

## MORPHOLOGY OF SERRATED GLASS FACADES. REPETITIVE AND NON-REPETITIVE SERRATION. SINGLE AND DOUBLE SERRATED FACADES

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### Abstract

Serrated building envelopes are a very eye-catching element of contemporary architecture. This type of façade in plan resembles the edges of a serrated blade, hence the name. Serrated facades substantially influence the building's tectonics understood as the relationship between the structural and the artistic form. They also have a major impact both on building physics (increased surface of heat exchange compared to flat facades, solar avoidance – decreased solar gains if properly designed) and on visual appeal. This paper examines façade morphology and analyses regular (repetitive) and irregular (non-repetitive) serration of façades and its influence on the aesthetic quality of the envelope. The morphological analysis also includes the direction of the serration. An exceptional feature of serrated façades is that the optical phenomena on the façade change depending on the viewing angle. The presented paper is based on case studies with special attention to morphological and qualitative analysis. Recently completed case studies serve as visual (photographs) and graphical illustrations (diagrammatic drawings). A review of technical and engineering justifications of the use of serrated facades is also included and briefly explained.

Keywords: Façade design; Façade geometry; Serrated façade; Double Façade.

## 1. INTRODUCTION

The interaction between transparent materials seems to be a key factor in contemporary architecture. Rather than being used independently, transparent panes are most often components of various systems and arrangements including serrated glazed building envelopes. «Serrated facades substantially influence the building's tectonics understood as the relationship between the structural and the artistic form. They also have a major impact both on building physics (increased surface of heat exchange compared to flat facades, solar avoidance – decreased solar gains if properly designed) and on visual appeal. Serrated facades are used to sculpt the planar façade (if arranged along a linear controlling axis), avoid the impression of flatness and to produce additional visu-

al impact. The main optical properties of serrated facades are the result of their geometry. According to [1] serrated facades belong to a group of modified planar vertical and horizontal facades whose visual characteristics deserve to be studied in detail» [2], as they are one of the most important factors influencing the appearance of the façade.

## 2. SERRATED FAÇADE GEOMETRY

«A serrated façade resembles the edges of a serrated blade, hence the name. This architectural solution is also commonly known as “zigzagged” [1] “folded” [3] or even “pleated” [4] facades. In the paper “Architectonics – A System of Exploring Architectural Forms in Spatial Categories” A. Niezabitowski addresses the serrated facades as the facades with

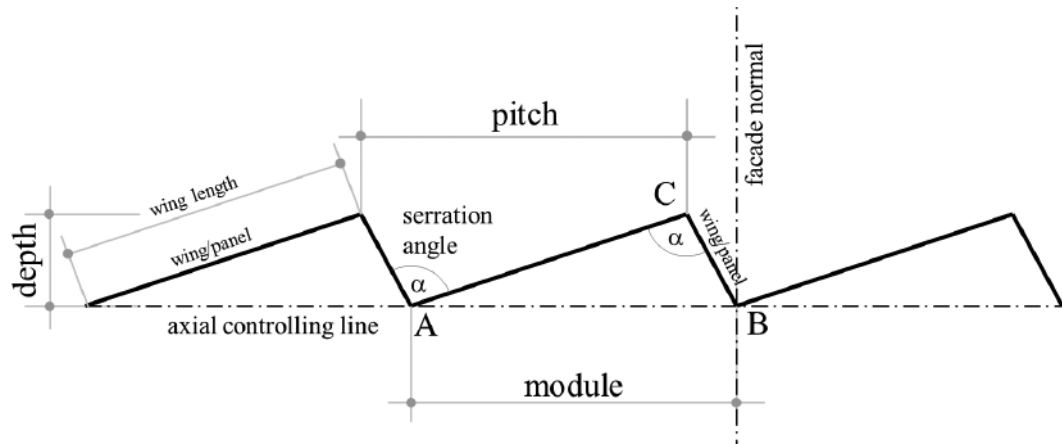
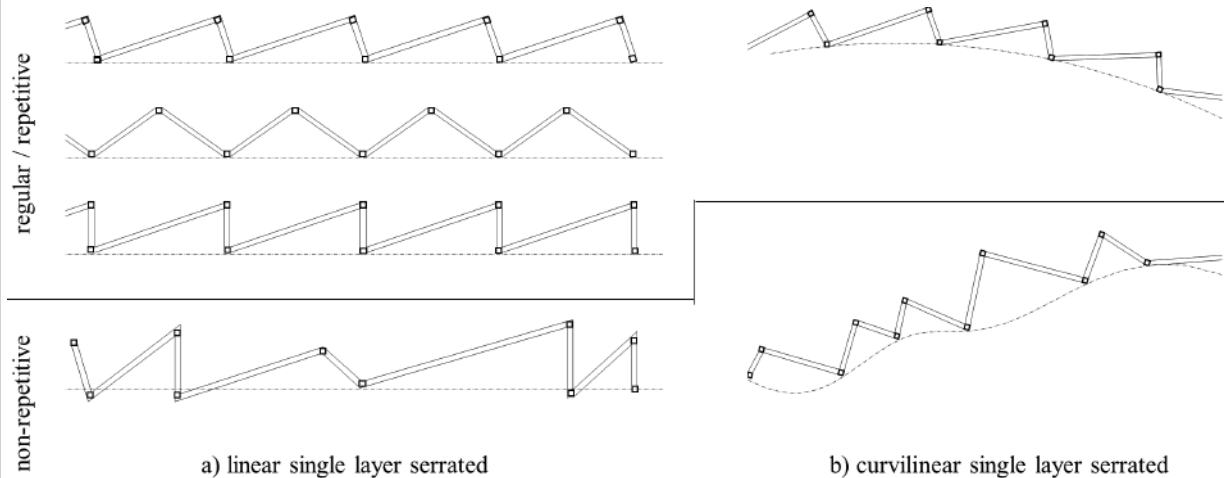


