Airport Link Project – Design Challenges for the Concrete Roof Structure of the Bowen Hills Ventilation Station Building

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ABSTRACT
The Bowen Hills Ventilation Station is one of three ventilation buildings housing large mechanical ventilation equipment for the Brisbane Airport Link Project, and is located adjacent to the road tunnel structure. The BVS is a 110 m long and 40 m wide partially buried concrete structure, varying between 10 m and 16 m in height. The northern sloped-roof section consists of multi-span composite prestressed precast roof units spanning between 2 m deep precast headstock beams. These beams are in turn supported on precast column capitals and cast-in-situ columns or walls. The design solution optimised structural performance, incorporated unique modelling and detailing to suit the roof shape, and integrated the station with the adjacent road tunnel structure. This paper discusses the design and modelling methods, the strengths and limitations of the software used, and detailing for the roof geometry.

KEYWORDS
Detailing; Modelling; Precast concrete; Prestressed composite; Ventilation Station

PROJECT DESCRIPTION
The Airport Link, Northern Busway (Windsor to Kedron) and Airport Roundabout Upgrades project is a Queensland Government initiative to link Brisbane city to the northern suburbs and airport precinct. Its purpose is to offer a faster, easier route for motorists and public transport users between the Brisbane CBD and the Brisbane Airport, as well as to cater for growth in the northern suburban communities and the city's rising population.

One of the largest road infrastructure project in Australia, Airport Link is a 6.7 km toll road, mainly underground, connecting the CLEM 7 tunnel, Inner City Bypass and local road network at Bowen Hills to the northern arterials of Gympie Road and Stafford Road at Kedron, Sandgate Road and the East West Arterial leading to the airport. It incorporates an integrated network of three ventilation stations, two tunnels, cut and cover structures, and bridges connecting the city and the airport precinct. Project design services include structural, geotechnical, tunnels, traffic, hydraulics, environmental, fire, urban design and acoustics.

INTRODUCTION
A longitudinal ventilation system for each tunnel was incorporated to maintain air quality and includes three ventilation stations: one each in Bowen Hills, Kedron and Toombul. The ventilation system will draw large volumes of fresh air into tunnel portals and then push air along by fans and vehicle movement for collection and high-level dispersion through outlets at each station.

Located adjacent to the tunnel Cut and Cover structure (CC101), the Bowen Hills Ventilation Station (BVS) houses fan equipment, dampers, transformers and attenuators that form part of the ventilation system for the southern end of the road tunnel. A 40m high ventilation exhaust outlet (VSO) is positioned above the southern end of the station roof. An electrical substation is located on top of the BVS at its south-western end. Maintenance access for replacing fans and other equipment is provided through a chamber on the eastern side of the building.

