

Article

Optimization of Lower Suspension Point Position in Attached Cantilever Scaffold

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Abstract: An attached cantilever scaffold, which mainly consists of a cantilever horizontal steel beam and a diagonal bar, is a new type of cantilever scaffold. The upper end of the diagonal bar is attached to an upper floor slab by a hinge, while the lower end is connected to a cantilever beam. Therefore, the position of the lower suspension point has a significant impact on the overall mechanical performance. However, current research on this topic is limited. Thus, in this study, we aim to optimize the mechanical behavior by changing the lower suspension point position. An optimization methodology based on the genetic algorithm is proposed. This methodology has been demonstrated to be efficient and accurate enough to determine the optimal lower suspension point position of a diagonal bar. The effects of different beam cross-sections, diagonal bar diameters, and upper suspension point positions are further investigated. The bearing capacity is shown to improve by more than 100% and 30% for hinged and rigidly connected cantilever beams when the proposed optimization methodology is adopted. The analysis in this study can serve as a reference for the optimal design of an attached cantilever scaffold and can provide a theoretical basis for developing related design software.

Keywords: attached cantilever scaffold; optimization methodology; finite element analysis; suspension point position; bearing capacity



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1. Introduction

Scaffolds play important roles in construction engineering. In the past, the most commonly used type of scaffold was the full-hall scaffold, which consumes large amounts of material [1]. Recently, a novel scaffold type called the attached cantilever scaffold has been increasingly used in practice [2]. Compared with traditional full-hall scaffolds, attached cantilever scaffolds only consume small amounts of material because the scaffold can be reused within an engineering project [3]. Figure 1 presents a schematic diagram of the main load-bearing components of an attached cantilever scaffold. As can be seen, the main load-bearing components comprise a horizontal steel beam and a diagonal bar.

The connection stiffnesses is a key factor affecting the behavior of the scaffold; thus, a series of studies have been performed to examine this behavior, considering the effect of connection stiffness. Kaewsawang and Chotickai [4] experimentally and analytically investigated the effect of bolt-tightening torques of couplers on the connection stiffness and structural bearing capacities. Similar research has also been conducted by Jia et al. [5] and Liu et al. [6]. An increase in the tightening torque has been found to possibly result in an increase in capacity by about 40%. The scaffold could suffer from cyclical load in practical engineering, which differs from a static load. Abdel-Jaber et al. [7] noticed this issue and conducted cyclic loading experiments on scaffolds with three common connection forms. According to the experimental results, the looseness affects the capacity

of the connections, a fact that should be considered during the design process. Zheng and Guo [8] investigated the effect of corrosion on the strength and rotation stiffness, and a two-stage four-parameter model to simulate the moment–rotation characteristic was proposed. In addition to the research on connection behavior, investigations into the global behavior of scaffolds have also been conducted. These investigations include those focused on the overall bearing capacities under different loading conditions [9–11], the effects of bracing and settlement [12,13], analysis methodologies [14–16], design software [17,18], the application of novel materials [19–21], and health monitoring [22].

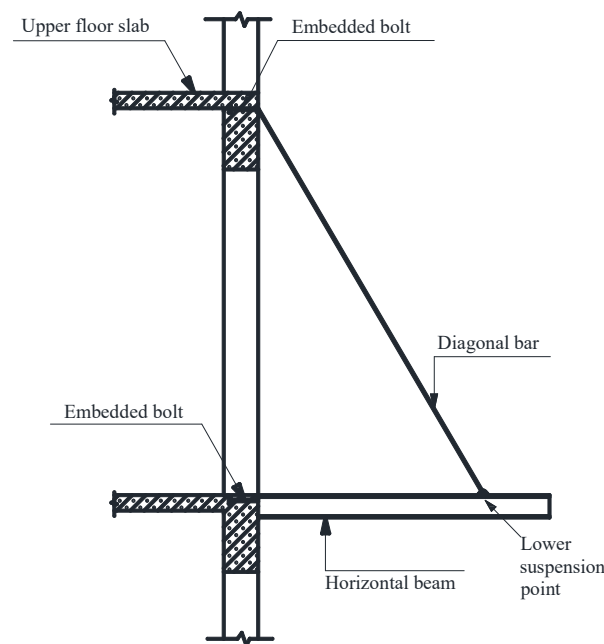


Figure 1. Schematic diagram of main load-bearing components.

