Research Article

Parameter Optimization and Bending Performance Analysis of a Corrugated Steel Plate-UHPC Composite Bridge Deck with PZ Shear Connectors

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Composite bridge decks consisting of steel plates and concrete are used to minimize fatigue cracking and damage of asphalt pavement of orthotropic steel bridge decks subjected to wheel loads. This paper presents a methodology to optimize the parameters and mechanical performance of a corrugated steel plate-ultrahigh-performance concrete (UHPC) composite bridge deck with panel zone (PZ) shear connectors using the improved non-dominated sorting genetic algorithm (NSGA-II). A 3-D finite element model is established in ANSYS Workbench software to conduct numerical parameter analysis, and ABAQUS software is used to analyze the optimized model’s mechanical performance. The results show a significant improvement in the mechanical performance of the optimized composite bridge deck, with a 27.66% decrease in the maximum stress in the UHPC layer. The vertical displacement of the optimized composite bridge deck increases sharply when the load reaches 90% of the ultimate load, and a significant change in the strain is caused by the sliding displacement between the UHPC layer and steel plate. The bottom part of the corrugation yields first in the middle span, followed by failures of the ribs. In addition, as the tensile stress increases, damage occurs first in the UHPC layer near the PZ shear connectors in the shear bending area and the bottom in the bending area, expanding significantly to the entire bending and loading areas. The results indicate that the parameter optimization of the corrugated steel plate-UHPC composite bridge deck using NSGA-II improves the structure’s bending performance.

1. Introduction

Composite decks consisting of steel plates and concrete pavement are used in bridge construction to minimize damage and improve the mechanical performance of bridge decks. However, the stress and damages under local loads and the optimization parameters of composite bridge decks remain unclear. Therefore, it is necessary to analyze the components of composite bridge decks and develop design methods to improve the structure’s mechanical performance.

Lu used experiments and numerical analysis to investigate the mechanical behavior of the Dongping Bridge deck structure and found that the overall stiffness of the composite deck slab was low [1]. Peng-Zhen et al. [2] found that Perfobond Leisten (PBL) shear connectors exhibited good anti-fatigue performance, and the perfobond strips reached the yield strength before failing [2]. Shao and Cao [3] conducted a fatigue assessment of a lightweight steel-ultrahigh-performance concrete (UHPC) composite deck (LWCD) and observed that the shear stress ranges of the headed studs were lower than the fatigue strength [3]. Field measurements and finite element (FE) analysis of the Fochen West Bridge indicated that 16 mm was the optimum thickness of the deck plate of an orthotropic steel deck (OSD) with a UHPC-deck plate composite system [4]. Maet al. [5] investigated the adhesive characteristics of the layers of medium early-strength engineered cementitious composites (MES-ECC). It was found that the MES-ECC and steel plate bonded by cotters had a larger push-out load.
and deformation capacity than the normal concrete/steel plate and mortar/steel plate [5]. Shao et al. [6] conducted a study on the performance of a steel-UHPC lightweight composite deck with large U ribs and found that the weld seam length in the OSD steel deck was 38.7% lower than that of the other bridge deck [6]. Field measurements were conducted on the Fengxi Bridge to examine the effects of a UHPC layer on the stress of the composite bridge deck. The UHPC layer resulted in a substantial decrease in the stresses of the rib-to-deck welds and the rib splice welds [7]. Wang et al. [8] conducted a fatigue test of a basalt fiber-reinforced polymer (BFRP) shell-concrete composite bridge deck with prestressed BFRP strips. The prestressed BFRP strips bonded on the inside of the BFRP shell operated in conjunction with the BFRP shell without debonding or rupture [8]. Concrete cracks occurred, and the bottom flange of the T-shaped ribs yielded first under the concentrated load in the midspan sections of the steel-concrete composite (SCC) deck [9]. The modified overlay significantly reduced the average stresses in the longitudinal rib deck of the sandwich plate system (SPS) and reactive powder concrete (RPC) system [10]. A pultruded fiber-reinforced polymer (FRP) shell was proposed for a concrete composite bridge deck, revealing that the prestressed FRP shell produced camber and significantly reduced the deformation under a construction load [11]. An optimized BFRP shell-concrete composite bridge deck was investigated experimentally and numerically, demonstrating that the optimized BFRP shell exhibited 30.9% less midspan deflection than the BFRP shell [12]. A study on the fatigue behavior of a novel bridge composite deck indicated that the deterioration of the compressive concrete differed from that of a conventional reinforced concrete bridge deck under a fatigue load [13]. Ye et al. [14] determined the fatigue performance and design parameters of a composite deck design with steel fiber-reinforced concrete (SFRC) and found that overlay cracking affected the fatigue strength of this composite deck [14]. A detailed FE analysis was conducted to investigate the failure mode and load-slip behavior of a steel-UHPC composite bridge deck. The authors derived the shear strength equation of a single stud to simplify the calculation [15]. A composite bridge deck composed of a corrugated steel deck and a UHPC slab was investigated. An increase in the width of the UHPC slab or the depth of the corrugated steel deck improved the yield load and ultimate load and minimized the level of deformation [16]. Zheng et al. [17] observed that the static nominal cracking stress of the UHPC layer with reinforcement spacings of 80 mm and 40 mm was far greater than the nominal stress in a prototype bridge [17]. A numerical method was proposed to predict the fatigue behavior of an orthotropic steel bridge deck with an ultrahigh-performance fiber-reinforced concrete (UHPFRC) layer. The maximum deflection and the strain in the steel deck plate were reduced significantly after applying the UHPFRC layer [18]. Experimental and numerical studies were conducted to investigate the fatigue behavior and failure mechanism of SCC deck slabs with perforated ribs, revealing that the crack propagation rate rose by 300% as the load amplitude increased by 54% [19]. A FE model verified by experimental results was used to conduct parameter analysis of headed studs embedded in engineered cementitious composite (ECC) material. The shear strength of the specimens slightly decreased as the stud height increased [20]. Xiang and Zhu [21] first investigated the stress responses of fatigue-prone components in a composite bridge deck using refined two-scale FE analysis. It was revealed that the rib-to-deck joint had an infinite fatigue life, whereas the floor beam of the rib-to-floor beam joint had a finite fatigue life [21]. Numerous studies were conducted on composite bridge decks with orthotropic steel plates, concrete pavement, and shear connectors, such as studs and PBL connectors. However, there is a lack of research on the mechanical performance (e.g., the bending stress and damage) of corrugated steel plate-UHPC composite bridge decks with PZ shear connectors. This study analyzes the bending performance of a corrugated steel plate-UHPC composite bridge deck with PZ shear connectors using numerical analysis in the 3-D FE analysis software ANSYS Workbench. After optimization by the improved non-dominated sorting genetic algorithm (NSGA-II), a new 3-D model is established to analyze the mechanical behavior of the optimized composite bridge deck, such as bending behavior and damages. The optimized corrugated steel plate-UHPC composite bridge deck with PZ shear connectors exhibits significant improvements in mechanical performance.