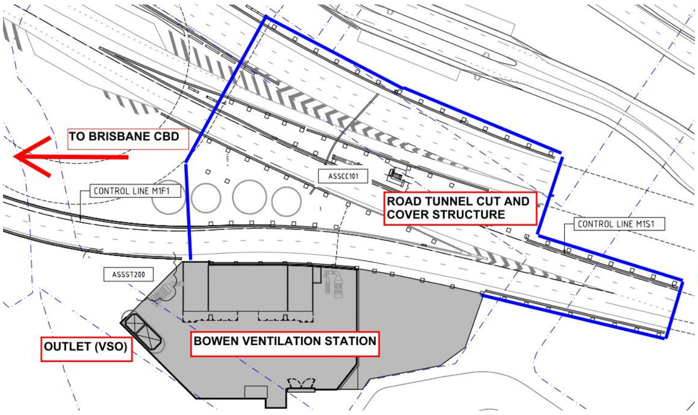

Figure 1. Plan View of BVS and CC101

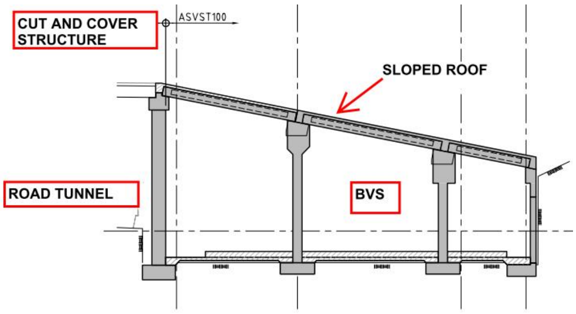

Figure 2. Cross-section at Northern Roof

With a floor area of approximately 4000 m^2, the BVS is largely underground with approximately two-thirds of its roof exposed. While the centre of the BVS is rectangular, the northern and southern parts are irregularly shaped to keep it within the cadastral boundary.

The BVS is divided into two main areas: the northern end containing a suction chamber, whose higher sloping roof is backfilled to form a designated landscape; and the southern end, with a lower, open, flat roof, which houses fan rooms and an exhaust chamber. A retaining wall structure, built on top of the BVS in between the lower and higher roof levels, interfaces with the landscape design. Figure 3 shows an aerial view of the BVS. The BVS shares a common perimeter wall with the adjacent CC101 tunnel.

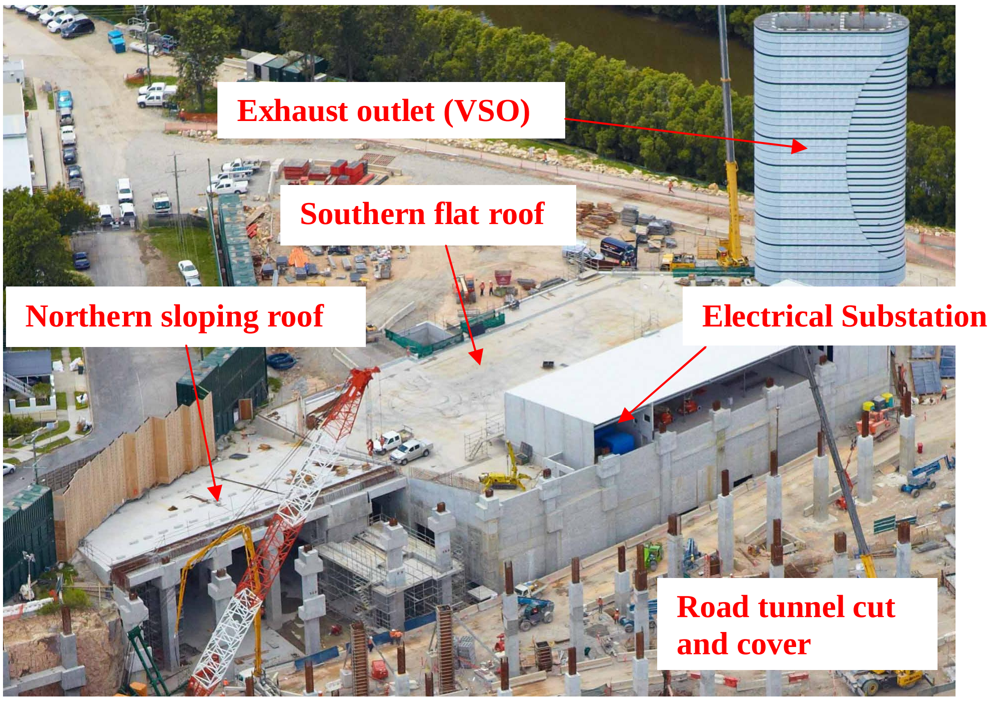

Figure 3. An aerial view of Bowen Hills Ventilation Station in Construction

THE OVERALL DESIGN OF THE STRUCTURAL SYSTEM

The BVS is a conventional reinforced concrete (RC) structure with precast concrete and prestressed concrete elements. Other structural elements include internal concrete and masonry walls fit-out to incorporate separate chambers for mechanical equipment. The connected roof diaphragms of BVS and CC101 act together as part of the overall lateral stability system.

