Glass Entrance Van Gogh Museum Amsterdam

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Abstract In September 2015 the Van Gogh Museum in Amsterdam has opened its new Glass Entrance to accommodate a growing number of visitors more comfortably. The architectural design is drawn by Kisho Kurokawa Architect & Associates and the detailed design by Hans van Heeswijk Architects and Octatube, complementing the curved and elliptical shape of the Kurokawa wing. The project fits in a trend of underground museum extensions enhanced by prominent structural glass geometries, such as the Louvre Pyramids in Paris, the Mauritshuis in The Hague and the Joanneum Quarter in Graz. The Van Gogh Museum Glass Entrance is featured by a spheroidal glass roof with glass fins stabilising the steel structure, a cold bent glass facade and a 1.5 m cantilevering glass canopy. Inside there are glass balustrades and a glass staircase supported by structural glass arches which are site-bonded to the stringers. All glass in the project is composed of low iron glass to create a high degree of transparency without discolouring. The shape of the glass roof is defined by mirroring the spheroidal surface of the existing wing. The so created roof consists of insulated and laminated glass units all different in width and supported by 30 triple laminated glass fins

with SentryGlas® (SG) interlayers. All glass fins are optimised and unique in length and height, the largest fin being 12 m long and 700 mm in height. The glass beams are supported by steel shoes connected to the main steel structure consisting of 400 mm circular hollow sections. This detail allows the glass fins to act like beams while stiffening the steel structure and supporting and stabilising the double glass units in the roof. Due to the complex geometry, the many glass fin connections and extremely tight tolerances, the entire steel structure of 60 m × 15 m × 10 m was pre-assembled, surveyed and checked in the factory scale 1:1. The IGU's in the roof's outer 1.3 m wide perimeter are cold-twisted to fit in between the roof surface and façade perimeter. The curved outer facade consists of cold-bent insulated glass units fixed to 20 unique triple laminated glass fins with SG, the longest being 9.4 m. The smallest bending radius of the elliptical curvature is 11.5 m.

Keywords Museum · Structural glass stabilisation · Glass fins · Cold-twisted glass · Cold-bent glass · Glass staircase

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1 Introduction

At the opening of the Van Gogh Museum's Glass Entrance in September 2015, director Axel Rüger recalled how he circumspectly took the plane to Japan to visit the architectural office of the late Kisho

Kurokawa (1934–2007). He wanted to discuss a little ‘problem’ with the architects who had designed the museum’s granite-clad exhibition wing in the nineties. Bluntly and without beating around the bush, the Japanese architects said: “It is the pond, isn’t it?”. Apparently, they were very well informed about the dysfunction of the sunken pool, once conceptualised as a contemplative intermediate space between Kurokawa’s new wing and the existing museum building of Rietveld. But the pool didn’t quite fit in the Dutch climate and often suffered from defects such as the broken water flow. A more compelling matter for the museum was the notorious length of the ticket queue, causing daily troubles at the small sized pedestrian walkway at the Paulus Potterstraat, which was not welcoming for the 90 % foreign visitors.

With the completion of the new wing of the Stedelijk Museum (2012) and the major refurbishment of the Rijksmuseum (2013), the time seemed right for the Van Gogh Museum—being the third major museum of the Amsterdam Museum Square—to embark on its own construction project. By enclosing the empty ‘sunken pond’, and creating a new main entrance, the museum was able to solve two problems at the same time. Without expanding the actual footprint on the Museum Square, a new transparent entrance was created on top of the former pool, being a ‘state of the art’ and innovative glass structure; the primary object of this paper.

In the first section, the role of glass at underground museum extensions is illustrated with three European precedents. The study of references is followed by an historical and architectural description of the Van Gogh Museum, after which the Glass Entrance is portrayed in detail, from the preliminary design for the glass wing of Kisho Kurokawa Architect & Associates (KKAA) to the detailed design by Hans van Heeswijk Architects in close collaboration with the designers and engineers of Octatube. Hereafter, the structure and its challenges are explained in detail from Sects. 5 to 9: the roof structure and its parametrically designed glass fins, the cold-bent glass façade with its varying bending radius, the ingenious interface details and the glass staircase which could literally and figuratively be considered as a project within a project. In the conclusion, the Van Gogh Museum’s Glass Entrance is placed in perspective, and it is described why glass structures seem to be so appropriate when it comes to museum extensions.

2 European precedents

Europe is home to many old cities which are popular tourist destinations. Over the centuries, these cities have preserved a fair amount of their cultural heritage and compact city centres. Nowadays many buildings are labelled as monuments, assuring their future conservation. Apart from churches, it is probably museums attracting the highest number of tourists. Massive visitor numbers and the phenomenon of special art exhibitions with queues stretching around the block, is known since the Enlightenment (Haskell 2000). In 1851 six million people poured into London to visit the Great Exhibition in Crystal Palace, and in 1857 1.3 million visitors were attracted to an exhibition of the Old Masters held in Manchester (Saumarez Smith 2015). But the visitor streams were occurring more and more often, queuing in the densely built and already crowded city centres. Although these visitors are boosting the local economy, they impose a logistical headache. In terms of visitor numbers, the leading European museums are currently the Louvre in Paris (9.3 million visitors in 2014) and the British Museum in London (6.7 million visitors in 2014). But even the relatively small-sized Van Gogh Museum had welcomed 1.6 million visitors in the same year. The allurements of museums and the ‘democratisation of art’ is accompanied by a paradox, referred to by van Heeswijk (2015) as ‘the down side of success’: museums are becoming a victim of their own successfulness.

If one would make a categorisation, there are two types of museum refurbishment projects in which glass plays a major role. The first one is the covered courtyard: an enclosed space for logistics, orientation and natural light. Regularly courtyards have been the playground for architects and engineers. Whether it is a grid shell, a transparent glass fin roof or a bespoke steel-glass structure, glass roofs seem to fit well in monumental museum architecture (Fig. 1).

The second category is the underground entrance. With their already heavy footprint in historic city centres museums are frequently forced to go below ground. In these projects, architects often decide to hide away the most congested area, being the entrance. Interestingly, this choice conflicts with the purpose of the museum entrance to be a visible welcome and identification point for tourists who may be first-time visitors. Whereas the entrance used to be easily recognisable in a symmetrical classicist facade or renaissance style

Fig. 1 a–d Examples of glass roofs covering monumental museum courtyards. From left to right the British Museum in London, the Maritime Museum in Amsterdam, the German Historic Museum in Berlin and the Municipal Museum in The Hague

museum building, it suddenly becomes a hidden architectural space, deprived from natural light. It is the task for architects to solve these two problems at once, and glass has proven to be a very suitable material. Impelled by new structural possibilities and technologies, this has led to a number of museums in which glass structures illuminate the underground spaces, mark the new entrance, and facilitate a larger welcome area.

Three projects are described hereafter, all with a very different architectural and technical use of glass in combination with an underground museum entrance.

2.1 The pyramids of the Louvre, Paris

In 1981 president Mitterrand appointed Ieoh Ming Pei to design a new entrance for the Louvre. Pei knew the centre of gravity had to be found by excavating the courtyard enclosed by the museum wings (Cannel 1995). The *Cour Napoléon* provided the necessary space that was lacking in the Louvre itself, and Pei employed this space to unify the existing buildings, including the Richelieu wing that was assigned to the museum. He could also address the problem of the building's confusing disorder by a new subterranean layout of corridors, interconnecting the museum wings. Moreover, the entrance problem could be addressed. Although the Louvre is an art museum with the world's highest number of visitors, these visitors were often wandering around the museum wings wondering where the entrance was. According to Pei, visitors need to be welcomed by some kind of great space, and that space had to contain volume, daylight and a surface identification (Cannel 1995). His design solution turned out to be the well-known glass pyramid, having enough

volume to ingest 15,000 visitors an hour in theory. In addition, there are three baby pyramids, one inverted pyramid and triangular reflecting pools with fountains, contributing to the quality of the urban space, opening up the Louvre and making an inviting gesture to the crowds. Another advantage was that the pyramid encloses the largest possible floor area within the smallest possible volume, so that the building volume would provide plenty of space for the large visitor numbers while standing as unobtrusively as possible (Chiple Slavicek 2009). The footprint of the main pyramid is only 1/30 of the courtyard (1000 m²), which provided Pei with a strong argument of architectural modesty (Fig. 2).

Still, the pyramid needed to be prominent enough to be the focal point, without compromising the Louvre's authenticity as a national monument (von Boehm 2000). The solution here was found in choosing a contrasting material for the pyramids that is both translucent and reflective at the same time. The pyramids had to be transparent to avoid upstaging the Louvre. No solid addition imaginable could gracefully blend with the surrounding building, while glass was able to reflect both the ornately stone facades as well as the Parisian skies. The ancient pyramidal form made of the modern materials glass and steel constitutes a dialogue between the old and the new, for it is at once much older and newer than the existing Louvre buildings (Cannel 1995).

