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Assessment and Damage Diagnostics for a Reinforced Concrete Skew Bridge

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ABSTRACT: Many recent bridges are often skewed due to space and alignment constraints in most urban areas. The use of skew bridge allows a designer to choose the best solution in roadway alignments. On the other hand, the stresses in skew bridges are much more complicated than in right-angle bridges due to complex geometry and skewed nature of the bridge. This paper presents forensic investigations of a highly skewed reinforced concrete slab bridge located in Saudi Arabia. The slab bridge 1m thick with a skew span of 31.9 m at one end and 52m at the other end showed signs of distress after it opened for service. High deflection on the longitudinal edge of the bridge, with numerous diagonal flexure-shear type cracks and several well-formed cracks were observed at the slab soffit. A field investigation and assessment and analysis were carried out to determine the cause of distress in the bridge. A non-linear finite element analysis (FEA) was also carried out using commercial software DIANA to investigate the cracking and excessive deflections. The study showed that the skewed slab geometry with heavy dead load on the cantilever portion of the bridge led to the development of high twisting moments throughout the deck slab. This, in combination with the bending moments in two orthogonal directions, resulted in high principal moments, which was not taken into account in the original design. The loads are carried in a narrow diagonal band between abutments, with a heavy concentration of reaction on the corner bearings, with other bearings carrying nominal load. The high reactions at the corner nodes resulted in shear and flexural–shear cracks at the edges. The crack patterns obtained from FEA matched very well with the observed crack pattern in the field. Strategies for rehabilitation of the bridge were proposed.

1 INTRODUCTION

In congested urban areas bridges are often of skewed geometry due to space constraints. The use of skew bridge allows a designer to choose the best solution in roadway alignment. The adoption of high skew angle bridges results in stresses which are significantly different than in right-angle bridges. In right-angled bridges, the load is transferred straight towards the support in the direction of the span but in skew bridges, load is transferred by a complex interaction of loads and moments. The complex geometry and highly skew angle also lead to the development of significant torsional moments in the deck slab with a decrease in longitudinal moment and increase in transverse moment. It results in concentration of reaction forces and negative moments at the obtuse corners and low reactions and a possibility of uplift reaction forces at the acute corners. These special characteristics of skew bridges make their analysis and design more complicated than right bridges (Kassahun, 2005).

Several researchers have investigated the behavior of skew reinforced concrete bridge decks using finite element analysis. Investigation of effect of skew (100° through 60°) with span varying from 12m to 20m showed that additional steel should be provided at the edge of the concrete slab adjacent to the abutment to compensate for enhanced stresses (Alasa'd, 1977). The neglect of Poisson ratio can lead to underestimation of maximum longitudinal (6%) and transverse (16%) moments (Sawko and Cope, 1969). The results from modeling of two-span continuous bridge under truck axle loading show that finite element analysis most accurately predicted the bridge behavior (Tiedman and Cayes, 1993). Al Mubaydeen (2005) found that increasing the skew angle moves the point of maximum positive moment towards the middle support of the bridge and also increases the value of the maximum positive moment of the girder in the same span length. Cusens and Besser (1980) investigated a skew bridge deck with particular focus on the obtuse corners and boundaries for the determination of shear forces in the slab. Significant reversals in bending moment were observed near obtuse corners as well as the largest values of torsional moment. Miah and Kabir (2005) have reported the behavior of reinforced concrete skew slabs under vertical concentrated loads.

This paper presents the field and finite element investigation of a skew bridge with a high skew angle, which showed signs of distress soon after it was opened for traffic. The bridge is located on the outskirts of the city of Makkah in Saudi Arabia. This bridge is a reinforced concrete slab bridge which is separated into four parts by expansion joints parallel to the highway as shown in Figure 1. This segment 4 of the bridge showed extensive cracking and high deflection.