2. Theoretical Model

The PZ connectors that connect the UHPC layer and steel plate ensure that the two parts can bear the bending moment. A theoretical model considering the stress and vertical displacement is established for the corrugated steel plate-UHPC composite bridge deck with PZ shear connectors under the bending moment. The UHPC pavement has much higher tensile strength than ordinary concrete; thus, it does not fail until the load increases to the ultimate state. The sliding between the corrugated steel plate and the UHPC pavement is ignored in the elastic phase due to the firm connection of the PZ shear connectors. An optimization model is used to optimize the bending performance of the composite bridge deck.

2.1. Bending Performance

2.1.1. Neutral Axis above Steel Plate. The steel plate and UHPC layer are connected by the PZ shear connectors to bear the bending moment. Negligible movement existed between the two parts. A flat cross section is assumed to compute the stress and strain of the composite bridge deck under the bending moment. As the load increased, the steel plate and tensioned UHPC layer yielded with equal-tension strain. When the load reached the ultimate state, the UHPC layer yielded with equal compressive stress, as shown in Figure 1.
Figure 1: Bending performance of the corrugated steel Plate-UHPC composite bridge deck (scenario 1).

According to $\sum X = 0$, 
\[ N_{ct} = N_{ct1} + N_{ct2}, \]
\[ N_{ct} = f_{ct} b_{0} x, \]
\[ N_{ct1} = N_{ct11} + N_{ct12}, \]
\[ N_{ct1} = (h_1 - x) b_{0} f_{ct}, \]
\[ N_{ct2} = \frac{1}{2} (b_1 + b') h_2 f_{ct}, \]
where 
\[ b' = 2b_2 + b_1, \]
where $N_{ct}$ and $N_{ct1}$ are the compression and tension areas of the UHPC layer. They are divided into $N_{ct11}$ and $N_{ct12}$, which are the tension areas of the UHPC layer above and below the top of the corrugated steel plate, respectively; $N_{ct}$ is the tension area of the steel plate, which is divided into $N_{ct1}$, $N_{ct2}$, and $N_{ct3}$, which are the tension areas of the bottom, ribs, and the top of the corrugated steel plate, respectively.

