

# Fire Resistant Roof Glazing Design

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## Summary

A large, mostly transparent roof had to be built over the bus station at Amsterdam Central station (Fig. 1 and 2). Due to several tunnel disasters, the fire brigade required that if two buses with full fuel tanks were to ignite simultaneously, no glass should fall into the area below during the first 30 minutes of the ensuing fire. This new requirement had to be met without a significant increase in cost and a special glass system had to be developed. Following a theoretical study of glass subjected to fire, specific design criteria were established. Fire tests then demonstrated the ability of the design method of glass to meet the requirements without a significant increase in cost.

## Introduction

A new design requirement for the bus station roof was added in the middle of the design phase. As less time was available for extensive research, a practical solution was developed with the use of cold bendable laminated glass already selected for the roof. The chosen method is an analysis of the fire behaviour of the glass and identification of possible causes of fracture. Taking the above as a basis, the glass system had to be detailed such that it could meet the 30 minutes requirement. Full-scale fire tests should validate the effectiveness of the performance-based design of the glass system developed, and hence the provision of the safety level demanded.

## Bus Station Roof

### Bus Station

The roof, which covers a bus platform, is a part of Amsterdam's IJ river project. Amsterdam Central is one of the largest public transport interchanges in the Netherlands. The platform will be located between the river IJ and the existing railway station. The roof will cover the entire platform, thus provid-

ing passengers' comfort and giving the bus station an image appropriate to the new, contemporary, water-oriented Amsterdam Central.

### Steel Structure

The bus roof is 360 m long and consists of steel arches, each with a span of over 60 m, spaced 12,5 m on centre. At the river, the arches rest on the edge of the quay, while the opposite supports are on the bus platform. The arches are linked by steel purlins, to which the roofing is fixed. Most of the roof is transparent and uses cold bendable laminated glass.

### Glass System

A laminated glass system is used, in which the panes are cold-formed on site using a patented process [1], [2]. The use of cold bendable laminated glass makes it possible to use curved supporting structures throughout.

This avoids segmenting the supporting structures, by minimizing the number of connectors and hence reducing costs. In addition, cold bendable laminated glass is less expensive than hot bendable. Because of these savings, the roof is only around 50% of expected costs.

The panes consist of a 5 mm tempered sheet below, with a 4 mm heat-strengthened sheet on top. A plastic film joins the two sheets. The lower sheet is toughened so that it is possible to walk on the glass. Each pane is 3,1 m long and 1,1 m wide. The long sides of each pane are secured to a continuous rolled I-section using an aluminium retaining strip. Stainless steel C-sections are glued to the short edges of the panes in the factory. This allows the glass to be supported on four sides, without the need to fit separate components during construction.

## Fire Safety Requirement

### Fire Brigade Requirements

Naturally, the structure meets normal fire safety requirements. The future public transport interchange, of which the bus station with its roof forms a part, is so complex on account of its size and its links with other parts of the project that normal fire safety specifications would not be sufficient. The fire brigade therefore formulated specific requirements. These set out the acceptable conditions on the bus plat-



Peer-reviewed by international experts and accepted for publication by SEI Editorial Board

Paper received: XXX  
Paper accepted: XXX



Fig. 1: Aerial photo of Amsterdam Central station as it is without the bus station roof (Photographer: Dick Sellenraad)

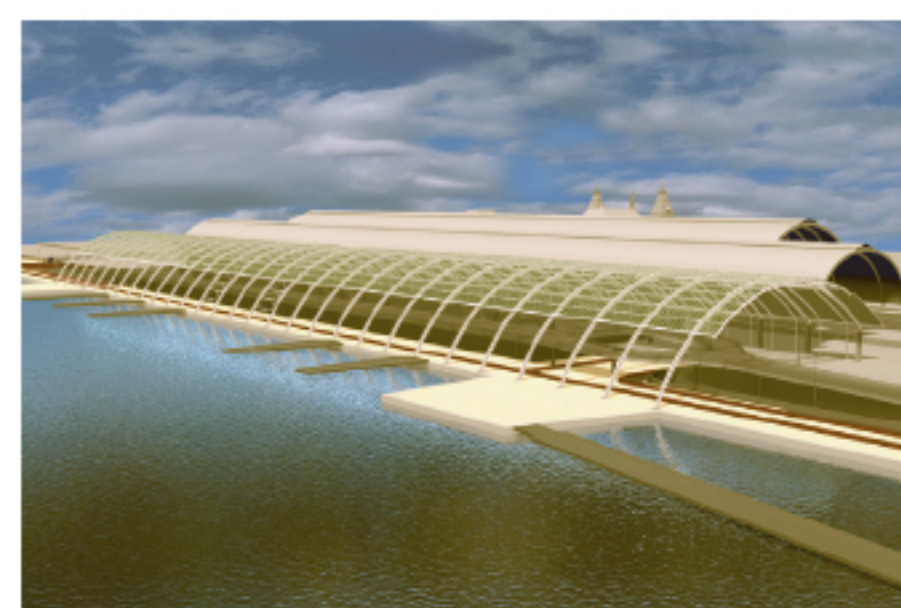


Fig. 2: Artist's impression of the bus station roof

form during a fire on the one hand, and the fire resistance of the structure and its ability to prevent glass from falling down into the area below on the other. These requirements are intended to ensure that passengers can escape and that fire fighting and rescue operations can be carried out safely.

