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Cracks in the box girders of Bongobondhu Jamuna Multipurpose Bridge-Identification of causes based on FE analysis

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ABSTRACT: The Bongobondhu Jamuna Bridge is at present the longest bridge of Bangladesh. The bridge has 48 spans, each having an approximate length of 100m. Thus, the bridge, when constructed also stood as the 11th longest bridge in the world. The role of this bridge in the economy of Bangladesh is vital as it provides strategic economic road-rail-energy-telecommunication link between northern and southern part of the country, by crossing the Jamuna River, one of the widest river of the world. Superstructure of the bridge is of prestressed concrete box girder constructed using balanced cantilever segmental construction technique. During March 2006-June 2006, BUET experts worked to identify the causes of extensive cracking of prestressed concrete deck, web and pear head units of almost all segments of the Bridge. The cracks were identified primarily on the longitudinal direction of the bridge deck with some secondary crackings also in the transverse direction. In the analytical investigation, three dimensional model of the bridge was developed in finite elements technique. The results of the analysis are discussed in the paper to show the design deficiencies for the loads the bridge is experiencing. The presentation ends with recommendations for remedy.

1 INTRODUCTION

The Bongobondhu Jamuna Multipurpose Bridge has a history of cracks from the beginning of construction (Hyundai 1997 (Annexure D), RPT-NEDECO-BCL 1998 (Annexure B)). The cracks appeared during construction were located at east approach viaduct, pier head units (first 13 units), deck slab surface, underneath of the soffit, hinge segment, 6E segment adjacent to the hinge segment, pile cap shell and the pile stem. After the increase of severity of cracking, the occurance of major cracks, the Jamuna Multipurpose Bridge Authority (JMBA) requested the experts of the Department of Civil Engineering, Bangladesh University of Engineering and Technology (BUET) in March 2006 to conduct a “3-D Finite Element Analysis” and to identify the possible causes of cracks in the Jamuna Bridge.

Figure 1. Longitudinal cracks along the box centre line (at top surface of the deck). Segment number: 959. Photo taken on 23 March 2006.

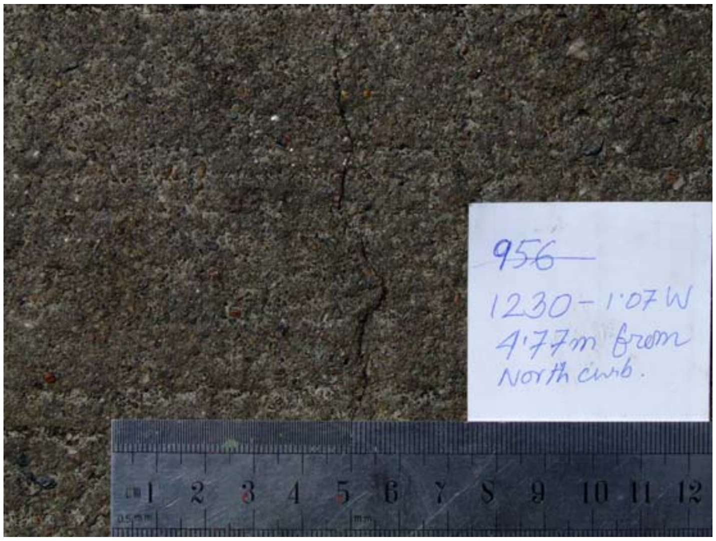

Figure 2. Longitudinal cracks along the box centre line (at top surface of the deck) (at top surface of the deck). Segment number: 1230. Photo taken on 24 March 2006.

BUET team considered the reports (Hyundai 1997, RPT-NEDECO-BCL 1999) as the baseline information for the crack history. These reports were compiled on the basis of joint crack survey conducted by Hyundai Engineering and Construction Ltd (HECL) and CSC during December 1997 (Volume III), June 1998 (Volume II), February 1999 (Volume I), June 1999 (Volume IV). HECL in their survey recorded the location of each of these cracks, crack pattern, time of appearance and the cause of appearance of most of the cracks. Hyundai (1997) also provides some calculations to support the reasoning of those cracks and presents procedures that were followed to repair those cracks. BUET team compared the current findings in regard to 2006 crack propagation in the main bridge superstructure as reported by the Marga Net One Ltd (operations and maintenance contractor) in their recent crack surveys conducted during December 2004-April 2006. Furthermore, BUET team visited the bridge site for a number of times during March-May 2006 to have an overview of the cracking pattern and their propagation history for assessing the structural significance of the cracking on the superstructure of the main bridge. Figures 1-2 show some typical cracks. The following sections summarize the findings of the BUET experts.

2 BRIDGE GEOMETRY

The BUET Consultants prepared a 3D model of a typical bridge span based on the as-built drawings and considering the design specification, part of design calculations, construction history and other relevant reports available to the JMBA (Figures 3-7).

