4

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Steel Construction

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Curved directly glazed steel structure

New departure station, E-Line, The Hague

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ZJA Zwarts & Jansma Architects have designed a new light rail departure station in The Hague, The Netherlands. The spatial roof structure of the station is made of rolled steel rectangular hollow sections arranged in two independent layers rigidly connected to each other. A glass envelope covering the roof structure matches the contours of the steel exactly. Since the diamond-shaped glass panes could only be attached to the outer layer of the steel grid, the panes (with edge lengths of approx. 1.30 m) are supported on two sides only. When optimizing the overall geometry, the double-curvature area at the nose of the roof structure became a special focus. Knippers Helbig Advanced Engineering has managed to minimize the deviation of each single glass pane from the single-curvature geometry to a maximum out-of-plane deformation of only 3 mm. Therefore, the project is a great example of how geometry development can influence structural design and enable new approaches.

1 Urban context and architecture of new E-Line departure station (HSE)

The E-Line is part of RandstadRail, a network of light rail systems connecting the cities of The Hague, Zoetermeer and Rotterdam and the region in between. After several studies, new tracks were positioned: one at a height of approx. 15 m above grade over an existing tunnel, one at grade in the street Anna van Buerenstraat and one at the level of the bus platform (see Figs. 1 and 2).

Locating the track and the station at this level made it highly visible and thus placed emphasis on the overall appearance of the combined viaduct and station. The client (essentially the municipality of The Hague and ProRail) asked ZJA to design a station with its own architectural identity oriented towards "Den Haag Centraal Station" and the newly established "Openbaar Vervoer Terminal" (Public Transport Terminal) and related in idiom to the light rail station at Beatrixlaan (designed and detailed by ZJA in the period 1998–2008). At the same time, the design needed to blend in seamlessly with an extremely complex urban context and, programmatically, become a part of the "transition machine" of the Openbaar Vervoer Terminal. The client asked for two light rail platforms and an arrival platform for the bus station.

The overall architectural shape represents the smooth transition from the "flat" viaduct to the spatial station and

Fig. 1. HSE Lightrailstation (ProRail, ZJA – Zwarts & Jansma Architects)

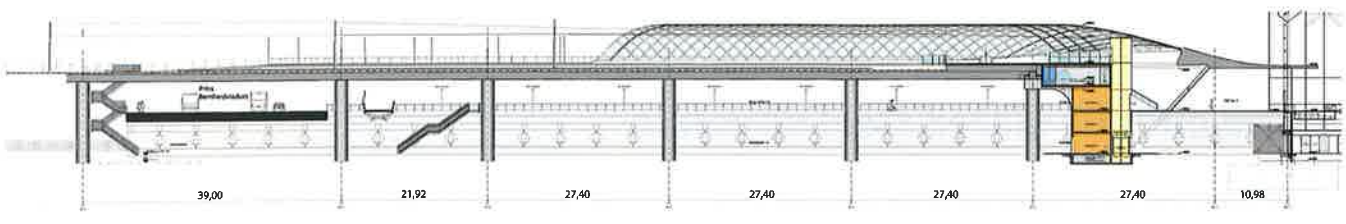

Fig. 2. Longitudinal section (ZJA – Zwarts & Jansma Architects)

Fig. 3. View towards nose of structure (ProRail, ZJA – Zwarts & Jansma Architects)

Fig. 4. View from the outside (ProRail, ZJA – Zwarts & Jansma Architects)

to the canopy that intersects the façade of the Openbaar Vervoer Terminal. The form therefore expresses the station's main function – to provide passengers with a clear, protective and comfortable route towards the Openbaar Vervoer Terminal and the bus platform, while also providing clear sightlines and visibility towards the HSE. Passenger and transportation flow are uniquely captured by a single sculptural gesture (see Fig. 3).

The actual roof has a total length of approx. 90 m and a maximum width (on plan) of 17 m; the first 22 m of the roof length are supported by the canopy, while the remaining 68 m are located on the bridge deck. The maximum height between roof support and roof centre is approx. 6 m. Roof supports are set 14.7 m above the ground, on top of the bridge deck and canopy. The structural members and the glazing create a quadratic pattern. The steel members, arranged in two separate layers, are curved and twisted following the overall shape. Curved glass strips follow the outer steel grid (see Fig. 4).

