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Reinforcement and numerical analysis on the corbel of a half-through arch bridge

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Abstract: Corbels support the crossbeams of half-through arch bridges. They are prone to cracking easily due to their characteristics and complicated loading conditions. Based on a practical diagnosis of a bridge crossbeam, we bonded steel plates onto bridge corbels to strengthen them. We carried out a numerical analysis on the effectiveness of the reinforcement by using the commercial software ANSYS. The numerical analysis shows that the stresses near the section break increased slightly, but the variation amplitude was small and all the stresses were within an allowable range. The loading test indicates that it is feasible to strengthen the corbel with vertical bonded steel plates. Therefore, the reinforcement is effective and economical. This reinforcement method is suitable for this type of corbel and can be applied in similar cases.

Keywords: reinforcement; corbel of crossbeam; half-through arch bridge; bonded steel plate; finite element method

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1 Introduction

Half-through or through arch bridges have been widely built since 1990s. In these types of bridges, three arch-ribs are commonly used, and a crossbeam is an important component for transferring loads. However, the crossbeam is long and is supported by three hangers. Thus, it usually is divided into two parts connected by a corbel.

Reinforcement with steel plates and fiber reinforced plastic (FRP) strips is easy. These materials have outstanding mechanical properties. Therefore, they have been widely used in old-bridge strengthening sectors [1-12]. However, there are few studies on the design, analysis and effective evaluation of corbel reinforcement using this method [13-15] and these experimental results are unilateral due to limited experimental conditions. We identified and surveyed defects of a crossbeam in a bridge. Then we bonded steel plates to strengthen the corbel of the crossbeam. We used finite element method (FEM) analysis to simulate the effectiveness of reinforcement.

2 Experimental subject

The Dangtu Road Bridge over the Nanfei River is located in Hefei City, Anhui Province, P. R. China. It was completed in June, 1997. It is a concrete box rib arch bridge of 230 m long and 43 m wide. Its five arches were laid out symmetrically (Fig. 1). The first and the fifth deck arches span 30 m; the second and the fourth ones are half-through arches of 50 m long ; and the third one is a half-through arch of 70 m long. Each one is composed of three arch-ribs. The designed load of the bridge is limited to auto-20 and trailer-100 for the high-speed lane while auto-10 for the slow-speed lane. The sidewalk loading is 4 kN/m^2 [16].

Some defects were found in a routine inspection in 2007. The deck slabs, which are closed to the short suspender at both ends of the middle span, were flaked-off and even the steel bars were exposed. The traffic was blocked. Therefore, a detailed inspection and a test on this bridge were carried out.

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Skew cracks were found in most auxiliary regions of the upper corbels at the end of the crossbeam (Fig. 2). Their angles were from 30° to 70°; their lengths were from 5 cm to 22 cm, while the widths were from 0.1 mm to 0.3 mm [17]. Some cracks were distributed symmetrically on both lateral surfaces of the corbels. During the bridge loading test, the cracks started to propagate when the bridge was loaded, and the cracks became closed after unloading [17]. Therefore, it can be concluded that these cracks were caused by the stress and the corbels needed to be reinforced.

Fig. 1 The Dangtu Road Bridge in 2007

Fig. 2 Corbels of the Dangtu Road Bridge before reinforcement

3 Reinforcement Measurements

Compared with large-sized corbels commonly used on rigid T-frame bridges with a suspended beam, the corbels supporting the crossbeam of a half-through arch bridge have the following characteristics.

1) As the connecting components of the crossbeam on which deck slabs are laid, they are small in size. Therefore, the strengthening space is very limited.

2) Considering the stability of the crossbeam when the deck slabs were moved, the upper and the lower corbels can not be separated because the separation would cause eccentric loading.

3) Parts of the upper corbels are located behind the stationary dogs, which makes the space for strengthening extremely limited.

Therefore, the reinforcement should be carried out on the lateral surfaces of the corbels. The main purpose of the reinforcement is to enhance the corbel capability to resist the shear stress. We bonded steel plates onto bridge corbels where the width of crack was wider than 0.1 mm.