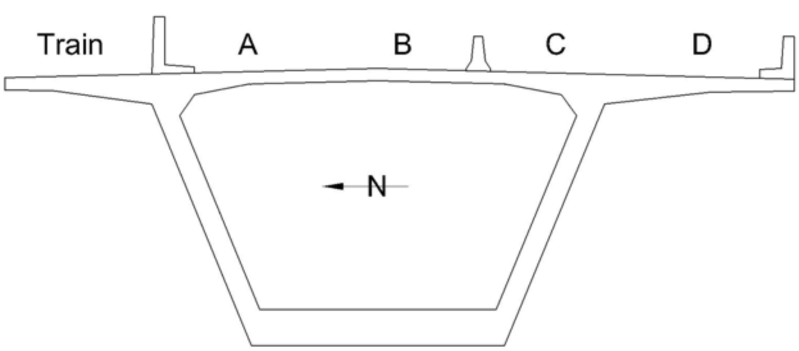

Figure 3. Lane marking

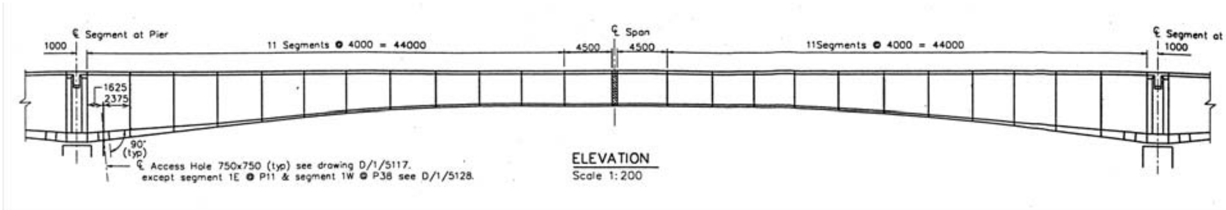

Figure 4. Typical bridge span (Type-C) (source: JMB As Built Drawing).

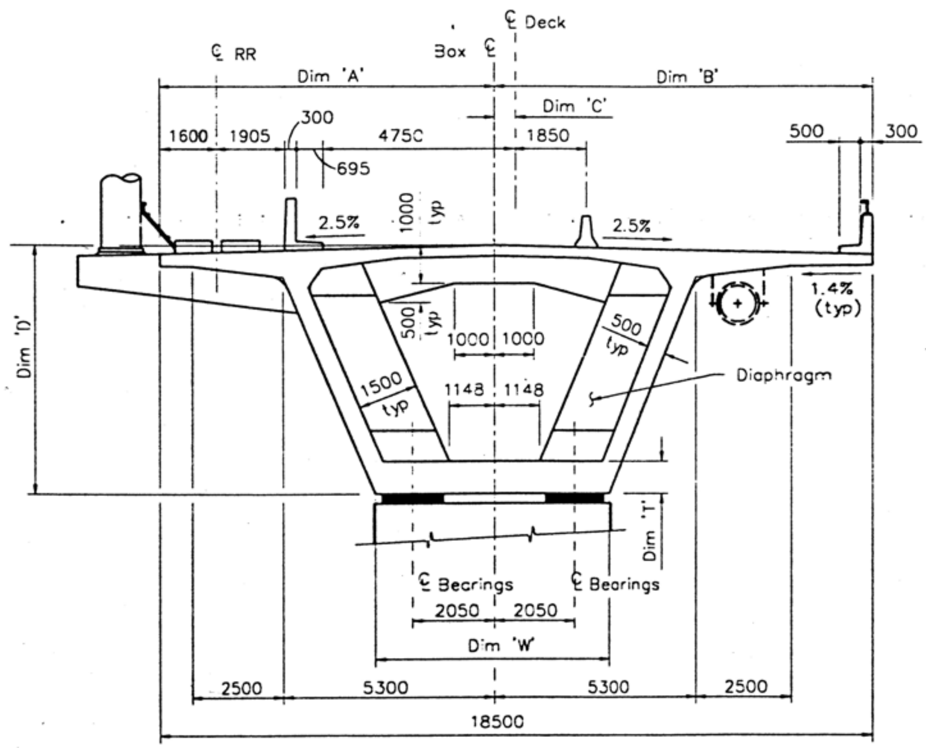

Figure 5. Typical section at pier (source: JMB As Built Drawing).

