OMA

Taipei Performing Arts Center

Introduction of corrugated glass facade

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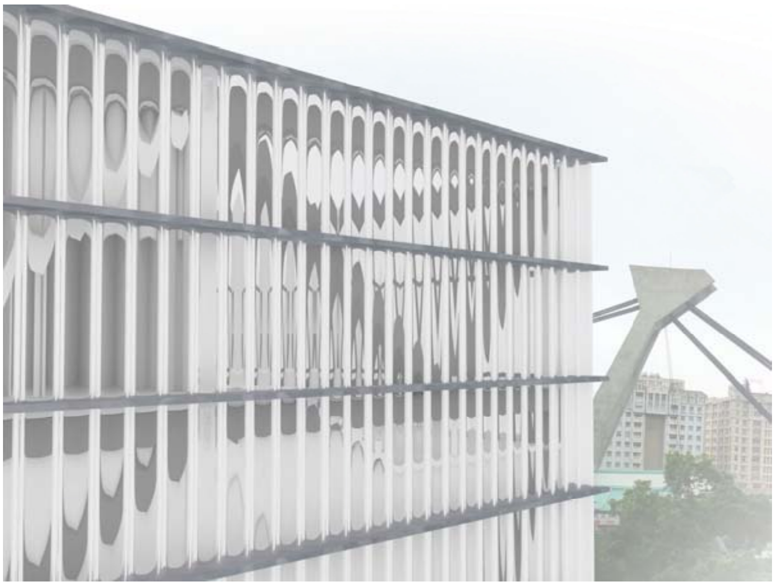
Set in the Shilin District of Taipei and scheduled for completion in 2015, OMA's design for the Taipei Performing Arts Center consists of three theaters with a total of 3,100 seats. The theatres plug into a central cube, which consolidates the stages, backstages and support spaces into a single and efficient whole. The individual auditoria protrude outward from the cube and float above this dense and vibrant part of the city. While each theater can function independently, this unique arrangement also allows stages to be merged, effectively combining the theaters for unsuspected uses and scenarios.

The building envelope consists of two primary materials: corrugated glass wrapping the cube and aluminum cladding for each of three auditoria.

The cube contains a range of different spaces with different characteristics and requirements: the stages, backstages, offices, rehearsal rooms, dressing rooms, storage, and other support programs. In typical theater design, these spaces are often fully concealed or hidden behind an opaque façade, reinforcing the misconception of the theater as an inaccessible monument. In order to avoid this scenario and create a relationship between the inner workings of the theater and the city, the design team chose to use corrugated glass to create the building envelope.



The corrugated glass reveals the perimeter mega-structure of the cube and its packing of different internal volumes and activities. At same time these elements are revealed, they are also concealed through the diffraction of light by the corrugated glass, creating an image of fragmentation and multiplication of what is behind. The glass itself consists of two layers of annealed, low-iron panes, laminated together with a slightly grey intermediate film for solar shading and energy control. Corrugated glass was chosen not only because of its optical properties, but also because of its inherent structural stiffness in resisting the forces of Taipei's environment, including seismic and typhoon lateral loads. As such, individual panes of corrugated glass span 5m between a series of layers of horizontal shelves that striate the perimeter of the cube.

While the cube is illuminated and animated, the auditoria projecting from it are intended to read like dark, opaque, and mysterious elements. These auditoria have their focus on the interior space and performance. Bare, large-format aluminum cladding was chosen and applied.

Cumulatively, the different materials of the TPAC envelope reinforce the overall relationship of parts. The corrugated glass cube and aluminum auditoria also achieve a reversal implicit in the initial diagram of the design: that the working infrastructure of the theater takes a central position and exhibits transparency in relation to the city, inviting the public to participate in its machine-like aura.

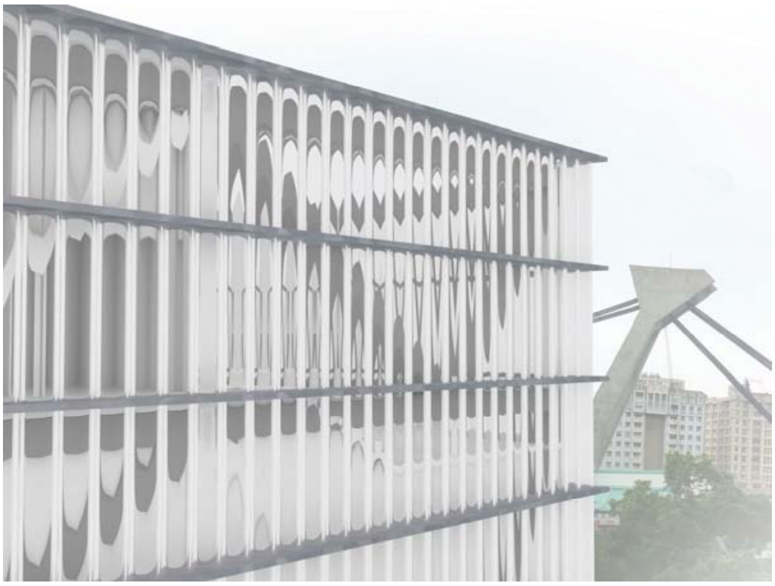
OMA

臺北藝術中心-外牆波浪玻璃介紹

坐落於台北市士林區，OMA設計並預計2015完工的臺北藝術中心，是由三個劇場共3,100座席組成。三座劇院嵌入一個中央方形量體，而這些劇院的舞台、後舞台及劇場服務設施均設置於此方形量體，結合成一個高效率的使用量體。而劇場觀眾席量體，則由中央方形量體向外凸出，漂浮於高密度而又充滿生氣的城市上方。此安排使舞台可被調整或合併使用，滿足超乎預期的假想和用法並提供了發揮各種自由及不確定性的優點。

