Experimental Study and Finite Element Analysis of Externally Prestressed RPC Box-Girder with Corrugated Steel Webs

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Abstract. Prestressed normal concrete (PC) box-girder with corrugated steel webs has been widely used in bridge engineering because of its favourable properties and wins general recognition of bridge practitioners, but researches on externally prestressed reactive powder concrete (RPC) box-girder with corrugated steel webs are still rare. In this paper, the experiment and ABAQUS finite element analysis considering materials nonlinearity are performed to study the mechanical properties of externally prestressed RPC box-girder with corrugated steel webs during its whole bending process. The experimental results show that compared with externally prestressed normal concrete (PC) box-girder with corrugated steel webs, the externally prestressed RPC box-girder with corrugated steel webs has higher ultimate bearing capacity, higher cracking strength, better anti-cracking performance and durability. The ABAQUS finite element analysis results have good agreement with the test results and the model of this article for the analysis of the whole bending process of externally prestressed RPC box-girder with corrugated steel webs is feasible.

1. Introduction
The PC box-girder with corrugated steel webs is the composite of concrete upper and lower flange, prestress tendons and corrugated steel webs, which is an improvement of traditional PC girder. PC box-girder with corrugated steel webs has the advantages of light weight, short construction period, convenient construction, improved economic benefit, attractive appearance, etc. The domestic and overseas studies on its bending, torsion, shear and buckling performance is already relatively perfect and systematic [1-3]. Due to the deficiencies of concrete property, the development of this girder to light weight, large span is limited, and its potential application can not fully display. RPC is new type of composite material and is getting widely attention in recent years. It has excellent compressive, bending, crack resistance and durability. In view of this, this article put forward to externally prestressed RPC box-girder with corrugated steel webs for the purpose of improving the performance of concrete and through experiment and ABAQUS finite element simulation, the mechanical properties of externally prestressed RPC box-girder with corrugated steel webs during its whole bending process is studied.
2. Experiment of Externally Prestressed RPC Box-Girder with Corrugated Steel Webs

2.1. Design of Test Beams

Two beams of beam A with RPC and beam B with normal concrete of standard cubic compressive strength of 80MPa are tested. Two beams both select box cross section and with the same calculation span of 4.4 m and high of 0.51 m as shown in figure 1. Corrugated steel webs are manufactured using Q345c through cold rolling and the geometry of corrugated steel web is shown in figure 2. The two test beams have the same designed section strength, and both without medium diaphragm. It is post-tensioned externally by two bundles of steel tendons with draped profile and draped at two symmetrically placed deviators at the quarter points. Each bundle has 3Φs15.24 steel tendons and the control tension stress is 1209 MPa. In addition, the upper and lower flange of beam B have 10 and 8  10 reinforcements. Beam A is not configured with common reinforced concrete, but blended with 3% content of steel fiber. Beam A and beam B have the same cross section stiffness and the cross section area of beam A is smaller than beam B, so the weight of beam A is lighter than beam B. The section of beam A and B are shown in figure 3.

2.2. Loading Process and Measurement

The main test items include deformation of locations of beam ends, deviators and mid-span, stress increment of externally prestressed tendons, concrete strain of the upper and lower flange at the mid-span cross section, the longitudinal strain of the corrugated steel webs. The deformation is measured using dial indicator, concrete and steel strain measured using resistance strain gauge, the stress increment of externally prestressed tendons is measured using pressure sensor under anchor. Figure 4 is the distribution of sensor and dial indicator.
The load is applied at the three dividing points. The load increment is 51.2 kN for every grade before cracking or 85% calculated cracking load, and after the bottom appears crack, reduce the load increment. The test data is acquired 2 minutes after every loading grade. The loading will finish when the crack of girder changes obviously or the test instruments show abnormal or not stable. Figure 5 shows the loading mode.