The structure of the glass pyramid is an early example of structural glazing that is stabilised by means of cables. Pei's team called on the expertise of naval engineering firm Navtec to manufacture the nodes and struts, and to install the structure that included 128 open trusses held in place by sixteen very thin cables

Fig. 2 Cross and longitudinal section of Cour Napoléon with the different pyramids (Pei Cobb Freed & Partners)

Fig. 3 **a** Construction photo of the Louvre's steel structure (Pei Cobb Freed & Partners). **b** The large entrance pyramid

(Jodidio 2008). The outside of the pyramid is a metal framework, with outriggers sticking inside, stabilised against inward and outward directed loading by continuous cables. Although the engineering challenge had been to create a structure as transparent as technology could attain, Pei was not too impressed by the transparency of the result. On this subject, Arup engineer Fernández Solla notes (2011) how the pyramid might be fairly more integrated than a glazed space frame, but the 675 diamond-shaped and 118 triangular glass panels are not part of the structure at all (Fig. 3).

The objective of transparency was also achieved by the colour of the glass (Wigginton 1996). In order to show the Louvre's facades without the greenish distortion visible in commercial glass, Pei advocated the installation of special clear glass without a green tint. Although the feasibility was questioned initially by one

of the big glass manufacturers, eventually the glass was produced using white and pure sand and the Louvre's pyramids got their extra uncoloured glass with a low iron content. Seen from the inside outward, the construction turned out to have a reasonable transparency, offering views of the historic facades. Seen from the outside there is much reflection.

Whereas the main pyramid was completed in 1989, it took four more years before the inverted glass pyramid at the underground shopping mall was realised. One of the leading firms for engineering tensile glass structures at the time was Rice Francis Ritchie (RFR). For the main pyramid, they had only been involved as a consulting office, but RFR was in full charge of the technical design of the inverted pyramid, one of the earliest examples of a frameless, suspended and point-fixed glass structure. The upper part acts as a

Fig. 4 **a** Interior photo of the main pyramid with the winding entrance staircase. **b** The inverted pyramid

tensile stressed floor structure, while the lower pyramid is mainly loaded on deadweight. The siliconised structure turned out to have an additional challenge in finding a way to allow the inside to be cleaned, a tricky job for abseilers to this day (Fig. 4).

In the 21 m high entrance pyramid Pei's philosophy about architecture can be perceived best. Besides the modulation of light and the creation of a geometric landmark, it celebrates the movement of people. Not the expansion itself, but the logistics have made the Louvre suitable for blockbuster art exhibitions (Cannel 1995) and the growing number of visitors. The museum has become a theatrical event for mass audiences, rather than a solemn art repository. The descent is marked by the pyramidal space and is symbolised by the glass pyramid that provides a central focus point in a huge complex of buildings which had no centre (von Boehm 2000). During the day, the courtyard is brought to life by tourists. At night, the courtyard is illuminated from within the glass pyramids, as if it were lanterns. Jean-Luc Martinez, the president of the Louvre, claims that his museum is the only one in the world whose entrance is considered to be a work of art.

2.2 Universalmuseum Joanneum, Graz

Taking a leap in time towards the twenty-first century, it appears that Pei's glass pyramids have inspired a new generation of architects. By the end of 2011, the trans-

formation of the Joanneum museum quarter in Graz (Austria) was completed. The design of Nieto Sobejano Arquitectos connects the Museum of Natural History, the Provincial Library and the New Gallery of Contemporary Art, that used to face a residual courtyard. Because the buildings belong to the same institution, there was a need for a common means of access and welcoming space. This resulted in the transformation of the rear courtyard into the focal point of the museum quarter and adding to the program of the buildings below ground. New facilities such as a visitors' centre, conference hall, reading areas, museum shop, depot and service areas are joined together in the new common access zone (Fig. 5).

Architecturally, the design is accentuated by a combined series of truncated glass cones protruding above ground. In fact, the courtyard is punctuated by the inverted cones, bringing light into the conical patios and redefining the horizontal surface of the new square. At night the urban space is illuminated from below by artificial light. In an interview the architects explain how they wanted to avoid the feeling of being in a buried building (Schwar 2013). This was done by the natural light shining through the curved glass towards the interior and by the visual links upwards towards the historical facades. Although most of the spaces are concealed beneath the pavement, the architects have certainly devoted a lot of time to the perforated streetscape, that is materialised as an intermediate between the World Heritage city level and the contemporary underground

Fig. 5 a, b Exterior and interior photo of the glass cones (Universalmuseum Joanneum/N. Lackner)

Fig. 6 a Photo of the entrance escalator (Universalmuseum Joanneum/N. Lackner). b Cross section by Nieto Sobejano Arquitectos

world. In the largest of the glass cones, two escalators provide access to the underground space. This physical connection between the ground floor and the basement is a bit graceless, but vital for the project. Apart from a dominant feature above ground and an aesthetic light well below ground, the cone is also a permeable glass structure (Fig. 6).

The smooth glazing surface of the cones is defined by two differently sized circles, one being shifted above the other. As a result the double glass units have various dimensions and radii, splaying out from a vertical position to an increasing sloped angle about the perimeter. The glass panels are supported on top and bottom only, thus eliminating vertical structural elements. The top-most glass panels are shaping the circular balustrade and are cantilevering from the hidden peripheral metal

sections at ground floor level. A flush glass surface has been realised by means of a hidden solid steel profile in every joint of the double glass units, and a bonded connection for the laminated balustrade glass panels, braced at the top by means of a stainless steel handrail profile. Since the curved glass holes are the materialisation of the project's concept, it can be understood why so much attention is given to the quality of the glass and the detailing. The glass segments of the cones are insulated and laminated glass units at the underground levels, while single laminated glass panels were used at the balustrades. The curved glass panels are furnished with a dotted screen print, with a radius decreasing towards the base. All glazing is low iron, to provide the best colour rendering index. Neugebauer (2014) has shown how various safety glass compositions of

conical-curved annealed glasses were used to realise the difficult shapes with an inclination varying from a vertical position to an angle up to 30° .

The architects pride themselves on not giving in to the temptation of developing an iconic structure, as has often happens in recent museum expansions (Schwar 2013). It is true that most attention was given to the intermediate space, rather than creating a blatant structure. The intervention could be considered as an embedded landmark within the urban landscape. It adds to the streetscape and opens up the buried world.

2.3 The Mauritshuis, The Hague

Before he was commissioned to work on the Van Gogh Museum's Glass Entrance, Hans van Heeswijk finished another Dutch underground museum extension: the Mauritshuis in The Hague. The city centre did not allow an increased footprint, so the solution for spatial expansion was to make an underground connection to a neighbouring building. Van Heeswijk introduced an opening in the forecourt with a staircase and a transparent elevator shaft sticking out above street level, a modest but innovative glass structure that is one of the project's pillars.

The Mauritshuis museum is housed in a prominent building that used to be a seventeenth century palace. The Dutch State acquired the building in 1820 to house the 'Royal Cabinets of Rarities and Paintings' and just like the Louvre, a royal museum had thus been opened to the public. Since the 1960s, before art became an affair of ordinary people, but it took

another five decades before the shortcomings of the Mauritshuis became apparent. The main entrance was no longer suitable for the growing number of visitors, who had to enter the building through a former service entrance at the side. In addition, the museum was forced to move the permanent collection in order to accommodate temporary exhibitions, depriving the visitors a view of unique paintings that had to be temporarily taken to the depot. The Mauritshuis suffered from its popularity, becoming a victim of its own success (Gordenker 2014), but a solution emerged when a building across the street became vacant. The opportunity was seized to excavate the forecourt and the design of an underground entrance foyer connecting the two buildings was born.

Van Heeswijk is aware of the fact that many visitors come to a museum for the first time. So a museum's organisation can never be too simple and the architecture should be welcoming (van Heeswijk et al. 2014). To satisfy the need for more space and improvement of the public amenities, the foyer is designed as a distribution centre. Just like the premises of the Universalmuseum Joanneum in Graz, there is little visible at street level except for a cylindrical glass structure which is situated—along with the museum—right next to the Dutch government buildings that house one of the oldest parliaments in the world. The most prominent added structure is an eye-catching all-glass elevator shaft that also casts light downwards and functions as an urban lantern in the evening. The elevator is an important cylindrical glass landmark that points out the new entrance of the museum and provides a spectacular means to ascent into the museum. The elevator shaft is

Fig. 7 a, c Photos of the glass elevator shaft (L. Kramer). b Section of the Mauritshuis extension by Hans van Heeswijk Architects

unique in the history of underground museum architecture because its structural stability is totally realised by glass components (Huisman 2014) (Fig. 7).

