

# **SOUTHERN CROSS STATION**

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## **ABSTRACT**

The redevelopment of the former Spencer Street Station has created a new multi-modal transport interchange serving Victoria's suburban, regional and interstate rail networks. The new facility, now renamed Southern Cross Station, has also become a major civic landmark for the city of Melbourne.

The main feature of the new station is its large wave-form roof, comprising a series of 'moguls' that reach up to 24 metres above platform level. The roof covers an area of 37,000 square metres, including 7,000 square metres of flexible skylights, and is enclosed on all sides by massive glass façades. This roof structure was constructed while the station remained fully operational, something not attempted previously in Australia and very seldom internationally.

Despite numerous difficulties and challenges encountered during its construction, the facility met and, in many areas, exceeded the requirements of the original brief. In delivering this project, the Southern Cross Station project team displayed tenacity and ingenuity to create a outstanding example of construction achievement.

## **KEY WORDS**

Station, railway, interchange, roof, structure, steel, tubular, ventilation, passive, design, construction, fabrication, ETFE, Kalzip

## **INTRODUCTION**

The new Southern Cross Station is the key transport hub for both the Melbourne metropolitan and the Victorian regional and interstate rail networks. Upgrading of the former Spencer Street Station involved relocating commuter traffic flows from underground subway access to a modern open-air transport interchange facility where the platforms are accessed from an elevated concourse. The track network and platform layouts were predominantly unchanged by the redevelopment; however, new infrastructure was built for ticketing, administration and retailing facilities. A feature of the new station is the total enclosure of the station with a spectacular wave-form roof, enclosed on all sides by glass façades.

The project was undertaken as a public private partnership between the Victorian Government and the Civic Nexus consortium. The Civic Nexus consortium comprises a maintenance and retail operator with the design and construction being undertaken by Leighton Contractors.

## **PRELIMINARY DESIGN DEVELOPMENT**

The main feature of the station is its large wave-form roof. Occupying a complete city block and covering 37,000 square metres, it is not only an architectural icon for Melbourne, but performs an important functional requirement for the station. The concept for the roof developed by architects Grimshaw Jackson was to not only provide an architectural feature but also to provide a form that would allow exhaust gases from diesel (and in some instances steam) locomotives to be exhausted without the use of costly mechanical fans or extraction systems. Grimshaw's past experience with railway stations in both Europe and the UK indicated that covered stations with large barrel vaulted structures tended to trap diesel fumes – hence the development of the domed or individual mogul-shaped roof which allows the fumes to rise to isolated points which can then be extracted from the station.

Air quality modelling using computer fluid dynamics techniques confirmed that this could be achieved. The roof moguls at the station reach a height of up to 24 metres above the platform levels at their highest point, dropping to a minimum height of 6 metres in some places. The roof was also required to be elevated at both the northern and southern ends to clear the existing Collins Street and Bourke Street bridges.

In order to assist the roof ventilation under prevailing cross winds, the moguls are offset across grid lines. This also reduces the risk of fumes being sucked back into the station environs under a cross-wind through an adjacent mogul. At the apex of each mogul is a louvred cap which enables exhaust fumes and gases to be extracted, but which also operates to prevent wind-driven rain from being blown into the station.

The roof structure essentially comprises a series of structural steel tubes forming a two-way net system. The original roof design was cut back to make way for a future commercial development on the western side of the station above the existing rail lines. This structure is an elevated slab which will support a future 10 storey building.

Introduction of this structure to the project after the initial design was commenced created a problem for the main station roof, as the largest internal bay of the roof now became an end bay. This resulted in higher stresses in the main roof rafters, requiring increased wall thicknesses in a substantial amount of members. A number of options were investigated, with the final solution adopted being to lean the roof on to the substantially stiffer elevated deck. This avoided having to use heavy wall pipe but meant that temporary works in the form of a series of arch ties could not be removed until the elevated deck had been completed.