![Figure 4](image1)

**Figure 4.** Distribution of sensor and dial indicator.

![Figure 5](image2)

**Figure 5.** Loading mode.

3. ABAUQS Finite Element Simulation

3.1. Constitution of Materials

The constitution of RPC using the model of Ref. [4]:

\[
\begin{align*}
    y &= a + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 & 0 \leq x \leq x_0 \\
    y - y_0 &= \frac{x - x_0}{x_c - x_0} & x_0 \leq x \leq x_c \\
    y &= y_c & x_c \leq x \leq x_u 
\end{align*}
\]

where \( x = \epsilon / \varepsilon_0 \), \( y = \sigma / \sigma_0 \); \( \varepsilon_0 \) and \( \sigma_0 \) are peak strain and stress, respectively and \( \epsilon_u \) is the ultimate compressive strain. This article using the measurement values of \( \sigma_0 = 105 \text{MPa}, \varepsilon_0 = 0.0016 \) and \( \varepsilon_u = 0.005 \). Parameter \( a = 0.006, b_1 = 1.153, b_2 = -0.9, b_3 = 1.829, b_4 = -1.088 \).

The constitution of concrete with standard cubic compressive strength of 80MPa uses the model of Ref. [5]:

\[
\sigma = \begin{cases} 
\sigma_0 \left( \epsilon / \varepsilon_0 \right) + \left( 3 - 2 \alpha_u \right) \left( \epsilon / \varepsilon_0 \right)^2 + \left( \alpha_u - 2 \right) \left( \epsilon / \varepsilon_0 \right)^3 & 0 < \epsilon \leq \varepsilon_0 \\
\frac{\sigma_0 \epsilon / \varepsilon_0}{\alpha_u \left( \epsilon / \varepsilon_0 \right)^2} & \epsilon_u \geq \epsilon > \varepsilon_0 
\end{cases}
\]

where \( \sigma_0 = 80 \text{MPa}, \varepsilon_0 = 0.0025 \). Parameter \( \alpha_u = 1.08 \).
where \( x = \epsilon / \sigma _0 \), \( y = \alpha / \sigma _0 \), \( \sigma _0 \) and \( \sigma _0 \) are peak strain and stress, respectively and \( \alpha _u \) is the ultimate compressive strain. This article using the measurement values of \( \sigma _0 = 80 \) MPa, \( \epsilon _0 = 0.0023 \), \( \alpha _u = 0.005 \), \( \alpha _a = 1.6 \), \( \alpha _d = 3.2 \).

The axial tensile stress-strain curves of RPC and concrete with standard cubic compressive strength of 80MPa are relative complex, and due to its high proportional limit, it can approximate take that before tensile zone of concrete cracking or quit job, the relationship between stress and strain is straight line. After concrete cracking or tensile stress reaching the tensile strength, ABAUQS suggests tensile stress dropped to 0 linearly and the ultimate tensile strain can take 10 times higher than the cracking strain. The RPC elastic modulus by test is \( E_c = 64944 \) MPa, tensile strength \( f_t = 16 \) MPa, cracking strain values for \( \alpha _a = 0.0002 \), take the limit tensile strain values for \( \alpha _u = 0.002 \). According to Ref. [5], for concrete with standard cubic compressive strength of 80MPa, the derived elastic modulus \( E_c = 46243 \) MPa, tensile strength \( f_t = 4.0 \) MPa, the cracking strain \( \alpha _a = 0.00009 \), the ultimate tensile strain \( \alpha _u = 0.0009 \).

The constitution of reinforcements and corrugated steel web uses ideal elastic-plastic model.

The constitute of external prestress tendon uses the model of Ref. [5]:

\[
\epsilon_p = \frac{\sigma_p}{E_p} + 0.002 \left( \frac{\sigma_p}{f_{0.2}} \right)^{1.5}
\]

(3)

where \( \sigma_p \), \( \epsilon_p \) and \( E_p \) are stress, strain, elastic modulus of external prestress tendon. This model takes the stress when the remanent strain is \( 0.2 \times 10^{-5} \).

### 3.2. Model Building

The same modeling methods are adopted to two test beams. The concrete elements, deviators and anchoring ends of are simulated using C3D20R elements and the reinforcement steels. The external prestress tendons are simulated using T3D2 elements. The corrugated steel webs are simulated using three-dimensional shell element S4R. The Tie constraints are used in ABAUQS to simulate the contact between corrugated steel webs and concrete flanges. Using the unit embedding technique, in the body can be the bonded reinforcements can be added to concrete elements. Every straight line segment of externally prestressed tendons is taken as one element.

