Research on Application of RPC Materials in Urban Pedestrian Bridge Reconstruction

Ping Lyu\textsuperscript{1a}, Peiheng Long\textsuperscript{2b}

\textsuperscript{1}School of Civil and Transportation Engineering; High-tech Innovation Center for Future Urban Design Beijing University of Civil Engineering and Architecture Beijing, China

\textsuperscript{2}High-tech Innovation Center for Future Urban Design; Beijing Energy Conservation and Emission Reduction Key Technology Cooperative Innovation Center Beijing University of Civil Engineering and Architecture Beijing, China

\textsuperscript{a}2108140618003@stu.bucea.edu.cn

\textsuperscript{b}bjjzdxlvping@163.com, blongpeiheng@bucea.edu.cn

Abstract—Aiming at the characteristics of poor corrosion resistance, high maintenance frequency and high cost of steel box girder pedestrian bridge structure, and the traditional concrete is thick and moderate in strength, this paper proposes a method to apply reactive powder concrete RPC to the existing pedestrian bridge deck and uses steel-RPC composite box girder as the bridge superstructure. Based on the research on the RPC material and the related performance of its components, the feasibility and reliability of RPC applied to beam-slab composite members are verified. By comparing steel-RPC composite box girder, steel box girder, and steel-general concrete composite box girder, it is found that steel-RPC composite box girder is superior in terms of mechanical performance, economic evaluation, and aesthetics. The research shows that the steel-RPC composite box girder is more suitable for the steel box girder pedestrian bridge reconstruction project and the new pedestrian bridge project across urban roads.

1. INTRODUCTION

Steel structures have been widely used in bridge engineering in recent years, but they have the disadvantages of poor corrosion resistance, greater flexibility, and high economic costs. In the long-term operation process of steel-ordinary concrete composite beams, under permanent loads, variable loads, and occasional loads, the structure will undergo resistance attenuation and damage accumulation, causing corrosion of steel bars and aging and cracking of concrete [1,2]. In severe cases, it can lead to a vicious circle and cause catastrophic accidents [3]. In addition, the thick steel-ordinary concrete composite beams have poor aesthetics and are not suitable for the reconstruction and new construction of urban bridges [4]. In order to find a high-strength material that combines compressive performance, durability, and lower price than steel, French scholars first verified the mechanical properties of the material compared to ordinary concrete by changing the ratio of the concrete material, the reinforcement ratio and the content of steel fibers There is a big improvement and it is named RPC, namely reactive powder concrete [5].
This article is based on the existing steel box girder overpass—Dajiaoting Footbridge. The bridge is located on Guangqu Road, Chaoyang District, Beijing, and has been built for 12 years, as shown in Fig. 1. During the routine inspection of Beijing's urban bridges in 2018, it was found that the bridge had been repaired several times, and the bridge deck was severely damaged again. The upper structure of the steel box girder was rusted. That is the durability of the superstructure. For the application of RPC materials in practical engineering, a steel-PRC composite box girder was proposed, and the steel box-girder pedestrian bridge and the steel-general concrete composite box girder were compared before the transformation to verify the high bearing capacity of the steel-RPC composite girder reliable durability and good economy, in order to provide reference for future maintenance of this type of old bridge and new bridge design.

![Figure 1. Vertical view of pedestrian bridge.](image)

### 2. RPC Performance Test

#### 2.1. PRC material component mechanical property test.

Reactive Powder Concrete (RPC) is a new type of ultra-high-strength concrete [5]. It mainly relies on the removal of coarse aggregates and the incorporation of cementitious materials such as silica fume to reduce the void ratio and reduce the water-binder ratio. To improve its compressive strength; RPC's special curing conditions are also one of the reasons for its increase in compressive strength, which can reach 200MPa through steam curing and 800MPa through high temperature and high pressure curing [6]. However, due to the lack of relevant technical specifications of RPC materials, it is necessary to verify the material properties to determine that its actual mechanical properties meet the design requirements.

