Cold-bent laminated glass and steel canopy for a bus station next to Amsterdam Central Station

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Summary

Construction of a new bus station has started on the waterfront behind Amsterdam Central Station. The finished canopy will be 360 m long and 63 m wide, and consists of steel arches. The arches are interconnected by purlins and covered mainly with a new material: cold-bent laminated glass panes. Cold-bent glass makes it possible to build a roof of this size to a limited budget. Not only is the glass itself cheaper than some other materials, but bent glass panes can be thinner, reducing dead weight. Furthermore, cold-bent glass can follow any deformation in the structure easily and the joints between the long, bent (unfacetted) glass-carrying profiles are simple. The glass detailing also ensures safety in the event of a fire. This paper presents the advantages of cold-bent laminated glass over traditional glass and plastics, and demonstrates that cold-bent laminated glass makes it possible to build a very elegant station canopy at an affordable price.

Keywords: Cold-bent laminated glass; daylight; glass; public transport; public quality; roof; station; steel; structural design; canopy.

1. Introduction

Amsterdam city council has commissioned a canopy for IJsei bus station, on the Amsterdam waterfront behind Amsterdam Central Station (Fig. 1). Work has already started on the canopy, most of which is transparent, and three-quarters of the length is complete (Fig. 3). The finished canopy will be a 360 m long, 63 m wide steel structure supporting cold-bent laminated glass panes (Fig. 2).

Fig. 1 Aerial photo of Amsterdam Central Station before construction of the bus station.

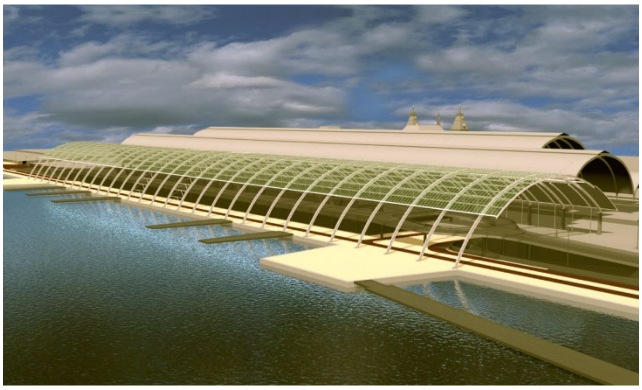

Fig. 2 Artist's impression of the canopy.

Fig. 3 Aerial photo of Amsterdam Central Station, taken on 11 October 2011.

But how do you build an impressive-looking canopy for around half the usual cost? That was the challenge the designers faced. Reducing the costs was primarily an engineering task, while preserving the aesthetics was the remit of the architect. Both aims were achieved, thanks to close cooperation between all those involved in the design process.

2. Reducing costs through structural design

2.1 Integrated approach

Right from the outset, it was clear that even with extremely advanced construction technology, it was not going to be possible to achieve the desired savings entirely from the canopy. An integrated approach to the project was therefore taken, to identify structural elements that were being built in any case and could yield large savings if minor modifications were undertaken.

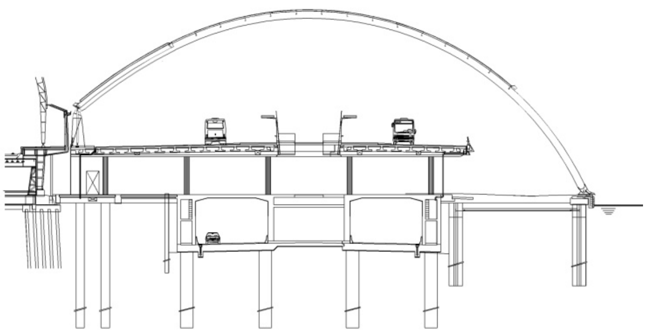

Fig. 4 Cross-section through the canopy, showing the right-hand side of the arch structure supported on the cofferdam.