The tension area of the corrugated steel plate is 
\[ N_{st} = N_{st1} + N_{st2} + N_{st3}, \]
where 
\[ N_{st1} = f_{qt} t_1 b_1 \left( H - x - \frac{t_1}{2} \right), \]
\[ N_{st2} = \frac{2 f_{qt} t_1 h_2}{\sin \alpha}, \]
\[ N_{st3} = 2 f_{qt} t_3, \]
\[ \tan \alpha = \frac{h_2}{b_2}, \]
The height of the compression area is 
\[ x = \frac{f_{ct} \left[ h_1 b_0 + h_2 (b_1 + b_2) \right]}{f_{ct} + 2 h_2 / \sin \alpha} t_1. \]

According to $\sum M = 0$, 
\[ M_u = M_{ct} + M_{st}. \]
Thus, 
\[ M_{cc} = \frac{N_{cc} x}{2}, \]
\[ M_{ct} = N_{ct1} \left( \frac{h_1 - x}{2} \right) + N_{ct2} \left[ \frac{h_2 (2b_1 + b')} {3(b_1 + b')} + (h_1 - x) \right], \]
\[ M_{st} = M_{st1} + M_{st2} + M_{st3}, \]
\[ M_{st1} = N_{st1} \left( H - x - \frac{t_1}{2} \right), \]
\[ M_{st2} = N_{st2} \left[ \frac{h_2 - t_1 \cos \alpha}{2} + t_1 + (h_1 - x) \right], \]
\[ M_{st3} = N_{st3} \left( \frac{t_1}{2} + h_1 - x \right), \]
where $f_{cc}$ is the compressive strength of the UHPC, $f_{ct}$ is the hardening stress of the UHPC, $f_q$ is the strength of steel, $M_u$ is the ultimate bending moment of the composite bridge deck, $b_1$ is the width of the bottom corrugation, $b_2$ is the horizontal width of the side panel, $b_3$ is the width of the top corrugation, $t_1$ is the thickness of the steel plate, $h_1$ is the thickness of the UHPC layer, $h_2$ is the height of the corrugated steel plate, $M_{cc}$ is the bending moment of the compression area of the UHPC layer, $M_{ct}$ is the moment of the tension area of the UHPC deck, $M_{st}$ is the moment of the tension area of the corrugated steel plate. It is divided into $M_{st1}$, $M_{st2}$, and $M_{st3}; M_{ct}$ is the moment of the compression area of the corrugated steel plate.

2.1.2. Neutral Axis in the Scope of Steel Plate. As the neutral axis of the corrugated steel plate, some of the steel plate is tensioned and the other is compressed. The steel bars do not yield and are in the compressive state, with a reduction factor of 0.5, as shown in Figure 2.

According to $\sum X = 0$, 
\[ N_{ct} = N_{ct1} + N_{ct2}, \]
\[ N_{ct} = f_{ct} b_{0} x, \]
\[ N_{ct1} = N_{ct11} + N_{ct12}, \]
\[ N_{ct1} = (h_1 - x) b_{0} f_{ct}, \]
\[ N_{ct2} = \frac{1}{2} (b_1 + b') h_2 f_{ct}, \]
the compression and tension areas of the steel plate. They are divided into Nsc and Nst, respectively.

According to $\sum M = 0$,

\[
M_u = M_{cc} + M_{ct} + M_{st} + M_{sc} + M_{Tsc},
\]

\[
M_{cc} = M_{cc1} + M_{cc2},
\]

\[
M_{cc1} = f_{cc} b_h h_1, (x - h_1),
\]

\[
M_{cc2} = f_{cc} b' (x - h_1),
\]

\[
M_{ct} = f_{ct} (b_1 + b') (H - x - t_1)
\frac{2}{2}
\]

\[
T_{sc} = N_{sc},
\]

\[
N_{cc} = N_{cc1} + N_{cc2},
\]

\[
N_{ct} = f_{ct} (b_1 + b') (H - x - t_1)
\frac{2}{2}
\]

\[
N_{st} = N_{st1} + N_{st2},
\]

\[
N_{st1} = f_{ct} t_1 b_1,
\]

\[
N_{st2} = \frac{2(H - x)}{\sin(\alpha)} t_1 f_q,
\]

\[
N_{sc} = N_{sc1} + N_{sc2},
\]

\[
N_{sc1} = 2f_q t_1 b_3,
\]

\[
N_{sc2} = \frac{2f_q t_1 [h_2 - (H - x)]}{\sin(\alpha)},
\]

where $N_{cc}$ and $N_{ct}$ are the compression and tension areas of the UHPC layer. They are divided into $N_{cc1}$ and $N_{cc2}$, which are the tension areas of the UHPC layer above and below the top of the corrugated steel plate, respectively. $N_{sc}$ and $N_{st}$ are the compression and tension areas of the steel plate. They are divided into $N_{sc1}$ and $N_{sc2}, N_{st1}$ and $N_{st2}$, respectively.

