STUDY ON SHEAR RESISTANCE OF FULL-SCALE PC BOX GIRDER REINFORCED BY SPCCS METHOD

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ABSTRACT

Steel plate and concrete composite strengthening (SPCCS) method is developed on the basis of steel and concrete composite girder, the process of which mainly includes welding studs on the reinforcing steel plates, planting rebars in the original concrete, and casting concrete between the original structure and steel plates, thus the new and existing concrete can work together. It can improve both the bearing capacity and stiffness of bridge significantly. In order to investigate the shear resistance of concrete girder reinforced by SPCCS method, two full-scale damaged box girder released from an actual bridge are tested for contrast, one without reinforcement and the other is reinforced by SPCCS method. The shear mechanical behavior and failure mode before and after reinforcement are obtained and analyzed. Furthermore, the shear mechanism and calculation formula of shear capacity for box girder reinforced by SPCCS method are presented. The comparisons show that the calculation results are in good agreement with the test results.

KEYWORDS

PC box girder, steel plate and concrete composite strengthening method, shear resistance, full-scale test, shear capacity calculation formula.

INTRODUCTION

Concrete bridges are widely used for their good bearing capacity and low cost. However, disease of different degrees is inclined to appear on concrete bridges under the action of environment and repeated loads. For instance, various forms of cracks are likely to appear on prefabricated concrete box girder, including longitudinal crack, transverse crack, diagonal crack and u-shaped crack, because of its own section form and tensile strength of material. All of the cracks and other damages will affect the service life and safety of bridges. Therefore, it is critical to reinforce the damaged bridges, restore the use function and prolong the service life (Kasan *et al*. 2014; Ludovico *et al*. 2010).

Traditional reinforcement methods are often accompanied by inevitable defects. For example, section enlargement method has higher requirements for clearance, and the cracks on bottom flange are unavoidable. CFRP strengthening method has limitation in improving the bearing capacity and stiffness of the structure, and so on. Therefore, better reinforcement methods are needed to be explored to meet the different needs of reinforcement. Steel plate and concrete composite strengthening (SPCCS) method is developed on the basis of steel and concrete composite girder, which can increase the bearing capacity and stiffness of bridge through encasing steel plates on the reinforcing concrete, and it makes the reinforcing portion integrally worked together with the original concrete structures by welding studs on reinforcing steel plates, planting rebars in existing concrete, and casting new concrete between the existing structure and steel plates. The reinforcement method has both advantages of section enlargement method and sticking steel plate method. Moreover, compared with section enlargement method, the deadweight of reinforced girder has less increase and the strength of steel plate is effectively used. Compared with sticking steel plate method, the connections in SPCCS method are more reliable, and the reinforced portion can be fully used to improve the bearing capacity largely.

SPCCS method was put forward by Prof. Nie in China, who conducted research on flexural behavior of rectangular beam reinforced by SPCCS method, and applied this method to practical engineering (Nie *et al*. 2001; Nie *et al*. 2007; Nie and Zhao 2008). The research team of Prof. Wang also conducted experiments and theoretical analysis on flexural and shear performance of concrete beam reinforced by SPCCS method (Wang and Gao *et al*. 2010; Wang and Yuan *et al*. 2010; Wang 2011 and Ren 2009). From the researches, it showed that the SPCCS method could significantly increase the flexural and shear bearing capacity of test beams. In this paper, full-scale experiments are carried out on concrete box girders with and without reinforcement by SPCCS method, and the girders are demolished from a real bridge after ten-year service. The shear mechanical performance and ultimate shear bearing capacity of the girders are analyzed before and after reinforcement, and theoretical formula on shear bearing capacity of box girder reinforced by SPCCS method is presented.