According to the force characteristics, span and layout of the pedestrian bridge across the main road in Beijing, the compressive strength of the activated powder concrete of the pedestrian bridge after the reconstruction was determined to be 120 MPa, and the three groups of RPC were designed: the first group was not mixed with steel fibers has a compressive strength of 120MPA; the second group is doped with steel fibers and the mixing ratio is slightly modified to give a compressive strength of 134MPA; the third group is doped with steel fibers and the compressive strength is 131MPA. The experimental materials are shown in Table 1 and the experimental results are shown in Table 2.

| Number | Water reducer | Water | Cement | Mineral powder | Silica fume | Fine sand | Coarse sand | Steel fiber | Expected strength |
|--------|---------------|-------|--------|---------------|-------------|-----------|-------------|-------------|------------------|
| 1      | 36.7          | 174   | 700    | 251           | 80          | 810       | 200         | 0           | 120MPa           |
| 2      | 40            | 170   | 700    | 251           | 80          | 960       | 240         | 118         | 131MPa           |
| 3      | 36.7          | 174   | 700    | 251           | 80          | 810       | 200         | 118         | 134MPa           |

| Test Block Number | Compressive strength of cube | Axial compressive strength | Tensile strength | Flexural strength | Elastic Modulus |
|-------------------|------------------------------|---------------------------|-----------------|------------------|-----------------|
| 1                 | 120.8                        | 123.4                     | 8.9             | 4.43             | 44.4            |
| 2                 | 121.5                        | 118.4                     | 9.3             | 14.62            | 41.2            |
| 3                 | 127.4                        | 123.1                     | 8.69            | 14.91            | Excessive error |
The compression stress-strain relationship curve of the test block is shown in Fig. 2. Since no steel fiber was added, the first group of RPCs suffered brittle failure under compression, so there is no need to continue to study this group. The elastic modulus of the third group of RPC without changing the RPC ratio is very unstable. The reason is that the internal structure is not uniform. Therefore, this group of ratios should be treated with caution. Therefore, the second group of test blocks is used for subsequent design. The tensile stress-strain curve of the second group is shown in Fig. 3. Compared with ordinary concrete, due to the steel fiber, its tensile performance is better than ordinary concrete, and the brittle failure is less. Both have great improvements, but cannot be used as tensile members alone.

Based on the cubic compressive strength, axial compressive strength, axial tensile strength, flexural strength, and elastic modulus of the RPC materials in Table 2, the constitutive relationship of RPC is calculated, and the proper structure of the pedestrian bridge in this paper is obtained. The constitutive relationship of group RPC, that is, the constitutive relationship of the second group of RPC mix ratio is as follows:

The equation of the compression constitutive relationship is:

\[
y = \begin{cases} 
1.22x + 0.12x^4 - 0.34x^5 & 0 \leq x \leq 1 \\
\frac{x}{8(x - 1)^2 + x} & x \geq 1 
\end{cases}.
\]  

1
The equation of the tensile constitutive relationship is:

\[
y = \begin{cases} 
1.1x + 0.6x^4 - 0.7x^5 & 0 \leq x \leq 1 \\
\frac{x}{5.5(x - 1)^{22} + x} & x \geq 1
\end{cases}
\]  \hspace{1cm} (2)

2.2. RPC board structure experimental phenomenon

Steel fibers have greatly improved the overall performance of RPC materials [7]. When the steel fiber is added, the group with slightly added aggregate is stronger than the group without the steel fiber, and the ductility is better than the group without the steel fiber and the group without the RPC ratio. Therefore, in the test, the proportion of the second group was selected, that is, a group that was mixed with steel fibers and slightly adjusted the amount of aggregate and gelling material to prepare plates for the experimental materials. The purpose of the slab structure experiment is the longitudinal reinforcement ratio. The three groups of boards are 4m long and 0.5m wide, with thicknesses of 60mm, 80mm, and 100mm, respectively. The cross-section reinforcement is shown in Fig. 4. The purpose of the three sets of experiments is to compare the effect of the reinforcement ratio on the mechanical properties of RPC components. The results are shown in Table 3.

