



Article Structural Optimization of Steel—Epoxy Asphalt Pavement Based on Orthogonal Design and GA—BP Algorithm

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Abstract: Fatigue cracks often occur in the deck asphalt pavement of steel bridges at the top of the longitudinal stiffening rib. To prevent this issue, the traditional design strategy of the steel bridge deck asphalt pavement structure was optimized, and a new approach is presented. This optimization technique exploits the strength simulation of the steel—epoxy asphalt pavement structure, and the stress concentration location is subsequently determined. A solid model of stress concentration including sensitive areas is then established. We examined the stress maximum point of the asphalt pavement layer at the top of the longitudinal stiffeners and the stress of the top pavement layer of the longitudinal stiffeners. To reduce the stress of the top pavement layer of the longitudinal stiffeners, an optimization method that combines orthogonal experimental design, neural network (BP), and genetic algorithm (GA) is presented. A design strategy for the steel—epoxy asphalt pavement for Sutong Yangzi River Bridge. We confirmed that the presented approach improved fatigue reliability and established the efficacy of the design strategy and optimization method.

Keywords: steel—asphalt concrete pavement; structural optimization; GA—BP algorithm; structural design strategy; orthogonal experiment

1. Introduction

The development and expansion of high-grade highways have highlighted the importance of steel bridges. Therefore, it is necessary to continuously improve the effective service life of asphalt pavements and reduce their structural dead weight. Moreover, the transport efficiency of the steel bridge deck under the existing traffic volume, vehiclemounted vehicles, and climate are of primary concern [1]. Asphalt pavement structure is one of the key technologies used to determine the service behavior and pavement performance of steel bridge decks. Fatigue damage and cracking of the asphalt surfacing are major problems that restrict the usage efficiency of steel bridges. Thus, improving the fatigue damage resistance of asphalt surfacing steel bridge decks has both theoretical and engineering significance [2]. To address the conditions of line bridge, traffic volume, vehicle type, axle load spectrum, and climate and environmental temperature, the design strategy and structural optimization of steel bridge deck pavement have been studied to ensure the economic efficiency and reliability of asphalt pavement. This is a critical problem that must be addressed during the design of steel bridge deck pavement [3,4].

In recent years, the design of steel bridge deck asphalt pavement structures has mainly focused on high-performance asphalt materials, such as epoxy asphalt [5–7]. There are few studies on the optimization of asphalt pavement structures of steel bridge decks [8,9]. Most of them focus on structural lightweight optimization design and consider structural



Citation: Xu, X.; Gu, Y.; Huang, W.; Chen, D.; Zhang, C.; Yang, X. Structural Optimization of Steel— Epoxy Asphalt Pavement Based on Orthogonal Design and GA—BP Algorithm. *Crystals* **2021**, *11*, 417. https://doi.org/10.3390/cryst11040417

Academic Editor: José García

Received: 4 March 2021 Accepted: 6 April 2021 Published: 13 April 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). strength, high-temperature rutting, low-temperature crack resistance, water stability, and flexural sink value as evaluation criteria [10–12]. However, the service environment of steel bridge deck asphalt pavements is relatively poor. In a lightweight design, more attention should be focused on the stress distribution of the sensitive components of the steel bridge deck structure, especially the stress distribution of epoxy asphalt pavement in sensitive regions of the orthotropic plate [13,14]. Apart from the structural optimization, the rheological and engineering properties of asphalt pavement is also essential to determine the adhesion behavior of steel—epoxy asphalt pavement system [15–17].

Extensive research on highway heavy load and pavement material technology has led to new requirements for the design of asphalt pavement structures on steel bridge decks under the new situation of highway transportation, and the existing design strategies for asphalt pavement structures of steel bridge decks should be constantly improved. At present, scholars have studied the theories and methods of structural optimization design from two main aspects: the design of mathematical models and solving algorithms [18–20].

The orthogonal test is a method for selecting representative test points instead of comprehensive tests based on principles of probability theory and statistics. Its primary approach is variance analysis. The selected representative points exhibit "uniformity" and "regularity," and the main advantage is the uniformity of the test point spread. An orthogonal experimental design is used to construct training samples for a neural network and combined with the global optimization of a genetic algorithm and the local optimization of the BP neural network, these techniques are used as a practical and effective method for the optimization of the asphalt pavement structure of a steel bridge deck [21].