EXPERIMENTS OVERVIEW

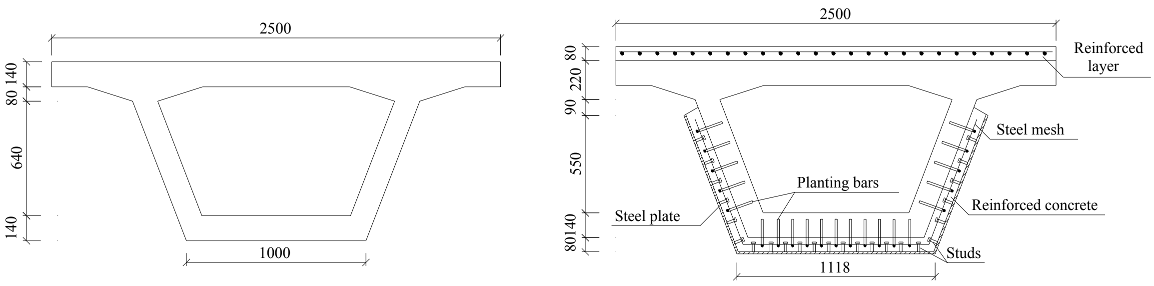
Test girder and reinforcement design

The two test girders are of 20m span prestressed concrete box girder released from a freeway viaduct in Yinchuan, China. Field test results showed that there were different degrees of disease on the components of the PC box girder, for example, the longitudinal and lateral cracks appeared in the bottom flange of box girder, vertical, diagonal and vertical cracks were appeared on the web. Shear capacity tests are carried out on test girders, one without reinforcement, and the other is reinforced by SPCCS method.

In the SPCCS reinforcement, in order to prevent the local damage caused by large counteracting force, the supporting parts of the girder are also reinforced by SPCCS method. Considering both the needs of shear reinforcement and economy, the height of concrete and steel is taller at the range of 500cm away from the supports and reduced in mid-span within 733.4cm. The thickness of reinforced concrete is 8cm, and C40 self-compacting concrete is adopted, the grade of which is the same with the original beam concrete. The thickness of reinforcing steel plate is 6 mm, the steel grade is Q235. At the same time, the top flange is also reinforced by a layer of 8cm thick reinforced concrete. Figure 1 shows the test girder before and after reinforcement by SPCCS method, and Figure 2 shows the cross section of the test girder before and after reinforcement.

(a) Girder before reinforcement (b) Girder after reinforcement

Figure 1 Test girders



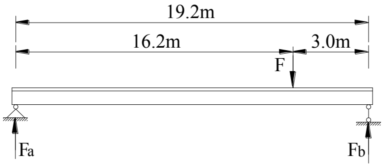
(a) Girder before reinforcement (b) Girder after reinforcement

Figure 2 Cross section of test girders (Unit: mm)

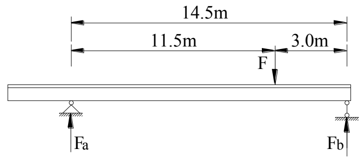
Loading device

The shear test girders are loaded by one-point loading method, and the distance between loading point to support point is 3m, as shown in Figure 3. Each beam is loaded twice. In the first loading, the calculation span is 19.2m, and then the test girder is turned 180 degrees to the other end, so the second loading is acted on the other end to avoid the damaged part resulted from the first loading, and the calculation span is 14.5m, as shown in Figure 4. The serial numbers of test girders are shown in Table 1.

Figure 3 Loading device of shear resistance test



(a) Loading motioned for the first time



(b) Loading motioned for the second time

Figure 4 Shear test load diagram

Table 1 Test girder number

Girder number	Reinforcement situation	Calculation span (m)	Girder depth (cm)
N-S-1	No reinforcement	19.2	100
N-S-2	No reinforcement	14.5	100
SPCCS-S-1	Reinforced with SPCCS method	19.2	116
SPCCS-S-2	Reinforced with SPCCS method	14.5	116

Arrangement of measuring points

The strain of concrete and steel is tested by strain gauges, and the test contents including the concrete strain of top flange, web and bottom flange, the strain of stirrup and the strain of reinforcing steel plate. The measuring point arrangements of web strain and stirrup strain of SPCCS-S-1 are showed in Figure 5 and Figure 6 respectively.

