AREP

Above It All

The three-layer roof gracing the new rail station in the southern district of Shanghai, China, offers not just an abundance of light but also a measure of serenity, providing an ethereal counterpoise to the hustle and bustle beneath it.

By Etienne Tricaud and Emmanuel Livadiotti

The Shanghai South Railway Station promises to chart new ground when it comes to the operation of a rail facility. Its innovative architecture comes from taking the functional model of Chinese railway stations and then making the link between train and road transport all but seamless. Both functionally and architecturally, this intermodal transport hub, which opened in July, has already established itself as a vital part of city life. Its design, the outcome of a three-stage competition in 2001 that ran from May to September and was won by the Paris-based firm AREP (MaP3, also of Paris, serving as structural consultant), was arrived at by combining the requirements set by Chinese authorities with French expertise, and its distinctiveness derives from the special care given to aspects that make travel both easy and pleasant. By coiling a typical Shanghai motorway viaduct around the station concourse and its waiting areas, the design makes transfers between road and rail practically effortless. The busy areas in which passengers are dropped off and that accommodate shops and services overlook the static square of waiting areas, just as in Chinese cosmology the circle of the heavens hangs over the square of the earth.

0885-7024-/06-0012-0054/$25.00 per article

The architects and engineers who worked on the Shanghai South Railway Station were not unmindful of its symbolic importance. Its lighting was designed to transform the station at night into a powerful, glowing beacon suggestive of a lighthouse, *opposite.* The station's open layout, *above,* helps travelers easily find their way as they transfer between trains and various modes of road transport.

Apart from its prime function as an intermodal transport hub, the Shanghai South Railway Station will serve as an architectural symbol of the city. As a contemporary gateway, it will be an expression of the city's energy as well as of its economic, financial, and cultural leadership and creativity. Its round shape offers considerable operating fluidity on six levels, providing smooth traffic flows for vehicles and offering passengers the shortest possible walking distance to waiting rooms or directly to train platforms. Having services on one level and waiting areas on another creates a large amphitheater whose sight lines help travelers orient themselves and easily find their way.

The most striking architectural feature of the new station is its roof, which although 277 m in diameter and covering 60,260 m^2, is light and elegant. It comprises three layers: an outer layer of brise-soleils, a middle layer of transparent polycarbonate sheeting, and a soffit of perforated metal. The three combine to filter and diffuse the natural light.

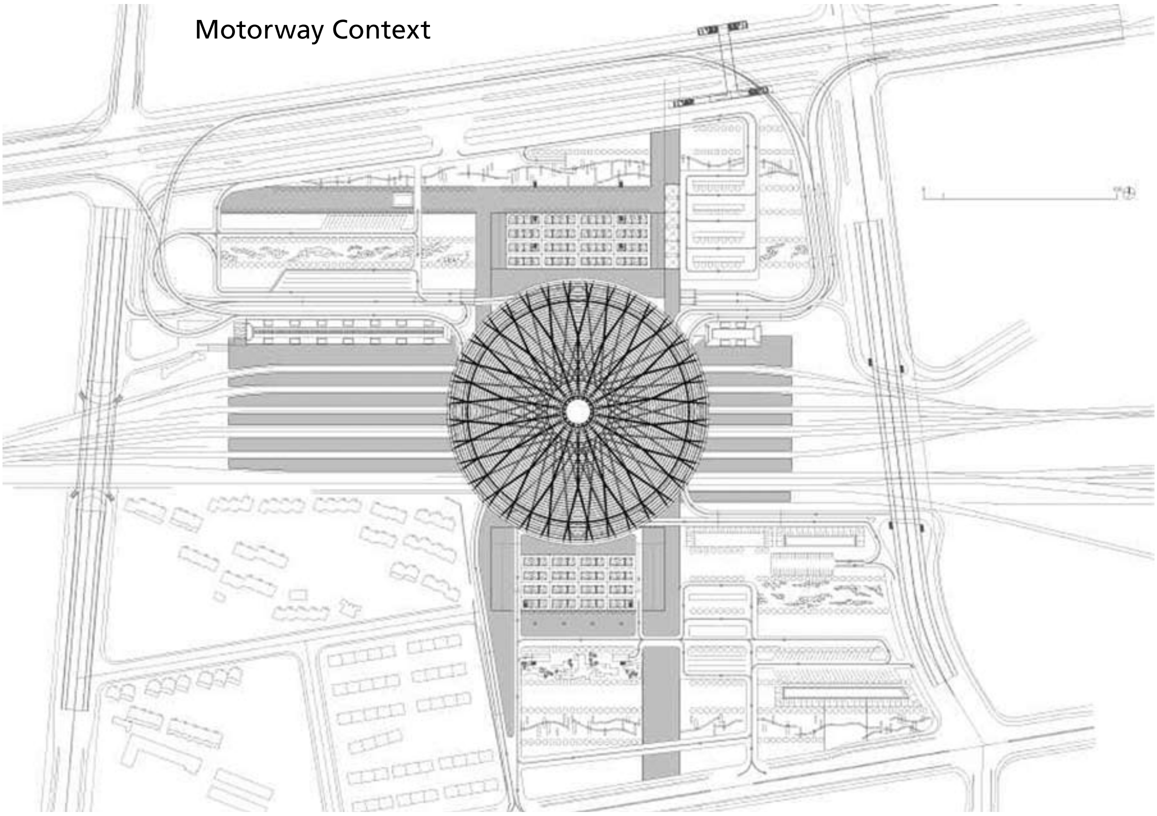
Lighting the station was an important factor at the design stage. All areas are lit by candelabra that follow a precise timetable. Indirect lighting created by reflections from the underside of the roof transforms the station at night into a powerful, glowing beacon suggestive of a lighthouse, and the lighting serves to punctuate and enhance passenger walkways.