Figure 1.  
Diagram of façade serration. Diagram by the author. Originally published in [2]

Table 1.  
Possible serrated façade variants a) linear single layer serrated, b) curvilinear single layer serrated. Diagram by author



multiplied “setoffs” [5] but this term is not widely used. The geometry of the serration is discussed below on the basis of a diagram (see Fig. 1). Because of the fact that the serration of a saw blade represents a well-documented reference to the serration of the façade, some of the definitions used in this paper are borrowed from the field of mechanical engineering. A façade is usually constructed along a linear (straight) or curved axial controlling line. The dimension of the façade (i.e. the distance between points A and B) is the “pitch” or “module”. The length of a perpendicular from C to the base containing A is the “depth” of the façade. The angle at point A ( $\alpha$ ) is the “angle of serration”. In repetitive solutions, the

angles at point A and point C ( $\alpha$ ) are usually of the same degree measure. The serrated façade panels will be referred to as “flanges”, as this term was used previously in the literature [6]. The flanges can be equilateral or have different lengths» [2].

«The serration can be applied in the plan (horizontally), in section (vertically) or in both directions/axes, although “intersecting edges and, in particular, «corners», at which three surfaces coincide, require special attention” [1]. The simplest and most frequently observed solution is the serration in the plan, which requires only vertical joints between the neighboring panels. A vertical joint functions as a



**Figure 2.**

a) Casuariestraat, DGMR in Hague (arch. Fokkema Partners, 2007). Originally published in [2],  
 b) ESO European Southern Observatory (arch. Auer Weber, 2008). Originally published in [2]. Photos by author

proper seal between the neighboring flanges and is easier to develop from a technological point of view because it resembles a standard right angle façade corner connection (which is a standard solution). The serration in the vertical section is also an option but requires a water-tight horizontal seal and proper runoff management (gutters and downpipes). Therefore, in terms of technology, such a solution is much more demanding and less popular. For instance, the Casuariestraat, DGMR in Hague (arch. Fokkema Partners, 2007) features only the serration of the external envelope which does not require a proper water-tight seal and heat flow management (see Fig. 2a). A water and heat management solution is necessary if the serration of the façade is designed in both directions e.g. Tiffany Ginza (arch. Kengo Kuma & Associates, 2008). This paper only focuses on the serration in the plan.

Serration can be applied to planar and curved facades (along a straight or curved axial controlling

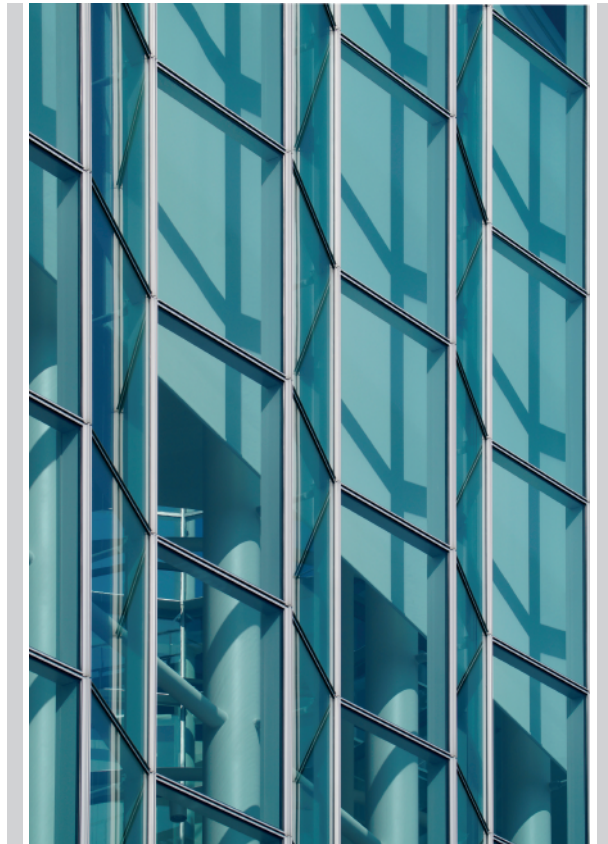
line). In the first case, the serration usually includes a repetitive module but the variable pitch is also possible. In the case of curved façades, the serration usually follows the curvature of the building while the prefabricated elements of the façade are usually repetitive and connected by articulated vertical joints. This solution allows for adequate angle tolerance. Serration is also one of the most elegant ways to approximate the curvature of the façade by means of straight segments. In the majority of cases the serrated façade – as in other curtain wall facades – is fixed to the loadbearing structure of the building at the slab level (see Fig. 2b).