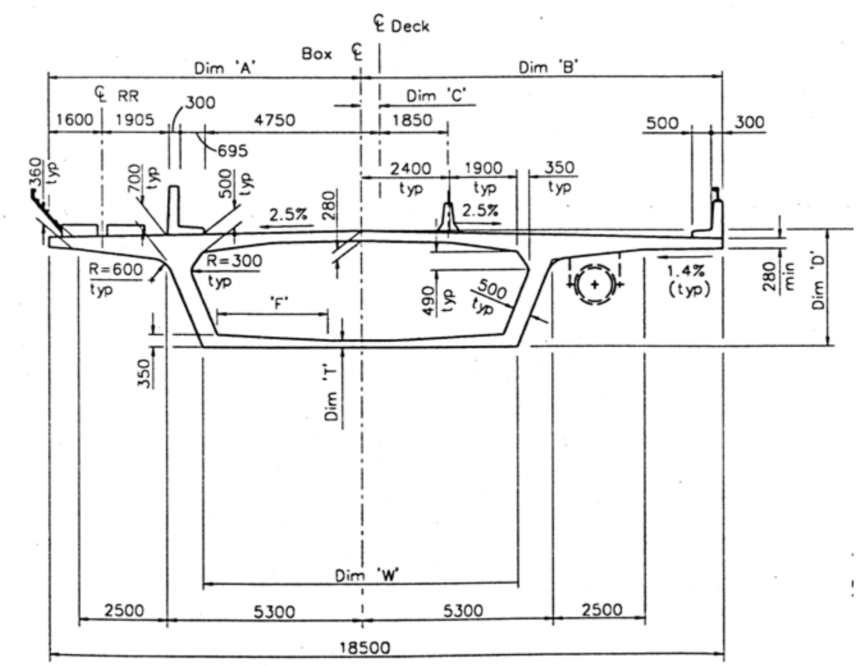

Figure 6. Typical section in span (source: JMB As Built Drawing).

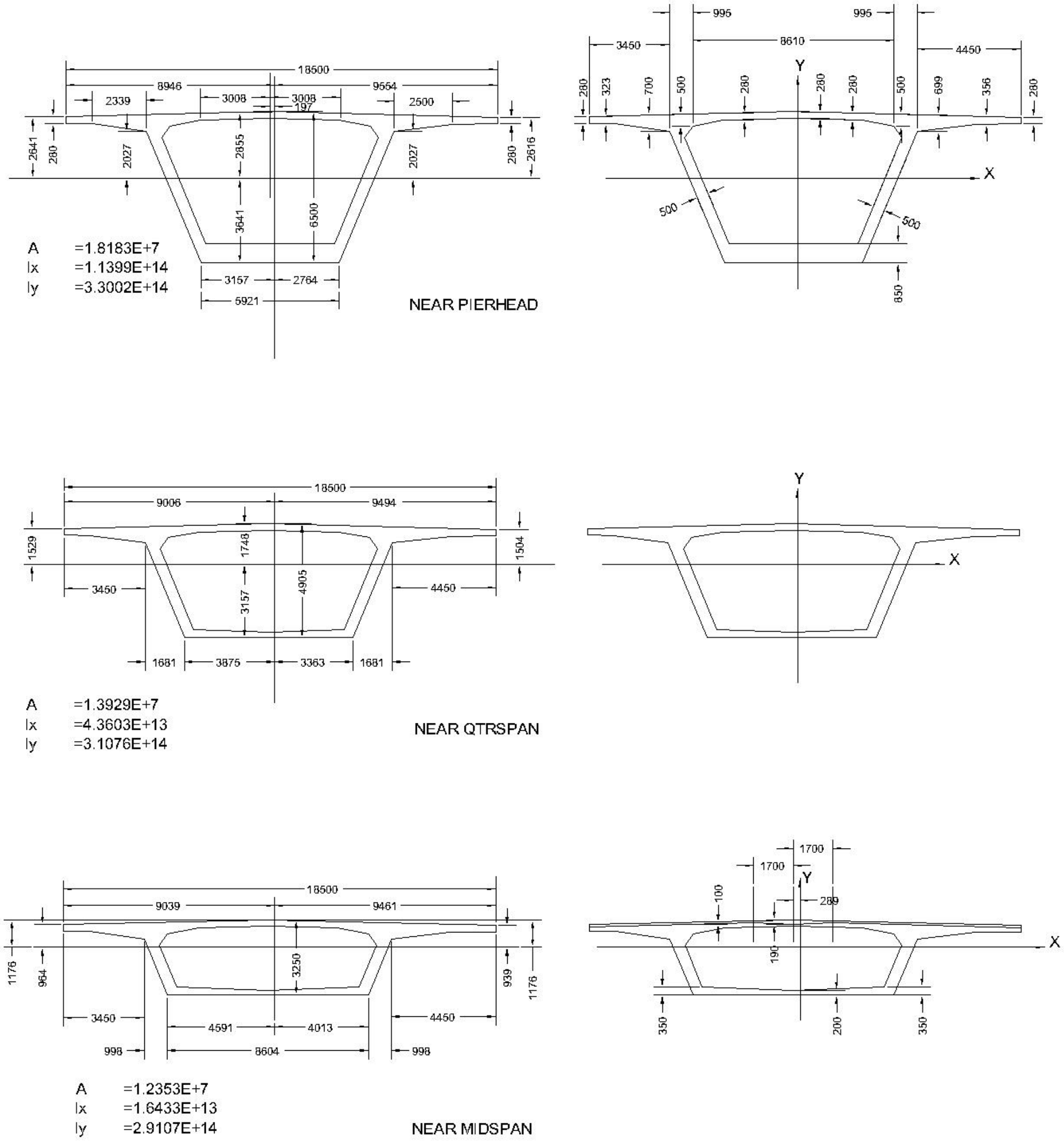

Figure 7. Section properties and dimensions.