### Type of Fire

The fire brigade specified 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, the combat of the fire being neglected. All involved parties, including the fire brigade, consider this a very exceptional event.

A Computational Fluid Dynamics (CFD) model, validated with metro and bus fire experiments, was used to determine the air temperature during the specified fire. The maximum fire load was assumed to be 70 MW, with a fast fire growth with unlimited oxygen supply and a peak level during five minutes of 35 MW. The local fire load per square meter bus surface can reach 2 MW/m<sup>2</sup>. Thus the fire was assumed to cover an area up to 14 m long and 2,5 m wide. This is smaller than the size of two buses. During this short but intense fire, flames would reach a height of 10 m. The roof design takes this scenario into account by ensuring that the glazing is above the 10 m level at all points (Fig. 3). This keeps the glass out of direct contact with the flames. The results were converted into a curve of the air temperature immediately under the glass, which was used to derive the heat load on the glass system. The fire would generate a maximum temperature of approximately 500°C

immediately under the glass and over the fire. That temperature would be reached after 15 minutes, at which point the fire would be most intense (Fig. 4). After 20 minutes, once the fuel tanks would have burnt out, the temperature would drop to 20°C in five minutes [3]. Where direct contact with the flames could occur, the much higher fire load of the standard ISO834 fire curve is taken into account. This is, a somewhat larger part of the structure than the part under 10 m height as indicated in Fig. 3, due to deflection of the flames along the structure, but the flames do not reach the glazing.

### Conditions under the Roof during a Fire

Both radiant heat and smoke density must be restricted while passengers are being evacuated. Excessive radiant heat would cause burns, while excessive smoke would cause smoke poisoning and impede evacuation. Computer simulation has shown that the bus station can be evacuated within 11 minutes [4]. This assumes that there is a bus at each bus stop, the buses are 75% full and have same number of people waiting on the bus platform. The evacuation time lies just below the limits specified. After 11 minutes, the smoke density could quickly become too high if the wind direction were unfavourable.

### Fire Resistance and Retention of Glass during Fire

The fire brigade demanded that the roof should be fire resistant for a period of 30 minutes. There are two aspects to this. Firstly, the structure must retain its structural integrity for a specified length of time, and secondly the fire