A serrated envelope usually serves as the thermal façade of the building but can also function as the external layer of a double-skin envelope, in which case it has single glazing – e.g. KfW banking group office tower in Frankfurt am Main, (arch. Sauerbruch Hutton, 2010)» [2]. The issues of double-skin serrated facades are addressed in detail in chapter 5.

### 3. VISUAL IMPACT

«One of the most important factors of glass facades are the optical parameters of the light-transmitting parts of the envelope. “Every transparent material with the surface, smooth enough to let the light through without deflection, simultaneously reflects light, due to its physical properties on the micro-level” [7]. This results in many perceptual phenomena which are caused by reflected light and depend on the viewing angle. When the glass is looked at perpendicularly, i.e. at an angle of  $0^\circ$  measured from the line perpendicular to the surface of the glass, it is mostly perceived as transparent. This viewing angle shall be referred to as “normal angle”. As the viewing angle increases the reflection grows and» [2] “increases dramatically above  $70^\circ$ , to almost 100% reflection at a glancing angle” [8]. This visual phenomenon and its influence on the architectural form was also discussed by U. Knaack [9] W. Celadyn [10] and E. Wala [11]. The author’s interest in the appearance of the glass envelope was directly inspired by the works of W. Celadyn [10].

«Due to the fact that the smooth glass surface can produce mirror reflections, serrated glass façades should be considered» [2], from the optical standpoint, as systems comprising two adjoining mirrors (sharing one edge and inclined) [12]. All effects resulting from the “reflective” nature of the façade’s glass flanges were extensively studied in the paper titled “Serrated glass facades. The influence of façade morphology on aesthetic quality” [2]. This paper discussed various perceptual zones that produce different phenomena, e.g.: (i) single flange visibility, (ii) mutual flange self-reflection, (iii) primary and secondary virtual images. However, further investigation revealed that these optical effects – although visible – influence the perception of a serrated façade at least to the same degree as the rhythm and proportions of façade elements. In certain cases, when the reflections are not visible at all – e.g. when the façade is illuminated by direct sunlight – the rhythm and perceptual properties (e.g. perspective) have a profound influence on the visual impact of the façade. See the example of Fuji Television Wangan Studio in Tokyo (arch. Kajima Design, 2010), see – Fig. 3.



**Figure 3.**  
Fuji Television Wangan Studio in Tokyo (arch. Kajima Design, 2010). Originally published in [2]. Photo by author

### 4. INFLUENCE OF SERRATION RHYTHM AND PROPORTIONS ON FAÇADE PERCEPTION

Initially, the setbacks in facade geometry allowed for additional light to penetrate the building in dense urban development like in Reliance Building (arch. Daniel Hudson Burnham, 1894), while in expressionist architecture the setbacks were frequently used to introduce the dynamism in static building form. After the first curtain walls appeared, the serration was used mainly to geometrically sculpt the façade and to play with light and shadow e.g. in Michigan Consolidated Gas Company Building in Detroit (arch. Minoru Yamasaki, Smith, Hinchman & Grylls, 1962) [13].

First flat fully glazed facades have been developed as a result of the modernist movement and large-scale optimization of the building’s skin, especially in commercial high-rise office towers. However, the clean appearance of flat glazed building facades remained unsatisfactory for some architects and clients. The

main reasons included the flat appearance of the façade and the lack of details and window recesses. In the mid-1960s, a strong desire to sculpt building facades arose. One of the few available solutions was to use the serrated façade geometry. It not only enriched the façade visually but also allowed for proper orientation of the glazed elements of the façade when the overall orientation of the building was not optimal.

