The design of Padma Multipurpose Bridge – challenges and solutions in design of the river spans

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ABSTRACT: At 6.15km in length the Padma Bridge will be a landmark structure in Bangladesh and one of the great river crossings of the world. In designing the bridge, consultant AECOM, has faced many major engineering challenges, particularly from the local environment. During the monsoon season the Padma River can become a fast flowing river, susceptible to deep scour, requiring deep piled foundations. The bridge site is also in an area of considerable seismic activity, leading to significant seismic loads being applied to the structure. To design the bridge, advanced computational analysis and engineering solutions have been employed, in order that the bridge will be able to meet the challenges of nature during its long life.

1 INTRODUCTION

1.1 *General*

Padma Multipurpose Bridge will be a landmark feature in Bangladesh when completed. The Padma River is one of the world's great rivers, with an overall width in excess of 6km at the crossing point. The design of a bridge has been a major challenge with the river changing in nature dramatically during the monsoon season, when the flow rate and major fluctuations in river bed level threatening to undermine any bridge piers. The bridge is also to be constructed in a region of strong seismic activity, which when combined with the deep scour leads to a very onerous design condition.

The Bangladesh Bridge Authority appointed AECOM as Design Consultant for the project. AECOM carried out a rigorous review of previous studies carried out on the bridge, before investigating in detail a series of different bridge forms. A two-level steel truss bridge, with composite concrete top slab was selected as most appropriate, with the highway running on the upper concrete deck and the railway on the lower level.

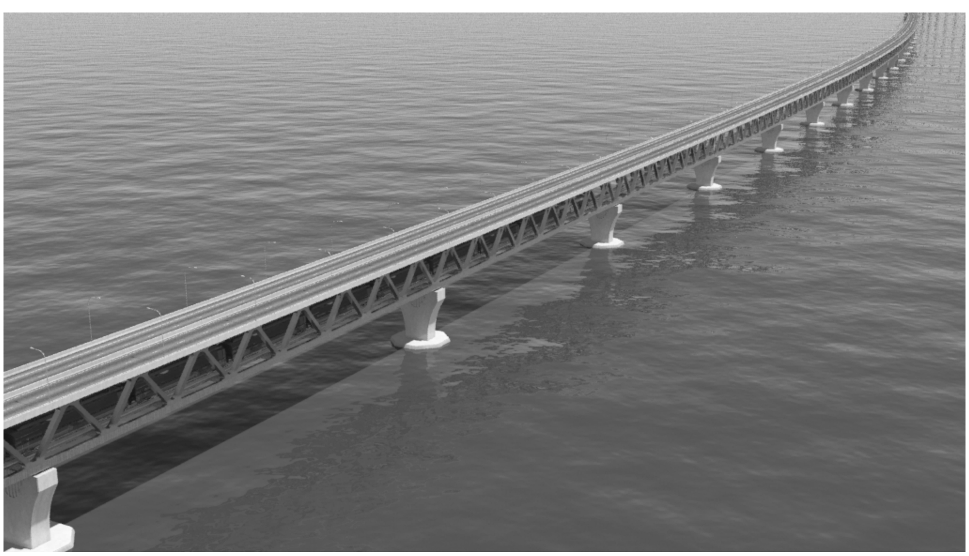

Figure 1. Padma Bridge will be a two-level structure with the highway running on the top concrete slab and the railway running between the chords of the truss.

1.2 *Multipurpose bridge*

Padma Bridge is a multipurpose structure carrying a highway, railway and utilities, including a gas pipeline and telecommunications cables. The two level structure of the bridge enables the road, railway and utilities to be arranged in a logical manner with good access for maintenance and inspection. The bridge is also provided with emergency access points in order to facilitate evacuation of a train on the bridge (Tapley, Sham & Holmberg, 2010).