建築立面由兩個主要的材料所組成：環繞著方形量體的波浪玻璃，以及包覆三座劇場觀眾席量體的鋁板。

方形量體內包括不同性質及需求的空間組合：舞台，後舞台，辦公室，排練室，更衣室，儲藏室及其它服務空間。於典型的劇場設計中，這些空間通常都被隱藏在一不透明之立面之下，加深劇場長久來具有不易親近之印象。為了避免重塑此印象，並考量如何加強劇場內部工作與城市空間連結之關係，設計團隊選擇使用波浪玻璃作為方形量體的立面材料。



透過波浪玻璃，方形量體四周主要結構以及內部空間量體與其活動可透現於外， 經由波浪玻璃的彎曲折射之光影而模糊化，顯現出如片段且重疊般內部幻影之效果。玻璃本身為兩層超白玻璃，加上一微灰色鍍膜於膠合層，以提供足夠之陽光遮蔽係數並有效控制能源。選擇波浪玻璃除了其獨特視覺特性外，同時也是基於其本身形狀所具備之結構強度足以抵抗台北環境之各種外力，包括地震及颱風等側向受力。組構的方式為，高5米的波浪玻璃延著立面展開併排，被固定於環繞方形量體各樓層邊緣的橫向平板之間。

對比於方形量體發光而且富有動感，這些觀眾席量體以黑暗又神秘的姿態，懸浮凸出於方形量體。這些觀眾席的焦點在於其內部精彩室內空間及表演，因此，無光澤， 大尺度分割的鋁板被選擇使用於外牆。

綜上所述，臺北藝術中心外牆利用材料的選擇來強化整體空間的個別關係。波浪玻璃的方形量體對比鋁板包覆之觀眾席量體反向的暗示出本案的基本精神：劇場工作的基礎設備被置於最中央，透明的將活動展示於城市，邀請公共大眾進入機械氛圍的內部世界。

附錄1 Appendix 1

玻璃結構型態之改良- 波浪玻璃

Corrugated glass as improvement to the structural resistance of glass

本篇文章為臺北藝術中心一案的OMA外牆顧問Rob Nijsse (ABT) 發表於Glass Performance Days 2009 期刊上的研究，分享波浪玻璃的優點，技術研究，及將來可能的運用方式。原文為英文，下方大綱翻譯僅供參考。

This article written by Taipei Performing Arts Center OMA facade consultant Rob Nijsse (ABT) is published on Glass Performance Days 2009 to share the advantage of corrugated glass, the technology research, and the possible future application. The original content is English, and the key summary is provided below for reference only.

1. General : 波浪玻璃之於平板玻璃結構優勢，以及製作方式
   - 波浪玻璃利用其彎曲面產生之立體結構行為，可達到較厚之平板玻璃之同等級抗壓力及拉力係數
   - 製作方式，誤差值及安裝固定原則
2. 案例說明 Casa da Musica in Porto （OMA 設計，2005年完工）
   - 設計要求及技術挑戰
   - 應用波浪玻璃之優點，包括結構，視覺，聲學及隔熱及防潮
3. 案例說明 Museum aan de Stroom (MAS) in Antwerp （Neutelings Riedijk 設計，2010年完工）
   - 設計說明及挑戰-高達11米高的玻璃帷幕
   - 結構系統及玻璃弧度設計(S 型玻璃)
4. 案例說明 University Library in Doha Qatar（OMA設計）
   - 設計說明及挑戰
   - IGU(insulated glass units) 波浪玻璃之選用對應 Qatar的日照問題
   - 結構系統說明及溫差變化大之玻璃變形對應方式
5. 波浪玻璃將來的運用方式:
   - 屋頂
   - 牆面
     - 案例： MVRDV 在荷蘭的一棟私人住宅，利用弧形玻璃作為結構系統。

Corrugated glass as improvement to the structural resistance of glass

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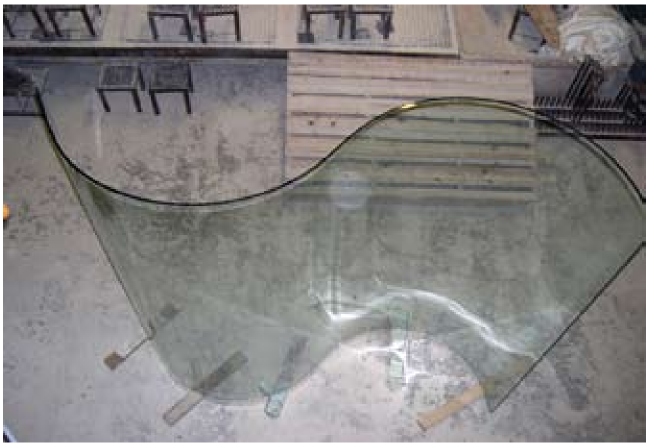
Keywords:

1=Glass 2=Corrugated 3=Façade.

It is a well known fact that if we take a flat piece of paper in our hands it is a weak, and slack.. However if you fold this piece of paper a few times the structural behaviour changes from weak to strong and form slack to stiff. .Luckily enough the glass manufacturing firms are more and more capable to create folded,or better, corrugated glass. Therefore we have started to create glass structures in corrugated glass. Two well known buildings have incorporated corrugated glass in their facades. They are the Casa da Musica in Porto (P),(architect OMA) and The Museum aan de Stroom (MAS) in Antwerp (B), (architect Neutelings Riedijk). Another project is now on the drawing boards; the University Library in Qatar (architect OMA) where a diamond shaped building has on four sides large facades composed by corrugated, insulated glass units up to a height of 17 meter. In these three buildings the corrugated glass panels are used to create, with a relatively thin sheet of glass an all glass facade without hardly any steel components. In this paper also possible future applications will be dealt with like the use of corrugated glass in floors, walls and roofs.

Fig. 1.