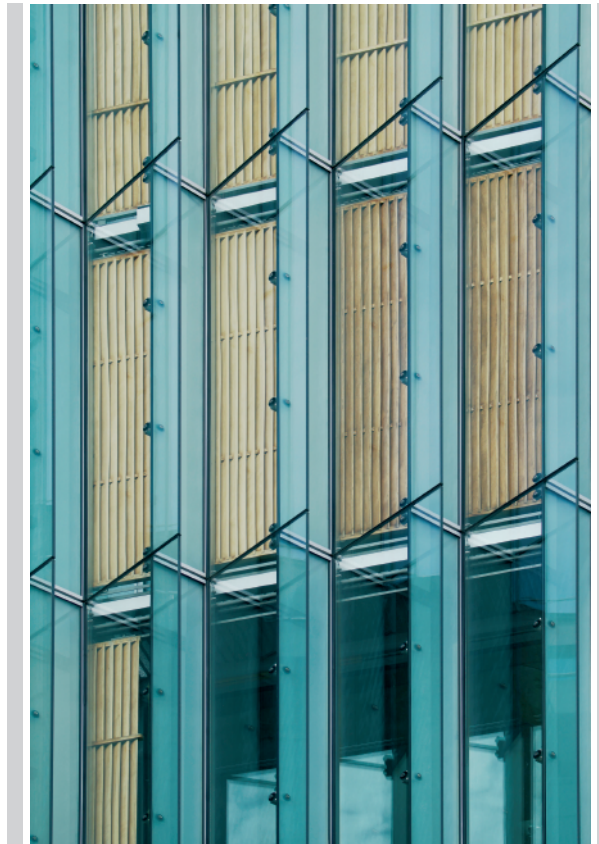
There are two main ways of altering the serrated façade's impact on the viewer. The first is the use of different/variable proportions of the flanges (variable pitch) resulting in repetitive and non-repetitive serration and the second is the modification of serration direction. The latter is available only when the façade flanges are not of equal length.

#### 4.1. Serration rhythm

Repetitive serration changes the perception of the facade primarily by modifying the façade's vanishing points and through rhythmical iteration. This method is deeply anchored in the perceptive qualities of surfaces themselves. Serrated elements – also called “angled oriels” [18] – are positioned at an angle in relation to the overall façade plane, thereby altering the perception of the building and making it seem more dynamic compared to an identical building with a planar facade. The vanishing points of protruding serrated elements are in different locations than the vanishing points of the overall façade plane. This also affects the perception of the building's scale. The iteration of façade elements makes the size appear smaller as the distance from the observer increases, which is caused by the foreshortening phenomenon. A planar façade is perceived as a polygon in perspective projection, while a serrated façade is perceived as a rhythmical sequence of polygons that are gradually reduced in size. This creates the visual effect of perspective and such a building is usually perceived as higher/taller than it actually is.

##### 4.1.1. Repetitive serration

Repetitive (regular) serration remains one of the most popular serration options as this geometry requires only a limited number of unique façade elements to be designed and manufactured. This is particularly true when the angle is equal to 90 degrees, in which case it is possible to use standard detailing as the internal and external corner details are usually developed as standard connections in the façade system. Thus custom solutions are not required.



**Figure 4.**  
Oskar von Miller Forum (arch. Herzog + Partner, Munich, 2009). Originally published in [2]. Photo by author

Standard repetitive serration could be further geometrically developed to provide even more pleasing aesthetic results. One of the available methods is by extending one of the façade flanges beyond the point of the flange's intersection. This was the case in Oskar von Miller Forum in Munich (arch. Herzog + Partner, 2009), where the light-transmitting flanges were artificially extended to form a rhythmical series of angled glass ribs protruding from the surface of the facade. As a result, a different geometry was formed, similar to popular timber shutter doors, with a series of narrow angled surfaces of glass panes. Fig. 4 shows the different appearance of the serrated façade depending on the viewing angle.



Figure 5.  
Osaka Fukoku Seimei Building (arch. Dominique Perrault Architecture, 2010). Photo by author

#### 4.1.2. Non-repetitive serration

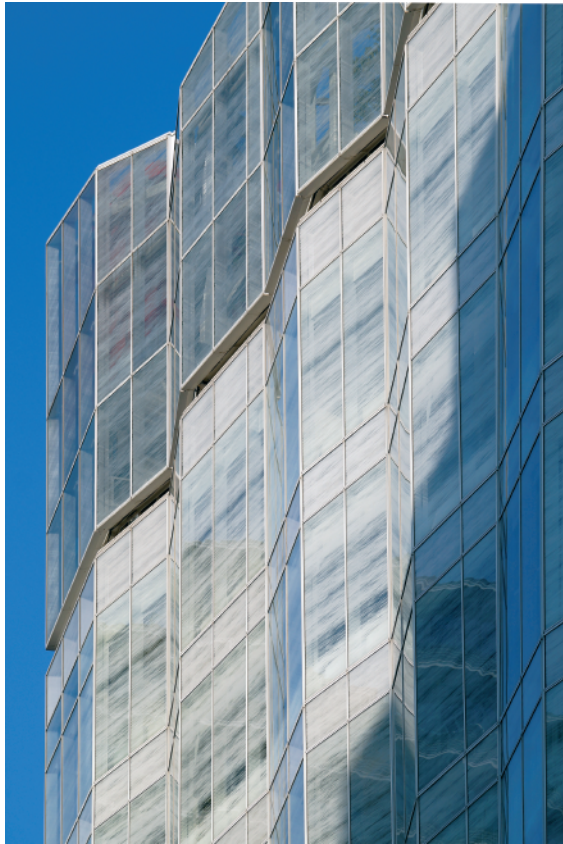
Non-repetitive (irregular) serration of the façade requires a different length, depth or pitch of its individual flanges. Irregular serration strengthens the perceptual phenomena described above. The vanishing points for the protruding elements not only do not match those of the whole façade, but they also differ locally with respect to their length, depth or pitch. While repetitive serration is perceived evenly along the whole façade, non-repetitive serration varies providing an even more irregular visual effect on the façade. Because irregular serration lacks rhythm it influences the perceptual qualities of the whole building not only the façade – e.g. Wakanoura Art Cube in Wakayama (arch. A.A.E., 2003).