The strategy and structure optimization design method are presented in this report for the structural design of steel—epoxy asphalt concrete composite pavement. Moreover, the main aspects for consideration in finite element simulation analysis of the structure of steel—epoxy asphalt concrete composite pavement are presented. Specifically, the stress variation of the relevant asphalt pavement at the stress concentration position is carefully considered, which is an important basis for the optimization of the bridge deck asphalt pavement structure. In the steel bridge deck epoxy asphalt pavement of the Sutong Yangzi River highway bridge, the proposed pavement structure design strategy is utilized with the genetic algorithm (GA)—BP optimization method based on the orthogonal design of steel bridge deck asphalt pavement structure optimization. The results revealed that not only is the structural reliability of the steel bridge deck asphalt mixture paving improved, but the applicability and feasibility of the proposed method are also established.

2. GA—BP Optimization Method Based on Orthogonal Design

2.1. Orthogonal Experimental Design Method

If the multifactor complete test scheme is adopted, assuming that the number of factors is m and the horizontal number of factors is q, then the number of multifactor complete schemes is $n = q^m$. Although the complete experimental scheme can be used to study the simple, main, and interaction effects of each factor, it can also provide the most complete sample for a neural network. However, with the increase in the factor number and factor level, the number of experimental schemes also increases significantly. If the orthogonal test table is used for testing, the optimization scheme can be effectively determined, test efficiency can be improved, and a number of tests can be reduced.

For the steel bridge deck asphalt pavement, in addition to the steel bridge deck and the basic components of the longitudinal and transverse stiffeners and the baffle plate welding, the optimization of the components determines their relative position to all components of comparable size. Moreover, the control parameter is relatively small, and the orthogonal design is generally applicable to a few levels. Therefore, the orthogonal test can be used as a representative design scheme to provide a specific number of training samples for GA—BP calculations without loss of generality and ensure the accuracy of the neural network response surface model.

2.2. BP Neural Network

The BP neural network is the most widely used model, which is a nonlinear uncertainty mathematical approach. It is a multilayer feedforward artificial neural network with a continuous transfer function. The training method utilizes an error back-propagation algorithm, and the weights and thresholds of the network are constantly modified to minimize the mean square error to fit the data with high precision [22].

A three-layer BP neural network can be used to optimize the asphalt pavement structure of a steel bridge deck, as shown in Figure 1.



Figure 1. Three-layer BP neural network.

In Figure 1, $X = (x_1, x_2, \dots, x_i, \dots, x_n)^T$ is the input vector of the input layer, $i = 1, 2, \dots, n$, and n is the number of nodes of the input layer. $Y = (y_1, y_2, \dots, y_j, \dots, y_m)^T$ is the hidden layer output vector, $j = 1, 2, \dots, n$ is the number of hidden layer nodes, $O = (o_1, o_2, \dots, o_k, \dots, o_l)^T$ is the output vector of the output layer, $k = 1, 2, \dots, l$, and l are the nodes of the output layer, $V = (v_1, v_2, \dots, v_j, \dots, v_m)$ is the weight matrix from the input layer to the hidden layer, $W = (w_1, w_2, \dots, w_k, \dots, w_l)$ is the weight matrix from the hidden layer to the output layer, $A = (a_1, a_2, \dots, a_j, \dots, a_m)^T$ is the threshold vector of the hidden layer, φ is the excitation function of the hidden layer, $B = (b_1, b_2, \dots, b_k, \dots, b_l)^T$ is the threshold vector of the output layer, and ψ is the excitation function of the output layer. In combination with Figure 1, the output of the k node of the output layer is given as

 $o_k = \psi(net_k),\tag{1}$

$$net_k = \sum_{i=0}^m \left(w_{jk} y_j + b_k \right), \tag{2}$$

where net_k is the input of the *k* th node in the output layer, and w_{jk} is the weight between the *j* th node of the hidden layer and the *k* th node of the output layer.

The hidden layer can have:

$$y_j = \varphi(net_j), \tag{3}$$

$$net_{j} = \sum_{i=0}^{n} (v_{ij}x_{i} + a_{j}),$$
(4)

where net_j is the input of the *j* th node of the hidden layer and v_{ij} is the weight between the *i* th node of the input layer and the *j* th node of the hidden layer.

The excitation function f(x) can adopt the unipolar Sigmoid function:

$$f(x) = \frac{1}{1 + e^{-x}}.$$
(5)

The bipolar Sigmoid function can also be used as

$$f(x) = \frac{1 - e^{-x}}{1 + e^{-x}}.$$
(6)

Equations (1)–(6) constitute a three-layer neural network. Among them, the BP neural network is the most important for weight adjustment.