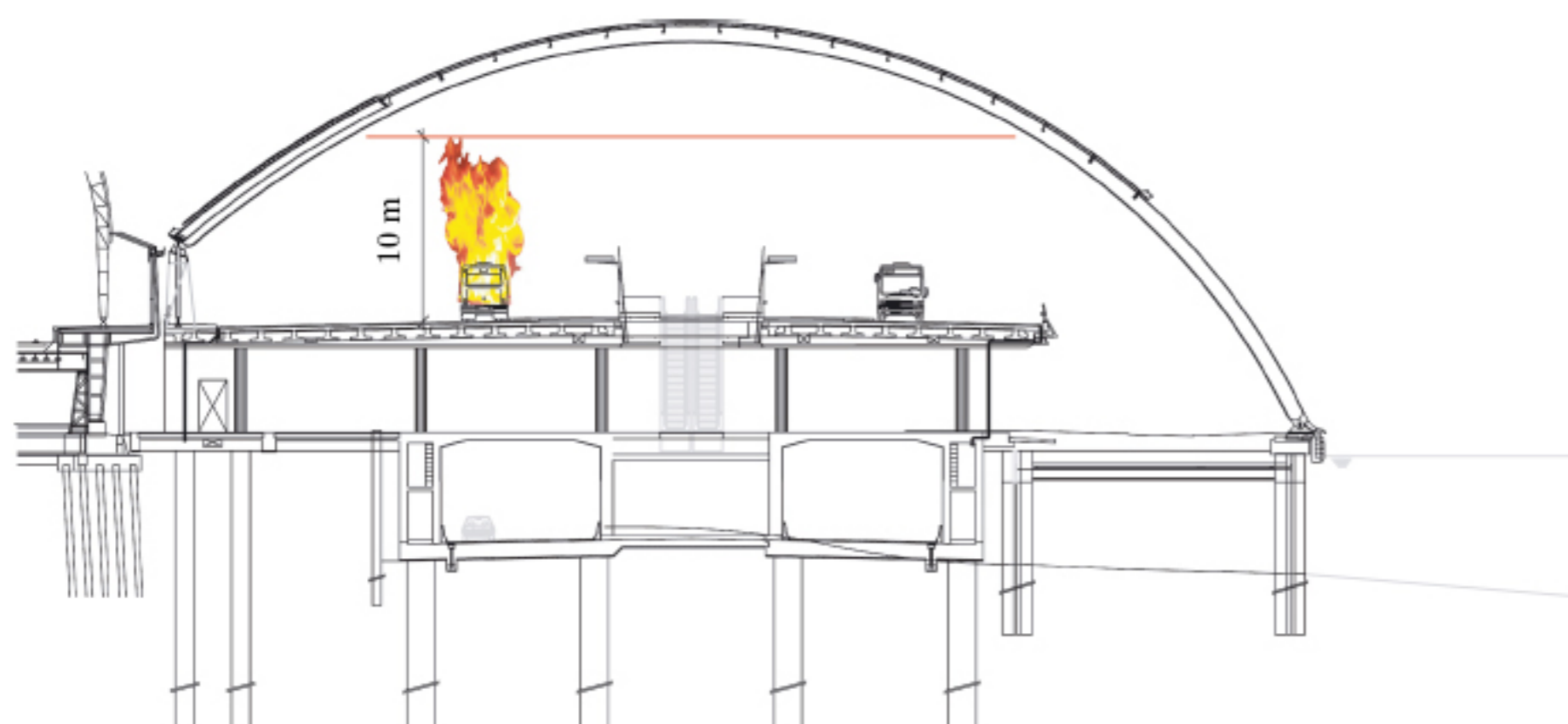


Fig. 3: Cross section through roof showing 10 m level (i.e. maximum height of flames)

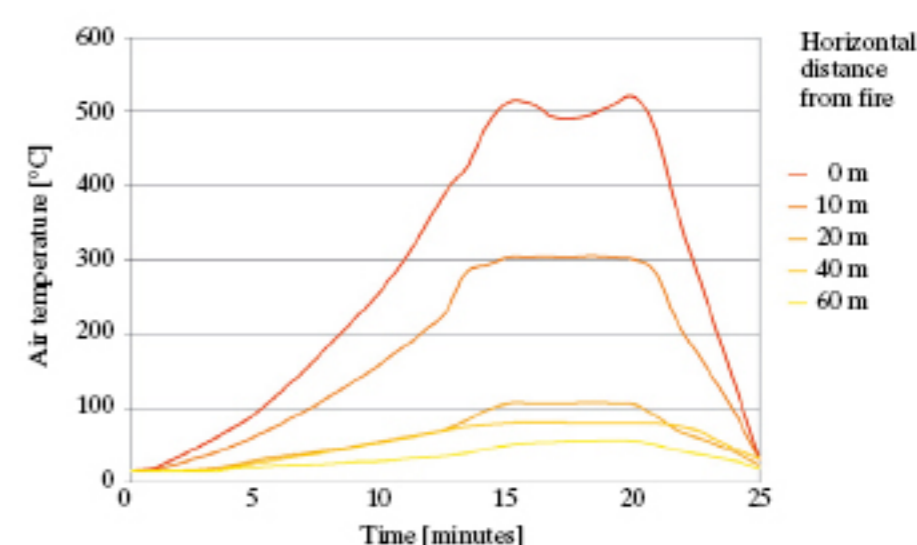


Fig. 4: Curve of air temperature immediately under the glass during a bus fire [3]

must not spread or break through to adjacent areas or escape routes for a specified length of time. For the transparent part of the roof, the fire spread and breakthrough requirements are irrelevant, as there are no areas adjacent to it. Structural integrity requirement is of relevance, in this case. Therefore, it has been designed such that only local damage will occur, thus ensuring limited interruption of traffic in a relatively small area and for a short period of time. It is important, however, that no pieces of the structure or the roofing fall down during evacuation or fire fighting. Hence, apart from a glass system providing 30 minutes fire resistance, the roof should also be able to retain its structural integrity during those crucial 30 minutes.

The issue of fire resistance mainly affects the steel structure, whereas the requirement that nothing falls down places stringent demands on the glass system.

### Resistance of the Steel Structure to Fire

#### Steel Arches

To ensure that the roof (Fig. 5), which has no expansion joints, can expand longitudinally, the lower 15 m of the arch must be able to deflect out of its plane. This means that it must not be braced laterally. The relatively long unbraced segment of the arch has a decisive affect on its fire behaviour. The upper parts of the arches are braced by the purlins between them, which are spaced 3,1 m on centre. Finite element method calculations were used to assess the stability of the arches with degraded material characteristics due to temperature increase, demonstrating that they had a fire resistance of 30 minutes.