The principle of an underground entrance has the benefit that visitors immediately have an overview of the layout while they enter from above. This concept is also the starting point for Apple's flagship store in New York, an all glass project that has been an inspiration for the glass elevator as well.

The glass elevator embodies two experimental steps (Eekhout and van der Sluis 2014): firstly the realisation of a cylindrical glass shaft in an outdoor environment with full wind loads and secondly the employment of two glass fins to guide the sides of the glass elevator cage directly. With additional sidelights and a glass floor at the forecourt, the spacious underground tunnel became a well-lit foyer, with the 9 m high glass elevator shaft as its business card. The Mauritshuis has become twice as large, but its distinctive and intimate atmosphere has been preserved.

3 The Van Gogh Museum, Amsterdam

At the end of the nineteenth century, the city of Amsterdam had grown out of its old city walls. In between the Rijksmuseum (1885), the Royal Concertgebouw (1888), and the Stedelijk Museum (1894), a new quarter emerged just outside the city centre, featured by an open space in between a number of cultural buildings. This area was soon referred to as the Museum Square and was shaped as an urban park. In 1963 architect Gerrit Rietveld (1888–1964), one of the members of Dutch modernist art movement *De Stijl*, was commissioned to design a new museum at the perimeter of this urban park, dedicated to the works of Vincent van Gogh. Rietveld was both at the height and the end of his career. His preliminary design was taken over by his successors, and the building came into completion in 1973. The museum terrain was becoming a playground for architects and urban designers in the decades to come. In 1989, Carel Weeber first suggested an expansion of the Van Gogh Museum at the side of the Museum Square. Only two years later, a new exhibition wing was about to rise from the drawing boards. The design came from Kisho Kurokawa and provided the Van Gogh Museum with a new exhibition wing, in line with the Museum Square master plan of Danish landscape architect Sven-Ingvar Andersson (Kloos

2015). Because the Kurokawa Wing was designed as a detached volume, one of Andersson's important optical axes perfectly coincided with the Van Gogh Museum's new layout, which had an underground connection. The floor plan of the new wing was a semi-ellipse completed by an adjacent pool. This sunken pond was designed as an intermediate space where visitors could 'purify their minds' whilst moving from the Rietveld building to the new Kurokawa wing (Fig. 8).

In terms of the museum's logistics there were also great benefits. Previously, temporary exhibitions took place in the Rietveld building, and just like in the Mauritshuis, the permanent collection had to be removed every time. With the new wing, this belonged to the past. The museum prepared itself for 1 million yearly visitors. Meanwhile the discussion and ideas about the transformation of the Museum Square were ongoing. The Van Gogh Museum's big brothers, the Rijksmuseum and the Stedelijk museum developed extensive and costly expansion plans, both with a new entrance directed towards the Square. The Van Gogh Museum couldn't fall behind.

4 The Glass Entrance

The design for the new Glass Entrance of the Van Gogh Museum in Amsterdam was a collaboration between Kisho Kurokawa Architect & Associates, Hans van Heeswijk Architects and the structural designers and engineers of Octatube, all with the application of glass at the forefront of their minds.

4.1 Kurokawa

Just like the museums described in Sect. 2, the Van Gogh Museum has been experiencing a notable increase of visitors since the opening of Kurokawa's exhibition wing on the Museum Square in the early nineties. When the adjacent Rijksmuseum underwent major refurbishment works between 2003 and 2013, the Van Gogh Museum eclipsed its neighbour in being the most popular museum in the Netherlands, hitting 1.6 million visitors in 2011. In order to respond to various problems, a more comfortable, safer and more spacious entrance was at the top of the museum's wish list. A new entrance was to replace a small entryway in the Rietveld Building at the Paulus Potterstraat that had no

Fig. 8 **a, c** The Kurokawa Wing and its sunken pool (Sels Clerbout). **b** Isometric view (Kisho Kurokawa Architect & Associates)

visual connection to the Kurokawa Wing whatsoever. The idea of moving the entrance towards the Museum Square was also in line with the newly opened Rijksmuseum, the Stedelijk Museum and the Royal Concertgebouw, which all had their new entrances directed to this urban lawn.

In April 2012, five years after the decease of Kisho Kurokawa, his Japanese office KKAA received the formal programme of requirements for designing a transparent entrance at the pond. In terms of the building's appearance, it stated that the museum had to be an experience for the visitor. Keywords were: daylight, openness, visibility and hospitality. Furthermore, visitors should explicitly not be given the impression that the entrance is located in the basement. The client wanted to be able to communicate the experience of the museum and its identity on the outside of the building. Kurokawa paid careful attention not to give excessive impact on the vicinity, including the Rietveld Building. The same had been done at the existing extension of the Kurokawa Wing (1990–1998), a closed volume which added a lot of space to the museum of which 75 % was situated underground. For the new entrance, the office also wanted to respect and maintain the architectural originality of the Kurokawa Wing, which didn't have a separate entrance and was nicknamed 'the Oyster'. This was done by creating an aesthetical tension between the two. The entrance is completely detached from the cantilevering cubical 'picture cabinet' and from the northern slanted wall of the Kurokawa Wing. The shape of the glass roof of the new Glass Entrance is defined by an upside-down version of the existing Kurokawa Wing's spheroid roof surface. In this way an expression is given to the continuation of the original design. Underneath, the for-

mer sunken pond is transformed into a spacious and well-lit basement floor. In a mail conversation with the author, KKAA explains why they proposed glass as the main building material: it is in line with the client's brief, and it is conceived to be a very durable material, without any wear and tear to the surface over time. With regards to the architectural meaning of glass, Kurokawa provided the impression of openness in the new entrance, with sufficient space and daylight. They aimed to identify the new entrance as a contrasting building next to the aluminium, titanium and granite stone Kurokawa Wing, and wanted to relieve the impact of the new entrance on the vicinity by the reflection of glass and its transparency. When spectators are walking by and looking through the building, or when museum visitors are at the basement of the new entrance looking outwards, the existing Rietveld and Kurokawa buildings are visible through a curved glass façade.

Kisho Kurokawa was not only an influential architect, but also a gifted and passionate philosopher. His comprehensive *Philosophy of Symbiosis* (1997) expresses his thoughts on architecture clearly. While Kurokawa applies the concept of symbiosis from the scale of a human being to entire cities and societies, it must have inspired his buildings too. That is why his office might have been so cooperative in obliterating the spirituality of the pond. The ambiguity of the intermediate space is surely related to the philosophy of symbiosis, both in its old state and in the redesign. In the 1990s, the symbiosis between the new wing and the Rietveld Building was attained through the open intermediate space of the pool, and from 2015 onwards by the new Glass Entrance.

Fig. 9 a–c Artist impressions of the preliminary design of Kisho Kurokawa Architect & Associates

Fig. 10 a–c Artist impressions of the detailed design (Hans van Heeswijk Architects)

4.2 Hans van Heeswijk & Octatube

After receiving the general concept from KKAA, it was obvious for the client—being the Central Government Real Estate Agency—they had to get a specialised glass façade company on board as soon as possible. That's how the design and build company Octatube got involved in the project, following a selection procedure. A few months later, the office of Hans van Heeswijk Architects was appointed for the detailed architectural design.

Although the concept and shape of the Glass Entrance had already been defined by Kurokawa, the entire glass envelope structure was redesigned. Whereas the initial Kurokawa design was featured by a massive structure of trusses and overlapping metal girders, the final design left only a minimal steel structure consisting of a 3D-curved CHS tube along the perimeter of the glass volume. This roof beam sits on ten steel columns. The rest of the main structural elements are completely made of glass. A comparison between the original artist impression of Kurokawa (Fig. 9) and the ones below demonstrate how the structure has been redesigned (Fig. 10).

The ambitions of Van Heeswijk had been to provide transparency, visual tranquillity and a high level of finish quality. Especially at the materialisation of the structure and the interior staircase, the latest developments in glass engineering and construction live up to these aspirations.

The inverted spheroid surface of the glass roof is supported by 30 parallel glass fins that are all unique in length and height, the longest being 12 m. Both the facade and the roof glass panels are stabilising the steel structure so that no wind bracings were necessary and the steel structure appears to be simple. The 600 m² glass roof surface consists of double glass units that are cold-twisted in the outer perimeter, to create a smooth transition between the roof and the elliptical curved facade. The facade is made of 650 m² cold-bent double glass units and supported by 20 unique glass mullions and bespoke metal purlins. The insulated glass units (IGUs) are cold-bent on site to a minimum radius of 11.5 m. This is done airborne by an electric robot curving machine, see Sect. 7.6. After being bent to a precise radius and brought to the right position, they are fixed by clamps with a bolted connection. The revolving glass doors at the entrance are marked by a 1.5 m

Fig. 11 Architectural section of the Van Gogh Museum (Hans van Heeswijk Architects)

Fig. 12 **a** Exterior photo (Ronald Tilleman). **b, c** Exterior and interior photo (Luuk Kramer)

cantilevering glass canopy. The majority of the visitors descend via a glass staircase (Fig. 11).