A corrugated glass panel directly after production in the workshop, note the convex and the concave part!.



General

In most facades flat glass panels are used to fill in the transparent part of the facades. This implies that all horizontal forces on the facades, read the wind, have to be taken up by bending of the flat panel. Bending is not a material friendly way of transporting forces over an element. For larger spans big thicknesses are required and therefore the building costs rise as well. One manufacturing "trick" to overcome this problem is by corrugating the flat panel, the corrugated steel plates are a good example of this. By corrugating or folding the flat plate a three dimensional action is possible and the lever of the pressure and tension areas in the material is enlarged dramatically compared to the thickness of the plate itself.

For glass it is the question how we can achieve this corrugated shape. One possibility is by cold deforming in a dictated shape but the elasticity of the glass makes it necessary to constantly push/ clamp the glass panel in its required shape. Also the stresses evoked by cold forming remain in the glass and have to be added to the stresses caused by the wind action. Therefore warm deforming is preferable. In this method a flat glass panel is heated in a furnace up to 600 C. At 600 C the material glass becomes more or less plastic and can be shaped in each desired form. It should be expected that the plastic deformation does not create residual stresses when produced over a prefabricated mould in the correct, desired shape. Another ill feature of the (warm deforming) production process is the fact that the thickness of the material may vary/ diminish due to the sagging out of the panel over the mould. Especially at places where higher curvatures are demanded this may lead to smaller thicknesses at the top of the curvature and, hence, a weaker spot in the panel.

Another serious critical point of the production of corrugated glass is the exactness in which the panel's dimensions can be made. Preferably we would like all elements to have the same dimensions and the same curvatures. Since it is a production process, that makes the elements one by one, exact uniformity is an illusion. In ref .(1) Thomas E. Noe gives guidelines for this issue and it is also our experience from the Porto and the Antwerp projects that tolerances of +/- 2 mm are possible.

There is different behaviour in stiffness when a concave element (hollow shape) or a convex element (rounded shape) is loaded. The convex shape is weaker and deforms easier. Therefore, if we look at the shape of the corrugated glass panel in fig. 1 we notice that this a-symmetrical shape has a convex and a concave half.

The convex part will move more under loading and will flatten out in the middle of the field. The concave part will stay more in the original shape and the overall shape of the total profile will rotate in the direction of the convex part.

However at the supports, the corrugated glass panel is forced in the steel profile that makes the support by clamping the glass (with an elastic intermediate). There the deformed, rotated shape is forced into the original radius, resulting in extra stresses in the glass and this may go as high as 25% more, locally at the supports.

2.Casa da Musica in Porto (P)

In 1997 the Office for Metropolitan Architecture (OMA) headed by the Dutch architect Rem Koolhaas won a competition for the Cultural Centre of Porto in Portugal. They had designed a, rather surprisingly shaped box of white concrete that contained the various cultural activities that had to be housed in it. In the white concrete box, large, very large openings were made to let the daylight enter the building and to present to the visitors of the building astonishing view over the town of Porto, located on the slopes of the river Douro.

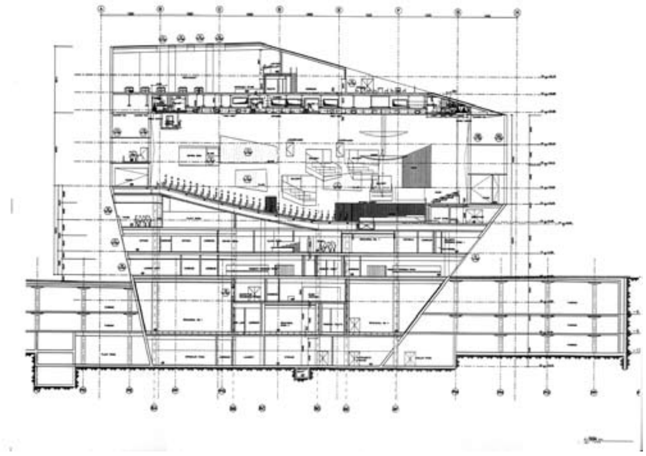


Fig. 2.

Cross section of the Casa da Musica. The large windows are directly adjacent to the big Auditorium.

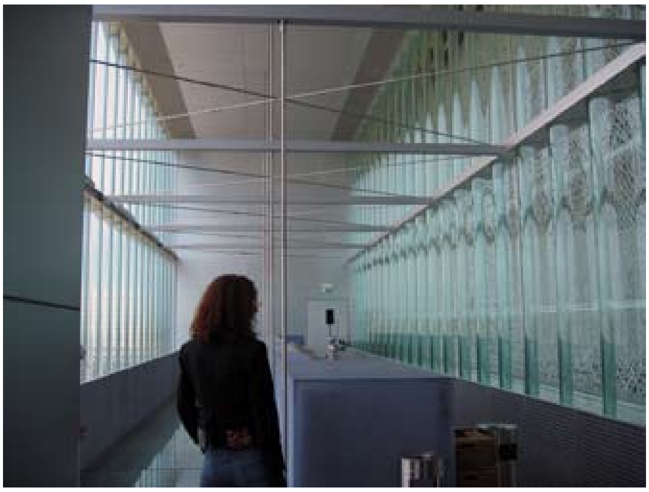


Fig. 3.

In between the two corrugated glass walls a bar, a glass one of course, was made. In the air the trusses that take up the wind load on the façade.