## **ADOPTED DESIGN**

The roof is set out on a geometric grid, with a series of five grid lines running down the centre of every alternate platform in a north–south direction. The platforms are set at a 12 degree skew to the adjacent Spencer Street. Grid lines labelled A to E run in the east–west direction. A total of 29 column supports for the roof are located at the intersection of all grid lines. Grid lines numbered 1 to 5 run in the north–south direction and are the central axis for the large triangulated trusses referred to as spine trusses. The 12 degree skew resulted in a complex intersection of trusses at the corner of Spencer Street and Collins Street.

A series of curved roof rafters, referred to as primary arches, run in the east–west direction and are spaced equally at 4 metre centres. These arches are not true arches as such, as their geometry has a reverse curve as part of the arch shape. Again, these intersect with the spine trusses at a 12 degree skew in plan. A series of short secondary members between adjacent arches help form the complex two way system. Columns at 40 metre centres along the spine trusses support the truss in its Y-shaped form. Columns are cantilevered out of the ground from a rigid pile cap and piled foundations.

The structure described above forms the main sub-structure, or the bottom of the roof's three layers. The second layer above the structure is a ceiling consisting of a series of triangulated ceiling panels. Over 7,000 ceiling panels of similar design but each with their own unique geometry provide both an architectural ceiling and an insulating barrier for the station roof as well as providing a work platform to enable construction of the third and final layer of roof sheeting above.

The ceiling itself also contains an important diagonal structural brace which is connected to the main supporting steel substructure. The architect intended that this diagonal bracing member should be hidden from view, although it is an essential element of the roof structure. An important feature of the ceiling panel design is that it allows air to flow and naturally ventilate the station environs. This was achieved by maintaining nominal gaps between panels to allow air to track through the gaps into the ceiling space, and rise to the top of each mogul before being vented out through the louvre cap.

The third and final layer is a weatherproof skin in the form of a metal deck to the station roof. The chosen product had to have the ability to be manufactured and installed to suit the continually changing geometry of the wave roof. It also needed to have a 25 year warranty. The choice of roof sheeting was a key issue in the final design solution. A standing seam aluminium tray deck system, stainless steel shingles and zinc roof sheeting

were the main alternatives considered. A number of early concepts using glass reinforced composite (GRC) panels, tensioned fabrics and sandwich panels were also considered, but dismissed as being either too difficult to weatherproof, not able to meet the warranty requirements or unable to meet the defined geometry of a flexible roof structure capable of accommodating thermal movements, settlement of the structure under self weight and fabrication/erection tolerances.

Other key features of the design include a syphonic drainage system. The steep roof sheeting drains to gutters located each side of a spine truss. Outlet discharge points are located at each column, where a sump gives way to a syphonic outlet discharging into the column arm down to the base of the column, along the platform into an abandoned subway tunnel, and then discharging to a common surge pit on the western side of the station.

A clear skylight system is located above each grid line, running north–south along the centre of alternate platforms. The skylight sits above each line of spine trusses. A number of solutions for the skylight were investigated. A solution suggested by the architect was the use of ethylene tetrafluoroethylene (ETFE) cushions. This is a tensioned fabric technology, with each cushion consisting of a twin layer fabric structure of ETFE (basically clear Teflon) in the shape of a cushion. A continual air supply is pumped into the cushion to maintain both shape and strength to the finished product. Grimshaw had successfully used this technology in a number of projects in the United Kingdom – most notably at the Eden Project in Cornwall, which is an environmentally controlled biosphere constructed entirely of ETFE cushions over a steel framework.

Alternatives such as traditional glazing were also investigated for the skylights. However, the logistics of installing large sheets of glass in situ on the roof together with the continuously changing geometry of the trusses would have made glazing a difficult option. The roof itself is a flexible structure, both in its final configuration and during the various stages of construction. This could have potentially created additional problems for glazing and sealants at construction completion. The flexible nature of ETFE ensures that movements of the roof will not impede the performance of the skylights.