For the HSE, the aim was to avoid both triangular glass panes (resulting in substantial material waste) and complex welded nodes (expensive, aesthetically unfavourable). Therefore, during the HSE assignment, an experiment began to create a quadratic grid geometry combined with rolled steel members (strips) stacked in two layers. This allowed the nodes to be very simple and – in combination with bent glass – resulted in a single design direction.

2 Geometry

2.1 General

The design selected is the outcome of an intense study at an early project stage in which various options were investigated, including different grid sizes – resulting in different tonnages, numbers of nodes and glass build-ups. Different node types were also studied, using various vertical/horizontal sections – in one plane, in two separate layers, with hinged nodes/rigid nodes.

The geometry of the roof structure was developed considering the architectural requirements, global structural design, glass analysis and fabrication constraints.

The roof geometry consists of a regular/generic part with a constant cross-section and an irregular doubly-curved geometry oriented towards the central station (see Fig. 5).

3 Steel structure

3.1 Structural concept

The spatial roof structure is made of rolled steel rectangular hollow sections placed horizontally and arranged in two independent layers rigidly connected to each other.

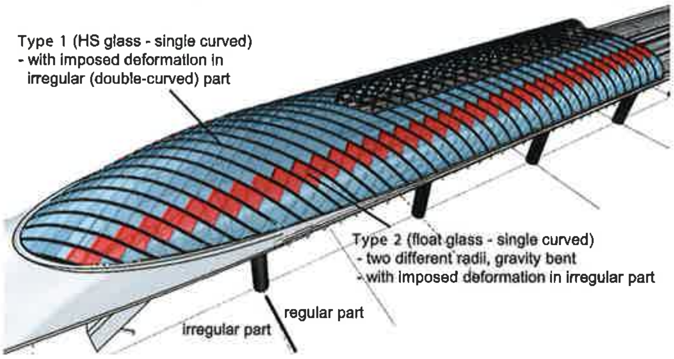

Fig. 5. Roof geometry consisting of irregular (double-curvature) and regular (generic) part, and locations of different glass types (Knippers Helbig)

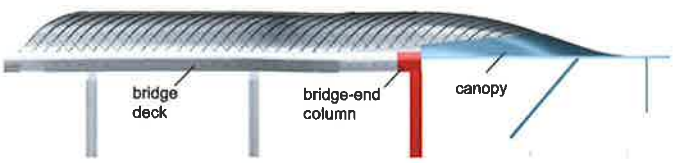

Fig. 6: Roof supported by three different structures (Knippers Helbig)

This diamond-shaped steel grid is supported by a continuous edge beam, which creates a series of stiff triangles along the base.

The roof cross-section is a compromise between the minimum clearance necessary for trains and platforms and the structural elements required to provide arch-like behaviour. The central opening – located at a position where all additional loads are most unfavourable for a shallow arch – helps to reduce the high bending actions and allows for a shallower arch shape. In order to achieve the required amount of lateral stiffness, a stronger edge beam is used along the front edge of the roof ("edge beam at entrance"). Furthermore, although the diagonal orientation of the strips/beams is unfavourable from a structural point of view, this is somewhat compensated for by the fact that the structural depth is increased by the stacking of the two layers.

At the closed end of the roof (towards the central station) the shape provides two-dimensional curvature, which helps to create a shell effect. Owing to this effect, the higher load coming from the fully closed glazing can be transferred to the ground.

The standard grid beams consist of 180 × 100 × 6.3 mm rolled rectangular hollow sections. In order to achieve the required structural performance, some elements required a thicker wall – 8 or 10 mm. All sections are steel grade S355.

3.2 Bearing conditions

One of the most important aspects is the fact that the roof is supported by three different main structures. Fig. 10 broadly outlines the relation between bridge deck, bridge-end column and canopy:

bridge deck supported by a series of cantilevering columns (grey),

bridge-end column with a very high transverse stiffness (red), and

canopy with a relatively low stiffness in the form of a steel framework providing access to the central train station (light blue).