The axis of Andersson's pedestrian walkway is untouched, but the sunken pond is transformed into a covered underground space. In the evening, the Glass Entrance functions as an urban lantern (van Heeswijk 2015), as we have seen at other glass museum structures. But in contrast with the Louvre's pyramid, the Van Gogh Museum's Glass Entrance Building is abstract and visually simple, whilst technically complex (Fig. 12).

5 Main structure

The structural design of the glass envelope is a typical mix of a steel structure with additional stabilisation from the glass roof surface and the glass façade. The glass envelope could be called a 'steel-glass structure' in its structural sense. The volume of the glass entrance was derived from the design of Kurokawa

and exactly followed the former balustrade around the deep pond on the outside. On the side of the Kurokawa Wing the inclinations were mirrored to obtain a unified elliptical stone and glass design. The curved top perimeter had to be lowered a bit, to allow the new roof plane to slide under the existing cubical volume of the cantilevering picture cabinet, low enough to be able to install the glass panels and to allow for maintenance (see Fig. 13b). The initial Kurokawa design of a perimeter space truss and steel purlins on vertical CHS columns (see Fig. 9) was further developed into a more abstract scheme of a perimeter CHS tube, curved downward next to the Kurokawa Wing and curved both horizontally and vertically at the side of the curved glass façade. The steel columns were maintained, but had to be positioned under an angle due to the total shape of the glass envelope. The explicit wish of the architects was to minimise the amount of metal components as much as possible, without the 'all-glass budgets' of Apple. The metal purlins of Kurokawa were replaced by glass beams in the cross direction at every glass panel seam,

Fig. 13 **a** 3D view of structural model (Octatube). **b** section (Octatube)

with a maximum length of 12 m. At the time of design development the façade glass panels were polygonal in shape and around 1.8×1.8 m in size. A later thought was to have a more fluent façade instead of the polygonal faceted façade. The glass panel size became 3.6 m horizontally over a height of 1.8 m vertically (the width of the glass panel) to minimise the support structure and visual distortions due to irregular reflections which are very visible when walking by the outside of the façade. Vertical glass fins at every 3.6 m in combination with horizontal steel curved purlins were designed to create a free panorama when looking horizontally between two rows of purlins, from left to right. As a result of this design, the main structural system is a steel CHS structure of two beams on steel columns, connected at various positions and stiffened by the roof glass structure. In the calculations of the total frame, the stiffness of the elliptical façade is not included, however in reality this will minimise deflections even further (see Fig. 13a). So the structural design is a CHS steel structure partly stabilised by the glass roof and the glass façades, along with bespoke connections and interface details. All in order to prevent steel wind bracings in the façade and the roof and to obtain an abstract view with a reasonable price level, usual in the Dutch market.

5.1 System description

The eye-catching elements of the Van Gogh Museum's Glass Entrance are the façade and roof, both supported by a hybrid system of steel tubes, glass panels and glass

fins. Two curved CHS tubes in the roof are supported vertically by ten tubular steel columns. The dimensions of all CHS are engineered at $\text{Ø}406.4 \times 12.5$ (S355) for a univocal appearance. Four columns positioned at an offset of 1.3 m of the curved glass façade are positioned vertically and four columns next to the Kurokawa Wing are tilted with the same 6° angle as the slanting metal clad façade that was realised in 1998. Two columns that support the intersection of the two curved roof tubes have a different inclination as if the steel structure is performing a balancing act next to the Kurokawa Wing.

In accordance with the static scheme (Fig. 13), structural stability and stiffness are created in four ways:

- Applying a moment-fixed connection between the tubular columns and tubular 3D shaped roof beams to create a portal frame structure [D1].
- Applying a hinged connection at the bottom of the six slanted columns next to the Kurokawa Wing in combination with a connection between these columns and the structure of the gutter [D2]. Due to these connections most column are in itself stable. The same principle of the slanted columns is applied to the vertical columns. However, these columns are not connected to the gutter structure but to the curved concrete edge at ground floor level [D2].
- Introducing eight hinged-connected tubular beams that connect the steel structure to the Kurokawa Wing for extra stiffness.
- Connecting the slanted glass beams in the roof (slope = 16.5°) and their bonded rectangular hol-

low steel sections (RHS) to the steel tubes in a way the normal forces are transferred [D3].

As glass is usually not used to stiffen steel structures, this last method is experimental and hence elaborated in more detail. Normally, both glass fins and regular glass units are mainly loaded by bending forces. Fins are then used to support glazing units in facade and roof structures that are primarily loaded by wind and snow. However, as glass is capable of withstanding high compressive forces, fins could be used as compression elements in a structure. The engineers of Octatube experimented successfully with glass stabilisations since the mid 1990s (BRN Catering, Capelle ad IJssel). For the Van Gogh Museum it was proposed to use the glass fins in the roof to vertically support the IGUs (8/16/1010.4) and to transfer horizontal compressive forces from the curved steel tube next to the facade to the curved beam next to the Kurokawa Wing. To transfer tensile forces, the bonded rectangular stainless steel sections (Figs. 15, 16) are connected to the steel structure as well.

The dimensions of the glass beams are chosen in relation to their span. Due to the elliptical shape of the floor plan and the resulting curved geometry of the façade, all glass fins differ in length. Downward loading, dead load in combination with snow load, is normative for the glass fins. This load is simplified as an equally distributed load on one glass fin. In the design of glass fins, dimensions are governed by strength as allowable stresses are relatively low. A ratio is determined in which this normative (simplified) load combination would lead to stresses equal to about 50 % of the allowable stresses. As bending stresses in an equally distributed loaded beam on two supports quadratically relate to the span, and stresses also quadratically relate to the height of the beam, a linear relation between the height h and span L was chosen for a fin with a glass composition of 3×15 mm:

$$h [\text{mm}] = \frac{L [\text{mm}]}{17} \geq 200 \text{ mm} \quad (1)$$

The longest span of a glass fin is 12 m for which a height of 700 mm is determined. In relation to the total thickness of less than 5 cm this is a very slender beam and therefore susceptible to lateral torsional buckling. Torsional stiffness of a laminated section is determined by the thickness of single sheets and shear interaction between those sheets. In the analysis the thickness of

the interlayer is omitted. Calculations of the glass roof fins were based on the interlayer PVB which resulted in almost no shear interaction between the glass sheets in case of long-term loading. e.g. $G = 0.05 \text{ N/mm}^2$ for a load duration of 50 years. Then, torsional stiffness is mainly determined by the thickness of the single glass sheets. Next to providing enough torsional stiffness, stability is determined by lateral support of the beam's areas in compression. In case of the roof fins of the Van Gogh Museum, stability is increased by connections (centre-to-centre 800 mm) on top of the glass fins to the IGUs of the roof with a maximum width of 1.8 m (see Fig. 16 for typical details). At these positions lateral movement at the top of the glass beam, that is loaded in compression in the normative load case, is prevented. Inverted upward loading due to wind suction is not normative as dead load of all glass elements is relatively high and the slope of the roof is quite modest. After finite element stability analysis of the glass fins, a glass composition of 3×15 mm was determined. A laminate of three sheets was chosen to make sure that after breakage of one glass sheet, the maximum characteristic load can still be resisted by the two remaining panes. Fully tempered glass was chosen to increase the allowable stresses. In combination with SentryGlas® (SG) interlayers, the post-failure characteristics have been improved in the event that all three glass panes of a laminated glass roof fin would be broken. However, this is very unlikely as they are high up in the air and cannot be reached by maintenance staff without special equipment.

A three dimensional structural finite element model was made to analyse the structure, e.g. determine normal forces in the glass fins (Fig. 13a). Femap, as pre- and postprocessor, is used in combination with NX Nastran as solver. In the main model, only one dimensional elements are used. Gap elements are used to transfer compression only and their spring stiffness is determined in relation to the design of the connection details. Two dimensional elements with properties according to the equivalent plate thickness approach are used in sub-models. The 12 m long roof glass beam was modelled as follows:

- Vertical nodal supports (z-direction) at the two bottom corners;
- Horizontal nodal supports (x-direction) at two third of the length of the vertical edges where the steel shoe supports the glass beam;

Fig. 14 Finite element model with instability shape (Octatube)

- Horizontal nodal supports (x-direction) every 800 mm at the top of the glass beam;
- Longitudinal nodal support (y-direction) in the center of one vertical edge;
- Equivalent plate thickness calculated for every load case with corresponding load duration according to NEN2608 for glass panes supported at three edges;
- Load in y-direction applied at nodes at position of intermediate material between steel shoe and glass beam (paragraph 5.3);
- Load in z-direction applied at top edge of glass beam.