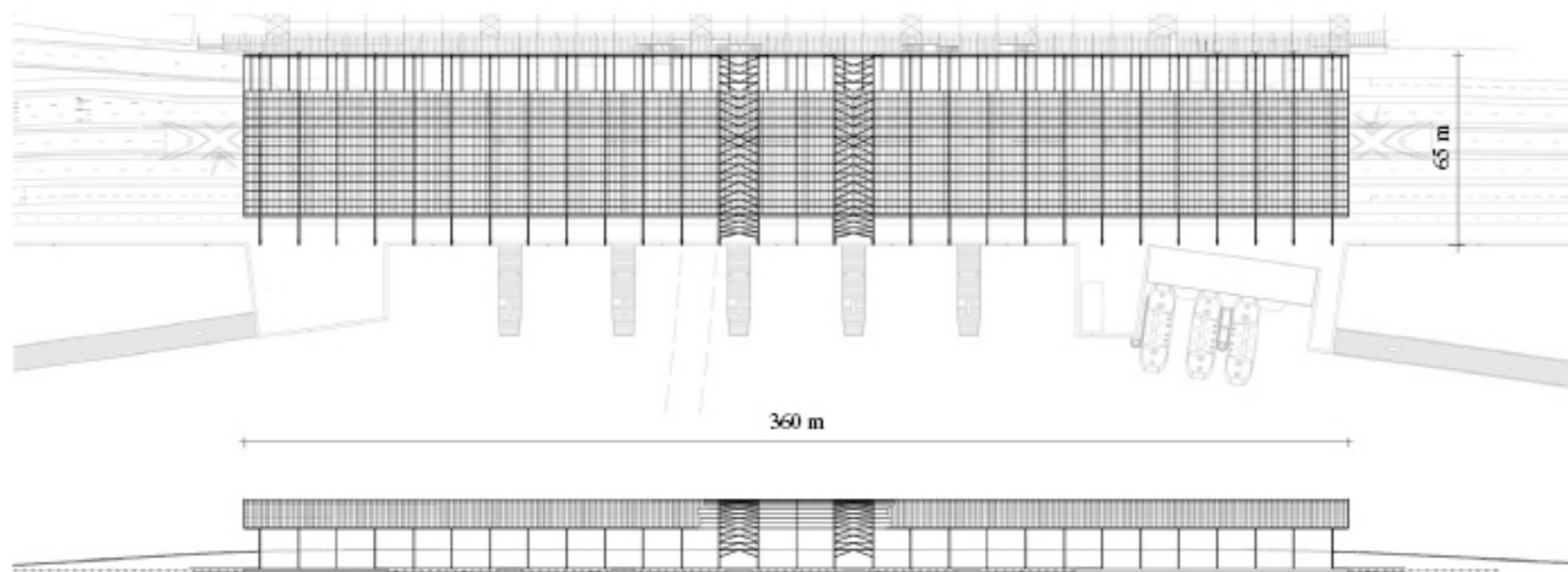


Fig. 5: Top and front view of the roof

### Braces

In order to build the roof with no dilatation joints along its entire length, the bracing that ensures longitudinal stability must be placed at the midpoint. Placing the fixed point halfway along the roof leaves it free to expand longitudinally from the centre as the temperature rises. To maintain stability during a bus fire, two braces are needed for redundancy. They have to be located as close to each other as possible, to avoid excessive temperature-induced stresses between them. However, to take account of the largest dimension of the fire surface area (14 m) they have been placed two arches apart, that is 25 m. This means that no more than one brace can collapse during the specified type of fire. The other brace is sufficiently strong to maintain the stability of the entire roof on its own.

### Purlins

The purlins will expand as the structure near the fire heats up. For the purlins between the bracing and the ends of the roof this is not a problem, as the arches offer relatively little lateral resistance to displacements. However, the purlins between the braces (Fig. 6) are restrained, which means that they will be subjected to high compressive forces. The connections between these purlins and the arches have therefore been designed in such a way that the purlins may expand prior to buckling due to restraining forces.