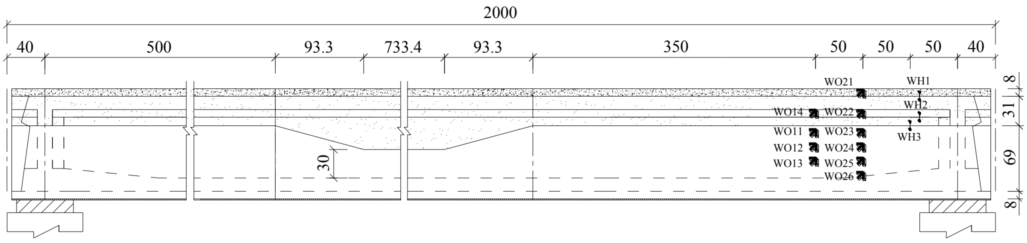


Figure 5 Web strain measuring point arrangement of SPCCS-S-1

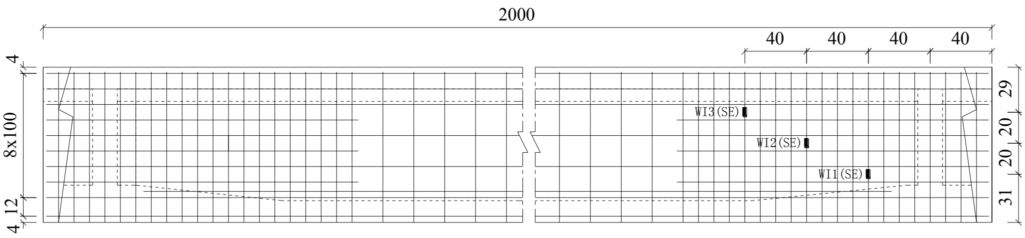


Figure 6 Stirrup strain measuring point arrangement of SPCCS-S-1

Test phenomena and failure mode

(1) Test girders without reinforcement

For test girder N-S-1, when the load is 600kN, the web in shear span has new diagonal cracks, the crack angle is about 50°, and the maximum crack width is about 0.15mm. Then the number of diagonal cracks and crack width increases with the load. When the load is 800kN, the web under loading point also appears diagonal cracks. The maximum crack width is 0.25mm when the load is 900kN, 0.4mm for 1200kN, and 0.5mm for 1400kN. When the load is 1500kN, the diagonal cracks extend to the haunch, and the maximum crack width is about 0.9mm. The load stops increasing when it reaches to 1815kN, and the test girder starts automatic unloading. When the load reduces to 1742kN, the top flange is crushed, and the load reduces to 533kN suddenly, it shows that the test girder is damaged.

For test girder N-S-2, when the load is 870kN, new diagonal cracks appear in shear span, and the maximum crack width is 0.2mm. When the load is 1000kN, the crack width increases to 0.33mm, and the diagonal cracks has extended to the haunch. When the load is 1240kN, the crack width is 0.5mm. When the load increases to 1400kN, 1600kN and 1800kN, the crack width is 0.7mm, 0.8mm and 1mm respectively. The load stops increasing when it reaches to 2000kN, and the test girder automatically unloads to 1921kN. When the load increases to 1965kN again, the top flange is crushed, and the load automatically drops to 764kN, and the test girder is damaged. Failure modes of the two test girders are shown in Figure 7.

(a) Web cracks of N-S-1

(b) Web cracks of N-S-2

Figure 7 Failure modes of test girders without reinforcement

(2) Test girders with SPCCS reinforcement

Test girder SPCCS-S-1 has no obvious change when the load is less than 1800kN, and stripping crack between reinforcing steel and concrete appears after 1800kN. When the load is 2100kN, cracks extend from the reinforcement concrete of the web. When the load increases to 3260kN, steel plate below the loading point strips from the concrete. The maximum load reaches to 3273kN, then local buckling occurs on the steel plate below the loading point, and the main diagonal crack appears from top flange to the haunch, the deflection of girder increases significantly, the test girder is damaged.