Some statistics for the roof are:

- Approximately 3,200 tonnes of structural steel;
- Roof area of 36,000 square metres of which 7,000 square metres are skylights;
- 29 supporting columns;
- 207 primary arches;
- 1,370 secondary members and 1600 diagonal braces; and
- 7,050 ceiling panels.

## STRUCTURAL DESIGN

The roof structure consists of structural steel tube, with the predominant size being 356 mm outside diameter (OD) circular hollow section (CHS). This size includes the main boom members of the spine trusses and all primary arch members (curved roof rafters). Wall thicknesses vary from 6.4 mm to 12.7 mm; however, some heavier wall tube up to 23.8 mm was used in some of the flatter arches. Secondary and diagonal bracing members in the roof proper consist of 168 mm diameter CHS of varying wall thicknesses between 4.8 mm and 25.0 mm.

The main support for the roof is a series of triangulated spine trusses running in a north–south direction along the centre of the platforms. The inverted triangle section is 8 metres in width at the top, with a depth varying between 4 metres at the columns and 2 metres at mid-span. These trusses also form an undulating profile arching between column supports along the platform. The spine trusses consist of 356 mm diameter members for the main chords and cross member of the triangle, with 273 mm diameter vertical members and 168 mm diameter plan bracing.

The roof structure is unique in that the primary arches spanning between spine trusses span one way in the construction condition. Once all the lacing members (i.e. secondary and diagonal members) are installed, the roof mogul begins to form a two-way system in the final condition. The roof mogul acts as a shell transferring the bulk of the roof loads back to the four columns in the corners of each dome, thus substantially reducing the amount of vertical load or dead load to the spine trusses on the grid lines. This was a chief architectural requirement, as the architect wished to see only a two-way net system/structure from beneath. The trusses therefore became a Vierendeel truss, with no diagonal bracing in elevation but diagonal bracing in plan achieve lateral restraint required by the out-of-balance forces provided by a flat arch opposing a steep arch on either side of the truss.

The choice of typical key connection types was critical early in the design process. These included:

- Primary arch to spine truss connection. A bolted halving joint was chosen as it provided a seat for the primary arch to land, enabling quick bolting and securing of the arch;
- Primary arches up to 40 metres in total length were generally broken into three sections for transport. This was not just because of their length, but also because the varying radii of most arches made them over-width for transport. Depending on the location of these joints, some varied from a full moment connection to pure compression, depending on the load in the arch, the point of contraflexure (virtually all arches contained a reverse curve in geometry). To maintain a consistent approach it was decided to butt weld all these joints on site. This also removed the difficulty where a connection of a secondary/diagonal member at a node point clashed with a primary arch connection, had these been bolted together. This decision was made during the early design development phase, before the geometry of the roof was fixed and the nodal points defined;

- Spine truss to spine truss main chord or boom member connections between adjacent truss lengths. A spliced angle plate/cruciform connection was chosen to allow some construction tolerance as trusses were erected over each column first with an infill section placed between them;
- Connections of vertical, diagonal and main chord members in each truss were fully welded. The use of similar tube sizes avoided issues with punching shear failure modes in the majority of cases. However in some connections, in particular in and around the column where a diagonal brace was installed, heavy wall pipe and/or stiffener plates were installed as part of the design and fabrication process; and
- Primary arch connection to diagonal roof bracing. An innovative connection detail was developed for this connection. As described previously, the diagonal brace sits above the main structure hidden within the ceiling panels. The diagonal bracing is an important element in transferring load from the roof shell back to the columns. In other words, some of the diagonal roof members in and around the columns carry substantial loads. This connection therefore induces an eccentric load on the primary arch. Due to this substantial load and the varying orientation of cleat plate connections for the diagonal braces, it was decided to locate individual cleats around a circular stub upstand welded on top of the arch. This stub also provided for a further upstand to pick up a roof purlin at a higher level again.

## **FABRICATION**

Structural steel tube was purchased from OneSteel, with some of the heavier wall pipe being sourced from overseas. On delivery of the tube, it was transported to a fabricator in South Australia to be cold rolled into its correct shape and radius. Once this was completed the members were then transported to various fabricators in Victoria, Tasmania and New South Wales for the next stage of fabrication.

