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Test study for full-scale hollow slab girder using UHPFRC reinforcement technology

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ABSTRACT: High performance fiber reinforced concrete (UHPFRC) is an optimal choice for concrete bridge reinforcement, which can significantly enhance resistance and durability of structural members to achieve life cycle cost economy. In this paper, full scale hollow slab girders were selected for loading behavior study before and after reinforcement, which were derived from an in-situ bridge. Test study was conducted firstly for full scale hollow slab test girder B1 in order to study the residual load carrying capability. Based on damage inspection result and residual performance study for this test girder B1, reinforcement measures were determined for another full-scale test girder B2, including steel plate and UHPFRC composite reinforcement for bottom plate, and composite UHPFRC layer for top plate. After test study, the behaviors of hollow slab girders were comparatively analyzed, including bending capacity, ductility, overall behavior and rigidity.

1 INTRODUCTION

Typical damages such as concrete cracking, excessive deflection, rebar corrosion and material degradation have observed in concrete girder bridges during the long-term in-service period, resulting in the decline of bridge loading capacity, inadequate safety, or even bridge collapse accidents (Figure 1). The reasons for these damages in concrete girder bridge can be divided into two kinds. The first kind of reason is environmental effect, such as concrete carbonization, chloride salt erosion, alkali aggregate reaction, freeze-thaw cycle damage and corrosion. The second kind of reasons include design and construction factors, such as relatively lower deign load grade and material strength in earlier time, improving vehicle load and volume, improper construction, et al. It is necessary to strengthen these in-service concrete girder bridges to achieve structural performance recovery and safety improvement.

(a) Concrete spalling and rebar corrosion (b) Pavement damage.

Figure 1. Typical damages in concrete girder bridge.

At present, the popular reinforcement methods for concrete girder bridge include enlarging section reinforcement method, bonding steel plate reinforcement method, bonding carbon fiber plate reinforcement method, external prestressing reinforcement method, et al. These reinforcement methods have their technical characteristics and suitable application field. These methods have been widely used in bridge engineering reinforcement. Learn from existing engineering experience, the bonding steel plate reinforcement method is characterize with simple construction and low cost, but the quality of bonding surface is variable in the reinforcement process. It was reported that the several concrete girder bridge strengthened with the bonded steel plate needs secondary reinforcement because of the failure of the bonded interface after four to five years opening to traffic. The reinforced concrete girders strengthened by bonding CFRP plates is not easy to fully utilize the high strength characteristics of CFRP plate. The external prestressing reinforcement method can be used to close the concrete crack and recover or improve the structural loading capacity. However, the concrete girder bridges constructed in earlier time are characterize with lower concrete strength, relatively smaller structural dimension, and different degrees of material property degradation, resulting in insufficient local pressure and difficult anchorage arrangement in external prestressing reinforcement method. Therefore, it is necessary to explore efficient reinforcement method for concrete girder bridge, which is characterize with safe, reasonable, reliable, easy construction, economical and practical.

Steel and concrete composite reinforcement method was firstly proposed by Nie et al (2008). Nie et al. (2011) and Wang et al. (2015) have conducted test and analysis for steel and concrete composite reinforcement method, which proved its advantages in improving structural capacity, rigidity, durability, seismic resistance and so on. Compared with traditional concrete, Bruhwiler et al. (2013a, 2013b) and Safdar et al. (2016) have shew that ultra-high performance fiber reinforced concrete (UHPFRC) has higher compressive strength, tensile strength, ductility, compactness, fluidity and lower creep coefficient, which is an ideal reinforcement material to meet the performance improvement requirements of concrete girder bridges. Using UHPFRC to replace concrete in steel and concrete composite reinforcement method, this steel and UHPFRC composite reinforcement method is expected to improve structural performance in the following two aspects. Firstly, when UHPFRC with superior flexural and tensile properties was used to replace the concrete in composite reinforcement, the dimension of reinforced part can be effectively reduced and the material consumption can be saved. Thus, on the premise of ensuring reinforcement efficiency, steel-UHPFRC composite reinforcement method can reduce the reinforcement weight and improve the structural ability to carry live load after reinforcement. Secondly, concrete part will quit working once concrete cracks in the steel-concrete composite reinforcement technology, resulting the reduction of section stiffness. However, UHPFRC with high flexural and tensile strength will not crack under the actions of service load and temperature. It can realize the full section working in service stage, thus improving structural stiffness and ensuring the service performance of reinforced concrete girder bridges.