3 FINITE ELEMENT MODEL OF THE BRIDGE

Two different models were developed independently for use in two different (Analysis) software. Though 3-D analysis of the bridge would provide a comprehensive global behavior of the bridge, two separate two dimensional (2-D) models were also developed (Figures 8-10)to study the transverse behavior of the bridge more closely at some critical sections like the mid-span and pier head sections (Figure 11). This was also intended to cross check the result of 3-D analysis (Figures 12-16).

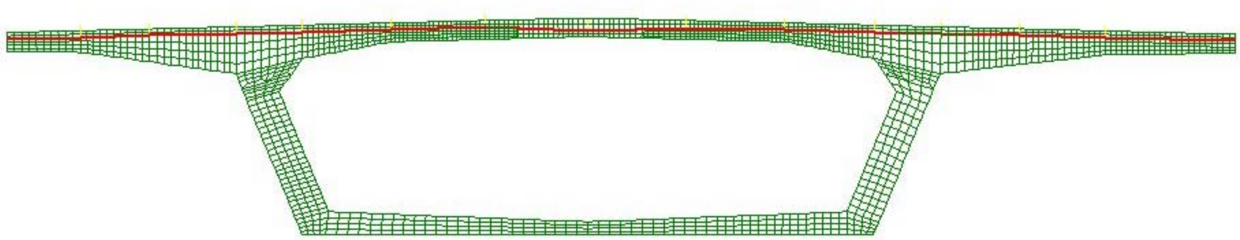

Figure 8. Plane stress model of bridge at mid-span

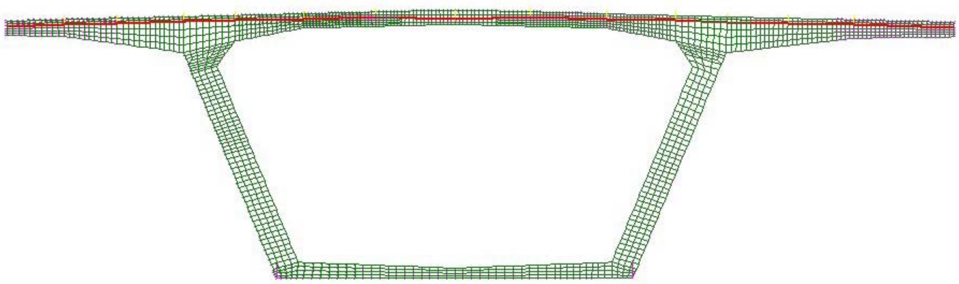

Figure 9. Plane stress model of bridge at quarter span

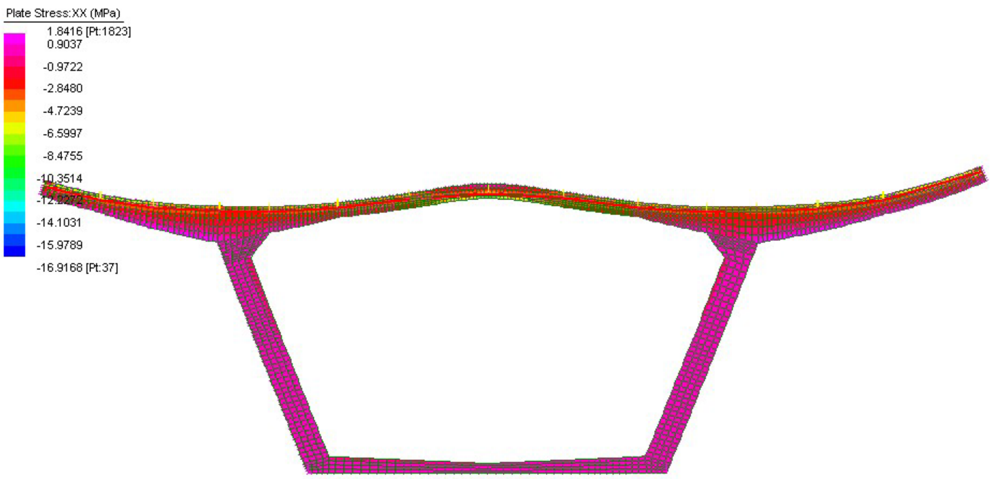

Figure 10. Deflected shape under transverse pre-stressing at quarter span.