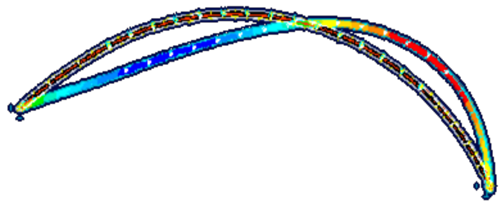

Fig. 5 Designing the canopy in the form of an arch effectively halves the span that determines the characteristic bending moments.

The decision was therefore taken to depart from the original plan and to design the canopy in the form of an arch, with the arches supported on the new cofferdam that was to form the quay (Fig. 4). This would both eliminate the need to build a separate foundation and allow an arch design to be used. Building the canopy as an arch effectively halves the span for the characteristic bending moments, which yields major cost savings (Fig. 5). Normally, one pays a high price for such savings, as the foundations must then be capable of resisting the large lateral thrust. In this case, however, the cofferdam was already designed to resist the much larger horizontal force of the sand pushing in the direction of the river IJ (the expanse of water behind the station), so the canopy foundations on this side were effectively “free”.

While the same situation did not apply as regards support for the opposite side of the canopy, it was possible for the lateral thrust of the arch to be transferred via cantilevered columns to the bus platform and the diaphragm structure that provides stability to the platform. This brought the horizontal force down to ground level, but did not actually transfer it into the soil. As a new concrete slab was to be poured at surface level, running from the stabilizing diaphragm to the newly constructed De Ruijter Tunnel, it was a simple matter to anchor the horizontal forces to the tunnel via the slab, allowing them to be resisted by passive ground pressure. Once again, this was a virtually “free” solution.

2.2 Structure

The IJsei canopy is approximately 360 m long. It consists of steel arches with a radius of 36 m, made up of composite 170 x 900 mm tubes. The arches are spaced 12.50 m on centres, to match the adjacent railway station canopy dating from 1925. The arches are joined by purlins (Figs 6 and 7). These purlins (made of UPE330 profiles and spaced 3.10 m on centres) support a largely transparent skin consisting of cold-bent glass panes, spaced 1.14 m on centres and fixed to curved IPE140A beams (Fig. 8). The longitudinal stability of the canopy is ensured by two wind braces, one either side of the mid-point. The arches (approx. 22 m high, with a span of approx. 63 m) provide their own lateral stability.