When the network output is not equal to the expected output, there is an output error *E*, which is defined as

$$E = \frac{1}{2}(D - O)^2 = \frac{1}{2}\sum_{k=1}^{l} (d_k - o_k)^2,$$
(7)

where, $D = (d_1, d_2, \dots, d_k, \dots, d_l)^T$ is the expected output vector, $k = 1, 2, \dots l$.

Expanding the definition of the output error (7) to the hidden layer, we have:

$$E = \frac{1}{2} \sum_{k=1}^{l} \left[d_k - \psi \sum_{j=0}^{m} \left(w_{jk} y_j + b_k \right) \right]^2.$$
(8)

Expanding Equation (8) to the input layer, we have:

$$E = \frac{1}{2} \sum_{k=1}^{l} \left[d_k - \psi \left(\sum_{j=0}^{m} \left(w_{jk} \varphi \sum_{i=0}^{n} (v_{ij} x_i + a_j) \right) + b_k \right) \right]^2$$
(9)

It can be deduced from equation (8) that the input error of the BP neural network is a function of the weights w_{jk} and v_{ij} of each layer. Therefore, the adjustment of the weights can change the network output error *E*.

The objective of adjusting the weights is to continuously reduce the error. Therefore, the adjustment amount of the weights should be proportional to the gradient descent of the error, that is:

$$\Delta w_{jk} = -\eta \frac{\partial E}{\partial w_{jk}} \ \Delta v_{ij} = -\eta \frac{\partial E}{\partial v_{ij}},\tag{10}$$

where η is the learning rate.

2.3. GA—BP Optimization Method

The BP algorithm is a method based on gradient descent, which may cause the network to fall into local extremes. The GA is a probabilistic adaptive iterative optimization process, which follows the principle of "survival of the fittest." It has reliable global search performance and effectively addresses the limitations of the BP algorithm local optimal [23]. The optimization process is as follows:

(1) Code to generate the initial population

In this study, a three-layer BP neural network and real coding are used. A complete chromosome is composed of weights *V* and *W* of the hidden and output layers of the neural network, respectively, and thresholds *A* and *B*, with a length of $n \times m + m + m \times l + l$.

(2) Evaluation function

In the evolutionary search process, the genetic algorithm is based on the fitness function. The fitness value of each chromosome is taken as the basis of the probability of inheritance to the next generation. In this study, the reciprocal of the mean square error is used as the fitness function, and it is calculated as

$$f(r) = \frac{1}{\sum \frac{(O-D)^2}{N}},$$
(11)

where f(r) is the fitness value of the chromosome r, and N is the number of chromosomes. (3) Perform genetic manipulation

In this study, according to the individual fitness value, the roulette method is used to calculate the individual selection probability, and a single point crossover and uniform variation method are adopted.

(4) Obtain the initial weight and threshold of the BP neural network and perform the calculation of the neural network.

3. Optimization Design of the Steel Bridge Deck Asphalt Pavement Structure

3.1. Optimization of the Design Strategy of the Asphalt Pavement Structure on the Steel Bridge Deck

The design strategy of asphalt pavement structures on steel bridge decks is mainly based on the structure layout of these traditional decks by applying existing mature technology and component structure. The static strength, creep, fatigue, and freezing—thawing of the asphalt materials are then simulated and analyzed [24–26]. If necessary, the structure dynamics and other simulation analyses should also be performed [24].

3.1.1. Traditional Design Strategy of Steel Bridge Deck Asphalt Pavement Structure

The traditional design strategy of the steel bridge deck asphalt pavement structure is divided into the following four steps:

Step1: Determine the main performance parameters and dimensions.

According to the service conditions of the steel bridge asphalt pavement and relevant environmental requirements, the main performance parameters such as the vehicle load, traffic volume, dynamic coefficient, and axle load action are determined. The main dimensions of the asphalt surface material, steel bridge surface thickness, longitudinal stiffeners geometry size, transverse spacing, transverse diaphragm thickness, and longitudinal spacing are determined.

Step2: Design of asphalt pavement structure on the steel bridge deck.

According to the determined main performance parameters and dimensions, the asphalt pavement structure scheme is designed by referring to the mature structure of existing steel bridge deck asphalt pavements.