The columns were made in two parts: the bottom section was a circular tapered tube, and the top section was a fabricated box structure forming the Y-shaped arms. The fabrication process was made difficult by the 12 degree skew of the column arm – because the cross section of the arm was not rectangular but effectively a rhombus. The fitting of the internal services including the syphonic downpipes and an electrical conduit also made the fabrication process difficult. Once on site, the bottom section was installed, the top part of the Y was inserted via a spigot connection into the bottom pedestal section, services connections were made and then the bottom pedestal section was filled with concrete, pumped from the bottom.

The primary arches were set out in a workshop to their completed final shape. The shop drawings were used to then set out all connection points and all cleat connections for secondary and diagonal members were fabricated in the shop, including the end connections for bolting to the spine trusses. Arches were then cut into three sections for transport, painted and then sent to site with set-out marks for welding on site.

The fabrication of the spine trusses was a more complex process. The triangulated trusses were fabricated in an inverted position. The shop detailer was able to provide additional set-out information to enable the fabricator to set up the truss in purpose-made jigs. Tube elements were cut with ends profiled to match the complex connection points around the main boom members. Some node points on the main boom member had five different tubes connecting at the same point.

The structural designer also had to nominate a priority for members coming into that joint, together with the specified welding type and extent. Set-out of the halving joint stub for connection to the primary arches was critical, as the connection relied on the full mating of matching plates in the field prior to bolting. Taking into account the 12 degree skew and the continually changing pitch of the arch and the undulating spine truss, this was no mean feat. Once the set-up was done, the trusses were fully welded, lifted and rotated into their upright position and the steelwork for the gutter beams was fixed. Finally, the truss was painted, installed into a transport frame and loaded on to a barge for its trip to the Port of Melbourne, for its final delivery to site.

Connection of the spine truss to the Y-shaped column arm was the one of the most complex connections. The concept, both architecturally and structurally, was to provide a three-point pin connection, one at the crutch of the Y and the top two at the column ears. However, lining up or matching three pins in this configuration within 2 mm oversized holes was almost impossible owing to fabrication tolerances, deformation of items during both transport and erection, and thermal movement. It was therefore decided to provide an architectural pin connection only. This involved large steel billets being shaped and fitted to the spine trusses and then welded to the column arm on site. This required a detailed survey of both the spine truss at the end of fabrication and the as-installed column arm to confirm whether any clashes or excessive gaps were likely to occur prior to erection of the element.

Secondary and diagonal members were simpler, being straight members with bolted cleat connections at both ends. However, the logistics of tracking these members through the fabrication, painting, expediting and final erection processes was a massive task as all elements were of varying length and had their own unique position on the roof. Similarly, the ceiling panels were relatively straightforward to fabricate but each had its own unique geometry resulting in its unique position on the roof.

## **CONSTRUCTION**

One of the key motives behind building a complete roof covering the entire station site was to come up with a concept that was both architecturally acceptable and capable of being constructed over an operating railway station. Up to 60,000 commuters use the station per day, with 700 metropolitan trains serving six platforms and 240 interstate and country trains serving eight regional platforms.

This was a key issue that had to be taken into account throughout the entire design development process, from early concepts through to the final detailed design. An important part of the process was to engage the shop detailer early in the design process, to not only assist and provide input during the design development, but also to save

significant time in the fabrication process. It reduced the amount of unnecessary and repetitive architectural drawing by making the shop detailer responsible for the roof geometry and all dimensional control. This also assisted greatly in the off-site fabrication process and the on-site survey installation by being able to interrogate any part of the theoretical model of the roof. The shop detailer therefore became an integral part of the design team with the architect and the structural consultant.