The height of the compression area is

\[
x = \frac{b' h_1 + f_{ct} (b_1 + b_2) (H - t_1) - 1/2 f_q A'_{sc}}{2f_q t_1 [1 + 1/\sin(\alpha)] + (b_1 + b_2) (f_{ct} + 1) + b_2}
\]

where $M_{cc}$ is the bending moment of the compression area of the UHPC layer; it is divided into $M_{cc1}$ and $M_{cc2}$, which are the bending moment due to the tension areas of the UHPC layer above and below the top of the corrugated steel plate, respectively. $M_{ct}$ is the moment of the tension area of the UHPC layer; it is divided into $M_{st1}$ and $M_{st2}. T_{sc}$ is the resultant force of the steel bars, $a_i$ is the thickness of the
2.2. Vertical Displacement. The vertical displacement of the corrugated steel plate-UHPC composite bridge deck in the equivalent cross-sectional area of the UHPC layer is computed based on the mechanical properties of the elastic material to determine the deflection in the elastic phase:

\[ A_c \sigma_c = A_s \sigma_s, \]
\[ \frac{\sigma_c}{E_c} = \frac{\sigma_s}{E_s}, \]
\[ A_s = \frac{E_s}{E_c}, \]

where \( A_c \) is the cross-sectional area of the UHPC layer, \( E_c \) is the elastic modulus of the UHPC, \( A_s \) is the equivalent cross-sectional area of the UHPC layer, \( E_s \) is the elastic modulus of steel, \( \sigma_c \) is the stress of the UHPC layer, \( \sigma_s \) is the stress of the corrugated steel plate, \( \varepsilon_c \) is the elastic modulus ratio of the steel and UHPC, \( l \) is the span length of the bridge deck, \( I_x \) is the inertial moment of the deck in the neutral axis, \( b \) is the total width of the composite bridge deck.

\[ \sigma_c = \frac{\sigma_s}{\varepsilon_c}, \]
\[ A_s = \frac{A_c}{\varepsilon_c}, \]

The vertical displacement in the middle span is

\[ w = \frac{F_b (3l^2 - 4b^2)}{24E_s I_x}. \]

2.3. Response Surface Optimization. The deterministic function is replaced by the fitting function obtained from the response surface optimization. The implicit function is expressed by the explicit polynomial:

\[ Y = y(x) + \epsilon = \bar{y}(x) + \delta, \]
\[ x = [x_1, x_2, \ldots, x_n], \]

where \( y(x) \) is the deterministic function, \( \epsilon \) is the random error in the test, \( \bar{y}(x) \) is the fitting function of \( y(x), x \) denotes the \( n \)-dimensional variables, and \( \delta \) is the total error.

A quadratic polynomial basis function \( \bar{y}(x) \) with cross terms is used to describe the interaction between the design variables, and \( \bar{y}(x) \) is defined as:

\[ \bar{y}(x) = a_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} c_{ii} x_i^2 + \sum_{1 \leq j < k \leq n} d_{ij} x_i x_j, \]

where \( a_0 \) is the constant; \( b_i, c_{ii}, \) and \( d_{ij} \) are the coefficients.

We use the coefficient of determination \( (R^2) \) and the relative root mean square error \( (R_s) \) to evaluate the goodness of fit of the response surface model:

\[ R^2 = 1 - \frac{\sum_{i=1}^{m} (y_i - \bar{y}_i)^2}{\sum_{i=1}^{m} (y_i - \bar{y})^2}, \]
\[ R_s = \sqrt{1 - \frac{\sum_{i=1}^{m} (y_i - \bar{y}_i)^2}{\sum_{i=1}^{m} (y_i - \bar{y})^2}}, \]

where \( y_i \) is the measured value of sample point \( i \), and \( \bar{y}_i \) is the predicted value of \( y_i \).

3. Corrugated Steel Plate-UHPC Composite Bridge Deck with PZ Shear Connector

The composite bridge deck with four waves consists of corrugated steel plates, UHPC pavement, a steel-bar mesh, and PZ shear connectors, as shown in Figure 3. This deck specimen is 2400 mm wide and 143 mm high; the corrugated steel plate is 90 mm high, and the UHPC layer is 45 mm high. The PZ shear connector has a height of 120 mm height and a width of 16 mm, as depicted in Figure 4. The properties of the corrugated steel plate, UHPC layer, steel-bar mesh, and PZ shear connectors are calibrated using the experimental results (Table 1).

4. Parameter Optimization of Corrugated Steel Plate-UHPC Composite Bridge Deck with PZ Shear Connector

A 3-D FE model of the corrugated steel plate-UHPC composite bridge deck is established in ANSYS Workbench software to optimize the structure’s parameters using the NSGA-II.