![Figure 4. Cross section of plate beam schematic diagram.](image)

| Test Block Number | Flexural strength (MPa) | Reinforcement ratio (%) | Cracking load (KN) | Flexural strength (KN) | Mid-span deflection at ultimate load (KN) |
|-------------------|-------------------------|--------------------------|-------------------|------------------------|-----------------------------------------|
| B1-2              | 14.62                   | 0.67                     | 1.6               | 6.7                    | 160                                     |
| B2-2              | 14.62                   | 0.75                     | 2.5               | 13.4                   | 169.5                                   |
| B3-2              | 14.62                   | 0.60                     | 5.5               | 17.7                   | 89                                      |

From the experimental data of the three major beams in Table 3, it can be seen that as the plate thickness increases, all load values increase except deflection, and the cracking load is about 25% of the ultimate load.
According to the load-deflection Fig. 5, the first two groups of members reach the peak load at a deflection of 170mm, while the B3-2 member has a tendency of brittle failure and the B1-2 member has a lower bearing capacity. Therefore, the better performing B2-2, that is, the plate 80mm thickness is most suitable.

3. APPLICATION OF RPC MATERIALS IN PEDESTRIAN BRIDGE PROJECT

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads-the template will do that for you.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

3.1. Bridge type selection of footbridge

Pedestrian bridges can be divided into concrete bridges, steel-concrete composite bridges, and steel bridges in terms of materials. The capital area has a growing demand for street bridges, and its safety, durability, and aesthetics are more valued [4]. The existing bridge of this project is a steel box girder bridge. Due to long-term soaking in rain and temperature changes, the surface of its main beam is seriously corroded. It is very important to choose a structure that is not easily corroded. Therefore, the RPC materials studied in this paper are used. The Daqiao Pavilion Bridge West flyover bridge information for this project is shown in Table 4, and the cross section is shown in Fig. 6. The choice of bridge type for steel-RPC composite box girder needs to be selected from three aspects of technicality, aesthetics and economic evaluation. Therefore, the design is as follows: stiffeners are provided at the connection between the bridge deck and the web box of the original steel box. Box single room structure, welded by Q345 steel plate, the box beam bottom plate is provided with 3 longitudinal stiffeners on average, 100mm high. The cross section of the pedestrian bridge is shown in Fig. 7.

| TABLE 4. STEEL-RPC COMPOSITE STEEL BOX BEAM FOOTBRIDGE RELATED DIMENSIONS (M). |
|-----------------|-----|-----|----------------|---------|-----|-----|
| Item            | Span | Calculate span | Width | Bridge panel thickness | Base plate thickness | Web thickness | Web spacing | Web height |
| Dimension       | 30   | 21.7           | 4     | 0.08               | 0.012               | 0.014         | 2           | 0.69       |
3.2. Finite element model and analysis of footbridge

The footbridge analysis uses ABAQUS finite element software to establish a solid element model. The composite beam body uses simple support to add constraints at both ends. One end can be rotated about the x-axis, and the other end can be rotated about the x-axis and slide along the z-axis. At the bottom of the box beam, a support with a first-order elastic modulus is provided at each end of the box beam, and the restraints at both ends are transmitted to the box beam through the support, so as to avoid a stress concentration effect at the constraint point. Taking into account the type of the closed thin-walled component to prevent the steel box beam from buckling under stress, transverse stiffeners are set at the fulcrum of the box beam at intervals of 50cm, and transverse stiffeners at the mid-span position are spaced at 150cm.

The steel-RPC composite beam pedestrian bridge is designed as follows: active powder concrete is used for the bridge deck, using the material properties of RPC-2; the steel bars are reinforced with the above 80mm test plate; and the steel box is Q345 steel.