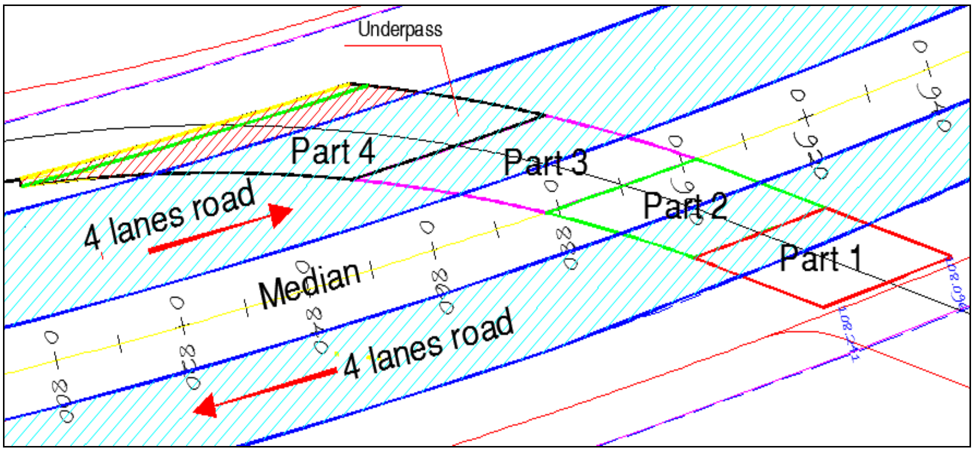


Figure 1. Plan view of the bridge with its four segments.

2 STRUCTURAL SYSTEM OF THE BRIDGE

The roadway and abutments of this bridge have a curved profile as shown in the Figures 1 and. 2. Figure 2 is a plan view showing the dimension of walkways and the curvature of the abutment in the Part-4 of the bridge which is under study. The span of the Part 4 of the slab bridge in the direction of the roadway (skew direction) on the eastern edge adjacent to the expansion joint is about 31.9 m which increases to a width of about 52 m at the western edge. The northern and southern abutments have a significant curvature dictated by the highway geometry. The northern abutment has six pot-bearing pads and the southern abutment has seven as shown by black dots in the figure. The cross section of the sidewalk at the western edge of the bridge is shown in Figure 3. The bridge consists of 100 cm thick reinforced concrete slab simply supported over the bearing pads on the abutments. On the outer edge on Western side there is reinforced concrete beam which is cast integrally with the RC deck slab. The total width of the walkway from the edge of the curb to the slab is about 4 m. A New Jersey barrier is placed at 3m from the roadway and the sidewalks are 25 cm thick. The thickness of asphalt concrete on the roadway is about 5 cm.

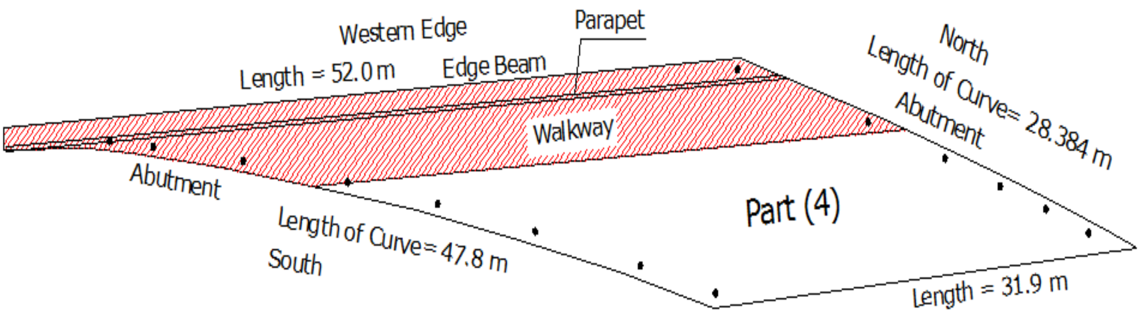


Figure 2. Plan showing the dimensions, curvatures and walkway of the Part 4 of the bridge.