For test girder SPCCS-S-2, cracks extend to the haunch when the load is 2000kN, but the width of crack is smaller, about 0.05mm. When the load is 3100kN, the reinforced concrete starts to strip off from the original girder, and steel plate and reinforced concrete are stripped obviously in shear span zone, steel plate under loading point appears local buckling. When the load is 3270kN, the concrete of top flange starts to fall off, then the steel plate and reinforced concrete strips continuously, accompanied with the sound of concrete crush. When the load is 3290kN, the test girder automatically unloads, and the maximum carrying capacity is reached. After that, the steel plate below loading point strips off from reinforced concrete completely and the maximum crack width in the haunch is 0.2mm. Steel plate appears several local buckling. Failure modes of the two girders are shown in Figure 8.

(a) Stripping damage of SPCCS-S-1

(b) Diagonal crack of top flange in SPCCS-S-1

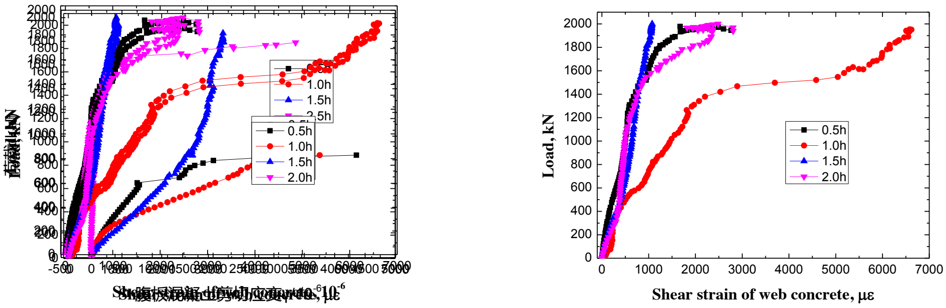
Figure 8 Failure modes of test girders with SPCCS method

DISCUSSION OF RESULTS

Test girders without reinforcement

Shear strain of web concrete

Figure 9 shows the load-shear strain curves of web concrete in different cross-sections of test girders without reinforcement. For test girder N-S-1, the distances from measuring points to support are 0.5h, 1.0h, 1.5h and 2.5h separately (h means depth of girder). For test girder N-S-2, the distances from measuring points to support are 0.5h, 1.0h, 1.5h and 2h separately. As shown in Figure 9, measuring points at sections of 0.5h and 1.0h in N-S-1 cannot carry more load when the load reaches to 800kN due to the cracks, so that shear force is carried by stirrups and concrete without crack. Other measuring points can carry shear force sustainably until the limit load is close when cracks appear. Shear stress in section of 1.0h is significantly greater than that in other sections.

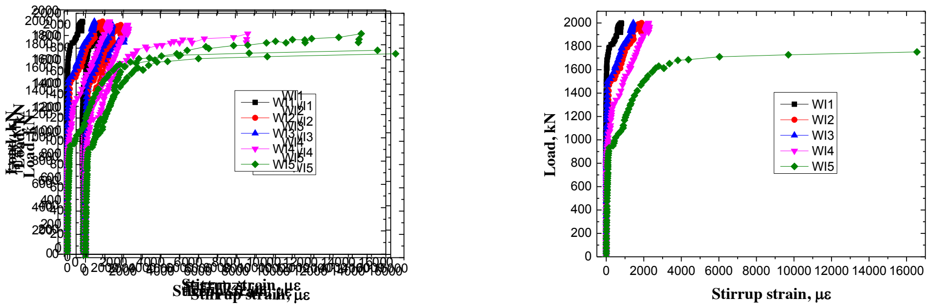


(a) Test girder N-S-1 (b) Test girder N-S-2

Figure 9 Load-shear strain curves of web concrete in different cross-sections

Strain of web stirrup

Figure 10 shows the load-strain curves of web stirrup, measuring points WI1~WI5 are located within shear span of 3m, of which the distance to support increases gradually. It can be seen from Figure 10, when the load is less than 800kN, stirrup strain is very small for there almost has no new cracks. After the appearance of diagonal cracks, shear force redistributes which resulted in sharply increase of stirrup strain, and stirrup turned into elastic-plastic stage quickly. When the limit load is reached, most of the stirrups have entered into yield status.