ABT/ Rob Nijsse was asked to make a proposal for the façade of the large windows, the biggest one measures 25 by 12 meter, using as much glass as possible and, preferably, no steel. We tried all kind of slender cable stayed structures but these remained unacceptable for the architect. Quote; "I don't want all that steel spaghetti around the glass". As we tried to figure our way out of this "mission impossible" I happened upon a publication of the Spanish firm Cricursa that made a large corrugated panel wall for the interior of a shop. Putting one and one together I made a proposal for a large window made out of large corrugated glass panels stacked on top of each other. Due to then valid production restrictions we could make 4.5 meter high corrugated glass panels, so the total height of 12 meter was divided in three parts which luckily enough fitted in with the position of the floors of the foyer/ circulation space that sometimes passed through the voids. The architects immediately embraced the proposal. As I later learned especially the contrast between the flat, smooth surface of the white concrete and the corrugated, shining, brilliant surface of the glass façade was appealing. The structural effect of a corrugated panel is clear; it can take up much more wind load then a flat one with the same thickness. Therefore no steel supports in the shape of cables, columns and beams are necessary for the glass. On an overall level support for the components of the façade is still needed. We combined these with the planes of the floors that crossed the voids behind the façade. Here were placed horizontal steel trusses made as slender as possible; so crossed diagonals in order to have always one on tensile stress. At places were there is no floor these diagonals simply hang in the air.

The architect wanted to have daylight in the big Auditorium, a feature rarely seen in theatres. So we had to make two walls of corrugated glass, one wall on the outside, to take up the wind load and to provide water tightness and insulation and one wall on the inside dividing the theatre from the foyer/ circulation area. It might be suspected that sound quality inside the theatre was affected by the presence of glass, a hard reflecting material. Study of the acoustical adviser learned that due to the corrugated surface a very effective dispersion of the sound was obtained and the effect of double glass wall resulting in a more then enough sound level reduction form inside to outside and the other way around.

The weight of the corrugated glass walls is carried by steel beams that are hung up to the concrete wall on top of the opening in the concrete shape of the building. In total six, more or less large, openings in the white concrete box were filled with this concept of corrugated glass walls.

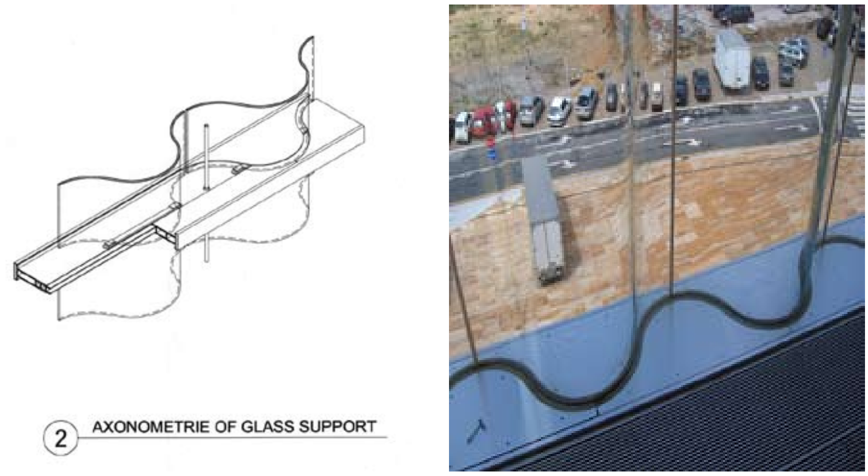


Fig. 4.

The support beam and detail for the corrugated glass panel.

Fig. 5.

The façade of the Casa da Musica ; corrugated glass and white concrete : an unexpected beautiful match.

These steel beams are a part of the horizontal steel trusses and have facilities for both mounting and adjusting the tolerances of the corrugated glass panels. Also waterproofing and thermal separation between outside and inside is taken care of.

3.Museum aan de Stroom (MAS) in Antwerp (B)

A desire to improve the quality/ atmosphere of the old disused harbour quarter directly situated near the historic City centre of Antwerp, led to plans to develop a new large Museum on an island in the Antwerp City harbour. A museum meant to house all the museums in Antwerp housing subjects diverting from historic to folkloric and modern art.

In 2000 an architectural competition was scribed out for 5 selected architects. The competition for the 12.000 m^2 floor space building was won by Neutelings Riedijk Architecten with ABT as structural advisor.

The design of Willem Jan Neutelings was simple but beautiful. By housing each category of the museums in a concrete flat box, security, fire proofing and optimal climate control was possible. By placing the in total eight boxes of the museums on top of each other and putting a entrance layer on ground floor and a restaurant on top a 60 meter high building was created. The stroke of genius on the part of the architect was that by twisting each layer of this stack of boxes over 90 degrees a spiral walkway connecting the various museums boxes was made. An other result of this twisting is that the visitors climbing up, while doing so, also have beautiful views over the city of Antwerp, each time from a different direction.

Although the structure of the MAS itself is interesting the glass facades filling in the space between the various museum boxes are the subject of this paper. As one can see in fig. 8 the height of this façade at the corner areas is two times the story height of a museum box, being 5,5 meter, so an 11 meter high glass façade results. Of course the architect desired only glass as façade. From the experiences with the Casa da Musica project, that was that time in the Design phase, we were able to propose corrugated glass for this project as well. The special challenge of the MAS project was that here a façade of 11 meter in one go had to be realised. Corrugated glass elements of 11 meter long are an illusion; they can not be made in the furnaces and the glass industry has a 6 meter length limitation due to production and transport restrictions. The Italian glass provider Sunglass was able to produce the desired shape of corrugated glass in the length of 5, 5 meter. So we divided the 11 meter in two parts of 5, 5 meter. This implied a “support” halfway that, of course had to be as slender as possible to not undo the desired overall transparency (and view) of the façade. This item was solved by connecting the two corners of the adjacent concrete blocks with a steel tube as intermediate support halfway (see fig. 8). This tube is only meant to carry the wind load and serve as a horizontal support for the façade; the own weight of the façade is carried by simply stacking the corrugated glass panels on top of each other. So for wind load the corrugated glass panel behave structurally as a plate on two lines of support, spanning 5, 5 meter. The fact that the glass panels are merely standing on each other led to some discussion.