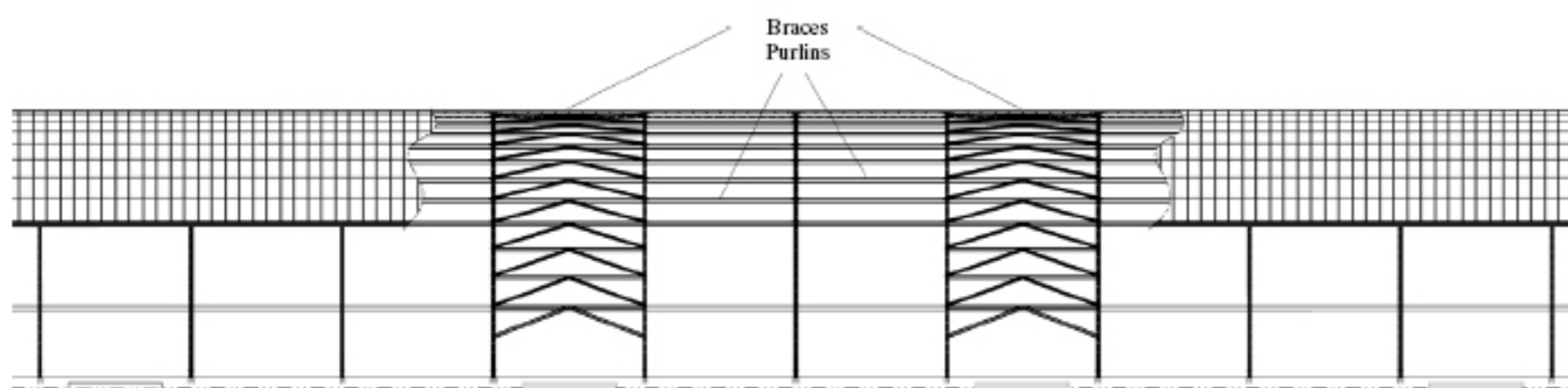


Fig. 6: Front view with braces and purlins

## Fire Resistance of Existing Glass Systems

### Fire-Resistant Glass

There are several glass systems in the market with 30 or even 60 minutes fire resistance. These usually use layers of gel forming foam in case of fire and sacrifice the glass sheet between the special layer and the source of the fire. If this type of pane is mounted horizontally, it is almost certain that the sacrificed glass sheet will fall down into the area below during a fire. These systems are designed to prevent fire spread and breakthrough, but not to prevent glass from falling down. They are therefore unsuitable for use in the roof.

It is also possible to use glass with fire-tolerant characteristics, such as a very low coefficient of expansion. Such glass was not used here due to its high costs.

### Spray and Water Mist Systems

A spray system can be used to extinct the fire and a water mist system can reduce air temperature to levels that do not endanger the glass. However, such a system would not be feasible for several reasons. First of all, it would have to be installed throughout the roof, whereas the fire would affect only one part. Furthermore, it would function during winter too, as this is an outdoor area. Such a system would also be expensive, reduce transparency and give birds a place to rest, thereby increasing pollution due to birds' excrements.

## Analysis of Glass Fracture during Fire

As the approaches listed above would not provide the required glass retention characteristics, the behaviour of glass during the specified type of fire was examined more closely.

### Deterioration in Material Characteristics

Initially, the characteristics of glass deteriorate slowly as temperature rises. Calculations of heat transmission indicate that the glass temperature during the specified fire would not be high enough to cause fracture due to impaired glass characteristics. Furthermore, the expected temperatures would not affect the tempering significantly. Thus, this glass is strong enough to withstand the required loads at the specified temperatures. This was later confirmed by the full-scale fire tests.

### Cohesion of the Pane

At high temperatures the pane will lose its cohesion. The plastic film begins to soften at 110°C, which means that if the lower sheet fractures, then the film will not be able to hold the two sheets together. It is therefore necessary to prevent the glass in the lower sheet from fracturing. It is also important to bear in mind that glass has low resistance to tensile and tensile bending stresses.

### Tensile Stresses due to Cold Pane Edges

One possible cause of tensile stress is the temperature difference between parts of the pane. Sudden application of heat leaves the edge of the glass, which is masked by the frame, at a relatively low temperature, as the frame protects it from the heat source. Neither the radiant heat from the fire nor the convected heat from the warm air can reach the part of the glass protected by the frame. As the edge heats up more slowly, it also expands more slowly. The large and warm, central area therefore generates tensile stresses in the narrow, cooler edge.

Because of damage to the glass, the edges of a pane are always the weakest area. High tensile stress in this weaker area may therefore cause the pane to fail. Grinding of glass edges is always recommended.

### **Tensile ending Stresses due to Restrained Edges**

A second potential source of tensile stress in the glass is its prevention from deflection. The glass on the directly heated inside of the pane heats up faster than the glass on the outside, which is in contact with the cooler outside air. As a result, the glass tries to deflect. If the pane is fixed rigidly into the framework, tensile bending stresses occur in the edges of the glass, which are the most vulnerable part.

### **Nickel Sulphide Inclusions**

A third potential source: cold bendable laminated panes, can fail as a result of nickel sulphide inclusions in the tempered glass. A nickel sulphide inclusion may expand during the fire, leading to internal stress and thereafter to fracture. Specifying a heat soak test for all tempered glass can minimize the risk of spontaneous fracture as a result of nickel sulphide inclusions. However for heat-strengthened glass the risk of failure due to nickel sulphide inclusions may be neglected.

### **Detailing the Glass System to achieve the Required Behaviour in Case of Fire**

Based on previous discussion, design solutions were developed to satisfy the requirement of 30 minutes glass retention.

### **Optimum Support for the Glass**

In order to minimize tensile stresses at the edges of the pane, the width of glass enclosed in the frame was kept to a minimum. This minimized the increasing temperature differences between the glass in the frame and the glass in the rest of the pane. To ensure that the

panes always overlap the supporting surface sufficiently, the stainless steel C-sections to which they were glued, project beyond the edges of the panes (Fig. 7). This prevents the glass itself from being pushed towards the aluminium sections 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 down. Furthermore, there would be a risk of fracture if the edge of the glass came into contact with the metal, due to the very concentrated loading that would be applied to the edge. There would also be a higher risk of the edges of the panes remaining wet. This is important, because the film is sensitive to long-term contact with water.