Notably, the abovementioned research is only about traditional full-hall scaffolds, and investigations into the behavior of attached cantilever scaffolds are relatively limited. Jian discussed the advantages of cantilever scaffolds in the construction of special-shaped curtain walls [23]. Mao et al. investigated the parameters that affect the behavior of a cantilever scaffold and found that the suspension point position could significantly affect the behavior [24]. Thus, in this work, we aim to examine the optimal suspension point position of a scaffold to obtain superior behaviors. Note that the upper suspension point position of a cantilever scaffold is always determined by the upper floor slab in practice (as shown in Figure 1); however, the lower suspension point position can be adjusted to ensure that the scaffold possesses superior mechanical behavior. Because of this, studying the lower suspension point position is critical for cantilever scaffolds. In this work, both hinged and rigid connections between the horizontal steel beam and the main structure are considered. Adopting an optimal method is an effective way to improve the structural behavior without consuming extra material [25–28]. In this study, an optimization method is firstly proposed based on the genetic algorithm [29–31]. The accuracy of the proposed method is then verified by comparing the optimized results with those obtained from the enumeration method. Subsequently, several optimization cases are conducted considering different beam cross-sections, diagonal bar diameters, and upper suspension point positions. Finally, a numerical analysis is performed to evaluate the behavior of the optimized scaffold by comparing that corresponding to current standard recommended forms [32].

2. Analytical Model

In practice, the connection between the horizontal beam and structure is usually designed to be rigid by using appropriate bolts. However, notably, an actual connection

is often not rigid because of bolt deformation or poor construction quality. Thus, in this work, both ideal hinged and rigid connections are considered to cover the two extreme conditions. Figure 2 demonstrates two simplified models of an attached cantilever scaffold. The horizontal beam uses a Q355 I16 section member [33] with a nominal yield strength of 355 MPa [34]. Both the steel beam and the diagonal bar have an elastic modulus of 201 MPa and a Poisson's ratio of 0.3 [34]. The total length of the horizontal beam is 1800 mm, with two applied concentrated loads denoted by N_1 and N_2 in Figure 2. In Sections 4 and 5, N_1 and N_2 have magnitudes of 9.0 kN and 11.5 kN, respectively [32]. The distances from these two concentrated loads to the beam connection end are 800 mm and 1650 mm, respectively [32]. The magnitudes and positions of the two concentrated loads do not change during the optimization. The symbol H denotes the distance between the horizontal connection end and the upper suspension point; the magnitude of H would be introduced in subsequent sections.