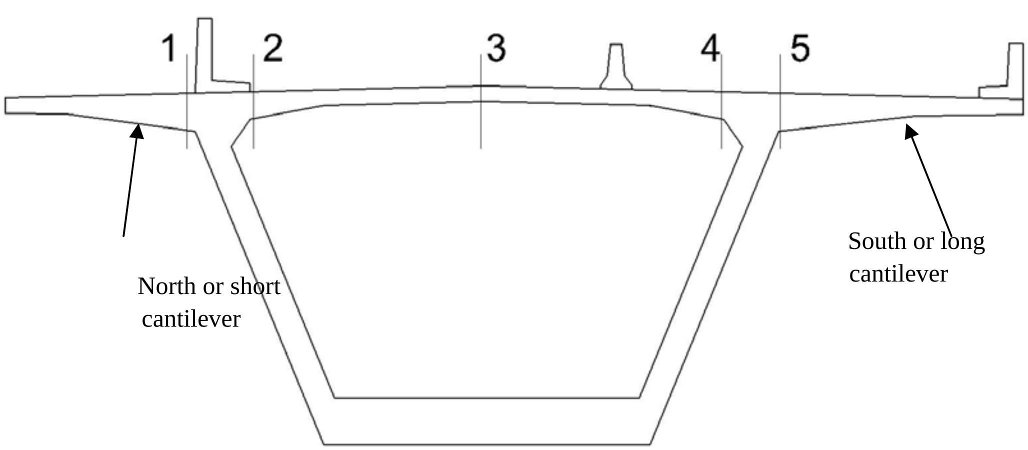

Figure 11 Locations of sections where stresses are examined

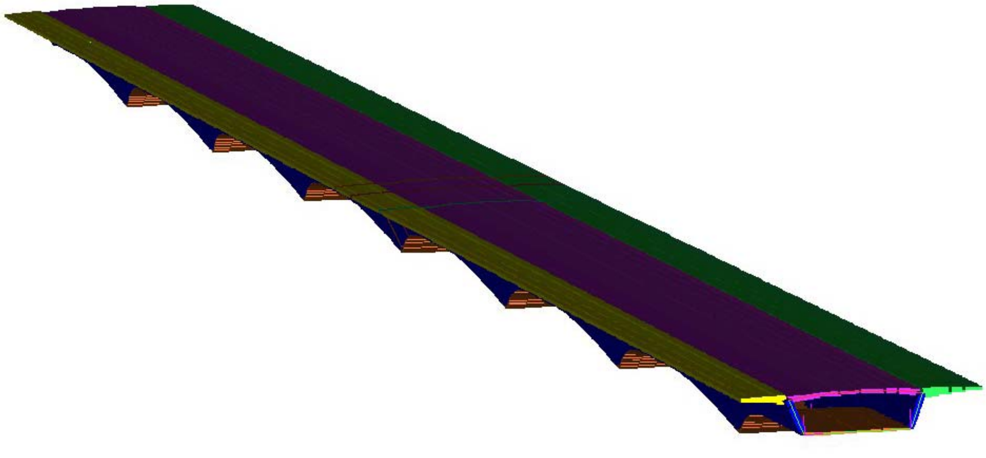

Figure 12. 3D finite element model of a seven span module.

Both the 3-D and 2-D models were subjected to all the design loads as prescribed in Jamuna Design Specification (JDS). Possible load combinations for worst effect were checked and the results were compared with permissible values as per JDS and/or other relevant specifications.

As the Jamuna Bridge is a prestressed precast segmental concrete bridge and it has been prestressed both longitudinally and in transverse directions, the effects of cable layout, compressive splitting and abnormal prestress loss etc. have all been investigated carefully. Effect of positive and negative temperature gradient on the behavior of Jamuna Bridge has also been carried out. Cable layout in transverse and longitudinal direction and non-prestressed bonded reinforcement layout provided in the segments of the Jamuna Bridge have been checked for adequacy under probable load combinations and environmental effects as per JDS.

The 2006 traffic loading on the Jamuna Bridge have been derived from review of traffic load survey reports conducted in the recent past by BUET and others. During the site visits of the BUET Consultants, some on-the-spot survey of apparently abnormal vehicles were carried out. The effect of present day vehicular loading on the Jamuna Bridge have also been investigated as it appeared to be different from what has been prescribed in JDS.