Fig.6.

The building of the Museum aan de Stroom (MAS) on the “Eilandje” in the old harbour of Antwerp.

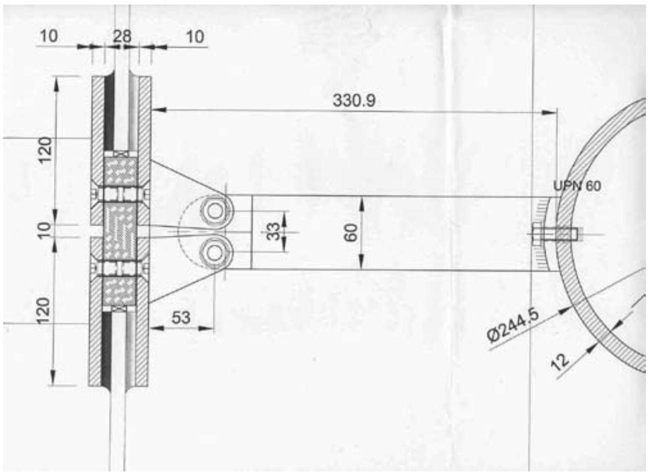


Fig. 7.

The horizontal, intermediate connecting middle detail of the 11 meter high corrugated glass façade of the MAS.

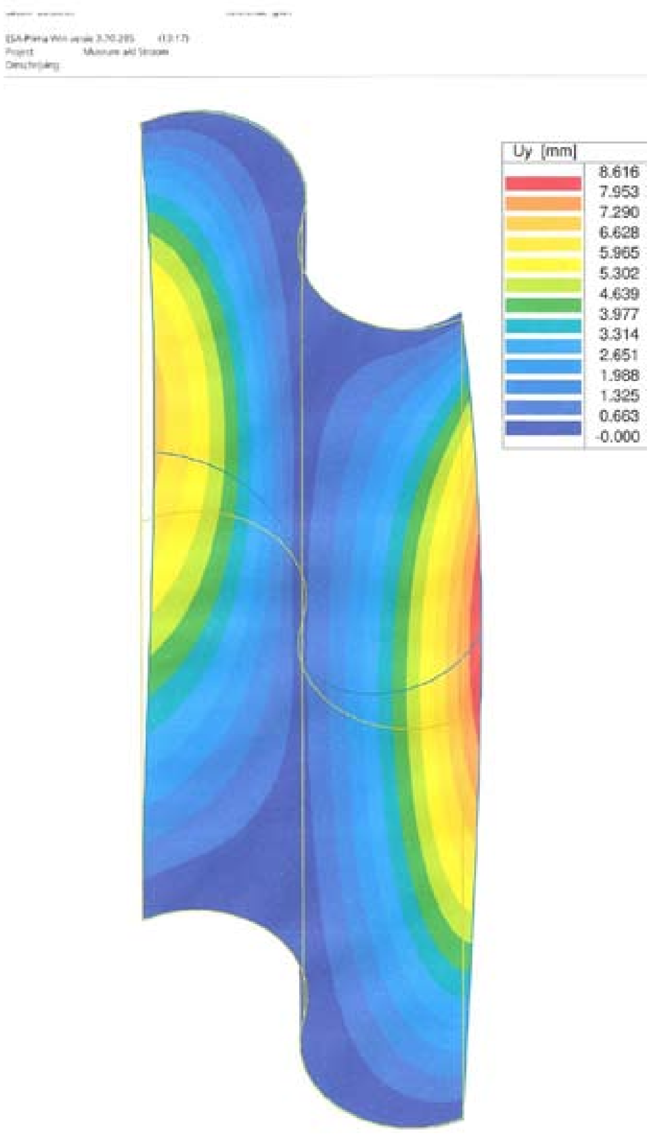
One; are the stresses called up by this stacking acceptable? And two; if a lower panel breaks, to whatever cause, will the top one not come down? and three; can the broken panel be replaced? Question one : stress level is depending on the spread made by the elastic layer between the two stacked corrugated glass panels. The level of normal stresses (compression) varies from 2 (concentrated points of support) to 0, 2 N/mm^2(uniform support), very acceptable values certainly for compression, one of the strong features of the material glass. Second question; breakage lower panel: if one simply let the panels stand on top of each other, this is a problem. Also in combination with question 3: the replacement, this is a critical aspect. Therefore it was decided to add a steel horizontal beam that was strong enough to carry the weight of the top one, when the lower panel collapsed, but slender enough to be incorporated within the connecting detail, see fig. 7.

As one can see in fig 7, steel plates follow the shape of the corrugated glass in order to make a good detail, easy to maintain and assemble. The making of the corrugated steel profiles proved to be difficult in practice since the steel always has an uncontrollable tendency to spring back after deforming and the effect of temperature change was also apparent. These problems were solved by extra attention and control during manufacturing and by making the steel elements not too long; more vertical joints were added. The waterproofing is guaranteed by silicone joints at both the in- and the outside. The connecting detail at the underside and the upper side was worked out with the same principle.Beauty is in the Details, so it is important to perfect them; also we have to have an open eye for maintenance and cleaning.

Up to now we have been talking about "a" corrugated glass panel. But how do you choose the corrugate ness of a corrugated panel? Two different visions have to come together; the structural engineer who wants to have a really present "wave-height" and the architect who wants to have a undisturbed view on the surrounding i.e. a flat as possible panel. During this discussion we made some reconnaissance calculations that learned that from a ratio of 1 to 20 of the wave-height to span the structural effect of the corrugate ness was evident. So we stuck to that but the architect reacted by doubling this value with the argument that view distortional effect from a distance is less and that people could stand "in" a wave of glass close to façade. The distortion close to the glass is also minimal. All this implied that our "wave-height" is now 2 X 300 is 600 mm. The elements were chosen to have the shape of a lying S, with a width of 1800 mm. We calculated a required glass thickness of 12 mm float glass.