During the design process these three structural parts were analysed by three different engineering companies. However, due to the close cooperation between parties involved (coordinated by the architects), this interface was handled with special care. Stiffness and support reaction forces were exchanged back and forth and discussed regularly.

Differential settlement and stiffness of roof supports were identified as the causes of internal forces and moments in the structural members of the roof. The stiffness and performance behaviour of the different parts of the structure were considered within the structural model by means of springs with certain stiffnesses. Some vertical supports located close to the bridge-end column were released in the vertical direction to allow for the associated differential vertical deformation. One pinned support on each side of the roof transfers longitudinal forces to the main structure, while all other supports slide in the longitudinal direction, allowing for expansion due to differential temperatures. In the transverse direction, all roof supports transfer arc shear.

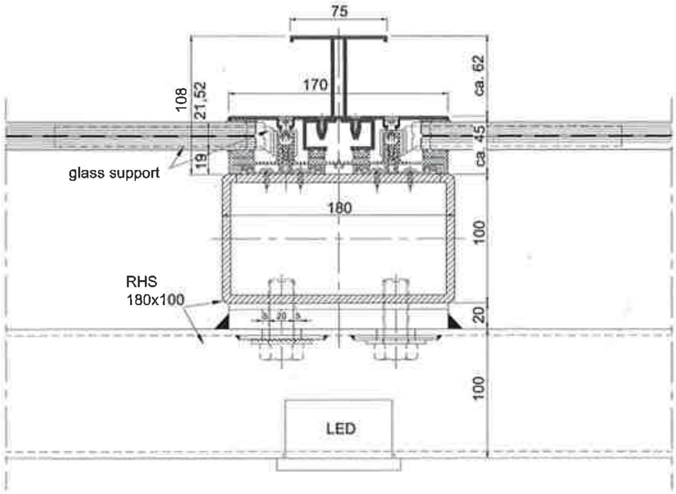

Fig. 7. Section through bolted connection (Knippers Helbig)

3.3 Typical leading details

3.3.1 Grid nodes

The hollow sections positioned horizontally and arranged in two layers have to be connected at the grid nodes; the required conditions have been achieved by using bolted connections with threaded holes, with the bolts being accessed from the inside through a hole. This hole will be used later for the installation of LED lighting elements, audio speakers and for attaching the overhead lines (see Fig. 7). This bolted connection is an important part of the overall concept. The strips were produced and delivered to site separately and could be connected without any site welding.

On the other hand, the torsional stiffness of the bolted joint connection, and therefore the in-plane rotation between outer and inner grid beam layers, has a major influence on the global deformation behaviour of the roof. To accommodate tolerances, the holes in the steel sections are oversized; however, shear forces due to torsional moments must be transferred between both steel sections. To transfer these shear forces, the remaining gaps around the holes in the steel plate are filled with liquid material called "Araldite" after the bolts are tightened (see Fig. 8). A mock-up test was carried out in order to evaluate the range of torsional stiffness provided by this solution.

3.3.2 Edge beam

The roof structure always ends at an edge beam; the sections are connected here with a spigot and bolted connection (see Fig. 9). The edge beam with dimensions of 250 ×