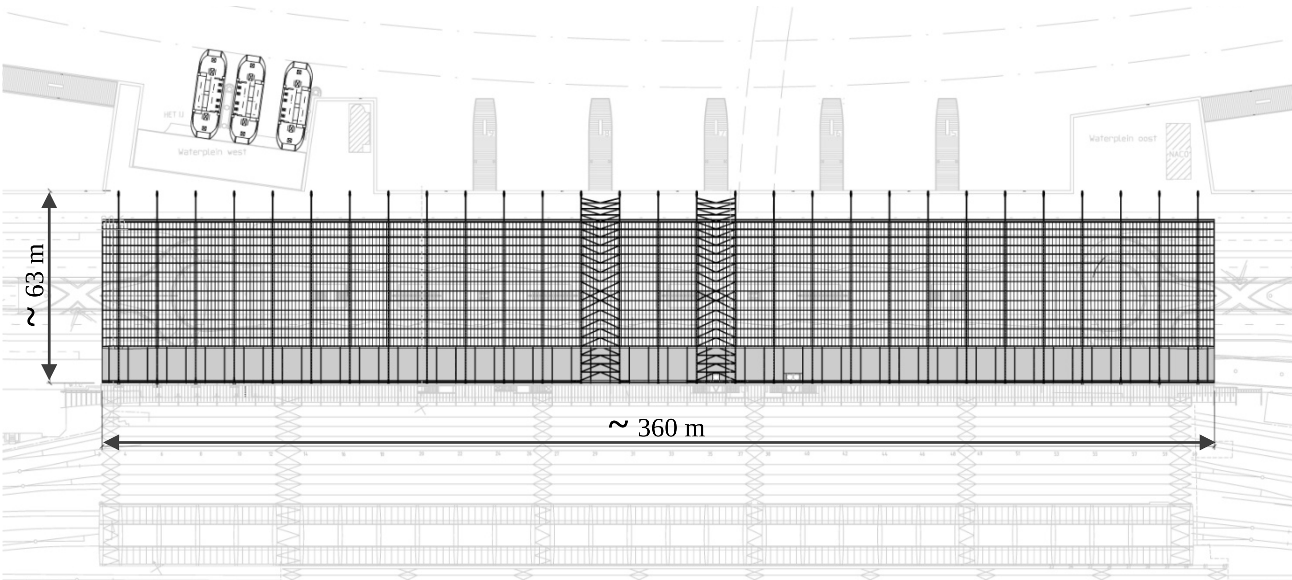

Fig. 6 Plan view

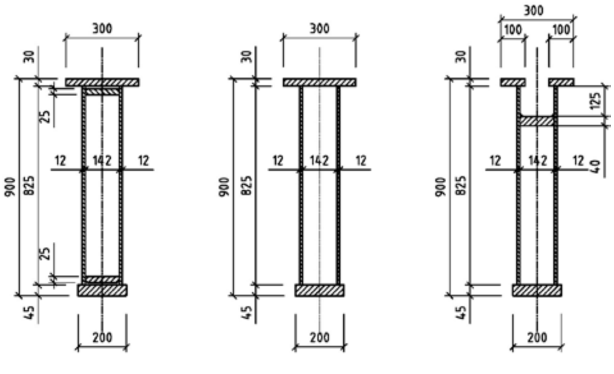

Fig. 7 The three characteristic cross-sections through the arches

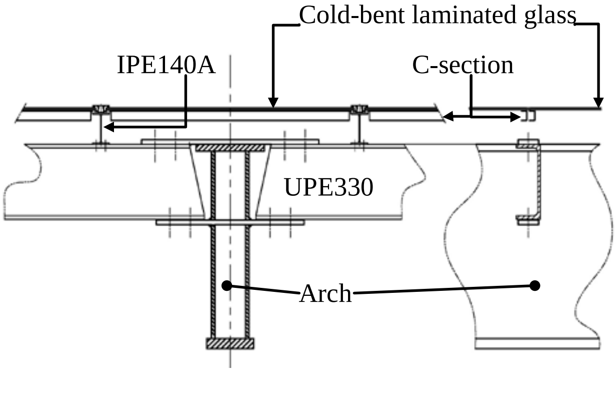

Fig. 8 The principle of the supporting structure.

The structural design aimed to limit the number of components and to make repeated use of the same components. It was also decided to use as many open profiles as possible, to simplify the connections that would have to be made on site. IPE(A) profiles were therefore selected for the beams supporting the glass panels and UPE profiles for the purlins, and even the tubular cross-section of the arches was so designed that the upper flanges were on the outside, so that the contractor could use bolts to secure the purlins. Ultimately, however, the contractor decided to weld the strips joining the purlins onto the arches rather than use bolts.

2.3 Cold-bent laminated glass

Major cost savings were achieved by using a type of laminated glass than can be bent cold [1], [2]. This type of glass is delivered flat to the site, where it is bent to match the shape of the curved supporting structure and fixed into place.

Cold-bent laminated glass both enhances sustainability and reduces costs. For one thing, it uses approximately half as much material as does hot-bent glass. For instance, a project in Den Bosch in 1997 required two sheets of 8 mm glass separated by 3 mm of artificial resin if hot-bent laminated glass were used. With cold-bent glass, two 4 mm sheets of glass separated by 1.4 mm of plastic were sufficient.