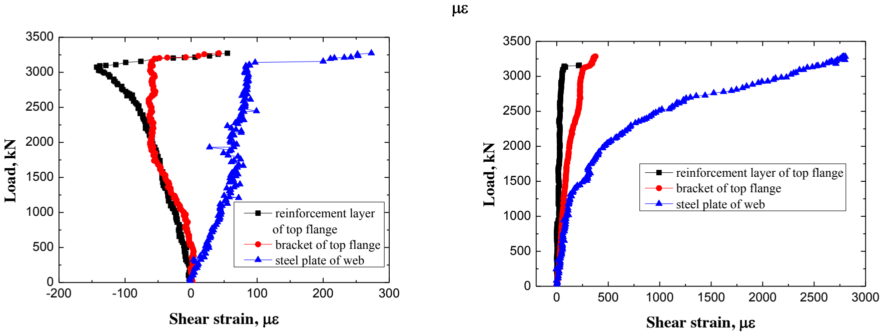
(a) Test girder N-S-1 (b) Test girder N-S-2

Figure 10 Load-strain curves of web stirrup

Steel plate and concrete composite strengthening test girders

Shear strain of web and top flange

Figure 11 draws the load-shear strain curves of web and top flange at different vertical positions in the section whose distance to supports is 1.0h. Figure 11 illustrates the reinforcement layer and haunch of box girder provide small shear capacity, and the web carry the most shear force, so SPCCS method can make full use of steel strength by setting steel plate at the outside of the reinforced concrete of web, and increase the shear carrying capacity of reinforced girders.

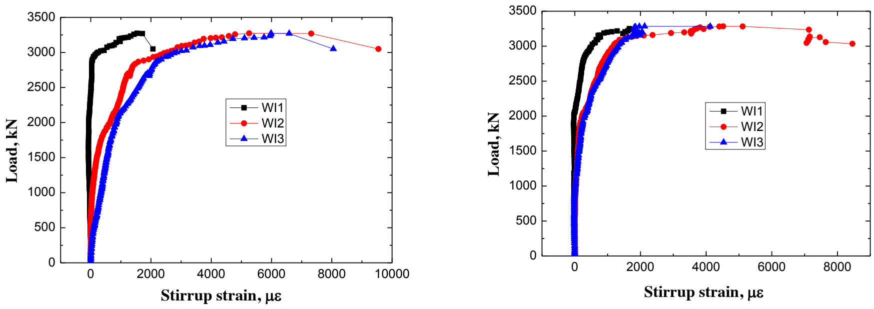


(a) Test girder SPCCS-S-1 (b) Test girder SPCCS-S-2

Figure 11 Load-shear strain curves of web and top flange in section of 1.0h

Strain of web stirrup

Figure 12 shows the load-strain curves of web stirrup. The distances from measuring points to support are 0.4h, 0.8h and 1.2h separately. As shown in Figure 12, when the load is less than 1500kN, stirrup strain is small because there is no new crack. After the load is larger than 1500kN, with the cracks increasing, stirrups carry more and more shear force, stirrup strain increases gradually, so that the slope of the curve grows faster and stirrup turns into elastic-plastic stage gradually. When the limit load is reached, load remains steady while strain continues to grow, and stirrups yield eventually.