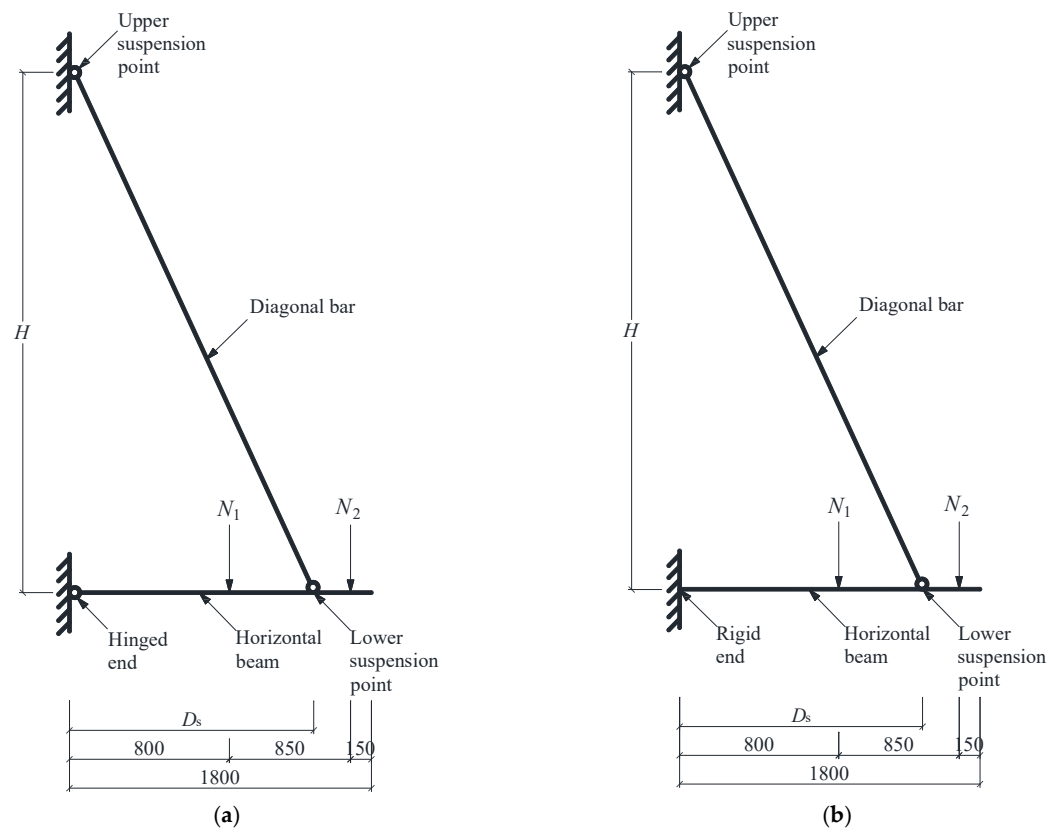


Figure 2. Simplified models of the attached cantilever scaffold. (a) Hinged, (b) rigid.

3. Optimization Method

For attached cantilever scaffolds, the mechanical behavior is affected by a series of factors, such as the beam connection type and bar diameter. The relationship between the lower suspension point position and the beam stress state is nonlinear. Thus, here, the genetic algorithm (GA) is employed to optimize the lower suspension point position of the diagonal bar. The GA is a global search optimization method, modeled after the principles of biological evolution (survival of the fittest, natural selection, and adaptation). The main feature of the GA is the direct encoding of the structure, unifying the expression forms of the objective function and decision variables. Compared with other optimization algorithms that require function differentiability and continuity, GAs are more advantageous for nonlinear problems [35–37]. By possessing potential parallelism and global search optimization capabilities, GAs can adaptively guide the optimization search space and adjust the optimization search direction. The corresponding strategy is introduced below, as follows:

1. **Selection:** The selection operation involves selecting individuals from the current population based on fitness criteria. Therefore, the individuals more suited to the environment are chosen. The number of offspring an individual produces is determined by its fitness. Individuals with higher fitness reproduce more, while those with lower fitness reproduce less or are directly eliminated. This iterative process results in a population with higher-adaptability individuals. The tournament selection algorithm is utilized to select individuals with higher fitness to create stronger offspring [38]. Figure 3 presents the process of the tournament selection. During each selection, two individuals are randomly chosen from the present population as contestants. The individual with the higher fitness value is the winner, and its replicator is selected into a population for the next genetic operation. The winner also returns to the original population to participate in the selection again. This step is repeated until a sufficient number (set as 20 in this study) of individuals are selected into the new population for the next genetic operation.
2. **Recombination:** The recombination operation involves randomly pairing individuals selected for reproduction and determination. The set crossover probability determines whether a crossover operation should be performed on each pair. If a crossover is to be performed, corresponding positions in the genotype of the pair are randomly chosen and swapped. Various methods exist for crossover operations. In this study, the two-point crossover strategy is utilized. Combined with the BG encoding approach, the two-point crossover strategy could generate more types of children within the searching space and could facilitate convergence.
3. **Mutation:** Based on natural gene mutation, a gene value is changed at a certain probability for each selected individual. When all individuals have identical genes but are not globally optimal, crossover will not change the genotype of the individuals. In the case of falling into local optima, a mutation is adopted to introduce new individuals and to enhance the global optimization capability of the algorithm. The Breeder GA mutation scheme is adopted in this study because of its BG code representation [39]. Each variable has an equal probability for mutation. When one variable is chosen to be mutated, its value is randomly changed within an interval around its original value, which helps the algorithm escape from local regions. Furthermore, the mutation scheme favors small adjustments, preventing large changes that might skip over the global optimum. The new variable x_i^1 is computed as:

$$x_i^1 = x_i \pm range_i \cdot \delta \quad (1)$$

where x_i represents the variable selected to be mutated. The probability of either a plus or minus sign being chosen is 0.5. $range_i$ is the mutation range, which is 1/10 of the variable search space. δ is computed as

$$\delta = \sum_{i=0}^k \alpha_i \cdot 2^{-i} \quad (2)$$

where each α_i is set to 0 before mutation and then mutated to 1 with a probability of 1/20 ($k = 20$).