It was found that the normative load case for stresses and stability is snow load in combination with a glass fin that has one broken pane (Fig. 14). Still, the eigenvalue is more than 30, and therefore no imperfections need to be taken into account and a geometrical linear analysis is sufficient. It was also checked if enclosing of the fins at both ends and rotation of the fin at its supports resulted in local tensile stresses, but this effect was not detected due to the very small deflections of the glass fin itself.

5.2 Loading

Standard load cases that need to be considered in structural design are dead load, live load and variable loading. Normative variable loads for the main steel and glass structure of the new entrance of the Van Gogh Museum are wind load and snow load. Temperature load is also investigated, both globally and locally.

Snow load is determined according to NEN-EN 1991-1-3 and the Dutch national annex. Due to the higher existing volume next to the gutter, snow drift should be taken into account. Therefore, the resulting loads are very high. The maximum characteristic snow load on the glass roof is determined to be 2.1 kN/m². Snow load in the gutter is calculated to be 2.8 kN/m². Assuming a volumetric weight of snow of 200 kg/m³

this is over 1 m snow, and therefore quite conservative for the Netherlands.

Wind load is determined according to NEN-EN 1991-1-4 and the Dutch National Annex. However, wind load on an elliptical shape is not mentioned in the code. Therefore, the wind load is determined according to the procedure that is stated for cylindrical shapes with a certain width and height. A conservatively high maximum pressure coefficient (wind pressure) of +1.0 and a minimum pressure coefficient (wind suction) of −1.5 was chosen. These pressure coefficients were used in combination with inner under pressure and overpressure, to calculate all facade glazing units and glass fins separately. Global calculations for the steel and glass structure were performed with simplified pressure coefficients. Due to the curved plan, asymmetric loading was found to be normative for the overall stiffness of the structure.

Global temperature load was considered in the main model for all roof elements (steel roof tubes and glass fins). A reference temperature of 17° was set and the temperature loads of −25° and +60° were applied to check deformations and stresses. These temperature differences are also used in the design of the thickness of the structural silicone between the glass and steel elements. Climatic loads are not normative for the design of the IGUs due to their (large) dimensions.

5.3 Connection of glass fins to steel tubes

To activate the glass beam as a compression element, and the stainless steel RHS section on top, as an element loaded in tension, a detail is designed as shown in Fig. 15. Forces on the façade are in the first place transferred by the double glass units in the façade to the vertical façade fin. By means of a mechanical connection, the forces are transferred with a steel rod to the curved steel tube that runs along the façade's perimeter. This steel tube is supported vertically by steel CHS

Fig. 15 Schematic section with connections of glass fins to steel tubes (Octatube)

columns. This connection is made by welding a square hollow section in the horizontal tube and a welded base plate that is connected with eight M30 bolts (8.8) to a head plate welded in the vertical tube. The set back of the head plate compared to the tube edge creates a shadow line. The horizontal tube has one plate welded to it in the direction of the glass roof fin onto which a welded steel bracket is screwed in a way a similar small set back is created as described before. The welded steel 'shoe' bracket in which the glass roof fin is placed has a screwed Polyoxymethylene (POM) block in it onto which the glass fin is placed. The same detail is made at the glass fin's bottom support. As the glass roof fin is under an angle of 16.5° , another POM block is placed at the bottom end of the fin to prevent shear behaviour. When resisted by this block a small gap between glass and steel at the top end of the fin of about 20 mm results. This gap was measured on-site to precisely produce the final keystone element. This element is designed as a composite of POM and neoprene of which the latter has a much smaller stiffness than the former. After a parameter study an axial connection stiffness of 9600 N/mm was chosen to be a good intermediate, stiff enough to transfer forces but flexible enough to reduce internal stresses in the glass beams in the two corners of the steel roof structure a lot in case of thermal contraction. The neoprene stiffness is much less than that of POM. As a result, the total axial compression stiffness of the glass fin and the connections is determined by the neoprene stiffness in combination with the axial stiffness of the glass beam. As the glass fin is modelled in Femap using beam elements with the right sections, the fin's axial stiffness is implicit. The formula of Rocard ([Aiken et al. 1989](#)) was used to determine the axial compression stiffness of neoprene. The formula calculates the

Young's Modulus E , out of a shear modulus G , shape factor S , that is calculated by dividing the surface area by the bulge area, and constants k_1 that equals 4.8 and k_2 that equals 4. The shear modulus of the applied neoprene is estimated to be 1.0 N/mm^2 and constants k_1 and k_2 are 4.8 and 4.

$$E = 3G \cdot \left(\frac{1 + k_1 \cdot S^2}{1 + k_2 \cdot S^2} + 2 \cdot S^2 \right) \quad (2)$$

A Young's Modulus of about 30 N/mm^2 was calculated for the neoprene block of $50 \times 48 \times 6 \text{ mm}$ (applied to fins with height $\leq 500 \text{ mm}$) and 20 N/mm^2 for a block of $100 \times 48 \times 10$ (applied to fins with height $> 500 \text{ mm}$). The difference in axial stiffness (EA/L) is about 20 %. It was shown in the finite element model that the increased stiffness of the block of neoprene with a 6 mm thickness had little influence on the forces and deflections. In addition, the formula mentioned by [Battermann and Köhler \(1982\)](#) was used to determine the neoprene stiffness. Differences in Young's Modulus were less than 10 % and were covered in a sensitivity analysis of the finite element model.

The axial compression design load in the beam elements in the model was found in the smaller glass fins with a maximum of 15.7 kN. Axial short term stresses in the neoprene of 6.5 N/mm^2 will be no problem. The calculated (compression) strain in this ULS combination is 20 %. The potential increased stiffness due to non-linear material behaviour is covered by the sensitivity analysis and added stiffness would mean that the glass fins will support the steel beams even better. A locally higher normal force is no problem for the system due to the high eigenvalue of the glass fins and relatively low stresses compared to the allowable stresses.

5.4 Test assembly

To check the production tolerances of the curved CHS roof beams, a full scale test assembly was made in the factory of Octatube. In the design of glass elements, allowable tolerances are very small. Especially in this case where glass is such an integral part of the construction, production tolerances of the roof structure were critical, as the theoretical supported width of the edges of the double glass units in the roof is only 15 mm. Furthermore, the supported width of a glass fins in the roof was quite small (3 cm for the smallest fins) and the detail of the steel support had no adjustment possibilities due to aesthetic reason. Therefore, the centre-to-centre distance of both tubes need to be checked carefully before welding all connection plates to them. To ease welding, the structure of the test assembly was inverted (assembled upside down). In that way most welds could be made by welding staff members standing on the factory floor. It was found that the difference in geometry between theory and practice was largest at the two end corners of the tubes, however these could be compensated for in the welding procedures of the steel plates.

6 Roof

The roof of the new entrance has a complex geometry and also plays a role in stabilising the glass roof fins. As it is made of glass, thermal greenhouse effects were also investigated. However, as the glass volume is oriented North, most of the time it is in the shadow of the stone clad Kurokawa Wing. The glass roof is made of insulated glass units that are supported by the glass fins.

As these fins are positioned parallel, but at an angle of 16.5° in one direction and differ in height in the other direction, most glass units are rectangular and positioned at an angle in two directions. The composition of the IGUs, 8/15/10/10.4, will be described in more detail. The outer pane is a 8 mm fully tempered single glass sheet with an Ipasol solar control coating 62/29 that lets most light in, but keeps most of the heat out. It's fully tempered to be able to resist a characteristic point load of 1.5 kN and the high snow load, even with reduced allowed stresses due to the 44 % white dotted frit on the inner side of the outer pane. The inner PVB laminated heat-strengthened glass pane makes sure that if one or more of the three glass panes should break, not one glass shard will fall down. The inner laminated glass pane also contributes in stabilising the glass fins.