3.1 Shape of the bonded steel plates

It is very effective if the steel plates are perpendicularly bonded to the cracks, because the principal tensile stress is directed to the crossbeam at 45°. However, the bonding cannot be completed on the upper corbels due to the stationary dogs.

The bonded steel plates should be U-shaped with different widths to enhance resistance of the corbels [18]. However, the lateral surfaces of the crossbeams were not smooth, and the thickness of the crossbeams are different. Thus, it is difficult to bond the U-shaped steel plates to the lateral surfaces, and the construction quality cannot be guaranteed.

We removed the soleplate of the U-shaped steel plates in the reinforcement. This measure is simple and convenient. We evaluated its effectiveness using FEM analysis.

3.2 Techniques of bonding steel plates

Pressing and grouting are two traditional techniques for steel plate bonding. Corbels are prone to breaking because they are small and have dense steel bars around them. A great number of drift bolts must be used when pressing, which introduces damage to the corbels. Grouting is used instead, because it can greatly reduce the number of drift bolts used. To be more advantageous, the locations of the drift bolts should be designed to avoid the pre-stressed cables.

4 FEM analysis

4.1 Loading

We established a simplified model based on the characteristics of the half-through arch bridge. We simulated the loading on the model as follows:

1) We considered 1.2 times of the structure weight as the body force of the elements.

2) The vehicle loads were auto-20 and trailer-100 for the high-speed lane. Based on the analysis, the loads were the most unfavorable when there were four vehicles crossing the bridge side by side.

3) We simulated the pre-stressed cable by giving an equivalent external force on the structure.

4.2 FEM model

The separate model, the combined model and the integral model are three ways to simulate a reinforced concrete structure. As the performance of the integral crossbeam and the mechanical performance of the corbel were considered, the separate model is adopted for the corbel in which the steel bars are non-uniformly distributed, whereas the integral model were chose for the rest of the crossbeam. In the separate model of ANSYS analysis, we used the SOLID65 element for concrete without steel bars and the LINK8 element for the steel bars. In the integral model, the steel reinforced concrete was considered homogeneous, and we used the SOLID45 element to simulate the reinforced concrete, the SHO-BOND colloid and the steel plate.

4.3 Boundary conditions

The vertical displacement of the suspender was neglected and the crossbeam was assumed to be simply supported.

We only give the results of numerical analysis on the upper corbels because they had more defects. The reinforcement design on the upper corbels is shown in Fig. 3. We built the FEM model for the upper corbels before (Fig. 4a) and after (Fig. 4b) the reinforcement, respectively.

5 Results

5.1 Distribution of localized stress in the corbel

The displacement of the front end varied greatly under the dead and live loads (Fig. 5). Meanwhile, the maximum tensile stress of the upper corbels before strengthening was 37.2 MPa at the corner (Fig. 6). The utmost tensile stress of concrete was 3.5 MPa. Therefore, it can be concluded that the upper corbel was damaged.

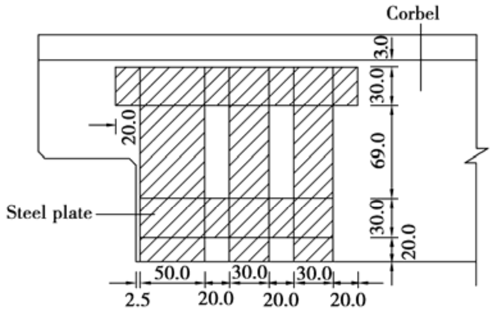
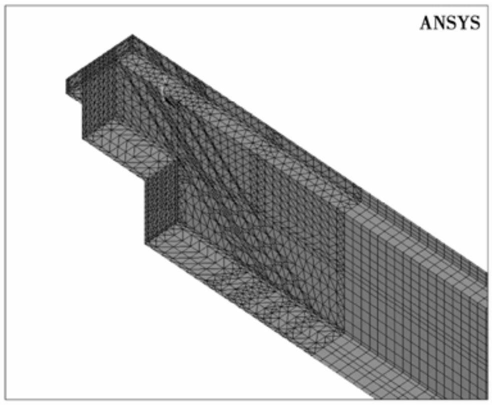