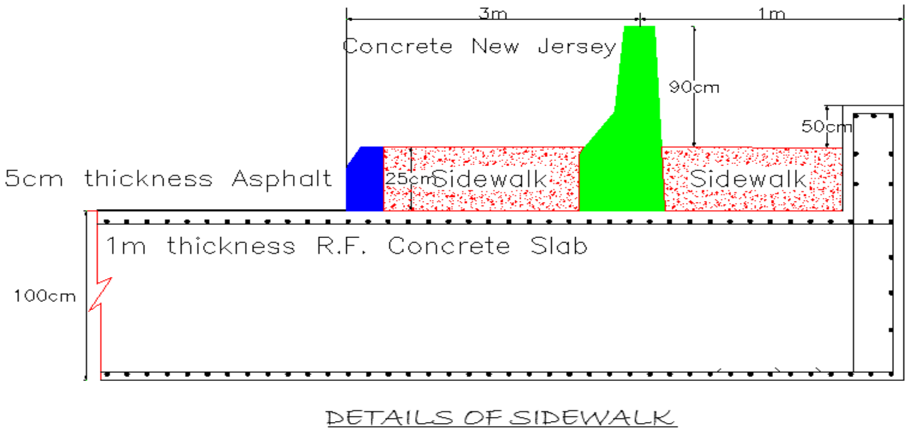


Figure 3. Section of sidewalk on the western edge.

3 OBSERVED DISTRESS IN THE BRIDGE

Visual inspection revealed several problems related to the structural condition and serviceability of the bridge. The high skew geometry of the deck slab and the curved abutment resulted in a very long skew span on the eastern and western edges on the bridge as shown in Figure 4. The following is a snapshot of the problems observed in the bridge:

- The long western edge of Part 4 shows a noticeable sag in the amount of about 210 mm. The maximum sag occurs about 20 m from the NW corner of the slab. Figure 4 shows the clearly visible large deflection at the Western edge.

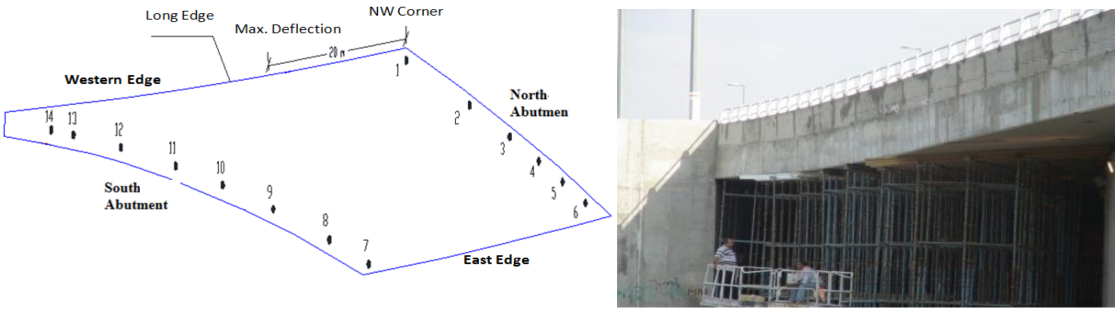


Figure 4. High Deflection of 210 mm at the Western edge

- The vertical face of the western edge shows numerous diagonal flexure-shear type cracks. These cracks can be seen over 60% of the span from the NW corner. The diagonal cracks become progressively more vertical away from the NW support end, displaying a cracking pattern similar to a simply supported beam subjected to high intensity distributed loading. Towards the mid-span where the shear is low, the cracks are predominantly flexural and caused by the high bending moment. Figure 5 shows a view of the diagonal shear cracks on the western edge. These cracks extend from the bottom of the slab to the top and do not extend into the edge barrier beam above it.

Figure 5. Diagonal shear cracks on the Western edge at the NW corner

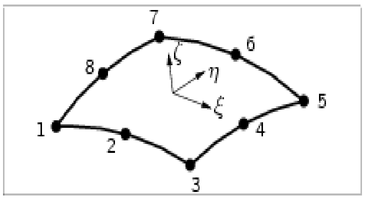
- Several well-formed cracks are also present at the soffit of the slab. They are visible despite an earlier attempt to repair them with repair mortar (Figure 6a). Figure 6(b) shows the cracks at the bottom of the deck slab which have developed after the repairs were carried out. A load test of the part 4 of the slab bridge was also carried out earlier by the contractor which showed that cracks increased in width on application of load.