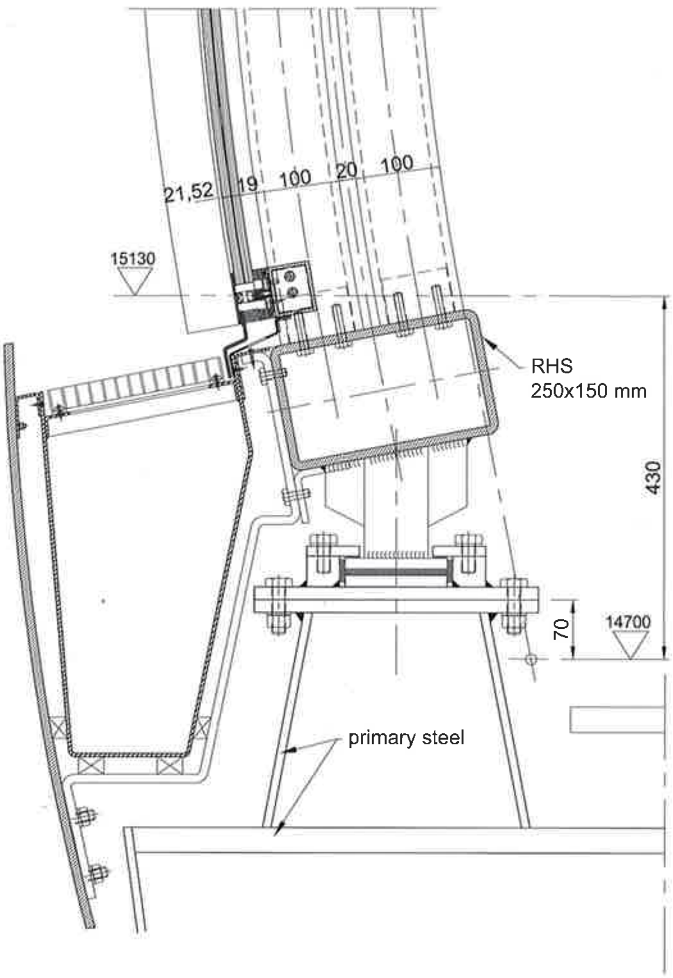

Fig. 9. *Section through edge beam showing typical bearing detail (Knippers Helbig)*

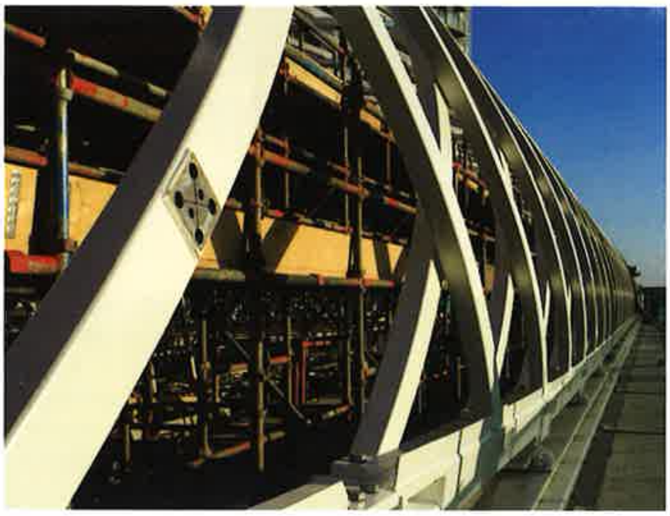

Fig. 8. Preparation for bolted connection prior to assembly (ZJA Zwarts & Jansma Architects))

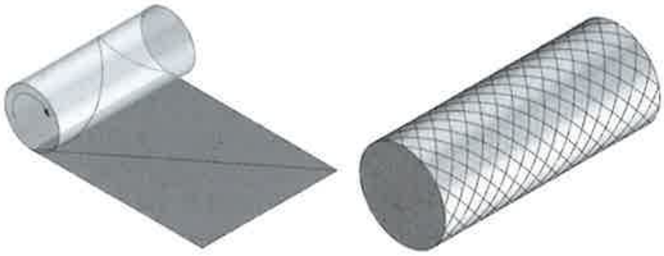

Fig. 10. General principle behind glass and steel geometry (Knippers Helbig)

150 mm is able to move in the longitudinal direction by means of a special horizontal sliding detail.

4 Fabrication

4.1 Form-finding and fabrication constraints

4.1.1 Regular part

The shape of the regular part is the result of various geometrical constraints and parameters. From an architectural standpoint, the clearances for trains, pedestrians, etc. had to be kept free from structural elements. At the same time, multiple constraints resulting from fabrication techniques had to be considered. Notably, state-of-the-art steel bending and glass bending machines can only produce single-curvature elements in economic and automated processes.