Dead load of the glass units, that are at an angle in two directions, is resisted in two ways. As the glass units are clamped to the glass roof fins, the slope is the same as the inclination of the fins. It is uncertain if friction between the supports of the glass units is enough to resist the dead load and therefore gliding is prevented by a steel element at the bottom end of the glass units that is connected to the rectangular hollow section. This is the first support method. In Fig. 16 three typical details are shown in which the varying slope of the glass units in the other direction is demonstrated. The second method to resist dead load of the glass units in this direction is found by stacking of the glass units. Stacking, because if we look at the total glass roof section, some glass units want to slide right and some left. If all panes are stacked, they counteract each other. As the roof is not symmetrical in the longitudinal direction, additional connections between the glass units and the steel supporting structure ensure

Fig. 16 a–c Connections of glass fin to glass roof units under varying degrees (Octatube)

Fig. 17 Images of previously built projects with cold shaped glass. **a** Loggia Wasseraalvingen (Bogenglas). **b** Parking hedges Westerlaan, Rotterdam (Octatube). **c** Floriade Pavilion, Hoofddorp (Octatube)

that an equilibrium is obtained. In addition, the detail is made in such a way that the element in between the glass units—transferring compressive forces—is screwed firmly to the steel substructure. The double glass units also press in the other direction compared to the ‘slide down direction’. Therefore, if both glass units at each side of a glass fin have the same size and are at the same angle, the detail is in equilibrium and the glass fin is only loaded in global z-direction and not sideways. Contrariwise, the glass fin will load the glass units in the roof if it is itself loaded vertically due to imperfections. When loaded vertically, the top side of the glass fin will be in compression while the bottom side is in tension. To prevent lateral torsional buckling the compression top side of the fin, as mentioned before, should be supported sideways every 800 mm. The longer the glass fins in the roof, the more important this support, because the shorter fins are much less sensitive for instability failure modes.

The roof glass to glass roof beam detail is made in different ways in relation to the angle between the glass units and the horizontal pane (see Fig. 17a–c).

- (a) Angle between horizontal pane and roof glass units $\alpha < 10^\circ$ and maximum fin length is 12 m: The small angle between stiff steel section and glass unit is compensated by flexible material. The POM block in between the glass units is screwed directly into the stainless steel rectangular hollow section. Out of plane forces at the top of the glass beam are transferred to the roof glass units via shear and tension in these EJOT screws and compression in the POM block.
- (b) Angle between horizontal pane and roof glass units $10^\circ \leq \alpha \leq 30^\circ$ and maximum fin length is 10 m: The angle between glass unit and steel section is

compensated by a combination of black coloured thin steel plate and a local plastic block. The POM block in between the glass units is screwed directly into the stainless steel rectangular hollow section. Out of plane forces at the top of the glass beam are transferred as mentioned before.

- (c) Angle between horizontal pane and roof glass units $\alpha > 30^\circ$ and maximum fin length is 4 m: The angle between glass unit and steel section is compensated by a combination of black coloured thin steel plate and a local plastic block. The POM block in between the glass units is screwed into the POM block that is previously screwed to the stainless steel rectangular hollow section. Out of plane forces at the top of the glass beam can be transferred in two steps via EJOT screws, and POM blocks, but are not really an issue due to the small length of these fins.

7 Façade

The cold-bent glass façade of the new entrance of the Van Gogh Museum is one of the eye catching aspects for architects and structural designers and engineers. Its curve completes the existing stone façade to be the complement of the stone wing as one continuous elliptical building shape. The facade consists of in situ bent glass units that are connected to the vertical glass façade fins.

7.1 Cold deformed glass

Normally, when an architect designs a curved façade or roof, this is executed with hot deformed glass, in

laminated panels or in IGUs. These so called ‘hot bent’ laminated glass units, are named after the manufacturing process in which the individual glass pane is heated to about 600 °C and then shaped (sagged) in a receiving mould. Cooling down can be done naturally to obtain an annealed glass panel or the glass can be cooled instantly by cold air simultaneously along both faces of the pane in case of obtaining fully tempered glass (very short cooling period) or heat-strengthened glass (longer cooling period). After cooling down, the single bent glass sheets can be laminated by using an autoclave. IGU units of annealed, heat strengthened or fully tempered glass, can be composed of single or laminated panes, depending on the analysis of stresses expected in the glass and the expected safety behaviour after eventual breakage of one of the panes. When the term ‘cold-bent glass’ is used, ‘cold’ refers to the installation process at ambient temperature at which the glass is bent in a certain shape. The flat glass unit from the factory is produced in the same way with the same PVB interlayer as is always done industrially to produce flat laminated glass units. PVB is a commonly used interlayer for laminated glass and its creep behaviour makes it a good choice for cold-bending. In reality laminated glass is always slightly cold-bent due to imperfections in the glass unit itself or in its substructure onto which it is fixed. Fixing inevitably introduces local cold bending of the glass panels. However, in engineering terms, the application is marked as ‘cold-bent’ when the deformation is more significant and specifically done with an engineering purpose, after thorough analysis.

The first experiments of Octatube with cold shaped glass date back to 2001 when the ‘spaghetti’ facades of the Town Hall of Alpen aan den Rijn and the Floriade Pavilion in Hoofddorp were realised. All over the world facades and roofs are now made with cold deformed glass. Often a distinction is made between cold-bent glass and cold-twisted glass in which the former is mostly referred in case of surfaces with a single curvature and the latter in case of double curved surfaces. However, in practice both have double curved surfaces as bending in one direction results in bending in the other direction. This is due to the fact that deformation in one axis results in deformation perpendicular to this axis as described by the Poisson’s ratio. This secondary curvature is often an undesired curvature as reflections can be different than if one would have a perfect one dimensional curved surface. In this paper, the general verb ‘bending’ will be used to refer to

single and double curvatures. Cold twisting is affiliated to the theory of cold bending, whereas the directions of bending are opposed to each other.

7.2 Short historic overview of cold-bent facades and roofs

To show that cold bending of glass units is done at least for several decades now, a few relevant projects and products will be described. In The Netherlands from 1993 the product RadiusGlas was used in projects such as in Leiden ([Staaks 2003](#)) and Haarlem ([Cobouw 1995](#)). Since 2000, Maier Glass from Germany sells the product MAGLA® Bogenglas that was used for example at the Loggia Wasseraalengen ([Maier Glas 2015](#)). For this product, the bent shape of originally flat glass panels is created by tensioning cables that cause out of plane bending of the planar (monolithic fully tempered or laminated heat strengthened) glass unit. In the Netherlands, cold-bent glass was applied in 1997 in roofs of the skylights of the central train station ‘s-Hertogenbosch ([Vákár and Gaal 2004](#)) and double curved glass in the town hall of Alphen aan den Rijn, designed in 1999 and completed in 2003 ([Staaks 2003](#)). Already in the early nineties, Octatube was researching cold-twisted glass use ([Eekhout et al. 2007](#)). Another company in the Netherlands, BRS, used it for the elliptical façade of the Jinso Pavilion in Amsterdam, built in 2008 ([Vollebregt 2009](#)).

Octatube has ample experience with cold-bent glass. One year after the aforementioned town hall, Dries Staaks graduated on the subject of cold-twisted glass and his ‘Theory of Staaks’. With the accumulated knowledge several double curved roofs were designed and built. For example, the Medieval & Renaissance Gallery of the Victoria & Albert Museum in London (designed by MUMA and Tim MacFarlane), featured by IGUs deformed about 100 mm out of their plane for a diagonal length of 3 m. The Floriade Pavilion designed by Asymptote Architects (New York) was developed and built with laminated cold-bent point fixed laminated glass units. Also some small entrance units of an underground parking garage in Rotterdam designed by Ector Hoogstad were constructed with cold-bent laminated glass. In addition, multiple canopies have been realised such as the bus and tram station ‘Zuidpoort’ in Delft designed by Mick Eekhout and ‘De Droogloop’ in Amstelveen, designed by Thijs Asselbergs. Both have

laminated glass panels with an out of plane deformation of about 100 mm. The Zuidpoort roof was made with rectangular panels and diverging silicone seams to realise the undulating roof form as a proof of the Theory of Staaks.

7.3 Geometry facade Van Gogh Museum

At both ends, between the existing stone façade and the new glass entrance, two flat glass panels are placed with a small recess to emphasise the transition between the old and new building. Between these glass units a curved façade of about 60 m in length stretches with a varying height and varying bending radius. The height of the facade is a result of the roof geometry, as mentioned in Sect. 4, and is varying between 8 and 10 m. The curvature of the façade is directly linked to the elliptical ground plan design of Kurokawa following the balustrade at the edge of the former pond. This elliptical shape with a varying curvature is approximated by several arcs with a maximal deviation of a few mm. The minimal bending radius that results in the highest curvature was found to be 11.5 m. The maximum radius is 42.5 m.

In the first design phase a centre-to-centre distance of the vertical supporting structure was sketched to be 1.8 m and the height of a glass unit would also be 1.8 m. The facade was faceted. After an investigation of the double curved surface that resulted if one would bend the 1.8×1.8 m glass unit it was concluded that the resulting reflections would become undesirable. To get better deflections, it was then expected that the width of the glass unit should be higher to get more bending length. A length of 3.6 m was chosen, and after building a mock-up it was also concluded that the vertical glass fin support in the centre of the glass unit could be omitted.

This was also quite economical. Thus, a centre-to-centre distance of 3.6 m between the glass fins resulted. To have an unobstructed view at eye height and to have a rigid element at 1.0 m above the surrounding pavements the height of the bottom glass unit was decided to be 0.9 m. To have a smooth curve with a variable height at the top of the façade, the top glass units of the facade all have varying dimensions.