4.1. Initial 3-D Finite Element Model. A 3-D FE model of the corrugated steel plate-UHPC composite bridge deck between two diaphragms is established. The UHPC layer is simulated with solid 65 elements to model the cracks and crushing of the UHPC, and the corrugated steel plate and PZ shear connectors are simulated with the shell 181 element, as shown in Figure 5. The interfacial slip between the UHPC layer and corrugated steel plate is negligible due to the firm connection by the PZ shear connectors. Thus, the two element types are connected by the same nodes. The FE model is simply supported by the bottom corrugations; therefore, we establish constraints in the x-, y-, and z-directions on one side of the deck and in the y- and z-directions on the other side. According to the General Specifications for the Design of Highway Bridges and Culverts, one wheel of a Highway-I level load (70 kN) is applied in an area of 600 mm x 200 mm; thus, the pressure of one wheel load is 0.817 MPa [22]. The gravity of the composite bridge deck and the asphalt pavement is considered.
The ultimate bending moment of the composite deck is 530 kN·m based on the 3D finite element model and 492.8 kN·m based on the theoretical model. Thus, the numerical model is validated for this research, with an acceptable error of 7.54%.

4.2. Assessment of Model Parameters. The composite bridge deck consisting of the steel plate and UHPC layer connected by PZ shear connectors bears the bending moment. The parameters $h_1$, $h_2$, $b_1$, $b_2$, $b_3$, and $t_1$ are optimized to improve the bending behavior, such as the maximum tensile stress of
the steel plate and UHPC layer, and the vertical displacement and weight, as shown in Figure 5 and Table 2.

In Figure 6, $b_2$ is the horizontal width of the rib, $h_3$ is the height of the PZ shear connector, $t_2$ is the thickness of the PZ shear connector, $h_0$ is the total height of the composite bridge deck, and the meaning of the other parameters is the same as above.

The central composite design (CCD) method is used to derive 46 results for each index, such as the maximum tensile stress of the steel plate $\sigma_{\text{stmax}}$, the vertical displacement $\delta$, the maximum tensile stress of the UHPC layer $\sigma_{\text{ctmax}}$ and the mass of the composite bridge deck $m$. The results are illustrated in Figure 7.

The $R^2$ and $R_s$ values obtained from equations (10) and (11) are listed in Table 3.

4.3. Parameter Optimization of 3-D Finite Element Model. The NSGA-II is used to optimize the indices of the corrugated steel plate-UHPC composite bridge deck with PZ shear connectors. The Pareto optimal solution is shown in Figure 8, and the optimized indices and three results are listed in Table 4.

The first optimization scheme is selected due to the low weight and economical construction. After parameter optimization, the composite bridge deck is 840 mm wide, 3200 mm long, and 1800 mm high. The PZ shear connector and corrugated steel plate are both 120 mm high, and the UHPC layer is 50 mm thick, as shown in Figure 9(a). The steel-bar mesh consisted of 30 straight bars and 20 curved bars with a spacing of 100 mm and 300 mm, respectively, as shown in Figure 9(b).

The mechanical performance of the optimized bridge deck under a wheel load improved by 20% to 30%, as shown in Table 5. The maximum tensile stress of the UHPC layer $\sigma_{\text{ctmax}}$ decreases by 27.66%, and the mass of the composite bridge deck decreases by 16.30%.

4.4. Optimized 3-D Numerical Model. A new 3D FE model is established of the optimized corrugated steel plate-UHPC composite bridge deck in ABAQUS software. It consists of 79826 nodes and 61124 elements. The C3D8R element is used for the corrugated steel plate, PZ shear connectors, and UHPC layer, and the T3D2 element is used for the steel-bar mesh, as illustrated in Figure 10.

The material properties and the stress-strain relationship of the UHPC are obtained from the model proposed by Yang et al. [23] and Yang [24]. The model is defined in equation (12):

$$
\begin{align*}
  y &= \begin{cases} 
    Ax + (3 - 2A)x^2 + (A - 2)x^3, & \text{Increase period,} \\
    \frac{x}{a(x-1)^{1/3} + x}, & \text{Decrease period,}
  \end{cases}
\end{align*}
$$

where

$$
\begin{align*}
  A &= 1.106, \\
  a &= 5.
\end{align*}
$$

The proportion of the steel fiber content is 2%.

Then, a concrete damage plasticity (CDP) model is established in the ABAQUS software to describe the plasticity and damage resulting from tension and compression and the plasticity behavior of the UHPC. The plasticity parameters are listed in Table 6.