### **Heat Conducting Rubber**

In order to minimize the increasing temperature difference between the edges and centres of the panes, the glass is mounted on heat conducting rubber. This involves adding aluminium powder to the silicon strip. The powder substantially reduces the insulating effect of the rubber inserted between the glass and the steel I-sections. This steel is subjected to direct heat radiation from the fire and is in direct contact with the hot air on three sides. As a result, the heat conducting silicon strip helps to minimize the temperature difference between the glass in the frame and the glass in the rest of the pane.

### **Interaction between Nylon Bolts and Cold Bendable Glass**

Giving the glass sufficient freedom of movement minimizes tensile bending stresses due to restrained deflections. The aluminium retaining strips are mainly secured to the I-sections using nylon bolts. These bolts are adjusted to the forces exerted by the glass so that

they soften during the fire, allowing the panes to be loose before restrained deflections can cause failure (Fig. 8). The middle two bolts are made of stainless steel, so that the panes do not become completely loose during a fire and fall down. The durability of such nylon bolts is proven in over 20 years of practice in several canopies in the Netherlands. A further advantage of the ends bending up is that the cold edges are heated by escaping hot air.

### **Verification by means of Fire Tests**

Full-scale fire tests were carried out in order to demonstrate that glass panes satisfy the requirement of 30 minutes fire resistance. The fire curve used is the one indicated in Fig. 4, with 20 minutes fire duration and a five minutes cooling period.

### **Two Tests**

The two relevant tests are compared, here. In the first test, the pane was fixed using the combination of steel and nylon bolts as mentioned above, whereas the nylon bolts were replaced by steel bolts in the second test.

The second test, with stainless steel bolts throughout, was conducted for practical reasons. If nylon bolts are used, the aluminium retaining strips at the ends of the glass have to be split, otherwise the glass cannot deflect. The split strips increase the number of components and hence the number of operations required during installation. Costs may be reduced if only bolts of stainless steel are used.