In order to bend a hot-bent glass pane, it must be heated almost to melting point while being bent over a form. Cold-bent glass requires no heating and no form, thus saving large quantities of energy. Furthermore, delivering flat panes to site is simpler and cheaper – a truck can carry more flat panes than curved. The extra energy required for installation is minimal and can safely be ignored.

Cold-bent laminated glass is also preferable to the plastics sometimes used as substitutes for bent glass. Glass is made primarily from sand, lime and soda, which are all available in large quantities, whereas plastics are petroleum products, with all the associated disadvantages. In addition, plastics become electrically charged, causing them to attract dirt. They also scratch more easily than glass and are less resistant to ultraviolet light. Glass does not suffer these maintenance problems.

However, it is in the supporting structure that the greatest savings can be achieved. There is less weight to support when using cold-bent glass and the structure can be less rigid – cold-bendable glass will simply deform with the structure. As a result, the supporting structure can be made far lighter. This reduces the amount of material required, further enhancing the sustainability of the structure. Assembly tolerances are also less tight; because the glass is bent to match the structure, it always fits, even if the radius deviates from that specified.

Fig. 9 Coloured plastic film inserted into some of the cold-bent glass panels will form the word AMSTERDAM once the canopy is complete.

Furthermore, the beams supporting the glass are considerably less expensive if the structure does not consist of multiple facets, as the beams are roller bent and much longer, which means there are fewer components to be installed. In addition, the connections required at each angle in case of facetted glass are eliminated.

In the project described here, coloured plastic film was inserted into some of the cold-bent glass panels to spell out the word AMSTERDAM (Figs 3 and 9).

2.4 Stability of canopy with no expansion joints

Ensuring stability is the very basis of structural design. Stability in the lateral direction is provided by the arches. These form the main supporting structure for the vertical load on the canopy. Because of their form, they are also able to resolve the horizontal load down to the foundation. Longitudinal stability is provided by wind braces. The number and positions of the braces are determined by the expansion design, the need for redundancy in case of an emergency and the wishes of the architect.

Technically, one single brace would be sufficient to stabilize the canopy. However, if that brace were to fail due to an emergency, such as a fire, the whole canopy would fail. At least two braces are therefore required, spaced sufficiently far apart. The section of the canopy that lies between them is enclosed horizontally, which means that changes in temperature will generate internal forces. The optimum spacing between the braces was found to be 37.5 m on centres. The braces are two purlin spans apart, which is close enough to avoid excessively high forces because of restricted expansion. At the same time, this distance is sufficiently large to prevent both braces failing as a result of a bus fire, for instance, as the area affected by a bus fire will always be less than 37.5 m across. The braces are sited either side of the mid-point of the canopy, leaving it free to expand and contract in the direction of the two ends (Fig. 6)

In order to allow the canopy to expand freely, the last 15 m of the arch structure on each side are separate from the stiff skin of the canopy (Fig. 10). On the side nearest the IJ, the structure is entirely open from the gutter downwards, whereas on the station side this part of the arch is roofed over. Unlike the rest of the canopy, this section is not transparent and consists of roofing panels. It is only fixed to the arches on one side, with the other side supported on hinged columns. The arches pass underneath the roofing, but are not connected to it (Fig. 11), allowing the arch and the roofing to deform independently of each other.

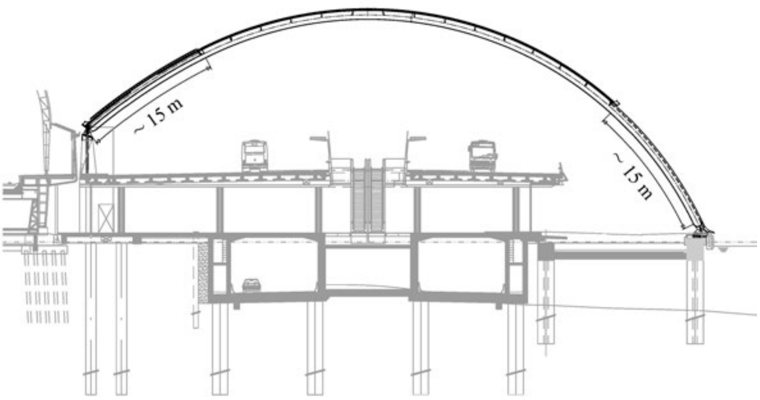

Fig. 10 The outer 15 m of the arch on both sides is free to deform.