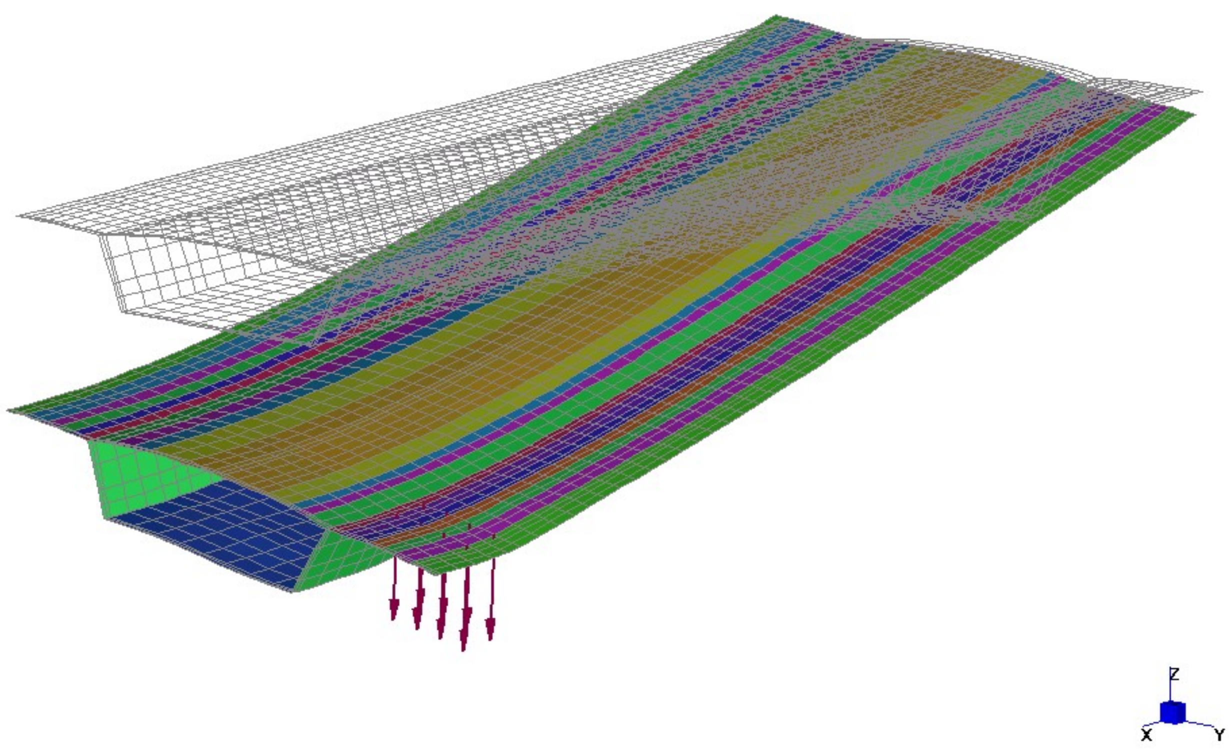

Figure 13. Deflected shape in cut-away view of a typical span due to HB loading.

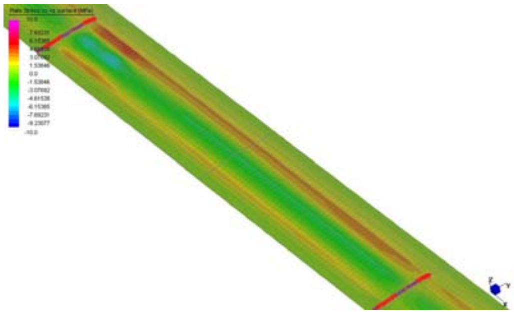

Figure 14. Transverse fiber stress contour on the top of deck for load combination 4 near pier

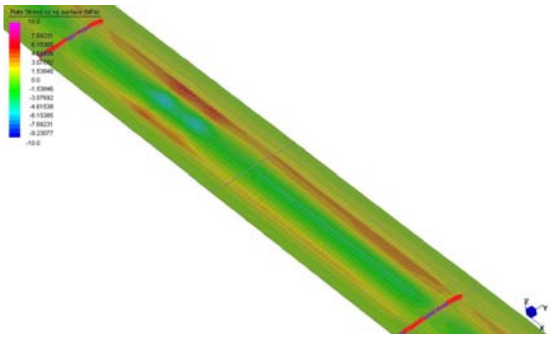

Figure 15. Transverse fiber stress contour on the top of deck for load combination 4 at quarter span

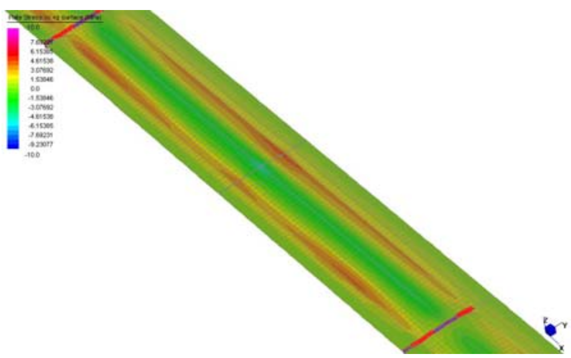

Figure 16 Transverse fiber stress contour on the top of deck for load combination 7 at mid-span

The findings of the BUET consultant on different aspects of Jamuna Bridge design and construction as it relates to the present cracks observed in the Bridge deck has been discussed in detail in the main report and are briefly presented in the following summary.

4 DIFFERENT CRACKS, DEFECTS AND INTERPRETATIONS FROM FINITE ELEMENT ANALYSIS

During the site visits, different cracks and defects as pointed out to the BUET Consultant by the O & M operator (The Marga Net One Ltd.) of the Jamuna Bridge were inspected by them. The crack report submitted by the O & M operator has been checked, the nature of cracking and crack width at some important locations were carefully inspected and measured. Brief description of the cracks and the possible causes for their formation are given below. Some practical defects that need attention are also included.