The use of such materials as glass (some of it screen printed), polycarbonate sheeting, perforated steel, and brushed aluminum contributes to the overall interplay of transparency and light that makes the station a thoroughly contemporary building.

As a vast multimodal transport hub on which municipal, regional, and national buses, along with light-rail lines, taxis, and private cars, converge, the Shanghai South Railway Station is far more than a transfer point. Rather, it is the southern gateway into the city and, as such, houses a vast array of shops and services for travelers and visitors alike.

The roof geometry is generated by superimposing the tree structure of 18 main beams, which have a Y shape, on concentric circles of purlins and bracing cables.

The underside of the roof is highlighted by lozenge-shaped luminous strips created by openings in the opaque layers of the roof (brise-soleils and perforated steel sheeting) that match up vertically. These



Motorway Context

lozenges are also highlighted by the bracing cables.

In addition to coping with winds that can impose pressures of 250 kg/m² and being able to resist earthquakes, the roof structure has the capacity to expand radially as a result of temperature variations (±3 cm at the roof edges).

To conform to Chinese standards, the molded components at the top of the columns supporting the main beams include springs ensuring that column movement does not exceed $^{1}/_{850}$ of column height. A tensioned system stabilizes the structure to prevent it from tipping over as a result of asymmetrical stresses.

The main purlins feature a traction belt in the form of a solid bar 150 mm in diameter that is capable of bearing stresses of up to 300 metric tons. The central ring, which has a diameter of 26 m, accepts compression up to 1,000 metric tons.

Although the brise-soleils ensure considerable transparency for daylight, the angling of their blades keeps the heat of the sun out in summer and allows it to penetrate the building in winter.

The manufacturing technique used for the 18 main beams derives from shipbuilding. All 18 beams were manufactured in six parts in Shanghai at the shipyard of the Jiangnan Heavy Industry Company, Ltd. Welding was done on-site, and the beams were erected using a rotating bridge crane with one end located in the center of the station and the other on a peripheral rail. Each beam weighs 160 metric tons and is 120 m long. The beams were raised by the Shanghai firm SMCC.

On March 28, 2005, the 18 provisional supports were removed using lorry jacks to avoid shocks and control the stressing of the central ring structure. As predicted in the calculations, the deformation amounted to 140 mm at the key point. A stressing operation introduced a natural posttensioning of 17 metric tons into the central ring's system of undertensioning, which by itself takes 60 percent of the strain necessary to prevent the ties from compressing in response to asymmetrical stresses.