The footing systems include strip footings (under walls) and pad footings (under columns) founded on hard rock. In the temporary condition, the perimeter walls were designed as cantilevered cast-in-situ RC against the stabilised rock surface prior to erection of roof elements and topping slabs which provide lateral support in the completed structure.

The roof structure consists of a combination of concrete composite slabs utilising precast planks and conventional RC slabs and beams. The concrete composite slabs covering two-thirds of the roof are supported by cast-in-situ or precast headstock beams. The completed roof system acts as a horizontal diaphragm and strut at the top of the perimeter walls. The roof diaphragm of the northern section of the BVS connects to the roof diaphragm of CC101.

Supported by the perimeter walls and internal roof beams, the slender VSO consists of pre-clad precast concrete units erected in sequence and progressively stressed together. Stress bar anchorages were cast into the supporting roof beams and the perimeter walls with couplers to provide connection to vertical stress bars in ducts provided in the VSO units. A predetermined number of the VSO precast units were installed each lift, the horizontal joints between units grouted followed by the units vertically stressed at designated locations. The procedure then repeated for the remaining lifts to the top of the VSO and stressing ducts then grouted.

THE ROOF DESIGN AND MODELLING

Modelling

The analysis and design of the BVS northern roof incorporated all stages of the erection of precast elements, placement of wet topping concrete and loads on the composite sections. A three-dimensional (3D) Microstran model (see Figure 4) was developed to analyse all applied loading conditions and sequence of construction. The model consists of the composite roof beams, perimeter walls, internal shear walls and footings to provide the overall lateral stability check for the structure. The results of that model were combined and/or compared with results of a 3D finite element model (FEM) incorporating both the BVS and CC101 structures for analysis of overall stability as described below.

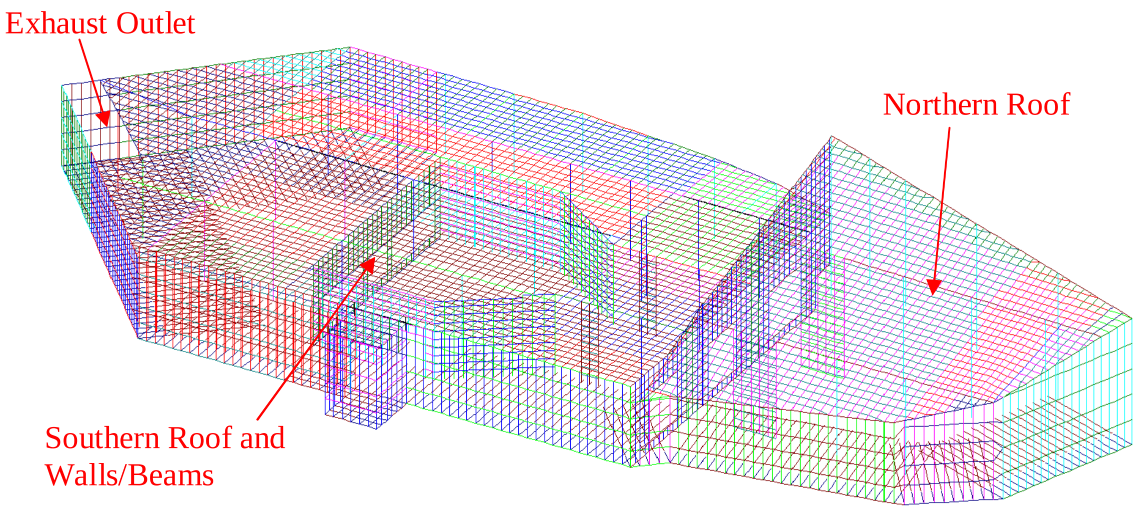

Figure 4. Extract from 3D Microstran Model

Applied loads on the northern roof are categorised as either permanent or temporary. Permanent loads included vehicular loads, internal ventilation air pressure, landscaping backfill and general imposed roof live load. Temporary loads included material loads, staged erection and equipment/crane loads at designated roof areas during construction. Other transient loading conditions including earthquake, temperature, and shrinkage and creep affects are also assessed in the design.