In terms of technical feasibility this type of serration is much more complicated than its repetitive counterpart. It requires the development of a larger number of untypical junctions between elements, which translated into increased design effort and manufacturing expertise. Despite their apparent irregularity, many serrated facades are assembled from repetitive elements in an arbitrary sequence. This helps to opti-

mize the costs and design effort. A good example of such a façade is the Osaka Fukoku Seimei Building (arch. Dominique Perrault Architecture, 2010) which features an apparently irregular serrated façade erected from standardized elements (see Fig. 5). Although such optimization offers some savings, expensive bona-fide non-repetitive serrated façades are still built e.g. Kirarito Ginza (arch. Jun Mitsui & Associates, 2014) – see Fig. 6.

#### 4.2. Variable serration direction

When façade flanges are not equal in length and angle, their serration direction can be defined/decided. Serration direction is a term borrowed from mechanical science and craftsmanship and it was originally used to determine the relation between the edge of a saw's tooth and the cutting direction. Coping saws, for instance, are designed to cut “on the pull stroke” so the edges of the teeth have to be directed toward the saw's handle. In terms of architectural form, “serration direction” defines if the serrated façade will be oriented towards the observer with its shorter or longer flange. This aspect



**Figure 6.**  
Kirarito Ginza (arch. Jun Mitsui & Associates, 2014). Photo  
by author



**Figure 7.**  
Music Conservatorium of Amsterdam (arch. van Dongen –  
Koschuch, 2005). Originally published in [2]. Photo by  
author

significantly influences the appearance of the façade because the “thinner” flanges/strips create a different rhythm than the “thicker/wider” ones. The proportions of the flange can be intentionally used by the designer to differentiate the possible visual impact of the building, e.g. by visually slimming the building from a given viewing point.

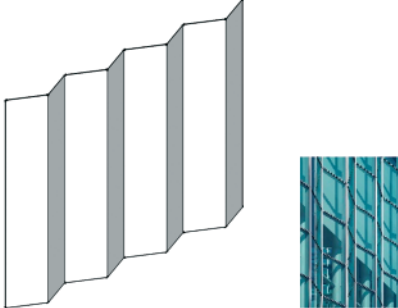
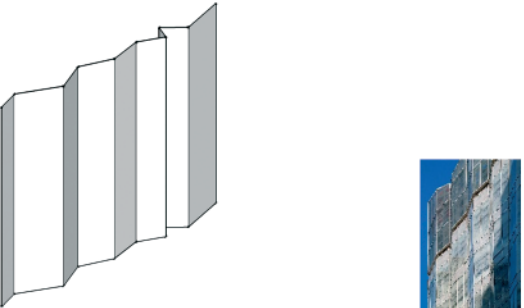
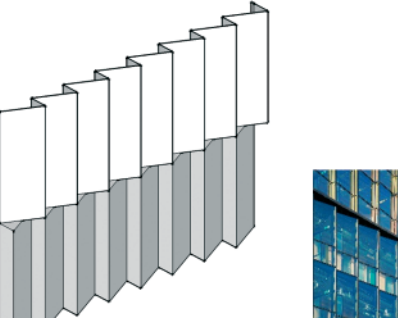
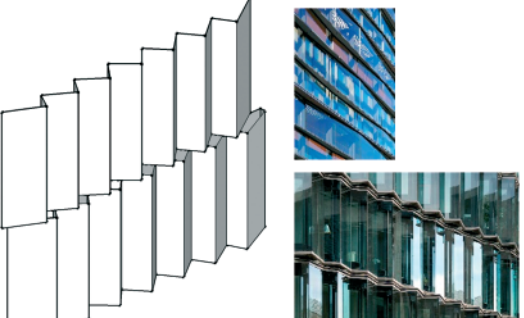
In technical terms, the change of the serratation direction does not require any substantial change in the design as the connecting details are simply mirrored. This, however, doubles the number of unique façade elements to be assembled on site.

The serratation direction can vary across the façade and different combinations are possible. Since one module of a facade element usually spans a single floor, the most popular choice is to change the direction of façade serratation on every adjacent floor. Other solutions are also possible, such as changing the direction every second floor. In contrast to prominent vertical divisions, typical of repetitive serrated facades, buildings with a variable direction of

serratation on individual floors have horizontal accents. It would be difficult to rationally justify the use of variable serratation e.g. by arguing that it is compensating with its orientation towards the prevailing direction of sunlight. Therefore the sculpting of the façade with different direction if serratation is generally more arbitrary than in the case of single-direction serratation.