2 DESIGN CRITERIA

2.1 *Selection of suitable design codes*

Detailed investigations were carried out to determine the most suitable set of codes for designing the bridge. The three options available were:

The British bridge design code BS 5400
The American code AASHTO LRFD Bridge Design Specifications
The recently released Eurocodes

BS 5400 was selected as it was felt that the highway loading criteria most closely corresponded to the situation expected in Bangladesh. Trucks are often heavily loaded, matching the load patterns predicted within the British standard. Eurocodes have been calibrated to give similar results to BS 5400, but some of the principles therein have not been studied in detail for such a major project outside of Europe and consequently were deemed unsuitable for the project, before a detailed study of the application of Eurocode in Bangladesh has been completed.

The railway crossing the bridge will connect to the Indian National Railways and hence railway loading has been based the codes adopted on that system. More particularly the bridge has been designed to be part of a Dedicated Freight Corridor (DFC), which implies an even higher loading than usual with a load of 32.5 tonne per axle.

2.2 *Seismic design criteria*

Padma Bridge will be constructed in an area of high seismic activity and consequently earthquakes are a critical consideration in the design. Bangladesh University of Engineering and Technology (BUET) has carried out a detailed study of the seismic hazard at the site to determine suitable seismic parameters for use in the design. Two levels of seismic hazard have been adopted:

Operating Level Earthquake (OLE) has a return period of 100 years a 65% probability of being exceeded during that period. In such an earthquake the bridge will experience a peak ground acceleration of 0.052g and shall remain operational for all traffic after such an event.

Contingency Level Earthquake (CLE) has a return period of 475 years with a 20% probability of being exceeded during the life of the bridge (100 years). The peak ground acceleration for such an event is 0.144g in the dense sand at -120mPD. Any damage sustained from such an earthquake shall be easily detectable and capable of repair without demolition or component replacement.

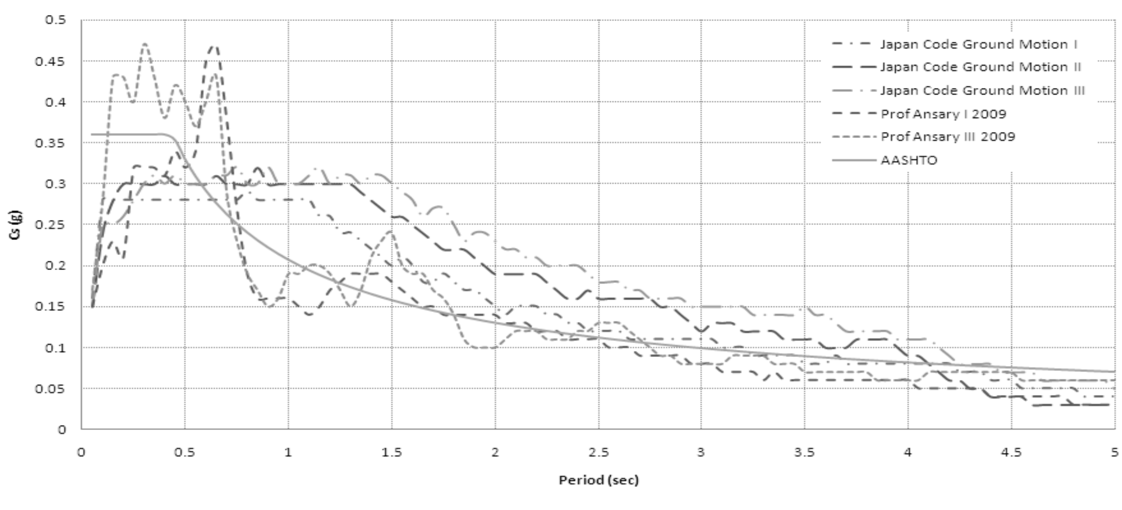

Figure 2. Response Spectra for CLE have been derived from the site specific study conducted by Professor Ansary and also the Highway Bridge Design Specification Part V: Seismic Design by the Japan Road Association

For such a major river crossing a step-by-step nonlinear time history analysis has been undertaken based on five AASHTO spectrum-compatible acceleration time histories representing the earthquake loading at the elevation of -120 m PD (refer to Figure 2).

2.3 *Foundation scour*

The other critical design criterion for the bridge has been scour. There are large fluctuations in the volume of water flowing along Padma River, having an impact both on the course of the river and the depth of river, particularly when bridge piers cause blockage to the flow. As a consequence extensive river training works will be required around the bridge (McLean, Neill & Oberhagemann, 2010) and the bridge piers have to be designed for potentially severe scour conditions.