7.4 Glass unit and supports

The cold-bent glass units are connected to glass fins for maximum transparency, which has most likely never been done before. The composition of the glass units consists of a laminated outer and inner pane, both with two sheets of 5 mm heat-strengthened glass and 4 layers of PVB in between. Normally, two layers of PVB would be applied by the glass supplier to cope with imperfections, but 4 layers have been chosen due to the lower (especially long term) bending stresses as the shear deformation of the PVB reduces shear interaction between the glass sheets. Normally, fully tempered glass is chosen in case of cold-bent glass for its higher tensile capacity, but in this case heat-strengthened glass was chosen after detailed analysis, for the benefit of favourable post-failure characteristics. Even when all glass sheets would have been completely broken, it stays in place (Fig. 18).

The supports of the cold-bent glass units are custom designed and also different than the usual linear clamped edges. The long edges are supported by small screw plates at the outside and a linear element at the inside, while the short edges are supported at the outside by a stainless steel solid linear section and at the inside by a rectangular hollow stainless steel section that is glued to the vertical glass fin. The small steel

Fig. 18 a Radii of façade curves (Octatube). b, c Geometry of two typical bent glass units (Octatube)

screw plates at the end of the long edges are used to generate a rotation at the end of the four corners of the glass unit. The ones in the centre of the glass unit are structurally active in case of wind suction, which often happens around a curved building. The horizontal steel section in between the glass fins is loaded by a bending moment at its ends when the end steel plates are tightened. The steel sections are mechanically connected to the glass fins to be able to partly transfer dead load and wind load. Dead load of the glass panels is transferred by compression from the top panels to the lower panels. This system thus enables the fixation of the glass unit, but due to the stiffness of the glass pane itself, the short edges would bulge if not restrained. To have a better reflection also these edges are restrained and screwed to the rectangular section that therefore pulls at the structural sealant between it and the glass fin. This is a permanent load acting on the silicone for which the allowable stresses are relatively low. Stresses depend on the stiffness of the glass unit and silicone itself, and after contact with Sika the high strength structural silicone adhesive Sikasil SG-550 was chosen that has an allowable static stress of 0.020 N/mm^2 . The total summed thickness of the glass sheets of the fin was needed for maximum tensile resistance. Tape that is applied during the production process as spacer between the stainless steel RHS profile was put at low stressed locations and the application process of the sealant in the factory was monitored closely to make sure this critical detail was executed perfectly.

The actual bending of the flat IGUs to their curved pre-stressed cold-bent shape is done airborne, by an electrically operated bending machine combined with vacuum suckers, as will be described in more detail in the next paragraphs.

7.5 Calculation of stresses in bent glass

In case of structural calculations of laminated glass units, time dependent behaviour of the laminate is very important. Finite element models were, just as the models described in Sect. 5, made in the pre- and postprocessor Femap. To reduce calculation time a laminated glass pane is modelled with plate elements instead of solid elements. Normally, when using plate elements, an equivalent glass thickness is applied to these elements according to the Dutch glass code NEN2608. This equivalent thickness takes into account

the shear interaction between laminated glass sheets that depends on the properties of the interlayer, load duration and temperature. When no shear interaction between the glass sheets is accounted for (long load duration and high temperatures) the lower bound of the equivalent thickness of two sheets of 5 mm (reduced according to NEN2608 to 4.8 mm) glass is:

$$\begin{aligned} t_{gg,ser,min} &= \sqrt[3]{n [-] \times t [\text{mm}]^3} \\ &= \sqrt[3]{2 \times 4.8^3} = 6.05 \text{ mm} \end{aligned} \quad (3)$$

However, this method is meant for distributing external loads over both glass sheets. In case of an enforced displacement with no shear interaction, the stresses should be calculated with the thickness of one single sheet. To check stresses for load combinations, a two-step procedure is used. The first step is the geometrical nonlinear calculation of geometry and stresses due to bending. No shear interaction between the cold-bent glass sheets is assumed due to the thick PVB interlayer and time for relaxation before the first significant external loads are applied. A higher thickness results in higher stresses. Therefore, the stresses are calculated with a thickness of 5.0 mm instead of 4.8 mm as mentioned in the code. The second step is the calculation of stresses and geometry due to an external load on the bent glass unit. First, the deformed geometry of the first calculation step is set to be the new geometry. Second, the equivalent thickness, calculated by the NEN2608, is applied to all plate elements. Third, constraints are set to match the final executed design. Fourth, the external loading is applied and extra stresses due to this external load are calculated. The total stress is determined by adding stresses with the corresponding safety factors for long term and short term loading (Fig. 19).

In addition to the aforementioned procedure, stresses during the initial bending process are investigated, to determine the actual stresses for different load combinations. In Fig. 19, boundary conditions and stresses are shown for two analyses to investigate stresses due to cold bending. Image (a) represents the airborne bending process by the bending robot and the stresses during that process. While bending, shear interaction between the sheets will be significant assuming an ambient temperature of less than 20° and a high bending speed. Therefore, a high equivalent thickness of 10 mm is applied to the plate elements. In the model, an outer pane is connected to an inner pane, to take into account that an IGU is bent. The 10 mm plate property thick-

Fig. 19 Comparison between two models of which the resulting global relative displacement in bending direction between corner and centre is about the same: 14 cm, that corresponds to a bending radius of 11.5 m. **a** Major principal stress in airborne situation suspended in the curving robot after geometrical non-

linear analysis of two plates $t = 10$ mm coupled at the edges and of which one plate is loaded with eight point loads (Octatube). **b** Major principal stress after geometrical nonlinear analysis of one plate $t = 5$ mm (Octatube)

ness is applied to both panes. The edges of the outer and inner pane are connected to represent the spacer and structural silicone of the IGU that have a high axial stiffness. As will be explained in the next paragraph, only the inner pane is loaded during bending. In reality eight point loads will act on this pane. In the model, the four loads in the centre of the IGU are modelled by point supports. Image (b) represents the bending process with the boundary conditions according to the final situation. Two curved stiff lines are modelled below the glass plate with gap elements in between that are loaded in compression only when the gap is zero. One single glass pane is modelled because boundary conditions of the outer and inner glass pane are about the same when loads and constraints would be applied to the glass edges. In the geometrical nonlinear analysis, four point loads are applied after which two line loads are added as well. The point loads resemble the clamp plates at the corners, and the line loads resemble the vertical solid steel sections that are screwed to

the stainless steel RHS profile which is glued on the glass fin. It is shown in Fig. 19 that the major principle stresses are three times higher in the post-stress situation (a) in comparison to the final situation (b). This is due to the higher stiffness of the elements ($t = 10$ mm instead of $t = 5$ mm) and the difference in loading. To prevent glass breakage during installation the bending process was tested several times, the bending speed was reduced and monitored closely during installation.

7.6 Testing and execution with a new designed bending machine

To investigate the bending procedure, fixation, geometry, air tightness, reflections and post-failure behaviour, a mock-up was built in the Octatube laboratory (see Fig. 20a). Two glass units of $3.6 \text{ m} \times 1.8 \text{ m}$ and two glass units of $3.6 \text{ m} \times 0.9 \text{ m}$ were bent to a frame with a curvature of 11.5 m. First by men power, later by using

Fig. 20 **a** Mock-up (Octatube). **b** The lifted bent double glass unit of which all four glass sheets are broken to test post failure behaviour (Octatube). **c** Vacuum machine (Octatube)

Fig. 21 **a–d** On site air borne bending, checking, flying, and installation of cold-bent glass units (Octatube)

a specially built robotic bending machine. This multi-purpose bending machine was developed together with the company ViaVac and is shown during test-phase in Fig. 21b, c. It is developed as a combination of a regular glass vacuum lifting machine with two vacuum circuits, and an electrically driven bending mechanism. The bending mechanism was designed to be very easy in use so one green button was designed as bending button and one red button as reverse-bending button. It was calibrated on site to accommodate the different bending radii.

To illustrate the procedure on site, a couple of execution steps are shown in Fig. 21. Flat IGUs are delivered on the building site first. Then, the special developed ‘robotic’ bending vacuum machine is fixed onto the glass and the IGU is lifted from the glass stillages and bent airborne to the desired curvature that is measured by the relative deflection. Next, the curved glass in the

bending robot is lifted by a crane and hoisted to its destination where the bent form matches the form of the substructure. To connect the bent IGU to the substructure, at least the four corner bolts with clamps are tightened and then, the bending machine is released.