The PZ shear connector is attached to and embedded in the steel plate to simulate the contact between the steel bars, PZ shear connector, and UHPC layer. Surface contact is used to simulate the contact between the steel plate and the UHPC layer. If the shear stress exceeds the ultimate value, friction occurs due to constant shear stress, as defined in equation (14):

$$
\tau_{\text{cr}} = \mu_2 p \geq \tau_b,
$$

where $\mu_2$ is the friction factor, $\mu_2 = 0.5$, $\tau_{\text{cr}}$ is the ultimate shear stress, $p$ is the pressure, and $\tau_b$ is the average bonding stress.

Uniform loads are applied to the bridge deck to simulate the wheel load of a Highway-I level load until the ultimate load is reached, as shown in Figure 11. The mechanical performance of the bridge deck is evaluated.

5. Results and Discussion

We evaluate the bending performance, stress, strain, and damage of the composite bridge deck.
5.1 Theoretical Results of the Bending Deformation. As the load increases, the vertical displacement of the composite bridge deck increases, and the maximum value occurs in the middle span, as shown in Figure 12. The composite bridge deck fails at the ultimate load of 5.521 MPa. The maximum vertical displacement increases stably from about 16 mm to 26 mm as the load increases from 20% to 80% of the ultimate load. In contrast, as the load increases to 90% of the ultimate value, the vertical displacement increases sharply, reaching the maximum value of 55 mm. Similarly, as the load increases to the ultimate value, the displacement rose significantly, reaching 90 mm in the middle span.

As the load increases, the sliding displacement between the steel plate and the UHPC layer increases. The sliding displacement decreases from the maximum value in the support area to 0 mm in the middle span, as shown in Figure 13. The maximum sliding displacement increases stably to approximately 1.7 mm during loading, indicating that the PZ connectors firmly connected the steel plate and UHPC layer.

The tensile and compressive strain increase in the cross section of the middle span as the load increases to the ultimate value, as illustrated in Figure 14. The UHPC layer is compressed above the neutral axis, while the UHPC layer and steel plate are tensioned below the neutral axis. The strain in the cross section increases linearly with increasing distance from the neutral axis as the load increases to 80% of the ultimate value. Noticeably, as the load increases to 90% of the ultimate value, the strain changes sharply on the surface between the UHPC layer and steel plate due to sliding displacement. The neutral axis moves 5 mm during loading, indicating the firm connection between the UHPC layer and steel plate.

5.2 Stress and Deformation. The maximum stress of the steel plate is 345 MPa in the middle span and the loading area in the ultimate limit state, as illustrated in Figure 15.

As the load increases to 70% of the maximum load, the bottom corrugations of the steel plate in the middle span yield first, as depicted in Figure 16(a). The ribs start to yield
Figure 8: Pareto optimal solution.

Table 4: The optimized indices (unit: mm).

| Indexes | Optimized solution |
|---------|--------------------|
|         | 1                  | 2                  | 3                  |
| $h_1$   | 49.738             | 55.692             | 59.490             |
| $t_1$   | 10.103             | 10.706             | 12.261             |
| $b_1$   | 120.260            | 120.140            | 128.070            |
| $h_2$   | 119.650            | 117.920            | 119.640            |
| $b_2$   | 70.142             | 70.120             | 70.231             |
| $b_3$   | 80.064             | 80.297             | 80.508             |

Figure 9: Optimized composite bridge deck. (a) Cross section. (b) Steel-bar mesh.
in the second step as the yield area increases due to the increasing load. The bottom and top of the corrugation yield in the middle span in the ultimate state, as shown in Figure 16(b).

Similarly, the bottom of the PZ shear connectors, which are attached to the bottom of the corrugated steel plate, yield in the middle span as the load increases to 70% of the maximum value. The PZ shear connectors are subjected to high stress in the loading area under the bending moment, as shown in Figure 17(a). As the load reaches the maximum value, the yield area expands significantly, as illustrated in Figure 17(b).

### 5.3. Damages

Damages develop in the UHPC layer as the load increases, as shown in Figure 18. As the load increases to 70% of the ultimate load, the maximum damage degree is 0.518 in the UHPC layer around the PZ shear connectors in the shear bending area due to the large shear stress at the interface between the UHPC layer and steel plate. As the load increases, the maximum damage degree increases to 0.861, and the damage area expands to the UHPC layer, as shown in Figure 18(b). As the tension load increases to 70% of the ultimate value, the UHPC layer fails at the bottom, with a maximum damage degree of 0.898. As the load increases, the damage level in the bending area increases, and

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**Table 5: The mechanical performance of the initial and optimized composite bridge decks.**

| Index              | Initial | Optimized | Change (%) |
|--------------------|---------|-----------|------------|
| $\sigma_{\text{ctmax}}$ (MPa) | 9.98    | 7.22      | 27.66      |
| $\sigma_{\text{stmax}}$ (MPa) | 46.61   | 36.52     | 21.60      |
| m (kg)             | 1616    | 1352      | 16.30      |
| Vertical displacement (mm) | 0.96 | 0.76      | 20.83      |