With regard to these major fabrication constraints, the concourse cross-section had to be created out of circular segments. The construction lines were defined by geodesics on a cylinder consisting of helices (see Fig. 10). Several options were investigated with three to five circle segments; finally, an option consisting of three circular arc segments – two identical ones located on the outside with a larger tangential one in the middle – was chosen. The tangent vector of the lower circle segments defines the radius of the larger central one. The steel members of each arc segment could be fabricated as a single piece – each steel member had to be joined to the adjacent one on site with hidden head plates and bolts. In order to simplify these bolted field joints and the typical node detail, the changeover between circle segments ("blend-line") is located in the centre between two structural nodes (see Fig. 11).

Various constraints also applied to the rationalization correction of the surface. For economic reasons it was decided to generate the grid with 90° corners only in an unrolled condition (see Fig. 11). Further, the cross-section was only filled with identical glass panes, thus avoiding any odd or irregular pieces; this resulted in a specific number of glass panes, radii and distances between grid-lines.

4.1.2 Irregular part

Similarly to the regular part, the geometry of the irregular/double-curvature part is the result of a form-finding strategy based on a series of technical constraints and multiple geometrical issues.

To achieve an economically reasonable solution, it was necessary to find a double-curvature geometry that could be described by single-curvature glass panes (cylindrical glass). The best results were achieved by a combination of a stretched translational surface and a grid relaxation, which applied a shear force to every group of panel vertexes, constraining them to a corresponding normal plane. This made it possible to generate cylindrical glass panes on top of the resulting mesh.

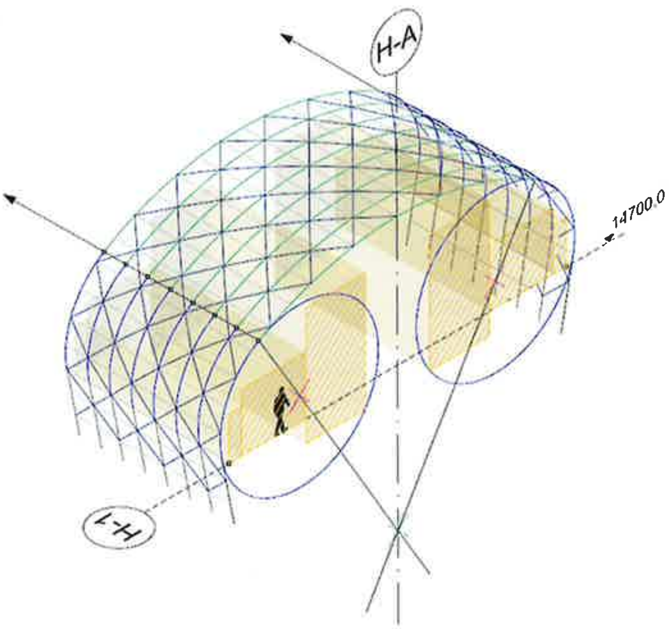

Fig. 11. Generic cross-section with diamond pattern (Knippers Helbig)

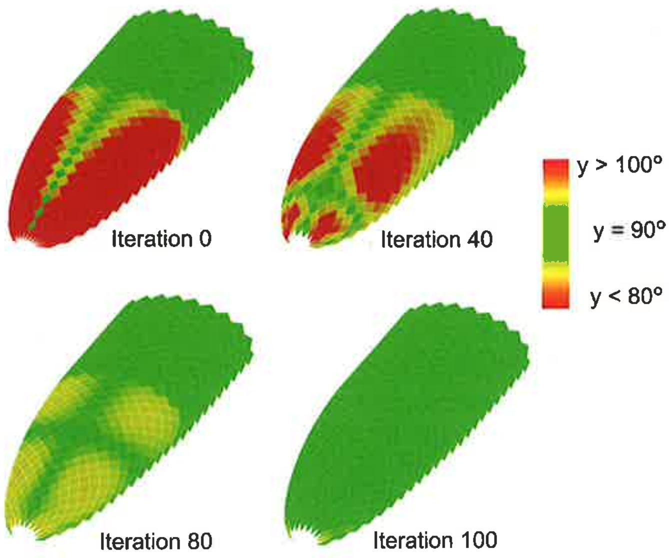

Fig. 12. Angle constraints (Knippers Helbig)

Furthermore, the aim of the grid optimization process in the double-curvature part was to align all the lateral structural members and equalize all angles between them in order to help generate the steel geometry (circular arc segments) below the glass layer (see Fig. 12).