Fig. 3 The reinforcement design on the upper corbels (Unit: cm)

a



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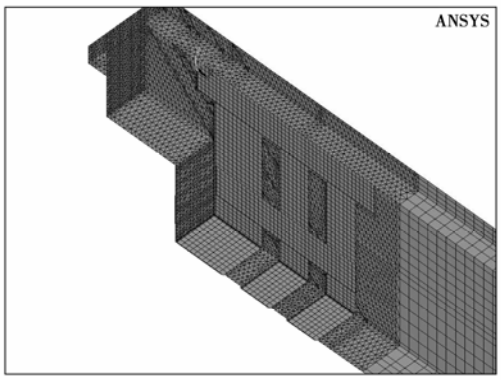

Fig. 4 The FEM (finite element method) model of the upper corbels (a) before and (b) after the reinforcement

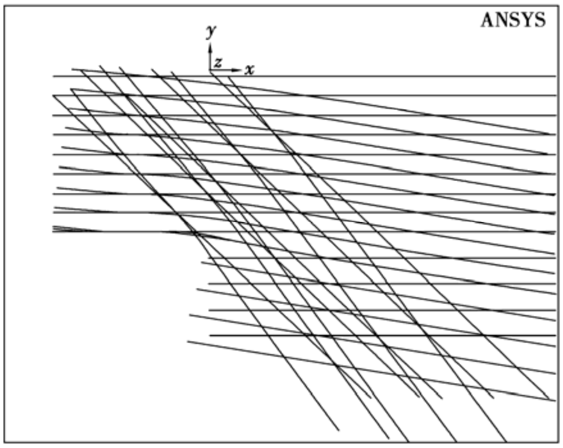

Fig. 5 Displacement of the longitudinal and diagonal steel bars inside the upper corbels before strengthening

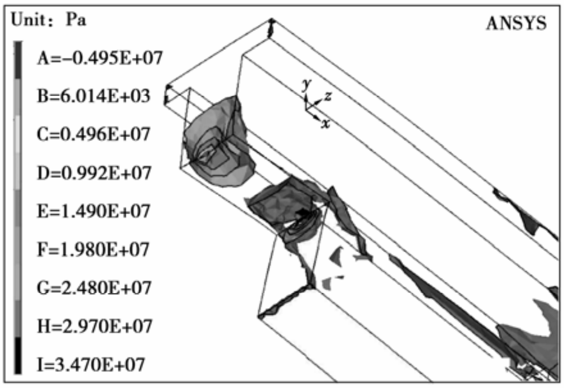

Fig. 6 The contours of the frist principal stress inside the upper corbels before strengthening

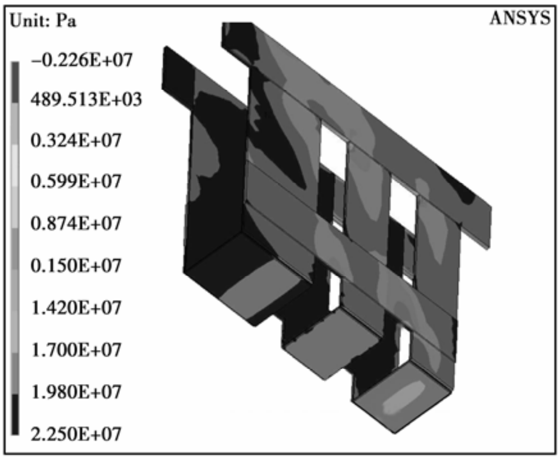

Fig. 7 The contours of the frist principal stress inside the steel plate and the SHO-BOND colloid after strengthening