**Table 6: The plasticity parameters of the UHPC.**

| Parameter         | Meaning                                           | Value   |
|-------------------|---------------------------------------------------|---------|
| $\rho$            | Density (kg·m$^{-3}$)                             | 2700    |
| $\nu$             | Poisson’s ratio                                   | 0.2     |
| $E$               | Elastic modulus (MPa)                             | $4.26 \times 10^4$ |
| $\Psi$            | Expansion angle                                   | 37°     |
| $m$               | Flow potential offset                             | 0.1     |
| $f_b/f_{co}$      | Ratio of the strength in multiple directions and single direction | 1.16    |
| $K$               | Viscosity coefficient                             | 0.001   |
| $U$               | Ratio of tensile stress and compressive stress    | 0.667   |

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**Figure 10: 3-D finite element model in ABAQUS software. (a) Corrugated steel plate. (b) UHPC layer. (c) Steel-bar mesh. (d) 3-D finite element model.**
Figure 11: Load placement. (a) Longitudinal position. (b) Plane position.

Figure 12: Vertical displacement of the composite bridge deck.

Figure 13: Sliding displacement between the Steel plate and UHPC layer.
Figure 14: Strain in the cross section of the middle span.

Figure 15: Stress of the steel plate in the ultimate limit state.

Figure 16: Stress in the cross section of the steel plate. (a) Under 70% of the ultimate load. (b) Under the ultimate load.
significant damage occurs around the loading area due to the total failure of the UHPC around the PZ shear connectors, as shown in Figure 18(d).

6. Conclusion

We conducted a 3-D FE analysis and used the NSGA-II to optimize the parameters of a corrugated steel plate-UHPC composite bridge deck with PZ shear connectors. The mechanical performance of the composite bridge deck under a wheel load, such as stress, deflection, and damage, is evaluated.

(1) The parameter optimization with the NSGA-II improved the bending behavior of the composite bridge deck. Consequently, the mechanical performance of the optimized composite bridge deck under a wheel load is improved by 20% to 30%. Specifically, the maximum tensile stress of the UHPC layer and the total mass of the bridge deck are reduced by 27.66% and 16.30%, respectively.

(2) The maximum vertical displacement of the bridge deck increases sharply from 26 mm to 55 mm as the load increases to 90% of the ultimate value. In contrast, the maximum sliding displacement increases stably to 1.7 mm during loading due to the firm connection between the steel plate and UHPC layer by the PZ connectors. Correspondingly, the strain at the interface between the UHPC layer and steel plate increases sharply because of the sliding displacement as the load increases to 90% of the ultimate value.

(3) As the load increases, the bottom of the corrugated steel plate in the middle span yields first, and the ribs yield second. The corrugated steel plate yields
completely in the middle span and loading area when the load reaches the ultimate value. The bottom of the PZ shear connectors in the middle span yields first. Significantly stress in the PZ shear connectors is observed in the loading area due to the combined effect of the bending moment and shear force.

(4) As the load increases, damages develop first around the PZ shear connectors in the shear bending area and expand in the UHPC layer. The bottom of the UHPC layer fails in tension as the load increases to 70% of the ultimate load, indicating that the tensile stress resulted in more damage in the UHPC layer than the compressive stress. Subsequently, damage develops rapidly in the bending and loading areas due to the failure of the UHPC layer around the PZ shear connectors.