Step3: Simulation of static strength of the steel bridge asphalt pavement structure

Given that the action area is far less than the length and width of the bridge panel, a finite element model of a steel bridge deck asphalt pavement with a plate and shell structure can be established for static strength simulation analysis.

Step4: Optimize the design of asphalt pavement structure on the steel bridge deck. According to the finite element simulation results, the maximum tensile stress point and the maximum stress point of the component of interest of the asphalt pavement are identified, and the relevant structure of the peak stress concentration component is generally optimized by trial and error.

3.1.2. Disadvantages of Traditional Design Strategy of Steel Bridge Deck Asphalt Pavement Structure

The fatigue crack source of the asphalt pavement of a steel bridge deck is usually at the stress concentration of the asphalt pavement at the top of the longitudinal stiffening rib. However, the finite element analysis of the plate and shell structures cannot robustly represent the stress distribution in this sensitive area. Finite element simulation results mainly focus on the stress maximum point or the stress peak point of the component of the steel bridge deck asphalt pavement of interest. However, it does not consider the overall stress distribution of the stress-concentrated component, and its stress variation [27,28].

3.1.3. Design Strategy Optimization

This study mainly optimizes the traditional design strategy of a steel bridge deck asphalt pavement structure from two aspects. The optimized design strategy flow is shown in Figure 2.



Figure 2. Design strategy flow of asphalt pavement structure on the steel bridge deck.

(1) Establish a local solid model for the asphalt pavement on the steel bridge deck. By determining the finite element model for the plate and shell structures, the stress concentrated part is determined, and the local solid model of the asphalt pavement covering the stress-concentrated component of the steel bridge deck is determined. The stress concentration behavior of the sensitive region is simulated, and the grid of the sensitive region is refined. To improve the computational efficiency, which is limited by the computer hardware conditions, entities with little or no influence on the stress-concentrated component were eliminated from the local solid model on the premise this component was not affected.

(2) The analysis of the results, stress distribution, and variations in the sensitive area. The stress change does not only show the position of the maximum stress point, but also the stress change position.

3.2. Mathematical Model for Component Optimization

The asphalt pavement structure of the steel bridge is generally composed of the asphalt pavement layer, steel bridge panel, longitudinal stiffeners, transverse partitions, and other components, and each set of components is composed of secondary components and related components [29]. The overall optimization of the bridge deck pavement is too difficult to realize because there are too many parameters for location relation and component size. However, the position relation of each component has a specific correlation, and the optimization of the local structure and the components is feasible. At present, the optimum design of a steel bridge deck structure takes the minimum mass as the objective function. However, during the normal use of the steel bridge deck asphalt pavement, fatigue cracks often appear in sensitive areas such as the longitudinal stiffening rib and the asphalt pavement layer at the top of the baffle. In addition, the weight of the local structure or individual parts has little influence on the coefficient of dead weight. Therefore, it is desirable to consider the minimum peak tensile stress of the asphalt pavement in sensitive areas as the objective function. The mathematical model for the local structure and component structure optimization in the asphalt pavement of the steel bridge deck can be summarized as follows:

$$\min \sigma(x) \ x \in \mathbb{R}^n \tag{12}$$

s.t.
$$g_i(x) \le 0$$
 $i = 1, 2, \cdots m$ (13)

$$l_j(x) = 0 \ j = 1, 2, \cdots n$$
 (14)

where *x* is the design variable, $\sigma(x)$ is the peak stress function, $g_i(x)$ is the inequality constraint, $l_i(x)$ and is the equality constraint.

3.3. Optimization Design of Steel Bridge Deck Asphalt Pavement Structure Based on GA— BP Method

Structural optimization design can be divided into dimension (section), shape (geometry), topology, and layout optimizations, according to the difficulty level. The service conditions of the steel bridge asphalt pavement structure are complex, and the design is generally based on the existing mature structure. However, the shape and topology optimization are mainly aimed at the optimization of geometric shape and material distribution, which does not facilitate the exploitation of mature technology and components for steel bridge asphalt pavement [16]. Layout optimization achieves an ideal overall organization of the components. Dimension optimization is used to reduce the structure quality and stress peak value by changing the thickness and section geometric parameters of the components. Both layout and dimension optimization satisfy the requirements related to the design of asphalt pavement structures on steel bridge decks [30,31]. Therefore, this report mainly focuses on the layout and size of the two aspects of asphalt pavement structure optimization. First, after determining the main performance parameters and dimensions of the steel bridge deck asphalt pavement, the relative positions of the main components are optimized. Second, the size of the component is optimized to further reduce the peak stress in the stress-concentrated area. As such, the design of the steel bridge deck asphalt pavement structure is more reasonable.