Scour can essentially be divided into two parts:

General scour – due to the action of the river and independent of any bridge constructed in the river; and

Local scour – due to an obstruction to the flow such as a bridge pier.

General scour has been studied by reviewing the data from the river over the last 40 years. River depth measurements have been taken on a regular basis and give a good indication of how the river changes during the monsoon season. For local scour model tests have been carried by sub consultant Northwest Hydraulic Consultants at its test facilities in Canada. Various foundation configurations have been studied, with the scour varying by over 7m depending on the piling configuration.

For a 100-year return period, the riverbed level has been determined to be -46.7m PWD near the river bank and -35.0mPWD towards the centre of the river. From the experimentation carried out in Canada, local scour is estimated to deepen the scour by a further 15m for a raking pile arrangement, or 20m for fifteen vertical piles.

2.4 *Combining loads and environmental effects*

The load combinations given in BS 5400 Part 2 have generally been followed, but this code does not adequately cover how to combine seismic loading, ship impact and scour of the foundations. In particular the effect of scour has been given special consideration as the nature of the Padma River is unique. Scour can occur over prolonged periods and when infill of scour holes later occurs, the material that fills the holes is loose and remains uncompacted for a long period after the event. The loose material will be susceptible to liquefaction and therefore cannot be relied upon during a seismic event.

With the liquefaction of the compacted fill material being a serious concern, scour with a 100-year return period has been adopted to be combined with loading from a seismic event. In the case of ship impact, liquefaction of the infill material is not considered a problem, and therefore a lesser return period of 10 years for scour has been adopted. Suitable partial safety factors have been selected to reflect the probability of occurrence of the events.

3 SCHEME OPTIONS

3.1 *General*

In previous studies for the bridge a number of options for the bridge form had been examined, with the final choice being a single-level extradosed bridge with spans of 180m. AECOM undertook detailed investigation of this bridge form by extensive finite element modelling, the model from which is shown in Figure 3. An extradosed bridge is a concrete box girder bridge, which uses stay cables to supplement the box girder thus reducing the structural depth. The railway however has very tight tolerances on displacement and rotation, and in order to meet these tolerances the girder would need to be stiffened, reducing the benefit of the stay cables and increasing the weight of the deck. With poor ground conditions and onerous loading combinations, it was critical to minimize the loads to the foundations, as the foundation costs would form a large proportion of the overall cost of the bridge. Consequently the extradosed bridge was not the preferred option.

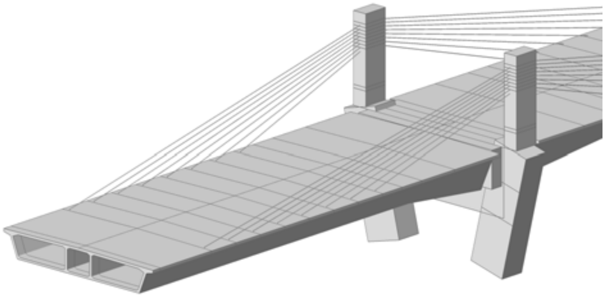

Figure 3. MIDAS model of an extradosed bridge

3.2 *Alternative bridge forms for two-level bridge*

Alternative concrete deck forms were investigated. Three examples are shown in Table 1, an extradosed concrete truss bridge, a concrete girder bridge and a steel truss bridge. In all cases a two-level structure was adopted as there are significant advantages over the single level structure:

- Separate highway and railway envelopes enable improved operation, inspection and emergency evacuation procedures for the bridge.
- The maximum permissible gradient on the railway is 0.5%, requiring long lengths of approach viaduct for the railway to descend to ground level. By reducing the structural depth beneath the railway (in a two level structure the railway runs inside the structural section), the length of the railway approach viaducts can be minimized.
- Construction cost – a two-level structure is more efficient, with a much reduced overall width of the structure.