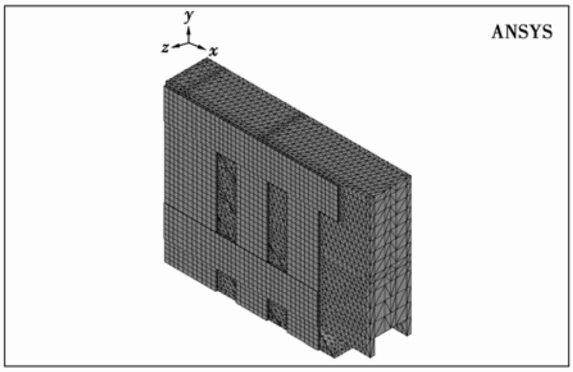

Fig. 8 The segments with the steel plates after strengthening

Partial loads acted on the steel plates after bonding the U-shaped steel plates (Fig. 7). The stress around the tip of the crack decreased greatly, indicating that the reinforcement effectively prevented crack development along a 45° direction. The maximum tensile stress in the steel plates was 22.5 MPa. The loads at the segments with the steel plates are shown in Fig. 8, and their values were compared as listed in Table 1.

The stress concentration at the corner increased after strengthening (Fig. 9). This was mainly caused by the increased rigidity at the right side of the corbel where the steel plates were bonded. The edge of the steel plates was only 25 mm away from the section break, while the rigidity of the left side of the corbel remained the same. The rigidity variation near the section break thus was magnified under the same loading, which contributed to the stress concentration.

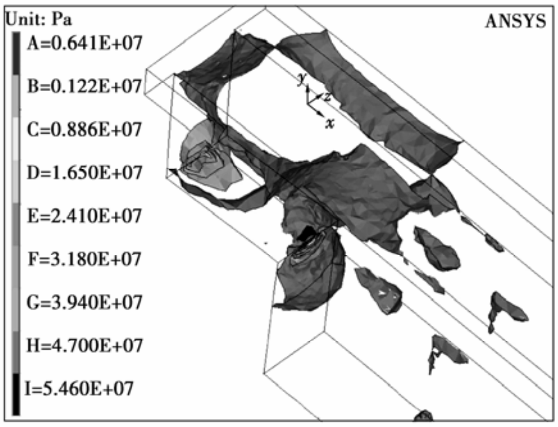

Fig. 9 The contours of the frist principal stress inside the concrete of the upper corbels after strengthening

The numerical results show that the reinforcement was effective. More attention should be paid to stress concentration and crack avoidance in the vertical section.

5.2 Comparison between two models

We established two models to determine the differences between the results of strengthening with and without soleplates (Table 1). It can be seen that the loads acting on the concrete in the model using U-shaped steel plates without a soleplate are almost the same as those of U-shaped ones with a soleplate. The differences of the stresses at the nook of the corbel in these models are not apparent, except the concentration of stresses (Fig. 10).

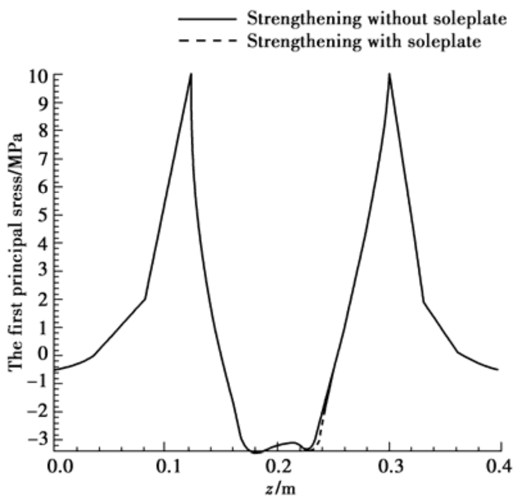

Fig. 10 The first principal stresses at the nook of the corbel strengthened with and without soleplates along the direction (z) parallel to the width of the crossbeam

6 Discussion and conclusions

The FEM analysis using ANSYS shows that the stress and displacement are both permissible, and the maximum stress occurs near the corner of the corbel, which means that it is reasonable to strengthen the corbel only.