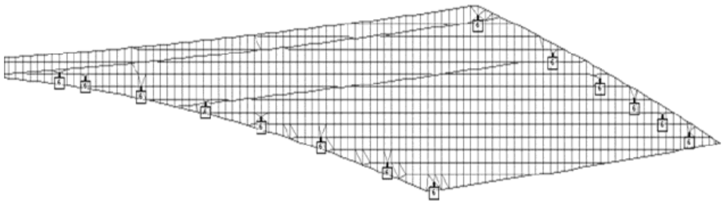
(a) (b)

Figure 6. Multiple cracks at the mid span

4 FINITE ELEMENT ANALYSIS OF BRIDGE

In order to ascertain the cause of cracking and excessive deflection of the skewed bridge, a linear and non-linear 2-D finite element analysis of the Part 4 of the skew bridge was carried out. The software DIANA 9.4 was used for nonlinear analysis. In DIANA, 8-node quadrilateral isoparametric plane stress elements CQ40S with 2x2 Gauss integration scheme was selected for the concrete elements (Figure. 7a). This element is amenable to the analysis of reinforced concrete structures with embedded reinforcement. The embedded reinforcing bar can be inserted anywhere within the body of the concrete elements. DIANA has provision for BAR element and GRID element for the reinforcement. The reinforcement in the model was assigned to have a perfect bond to the concrete element. The finite element model in DIANA comprises 3074 elements and 10279 nodes. For a linear analysis STAAD Pro 2007 with plate elements was used for modeling the slab (Figure 7b).





(a) Eight noded isoparametric element (DIANA)   (b) Plate elements (STAAD PRO)

Figure 7. Elements of the segment 4 of the Bridge in DIANA and FE mesh in STAAD PRO

5 DISCUSSION ON RESULTS

5.1 Shear stress in the Deck Slab

STAAD Pro 2007 was used for computing the stresses in the deck slab. The plot of vertical shear stress in the deck slab (SQY) under service load conditions is shown in Figure 8(a). It can be seen that very high shear stress of about 2.73 MPa and an average shear stress of about 2.5 MPa occurs on the free long edge of the deck slab at the western end of the underpass. The shear stress on the western edge decreases to 1.5 MPa towards the middle of the western edge. This high shear zone is limited to narrow band adjacent to high reaction node on the NE abutment and reduces to about 1 MPa further away. In the main central region of the deck slab the shear stress is very low. It can be seen from Figure 8(a) that localized high shear stress also exists on the eastern edge of the expansion joint. The magnitude of shear stress in this zone is in the range of 1 MPa and may lead to some shear cracks which cannot be seen due to the adjacent Part 3 of the bridge. Localized shear stress of 1 MPa is also observed at the supports on the NE and SW abutments as seen in Figure 8 (a).

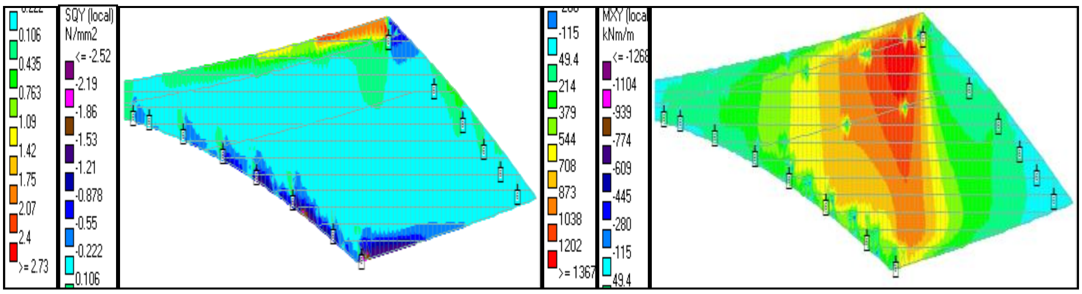
5.2 Torsional Moment M_{xy} under Service loads

The linear FE analysis also shows that a high torsional moment is generated in the deck slab due to complex geometry and highly skewed nature of the bridge under service loads. The high torsional moments occur in a band extending on both sides of the line joining the NW and SE supports. The variation of torsional moment M_{xy}, in the slab is shown in Figure 8 (b). The maximum service load torsional moment in the range 1244 to 1367 kN-m/m occurs in the zone near the western edge as shown in Figure 8 (b). The torsional moment decreases towards the SE corner with an average value of about 600 kN-m/m.