In this paper, typically hollow slab concrete girders were selected for residual bending capacity study and UHPFRC reinforcement efficiency study. Two full scale hollow slab girders were adopted for bending test study, which were derived from an in-situ bridge. Firstly, test study was conducted for original full scale hollow slab girder in order to study their residual load carrying capability. Secondly, based on damage inspection result and residual performance study for hollow slab girders, reinforcement measures were determined for another full-scale test girder, including steel plate and UHPFRC composite reinforcement for bottom plate, and composite UHPFRC layer for top plate. Thirdly, test was conducted for this reinforced hollow slab girder to analysis post-reinforcement behavior. After experimental study, the behaviors of hollow slab girders were comparatively analyzed, including capacity, failure mechanism, ductility, overall behavior and rigidity. Learned from test and analysis results, strengthening technique in this paper can significantly increase the yield capacity and ultimate capacity.

2 EXPERIMENTAL PROGRAM

Two full-scale concrete slab girders were selected for UHPFRC reinforcement effect study, which were labeled as B1 and B2 respectively. The inspection result shows that these two full-scale concrete slab girders have insufficient bending capacity and rigidity, which fail to satisfy serviciablity requirements. Test girder B1 was loading to study residual bending performance, while test girder B2 was loaded to study reinforcement efficiency after adopting steel - UHPFRC composite reinforcement measures.

2.1 *Information of test girders*

The total lengths of simple supported test girders were 19.96m, and the calculated span lengths were 19.26m. The test girders had a cross section with a depth of 0.95m and width of 1.24m for bottom flange. The cross section of the test girders is shown in Figure 2.

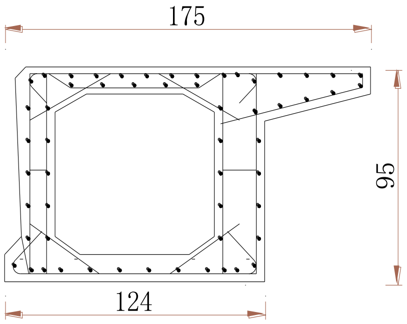


Figure 2. Mid-span cross section of full-scale test girders.

These two full-scale concrete slab girders adopt concrete grade of C40. Learn from the compressive test for cylinder concrete specimens, the average compressive strength of concrete for these two test girders was 39.4MPa. The rebar of R235 with diameter of 8mm was used for top plate and also for stirrup, the longitudinal rebar of HRB335 with diameter of 16mm was used for bottom plate, and the longitudinal rebar of R235 with diameter of 6mm was arranged at web. The steel strands in test girders have tensile strength standard value of 1860MPa and nominal diameter of 15.2mm. Table 1 shows the material properties based on tensile tests for rebar.

Table 1. Material properties of rebar in full-scale test girders

Diameter of rebar (mm)	Yielding strength (MPa)	Ultimate strength (MPa)	Elastic moduls (MPa)
16	435	580	2.04×10^5
8	318	483	2.06×10^5

2.2 *Reinforcement measures*

Learn from inspection results for concrete slab girders, the effective prestress and the thickness of the top plate were not enough. Some cracks were detected at the bottom plate and the web near the mid-span regions. Following reinforcement measures were determined according to inspection results. Firstly, the 4cm UHPFRC layer was casted on the top plate for entire span length. This UHPFRC layer was composited with original concrete top plate by planting rebar. Secondly, steel and UHPFRC composite reinforcement method was used for bottom plate with strengthening length of 18m, adopting UHPFRC layer with thickness of 4cm and Q235qD steel plate with thickness of 3mm. The overall working ability was realized by planting fixing bolt between original concrete bottom plate and reinforcement part. Figure 3 show the test girder B2 after reinforcement.