Detailed analyses of the upper corbel indicate that the strengthening can prevent cracks from propagating in the 45° direction and improve the stress states. After the reinforcement, the stresses near the nook of the corbel were less than the ultimate tensile strength of concrete. However, attention should be paid to stress concentrations near the section break.

U-shaped steel plates without soleplates can save the steel plates and make construction more convenient.

Based on the FEM analysis, reinforcement with U-shaped steel plates without the soleplate can be applied. The reinforcement construction was finished in October, 2007. The loading test after reinforcement indicates that the reinforcement was effective. In the static loading test, the strains at the nook of the corbel varied slightly, which indicates that this area was in a sound stress state, namely the elastic state. Therefore, the reinforcement was successful.

Crossbeams are important components of half-through or through arch bridges with suspenders. Their dimensions are small, and the stress condition is very complicated. Therefore, the corbels of crossbeams are particularly prone to cracking and special attention should be paid to their design, construction and reinforcement. Both the numerical analysis and the bridge loading test show that strengthening crossbeam corbels with bonded steel plates is reliable. The grouting technique should be used to bond steel plates.

The numerical analysis shows that the stresses near the section break increased slightly, but the variation amplitude was small and all the stresses were within an allowable range.

Table 1 Loads of the nodes in the segments with the steel plates (Case 1) before reinforcement, (Case 2) after reinforcement with U-shape steel plates, and (Case 3) after reinforcement with U-shape steel plates without soleplate

Case	Loads					
	F_X/N	F_Y/N	F_Z/N	$\boldsymbol{M}_X$/(N·m)	$\boldsymbol{M}_Y$/(N·m)	$\boldsymbol{M}_Z$/(N·m)
Case 1	0.305 E–10	–31 082.73	0.751 E–11	–0.571 E–10	–0.725 E–11	–29 779.37
Case 2	0.224 E–10	–36 743.69	–0.122 E–11	–0.702 E–11	–0.831 E–11	–34 326.66
Case 3	–0.235 473 9 E–10	–36 743.69	0.300 559 6 E–11	–0.103 526 1 E–10	–0.571 986 9 E–11	–34 326.66

Notes: F_X, F_Y, and F_Z are forces along the X-axis, Y-axis, and Z-axis, respectively. $\boldsymbol{M}_X$, $\boldsymbol{M}_Y$, and $\boldsymbol{M}_Z$ are moments along the X-axis, Y-axis, and Z-axis, respectively, respectively.

The loading test indicates that it is feasible to strengthen the corbel with vertical bonded steel plates. This type of reinforcement can effectively reduce stresses of the skew section at 45° to the axis of crossbeams. It is also economical and can be applied conveniently.

References

[1] Kim YJ, Green MF, Fallis GJ. Repair of bridge girder damaged by impact loads with prestressed CFRP sheets [J]. Journal of Bridge Engineering, 2008, 13(1): 15-23.

[2] Schnerch D, Rizkalla S. Flexural strengthening of steel bridges with high modulus CFRP strips [J]. Journal of Bridge Engineering, 2008, 13(2): 192-201.

[3] Chowdhury EU, Bisby LA, Green MF, et al. Residual behavior of fire-exposed reinforced concrete beams prestrengthened in flexure with fiber-reinforced polymer sheets [J]. Journal of Composites for Construction, 2008, 12(1): 61-68.

[4] Hii AKY, Al-Mahaidi R. Experimental investigation on torsional behavior of solid and box-section RC beams strengthened with CFRP using photogrammetry [J]. Journal of Composites for Construction, 2006, 10(4): 321-329.

[5] Dempsey DD, Scott DW. Wood members strengthened with mechanically fastened FRP strips [J]. Journal of Composites for Construction, 2006, 10(5): 392-398.

[6] Rasheed HA, Larson KH, Peterman RJ. Analysis and design procedure for FRP-strengthened prestressed concrete T-girders considering strength and fatigue [J]. Journal of Composites for Construction, 2006, 10(5): 419-432.