8 Connection of roof and façade

The façade is based on an elliptical ground floor shape and sloped line visible from the Stedelijk Museum and the Rijksmuseum. This slope is derived from the existing roof of the Kurokawa Wing and goes down in the direction of the new entrance as shown in Fig. 14b. An elliptical shape is then generated as edge curve of the existing roof and new top façade edge. The inverted spheroid surface of the glass roof is approximated by a cylinder under an angle, starting low near the existing

Fig. 22 a–d Major principle stress patterns of cold-twisted glass roof panels under varying conditions (Octatube)

stone façade and ending high at a distance of 1.3 m of the façade, above the double curved steel roof tube.

The double curved surface between the elliptical edge curve that is at angle and the cylindrical surface is populated with cold-twisted glass units of about 1.2 m × 1.8 m. The IGU has an 8 mm fully tempered outer pane and a double laminated heat strengthened 88.2 inner glass pane. The maximum out of plane deformation or cold-twisting is about 70 mm. Figure 22 shows stress patterns of such panels for multiple load cases and combinations. Figure 22a shows the stresses due to out-of-plane deformation of 70 mm. Figure 22b–d show stresses due to extra added upward wind load, snow load and a point force respectively.

9 Glass staircase

The glass staircase, architecturally designed by Hans van Heeswijk as a welcoming gesture and to open up the underground space for visitors, connects the entrance at the Museum Square at ground floor level with the underground entrance. The architect envisioned a stairs reflecting the architectural appearance and technology of the new glass entrance. The staircase is state-of-the art in terms of glass technology, spanning a height of 5.5 m and being supported and stabilised sideward by a glass portal frame. The total glass mass is about 4 tons and can be subdivided in: over 30 triple laminated fully tempered glass steps and glass platforms with embedded LEDs, 16 double laminated fully tempered glass balustrade elements, and two spectacular triple laminated fully tempered glass units of the portal frame. Welded steel box sections are designed to span between glass portal frame and concrete bottom and top floor. In principle the RHS steel beams could have been replaced by glass beams including the full height of the

balustrade, much like the stairs in the Apple Stores, but this would have added too much to the project costs here.

9.1 Glass steps

The glass steps have a depth of 320 mm and a maximal length of 2.7 m. They are made of three PVB laminated fully tempered glass sheets with a thickness of 12 mm. To have a walkable surface with maximum friction and high durability the CriSamar®STEP Lunarix-X frit is applied to the topmost glass pane. All glass steps are supported and connected at three positions. Glass supports are executed with 2.3 mm thick 3M VHB Tape 4991. This was chosen due to its clean application and flexibility compared to glue. Each support has a taped surface area of $38 \times 250 \text{ mm}^2$. The tape was applied to the glass step first, after which stainless steel elements with threaded holes were pressed onto the tape. Then the stainless steel sections were bolted to the sections that had been welded to the steel stringers. In the engineering analysis, a maximum characteristic point load of 300 kN on a surface of $50 \times 50 \text{ mm}^2$ was assumed. The structural glazing tape was checked to cope with rotations due to deformation of the thread and also for enforced displacement of the steel stringers. All steel elements are relatively flexible since they have been designed with a minimal height. The static indeterminacy of the three-point supported glass steps proved to be the main difficulty for the structural analysis and for validating the steps and connections.

9.2 Balustrade

The balustrade glass units all have a different geometry. They are connected to the sides of the welded

Fig. 23 **a** Artist impression of the glass staircase (Octatube). **b, c** Photographs of the glass staircase (Luuk Kramer & Ronald Tilleman)

box profiles with an offset of 20 cm. Torsion in the stringers is resisted via the connections at the bottom to the concrete and by rotation fixed connections to the other stringers at the centre and top of the staircase. Four point-fixed mechanical connections are used to connect each glass unit to the steel stringer. Around these connections, stresses in the glass are high due to the holes needed for the mechanical connections. To resist all applied loads with minimal connections, fully tempered glass with a thickness of 12 mm was chosen for the laminated glass panes. SG is applied as interlayer for safe post-failure behaviour. An extensive analysis was done of all glass panes connected by the handrail, in which the characteristic point load (1 kN) and line load (0.8 kN/m) on the guardrail still had to be resisted if one glass sheet would break.

9.3 Glass portal frame

The main—almost invisible—eye catcher of the staircase structure is the glass portal frame that is composed of two half-portal glass elements made by laminating three glass sheets of 15 mm. Three main stringers rest on top of this glass structural element that acts like a three-hinged portal frame to transfer vertical and horizontal forces from the steel stringers to the concrete base floor. The steel profiles are hinge-divided just after the glass portal frame to cope with relative vertical deflections of the top connection of the staircase to a relative flexible free concrete floor edge. In this way a static determined system is created that is less susceptible to unforeseen movements. The centre steel stringer runs through the portal frame and the connection should

transfer a vertical design load of over 90 kN to the glass. Horizontally the portal frame is calculated to resist a force of 10 % of the total vertical load. This percentage was chosen arbitrarily as a design value to ensure horizontal stability of the frame. A horizontal load on the portal frame results in upward and downward force on the lower two connections of the glass elements. However, no upward force results from load combinations, because the dead load is very high. The centre connection needs to transfer compression between both glass elements when it is loaded vertically and shear forces when loaded horizontally. The 10 mm gap between the laminated glass and steel is injected with Hilti HIT-HY 70 mortar (coloured yellow in Fig. 24c) of which long term and short term stresses are checked for the relevant load combinations. Local buckling of the glass arch elements is checked by applying an initial imperfection of 10 mm according to the normative instability mode and running a geometrical nonlinear analysis if no shear interaction between glass sheets is assumed. This eccentricity is chosen as a conservative value as an out of plane deviation of over 10 mm is visible and would not be accepted by Octatube (contractor and structural designer).

Out of plane stability of the glass portal frame is increased by connecting the glass portal frame to the adjacent balustrade glass units, as is visible in Figs. 23b and 24b. These vertical edges have each five mechanical connections with bolts through holes in the glass and bent stainless steel elements. To check interaction between deformation of the steel stringers and connections to the glass balustrade and glass portal frame an integral finite element model was made. To cope with the relative deflections of the steel stringers at the

Fig. 24 a–c Images of glass portal frame and centre connection (Octatube). (Color figure online)

position of the connections to the balustrade and at the connections to the portal frame, the balustrade units are executed to stand on the concrete floor with invisible steel footings (and not to be suspended from the balustrade). A connection detail with large holes and low rotational stiffness allows relative vertical deflection between the glass unit and steel beam.

10 Conclusion

Present-day underground museum entrances could be defined as a distinct architectural typology, in which glass structures are playing a major role. Pei's team was ahead of its time designing the glass pyramids of the Louvre. The iconic glass entrance pyramid is a symbol that welcomes a global public. This function of a glass structure being a point of attraction or even an art object in itself, can also be recognised at the Mauritshuis and the Van Gogh Museum. Sometimes, glass is more an intermediary between monumental facades and a new space below ground, as can be seen at the Universalmuseum Joanneum. In every case, the stately nineteenth and twentieth century ascend towards the entrance of a historic museum building is replaced by a modern and theatrical descend.

The Glass Entrance of the Van Gogh Museum has been designed by Kisho Kurokawa Architect & Associates, while Hans van Heeswijk and Octatube developed it further in all its elements, components, connections, its total composition and overall transparency. The completion and its contrast with the Kurokawa Wing is striking and the integrally designed and developed glass and steel structure has its prime enchant-

ment due to its transparency and abstraction. The glass entrance is composed of a load bearing steel structure of CHS beams in the roof and as columns, stiffened by the glass roof. The transparency of the total envelope is even more prominent than its technological composition. At first glance the entrance hall may be composed of known elements and components in a very transparent composition, but a number of innovative engineering glass features characterise the project:

- The form of the building envelope as a mix of different geometries and components, leading to a semi-free-form design with the geometric complications of the constituting components;
- The triple laminated glass fins in the roof span up to 12 m and stiffen the steel CHS beams;
- The glass roof IGU panels stabilise the glass roof fins;
- The glass fins in the facades are stabilised by the post-curved IGU's;
- Connections between glass fins and IGU panels are made by fully siliconised stainless steel RHS profiles.
- The IGU glass panels in the façade are cold-bent by a robotic curving machine before installation;
- The glass stairs is supported and stabilised by a laminated glass portal frame;

The project shows how the structure is effectively designed to create a physical collaboration between glass and steel in many ways, in strong contrast to a mere application of glass as an infill material. Whereas museum architecture often stands out by its 'extravaganza', the geometric glass volume is more an abstract

Fig. 25 **a** Exterior photo (Ronald Tilleman). **b** Interior photo of the staircase (Ronald Tilleman)

shape, refined in its detailing. Architecturally the glass entrance hall constitutes a balance between the historic Rietveld building and the Kurokawa Wing, while providing an state-of-the-art window to the Van Gogh paintings (Fig. 25).

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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