After generating a "perfect" geometry for the glass pattern, the steel grid still had to be generated following the glass joints. This meant generating a series of arc segments with constant curvature, constant twist and tangential changeover between arc segments, minimizing the deviation with respect to the glass grid.

In a last step, the steel and glass geometries were compared using a custom grasshopper tool, resulting in max. 3 mm deviation. This value had to be considered besides other effects in the glass analysis.

4.2 Steel

The target was always to realize an economic structural solution using state-of-the-art steel bending techniques. One major issue was that a constant force being applied to a member during the bending process will lead to a constant curvature or twist (see Fig. 13).

4.3 Glass

Designing with curved glass requires a series of technical considerations in order to define which bending technique is applicable for fabrication; these are predominantly shape, size, strength and coating. For example, automated glass bending can only be used to produce single-curvature glass with a constant bending radius. Other geometries, such as cones, spheres, paraboloids and hyperbolic paraboloids, can all be formed by means of gravity bending (slumping process), but require individual custom moulds to achieve different glass geometries. Heat treatments are typically unavailable with slumped glass, since adding heat after slumping would only undo the original forming. If a design requires slumping for geometrical or optical quality reasons, the glass can only be annealed or chemically treated [1].

Since all glass panes located on the blend line consist of two different radii, automated glass bending processes could only be used for the fabrication of glass type 1, consisting of two 10 mm heat-strengthened plies laminated with an PVB interlayer (see Fig. 5). All other glass panes (type 2) had to be fabricated by means of gravity bending, and so the glass cannot be tempered and a glass build-up consisting of two 10 mm float glass layers laminated with a sentry glass interlayer (SGP) was chosen.

All the parameters for type 2 glazing were similar, no matter whether they were located within the regular or ir-

Fig. 13 Typical bending process (left) and double-curvature steel member by Kersten Europe (right)

regular part of the roof structure. The only difference was the additional imposed deformation due to the double-curvature geometry within the irregular part, which is based on the fact that these glass panes must follow the geometry of the outer members at the nose of the steel structure where the global geometry is double-curvature; they therefore deviate slightly from single curvature. The imposed deformation was applied during installation by pressing one corner of the glass pane into the position required.

A modification to the bending radii was determined during fabrication. Similarly to pre-cambering of steel beams, the idea behind this was to keep the stresses caused by constraint forces below the allowable maximum. Therefore, all panes of glass type 2 – where the allowable stress limits of permanent action and snow load effects are exceeded – are therefore the subject of a geometry modification [5].

Credits

- Principal: Municipality of The Hague, The Netherlands
- Client during design stages: ProRail
- Client during execution stages (engineering and construction): BAM Infraconsult BV
- Architects: ZJA Zwarts & Jansma Architects, Amsterdam, The Netherlands
- Design Development and Geometry Optimization of roof structure: Knippers Helbig GmbH, Stuttgart, Germany; ZJA Zwarts & Jansma Architects, Amsterdam, The Netherlands
- Structural design of roof structure and glass design: Knippers Helbig GmbH, Stuttgart, Germany
- Main contractor: BAM Infra Nederland, The Netherlands (part of the Royal BAM Group)
- Design, fabrication and erection of roof structure and glazing: Jos van den Bersselaar Constructie B.V., Brakel Atmos, The Netherlands
- Glass supplier: IFS-SGT, The Netherlands
- Official opening: 22 August 2016

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Keywords: curved steel structure; geometry optimization; doubly-curved; double curvature; bent glazing

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News

New website launch "Construction Histories Brussels"

An interdisciplinary team of researchers from the Université Libre de Bruxelles (ULB) and Vrije Universiteit Brussels (VUB) combines expertise on construction history. Current projects and new events are presented to a wider public on their new website "Construction Histories Brussels": www.constructionhistory.eu.

Following the links on the start page, information is available about e.g.

- Mission statement
- The participating teams
- The participating people and their publications
- Current research projects