Table 1. Comparison of Alternative Bridge Forms

Bridge Form		Advantages	Disadvantages
	Extradosed Concrete Truss Bridge	Truss structure enables significant weight savings over box girder solutions. Use of stay cables increases potential span lengths.	Truss connection details would be difficult to construct leading to a longer construction period and additional cost. Heavier than steel deck solutions.
	Twin Box Girder with the Railway Carried by an In Situ Concrete Slab Spanning between the Boxes	Straightforward erection method, similar to other major bridges in Bangladesh.	Heavy girder leads to increased demand on the foundations and shorter span lengths. Increased cost for foundations and deck due to additional weight Completely enclosed railway is a potential safety hazard.
	Steel Truss Bridge with Composite Concrete Top Slab	Steel truss is the lightest option, leading to a reduced number of piles and lowest overall cost. Truss is rigid and does not deflect excessively under rail loading.	Steelwork will require repainting at regular intervals

Analytical models were developed for each of the bridge forms to determine member sizes and in particular the weight of the superstructure. The steel truss bridge was found to be the most efficient with the lightest deck. Further studies were conducted on this option to determine the optimum span length. Overall deck weight and foundation loads were compared for three span lengths: 120m, 150m and 180m. From this data a construction cost was estimated for each span length with the optimum span length found to be 150m.
The conclusion of the studies carried out on bridge deck, was that the steel truss bridge with a concrete top slab acting compositely with the truss, would be the most economic and suitable bridge form for the bridge.

3.3 *Foundation form*

In conjunction with these studies, further analysis has been carried out on the optimum form for the foundations (Sham, Yu & De Silva,2010). Two types of pile were investigated:

- Large diameter (3m) raking steel tubular piles and
- Large diameter cast in situ concrete bored piles

The raking piles were found to be more efficient in resisting lateral loads resulting from earthquake motions. The lateral loads are resisted as axial forces in the steel piles. For the concrete bored piles the lateral loads are resisted by the flexural capacity of the piles. The very large bending moments generated by a seismic event dictated that insufficient flexural capacity could be generated by reinforcement alone, a permanent steel casing would required to enhance the capacity down to 10m below the riverbed level, which for a 100-year scour event would be -61mPWD. It would also be necessary to have more than fifteen 3.0m diameter vertical concrete piles, compared to eight raking steel tubular piles. The large number of piles increased the weight of the pile cap and also the local scour. All of these factors had an adverse effect on the cost and constructability of the foundations and hence the preferred solution was recommended to the raking steel tubular piles.

4 METHODOLOGY OF SEISMIC DESIGN

4.1 *Analytical method and model*

A 3-dimensional non-linear time history dynamic analysis has been performed for the Main Bridge to determine the impact on the structure of seismic action. For the plan alignment of the main bridge, the subtended angle is less than 18 degree (the radius is 3000m and one module of the Main Bridge is 900m) and consequently the structure may be modelled as a straight line in plan.

The behaviour of the bridge is complex due to its height (120m when the effects of scour are considered) and the large mass of the superstructure, pile caps and piles. A three dimensional non-linear time history dynamic analysis, using a modified Penzien model, has been adopted for carrying out the design. This model is divided into two parts, the structure and the free field soil. The interactions between the structure and the free field are simulated by lateral spring links. In order to determine the equivalent shear modulus and effective damping ratio between each layer of the soil, free field analysis has been carried out beforehand by program SHAKE. Subsequently, a 3-dimensional dynamic analysis has been carried out using the equivalent shear modulus and effective damping as input data.