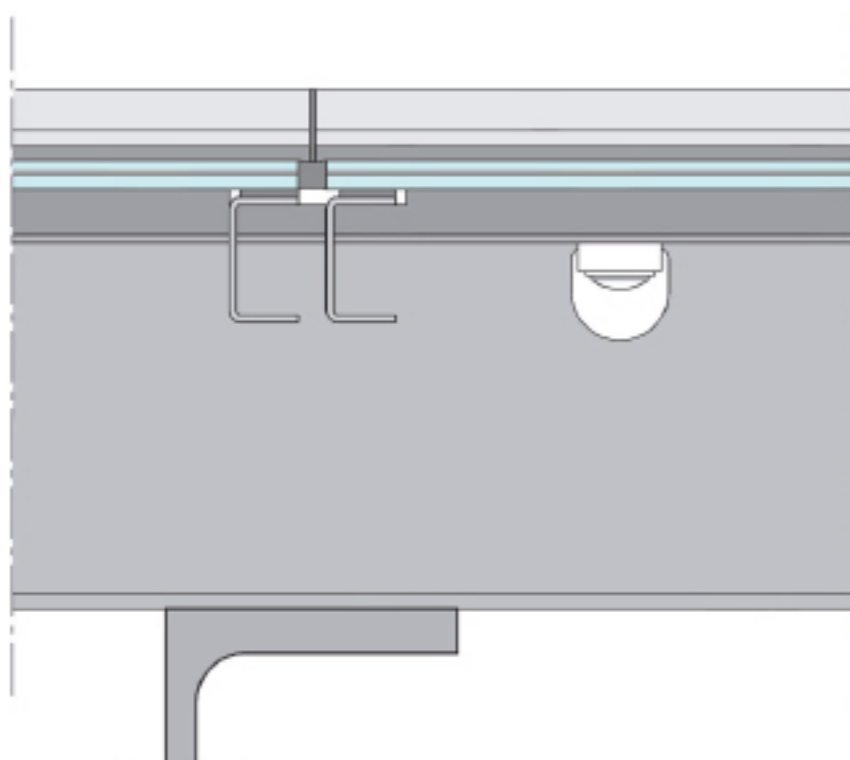


Fig. 7: Glass mounting detail

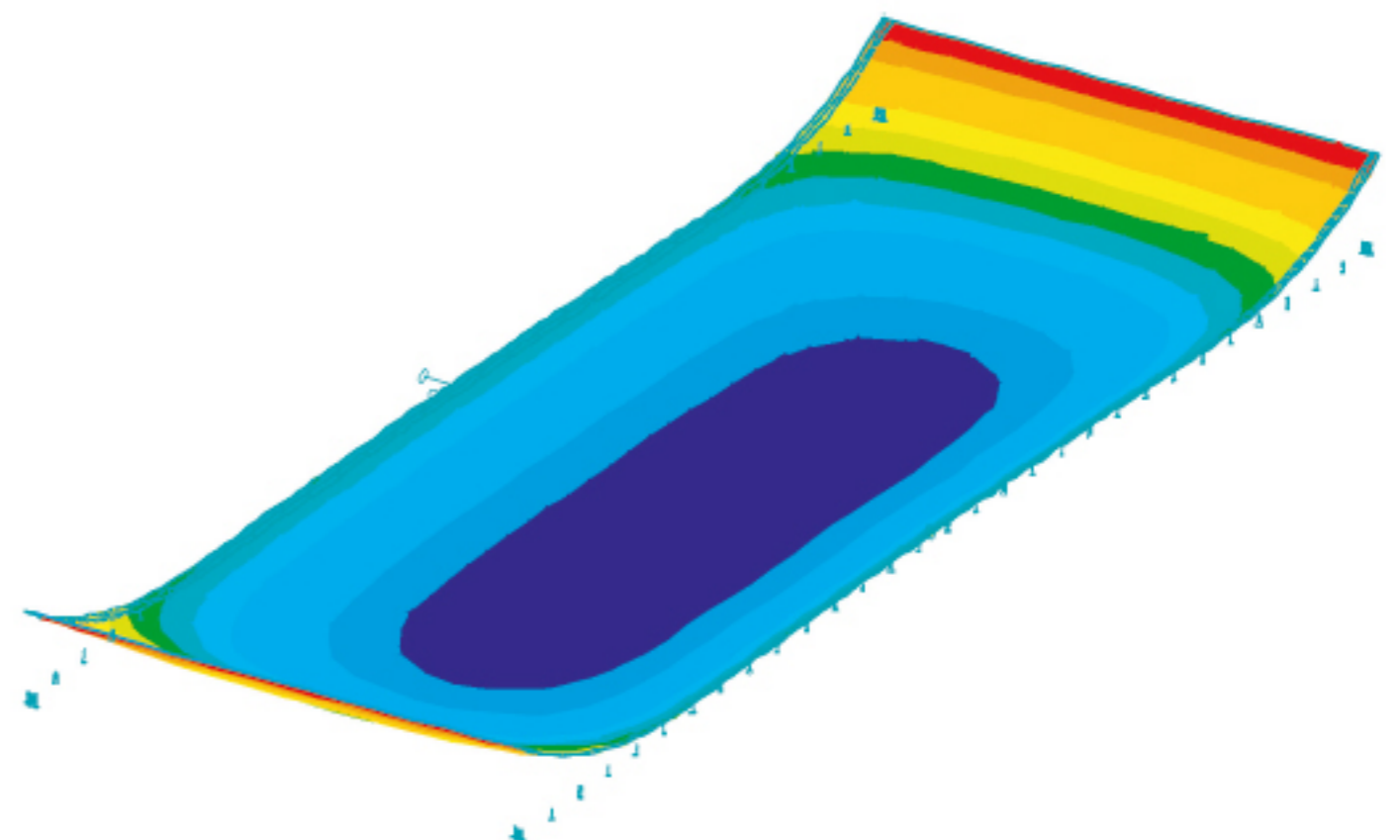
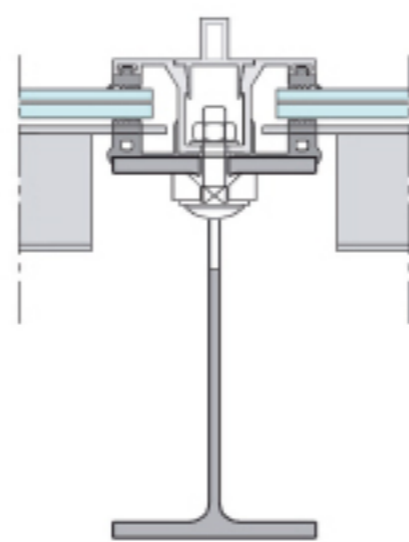


Fig. 8: The glass sheet deflects after the nylon bolts have softened



Fig. 9: The nylon bolt softens

### Test using Nylon Bolts [5]

The first of the nylon bolts gave way approximately 14 minutes after the fire started (Fig. 9). From that point on, deflection of the pane as a result of temperature differences across its thickness were no longer restrained. This is apparent from the displacements measured in the short edge of the pane. Maximum deflection was approximately 1 cm (Fig. 10).

After approximately 17 minutes, the first small bubbles started to appear in the plastic film separating the two