In this study, the objective function as well as individual fitness is taken as the minimum controlling stress (the maximum stress) of the horizontal beam. In other words, the optimization objective is to minimize the horizontal beam controlling stress. This is because a smaller control stress value always indicates greater material strength redundancy and superior bearing capacity. Individuals are also sorted according to their fitness in each iteration. Therefore, the optimization problem can be expressed as follows:

$$\begin{cases} \min f(X) \\ s.t. X \in R \\ R \in U \end{cases} \quad (3)$$

In Equation (3), $X = \{x_1, x_2, \dots, x_n\}^T$ represents the decision variables, where n denotes the n -dimensional decision variable. $f(X)$ is the objective function. R is the global search space of the optimization problem. In this study, the variable search space corresponds to the range (0,1800) for the distance between the beam connection end and the lower suspension point.

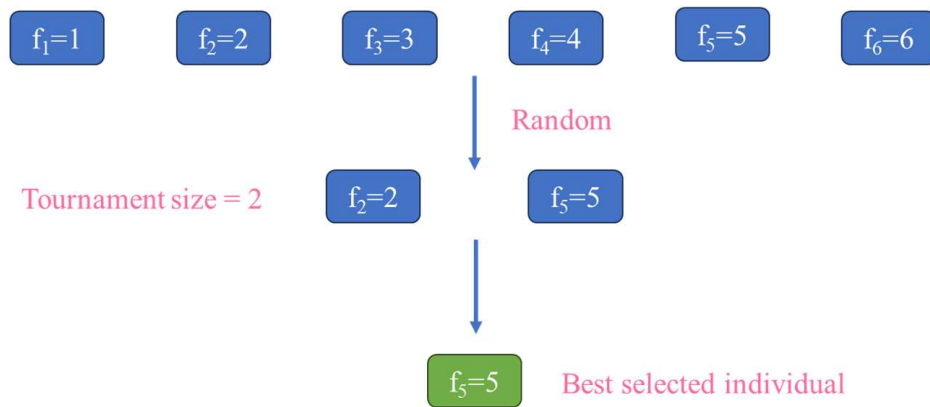


Figure 3. Example of tournament selection.

Parametric modeling is conducted in Python, with the geometric forms, constraints, solutions, and post-processing modules scripted in ABAQUS files. The genetic algorithm is programmed using Python as well, which calls ABAQUS to run a finite element analysis automatically. The post-processing statement in the script file reads the maximum beam stress as well as the lower suspension point position and outputs them into a text file. The main program then reads the file, obtains the parameters, and assigns the fitness. Finally, the GA process is terminated when the maximum iteration step is reached or the change in the objective function is relatively small for the last four iterations. Otherwise, it proceeds with the selection, crossover, and mutation operations to propagate the next generation, iterating until the convergence criteria are met. The specific procedure is shown in Figure 4.

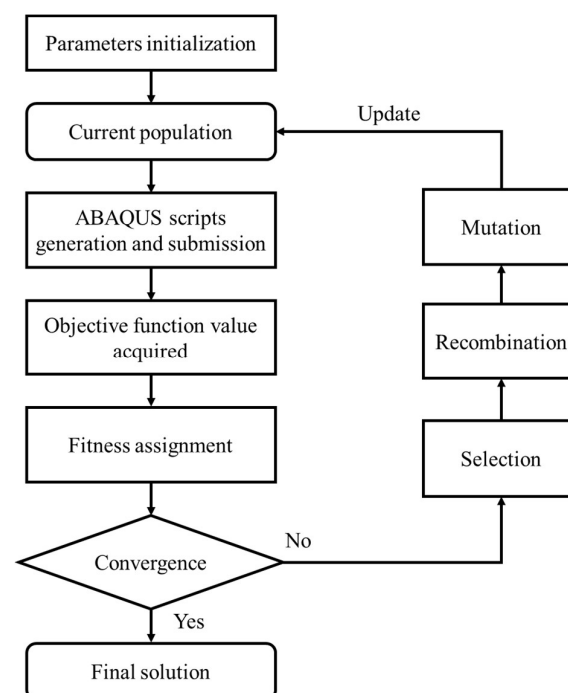


Figure 4. Procedural flowchart of the optimization method.