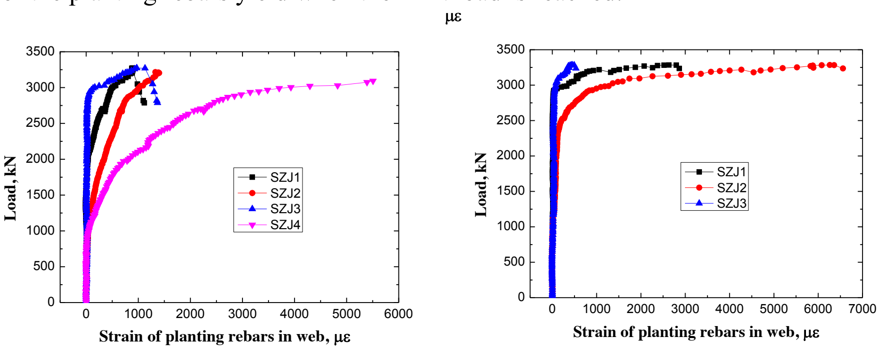


(a) Test girder SPCCS-S-1 (b) Test girder SPCCS-S-2

Figure 12 Load-strain curve of web stirrup

Strain of planting rebars in web

Figure 13 shows the load-strain curves of planting rebars in web, and the measuring points are set at the end of girder web on the loading side. As shown in Figure 13, in the early stage of loading, the stress of the planting rebars is smaller. At this time, shear stress and normal tensile stress of the interface between new and existing concrete is mainly carried by the bonding strength of the interface. Then the strain of the planting rebars grows rapidly with the increase of load, which showed that planting rebars have good force transfer effect, so that the strengthening part and the original girder can carry load together, thus the shear capacity of the original girder is improved. Part of the planting rebars yield when the limit load is reached.



(a) Test girder SPCCS-S-1 (b)Test girder SPCCS-S-2

Figure 13 Load-strain curves of planting rebars in web

Figure 14 shows the relative slip between new and existing concrete of SPCCS-S-2, and measuring points are set at the end of girder on the loading side. As can be seen from Figure 14, there is almost no relative slip between new and existing concrete before limit load. When limit load is reached, slide grows rapidly and the relative slip up to 6.2mm. Therefore, in the process of loading, the reinforced concrete and the original concrete work together and can bear the load as a whole, and the strengthening effect is good. The regularity in SPCCS-S-1 is similar to that in test beam SPCCS-S-2.

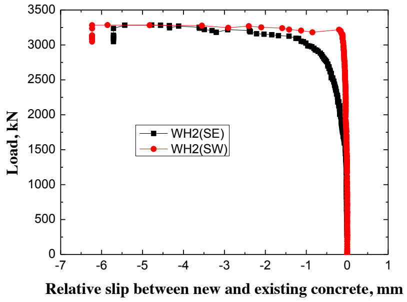


Figure 14 Load-relative slip curves between new and existing concrete

Figure 15 illustrates the load-relative slip curves between new concrete and reinforcing steel plate of SPCCS-S-1, and measuring points are set at the end of girder on the loading side. From Figure 15 we can see that there is basically no relative slip on the interface until limit load is reached. When the load is close to the limit load, the slide has a great increase and the maximum relative slip up to 0.12mm. It is indicated that the reinforced concrete and the steel plate can work as a whole in the process of loading, and the strengthening effect is good. The regularity in SPCCS-S-2 is similar to that in test beam SPCCS-S-1.

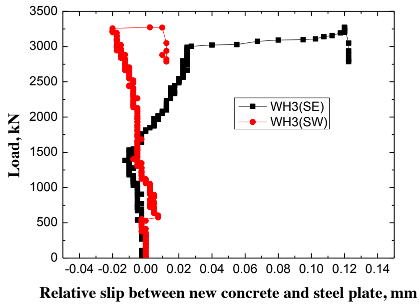


Figure 15 Load-relative slip curves between concrete and steel plate

Comparison of shear carrying capacity

Shear carrying capacity of test girders without reinforcement and reinforced by SPCCS method are shown in Table 2.

Table 2 Comparison of shear carrying capacity

Test girder number	Ultimate shear capacity Vu/kN	Stirrup yield shear force Vy/kN	Increase proportion of shear carrying capacity after reinforcement
N-S-1	1531	1304	——
N-S-2	1588	1207	——
SPCCS-S-1	2761	2185	77.0%
SPCCS-S-2	2605	2230	67.0%

From Table 2, it can be seen that shear carrying capacity of test girders is increased by 67.0% and 77.0% respectively after reinforced by SPCCS method. Obviously, SPCCS method can effectively improve the shear capacity of box girders, and the shear reinforcement effect is great. Moreover, yield shear force of stirrups after reinforcement is greater than that before reinforcement, it is indicated that because of the effect of reinforcing part, the yield time is delayed and the shear capacity of the test girder is improved.

