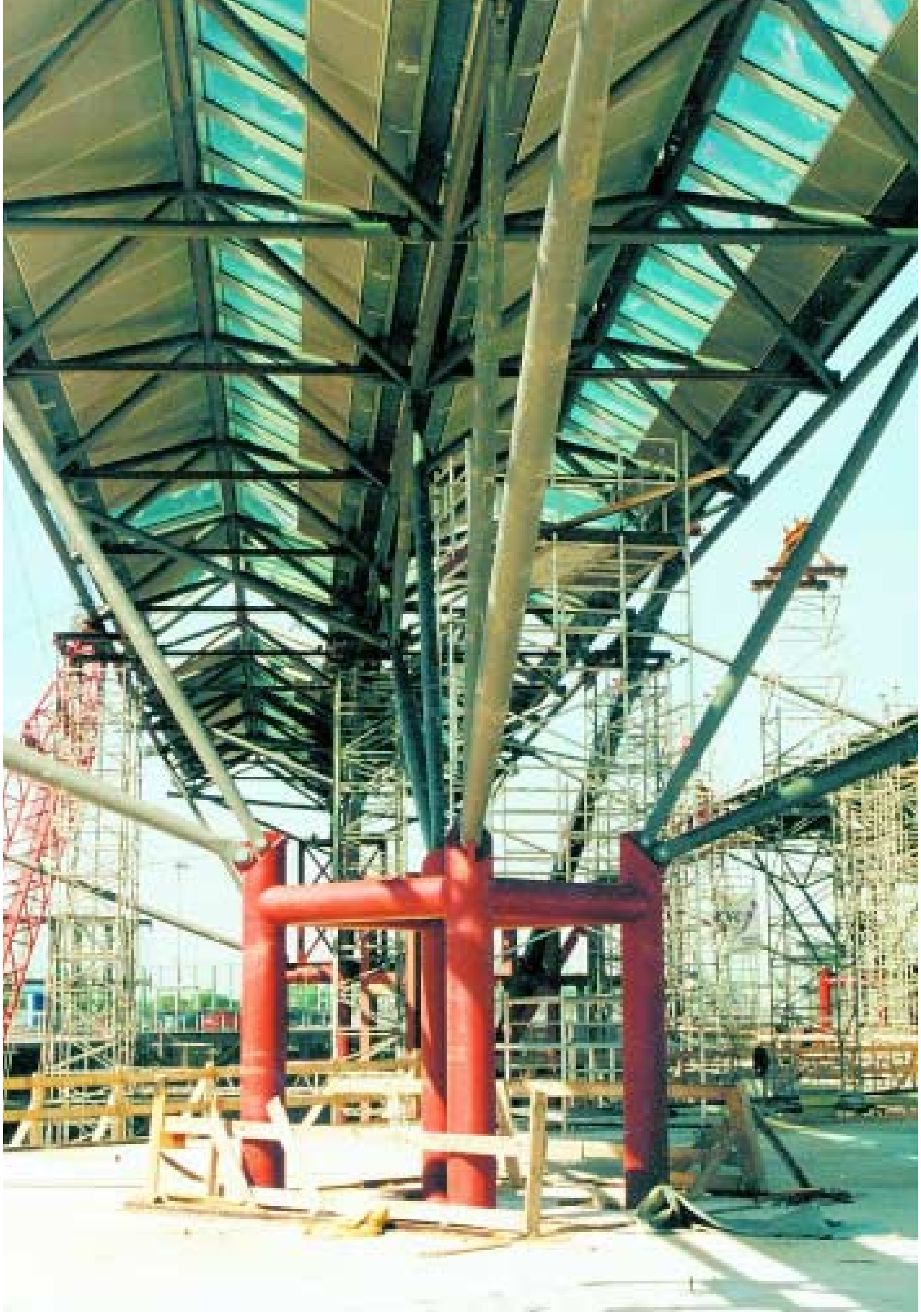

Up in the Air: New Airport Highlights Steel-Framed Roof

By Dieter Feurich

Cologne/Bonn Airport in Germany is currently undergoing its biggest construction project to date. For a total cost of approximately $600 million, the airport is being expanded extensively in order to manage the continuously increasing number of passengers. From 3.3 million in 1990, the annual passenger flow of the airport will likely increase to 7.5 million in 2000. Since the existing 30-year-old terminal building—an architectural concrete structure that will remain in service—was designed for a maximum passenger capacity of 4.5 million per year, it will no longer be able to handle the challenges of the future by itself.