4. Validation

Prior to conducting the optimization analysis on the attached cantilever scaffolds, the accuracy of the proposed optimization methodology should be validated. In this section, validation was performed by comparing the lower suspension point position obtained from the current proposed optimization methodology and the traditional enumeration method.

4.1. Validation Model

The validation model is shown in Figure 2, in which the distance between the upper suspension point of the diagonal bar and the beam connection end is 3000 mm. The other parameters of the model, such as the loading conditions and material properties, are introduced in Section 2. For the proposed optimization methodology, the commercial software ABAQUS 2020 needs to be invoked for the finite element analysis. The finite element models of the attached cantilever scaffolds established using ABAQUS are shown in Figure 5. The only difference between the models shown in Figure 5a,b is the boundary conditions of the horizontal beam. For the model shown in Figure 5a, the boundary condition of the horizontal beam is hinged. However, that of the model shown in Figure 5b is rigid. A beam element with a mesh number of 30 and a truss element with a mesh number of 1 are used to simulate the horizontal beam and the diagonal bar, respectively.

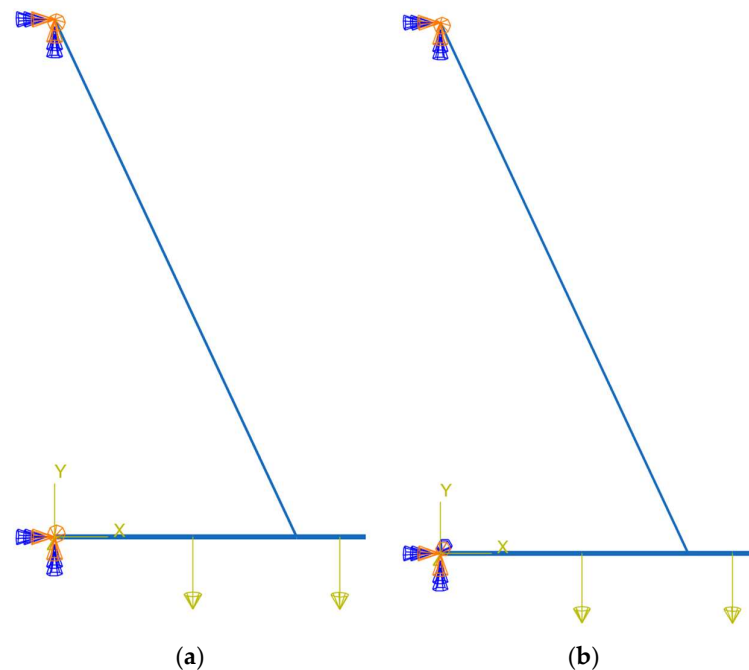


Figure 5. FE models of the attached cantilever scaffold. (a) Hinged. (b) Rigid.

4.2. Validation Results

(1) Results of the proposed methodology

By using the optimization method introduced in Section 3, the optimization results of the models, as shown in Figure 5, can be obtained. The optimization convergence processes of the controlling stress (the maximum stress) denoted by the relationship between the lower suspension point position D_s and generation number are shown in Figure 6. In this work, the lower suspension point position D_s is defined as the horizontal distance from the lower suspension point of the diagonal bar to the beam connection end. As can be seen, when the beam is hinged, the beam controlling stress converges around the eighth generation, and the optimal lower suspension point position is 1464 mm. That is, when the lower suspension point is 1464 mm from the beam connection end, the controlling stress of the horizontal beam reaches the minimum value in this load condition. When the beam is rigidly connected, the beam controlling stress converges around the ninth generation, and

the optimal position of the lower suspension point is 1302 mm. That is, when the lower suspension point is 1302 mm from the beam connection end, the controlling stress of the horizontal beam is minimized.