As mentioned in the previous section, the BVS perimeter retaining walls (Northern, Eastern, Southern) are laterally supported by the roof diaphragm through rigid connection in the completed structure. The retaining walls are subject to surcharge loads from backfill above rock levels, vehicular loads, and hydrostatic loads from groundwater in the abutting rock stratum. The reaction from these lateral loads at the top of the perimeter walls transferred into the shear walls via the roof diaphragm to ensure the building's overall stability.

In combination with other load affects, the BVS is also subject to lateral earthquake load. The adjacent CC101 tunnel is structurally integrated with the northern roof of the BVS, but lacks major laterally resisting elements to withstand the seismic effects. Consequently, the design had to incorporate results from analysis of the combined BVS and CC101 structures to access that part of the overall seismic lateral loads would be transferred through to the northern roof diaphragm into the BVS's shear walls.

To investigate the increased seismic load effects on the BVS, the CC101 tunnel was added to the 3D model. However, accurate assessment of the localised effects of concentrated loads around wall/roof openings and wall/roof intersection using Microstran was limited because the model consists simply of lines (representing roof/wall elements) of uniform width. Hence, a FEM program, Strand 7, was used to verify the analysis and assess areas for localised stress (see Figure 5).

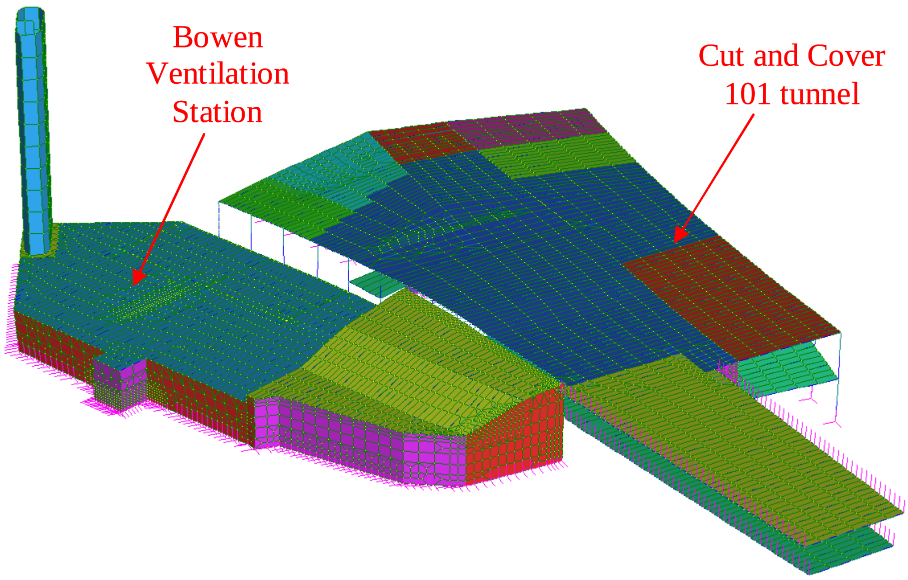

Figure 5. Extract from Strand 7 program

The Strand 7 program also incorporated a 3D modelling of the BVS and the CC101 tunnel to analyse the lateral loads from the retaining walls and seismic loads. Results were extracted from the model and compared to the Microstran model. The larger values of load affects from the two models were used in the final design member capacity check. The results from Strand 7 and Microstran models were close in most areas except for corners, openings and intersections between different structural elements. Reason for the difference in results is Strand 7 is more accurate in determining localised concentrated stresses around complex and irregular elements.