In addition to a new terminal building with a capacity of 6 million passengers per year, the future airport will feature an underground inter-city express and local train station, two modern multi-story car parks and a completely redesigned road approach system. The new underground train station will link the airport to the European high-speed rail network via a 15 km-long loop railway line resulting in a number of advantages: the airport is likely to become a central traffic hub for the west of Germany and thus an important and appropriate gateway for the nearby Rhine/Ruhr economic region, whose economic strength compares to that of Greater London. Many short-distance flights from and to other German or nearby European cities will soon be replaced by express rail journeys—a significant improvement for the environment.

In 1992, the consulting engineering firm Ove Arup & Partners won a design competition for the new terminal building together with Chicago-based Murphy/Jahn Architects. Ove Arup & Partners' New York office carried out the structural design for the steel-framed roof and most of the other steel structures of the building. The engineers also had significant input on the building environment, such as day-lighting and temperature conditions in the departure hall space. A complete set of German language design documents was produced and smoothly steered through the very strict German approval process. Close and productive collaboration between the New York engineers and the local German contractors ensured a swift construction development.

The new terminal building is a five-story reinforced concrete structure (top to bottom: departure, baggage distribution, arrival, train passenger distribution, train platforms) with a steel roof as the architectural highlight. The architect's design of the new terminal building's departure hall aims at lucidity and visibility: slender tree-shaped columns support a light steel skylight with glass bands that allow daylight to enter. A pre-stressed cable glass façade surrounds the space. At the north and south side, atriums penetrate the building over its entire height and thus connect the different levels visually. In addition, the terminal features light steel framed floors with glass finish, steel stairs with glass treads and glass-clad elevators.

The roof structure of the new departure hall consists of a flat skylight supported by 22 tree-shaped columns, located on a 99' by 99' (30 m by 30 m) grid. The plan dimensions of the roof are 990' by 300' (300 m × 90 m). The skylight is a corrugated truss structure, so that two neighboring trusses share a common top or bottom chord. The trusses consist of pipes and run continuously over the tree columns. The facade mullions typically support the skylight at the roof edge. At the building's landside however, the skylight cantilevers 50' (15 m) beyond the façade line to provide a roof for the car arrival area in front of the building. The tree column solution to support the skylight is not only visually attractive, but it allows a relatively large column spacing while keep-

The tree scheme allows a relatively large column spacing while keeping the skylight structure shallow. Each tree provides 16 support points for the skylight. The maximum spread of the branches at the top of the tree is 50' (15 m).

ing the skylight structure shallow and the roof shape flat—a common requirement for terminal buildings.

The trunk of the tree column consists of four vertical pipes with a center-to-center spacing of 8.2' (2.50 m). The typical trunk measures 8.5' (2.60 m) in height, except for the tree columns supported at a lower level and 43' (13 m) high along the landside façade. The maximum spread of the branches at the top of the tree is 105' (32 m). Typically, the clear height between the finished floor of the departure hall and the skylight bottom chords measures 30' (9.15 m). Each tree provides 16 support points for the skylight. The top branches connect to the skylight bottom chords with pin connections and 2" (50 mm) thick node plates. The pipes for the trees vary in diameter and wall thickness from typically 16" by 0.75" (406 mm by 20 mm) for the trunks to 6.6" by 0.4" (168 mm by 9 mm) for the top branch elements.

Although all branch connections are simple pinned fork-and-eye connections and are therefore easy and quick to install, the trees provide very stiff supports. The maximum vertical skylight deflection under live loads is only 0.6" (14 mm). The tree columns not only transfer gravity loads to the reinforced concrete structure below, but also provide for the lateral stability of the steel roof. Because of the spread of the tree branches from the top of the trunks to the underside of the skylight, the structure as a whole can act as a three-dimensional moment frame and thus resist lateral loads. The tree trunks act as moment frames and most of them are moment connected to their concrete base. Additional lateral bracing is not required allowing a light glass façade, uninterrupted by any additional lateral load-resisting elements. The maximum lateral deflection of the skylight under wind load is 0.6" (14 mm).