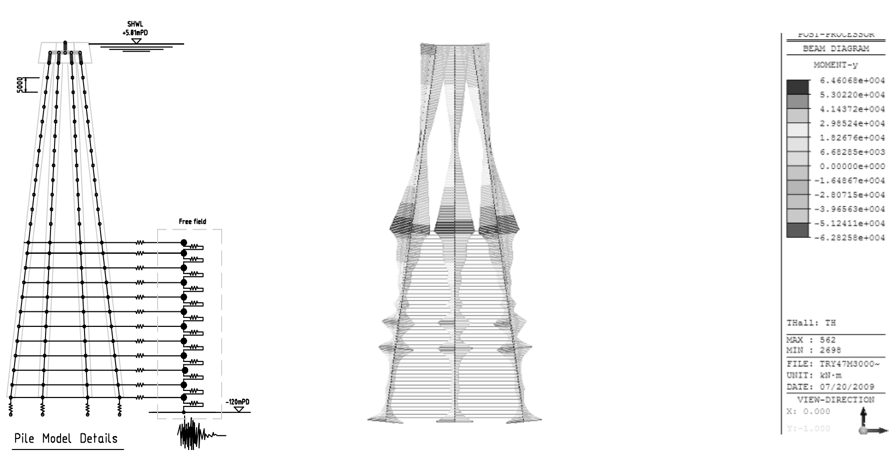

Figure 4. Modified Penzien Model and Results for Raking Pile Foundations

The ground motions shown in Figure 2 were applied to the model to simulate the earthquake case and loads were generated in the piles and substructure accordingly. Other load combinations were considered such as ship impact and wind, although generally these effects were not found to be critical for the substructure, the seismic load combination dictated the design.

A further global model was developed to investigate the global behaviour of the bridge. The bridge is divided into six span modules, each span of 150m. The global model examined an individual six span module and applied different levels of scour at each pier. A scour hole may form around an individual pier, or it can form around two or more piers. The global model looked at various combinations of scour on piers, in order to determine the critical axial load, shear and bending on the foundations of any particular pier.

4.2 *Seismic isolation*

Initial studies of the bridge were based on the deck being supported off its piers by traditional sliding bearings, with the point fixity being the central pier of the six-span module. To avoid the fixed pier being heavily loaded during a seismic event by a longitudinal translation, shock transmission units (STUs) were provided at the free piers to ensure even load distribution between the piers. The loads applied to the piers were however still large and therefore as part of a Value Engineering process, alternative forms of articulation were examined.

Isolation bearings have been used worldwide to mitigate seismic response by isolating structures from seismic input. Isolation bearings can accommodate thermal movements with minimum resistance, but will engage under seismic excitations. In this strategy, all primary structural members will remain elastic without any damage (or plastic hinging).

Isolation bearings comprise the following key elements: an element that provides rigidity under service loads and provides lateral flexibility beyond service loads, an element that provides self-centring capability and an element that provides energy dissipation. These key elements have to be properly designed and fine tuned to achieve an optimal seismic behaviour.

Analyses indicate that seismic forces can be greatly reduced by replacing the conventional pot bearings with isolation bearings. Friction pendulum bearings use the characteristics of a pendulum to lengthen the natural period of the isolated structure so as to reduce the input of earthquake forces. The damping effect due to sliding mechanism also helps mitigating earthquake response. Since earthquake induced displacements occur primarily in the bearings, lateral loads and shaking movements transmitted to the structure are greatly reduced.

The reduced seismic loading generated at the top of the piers, leads to significantly reduced pile loads. With the conventional scheme of bearings and STUs, eight raking steel piles were required for each pier, with seismic isolation this number of piles can be reduced to six, leading to a saving in foundation cost of greater than 20%.