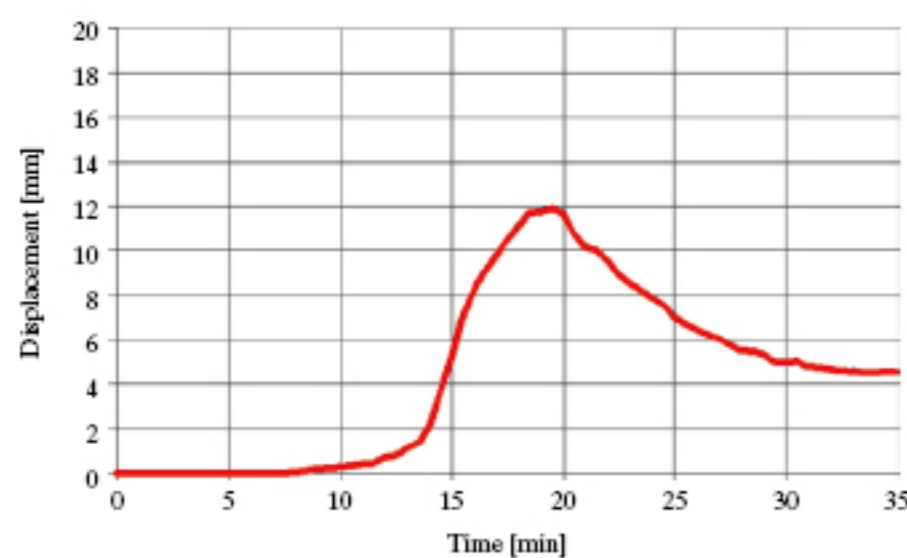


Fig. 10: Curvature measured at edge of pane [5]

sheets of glass. The cohesion given by the plastic film to the laminated glass deteriorated rapidly. In the twentieth minute, the plastic film melted over its entire surface and exhibited large, gently boiling bubbles. The film changed from transparent to a yellow/brown colour, a sign that it had reached a temperature of 160°C (Fig. 11). Immediately after, the burners were switched off and the oven was force-cooled with cold air. The bubbles then disappeared slowly.

The panes survived the high heat loading and forced cooling without frac-

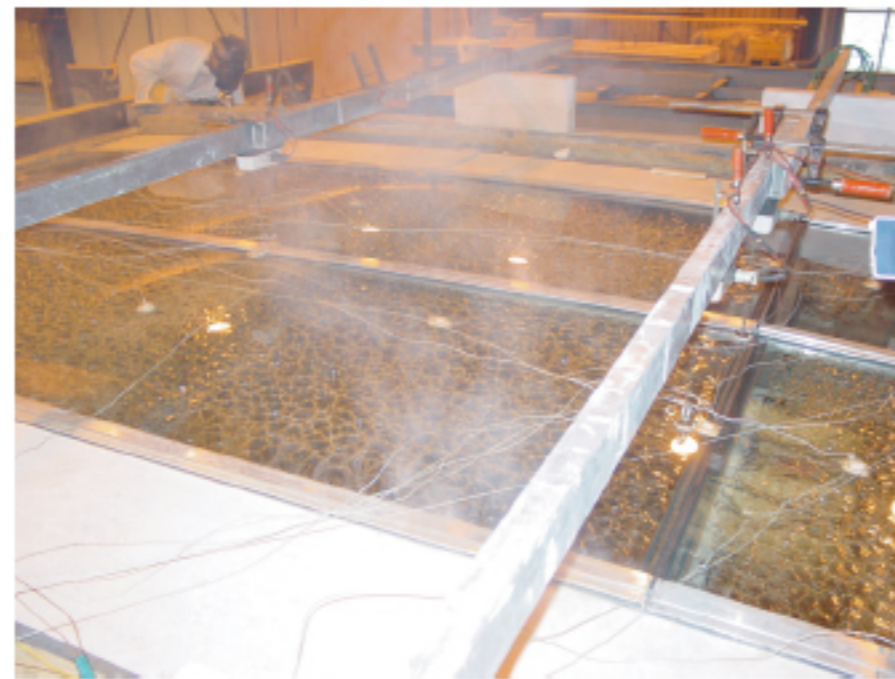


Fig. 11: Test after 20 minutes

ture. It may therefore be concluded that nylon bolts melt when they are required to do so, and the glass makes use of the space available to it.

The cohesion between the layers of laminated glass is lost during the fire, but recovers during cooling. Following the test, a sledgehammer was used to smash the hardened glass at the edge. The energy required to achieve this indicates that the glass had virtually recovered all of its original strength. Earlier sledgehammer blows to the lower, hardened sheet had caused no more than starring in the upper, semi-hardened sheet.

### Test without Nylon Bolts [6]

The pane in the second test failed after 20 minutes. After 19 minutes and 52 seconds, extensive cracking occurred in the lower sheet. A few seconds later almost the entire sheet fell out.

The failure occurred because the edges of the pane were restrained. The deformation of this pane differed substantially from that of the pane in the first test. Instead of both sheets deflecting upwards at the ends, the lower sheet deformed sharply downwards along approximately a quarter of the span. As a result, bending (and hence tensile stresses) was much higher than in the first test, leading to fracture. When the lower plate fell down in the twentieth minute, the rates of temperature increase at the measuring points on top of the glass rose sharply, as the upper sheet was now in direct contact with the hot air.

This second test shows that it is necessary to use nylon bolts in order to meet glass retention requirements. The

use of nylon bolts has a favourable effect on stress distribution in the glass sheets.

## Conclusions

A glass roof has been developed for the roof over the bus station at Amsterdam Central that satisfies the requirements for 30 minutes of fire resistance. Normally, such requirements would lead to a significant increase of cost. The use of patented cold bendable laminated glass [2] in combination with detailing specially developed for this project made it possible to meet the requirements specified by the fire brigade without increasing costs significantly.

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