Precast column capitals

In the northern roof area, the precast roof units and headstock beams are similar shapes to the adjacent CC101 tunnel roof system. The beams are supported on the BVS perimeter walls and precast column capitals resting on cast-in-situ columns. Each precast column capital has a hollow core, which allowed starter bars from the column underneath to pass through and connect to the roof topping slabs. The hollow core was then grouted to ensure the column integrated fully with the roof diaphragm (see Figure 6).

The top of the capital is sloped to suit the roof profile and to provide a stable bearing surface to support the beam and roof units. As the beam and roof units were erected at different stages, the design analysis capital accommodates for eccentric loadings for varying roof spans and loadings on all four sides of the capital. Finite element analysis was used to analyse the load behaviour on the capital for the grouted and ungrouted core conditions, and to design the reinforcement in the precast 'shell' of the capital.

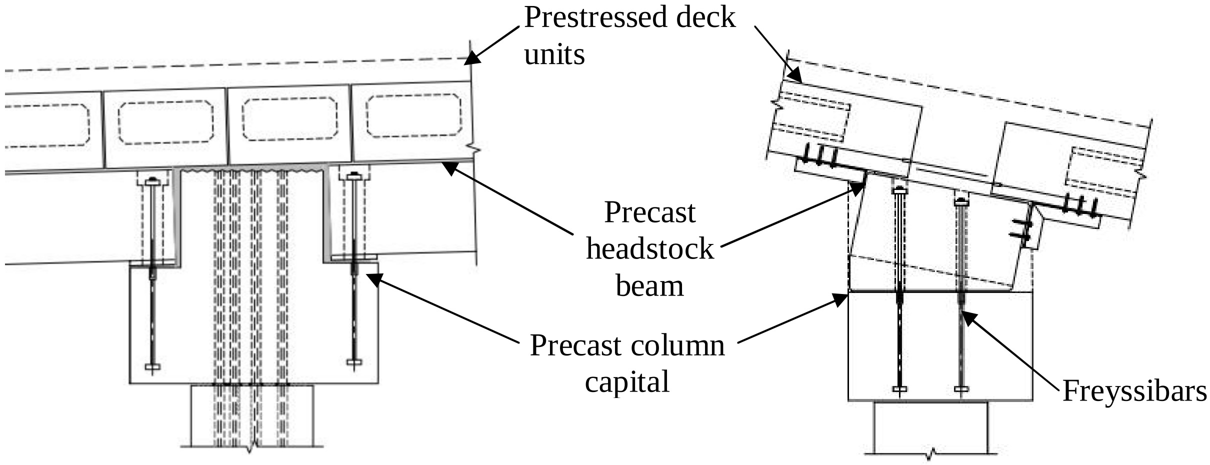

Figure 6. Column capital cross-section **Figure 7.** Headstock cross-section

Headstocks and beams

Precast headstock beams and cast-in-situ beams have been used in the northern roof and the southern flat roof respectively. Figure 7 shows a typical cross-section of the precast headstock beam located in the northern roof.

In the northern area, precast headstock beams are designed to span large distances between internal columns/walls and to support self-weight, temporary construction loads, the roof units, wet topping concrete and other imposed loads. Analysis of the temporary load conditions were analysed for all erection stages and combined with load effects on the completed structure as appropriate.

The remaining southern areas of the BVS generally consist of internal cast-in-situ load-bearing walls running in a north–south direction. Cast-in-situ beams were placed above the load-bearing walls before the precast roof units were erected.

Like the precast column capitals, the headstock and the cast-in-situ beams are also subject to eccentric load effects due to the varying roof spans and erection sequence of roof units. Design checks were carried out on roof beams to satisfy these uneven loading effects in section design. Once a designated section of the roof units were erected, the topping slab is cast, which fully restrains the beams via the roof diaphragm, greatly reducing the eccentric load effect. Thermal stresses were also accessed for this exposed roof area and the results combined with output from the Microstran analysis.