Figure 3 shows the optimization process for the design and optimization of the asphalt pavement structure on the steel bridge deck, which is as follows:

Figure 3. Optimal design flow of asphalt pavement structure on the steel bridge deck.

Step1, determine the entity model of the local structure according to the simulation results of the finite element model of the shell element. The local entity model shall be loaded and constrained with no influence.

Step2, optimize the layout of the asphalt pavement components on the steel bridge deck according to the simulation results of the local entity model. The optimization of the structural layout of the steel bridge asphalt pavement involves the minimization of the stress peak in sensitive areas by changing the relative positions of each component of the asphalt pavement, resulting in a small stress variation.

Step3, on the premise that the overall layout of the asphalt pavement structure on the steel bridge deck meets the requirements, structural optimization is performed for the components associated with the sensitive areas of interest. In this study, the model base of components is established using the orthogonal test method, which is used as the training sample. The component size parameters with low stress values are obtained by combining a genetic algorithm and a BP neural network.

4. Optimization of Epoxy Asphalt Pavement Structure of Steel Bridge Deck

The asphalt mixture with high viscosity was first used in Germany in 1982. Since then, it has been widely used in Britain, Japan, and China. In the late 1990s, a British single-layer pouring surfacing structure was introduced for the construction of the Jiangyin Yangtze River Highway Bridge in China. For the construction of the second Nanjing Yangtze River Bridge, Runyang Yangtze River Highway Bridge, Chongqi Yangtze Bridge, and other long-span steel box girder bridges, there has been a breakthrough in China's steel bridge deck pavement research. In the paving material that is formed, epoxy asphalt mixture is used as the main paving materials [5,6,32]. Given that asphalt pavement is used to characterize the bridge structure under a constant load, the designer often does not adequately consider its design, and fatigue cracks typically appear one to two years after service is initiated [2,5,33].

The Sutong Yangtze River Highway Bridge is located in the Nantong section of the Yangtze River estuary in the southeastern Jiangsu Province, connecting Suzhou and Nantong. The bridge is an important passage across the Yangtze River between the Heilongjiang Jiayin highway and the Fujian Nanping National key trunk Highway planned by the Ministry of Communications. It is also an important part of the Ganyu Highway and Wujiang Highway, the main highway in Jiangsu Province. The span of the main bridge is 1088 m. The Sutong Bridge adopted a flat steel box girder structure. The orthotropic bridge has a small stiffness, large local deformation, and poor heat capacity. The pavement structure on the bridge deck can easily produce early problems due to its complex conditions. It is a very challenging engineering construction problem, and therefore, a suitable bridge deck pavement is a key aspect of bridge construction [25]. Therefore, taking the Sutong Yangtze Bridge as an example, it is possible to not only verify the applicability and feasibility of the proposed structural design strategy, but also the structural optimization method based on the GA—BP algorithm. In addition, the optimization of the asphalt pavement structure and the design of the asphalt pavement structures of long-span steel bridges are of important reference.

4.1. Finite Element Simulation of Epoxy Asphalt Pavement on the Steel Bridge Deck

The stress of the epoxy asphalt pavement on a steel bridge deck is affected by the bridge faceplate, longitudinal stiffeners, transverse diaphragm, and loading conditions. As a result, the center of the longitudinal stiffened lateral wall, diaphragm, and load are not consistent, leading to the local stress concentration of the structure [34,35]. Therefore, in finite element analysis, the maximum stress point of the pavement layer at the connection between the longitudinal stiffened ridged wall, bridge faceplate, and the change of the peak stress of the connection should be emphasized [36,37]. In combination with the location of cracks on the asphalt pavement surface in the application process, this report focuses on the subsequent analysis, as shown in Figure 4.

To analyze the stress variation rules of the steel bridge deck epoxy asphalt pavement when the load changes along the transverse and longitudinal positions of the bridge deck for the steel bridge deck pavement without a media sternal plate, three load action positions are arranged along the bridge deck according to the relative positions of the stiffeners. Load I is applied directly above the center of two adjacent stiffeners, Load II is symmetrically applied directly above with a stiffening rib as the center, and Load III is applied symmetrically above a stiffener, as shown in Figure 4a.



Cross section view

(a) Different positions along the cross-section of the vehicle/mm.