One of the most prominent buildings with variable serratation direction is the Music Conservatorium of Amsterdam (arch. van Dongen – Koschuch, 2005). Façade serratation is characterized by a large difference in length of the flanges. As a result, either only one façade flange is visible – the longer one or two of them, but from a different perspective (with different vanishing points – see Fig. 7). Therefore, the strips/ribbons of the façade seem to “ruffle” in different directions. It should also be noticed that the shorter flange is visually doubled as it is reflected in the longer flange. This optical effect substantially influences the perception of façade’s proportions [14].

**Table 2.**  
A table showing in diverse serration direction options in 3rd dimension (axonometric view)

	repetitive	non-repetitive
single direction	 <p>Fuji Television Wangan Studio in Tokyo</p>	 <p>Kirarito Ginza</p>
diverse direction	 <p>Music Conservatorium of Amsterdam</p>	 <p>The House of Representatives in Berlin</p>

A similar solution, but on a smaller scale, is featured in the building of the Centre for Virtual Engineering (arch. UNStudio, 2012) in Stuttgart. Glazed serrated façade strips are interwoven with horizontal strips of the white flat curved façade. Serration follows an arbitrary curved axial controlling line. The longer flange is glazed, while the shorter one is equipped with an opening flap for natural ventilation of office rooms. The short flanges are blue and yellow, which changes the building's colour scheme depending on the observer's standpoint – see Fig. 8.

Variable serration direction can be used simultaneously with irregular serration. In this rare case, highly complicated façades are produced which require a large number of unique elements that have to be handled individually (see Table 2).

## 5. SERRATED DOUBLE-SKIN FAÇADES

A serrated envelope can also perform the function of a façade layer in double-skin façades. Morphologically there are many possible variations but there are two distinctive types: (i) with both layers of the façade serrated or (ii) with only the external layer representing the serrated geometry. Different strategies are also

used for air-exchange in the façade, see Table 3. The external envelope can be air-tight – usually with sealed openings for occasional air exchange, or vented – with permanently open ventilation gaps. The latter usually serves as a preliminary weathering shield for the internal layers of the façade.

### 5.1. Single layer serration

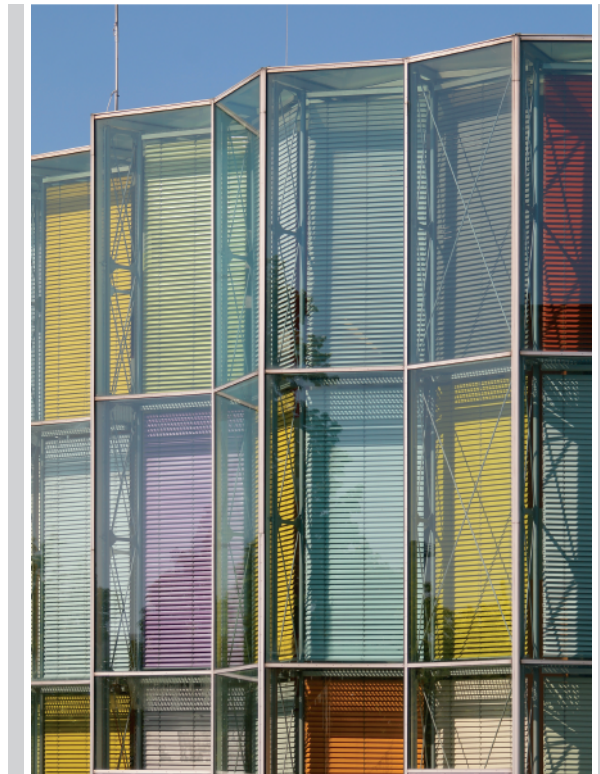
Technically simpler solutions feature only one serrated layer of the façade. In KfW banking group office tower in Frankfurt am Main, (arch. Sauerbruch Hutton, 2010) the external envelope is a serrated, water-tight, single glazed façade with ventilation flaps, while the internal envelope is insulated, double glazed and basically flat. Similarly, in Photonik Zentrum in Berlin Adlershof (arch. Sauerbruch Hutton Architects, 1998) the external part of the envelope is serrated, while the internal one is curved and smooth – see Fig. 9. In the Insurance Company building in Munich (arch. Baumschlager und Eberle, 2002) only the external layer is serrated (simple panes of glass), while the internal façade is a standard flat curtain wall with opening windows – see Fig. 10. A similar solution is executed at Jonsvollskvartalet in