Pedestrian load is 5kN / m² according to the "Code for design of the municipal bridge" (CJJ11-2011) [8]. According to the "General Code for Design of Highway Bridges and Culverts" (JTG D60-2015), the combined action of 1.2 times the dead weight and 1.4 times the live load (pedestrian load) is adopted [9], that is, 7kN / m² uniformly distributed loading and eccentric loading and single loading Analysis of carrying capacity under self-weight.

4. Comparison of steel-RPC composite box girder bridge and original steel box girder bridge

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

4.1. Style and spacing

According to the edge stress of the RPC in the compression zone, the formula must be satisfied.

\[
\sigma_{ck} \leq 0.8 f_{ck}
\]  

(3)

In (3): \( f_{ck} \) is the standard value of axial compression

The stress of the tensile steel bar needs to satisfy the formula:

\[
\sigma_{tk} \leq 0.75 f_{sk}
\]  

(4)
In (4): $f_{st}$ is the standard value of the tensile strength of the reinforcement.

The axial compressive strength measured by the test was 118.4 MPa and the axial tensile strength was 9.3 MPa. The allowable axial compressive strength is 94.72 MPa, the axial tensile strength is 7.44 MPa, and the allowable tensile stress of HRB500 steel bar is 417.45 MPa. According to the above formula, the stress check calculation of the pedestrian bridge under each working condition is performed. The results are shown in Table 5. The calculated values in the table are the maximum values in the corresponding parts.

| Bridge type          | Steel-RPC composite box girder bridge | Steel box girder bridge |
|----------------------|--------------------------------------|-------------------------|
| Location             | Term                                 | Self-weight             | Eccentric loading     | Loading capacity limit state | Loading capacity limit state |
|                      | Calculate d value | Allowable value | Calculate d value | Allowable value | Calculate d value | Allowable value | Calculate d value | Allowable value |
| RPC Bridge deck      | $\tau$                                | 3.28                   | 94.72               | 6.81              | 94.72               | 9.62              | 94.72               | -                | -                |
|                      | $\omega$                              | 0.35                   | 7.44                | 1                 | 7.44                | 1.02              | 7.44                | -                | -                |
| Steel box girder     | $\tau$                                | 6.07                   | 275                 | 13.36             | 275                 | 17.98             | 275                 | 41.62             | 275               |
|                      | $\psi$                                | 27.35                  | 275                 | 56.52             | 275                 | 79.95             | 275                 | 58.33             | 275               |
| Underside board      | $\tau$                                | 4.11                   | 160                 | 10.21             | 160                 | 11.83             | 160                 | 6.3               | 160               |
| Side board           | $\tau$                                | 8.01                   | 160                 | 20.95             | 160                 | 22.71             | 160                 | 12.53             | 160               |
| Rebar                | $\sigma$                              | 61.89                  | 417.45              | 147.2             | 417.45              | 153.1             | 417.45              | -                | -                |

Under self-weight, normal use limit state, and eccentric load, the stress distribution of the footbridge is shown in Fig. 8 to Fig. 13.
Figure 12. Longitudinal stress cloud diagram of bridge deck under eccentric loading.

Figure 13. Longitudinal stress cloud diagram of steel box girder under eccentric loading.

It can be seen from Table 5 of the experimental results that the two footbridges meet various standards and have a large amount of safety. Comparing the limit states of the bearing capacity of the two bridges, it can be seen that the RPC maximum compressive stress of the composite box girder bridge is 0.432 times that of the steel box girder, and the maximum tensile stress is 1.371 times that of the steel box girder. It can be seen that some of the compressive stress of the bridge after the transformation has been assumed by RPC, and RPC has similar compressive properties as ordinary concrete, which can solve the problem of instability of thin-walled steel. Therefore, the use of RPC-steel composite beam bridge to carry out the reconstruction of the footbridge is qualified in terms of bearing capacity.

4.2. Comparison of deformation calculation of main beam

Under the action of pedestrian load and self-weight, the steel-RPC footbridge can calculate the maximum deflection of the footbridge according to (5).

\[
\omega = \frac{5ql^4}{384EI}.
\]  

(5)

\(q\), uniform load under self-weight and pedestrian load;
\(l\), calculated span of footbridge;
\(EI\), stiffness of footbridge.