Data Availability
The figures and tables used to support the findings of this study are included within the article. The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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References
[1] P. Lu, “Fatigue behaviour in full-scale laboratory tests of a composite deck slab with PBL reinforcement,” Journal of the South African Institute of Civil Engineering, vol. 59, no. 2, pp. 11–18, 2017.
[2] L. Peng-Zhen, C. Lin-Feng, L. Yang, L. Z. Lun, and S. Hua, “Study on mechanical behavior of negative bending region based design of composite bridge deck,” International Journal of Civil Engineering, vol. 16, no. 3, 2017.
[3] X. Shao and J. Cao, “Fatigue assessment of steel-UHPC lightweight composite deck based on multiscale FE analysis: case study,” Journal of Bridge Engineering, vol. 23, no. 1, 2018.
[4] Z. Zhu, T Yuan, Z. Xiang, and Y. Huang, “Behavior and fatigue performance of Details in an orthotropic steel bridge with UHPC-deck plate composite system under in-service traffic flows,” Journal of Bridge Engineering, vol. 23, no. 3, 2018.
[5] H. Ma, Z. Zhang, B. Ding, and X. Tu, “Investigation on the adhesive characteristics of Engineered Cementitious Composites (ECC) to steel bridge deck,” Construction and Building Materials, vol. 191, no. Dec.10, pp. 679–691, 2018.
[6] X. Shao, W. Qu, J. Cao, and Y. Yao, “Static and fatigue properties of the steel-UHPC lightweight composite bridge deck with large U ribs,” Journal of Constructional Steel Research, vol. 148, pp. 491–507, 2018.
[7] B. Pei, L. Li, X. Shao, L. Wang, and Y. Zeng, “Field measurement and practical design of a lightweight composite bridge deck,” Journal of Constructional Steel Research, vol. 147, pp. 564–574, 2018.
[8] X. Wang, Z. Peng, Z. Wu, and S. Sun, “High-performance composite bridge deck with prestressed basalt fiber-reinforced polymer shell and concrete-ScienceDirect,” Engineering Structures, vol. 201, 2019.
[9] Q. Su, C. Dai, and X. Jiang, “Bending performance of composite bridge deck with T-shaped ribs,” Frontiers of Structural and Civil Engineering, vol. 13, no. 4, pp. 990–997, 2019.
[10] S. Wang, Z. Ke, Y. Gao, and Y. Zhang, “Long-term in situ performance investigation of orthotropic steel bridge deck strengthened by SPS and RPC solutions,” Journal of Bridge Engineering, vol. 24, no. 6, pp. 04019054.1–04019054.15, 2019.
[11] L. Ding, J. Shi, X. Wang, S. Sun, and Z. Wu, “Optimization of a prestressed fiber-reinforced polymer shell for composite bridge deck,” Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, vol. 15, pp. 1–13, 2019.
[12] Z. Peng, X. Wang, L. Ding, Y. Yang, Z. Wu, and Z. Zhu, “Static and sustained loading behavior of a basalt FRP shell–concrete composite bridge deck: an experimental and numerical study,” Engineering Structures, vol. 230, no. 2, 2020.
[13] X. Wang, Z. Peng, W. Deng, and Z. Wu, “Fatigue behavior of a composite bridge deck with prestressed basalt-reinforced polymer shell and concrete,” Journal of Bridge Engineering, vol. 25, no. 10, Article ID 04020088, 2020.
[14] H. Ye, Z. Yang, B. Han, Z. Duan, and Y. Zhou, “Failure mechanisms governing fatigue strength of steel-SFRC composite bridge deck with U-ribs,” Journal of Bridge Engineering, vol. 26, no. 4, Article ID 04021014, 2021.
[15] Y. Huang, S. Chen, and P. Gu, “Static and fatigue behavior of shear stud connection embedded in UHPC,” Structures, vol. 34, pp. 2777–2788, 2021.
[16] Z. Cheng, Q. Zhang, Y. Bao, P. Deng, C. Wei, and M. Li, “Flexural behavior of corrugated steel-UHPC composite bridge decks,” Engineering Structures, vol. 246, no. 3, Article ID 113066, 2021.
[17] F. Zheng, C. Li, J. He, Ke Lu, Z. Lei, and V. George, “Static and fatigue test on lightweight UHPC-OSD composite bridge deck system subjected to hogging moment,” Engineering Structures, vol. 241, Article ID 112459, 2021.
[18] H.M Chi, P. Deng, and M Takashi, “Fatigue analysis of a UHPFRC-OSD composite structure considering crack bridging and interfacial bond stiffness degradations,” Engineering Structures, vol. 249, Article ID 113330, 2021.
[19] D. Xiang, M. Gu, X. Zou, and Y. Liu, “Fatigue behavior and failure mechanism of steel–concrete composite deck slabs with perforated ribs,” Engineering Structures, vol. 250, Article ID 113410, 2022.
[20] Y. Guan, J. Wu, R. Sun, Z. Ge, Y. Bi, and D. Zhu, “Shear behavior of short headed studs in Steel-ECC composite structure,” Engineering Structures, vol. 250, Article ID 113423, 2022.
[21] Z. Xiang and Z. Zhu, “Multi-objective optimization of a composite orthotropic bridge with RSM and NSGA-II algorithm,” Journal of Constructional Steel Research, vol. 188, Article ID 106938, 2022.

[22] CCCC Highway Consultants Co Ltd. General Specifications for Design of Highway Bridges and Culverts, China Communications Press Co., Ltd., China, 2015.

[23] K. Yang, G. Li, and L. Chen, "Constitution and application of RPC damaged plasticity model,” in Proceedings of the 23th China Structural Engineering Conference, pp. 170–176, 2014, in Chinese.

[24] Z. Yang, Study on Tension Mechanical Performance of Reactive Powder concrete in Different Steel Fiber Volume Fractions, Beijing Jiaotong University, Beijing, China, 2006, in Chinese.