(**b**) Vehicle-mounted vehicles are located in different directions along the longitudinal deck/mm.

Figure 4. Calculation model and load action of orthotropic steel bridge deck pavement system.

The deck pavement of the Sutong Yangzi River Bridge is a laminate structure. According to the symmetry of the box girder, eight longitudinal rib models can be discretized using plate and shell elements. Moreover, to maintain consistency with the actual structure of the bridge deck pavement as a simplification principle, all structures that contribute to the overall stiffness and local strength of the pavement structure are considered. The shell element was established at the physical location of the middle surface of the thin plate, and the mesh was refined at the focal points. The finite element model that was used is shown in Figure 5.



Figure 5. Tire/bridge coupling solid model.

According to the requirements [38] identified in the literature and according to the design strategy process of the steel bridge deck epoxy asphalt pavement structure proposed in this report, the influence of load position 1 in the first working condition, load position 2 in the second working condition, and load position 3 in the third working condition on the stress of key positions was analyzed. The simulation results show that the maximum stress occurs near the top of the longitudinal stiffener, and the transverse tensile stress peak is larger, compared to that far from the center of the vehicle-mounted action position. Therefore, this study focuses on the stress, its variation near the top of the panel beam, and the longitudinal stiffeners of the bridge at the center of the wheel load action. The stress at this point on the top of the panel beam is referred to as the stress peak. The simulation results are shown in Figure 6. It is observed that the longitudinal ribs and vertical forces of the vehicles have the greatest influence on the transverse tensile stress distribution. Therefore, we perform an in-depth study of the stress in this region under the action of vertical forces.



Figure 6. Transverse tensile stress distribution under different working conditions.

4.2. Verification of Epoxy Asphalt Pavement Testing on the Steel Bridge Deck

The test bridge epoxy asphalt mixture pavement surface strain/stress results test are shown in Figure 7. During testing, the weather was sunny and windy, the highest atmospheric temperature was 11.6 °C, and the highest temperature of the steel bridge panel was 12.6 °C. Two temperature-compensation tablets were added during testing. The results for a comparison of the measured and calculated stresses on the surface of the epoxy asphalt mixture pavement under the condition of no overload or 30% overload are shown in Figures 8 and 9.



Figure 7. Surface strain measurement for epoxy asphalt mixture pavement.



Figure 8. Comparison between the measured and simulated results of the transverse maximum tensile stress of asphalt pavement on the steel bridge deck under the action of BZZ-100 axle load.



Figure 9. Comparison between the measured and simulated results of the transverse maximum tensile stress of asphalt pavement on the steel bridge deck under the action of BZZ-130 axle load.

Figures 8 and 9 show that the deviation between the simulation and the experimental results is less than 10%, which is indicative of high consistency. The transverse tensile stress of load II and load III have significant influence on the stress of key positions. The maximum tensile stress of the asphalt pavement occurs at the weld joint between the longitudinal stiffeners near the center of the load and the bridge panel, and the variation of the tensile stress in this area is higher, compared to the transverse tensile stress far from the load center. Therefore, this report focuses on the stress and its variation in the asphalt pavement layer near the connection between the longitudinal stiffener of the load center and the weld seam of the bridge panel. The transverse tensile stress in this area is referred to as the tensile stress peak. The simulation results are shown in Figures 8 and 9. The results show that the vertical force of the load has the greatest influence on the tensile stress in this area under the asphalt pavement. Therefore, an in-depth study of the stress in this area under the action of a vertical force is conducted.

4.3. Epoxy Asphalt Pavement Structure Layout Sensitivity

Due to the limitations of the overall steel bridge deck asphalt pavement structure and the loading condition, the longitudinal stiffeners, sidewalls, and loading area near the tire center are not consistent, which induces local stress concentrations, and causes an increase in the transverse tensile stress of the bridge deck and the top of the longitudinal rib wall. Moreover, there is a relationship between the transverse tensile stress of the pavement surface and the longitudinal rib stiffness (geometric size). Therefore, it is necessary to not only adjust the position relationship among the longitudinal stiffness to achieve layout optimization. Based on the design experience, the internal strength of the side column is generally consistent with the center of the side column. Therefore, the geometric stiffness (upper width, height, and sidewall thickness) of the longitudinal stiffeners at loading positions II and III were selected. For the thickness of the steel box girder bridge faceplate $t_g = 14$ mm, spacing L = 3.25 m, thickness of the pavement layer $t_i = 50$ mm, modulus ratio of the steel bridge deck and asphalt pavement n1 = 200, and transverse spacing of the longitudinal stiffeners d = 300 mm, the maximum transverse tensile stress of the pavement

surface under different combination schemes (Table 1) was calculated. Figures 10 and 11 show a comparison of the distribution of the large transverse tensile stress values for seven schemes.