Fig. 8.

Stress distribution for a single corrugated glass panel, note the different behaviour between the left- and the rightside at the support, by carefully avoiding clamping in the support-details the negative effect of a-symmetry was prevented



4. University Library in Doha (Qatar).

For the new University of Doha in Qatar, a library was needed. OMA was asked to make an architectural design for this building. This resulted in a building with floor with a amphitheatrical aspect, sloping from a flat side to the edges of the building. Over this large area of about 5500 m2 a sloped roof shaped in such a way that three facades (west, east and south) took the shape of an horizontal placed kite and one façade, the north façade remained a rectangular. It were the facades that OMA asked to be filled in as transparent as possible. Of course the danger of sunheat entering the building and the effect of glare were recognised and measurements in the shape of sunshading and a fritting on the glass to deal with this were taken.

However this meant that for each tapered façade an area of about 80 meters long and maximum 17 meter high had to be glazed. By using 5.60 meter high panels we were able to create a partition in three with horizontal steel beams at two levels. For temperature control it was essential to use insulated glass units. These proved to be makeable. So we designed this tapered façade in insulated glass units of a variable height and a constant width of 1.80 meter. The steel beams at two levels were made of about 800 mm deep horizontal steel plates welded together in a laying I-shape.. On a few points they were held in position by vertical columns in the plane of the façade or supported at existing columns in the project. The maximum distance between these supporting elements was 16 meters. It was decided to hang the façade from the top; the roof plate. Connected to steel beams in the roof massive steel ties, D= 40-60 mm held up the horizontal running steel beams where the corrugated insulated glass units stand on. This choice was made to minimalize the steel in the façade itself and because the floor beams did not have enough capacity to carry the weight of this façade. Also temperature induced movement can be taken up much more sophistically although a difficult detail had to be solved to take

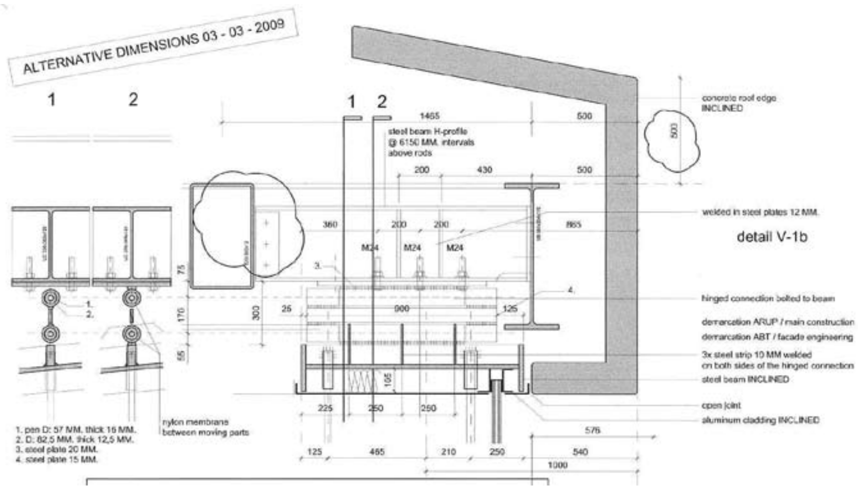


Fig. 9.

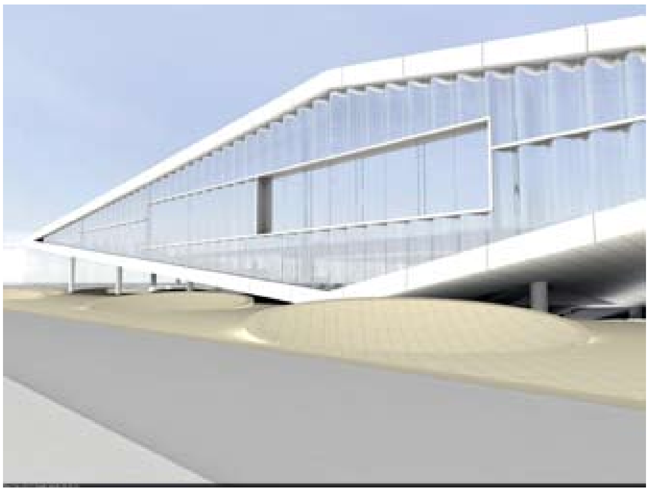
The double-hinged top detail of the Qatar hanging corrugated glass façade.

up horizontal forces from the the wind but still to allow (horizontal) movement due to shrinking and expanding of the façade due to temperature changes. A choice was made for a steel pin, sliding with a nylon cover in an elliptical hole

Not only the façade moves perpendicular to the plain of the façade but also in lateral direction. Since the facade is 80 meter long, the deformation due to temperature can be considerable, about 35 mm when fixed in the middle. This means that the façade has to move horizontal, in his plain and, since we have to avoid bending in the vertical elements in the façade this means we have to make an hinged connection. To do this correctly we even had to make two hinges on top of each other (like a real door hinge) to avoid breaking of the glass units since the top is stretched out less then the bottoms of the glass units. Due to the two hinges they move perfectly vertical in this temperature induced movement.

Fig. 10.

External view of the Qatar corrugated glass facade



5. Future Applications for Corrugated Glass Panels.

Now it is possible to make facades out of corrugated glass, even in laminated glass and insulated glass units, we may think about another possible use in the construction of buildings.

1. Roofs. Why not? If the improved statical behaviour (compared to flat glass panels) works for the windload; why not for the dead load or the snowload when it is placed horizontally, as a roof? The transparancy combined with the natural waterthightness of glass makes it a very interesting roofing material. Of course sunshading is an important issue that has to be taken care of. The drawings below illustrate the possibilities of corrugated glass as a roof.