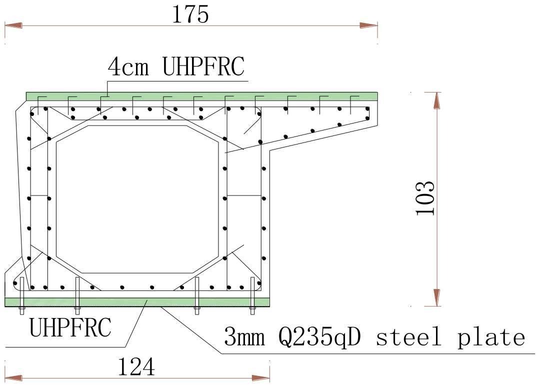


Figure 3. Full-scale test girder B2 after reinforcements (Unite: mm).

2.3 *Test setup*

The bending test setup was shown in Figure 4. Learn from Figure 4, test girders were simple supported on two concrete piles, and the four-point loadings were adopted with loading distance of 2m. During the loading process, the loads was monitored by a load sensor connected with a 2000 kN hydraulic jack, deflection was measured by displacement meter, and strains were by strain gauges at concrete, reinforcing bars and steel plates.

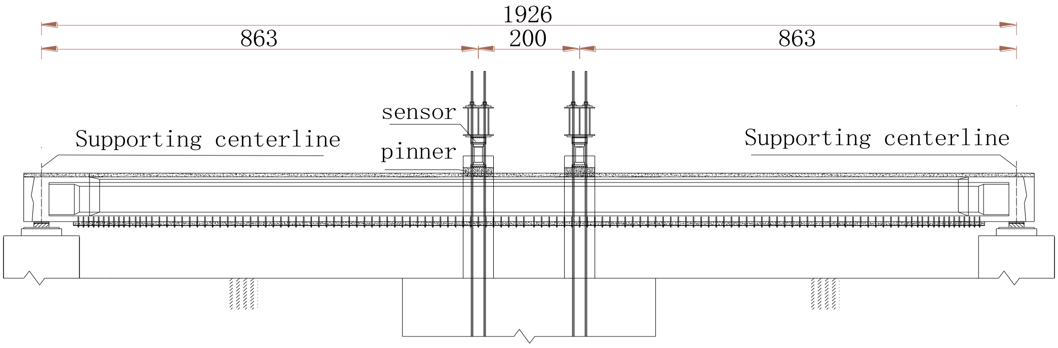
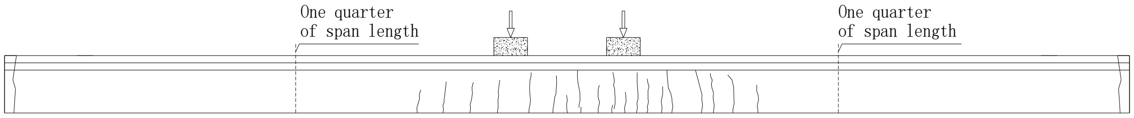


Figure 4. Test setup (Unite: mm).

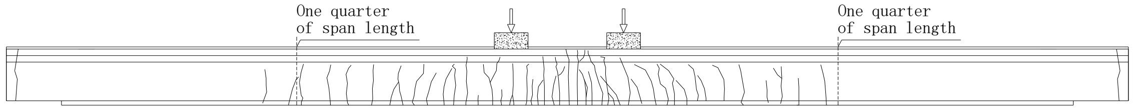
3 TEST RESULTS ANALYSIS

3.1 *Bending process and failure modes*

The test girders were preloaded for several times to check workability of sensors and eliminate mechanical hysteresis of strain gauges. Figure 5 show the crack distructions of test girders after bending test. Test girder B1 shew fine overall working behavior at initial loading level. When loading beyond 150 kN, vertical cracks at bottom plate propagated with greater growth rate, resulting stiffness reduction and faster deformation increasement. As loading to 300 kN, the vertical cracks were propagated to 45cm long at pure bending region, attaining one half of girder height. What's more, vertical cracks were also observed near two loading section, with maxiumum length of 35cm. When loading to 470 kN, the vertical cracks were propagated nearby top plate with the maximum crack width of 0.4mm, and the cracks grew entire width of bottom plate. For test girder B2, cracks were observed at bottom plate as loading beyond 120 kN, and the vertical cracks propogate up to web for 30cm long. When loading attained 400 kN, the cracks propagated to 40cm height away from bottom plate, with maxiumum crack width of 0.33mm. The cracks in pure bending region grew achieving haunch at load level of 560 kN, and the cracks at mid-span section propagated into haunch with maximum width of 0.6mm, when loading to 720 kN. Several cracks propagated into top plate within mid-span region, as loading beyond 900 kN. The crush of concrete at both bottom top plate and web was observed as achieving ultimate capacity of 997 kN.