Due to the greater rigidity of steel-RPC, the deflection of the main beam under the combined action of its own weight and pedestrian load is 24.9mm, 23.4mm under eccentric load, and 32.7mm under the limit of load capacity. 25mm pre-arch. Due to the large flexibility of the original steel box girder, a 300mm pre-camber is set to control its flexible deformation, but for pedestrians, its excessive deflection will have a certain impact on the passage of pedestrians and non-motorized vehicles.

4.3. Economic analysis and comparison

Under the action of pedestrian load and self-weight, the steel-RPC footbridge can calculate the maximum deflection of the footbridge according to (5).

| Bridge type            | Consumption of RPC (m³) | Unit price (thousand/m³) | Consumption of rebar (t) | Unit price (thousand/t) | Consumption of steel | Unit price (thousand/t) |
|------------------------|-------------------------|--------------------------|--------------------------|-------------------------|----------------------|-------------------------|
| Steel-RPC box girder   | 8.63                    | 3.81                     | 0.36                     | 5.33                    | 11.18                | 8.125                   |
| Steel box girder       | 40                      | 3.81                     | 0                        | 5.33                    | 27.54                | 8.125                   |
It can be seen from Table 6 that the steel consumption of the steel-RPC box girder is significantly reduced, only 0.42 of the steel box girder. The material cost for the upper structure of the steel-reactive powder concrete composite box beam footbridge is 125,600 yuan, and the material cost for the upper structure of the steel box girder pedestrian bridge is 226,600 yuan. A new steel-reactive powder concrete composite box girder footbridge will save a lot of cost compared to a steel box girder footbridge. This project is a retrofit project. There is no need to add new steel plate on the existing bridge, only RPC and steel bars are added. In the structure, the price of materials is only 32,800 yuan, which saves costs.

From the perspective of time value, on the one hand, the removal of a part of the steel box girder takes less time than the overall replacement. On the other hand, because it is located above the urban road, the overall demolition will cause traffic interruption, and the removal of part of the structure on the steel box girder will use jacks and temporary pier to ensure safe and smooth traffic under the bridge [10]. Therefore, from the perspective of engineering cost, it is also reasonable to use steel-RPC composite box girder bridges to reconstruct footbridges than to replace steel box girder as a whole.

5. COMPARISON OF STEEL-RPC COMPOSITE BOX GIRDER BRIDGE AND STEEL-ORDINARY CONCRETE COMPOSITE BOX GIRDER BRIDGE

Before you begin to format your paper, first write and save the content as a separate text file. Keep your text and graphic files separate until after the text has been formatted and styled. Do not use hard tabs, and limit use of hard returns to only one return at the end of a paragraph. Do not add any kind of pagination anywhere in the paper. Do not number text heads—the template will do that for you.

Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

5.1. Transverse stress comparison
Steel-RPC composite box-girder bridge slabs and steel-ordinary concrete composite box-girder bridge slabs are subject to the weight of the slab and pedestrian load along the cantilever end of the transverse bridge under the same thickness. The internal stress distribution of the cantilever end according to (6).

\[ \sigma = \frac{My}{I} \]  

(6)

Suppose the thickness of the slab is x, the concrete weight g is 23.52kN/m2, and the uniform load q is 5kN/m2. Load distribution still uses 1.2g + 1.4q. The bending moment M of the cantilever end is

\[ M = 1.2 \times 1.0 \times 0.5g + 1.2 \times 0.2 \times 0.1 \times 0.9g + 1.4 \times 5 \times 0.8 \times 0.4 \]  

(7)

When the plate thickness is 80mm, \( M = 3.37 \text{kN}\cdot\text{m} \), and taken into (7) to account. The maximum stress at the end of the cantilever is calculated to be 3.16MPa, so the cantilever end of the RPC bridge deck meets the requirements without cracking. For a C50 concrete slab of the same thickness, the design value of the transverse bridge tensile strength is 1.83 MPa, which is about half of the bearing capacity requirement. Therefore, the steel-ordinary concrete composite box girder does not meet the specifications. To meet the requirements, the C50 ordinary concrete slab thickness needs to be at least 190mm, and the light and beautiful features of the pedestrian bridge will be destroyed.