[7] Nezamian A, Setunge S. Case study of application of FRP composites in strengthening the reinforced concrete headstock of a bridge structure [J]. Journal of Composites for Construction, 2007, 11(5): 531-544.

[8] Liu ZH, Zhu BL. Analytical solution for R/C beams strengthened by externally bonded steel plates [J]. Journal of Tongji University, 1994, 22(1): 21-26. (In Chinese).
刘祖华,朱伯龙.粘钢加固混凝土梁的解析分析[J].同济大学学报,1994,22(1):21-26.

[9] Zhang L. On finite element analysis of steel reinforced concrete beam using external adhesion steel plate [J]. Journal of Chongqing University of Science and Technology: Natural Science Edition, 2005, 7(2): 53-55, 68. (In Chinese).
张雷.钢筋混凝土梁采用外粘钢板加固的有限元分析[J].重庆科技学院学报:自然科学版,2005,7(2):53-55,68.

[10] Kuang ZP, Wang HB. Field test study on bridges bonded with carbon fibre reinforced plastic [J]. Journal of Tongji University, 2002, 30(2): 146-150. (In Chinese).
匡志平,王皓波.用碳纤维加固桥梁的现场试验研究[J].同济大学学报,2002,30(2):146-150.

[11] He H, Liu Yh, Xu JJ, et al. Application research on carbon fiber reinforced bridge [J]. Transportation Science and Technology, 2007(3): 104-106. (In Chinese).
何辉,刘永红,许建军,等.碳纤维在桥梁加固中的应用研究[J].交通科技,2007(3):104-106.

[12] Tan Y, Zhou JT, Shen XJ, et al. Analysis of common reinforcement methods and application characters of arch type bridges [J]. Journal of Chongqing Jiaotong University: Natural Science, 2007, 26(4): 29-31. (In Chinese).
谭勇,周建庭,沈小俊,等.常用拱式桥梁加固技术及适用特点分析[J].重庆交通大学学报:自然科学版,2007,26(4):29-31.

[13] Chansawat K, Yim SCS, Miller TH. Nonlinear finite-element analysis of a FRP-strengthened reinforced concrete bridge [J]. Journal of Bridge Engineering, 2006, 11(1): 21-32.

[14] Brownjohn JMW, Moyo P, Omenzetter P, et al. Assessment of highway bridge upgrading by dynamic testing and finite-element model updating [J]. Journal of Bridge Engineering, 2003, 8(3): 162-172.

[15] Zanardo G, Hao H, Xia Y, et al. Stiffness assessment through modal analysis of an RC slab bridge before and after strengthening [J]. Journal of Bridge Engineering, 2006, 11(5): 590-601.

[16] Hefei City Planning and Design Institute. Blueprint of Nanfei River Bridge on the Hefei road [Z]. Hefei: Hefei City Planning and Design Institute, 1996. (In Chinese).
合肥市规划设计研究院.合肥路南淝河大桥设计图[Z].合肥:合肥市规划设计研究院,1996.

[17] Shanghai Tongji Construction Work Quality Check Station. Supplementary test and load test of Nanfei River Bridge on the Dangtu road [R]. Shanghai: Shanghai Tongji Construction Project Quality Inspection Station, 2007. (In Chinese).
上海同济建设工程质量检测站.合肥市当涂路南淝河大桥加固前技术状况补充检测及补充荷载试验报告[R].上海:上海同济建设工程质量检测站,2007.

[18] Ministry of Construction of P. R. China, General Administration of Quality Supervision, Inspection, and Quarantine of P. R. China. GB50367-2006 Design code for strengthening concrete structure [S]. Beijing: China Architecture and Building Press, 2006. (In Chinese).
中华人民共和国建设部,中华人民共和国国家质量监督检验检疫总局.GB50367-2006混凝土结构加固设计规范[S].北京:中国建筑工业出版社,2006.

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