5.3 Non-linear Analysis of Bridge Deck Using DIANA

5.3.1 Deflection under Service Loads

Figure 9 shows the maximum deflection at the western long edge of the bridge. The maximum deflection of the edge nodes under service load condition is about 195 mm. This is close to the observed deflection of 210 mm in the bridge as measured during the field inspection at the site. This deflection at the western edge towards the North abutment is clearly evident on the bridge at the site (Figure 4). The computed and observed deflection in the slab is significantly higher than the allowable limits. The high deflection however, occurs in a zone which has a side walk of 4m width on the main highway.



(a) Shear stress (SQY) (b) Torsional moment M_{xy}

Figure 8. Shear Stress (SQY) and Torsional moment M_{xy} on the deck slab under service loads

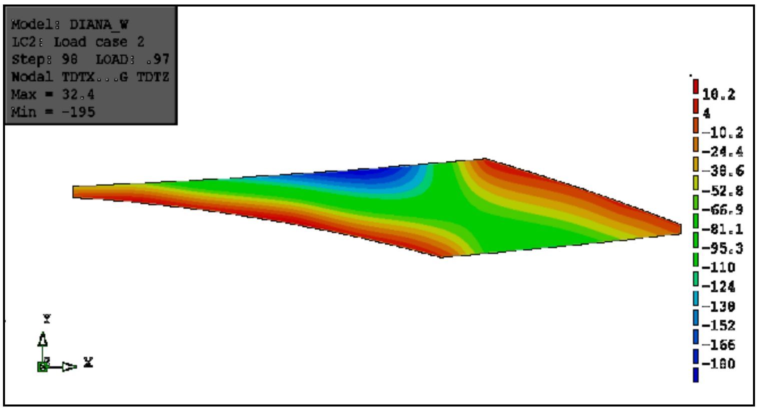


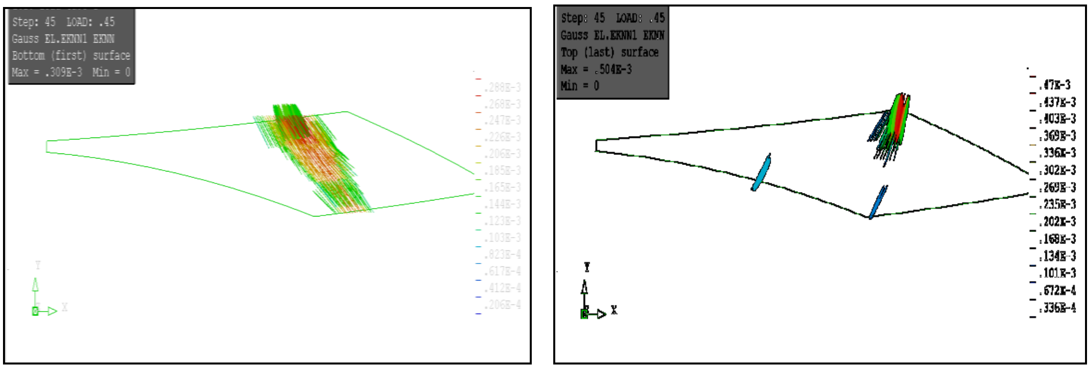
Figure 9. Deflection under service loads

5.3.2 Cracking Pattern in the Bridge Deck

Due to the skewed nature of the bridge the tension at the bottom of the slab occurs due to the moments M_x, M_y and M_{xy}. The principal moments and the associated principal stress cause cracking in the deck slab. The analysis shows existence of high normal stress at the bottom and top of the slab which caused the flexure cracks. The cracking pattern contours at the bottom match very well with the observed crack pattern as shown in Figure 10(a) and 10(b).