**Figure 8.**  
Centre for Virtual Engineering (arch. UNStudio, 2012).  
Photo by author

Bergen (Arkitektgruppen Cubus AS and Brandsberg-Dahl Arkitekter AS, 2015), but a different serration pattern is used that reminds ripples on the water – see Fig. 11. In general diverse venting strategies are used as the vertical gaps between the panes of glass in the external layer allow for a permanent air flow. This type of façade can be further developed as a dynamic façade, as was done in the State Museum of Egyptian Art in Munich (arch. Peter Böhm Architekten, 2011). In this building, the single-glazed external envelope of the double-skin façade can be opened depending on the weather conditions. The glass panes in the external envelope are point-fixed to steel hinged cantilevers. As the cantilevers rotate vertically the panes open and form a serrated geometry with vertical gaps for air-exchange within the plenum of the façade (see Fig. 12)



**Figure 9.**  
Photonik Zentrum in Berlin Adlershof (arch. Sauerbruch Hutton Architects, 1998). Photo by author

## 5.2. Double layer serration

The House of Representatives (Deutscher Bundestag Office) in Berlin (arch. Lieb + Lieb Architekten BDA, 2011) features a much more complicated geometry, where both façade layers are serrated. The external layer is irregularly serrated and is vertically sealed with a ventilation opening at the bottom of the module, while the internal layer is made of IGU and is repetitively serrated – see Fig. 13. “The asymmetry of the oriels (with short and long flanges) adds a dynamic component that is strengthened by the local variation of elements to create «waves». Any onlooker walking along the building is aware of his standpoint and speed. The changing interplay of reflections on the glass surfaces, depending on the direction and view of the movement, makes the façade seem sometimes smoother and sometimes rougher as if brushed against the grain” [6]. The facade also reflects the surroundings in a very specific way. As the angle of each flange is different, a different part of the townscape is visible in the reflection: 19<sup>th</sup>-century brickwork is juxtaposed with the reflection of other contemporary buildings. This outstanding example of a different rhythm of serration presents



**Figure 10.**  
Insurance Company building in Munich (arch. Baumschlager und Eberle, 2002). Photo by author



**Figure 11.**  
Jonsvollskvartalet in Bergen (Arkitektgruppen Cubus AS and Brandsberg-Dahl Arkitekter AS, 2015). Photo by author

not only excellence in design but also a high level of engineering.

ESO European Southern Observatory (arch. Auer Weber, 2008) in Garching-Forschungszentrum also features a serrated double façade, but in this case – serration follows a circular axial controlling line. The building was conceived as four large interlocking concave cylindrical single-story volumes. However, in contrast to other abovementioned examples – in ESO’s façade only one flange is a double façade with Venetian blinds, while the one other flange features a grill for external air ventilation – a similar solution to the Centre for Virtual Engineering in Stuttgart – see Fig. 14. An opening flap behind the grill allows users to regulate the air exchange according to their needs.

## 6. THE TECHNOLOGICAL RATIONALE BEHIND THE DESIGN

«The application of a curved or folded/serrated geometry to the façade requires much more effort in the designing, proofing and manufacturing stages» [2]. This type of façade uses more material for cladding (in this case glass) and framing, which means that an increased area of heat exchange with the surroundings has to be taken into account. But – apart from the aesthetical reasons discussed above – some rational engineering justification for choosing this façade morphology should also be mentioned.

### 6.1. Structural enforcement

«The main advantage of serrated geometries comes from their stiffening effect because the serration “actually makes it (glass) highly load resistant” [15]. When used properly, serration also minimizes deflections. Due to their geometry, folded/serrated facades are much more rigid and resistant to e.g. wind blows.



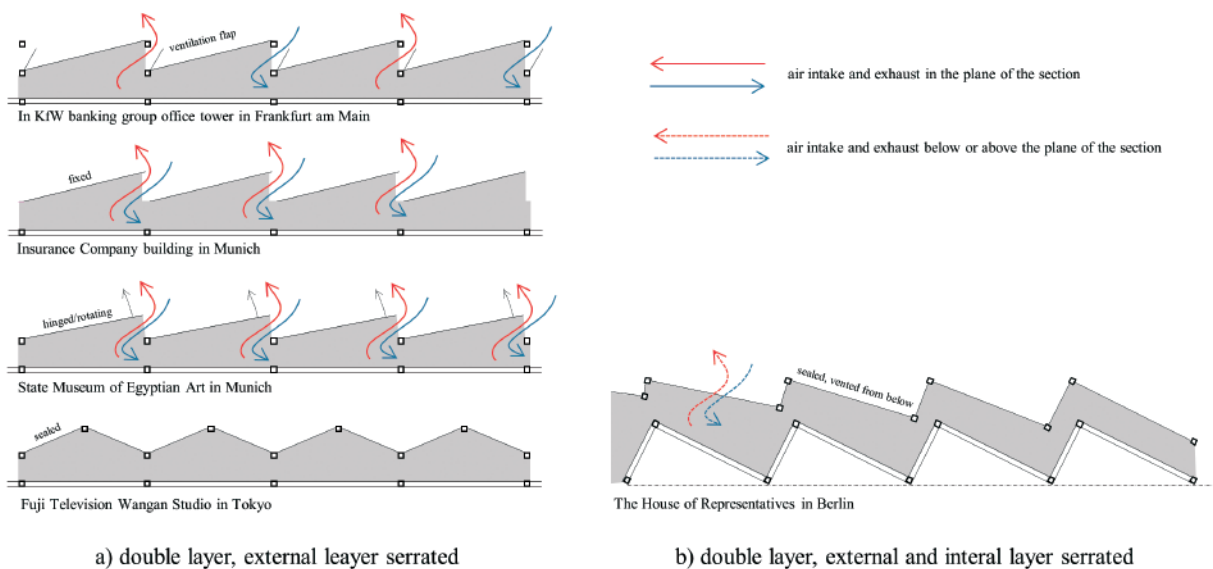
**Figure 12.**  
State Museum of Egyptian Art in Munich. Façade in the closed condition (arch. Peter Böhm Architekten, 2011). Photo by author