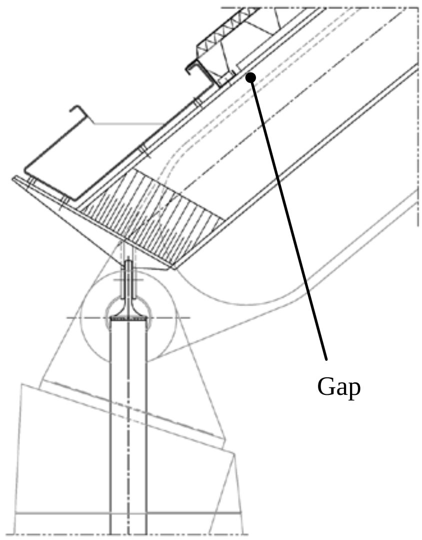

Fig. 11 The closed roofing section is independent of the arch.

The arches exhibit relatively little stiffness around their weaker axis. This low stiffness, in combination with the 15 m gap on both sides, ensures that the canopy can expand as far as it needs to without generating excessively high internal forces. The roof surface expands by a maximum of plus/minus 10 cm on each side (approximately) and does cause the arches to bend, but the low stiffness ensures that bending moments remain within acceptable limits.

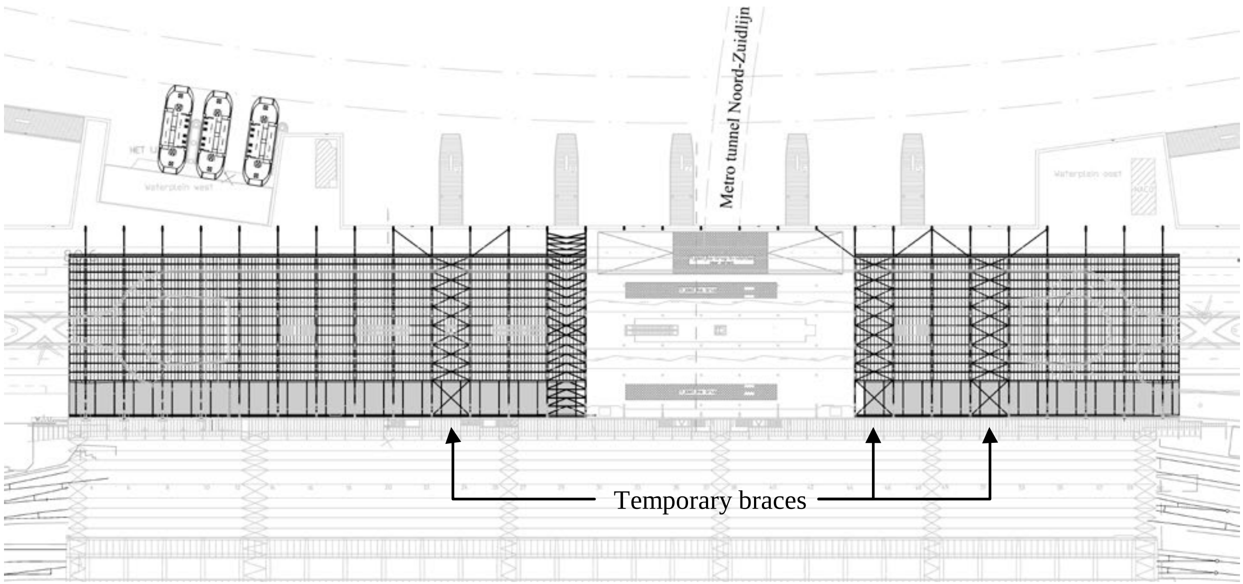

Fig. 12 Situation during Phase I. Plan view.