(a) Crack distributions of test girder B1



(b) Crack distributions of test girder B2

Figure 5. Crack distributions of test girders after bending test.

The measured maixmum relative displacement between steel plate and UHPFRC in refinforcement part was 0.075mm during all the bending test process. What's more, the relative dispalcement between concrete in original test girder and UHPFRC in reinforcmenet part was no more than 0.07mm in all loading period. These small values of tested relative dispalcements have testified fine overall working behavior between reinforcement part and original concrete girder.

3.2 Load and deflection behavior

Figure 6 shows the load and deflection curves at mid-span for test girder B1 and B2. For test girder B1, the deflection inceases linearly to 10.2mm within load of 150 kN, corresponding to elastic stage. As loading beyond 150 kN, the structural rigidity decreased when concrete cracking was found at mid-span region and the deflection increased nonlinearly, corresponding to elastic-plastic stage. When loading to 469.7 kN, the deflection at mid-span section was 84.7 mm, the maximum crack width was 0.4mm and the vertical concrete crack was propagated from web to haunch of top plate. The test girder B1 was unloaded and the residual deflection was 10.48mm. For test girder B2, the deflection increased linearly to 2.57mm within load level of 120 kN, and no new cracking was found in this period. The deflection of test girder B2 grew quickly as loading continuously increased to 990 kN, and cracks were observed at both bottom plate and web of test girder. When loading to 997 kN, the concrete top plate and web at mid-span region were crushed and the deflection was 220 mm, attaining ultimate capacity. After then, the test girder B2 unloaded automatically and the deflection grew to 231.5 mm.

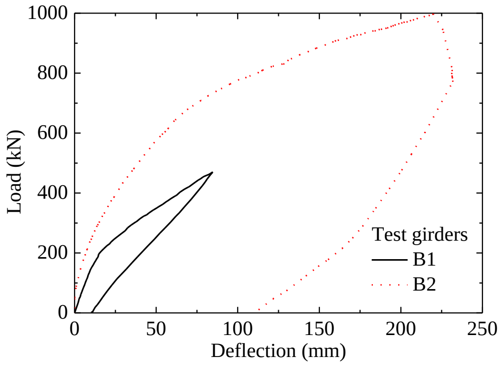


Figure 6. Load and deflection at mid-span section.

3.3 Strain analysis

3.3.1 Strain of rebar in bottom plate

Figure 7 shows the curves between load and strain of longitudinal rebar at bottom plate in mid-span section. Learn from Figure 7, test girder B1 and B2 show linear relationship between load and strain of longitudinal rebar before cracking load. As loading beyond 150 kN, the load and strain curves turn more flat, signifying concrete cracks propagation and strain redistribution period. The strain attained 1955με when loading to maixum load of 469.7 kN for test girder B1, and the residual strain was 128με after unloading. For test girder B2, the rebar began yielding as loading beyond 606 kN, and the strain of rebar at bottom plate didnot grow with loading increasement anymore as load ranging from 700 kN to 900 kN, because load increasement was carried by strands after yielding of longitudinal rebar in original girder and steel plate in reinforcement part. The cross section of test girder B2 turned into plastic at load level of 900 kN.

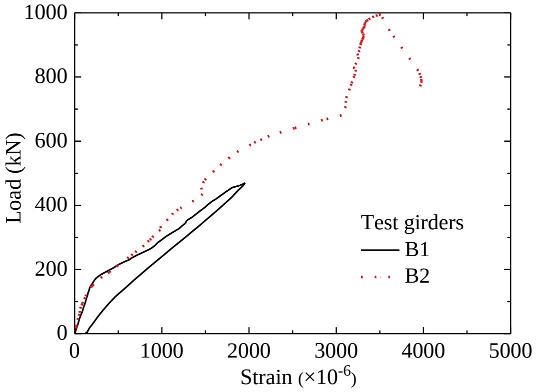


Figure 7. Load and strain curves of longitudinal rebar in bottom plate.