4.1 *Longitudinal cracking of the deck slab over the south side web*

Longitudinal cracks primarily on the top of the box web in the south have been observed almost all along the length of the bridge. This has been found almost in all the segments. In almost all the segments longitudinal cracks of the deck slab have been observed clearly over the inside and outside faces of the south web. During the visits by BUET Consultant some longitudinal cracks were observed more southward in the south cantilever in addition to the cracks over the box web.

These cracks have formed primarily as shrinkage cracks as evidenced by the Consultants' (RPT-NEDCO-BCL, January, 1998) report where similar cracks were reported during erection of segments. The trial erected segments kept at the construction yard was also found to have cracks at the south cantilever. These shrinkage cracks opened further and become easily visible due to temperature variations. It is observed from the as built drawings that temperature and shrinkage steels provided in the top deck is grossly inadequate with respect to the provisions of BS 5400 : Part 4 which has been referred to in the JDS as Design Standard.

The RPT-NEDECO-BCL, 1998 report also demonstrated that for an average of 500 mm thick slab, minimum 16 mm dia reinforcement area per metre should be 2065 mm^2 (0.41%) on each face to limit the crack width to 0.25 mm and control early thermal cracking of concrete. BUET Consultant finds similar requirements of temperature and shrinkage reinforcement as per BS 5400: Part 4. But the amount of reinforcement provided in the deck slab and in other elements of the Box Girder segments is far too less than what has been shown by RPT-NEDECO-BCL experts and as required by BS 5400: Part 4. These shrinkage and temperature cracks may have been significantly widened and more cracks became visible due to passage of heavily loaded trucks in the recent times over the bridge.

However, it needs mentioning that 30 unit HB load along with appropriate HA loading combinations has been found to produce significant tension in the deck top adjacent to the inside face of the south web. So, it may be viewed as a design deficiency.

4.2 *Longitudinal cracking of the deck slab at the centre of the box girder*

Distinct, more or less straight longitudinal cracks were observed in the top of the deck slab at centre of the boxes. Similar cracks had been detected in some of the segments quite early during erection of the bridge segments (RPT-NEDCO-BCL, January, 1998). It is believed that these cracks have been initiated by shrinkage of concrete between two webs. Later they got widened due to temperature effects. Further, they got prominence due to negative temperature gradient (deck top colder than inside). BUET Consultant from their 3-D analysis obtained tension over 2.5 MPa at the top side of box centre under self weight and temperature gradient. RPT, 1998 report also explained that cooling of the exterior surface of the bridge deck due to sudden drop in temperature. These crack width are getting wider quite fast recently and has reached nearly 0.5 mm width as per reports of Marga Net One Ltd.

4.3 *Longitudinal cracks in the bottom slab of the box*

These cracks were observed in 1997 by Hyundai (HDEL) at the centre of bottom slab soffit in quite a significant number of segments. Cracks were found in segments lying between centre half spans. Crack widths are reported to be 0.1 mm to 0.3 mm. It is reported by RPT-NEDECO-BCL (1998) that these cracks were noticed during inspection of finishing works and repaired by HDEL in March 1998. BUET Consultant checked the effect of radial forces generated by the curved bottom slab tendons in the longitudinal direction. It is found that these radial forces had caused the crack in the soffit of the bottom slabs. These are typical phenomenal cracks which would occur in curved PC box girders if the radial force effect due to curved tendons are not appropriately taken care of. Reappearance of these cracks after repair are not reported. However, regular inspection should continue to detect any such longitudinal cracks at the soffit of the bottom slab.

4.4 *Transverse cracks in the top deck slab and bottom slab*

In recent times some transverse cracks have been observed in both the top deck slab and bottom slab soffit. On the top deck these cracks are located at the centre span of the box and over the south side web extending south ward to the cantilever. In the bottom slab these transverse cracks are in the north south direction at random. It is believed that these are secondary stage shrinkage and temperature cracks. As longitudinal cracks are now well developed and has increased in numbers and location, secondary temperature cracks have started to develop in the transverse direction. Cracks may now develop in any other inclined orientation too. The cracks at the soffit of the bottom slab are more or less perpendicular to the bridge alignment.

4.5 *Longitudinal cracks in webs at the deck slab junction*

Longitudinal cracks in both north and south webs at the web-deck slab junction have been observed in some segments. The numbers and extent of cracking are not so extensive at the moment. It is suggested that regular inspection be carried out and see whether such cracks are visible at similar locations for other segments. At the moment it is anticipated that inherent constructional weaknesses may have caused these cracks due to live load moment and torsional effect. Partly temperature difference may also have influenced its formation and/or extension.

4.6 *Longitudinal crack at the bottom surface of deck slab*

A longitudinal crack observed at the bottom face of the deck slab in segment 1230. It is located at half way between the boxwebs. The crack appeared to be very fine. However, the top surface of the deck over this crack is also cracked in the longitudinal direction. This indicates that the top crack may have penetrated through the total depth of the deck slab. Such cracks at the soffit of top slab are not reported in any other segment of the bridge. It is anticipated that it is an incidental happening perhaps due early shrinkage cracks which extended across the depth.