The choice of structural connection types and location of construction splices was another key factor in the design stage. Connections had to be located at convenient locations from both a design and installation point of view. Connection types had to allow for easy installation given the time constraints of constructing over live railway lines in limited blocks of time, as well as achieving the architectural and structural capacity desired by the roof designers. Bolted connections were the preferred choice; however, it was necessary to site weld the large primary arches (roof rafters) as they were delivered to site in transportable segments.

The station constraints were related to two main areas. Approximately one quarter of the roof was built over the electrified metropolitan lines, with the balance over the non-electrified country and regional platforms. The particular challenge over the electrified lines was that opportunities for installation were only available between the last train at night and the first train the next morning. Allowance within this period also had to be made for the overhead power to be isolated. This therefore further restricted the available window of opportunity to approximately two and a half hours each night to install all elements of the roof over the electrified lines.

To minimise the number of lifts over the metropolitan lines, it was therefore decided to construct large roof modules on the western side of the site, in the median strip of Wurundjeri Way, and to lift these large units into position with a 600 tonne crawler crane. The main spine trusses that supported the roof modules and ran along the length of the platforms were installed with this same crane.

The spine trusses were fabricated off-site in Geelong, Tasmania and New South Wales and towed to Port Melbourne on large barges. They were then transported at night to the site from the South Wharf, approximately 5 kilometres away, and lifted directly into their final positions. Each truss section was fabricated in 20 metre lengths. With 40 metres between column supports, a truss section was installed firstly over each column and then a 20 metre long infill truss was lowered into position and bolted. A similar process was adopted for installation of the remaining spine trusses over the entire project, but the full-time occupation of other areas of the station, such as over the regional platforms, enabled smaller cranes to be used.

Owing to the full-time occupation of regional platforms being attained in stages, it was more efficient to install the roof segments between trusses piece by piece. This meant the primary arch or main roof rafter (spanning from truss to truss) was installed first, followed by the series of secondary members and diagonal members, followed by the ceiling panels. The ceiling panel installation ensured that a working deck was in place to enable the roof sheeting to be installed during normal working hours, without the danger of dropping materials on to the public or workers below.

A series of safety nets were also installed immediately beneath the top of the trusses where the ETFE skylights were to be installed. Again, these nets enabled installation of the skylights to proceed during the day.

## **INNOVATION**

The constraints of the site dictated that the main spine trusses had to run centrally down the platform centres on every other platform. This set the grid lines in the east–west direction, whereas along the length of the platform a nominal grid spacing of columns at 40 metres (and therefore main roof arches at 4 metre centres) was adopted. The complex intersection at the corner of Spencer Street and Collins Street where the two spine trusses entwine presented its own construction challenges. This intersection was fabricated in one piece in the workshop off site, strategically cut to enable its transport to site, then reassembled on the ground beneath the supporting columns. The sections were then re-welded into one piece and lifted into its final position as a complete unit. The resulting effect is a remarkable feature of the main entrance to the station.

A full-scale prototype of an 8 metre by 8 metre section of the roof was constructed early in the design development stage. This was intended to not only provide a real-life part of the roof to be reviewed for its architectural aspects, but also to confirm concepts developed for the connection of steel members to steel members, and the connection of ceiling panels and roof sheet purlins to the main structure. Standard connections had to be adaptable for the full range of geometries encountered by intersecting members over the entire roof. The prototype also confirmed a connection detail for the triangulated ceiling panels that cover the entire roof. There are over 7,000 individual triangulated ceiling panels, each with its own unique geometry, however connection details were required that could be applied over the entire structure. From this prototype, more testing was done to replicate the performance and capacity of the ceiling panels.

Although the ceiling panel was a relatively straightforward design, the connection details were unique. The connections had to allow for not only structural adequacy, but also for tolerances associated with steelwork fabrication and erection out of position. The connection also had to allow for movement as the structure was progressively loaded during construction and again at completion under in-service thermal and wind loading. A unique pin/barrel connection was developed which allowed rotation to suit the geometry of the roof, and lateral movement with an adjustable pin for construction tolerances.