### 4. Test and ABAUQS Finite Element Simulation Results Analysis

Figures 6 and 7 are the stress increment of external prestress tendons and midspan deflection of two test beams by measurement and ABAUQS finite element calculation in the whole bending process. It can be seen from figures 6 and 7 that the whole bending process of externally RPC box-girder with corrugated steel webs three line and externally PC box-girder with corrugated steel webs have the similar changing characteristics and from loading beginning to destruction two beams have experienced three stages, that is elastic stage, cracking elastic stage and plastic stage. After the reinforcements and getting to yield, beam B reaches destruction.

It can be seen from figures 6 and 7 that compared with beam B, the cracking load and the ultimate load of beam A increases respectively.

Although beam B have reinforcements in the lower flange, the cracking strength of beam B is much smaller than beam A, and RPC can improve the cracking strength of externally PC box-girder with corrugated steel webs. Although beam A and beam B have the same cross section stiffness, the ultimate bearing capacity of beam A, which has smaller cross section and lighter weight, is improved and RPC can improve the ultimate bearing capacity of externally PC box-girder with corrugated steel webs.

Beam B have reinforcements in the lower concrete flange, its deformation performance, and stress increment of externally prestressed tendons got full play. Adding the RPC of beam A certain amount of steel fiber, which enhances the crack resistance of beam A, but its ductility is poorer than beam B, therefore, reinforcements in the lower flange are important for externally RPC box-girder with
corrugated steel webs.

\[\text{Figure 6. The load-midspan curves by measurement and ABQUS analysis.}\]

\[\text{Figure 7. The load-external prestress increment curves by measurement and ABQUS analysis.}\]

During the process of loading, two test beams both crack early at the bottom of mid-span and L/4 cross section, and with the increasing of load, the number of cracks increase. When the beams reach destruction, three cracks distribution areas have formed. The differences between beam A and beam B are that when reaching destruction, a large number of transverse penetration cracks are formed at the bottom of the beam B, but the cracks of beam A are mainly small cracks, and have no obvious transverse penetration cracks. So the RPC box-girder with corrugated steel webs has better durability. Figures 8 and 9 are cracks distribution of beam A and B when they reaching destruction, respectively.

It can be seen from figures 8 and 9 that during the whole bending process, for beam A and beam B, the ABQUS calculation values are in good agreement with the measurement values, using this ABQUS finite elements model for the analysis of the whole bending process of externally prestressed RPC box-girder with corrugated steel webs is feasible.

5. Conclusions

(1) Compared with PC box-girder with corrugated steel webs, externally RPC box-girder with corrugated steel webs have higher cracking strength, bearing capacity of beam A and much lighter weight.

(2) When reaching destruction, a large number of transverse penetration cracks are formed at the bottom of the externally PC box-girder with corrugated steel webs. The cracks of externally RPC box-girder with corrugated steel webs are mainly small cracks, and have no obvious transverse penetration cracks, which has better durability.
(3) The RPC of externally RPC box-girder with corrugated steel webs is added with certain amount of steel fiber, which enhances the crack resistance of this girder, but its ductility is poorer than externally PC box-girder with corrugated steel webs, therefore, reinforcements in the lower flange are important for externally RPC box-girder with corrugated steel webs.

(4) Using ABQUS finite elements model of this article for the analysis of the whole bending process of externally prestressed RPC box-girder with corrugated steel webs is feasible.

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References
[1] Mo Y L, Jeng C H and Chang Y S 2000 Torsional behavior of prestressed, concrete box-girder bridges with corrugated steel webs ACI Structural Journal 97 (6) 849-859
[2] Yazeed E and Ahmed S 2001 Behaviour of steel and (or) composite girders with corrugated steel webs Canadian Journal of Civil Engineering 28 (4) 656-672
[3] Elgaaly M, Seshadri A and Hamilton R W 1997 Bending strength of steel beams with corrugated webs Journal of Structural Engineering 123 (6) 772-782
[4] Xu Q, Du J S and Zhang J Q 2011 Experimental of mechanical properties of reactive powder concrete in compression Journal of Highway and Transport Research and Development 28 (7) 8-13
[5] Guo Z H and Shao X D 2003 Principle and Analysis of the Reinforced Concrete Beijing: Tsinghua University Press

Figure 8. Bottom cracks distribution of beam A at the time of destruction.

Figure 9. Bottom racks distribution of beam B at the time of destruction.