS polymers, were developed in Japan during the late 1970s and early 1980s. These adhesives are so-called hybrid one- or two-component air-moisture curing adhesives, which are close to polyurethane adhesives in their material characteristics. However, unlike polyurethanes, they do not contain an isocyanate component, and no carbon dioxide or other volatile gas is released during curing. For this reason, they are often referred to as an environmentally friendly option. MS polymers combine the positive properties of both, polyurethanes and silicones, increasingly replacing these two alternatives. According to many manufacturers, they are more resistant to UV radiation and high temperatures and do not require demanding treatments of the bonded surfaces, differentiating them from polyurethane adhesives.

4 DISCUSSION

The previous chapters have described the basic parameters that are important to reflect upon when considering the application of a bonded joint. The information presented has sought to demonstrated in sufficient detail the advantages offered by bonded joints.

Thus, this subchapter serves as a summary of several key advantages as well as disadvantages of bonded joints. The pros and cons of bonded joints are mainly based on the properties of the materials used, some of which have already been mentioned or described in previous chapters.
Advantages of bonded joints [28], [29], [30], [33], [37], [41]:

- Ideal strength-to-weight ratio.
- Uniform stress distribution in the joint without local concentrations.
- Joining materials of different thickness with different material characteristics, eliminating of stresses caused by different length expansion.

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- Prevention and minimisation of electrochemical (galvanic) corrosion between dissimilar materials.
- High fatigue resistance under periodic (cyclic) loading.
- Aesthetically attractive joints – clean, hidden or with fine contours.
- Realisation of joints in different environments including water, wet or excessively dry environments.
- Vibration absorption and reduction.
- Faster and/or cheaper option than mechanical joints – possibility of simultaneous application, reduced structure weight, lower energy consumption during installation, prevents corrosion, and improves acoustic properties.
- Elimination of thermal bridges or prevention of electrical conductivity – insulate (products allowing conduction of electricity can also be used).
- Multi-purpose use – certain adhesives, specifically elastic adhesives, can also act as sealants – i.e., they fill joints and gaps, creating a tight bond that prevents the passage of liquids or gases (products that are resistant to chemicals can also be used). In some processes, additional sealing is required, but using a bonded joint eliminates the need for this step.

Disadvantages (limitations and restrictions) of bonded joints [28], [29], [30], [33], [37], [41]:

- The use of a bonded joint requires verification on a case-by-case basis.
- Non-detachable joint.
- It is not possible to visually asses the quality of the joint (only partial limitation for transparent materials).
- High demands on the cleanliness of the bonded surface and the working environment.
- Curing period, i.e. the curing time of the joint.
- Generally low operating temperature variance, i.e., low temperature resistance, often necessitating the use of special higher-priced adhesives.
- Prone to flaking and peeling.
- The service life of the joint is proportional to the influence of the degree of aggressiveness of the surrounding environment, design, quality of workmanship and subsequent regularity of maintenance. Inappropriately chosen cleaning procedure or agents can significantly degrade the properties of the joint.
- Natural-based adhesives are susceptible to attack by bacteria, mould, rodents or insects.
- Environmental pollution resulting from the production of adhesives.

5 CONCLUSIONS

Bonding is a popular alternative to mechanical joining and its advantages and limitations have been discussed in the previous chapter. Adhesive mounting systems are an adequate replacement for traditional joining methods, particularly in façade applications. However, the main problem related to bonded joints is the inherent complexity of adhesion and the definition of adhesive properties of the bonded materials. Regardless of the type of material, the study of this area requires a microscopic approach in addition to the macroscopic one which is more time demanding compared to traditional mechanical joining methods. Furthermore, it is advisable to consider the influence of stiffness of the selected assembly system on the mechanical resistance of the façade system.

Many authors confirm that for some façade cladding materials, such as particleboard or solid wood glued board, the glued joint is a more suitable fixing method due to the high thermal and moisture expansion of the cladding. It has also been shown that this method of anchoring is more suitable for large format tiles. Even though, the size of the tiles is not the limiting element, it can be concluded that this application area has very high potential. However, a comprehensive further research is needed.

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