THEORETICAL ANAYLYSIS OF SHEAR CAPACITY

Shear mechanism of steel plate and concrete composite strengthening method

Test results showed that as for box girder reinforced by SPCCS method, before the diagonal cracks appear, the strain of both reinforcing steel plates and stirrups is small. After the diagonal cracks appear, the internal force of girder redistributes, and the strain of both reinforcing steel plates and stirrups increases rapidly. The reinforced part plays a significant role in improving the shear capacity of box girder. Generally, the load transformation system of a girder with diagonal cracks can be compared as a group of tied-arch structure, as shown in Figure 16. It is composed of basic arched-body I upon the critical diagonal cracks and a group of small arched-body II and III below the critical diagonal cracks. SPCCS method improves the shear capacity of girder in the following aspects:

(1) Reinforcing steel plates of web hold on to the small arch system, then the small arch system can carry more shear force. Therefore, the pressure on the basic arched-body I decreases and the propagation of diagonal crack is constrained; at the same time, the strength of reinforcing steel plates is higher than that of concrete, which can carry larger shear force.

(2) Reinforcing steel plates and longitudinal rebars of bottom flange transmit the principle compressive stress of the small arched-body II and III to the support by dowel action; at the same time, steel plate of bottom flange distributes the normal stress of longitudinal rebars, and improves the dowel action of longitudinal rebars.

(3) The reinforcing concrete can increase the shear area of web concrete, and lower the neutral axis of box girder, thus improving the shear capacity of box girder.

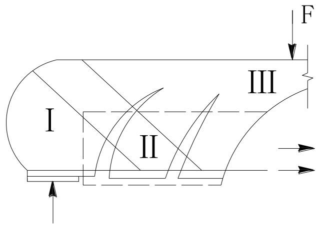


Figure 16 Mechanical model of box girder after diagonal cracks appear

Shear capacity calculation of box girder reinforced by SPCCS method

Shear capacity calculation of box girder reinforced by SPCCS method should take following factors into consideration: cracks on the original structure has effect on shear capacity of the box girder after reinforcement; lateral steel plates have contribution to shear capacity after reinforcement, and the area of steel plates should be transformed into concrete area; shear connection degree between new and existing concrete and that between reinforcing steel plates and new concrete has effect on shear capacity after reinforcement.

On the basis of experimental research, considering the effect of connection degree of shear connectors, Chunsheng Wang and Tengxian Ren put forward the shear capacity calculation formula of reinforced concrete T beam reinforced by SPCCS method (Ren 2009; CCCC Highway Consultants Co. Ltd 2004; Nie and Zhao 2010). Considered the contribution of bent-up rebars and prestressed reinforcement to shear capacity, the formula is revised in this paper, as shown in Equation (1).

$$V_{\mathrm{u}} = \alpha_1\alpha_3\left(1.964 - \frac{0.964}{1+12.807\bar{r}^{2.168}}\right)\sqrt{(2+0.6p)\sqrt{f_{\mathrm{cu,k}}}\rho_{\mathrm{sv}}f_{\mathrm{sv}}}\,(0.43\times10^{-3}A_0\psi_{\mathrm{cs}}+0.45\times10^{-3}A_{\mathrm{n}}) + 0.75\times10^{-3}f_{\mathrm{sd}}\sum A_{\mathrm{sb}}\sin\theta_{\mathrm{s}} + 0.75\times10^{-3}f_{\mathrm{pd}}\sum A_{\mathrm{pb}}\sin\theta_{\mathrm{p}} \qquad (1)$$