5.2. Durability comparison
In this year's routine regular inspection technical service project for urban bridges, during the inspection of 209 pedestrian bridges in Beijing, it was found that a large number of reinforced concrete pedestrian bridges that were built at the end of the last century produced cracks, water seepage and corrosion, and concrete peeling. In the long-term use process, microcracks are gradually generated inside the main beam, which provides opportunities for sulfate intrusion and chloride ion penetration [11]. If it is not repaired in time, it will continue to develop in the next test. Its crack resistance will decline rapidly within several years under repeated thawing and chloride ion erosion. Therefore, the use of ordinary concrete as the superstructure material of the pedestrian bridge should be gradually reduced.
5.3. Economic analysis and comparison
Considering the cost of the project, the unit price of the active RPC material used in this experiment is higher than 0.3 million yuan per ton of ordinary concrete materials. Reduced maintenance costs.

6. CONCLUSION
Through the material test and the test design of the pedestrian bridge, it is proved that the RPC material has good compressive and tensile properties. Compared with the original steel box girder, it has stronger corrosion resistance and better durability. Compared with steel-ordinary concrete box girder, its strength is high, it is not easy to crack during long-term use, and as an urban landscape, it has a thinner appearance and better aesthetics. If the project can be widely used in urban bridge reconstruction, it can fully exert the tensile properties of steel and the compression resistance and durability of RPC concrete. At the same time, its prefabricated steel box girder floor and RPC bridge deck can have a small impact on traffic under certain conditions, it can reduce the cost and shorten the construction period to a certain extent.

REFERENCES
[1] Xiang, H.F. Advanced Theory of Bridge Structures. China Communications Publishing, Beijing. (2013)
[2] Liu, J. History and Status of American AASHTO LRFD Highway Bridge Specifications. Highway Transportation Technology (Application Technology Edition), 11: 406-410. (2010)
[3] Wu, F.W., Feng, B.L., Xue, C.F. Durability Assessment on Railway Reinforced Concrete Arch Bridge. Journal of Railway Engineering Society, 05: 42-47. (2016)
[4] Guo, L.F. Analysis on the aesthetic problems of Beijing pedestrian bridge. Municipal Engineering Technology, 02: 35-38. (1988)
[5] Richard, P., Cheyrezy, M. Reactive powder concretes with high ductility and 200-800 MPa compressive strength. Aci Special Publication, 114: 507-518. (1994)
[6] Liu, J.H., Wang, D.M., Song, S.M., Huo, W.L. Research on Durability and Micro Structure of High Volume Fine Mineral Mixture of Reactive Powder Concrete. Journal of Wuhan University of Technology, 11: 54-57+68. (2008)
[7] Zeng, J.L., Wu, Y.H., Lin, Q. Researches on the compressive mechanics properties of steel fiber RPC. Journal of Fuzhou University(Natural Sciences Edtion), S1: 132-137. (2005)
[8] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Code for design of the municipal bridge CJJ11-2011. China Architecture and Building Press, Beijing. (2011)
[9] CCCC Highway Consultants CO.,Ltd. General Specifications for Design of Highway Bridges and Culverts JTG D60-2015. China Communications Press, Beijing. (2015)
[10] Xu, S.L. Applied Study on Integrated Support System for Bridge Jacking-up. Municipal Engineering Technology, 04: 69-71. (2019)
[11] Jiang, Z.J. Degradation Mechanism of Concrete Pore Structure Under the Action of Freeze-Thaw Cycle. Journal of Huaqiao University(Natural Science), 06: 716-720. (2015)