Prestressed roof units

The Beam Module of SAM Leap-5, a bridge software package, was used to design the sagging moment of the prestressed roof units. These deck units are 1200 mm wide x 800 mm deep (Figure 8). Figure 8 shows the varying lengths of roof units that were analysed and designed to manage the different loading conditions on the roof structure, such as the varying soil level above and monorail loadings hung from the roof soffit.

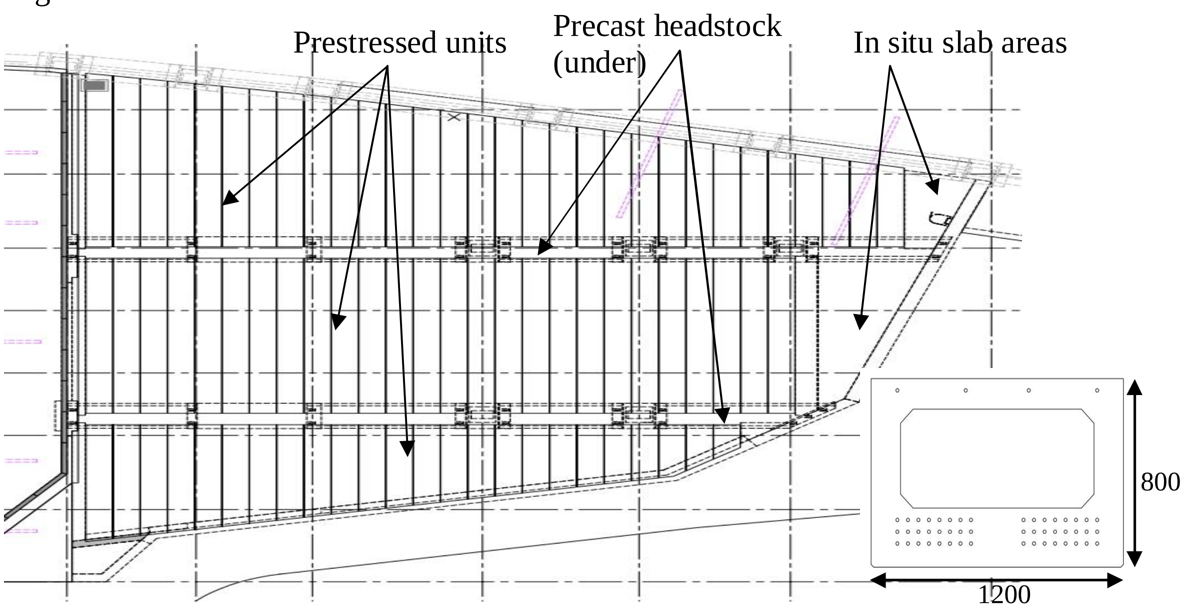

Figure 8. Roof plan and a cross-section of a typical prestressed unit

The designer enters the different loading conditions, factors and combination for each of the units into the software, which then analysed the beam and provides the stresses and bending moment results and the allowable capacity. The results provided were: stresses at transfer stage, beam erection stage and construction stage; final condition bending moment; and shear forces. If stresses do not satisfy the design requirements, the software allows the designer to adjust the inputs until all conditions are met. Figure 9 shows a typical output produced by SAM Leap-5 — in this instance, the design stresses and stress limits of the final condition a composite beam.