4.7 *Leaking joints*

It has been reported by the O & M Operator Marga net One Ltd. that about 12 to 14 segmental joints have persistent leaking problems. Rainwater leaks through these joints from the top of the deck slab in to the box. Sealing these with epoxy temporarily prevents water percolation and leaking starts again after 6 months or one year when monsoon reappears. Leaking problems of some segmental joints goes with its commissioning. So, it is believed that faulty construction or inappropriate maintenance may be responsible for these leaking problems. Hence, appropriate measures should be taken to solve these permanently.

4.8 *Defective expansion joints*

It is reported that severe vibration of the bridge deck occurs as vehicles pass over the construction joints. BUET consultant found this problem with the first joint from the east end. Specially when east bound vehicles cross this joint, tremendous noise and significant vibration is felt. This indicates that perhaps the bearing seat is unevenly placed. Similar problems, if exists in other expansion joints, should be taken care of and repaired. Uneven bearing in the joints can multiply the impact effect of vehicles by two fold.

4 CONCLUDING REMARKS

It is observed that most of the cracks described in here are nothing new for different elements of the Bongobondhu Jamuna Bridge. Most of these have been formed and noticed soon after its erection. It is to be noted that these cracks have been formed primarily as shrinkage cracks and later temperature effects have widened them. Steel provided for control of shrinkage and temperature cracks are much too less compared to the provisions of BS 5400 : Part 4. RPT-NEDCO-BCL have shown that steel requirement for these effects are even higher if British Transport technical memorandum BD 28/87 titled ‘Early thermal cracking of concrete’ was used to determine the amount of reinforcement necessary. Considering the segments as precast reinforced concrete units, at least before prestressing is applied, the minimum reinforcement prescribed for such construction in BS 5400 : Part 4 should have been provided.

Besides, some basic design discrepancy is also noted by the BUET consultant from their 3-D analysis of the bridge. It appears that some of the critical load combinations were not perhaps considered by the designer. For example, HB loading on 2nd roadway lane (Lane B) from north with HA loading on the adjacent lanes (Lane A & C) or HB-loading on lane B and HA-loadings on remaining 3 lanes (lane A, B & C) are seen to cause significant tensile stress in the top of deck slab at the inside junction with the south side web.

The second inadequacy appears to be inappropriate assessment of negative temperature gradient effect. A sudden drop of deck slab temperature by 10° C compared to the bottom of the deck slab is found to produce tensile stress close to 3 MPa at the top of the deck slab at the centre of box. Hence, the top longitudinal crack at the centre of the deck slab was inevitable. The BS 5400 prescribes similar (about 8°C) negative gradient for deck slabs. But the designer seems to have made some averaging assumption which reduced it to 4°C within the depth of top slab.

It may be noted that no significant crack is reported as yet in the north side cantilever over which the Railway track exists. The critical locations of the top of north side web is covered with railway-roadway barrier and over 80% of the north cantilever is covered with railway track bed blocks. So, the effect of temperature on this part of the deck is not so pronounced and the deterioration is expected to be slow.

Finally as Bangladesh has no standards for truck loading and government has limited control on the shape, size and weights of trucks, some heavy weight trucks are plying over the Bongobondhu Jamuna Bridge.

These 3-axle trucks are known to carry at least a gross weight of 40 metric tonne. The effect of these heavy axles may be slightly higher than the 120 tonne HB design trucks on the Jamuna Bridge for some specific lane position of the vehicles.

5 RECOMMENDATIONS

Based on the findings of investigation on the causes of cracks and the cracks itself, the following recommendations are put forward for consideration.

(a) Appropriate measures should be taken immediately to seal the cracks on the deck and lay 50 mm wearing course with material that can take significant tension and is abrasion-resistant.
(b) Cracks at other locations (e.g. junction of webs and deck inside the box, bridge soffit etc.) should also be sealed immediately using standard and approved procedure.
(c) Restriction should be imposed on the maximum weight of vehicles. For two axle trucks, maximum limit of gross vehicle weight should be 20 tonnes and for 3 axle trucks 25 tonnes. For other types of vehicles, axle loads should be limited to 12 tonnes if minimum axle distance is 1.5 m along the length of the vehicle.
(d) Heavier vehicles (Bus/Truck) should have designated lanes until the cracks are appropriately repaired and wearing course laid. For westward journey, the right lane (Lane-C, adjacent to central barrier) should be reserved for heavy vehicles and for eastward traveling, the left lane (Lane-A, adjacent to the Train Line) should be designated for heavy vehicles.
(e) Train may continue at the present speed limits of below 20 kph with single pulling locomotive in the front..
(f) The leaking segmental joints should be sealed appropriately.
(g) The expansion joint systems should be repaired so that excessive vibration and jerking be minimized as the vehicles cross over these joints.