The roof structure, as mentioned above, takes the shape of a conical dome 277 m in diameter that ends in a skylight located 43 m above ground level. Since the top of the skylight is flat, the conical dome is truncated. The main framework comprises 18 radiating beams that branch to form a Y, and each branch of the Y branches a second time to form two more Ys. Each main beam thus creates three Ys. Each beam is supported by three columns, one of them 15 m tall (at the branching point of the first Y) and the other two 9.8 m tall (at the branching points of the smaller Ys). The taller column is closer to the center of the roof. The beams, anchored by stressed circular belts, meet at the central ring, which, as mentioned above, has a diameter of 26 m. The beams are stiffened by means of an undertensioning system: two ties are suspended from the beam by a series of conical struts

The roof's 15 m columns, of which there are 18, are closer to the center of the station. Its 9.8 m columns are farther from the center and form part of the facade, *above.* These shorter columns are reinforced by a bracing system comprising two ties 100 mm in diameter and are connected to the main roof beams using yokes of cast steel.

spaced 7.2 m apart. In the vicinity of the central ring and at the ends of the struts, the undertensioning elements, that is, the ties, are connected together to form the lower chord of the central ring.

The domelike system is capable of withstanding vertical symmetrical forces. It is too flexible, however, to withstand asymmetrical forces generated by, for example, high winds or earthquakes. Pressure on one side of the cone, combined with a lifting effect (negative pressure) on the opposite side, tips the central ring, which then can only be held in place if the main beams act as a cantilever.

But the undertensioning can make the beam act like a large-scale open-frame girder in which the upper chord represents the main beam and the lower chord represents the undertensioning ties. This effect disappears if the two members are not linked with respect to the shear force. But the struts are flexible enough not to act like the two members of an open-frame girder. However, this is not the case with the end ones, which in the vicinity of the 15 m columns are very short and hence very rigid. What is more, in the vicinity of the support, the bending moment in the beam turns positive and calculations show that the ties would be significantly compressed. To neutralize the compression, we modified the type of link between the tie and the last two struts in favor of a "sliding" connection.

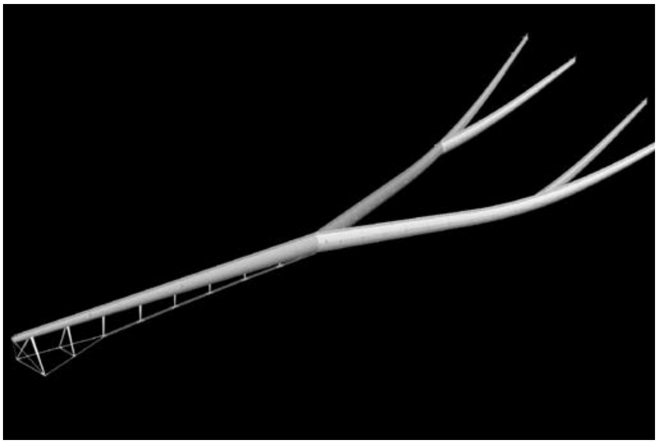
As the main structural components, the beams, weighing around 160 metric tons each, called for meticulous design work, the goals being a straight or slightly curved profile for the intrados and extrados, variations in height and width, and a lens-shaped cross section. To comply with Chinese standards, the height of the beams had to be increased on the basis of results from wind tunnel testing. At the manufacturing stage, we opted to cut the beams according to vertical planes rather than planes perpendicular to their pitch line. This choice called for skewed cuts for the shells forming the box beams and accordingly complicated the fabrication process, since the cut edges were then sinusoidal rather than rectilinear. This option was adopted for architectural reasons, as the vertical planes thereby created allow the eye to re-create the conical nature of the roof, which is not the case when the joints are perpendicular to the beam. (Neither the joints nor the struts are perpendicular to the beam's axis.) The roof's dimensions are such that the perspective effect substantially flattens its shape and accentuates the effect of a flat plate. The undertensioning struts also highlight the vertical planes that serve to guide the eye. The diameter of these struts must be sufficient to ensure that they are easily distinguished from the purlins and the ties themselves. The struts were designed with a faceted elliptical section (of 300 by 360 mm at the bottom) manufactured using the same technologies as those used for lighting masts made from bent sheet metal.

However, for manufacturing reasons, the struts were manufactured in a smaller, circular shape (300 mm).