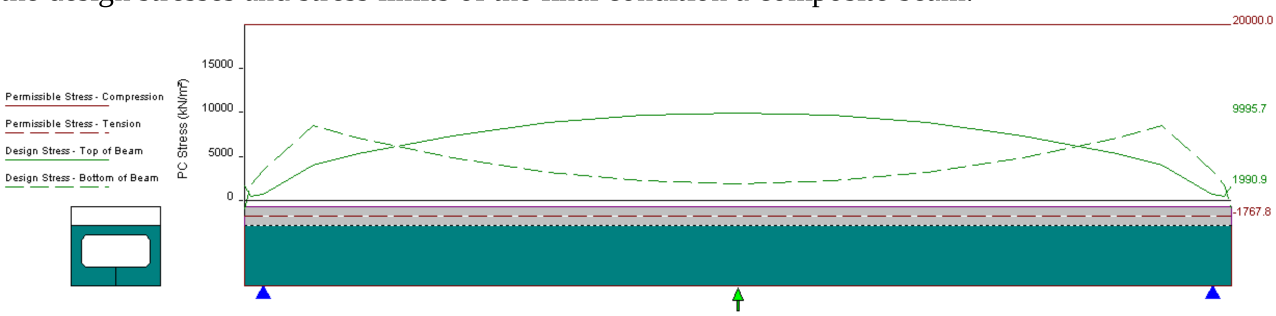

Figure 9. Typical output by SAM Leap-5

The software analyses the units as a simply supported element. This provides a conservative design for the units in the final condition in composite roof construction where units perform as a continuous beam when the topping slab is cast as shown in Figure 10. However, this software does not calculate the hogging displacement of the prestressed unit; this is its only disadvantage. This figure was calculated separately using the output stresses from the software.

Topping slab

The Microstran 3D model was used to design the hogging moment in the composite slab cast above the prestressed unit (See Figure 10). The section properties obtained from SAM Leap-5 for the overall composite section was input to Microstran to give the model representative stiffnesses. The same loading conditions and factor in the prestressed roof units were used, and the model was analysed accordingly. The worst scenarios for the ultimate and serviceability hogging bending moment were obtained from the 3D model. The ultimate bending moment was then checked against the capacity from SAM Leap-5. The reinforcement stresses under serviceability condition were checked separately to satisfy the allowable stress conditions. Reinforcement in the slab was adjusted until both ultimate and serviceability limits are satisfied.

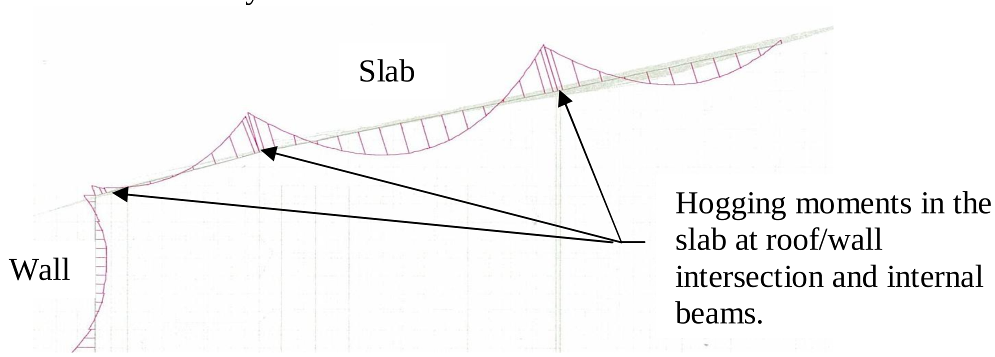

Figure 10. Typical bending moment diagram output by Microstran

The topping slab is also subjected to axial and shear forces as part of the roof diaphragm actions. The maximum force comparing output between Strand 7 and Microstran modelling used to design the slab axial and shear capacities of the system.

ROOF DETAILING

Composite roof

The northern roof system of the BVS required careful detailing and design assessment given the irregular shape and sloped roof. Roof's precast units were orientated to suit the sloping roof profile and were progressively erected on each side of the precast headstock beams. Temporary restraints were provided to tie the precast roof units to the side faces of the precast headstock beams to maintain stability in all stages of erection on the sloped roof. These restraints later removed when the composite topping slabs and the roof diaphragm action achieved sufficient strength to restrain lateral movement.

The composite precast units were designed to resist both sagging and hogging bending moments to allow for thermal expansion and contraction in the roof system in addition to the normal loading conditions. To achieve this design requirements, threaded bottom reinforcing bars with couplers protruding from the end faces of the precast units were provided above internal support beams, and lapped with protruding bars from opposing units (see Figure 11).