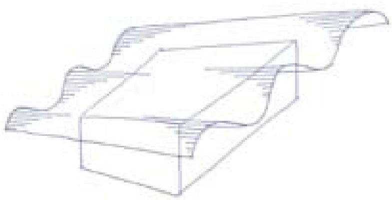


Fig. 11.

A corrugated glass roof

2. Walls. Flat glass panels have a very unfavourable structural behaviour concerning axial loads. Buckling or plying will occur very quick at already low normal-stress levels. For corrugated glass this is far better. A simple test with a piece of folded paper to act like a wall demonstrates the enormous rise in bearing capicity compared to the same piece of paper as flat panel. Also from a stabilty point of view : a flat panel tilts over easily while a corrugated panel stands firmly, a choice for a corrugated panel is obvious. We did make a proposal for a load carrying, corrugated and insulated glass wall as a perimeter to a villa designed by the Dutch architects MVRDV. It would have been a fantastic sight, the German firm of Finiglas was able to make the corrugated insulated glass units in a save and even cost-likely attractive way : 120% if compared to a standard brick wall with large glass windows.

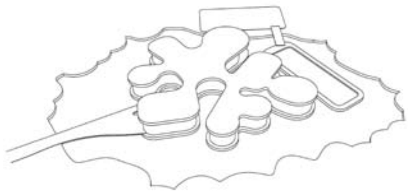


Fig. 12.

Villa in NL, designed by MVRDV

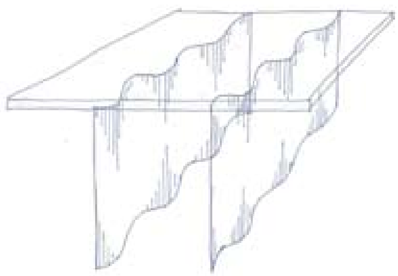


Fig. 13.

Corrugated glass walls carry the roof; stability automatically guaranteed!

Fig. 14

Internal view of the villa with load carrying glass walls.

5. References

Noe, Thomas E., Tempered Bent Glass Quality, proceedings of the 9th International Conference on Architectural and Automotive Glass (Glass Processing Days), Tampere, Finland, 2005.

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Nijsse. Rob, Structural Glas, Birkhäuser, Basel, Switzerland, 2003.

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El Croquis 131/132, OMA Rem Koolhaas, Croquis editorial, Madrid, Spain, 2006.

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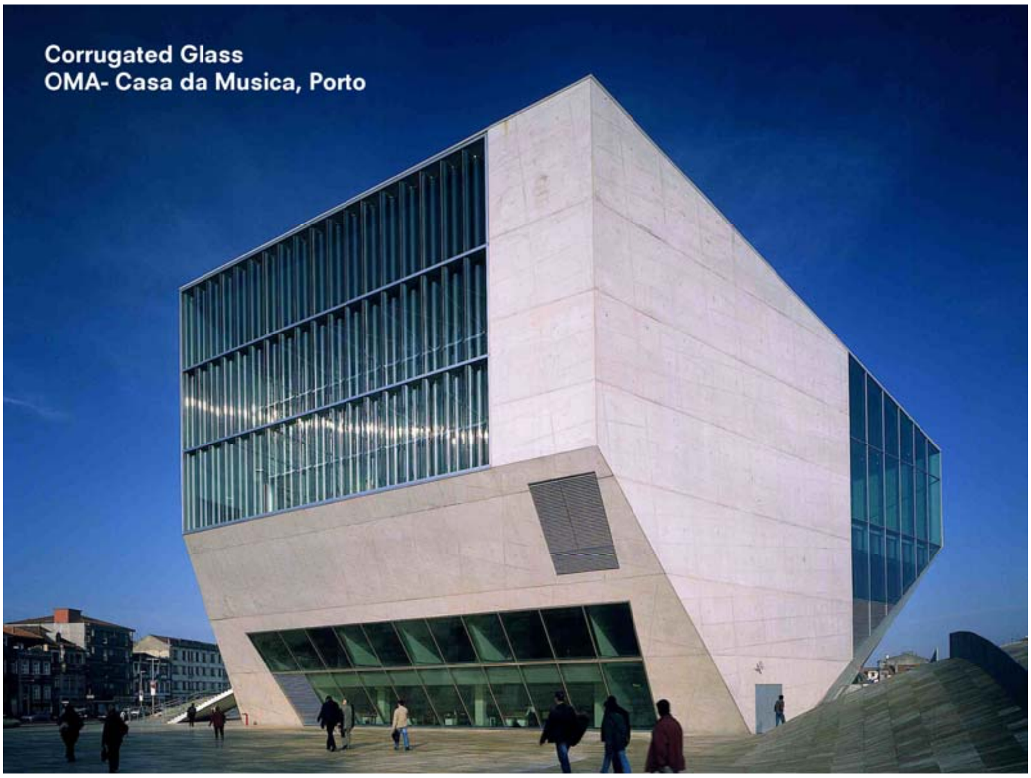
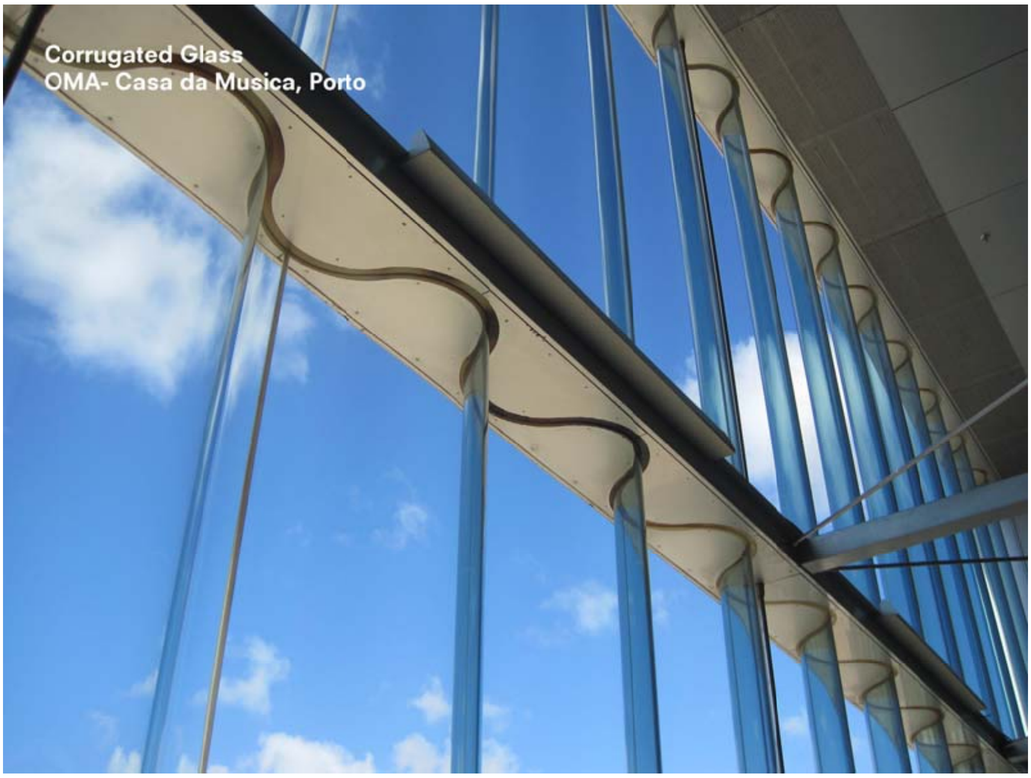
附錄2 Appendix 2 – 案例參考 Project Reference