The primary beams were manufactured in the same way as the box sections of a boat, that is, by welding bent conical shells 8 mm thick onto stiffeners to form a skeleton with the two upper and lower members. The running stiffeners are 15 mm thick and have cutouts to reduce the weight of the beams, provide room to move inside the box sections during construction work, and disseminate air and moisture throughout the building. The beam cross section features a groove to hold the edges of the polycarbonate sheeting. The groove continues as a gutter to collect any water that could flow up the slope of the roof in high winds. The shells are 1.8 m wide and 8 mm thick, giving them a slenderness ratio in excess of 200. Although the curve boosts their stability, it was necessary to stiffen them to counteract any warping caused by the intermediate vertical stiffeners. The shells' resistance to blistering and warping was verified using finite-element modeling with two different software applications (Robot, developed by Robobat, of Grenoble, France; and ANSYS, developed by ANSYS, Inc., of Canonsburg, Pennsylvania).

The purlins linking the main beams were designed to take the form of concentric circles. A succession of regularly spaced concentric circles constitutes a dominant geometric system, more pronounced than the principal elements of the cone formed by the main beams. The aim was to visually highlight the main beams and polycarbonate sheeting at the expense of the purlins. Designed as very simple lattice girders lacking a central diagonal, the purlins were made as narrow as possible (11 cm for lengths of up to 26 m), despite the stringency of Chinese standards. However, since purlins comprising two chords could have detracted visually from the roof's lightness and transparency, we decided to space them approximately 3.6 m apart so that from the principal vantage points the upper members would be hidden by the lower members of the foreground purlins.

The 15 m high columns have a batter, tapering from a diameter of 1 m at the base to one of 60 cm at the top. The 9.8 m high columns, which are farther from the center than the ones 15 m tall, are cylindrical but are reinforced by a bracing system comprising two ties 100 mm in diameter. They are connected to the main roof beams using yokes of cast steel. This type of yoke assembly means that the profile of the beam can continue beyond the support and therefore enhance the illusion of suspended lightness conveyed by the roof. The yokes are large components, being roughly 2 m high and weighing more than 2 metric tons. They are connected to the roof by means of solid steel axles 20 cm in diameter. The axles are attached to the skeleton of main beams by being welded to the full-length, 20 mm thick interior stiffeners.



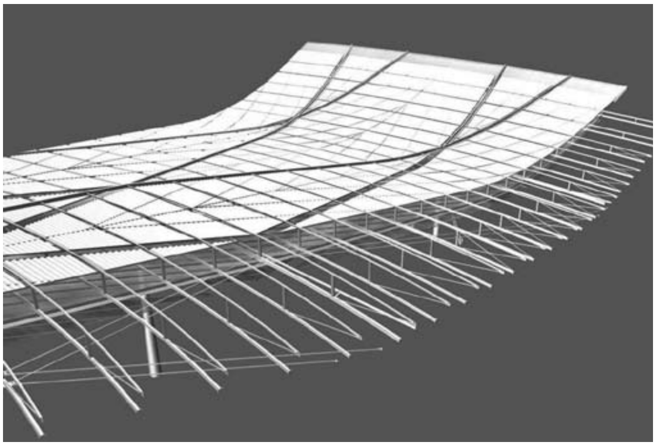
Each of the 18 main beams branches to form three Ys. The techniques used in manufacturing the beams, each weighing 160 metric tons, derive from shipbuilding.

The yokes on the columns farthest from the center (the ones 9.8 m high) are more complex owing to their location; that is, they form part of the plane of the facade. It took more than three months to design them using three-dimensional drawing and modeling techniques. Special attention had to be given to the ribs; the external recesses; the positioning of stiffeners in the places of greatest stress; the design of extremities equipped with screws to facilitate erection; the design of points of connection with the columns; the coupling sleeves for connection to the bracing; and the grooves to take the facade glazing.

The extremities of the arms of the facade yokes have 26 by 28 cm cavities housing springs. These springs absorb the 30 mm expansion of the roof as the temperature rises. In this way the ends of the posts move no more than 10 mm, the maximum allowed by Chinese standards. The development of these systems also called for detailed studies in conjunction with Chinese manufacturers and the design arm of the East China Architectural Design and Research Institute Company, Ltd. (ECADI), of Shanghai. The sides of the 20 cm axle are chamfered so that the spring rests against a flat surface—an important consideration given the stresses that come into play. The spring rests against a cast stainless steel part attached to a neoprene plate that allows the assembly to move freely.