Where hangers for internal monorails were required to be fixed to the underside of roof units, internal diaphragms in the units were provided to facilitate the connection design and allow anchors to be positioned clear of prestressed strands.

Landscaping backfill and retaining walls were placed on top of the sloping roof slab with a tanking membrane providing water proofing for the roof structures. A cover protection slab is placed directly over the membrane. Given the low frictional resistance provided by the roof membrane, concrete shear keys were designed to provide adequate sliding resistance to the cover slab and landscape retaining walls to this area of the roof. The shear keys are integral with the topping slab of the composite roof system.

Headstock beams

As mentioned previously, the headstock beams were subject to eccentric loads from the precast units due to uneven load configuration. Two restraining Freyssibars (see Figure 7) were provided to connect each end of the headstock beams to the column capital. The Freyssibars were designed to resist tensile loads derived from overturning moment at the beam supports for all stages of erection and in the completed structure.

As well as being supported on internal column capitals, the headstock beams are supported on perimeter retaining walls at the roof's northern end. The walls form an acute angle to the headstock beams due to the irregular shape of the roof. To suit these wall boundary conditions, the precast headstock beams were cast with angled/profiled ends and as with the column capitals, Freyssibars were used to restrain the beams to the walls and designed to resist overturning forces. Additional downturn at each end of the beam was cast and detailed to provide a flat surface for bearing to the underside of the precast headstock beam (see Figure 11).

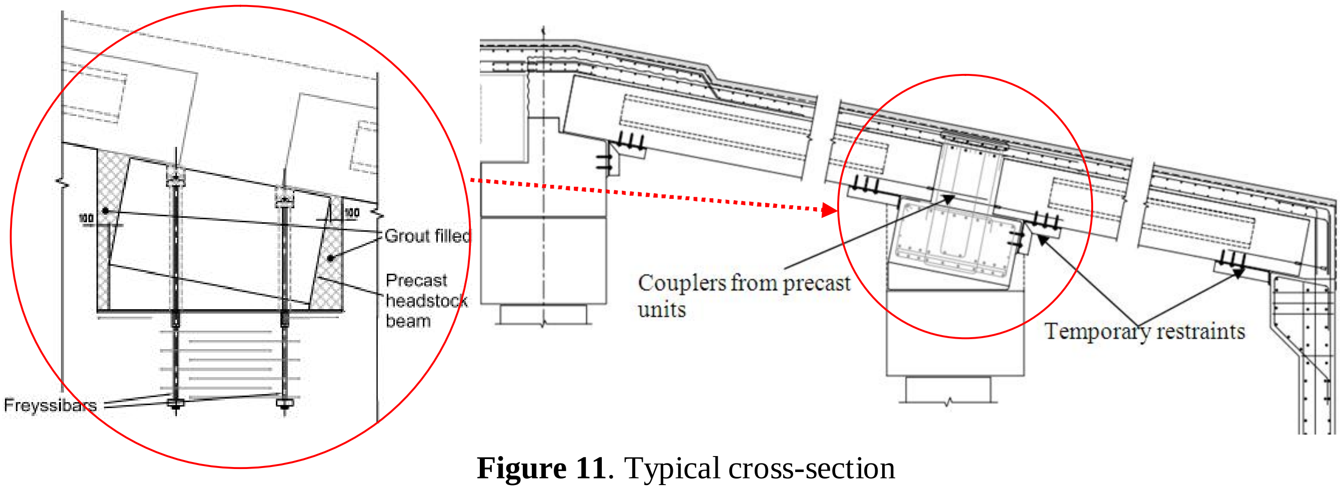

Figure 11. Typical cross-section

CONCLUSION

The BVS illustrates effective techniques for engineering design modelling, analysis and detailing under challenging conditions when mainly precast roof elements are to be used in composite construction. It demonstrates how designers can validate the designs using different but complementary software, and current design tools incorporating constructability for complex geometry structures.

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