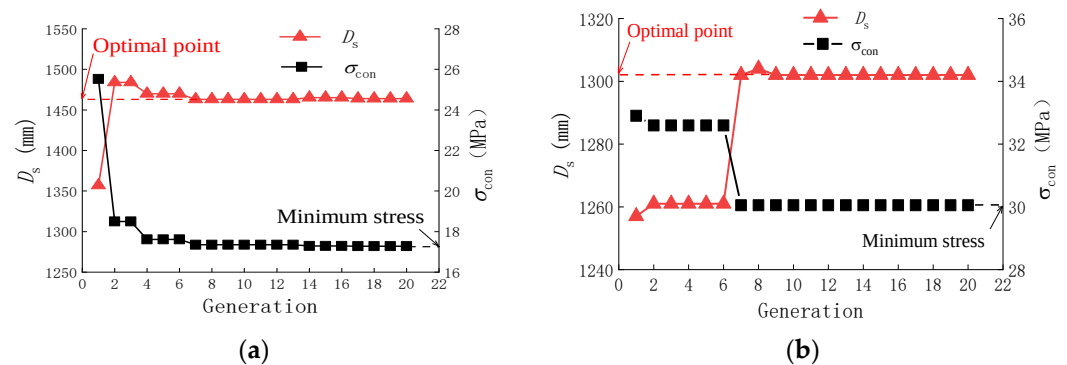


Figure 6. Optimization convergence processes of validation model. (a) Hinged. (b) Rigid.

(2) Results of the enumeration methodology

As mentioned above, the enumeration methodology is used to validate the accuracy of the GA-based optimization method. The basic idea behind the enumeration method is to establish a series of models with different lower suspension point positions. According to the comparison of the controlling stresses in the different models, the optimal lower suspension point position can be obtained. In this section, the controlling stresses are calculated using ABAQUS. The analytical models in this section possess 36 different lower suspension point positions, varying from 50 mm to 1800 mm, with an interval of 50 mm. The other parameters in this section remain the same as those introduced in Section 4.1. The results obtained from the enumeration method analysis are shown in Figure 7. The controlling stress is minimized when the lower suspension point position is 1450 mm for the hinged horizontal beam case. However, the minimal controlling stress of a rigidly connected beam corresponds to a lower suspension point position of 1300 mm.

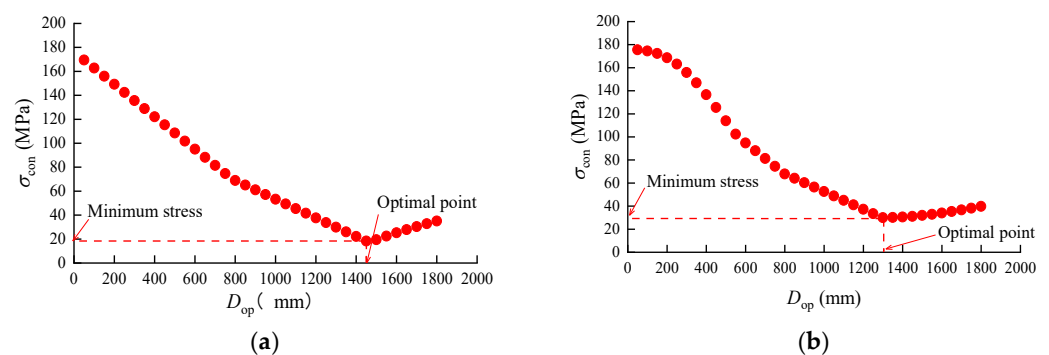


Figure 7. Results of the enumeration method. (a) Hinged. (b) Rigid.

(3) Result comparison

Table 1 presents the optimal results obtained from the proposed optimization method and the enumeration method. Overall, both the minimum controlling stresses and optimal lower suspension point positions calculated from the proposed optimization method and traditional enumeration method are similar. Due to the interval between the lower suspension point positions in the enumeration method being set at 50 mm, a very small difference exists between the optimal results obtained from the different methods. If the interval could be further reduced, the optimal results of the proposed and traditional methods could be completely the same as one another. In other words, the proposed optimization method is accurate and efficient enough to evaluate the optimal lower suspension point positions

of attached cantilever scaffolds. Therefore, the proposed optimization method is used for further analyses in the subsequent sections.

Table 1. Optimal results obtained from different methods.