Moreover, the aerodynamic analysis shows that serrated façades can utilize the prevailing wind direction for the purpose of the building’s natural ventilation. This was the case in KfW Westarkade in Frankfurt am Main (Sauerbruch Hutton, 2010) [16]. “It should also be stated that segmented façades require careful water run-off management, as the multifaceted geometry can allow for easy water ingress” [17] [2].

**6.2. Sun- and daylight optimization**

«The fact that the façade uses more glass to cover the same area could be regarded as a disadvantage, but a detailed analysis shows that serration allows for the optimization of the transparent part of the façade in order to avoid direct solar gain» [2]. If one of the building’s façades is unfavorably oriented (for example, to an exact southern exposure) repetitive serration can be used to change that orientation, at least in the case of one of the façade’s flanges (e.g. transparent ones might face north, non-transparent – south). Because of the Sun path, only repetitive serration can be used to alleviate this problem, while irregular serration – despite having other potential benefits – does not work. Serration can also perform a self-shading function for the façade’s elements thus reducing the direct insolation and heat build-up in the rooms. As it was shown in the analysis of the 25 Ropemaker Place building in London (arch. Arup Associates, 2012) “angled window treatment is stated

**Table 3.**  
Possible venting strategies in double layer serrated façades. Horizontal schematic section of the façade. Air plenum showed in grey. The description given in the figure. Diagram by author





**Figure 13.**  
The House of Representatives (Deutscher Bundestag Office) in Berlin (arch. Lieb + Lieb Architekten BDA, 2011). Photo by author



**Figure 14.**  
ESO European Southern Observatory (arch. Auer Weber, 2008). Photo by author

to reduce solar heat gain by 27% from an equivalent flat façade” [18] because of the proper arrangement of the opaque and light-transmitting parts of the serrated oriels. The application of serrated geometry also allows for deeper daylight penetration into the core of the building, as “(...) facade convolution implemented in the «deeply serrated» design may actually increase facade area, allowing light coming from side to penetrate deeper into the rooms behind the facade and thus increase the light level at the inner part of the interior spaces” [19]. The author of the paper currently researches the issues of the daylight management and the user’s visual comfort in buildings clad with serrated facades. „De Luminae” simulation software is used to produce scientifically verified results.

### 6.3. Acoustic attenuation

The sound environment in urban areas is complex as there are many sources of sound that are further influenced by a variety of acoustic propagation effects. One of the most important noise-amplifying factors are the parallel, flat and rigid surfaces of glass façades which reflect sound multiple times. In this context, the sawtooth geometry of façade serration should be recognized as large-scale surface irregularities that make the “sound wave diffusely reflected” [20]. In consequence “saw-toothed, diffusor like, solutions are causing the biggest sound reductions” [21] in urban environments. Of course, glazed serrated façades still function as a rigid sound reflecting surfaces but the sound is diffusely reflected and can be, therefore, easily dispersed.

## 7. CONCLUSION/DISCUSSION

«Serrated facades are a great potential for the industry of glass façade engineering with an abundance of interesting optical and spatial phenomena that can be produced. Since the visual outcome depends on the façade’s geometrical parameters (pitch, serration angle, flange length, and depth) the morphology of the façade should be extensively studied with the application of descriptive geometry (representation of three-dimensional objects in two dimensions) and computer-aided simulations» [2]. While the engineering solutions for single-layer facades are already very complicated, double-layer serrated façades are engineering masterpieces. The higher craftsmanship effort and cost are well worth the final stunning architectural result.

## ACKNOWLEDGMENTS

In accordance with point 3. COPYRIGHT included in the manuscript preparation guide for authors, this paper is the extended and modified version of the conference paper titled “Serrated glass facades. The influence of façade morphology on aesthetic quality”. The original paper constitutes less than 30% of this paper, and the original part is marked in chevrons: «». The collection of the data for this paper was funded by the Polish National Science Centre grant entitled: “New trends in the architecture of transparent facades – formal experiments, technological innovations”, ref. no. 2014/15/B/ST8/00191. The participation in the conference has been funded by the Ministry of Science and Higher Education, Poland, grant, ref. no. S70401-0082-17-K0106.

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