It is important to note that the skylight is a one-way spanning structure that, together with the columns, takes part in both the gravity load and the lateral load-resisting system. The skylight acts as an anisotropic plate, providing flexural stiffness and in-plane stiffness in the direction of the trusses. Looking at the building in plan, the span direction of the skylight trusses is not parallel to the column grid but runs at a 45 degree angle to it. The reason for this rotation of the skylight with respect to the building's main axes is to turn the glazed bands in the roof toward the north and thus to achieve more evenly distributed daylight in the departure hall. However, this rotation makes the inclusion of movement joints in the skylight impossible. The joints would have interrupted the required continuity of the trusses and the desired uniform appearance of the roof throughout the building would have been impaired. Consequently, the key design issue became the control of the roof temperature movements and their interaction with the façade and the base concrete structure.

Without expansion joints the skylight acts as a 990' by 300' (300 m by

90 m) uninterrupted piece of steel. The difficulty was to come up with a scheme that on one hand could limit the significant temperature stresses that occurred in the tree columns and in the supporting concrete structure, while on the other hand kept the lateral temperature movements at the roof edge within limits compatible with the design of the cable-glass façade.

The solution includes a number of measures. As expected, the columns farthest away from the building center attracted the biggest forces because of the increasing lateral skylight movements towards the building edge under temperature. A force reduction in these columns was achieved by releasing the tree trunk supports and allowing them to rotate. The outermost columns therefore have pinned fork connections at the bottom of the trunk pipes while the other columns are fully fixed.

In addition, it was necessary to vary the wall thickness of the vertical trunk pipes. The pipe walls, especially of the outermost columns, had to be thin to reduce the lateral stiffness of the trunks and have them attract less force. We wanted to distribute the temperature loads more evenly among the other columns of the building. However, the design of the pipe-to-pipe joints at the trunk top, where horizontal and vertical trunk pipes meet, demanded rather thick pipe walls in order to provide against local pipe buckling or punching. As a result, the wall thickness of the vertical pipes varies along the height, with a thickness at the pipe joints about twice that along the rest of the pipe.

The maximum lateral temperature movement that can be expected at the skylight edge is 1.6 in. (40 mm), a value that can be accommodated by the façade structure. Square reinforced concrete shafts which carry the vertical loads from the roof down to foundation and connect the steel structure with the horizontal diaphragms of the concrete building

below typically support the tree columns. The vertical and lateral flexibility of the concrete structure was allowed for in the roof design.

The considerable design effort put into the development of the tree trunk shape and the branch arrangement eventually resulted in a design with manageable steel and concrete stresses that met the façade engineers deflection requirements. The structure is also very efficient with a steel mass of 9.8 psf (0.47 kN/m^2), a low value for a flat steel roof.

The steel contractor, Stahlbau Plauen, erected the 19,800 m^2 (215,600 ft^2) roof over a four month period. After the installation of the tree trunks and the positioning of the tree branches with temporary steel work, the skylight modules, measuring up to 10 m × 55 m (33' × 180'), were lifted, pin-connected to the branches, and field-welded to the neighboring modules.

The skylight steel came to the field in the form of individual plane trusses which then were welded together to modules on template scaffoldings to ensure proper geometry and minimize the need for adjustments during the lifting process. The roof cladding (aluminum, stainless steel and glazing) was pre-installed onto the modules and lifted together with the steel trusses, making the average module about 2.5 times heavier than the steel alone. The individual modules thus weight up to 70 tons. Since lifting occurred only from the building perimeter and the maximum normal crane range was approximately 54 m (180'), the job required high-capacity cranes. The advantage of erecting the skylight steel and the cladding "at one go" allowed a significant time saving in the roof erection process.

The slender tapered branches of the tree columns are perhaps the most significant architectural feature of the roof steel structure. The tapered portions of the branches are seamless and were manufactured using a forging method by which solid square steel blocks are first pierced with mandrels. Then the excess material is forged and removed in a repeated process until the specified diameters and wall thicknesses are achieved. The fork-and-eye end pieces of the branches are castings that continue with the same taper as the forged pipes, resulting in very elegant connection details.

Fully automatic flame-cutting machines cut the ends of the diagonal pipes in the skylight trusses in curved shapes. Computer-generated templates hand-cut the pipe-to-pipe connections in the tree trunks. All pipes in the roof structure are seamless. The tree trunk pipes are F30 fire-rated with intumescent paint.

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