Connection Types Methods	Hinged		Rigid	
	Minimum Controlling Stress (MPa)	Optimal Lower Suspension Point (mm)	Minimum Controlling Stress (MPa)	Optimal Lower Suspension Point (mm)
Proposed method	17.274	1464	30.051	1302
Enumeration method	18.353	1450	30.052	1300

5. Optimization Analysis

The accuracy of the proposed optimization method has been validated in Section 4. Thus, an optimization analysis can be performed to determine the optimal lower suspension point positions of attached cantilever scaffolds. This section aims to investigate the optimal positions with different scaffold parameters.

5.1. Analytical Results with Varying Beam Cross-Sections

In order to analyze the optimal lower suspension point positions of attached cantilever scaffolds with different beam cross-sections, three different sections, shown in Table 2, were adopted. As can be seen, the section type was varied from I14 to I18 [33] with a sectional height varying from 140 mm to 180 mm. The diagonal bar diameter was set as 20 mm, and the vertical distance between the upper suspension point of the diagonal bar and the beam connection end was set as 3000 mm. The other structural parameters of the attached cantilever scaffold are the same as those in Section 2.

Table 2. Information on section types I14, I16, and I18.

Section Type	Dimensions (mm)			
	h	b	t _w	t
I14	140	80	5.5	9.1
I16	160	88	6.0	9.9
I18	180	94	6.5	10.7

Note: h and b are the cross-sectional height and width, respectively; t_w and t are the web and flange thicknesses, respectively.

Figure 8 presents the controlling stress varieties with varying generation for different beam cross-sections in both the hinged and rigid cases. The horizontal axis in Figure 8 represents the different generations during the optimization process. The convergence speed of the beam controlling stress increases as the section size decreases but decreases with a change in connection type from hinged to rigid.

The optimization results of models with different beam cross-sections are shown in Figure 9. Here, the horizontal axis represents the different beam cross-sections. $\sigma_{\text{con,hin}}$ represents the optimal beam controlling stress when hinged, while $\sigma_{\text{con,rig}}$ represents the optimal beam controlling stress when rigidly connected. $D_{\text{op,hin}}$ represents the optimal lower suspension point position of hinged cases, while $D_{\text{op,rig}}$ represents those of rigid cases. D_{op} represents the optimal lower suspension point position. When the beam is connected by a hinge, the corresponding controlling stress is smaller, and the optimal lower suspension point position is farther from the beam connection end. Conversely, when the beam is rigidly connected, the corresponding controlling stress is larger, and the optimal lower suspension point position is closer to the beam connection end. Of note, the optimal lower suspension point position could not be affected by the beam cross-section dimensions because, in this case, the primary load-bearing components of the attached cantilever scaffold form a statically determinate structure in the plane.

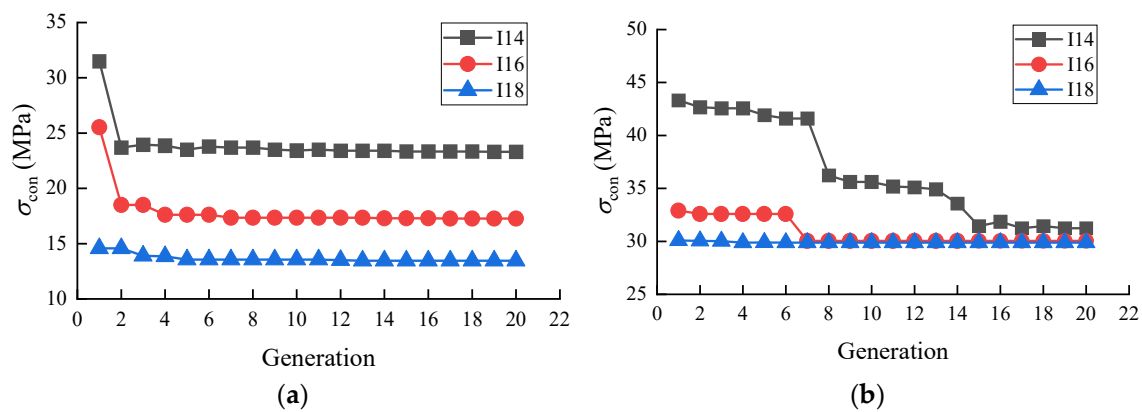


Figure 8. Optimization convergence processes with different beam cross-sections. (a) Hinged. (b) Rigid.