The facade is one of the most complex parts of the station. From an architectural point of view, the aim was to achieve a light, transparent structure that would offer panoramic views of the city and give visitors inside and outside the station the impression that the roof somehow floats above the edifice. In accordance with Chinese architectural practice, the glass surface is in the axis of the posts. The facade is doubly glazed.

The water that collects on the roof is channeled down to ground level by a suction downspout



The roof's outer layer of brise-soleils, middle layer of transparent polycarbonate sheeting, and soffit of perforated metal combine to filter and diffuse the natural light.

system. Each downspout is 200 mm in diameter and serves approximately 800 m^2 of roof.

Structurally, the facade is connected to the 9.8 m columns, which are connected to the roof with the aid of the springs mentioned above. A zone therefore exists in which differential movement must be absorbed.

Four different trade groups were involved in the construction: roofers, facade builders, the contractor laying the roof covering, and the contractor responsible for the downspout system.

As mentioned previously, the roof comprises three layers: an outer layer of aluminum brise-soleils, a transparent, watertight layer of polycarbonate sheeting, and an acoustic soffit made of perforated sheet metal. The decision to place the layer of brise-soleils on the outside was quite natural. The infrared radiation they emit is blocked by the polycarbonate sheeting. This affected the design of the twin-member purlins, as the top member is used to support the brise-soleils. The purlins are located wholly outside the skin so as to discourage heat exchange by direct contact ("thermal bridges") and to avoid jeopardizing watertightness.

The angled pattern informing the layout proved to be well suited to the polycarbonate sheeting, which can only be laid in parallel, continuous bands. It also accommodated the lozenge-shaped luminous strips mentioned previously. The orientation of the sheets channels the water to radial gutters between the main beams. The Chinese experts rejected the initial orientation, in which the water would have traveled inside the beams themselves. The sheets were designed on the basis of Danpalon, a polycarbonate glazing system developed by Danpal. The honeycomb sheets, which are watertight and do not require caulking or adhesives, would have been attached to aluminum frames by clips. However, in the competitive bidding, this system was not chosen by the owner. Another manufacturer tried to reproduce a similar system of polycarbonate sheets, but the system has proved unduly complex and not very reliable. Leaks have been found, and it has been necessary to use bitumen to ensure watertightness. The total length of the polycarbonate sheets is 60 km.

The total length of the aluminum sheets of the brise-soleils used in the roof amounts to 150 km. The work, fortunately, lent itself to customized sections. The length of the sections had to be such that the laying time would be minimized and the angle of the roof preserved. It also had to ensure that light would be properly reflected, and each section had to have sufficient inertia to support a span of 3 m and to withstand wind pressures of 250 kg/m^2. Steps were also taken to ensure that the soffit would not become a repository for moisture and dust.

To accelerate the laying process, we had plans to use semiarticulated frames of 3 by 4 m that would have been assembled in the workshop and been ready for placement between the purlins. This approach would have saved on labor but would have made greater demands on the lifting equipment. As it turned out, the contractor preferred to lay the roof sheet by sheet.

Designing the Shanghai South Railway Station proved to be a great experience for the AREP and MaP3 teams. It gave our staff an opportunity to participate in a major project in China from the design competition phase to final construction. Success on such a project, however, depends on far more than expertise in architecture and engineering; good working relationships with other members of the project team in a spirit of mutual confidence are indispensable. Modern forms of communication—in particular, online forums—helped those in different parts of the globe provide valuable input in a timely manner. The mayor of Shanghai was closely involved in many of the decisions necessary to realize the station. It is our earnest hope that we justified the trust reposed in us. ■

Etienne Tricaud is an architect and the general manager of AREP, of Paris. Emmanuel Livadiotti is an engineer and the general manager of MaP3, also of Paris.

PROJECT CREDITS
Owner: Ministry of Railways (station) and City of Shanghai (urban development, access, infrastructure)
Contractors: AREP, Paris, and East China Architectural Design and Research Institute Company, Ltd. (ECADI), Shanghai, China
Structural consultant: MaP3, Paris