3.3.2 Strain of steel plate in reinforcement part

Figure 8 shows the load and strain of steel plate in UHPFRC – steel plate composite reinforcement part for test girder B2. Learn from Figure 8, the steel plate was yielded as loading beyond 800 kN and the maximum strain attained 15836με, which illustrated completely plastic of steel plate and fully utilization the material properties of steel plate. The strain of steel plate increases linearly within load of 150 kN. The concrete cracking continuously developed and the strain of steel plate grew nonlinearly to yielding period as loading increasing to 800 kN. The yielding field of steel plate expanded after loading level of 800 kN, corresponding to reduction of structural rigidity and small growth rate of loading.

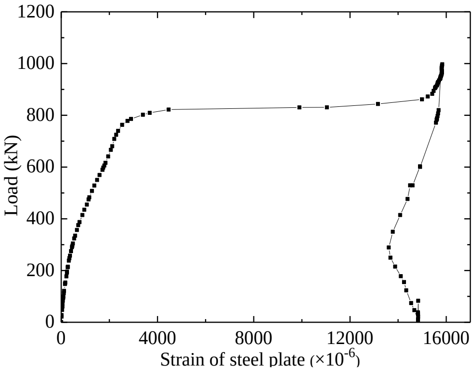


Figure 8. Load and strain of steel plate at mid-span section for test girder B2.

The distributions of strains of steel plate were also measured in transvers direction and longitudinal direction. In transvers direction, the strains of steel plate was relatively even distributed under the same load level, and the strains revealed obviously variability as attaining 0.9F_u (0.9 times the ultimate loading capacity). In longitudinal direction, the strains of steel plate between two loading points shew uniform distribution at small loading level; the nonuniform coefficient of strains (defined as the ratio of maximum strain to average strain) increased to 1.08 and 1.52 at loading of 0.5F_u and 0.7F_u. These nonuniform of strains at steel plate was caused by different local damage degrees.

3.3.3 Strain of rebar at top plate

Figure 9 shows the curves between load and strain of rebar at top plate at mid-span section, in which negative value of strain means compressive state. For test girder B1and B2, there were linear relationship between load and strain of rebar at elatic state. Then, the strain increased with greater rate as concrete at tensile part cracking, rebar yielding or steel plate yielding. For test girder B1, the strain of rebar at top plate increased quickly as loading beyond 180 kN, and the strain of rebar reached -835με at loading attained 469.7 kN. For test girder B2, when loading above 120 kN, concrete cracking propagated from bottom plate upto web, longitudinal rebar at bottom flange and steel plate in reinforcement part turned yielding, resulting neutral axis moving up and strain of rebar at top plate increasing quickly. The strain of rebar at top plate reached -2271με as attaining ultimate capacity and decreased to -4397με after unloading, which signifying fine plastic behavior.

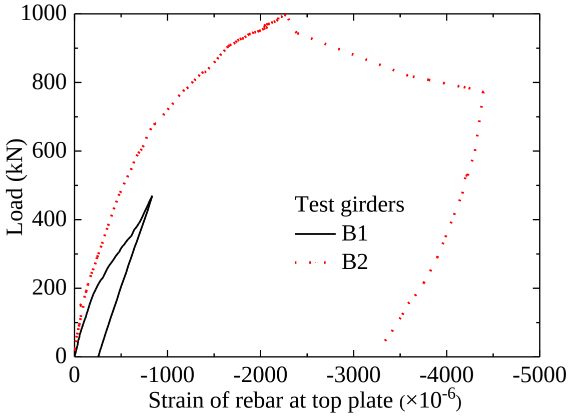


Figure 9. Load and strain of rebar at top plate.

4 CONCLUSION

Two full-scale hollow slab concrete girders were selected for residual bending capacity study and UHPFRC reinforcement efficiency study. Based on the experimental study results, the following conclusions can be drawn:

(1) The bending process were acquired before and after UHPFRC reinforcement, respectively. The bending capacity of test girder B2 increased two times than that of test girder B1.

(2) Learn from deflection and strain analysis results, the hollow slab test girder B2 after UHPFRC reinforcements can make effectively use of material properties in reinforcement part. What's more, the test girder B2 have fine ducility behaivor.

(3) When adopting steel – UHPFRC composite reinforcement method, the hollow slab test girder have fine overall working behavior between reinforcement part and original concrete girder.

5 ACKNOWLEDGEMENTS

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