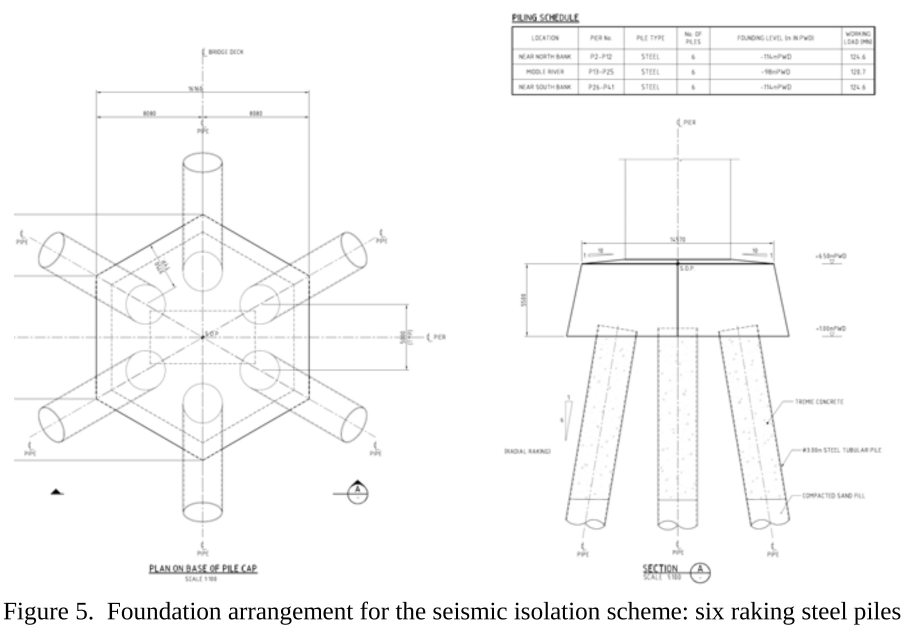

Figure 5. Foundation arrangement for the seismic isolation scheme: six raking steel piles

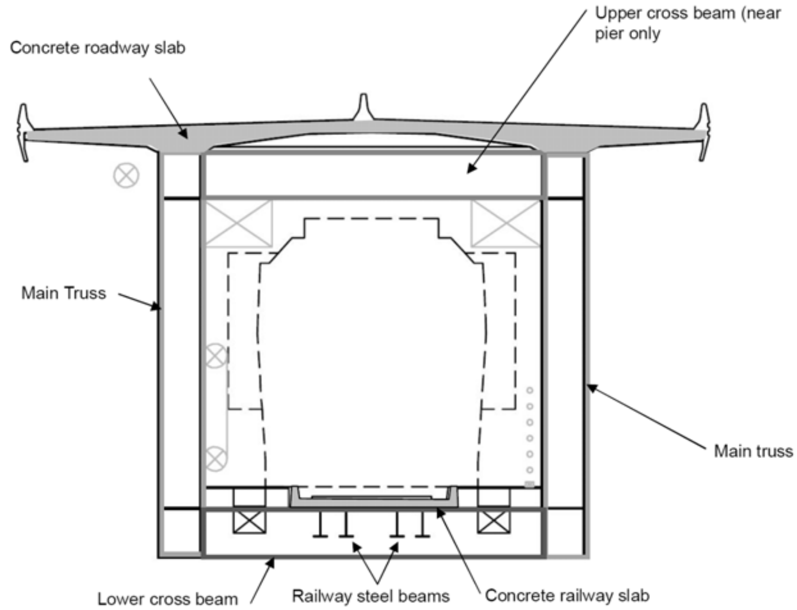

Figure 6. Typical cross section of the main bridge

The impact of the seismic isolation scheme is not however limited to the substructure, the reduced seismic loading leads to reduction in section sizes for truss members, with an overall saving in truss steelwork of greater than 4%.

5 STRUCTURAL ANALYSIS OF SUPERSTRUCTURE

5.1 *Bridge deck cross section*

Figure 6 shows the typical bridge deck cross section. The highway runs along the concrete top slab, which is designed to act compositely with the steel truss for live load effects. The railway runs between the truss planes at the lower level. It also runs on a concrete slab, the slab being supported by four steel beams, located beneath the wheels. The slab shown is structural and it will include fixings to connect to the track slab. The cross section also shows the intended locations of utilities such as a high pressure gas pipeline and telecommunications ducts. Walkways will also be provided to each side of the railway for inspection and maintenance purposes and also emergency evacuation routes.

The top chord, bottom chord and diagonal members of the main truss are in the form of hollow steel boxes. Plate thicknesses of the boxes vary depending on the location of the member. For thin plate thicknesses, longitudinal stiffeners are present to increase the efficiency of the section in resisting compressive stress. Box sections are also adopted for other members including the lower cross beams and upper cross beams. The concrete roadway slab is reinforced concrete in the transverse direction, and is a prestressed concrete structure in the longitudinal direction. The longitudinal prestress will be carried out before the composite connection is established such that no additional stresses will be generated in the steel truss members. The railway concrete slab is reinforced concrete with no prestress. For all steel members except railway slab beams, the steel grade shall be S420M for plate thickness up to 40mm and S420ML for plate thickness over 40 mm. For railway slab beams, the steel grade shall be S355M.