1. Casa da Musica in Porto





2. The Museum aan de Stroom (MAS) in Antwerp (S 型玻璃)

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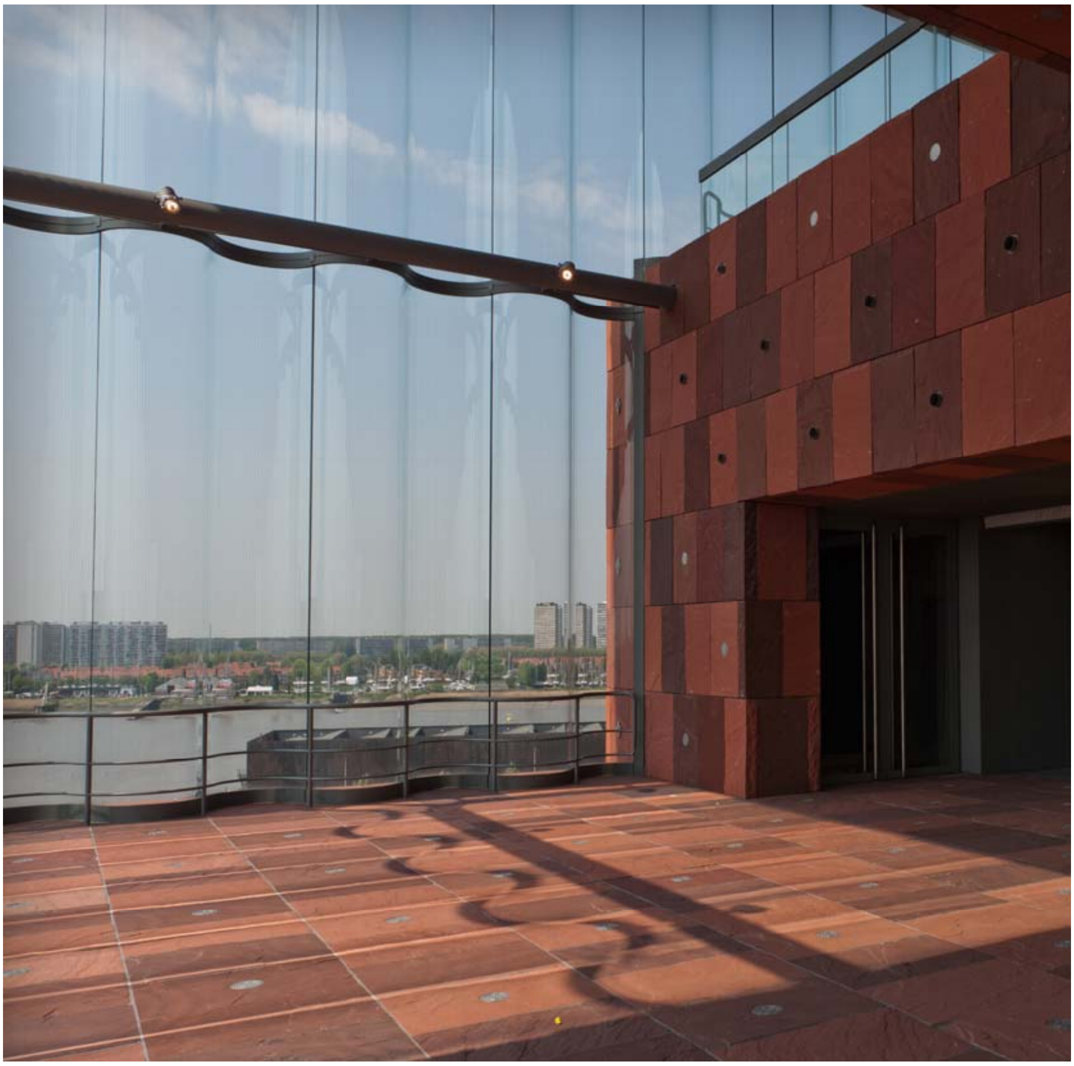

The Taipei Performing Arts Center - Introduction of corrugated glass facade

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