A north-south metro line (the Noord-Zuidlijn) is under construction, and will run through Amsterdam Central Station. Because of this, the IJsei canopy is being built in two phases. Phase I comprises construction of the eastern and western ends of the canopy, while the central section, above the metro line, will be built in 2014 during Phase II. Dividing construction into two phases has consequences for the longitudinal stability of the canopy; one of the two braces that will provide stability when the canopy is finished will be absent until Phase II, and one section of the roof has no permanent bracing at all in Phase I. Three temporary braces were therefore added during Phase I (Fig. 12).

3. Loads and emergencies

3.1 Loads

The canopy is designed for the usual loads, such as dead weight, snow and wind. The design also takes account of loads due to emergencies, such as fire and impacts from road vehicles or shipping.

3.2 Impacts from road vehicles

When the canopy is in service, the area around the supports will only be used by cyclists and pedestrians. No motor vehicles are supposed to be on the quayside, e.g. to make deliveries or to deposit passengers, as there are designated areas for these purposes elsewhere.

Nevertheless, there is a risk of an arch on the quayside being struck by a maintenance or emergency vehicle.

As emergency vehicles will only be present in the case of an emergency, we shall ignore this eventuality. Maintenance services, however, will often be present on the quayside.

The highest load that could occur is that caused by a fully-loaded street sweeper weighing 12 t and moving at 5 km/h striking an arch. The risk of an arch being struck at a higher speed is small, as the street sweeper only approaches the arches during the actual cleaning process, during which it is moving at less than 5 km/h. When moving (at higher speeds) to or from the areas to be cleaned, these vehicles use the cycle path, which is approximately 4.5 m from the area in which it would be possible to hit an arch.

During the construction phase, and while the incomplete canopy is in use, road traffic will be diverted from De Ruijterkade over the cofferdam that forms the quay, as the road tunnel will not yet be finished. Vehicles will pass relatively close to the arch supports, so structures will be in place to protect them against impact. The design calculations do not provide for impacts other than the street sweeper impact mentioned above.

3.3 Impacts from shipping

In designing the arches and their supports, it was assumed that no direct impacts with shipping could occur. While an indirect impact could occur if a vessel were to hit the cofferdam, the resulting displacement and impact loads would be so small as to have no harmful effect on the canopy structure itself, but could cause glass panels to break.

If a vessel were to hit the cofferdam, it would cause the support to move and would generate an impact load on the canopy. The response of the structure to this impact load was determined by means of dynamic analysis, and an experimental study was then undertaken to establish whether the glass panels and fixings would be capable of resisting the load. The conclusion was that the canopy would be able to resist such an impact, as the impact load would be relatively small, and the glass is relatively free to move in its support.

3.4 Fire

A comprehensive article on the effects of fire on this canopy has already appeared in SEI [3].

3.4.1 Fire safety requirements

The fire brigade formulated specific requirements for this structure. In addition to the normal 30-minute fire resistance requirement, no debris may fall into the area below the canopy during the first 30 minutes of the fire. It was also the fire brigade that stipulated the type of fire to be considered: the fuel tanks of two buses ignite at the same time and in the same place, both tanks are full and the buses provide no protection against the effects of the fire. Clearly, this would constitute an “extreme event”.

3.4.2 Analysis of glass fracture during fire

To meet the fire brigade requirements, the fire behaviour of cold-bent laminated glass was subjected to a thorough analysis.