5.2 *Global model*

Global models were developed using the analysis package MIDAS for the superstructure. There were three models each representing different stages in the construction of the bridge:

- An initial model of a simply supported span of the truss without concrete top slab, representing the stage when a single span of the truss is lifted into place (see Figure 7).

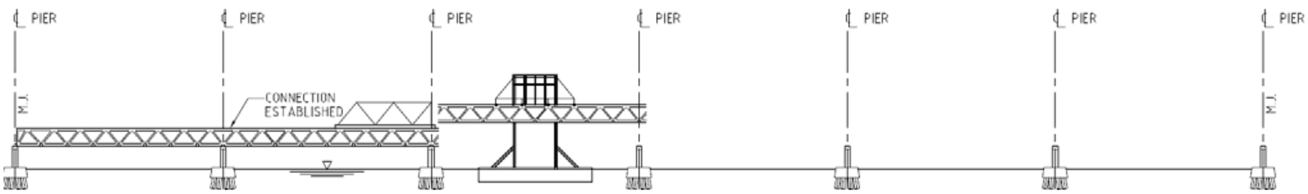

Figure 7. Deck erection is anticipated to be by lifting and placing individual spans

- A second model of a complete continuous module of the bridge without the concrete top slab, representing the stage when the steel trusses are connected together but prior to the placing of the concrete slab (see Figure 8).
- A final stage model of a complete bridge module including concrete deck slab.

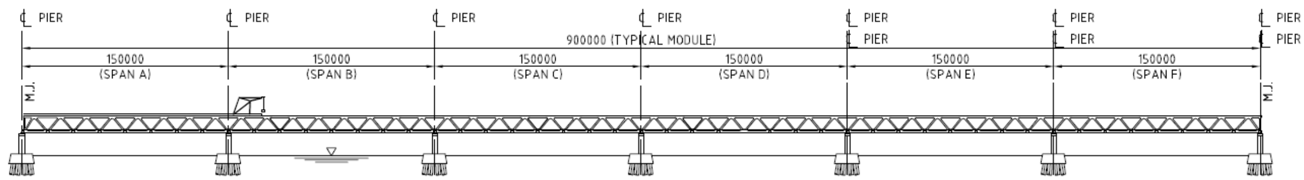

Figure 8. Placement of the deck slab will take place after completion of the steel truss for a six-span module

The bridge is modelled for the tightest bridge curvature, a radius of 3000m. Although the deck is curved the trusses are straight over each span, angular changes for deck curvature concentrated at the support points.

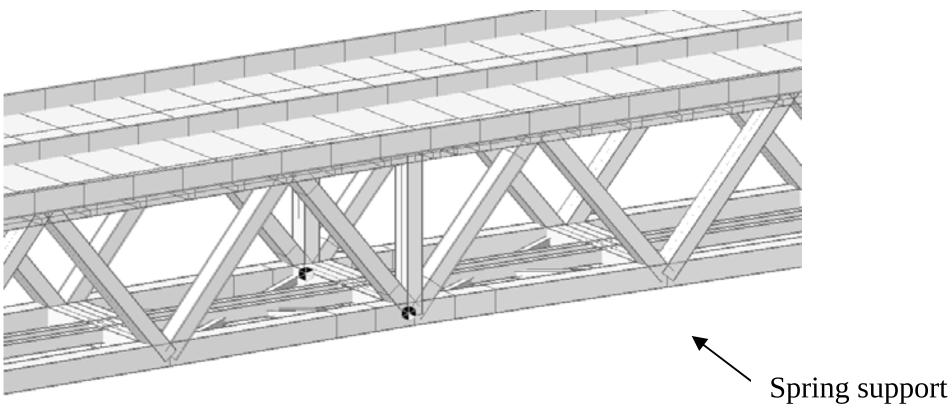

Figure 9. Extract of analytical model of superstructure

At each pier location, the truss is supported on elastic springs. Only translation stiffness is present and there is no rotational restraint as the truss is supported on seismic isolation devices. The stiffness of these elastic springs represents the stiffness of the pile group. Figure 9 shows part of the global model and the location of the support springs. The spring values are derived in a separate pile group analysis and are given in Table 2.