where α_1 is the opposite sign bending moment coefficient, $\alpha_1 = 1.0$ when calculating shear capacity of the simple supported beam and segment of continuous beam that near side supports, and α_1 =0.9 when calculating shear capacity of the cantilever beam and segment of continuous beam that near middle supports; α_3 is the influence coefficient of compression flange, and $\alpha_3 = 1.1$; $\bar{r} = r/(r+1)$, r is shear connection degree, $r = n_{\mathrm{d}}/n_{\mathrm{f}}$, n_{d} is the actual amount of shear connectors in shear span, n_{f} is the calculated amount of shear connectors in shear span by plasticity design method, as for box girder reinforced by SPCCS method, r takes the minimum value of studs and planting rebars which has the smaller shear connection degree; p is the reinforcement ratio of longitudinal tensile rebars in diagonal section after reinforcement, $p = 100\rho$, $p = 2.5$ when $p > 2.5$; $\rho = (A_{\mathrm{s1}}+A_{\mathrm{s2}})/(A_{\mathrm{o}}+A_{\mathrm{n}})$, A_{s1} is the total area of longitudinal rebars and prestressed reinforcement in diagonal section of original girder, A_{s2} is the total area of longitudinal rebars in reinforcing concrete and reinforcing bottom plates, $A_0 = bh_0$, b is the width of the original girder, h_0 is the effective height of the normal section of original girder, A_n is the total area of new concrete and transformed area of reinforcing steel plates; $f_{cu,k}$ is the cube compressive strength of original concrete; ρ_{sv} is the reinforcement ratio of stirrups; f_{sv} is the tensile strength of stirrups; ψ_{cs} is the correction factor related to diagonal cracks of the original girder, $\psi_{cs} = 1.0$ when there is no diagonal crack before reinforcement, $\psi_{cs} = 0.835$ when the width of crack is smaller than 0.2mm, and $\psi_{cs} = 0.78$ when the width of crack is larger than 0.2mm; A_{sb} and A_{pb} are the area of general bent-up rebars and prestressed bent-up reinforcement in the same bending section at the diagonal section respectively; θ_s and θ_p are the intersection angle between longitudinal axis and tangent line of general bent-up rebars and prestressed bent-up reinforcement respectively; f_{sb} and f_{pb} are the tensile strength of general bent-up rebars and prestressed bent-up reinforcements respectively.

The shear capacity of test girders reinforced by SPCCS method is calculated according to Equation (1), and then the calculated value is compared with the test value, as shown in Table 3.

Table 3 Comparison of shear capacity by calculation and test

Test girder number	Test Value V_{exp} /kN	Calculated Value V_u /kN	V_u / V_{exp}
SPCCS-S-1	2761	2844	1.03
SPCCS-S-2	2605	2844	1.09
Average Value	2683	2844	1.06

Table 3 indicated that the difference between test value and calculated value is below 10%, thus the formula proposed by this paper can well reflect shear capacity of box girder reinforced by SPCCS method, as well as can provide reference for calculation in engineering.

CONCLUSIONS

Though experimental and theoretical researches on shear capacity of damaged full-scale concrete box girder before and after reinforced by SPCCS method, following conclusions can be obtained.

(1) SPCCS method can improve the whole working performance of existing structure and new reinforcement part by the shear force transforming through planting rebars and studs. Test results showed that the reinforcement part can carry the loads with the existing girder together, and the shear capacity of PC box girder is improved effectively.

(2) The failure mode of PC box girder reinforced by SPCCS method is that diagonal cracks propagate rapidly, which are caused by stripping between new and existing concrete or new concrete and steel plate, then the stirrups yield and the girder fails eventually. Therefore, it is important to choose the diameter, spacing, and number of planting rebars and studs reasonably.

(3) The shear capacity of PC box girder after reinforced by SPCCS method is improved 67% at least, and this reinforcement method can constrain the development and propagation of cracks effectively as well as delay the yield of stirrups.

(4) The shear mechanism and calculation formula on shear capacity of PC box girder reinforced by SPCCS method are proposed, and the calculated results and experimental results coincide well.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Special Fund for Basic Scientific Research of Central College of the P. R. China, Chang'an University (10821153501, 310821153401 and 310821153314), the innovation project of science and technology key laboratory project in Shaanxi province (2014SZS19-D03, 2014SZS19-Z02),the financial support provided by the Science and Technology Project of Communications Department of Ningxia

Hui Autonomous Region, the China Postdoctoral Science Foundation (Grant No. 0306-332100000101, 2014M552394), the Natural Science Foundation Research Project of Shaanxi Province (2014JQ7236), and the Transportation Science and Technology Project of Ministry of Transport of China (2013318223040, 2014318223030).

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