A significant number of temporary works were required to stabilise the roof during the construction and to avoid excessive member sizes in the permanent structure to accommodate temporary construction loads. Temporary propping had to be minimised to avoid track pits and commuter traffic on platforms. These temporary works included:

- An arch tie “bow-string” which connected at the base of all primary arches (roof rafters). These were designed to take out the out-of balance lateral forces on the spine trusses prior to the adjacent bay being installed;
- A temporary spine truss prop located midway between columns to provide support for the spine truss until the roof modules were fully completed in adjacent areas of

the roof. As described above, the spine trusses do not have sufficient vertical capacity to carry the weight of the roof. At the completion of construction, the roof structure transfers loads diagonally back to the columns; and

- An adjustable jig stand installed in the median strip of Wurundjeri Way to assemble the large roof modules for installation over the metropolitan lines. This jig had to replicate the changing geometry and the connection details of the spine trusses to which the roof modules were landed. Again, this jig had to be uniquely developed for this roof. The jig was set at the spacing of the spine trusses where the roof modules were to be placed. The jig allowed for vertical adjustment to match the individual locations where the roof module would land in its final position. The roof modules were erected in the jig, but effectively floated in the jig, relying on the arch tie connected at the feet of each arch to maintain the horizontal spread of the arch. This ensured that once the roof module was removed from the jig on lifting, it did not spring apart or contract on lifting, thus maintaining its correct shape (spread on connections) which ensured a correct fit in its final position.

The two systems considered for the roof cladding were zinc and aluminium. Both met the long-term durability requirements for the station, and both were capable of being profiled to the unusually shaped roof. However, the support structure required by each system was totally different. Zinc sheeting, being a soft material, requires a fully supported surface in the form of a curved plywood surface. The ceiling panels for zinc sheeting would have therefore required a curved top surface. This could have been achieved by either curving the top surface of each individual ceiling panel (without visible steps at the joint of each panel) or by building the curved plywood surface in situ after the ceiling panels were installed. The aluminium solution was a standing seam tray deck system, with traditional purlin supports at nominal spacings. Both these systems were trialled on the 8 metre by 8 metre prototype before the aluminium solution was selected.

The aluminium roof sheeting system adopted for the roof is a proprietary system called Kalzip. This system, supplied by Corus Bausysteme from Europe, was chosen for both its long-term durability and its flexibility in both design and installation to accommodate the continually changing shape of the Spencer Street wave roof in three directions. The support system of purlins was a series of circular steel purlins that snaked their way continuously along the entire length of the roof. More than 24 kilometres of unique shaped purlins in nominal 8 to 9 metre lengths were designed, drawn, fabricated and installed on the roof. The circular purlin was ideal for this roofing system as the clip for fixing the roof sheeting to the steelwork had to be preset for location and a correct angle in two directions. This entailed a complex survey set-out to orientate and place the clips prior to landing the roof sheeting.

The roof sheets were individually made. The width of each sheet between standing seams varies across the roof, as does the vertical curve, somewhat like the effect of peeling an orange. The profiling equipment for producing roof sheets was set up in an off-site facility. Flat coil was imported, then cut to length and shape, the standing seam was produced, before a taper was introduced and then finally a vertical curve. Each sheet was required to go through this four stage process. Sheets were then delivered to site and

installed on the clips in their own unique position. A similar process was required for cladding the louvre caps, also in Kalzip. The system creates a unique finish for the outer skin of the station roof.

## **CONCLUSIONS**

The new Southern Cross Station is the most significant piece of public transport infrastructure completed in Melbourne since the 1970s. Its construction on a site that was fully occupied by operational railway activities presented unprecedented challenges for the design and construction team. Their persistence in overcoming the numerous technical and logistical problems, and their ability to work productively with the large number of stakeholders involved, were outstanding features of the project.

The complexity of the project in terms of design, fabrication and construction, plus the unique constraints of the site, challenged the team but also provided opportunities for innovation during project development and delivery. A collaborative approach to problem solving with the project's designers, suppliers and subcontractors enabled innovative solutions to be implemented during construction and led to a successful outcome.

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