Table 2. Spring stiffness for analytical model of superstructure

Stiffness	Spring Constant (scour @ -20 mPD)	Spring Constant (scour @ -62 mPD)
Transverse	52 kN/mm	33 kN/mm
Longitudinal	19 kN/mm	12 kN/mm
Vertical	1700 kN/mm	

Two further models were used in the analysis of the superstructure.

- *Plate element model.* The concrete top slab includes longitudinal prestressing tendons to ensure there is no significant cracking of the slab over the piers when acting compositely with steel truss. A plate element model was developed to investigate the stresses in the slab, with the steelwork and slab members being modelled discretely. The model was also used to investigate the effects of shrinkage and creep of the concrete and also the effect of transverse wind acting on the slab.

- *Concrete Slab Solid Element Model.* In order to investigate the effect of highway loading on the concrete deck slab, a separate model of solid elements was developed to determine the critical bending moments and shears in the slab. To limit the overall thickness of the slab, transverse ribs at 2m centres are provided to enhance the transverse bending capacity of the deck. Figure 10 shows the solid element model.

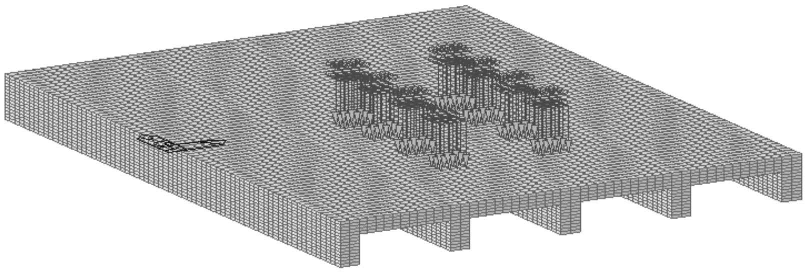

Figure 10. Solid element model of the deck slab with 45 units of HB vehicle load applied

5.3 *Railway deck*

The railway will be supported by four steel beams acting compositely with a concrete deck slab. A special model was prepared, composed of four longitudinal composite sections, connected by transverse members and cross beam at each end. The composite sections are steel universal beams. The width of concrete slab is 1295mm and height of 200 mm. For the steel girder, the adopted steel section is UB - 914 x 419 x 388.

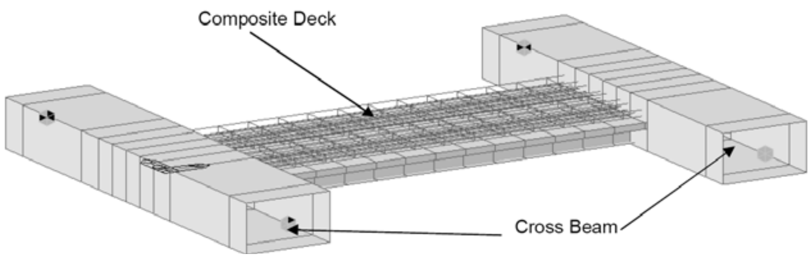

Figure 11. Modelling of railway track slab and its connection to the cross girders between the truss lower chords

Beam end releases are added at the connection point of composite decks and cross beams, so that no hogging moment is induced at these points on the composite decks and to simulate a shear connection between the deck and cross beams (see Figure 11). Three different types of railway live load have been applied on the composite deck section (railway deck) to simulate different wheel patterns. Since the bridge is curved on plan, there exists a maximum transverse offset of 500 mm between the railway alignment and composite deck centreline at the tightest radius. Consequently for each load type, two cases are considered: one for the railway load applied along the deck centreline, and the other for the railway load when shifted transversely by 500 mm.

6 CONCLUSIONS

The Padma Multipurpose Bridge will stand as a landmark structure in Bangladesh, not only providing a vital communications link, but also signalling another milestone engineering solution in a region of extreme environmental hazards. The combination of deep scour and regular seismic activity has required design consultant AECOM to apply state-of-the-art bridge technologies to robustly integrate bridge design with construction to ensure the bridge will not only serve the Bangladesh people of today, but also many generations to come.

7 ACKNOWLEDGMENTS

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