6 REPAIR AND STRENGTHENING OF THE BRIDGE

Two options which are possible for rectifying the deficiencies and ensuring the safety of traffic on the bridge are: (1) Strengthening the existing bridge to the required level of safety and (2) Demolishing the Part 4 of the bridge and rebuilding it. The first option is appealing and cost-effective as it aims to save the bridge and to avoid extended loss of service. However, this option has limitations, as the deck slab has problems related to high support reactions and the possibility of punching shear failure, excessive deflections and cracking due to high moments. The second option, ‘demolition and rebuild’ is an extreme choice that appears to be highly expensive. However, this option offers a cleaner solution that would be far more reliable.



(a) At the bottom of the slab　　(b) At the top of the slab

Figure 10. Cracking pattern at 45% of the load

6.1 *Objectives of the strengthening Strategy of the Bridge*

A viable strengthening strategy for the skew bridge should focus on the two fundamental factors namely, increased safety and cost-effectiveness. The strengthening strategy should encompass the following aspects: (1) The possibility of punching of the slab at the NW corner bearing should be addressed, (2) The crack damage should be arrested and not allowed to propagate further under traffic loads, (3) Retrofitting should be carried out with minimal disruption to flow of traffic on the bridge, and (4) The selected repair technique should lead to an enhanced load carrying capacity of the deck slab in view of its less than required and minimal reserve capacity.

6.2 *Removal of Superimposed Dead Load on the Western End*

It was found from results of finite element analysis that the western end of the slab is highly distressed. Also, the western end of the bridge carries a large dead load from the barriers and walkways (Figure 3). This heavy load also contributed to cracking and deflection at the western edge. Using the FE investigations it was found that the removal of the concrete New Jersey barrier and 25 cm thick sidewalks and replacing it with lightweight steel barriers with a small kerb and steel fence would result in significant reduction in the loads along the western end of the bridge. It was proposed as an immediate solution for implementation at the site. It was found that the removal of walkways and barriers from the top of the slab results in (1) A significant reduction in reaction at the NW corner from 7394 kN to 5725 kN (2) The shear stress is reduced from 3.2 MPa to 2.1 MPa (3) Reduction of 9% and 26.4% in the values of M_x and 27.3% and 25% in the values of M_y and (4) Reduction of about 22.2% in the twisting moment.

6.3 *Strengthening Options*

For the strengthening of the deck slab, the options investigated include: Option-I: Using stiffer edge beams at the Western edge of the slab at the top; Option-II: Supporting the deck slab on the soffit side, using a steel beam-column frame along the center line of the roadway, effectively creating two spans; Option-III: Supporting the deck slab by a series of steel beams at the soffit; and Option-IV: CFRP strengthening of the deck slab.

The CFRP repair option was found to be the most viable option. CFRP sheets applied at the slab soffit at the critical central location extending from NW to SE corners was found to provide additional flexural strength to the deck, which would help in arresting the crack growth, especially under fatigue due to live loading on the deck. CFRP sheets were also recommended to be applied to the part of the western edge to provide additional shear strength and arrest further crack growth.

7 CONCLUSIONS

A linear and non-linear finite element analysis of the deck slab with high skew angle was carried our after detailed site investigation. The highly skewed slab geometry of segment 4, accentuated by curving abutments resulted in the development of significant torsion in the slab, which was neglected in the original design. The analysis also shows existence of high normal stress at the bottom and top of the slab which caused flexure cracks. The skewed slab geometry has contributed to the development of the high torsional moment throughout the deck slab. This, in combination with the bending moments in two orthogonal directions, has resulted in high principal moments. CFRP rehabilitation was suggested for the strengthening of the bridge. As a temporary relief the heavy dead load on the cantilever portion of the bridge was removed which resulted in significant reduction in flexural and torsional stresses. The Client implemented the immediate solution for the Hajj season after which the Client selected the option of demolishing the span 4 of the bridge, which was implemented and new solid slab bridge incorporating in design all lapses identified in this study, and the bridge has been rebuilt and opened to traffic.

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