Table 1. Geometric stiffness of lo	ongitudinal	stiffeners.
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Scheme	Sidewall Thickness t_w/m	Upper Width <i>u</i> /mm		
1	250	10	300	
2	350	10	280	
3	250	8	280	
4	280	8	300	
5	300	6	320	
6	320	6	320	
7	300	8	300	



Figure 10. Comparison of the transverse tensile stress distribution of the pavement under different schemes under load II.



Figure 11. Comparison of transverse tensile stress distribution of the pavement under different schemes under load III.

Based on Figures 10 and 11, the variation of the stress in each scheme is the same. However, for schemes 4 and 5, the variation is relatively minimal, and the stress in the entire high-stress zone is lower than that of the other schemes. This indicates that the height of the longitudinal stiffeners has a significant influence on the transverse tensile stress of the pavement. The lateral wall thickness of scheme 2 is large and the stress is reduced. However, the stress variation is relatively flat. Therefore, scheme 4 is determined as the optimal scheme after layout optimization.

5. Optimization of the Epoxy Asphalt Pavement Structure of the Steel Bridge Deck

The transverse tensile stress of the epoxy asphalt pavement is not only affected by the position under the influence of a load, geometric form of the longitudinal stiffeners, and relationship of the stiffness, but is also affected by the thickness of the steel plate, the spacing of the longitudinal stiffeners, paving material, and thickness. Trapezoidal longitudinal stiffeners have been used in steel bridge deck pavements for many years. Their performance is excellent, and they have developed into a mature structural form in engineering. Therefore, the GA—BP optimization method based on the orthogonal experimental design in Section 1 is mainly utilized in this study to optimize the structure of asphalt pavement, to further reduce the peak transverse tensile stress on the surface of the steel bridge deck pavement.

5.1. Optimization Objective and Optimization Parameter Selection

The steel bridge deck pavement structure is composed of a steel plate, longitudinal ribs, an asphalt pavement layer, and a transverse partition box structure. Based on the design experience, it is determined that the transverse tensile stress of the pavement surface is mainly affected by the thickness of the steel plate, epoxy asphalt pavement layer, and longitudinal rib spacing. According to the analysis results in Section 4, the transverse tensile stress is a maximum at the top surface of the asphalt pavement of the longitudinal rib wall web. Therefore, this study investigated the determination of the stress peak value near the location of each model as the initial value of the training neural network, and took the minimum stress value near the location as the optimization objective. The following mathematical model can then be established as follows:

Stress σ requirement is:

$$\min\sigma(t_i, t_g, d) \tag{15}$$

where t_g is the design variable of panel thickness, the range of t_g is $12 \le t_g \le 16$; t_i is the design variable of asphalt pavement thickness, the range of t_i is $30 \le t_i \le 70$; d is the design variable of longitudinal rib spacing, the range of d is.

5.2. Orthogonal Experimental Design

An orthogonal experimental method was adopted to design the combination optimization test for the pavement structure. According to the preceding analysis, the three levels t_g , t_i and d to be optimized were determined, as shown in Table 2.

Table 2. Factors and levels for the orthogonal test.

Level	t _g /mm	t _i /mm	<i>d</i> /mm
1	12	30	320
2	14	50	280
3	16	70	240

According to the established factor and the level table, an orthogonal test table $L_9(3^4)$ of four factors and three levels was established to obtain nine groups of test plans, a solid model for the pavement structure of nine groups of plans was established, and a finite element simulation analysis was performed. The results are shown in Table 3.

Number	t _g /mm	t _i /mm	d/mm	$\sigma/{ m Mpa}$	
				II	III
1	12	30	320	2.4135	2.3108
2	12	50	280	2.0493	2.1237
3	12	70	240	1.4006	1.5631
4	14	30	280	1.7905	1.6981
5	14	50	240	1.2615	1.3542
6	14	70	320	0.7106	0.7914
7	16	30	240	1.3430	1.4256
8	16	50	320	0.5786	0.6245
9	16	70	280	0.3939	0.3786

Table 3. L₉(3⁴) Orthogonal test data.