This analysis revealed there to be three main causes of fracture. Firstly, the temperature is lower at the edge of the pane than in the centre, as the structure shields the edges against the heat of the fire. This leads to tensile stress at the edge of the pane. Secondly, the temperature gradient through the pane makes it try to bend. If it cannot do so, tensile bending stresses are generated in it. The third possible cause of fracture is the expansion of a nickel sulphide inclusion.

It is important to note that the maximum temperature in the glass is too low for any degradation in the characteristics of the glass to cause fracture on its own. What does happen at these temperatures is that the pane loses cohesion: the plastic film softens, and is no longer capable of keeping the two sheets together. In order to meet the glass retention criteria, it is therefore necessary to prevent the glass in the lower sheet from fracturing.

3.4.3 Detailing the glass system to achieve the required behaviour in case of fire

The width of glass enclosed in the frame was so optimized as to minimize the difference in rate of temperature increase between the glass in the frame and the glass in the rest of the pane, and hence to minimize tensile stresses at the edges of the pane. To ensure that the panes always overlap the supporting surface sufficiently, the stainless steel C-sections to which they are glued project beyond the edges of the panes (Fig. 13). This prevents the glass itself from being pressed against the aluminium section, and hence sliding so far in one direction that the opposite edge of the pane could slip off its support, allowing the pane to fall. Furthermore, the glass is mounted on heat-conducting rubber, reducing temperature differences still further. The rubber was rendered heat-conducting by adding aluminium powder to it, which reduced its insulating properties considerably.

Tensile bending stresses due to restricted bending are minimized by giving the glass sufficient freedom of movement. The aluminium retaining strips are mainly secured to the IPE(A) sections using stainless steel bolts with nylon blocks. These are so dimensioned that they soften as they are heated by the fire, allowing the panes to loosen before restricted bending can cause them to fail. The middle two bolts are fitted without nylon blocks, so that the panes do not become completely loosened during a fire, which could allow them to fall out after all.

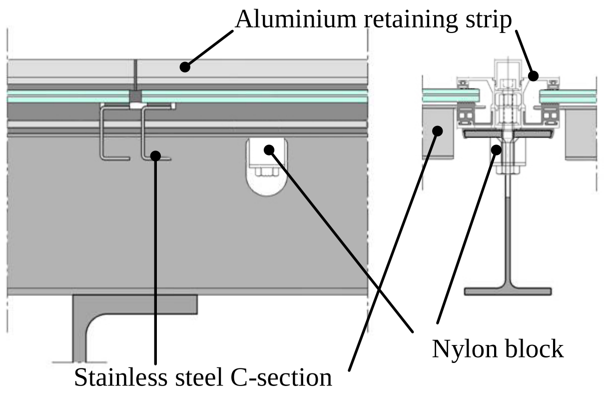

Fig. 13 Glass mounting detail with nylon blocks

Fig. 14 Fire test: situation after 20 minutes

3.4.4 Verification by means of fire tests

Full-scale fire tests (Fig. 14) demonstrated the ability of the design to retain the glass under the conditions specified [4]. The results of the tests clearly show that the detailing is effective. The nylon blocks prevent the glass from fracturing by softening and then melting, allowing the pane to bend.

4. Conclusion

An integrated approach and the use of a new material – cold-bent laminated glass – made it possible to achieve huge savings in the construction of this very large canopy.

Not only is the glass itself cheaper than some other materials, but bent glass panes can be thinner, reducing dead weight. Furthermore, cold-bent glass can follow any deformation in the structure easily, making it possible to design an even more slender structure. The joints between the long, bent (unfacetted) glass-carrying profiles are simple. Cold-bent laminated glass has advantages over flat glass and plastics and the glass detailing also ensures safety in the event of a fire. Cold-bent laminated glass therefore makes it possible to build a very elegant station canopy at an affordable price.

5. References

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Figure 1	Aeroview, Dick Sellenraad
Figure 3	DIVV
Figure 9	Tom de Vries
Figures 2, 4-8,-13	Movares
Figure 14	Centre for Fire Research TNO