5.3. GA—BP Optimized Analysis

The orthogonal experimental data given in Table 3 were used as training samples for normalization processing. We used the function Newff (in MATLAB (version.R2020a, MathWorks.Inc, Natick, MA, USA)) toolbox to create the neural network. A three-layer network structure was adopted, including three input neurons, seven hidden neurons, and one output neuron. The total number of training steps was 200, and the target of the mean square error was 10–3. A genetic algorithm was then used to further optimize the data. The initial population size was 50, and the number of iterations was 500. Real number coding and the roulette wheel method were used to select new individuals. According to the fitness change curve of the genetic algorithm, the optimal fitness value was obtained after approximately 80 generations of the genetic algorithm. As such, the optimal solution was obtained. The optimization results are shown in Table 4.

Method	t _g /mm	t _i /mm	d/mm	σ/Mpa	
				II	III
Initial design	14	60	300	0.78139	0.7639
-	-	-	-	-	-
GA—BP optimized	16	55	280	0.6201	0.5724
Simulation	16	50	280	0.5986	0.5602

Table 4. Comparison of the optimization results and finite element calculation value.

5.4. Verification of GA—BP Optimization Results

In this report, we evaluated the efficacy of using the GA—BP method to obtain the optimal solution based on the two following aspects:

(1) A large beam finite element model was established according to the parameters obtained using GA—BP optimization, and finite element simulation was performed. The simulation verification results are presented in Table 4. This table shows that the stress value obtained using the GA—BP optimization method differs little from the simulation result, and is the minimum value compared to the target value in Table 4. Using the results in the table, it can be seen that the longitudinal stiffener spacing *d* has a great influence on the tensile stress peak of asphalt pavement.

(2) The relevant size parameters obtained using GA—BP optimization were introduced into the model of level 3 for finite element simulation. Figures 12 and 13 show the calculation results. These figures reveal that the maximum transverse tensile stress for the optimized layout of 0.5986 MPa (II), 0.5602 (III), and for optimization using the GA—BP big beam weld stress and the maximum of 0.6201 MPa (II), 0.5724 (III), the maximum stress reduction is 0.26 MPa, and the optimized high stress area is less compared to before optimization. After optimization, the transverse tensile stress change is relatively constant.



Figure 12. Comparison of the peak stress distribution of optimized pavement under load II.



Figure 13. Comparison of the optimized peak stress distribution of the pavement under load III.

The GA—BP method based on an orthogonal experimental design was used to optimize the composite structure of a steel bridge deck pavement, which not only effectively reduced the horizontal and stress variation gradient of the transverse tensile stress of the steel bridge deck, but also showed that the GA—BP method was feasible for optimizing the structure of the steel bridge deck asphalt pavement. Therefore, the optimization results are credible.

6. Conclusions

(1) The design strategy of the steel bridge deck pavement structure was systematically presented in this report. Compared to the traditional design strategy of the steel bridge deck pavement structure, we proposed that the stress distribution of the relevant pavement layer in the stress concentration position should be carefully considered when evaluating the viability of pavement designs. Attention should be focused not only on the maximum stress of the epoxy asphalt pavement, but also on the stress variation of the stress-concentration related components. Considering the traditional focus on only the maximum stress point to examine the stress change in the sensitive area of the pavement layer, a more comprehensive understanding of the stress distribution at the stress concentration site is required as an important basis for structural optimization.

(2) We proposed the optimization of steel—epoxy asphalt pavement structures from the two aspects of layout and size. Additionally, the structure design was determined to be feasible and to meet the requirements [39].

(3) By utilizing the design strategy of the steel—epoxy asphalt pavement structure and the design optimization method proposed in this report, the optimization of the trapezoidal stiffener component was achieved. This not only facilitated the determination of the optimal scheme, but also improved the reliability of the overall structure of the steel—epoxy asphalt pavement. Moreover, the applicability and feasibility of the design strategy of the steel—epoxy asphalt pavement structure and the local structure optimization process proposed in this report were evaluated. The results will serve as a reference for the optimization of newly designed steel—epoxy asphalt pavement structures.

Author Contributions: Conceptualization, X.X.; methodology, C.Z.; software, Y.G.; investigation, D.C.; visualization, X.Y.; supervision, W.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, No. 2016YFB0303100, Postgraduate research and Practice Innovation Project in Jiangsu Province, No. KYCX20_2831, Natural Science Foundation of Nantong, No. JC2019065, MS22020026, and XG202009-1.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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