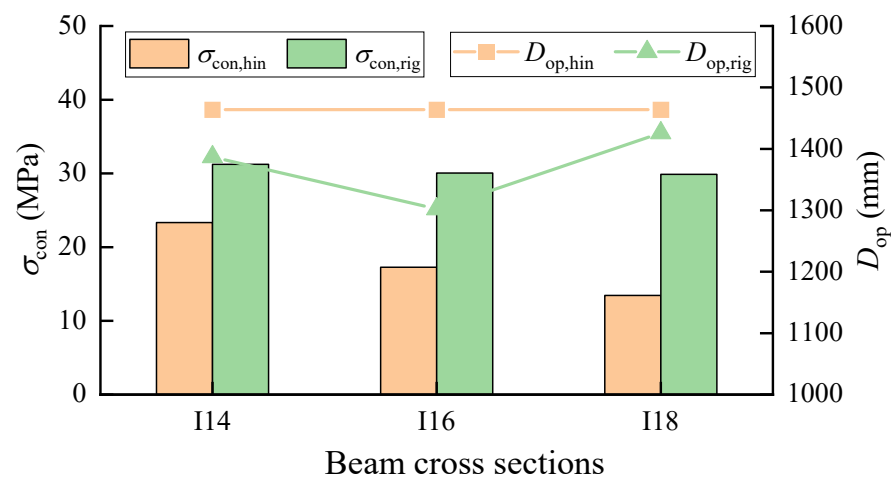


Figure 9. Optimization results of a cantilever scaffold with varying beam cross-section.

5.2. Analytical Results with Varying Bar Diameters

When investigating the effect of different diagonal bar diameters on the optimal lower suspension point position, the vertical distance from the upper suspension point to the beam connection end was set as 3000 mm. The beam cross-section was set as I16, and the diagonal bar diameters were set as 18 mm, 20 mm, and 22 mm. Figure 10 shows the different controlling stresses with varying generations for different bar diameters. The beam controlling stress converges after a maximum of eight generations in both the hinged and rigid cases.

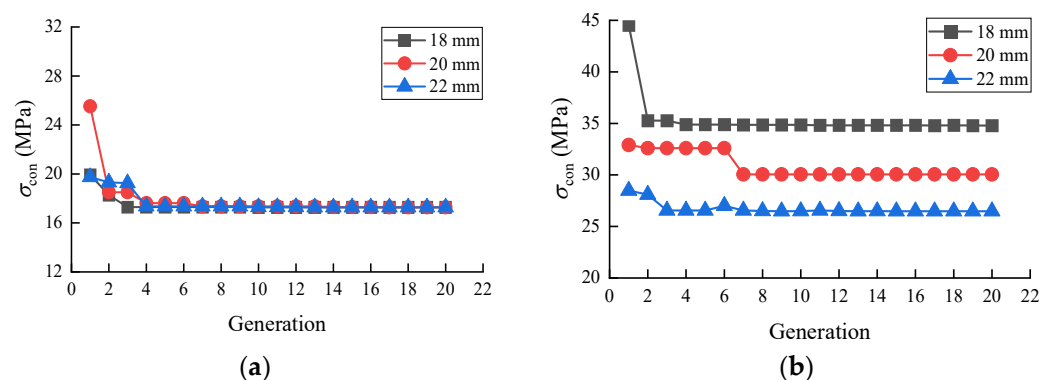


Figure 10. Optimization convergence processes with different bar diameters. (a) Hinged. (b) Rigid.

The optimization results of models with different bar diameters are shown in Figure 11. Here, the horizontal axis represents the different bar diameters. Similar to the results in Figure 9, when the beam is connected by a hinge, the optimal lower suspension point position does not change with a variation in the bar diameter because the main load-bearing components of the attached cantilever scaffold also form a statically determinate structure. When the beam is rigidly connected, the main load-bearing components of the attached cantilever scaffold become statically indeterminate. In this case, the optimal lower suspension point position changes with varying bar diameter, and the minimized beam controlling stress decreases as the bar diameter increases.

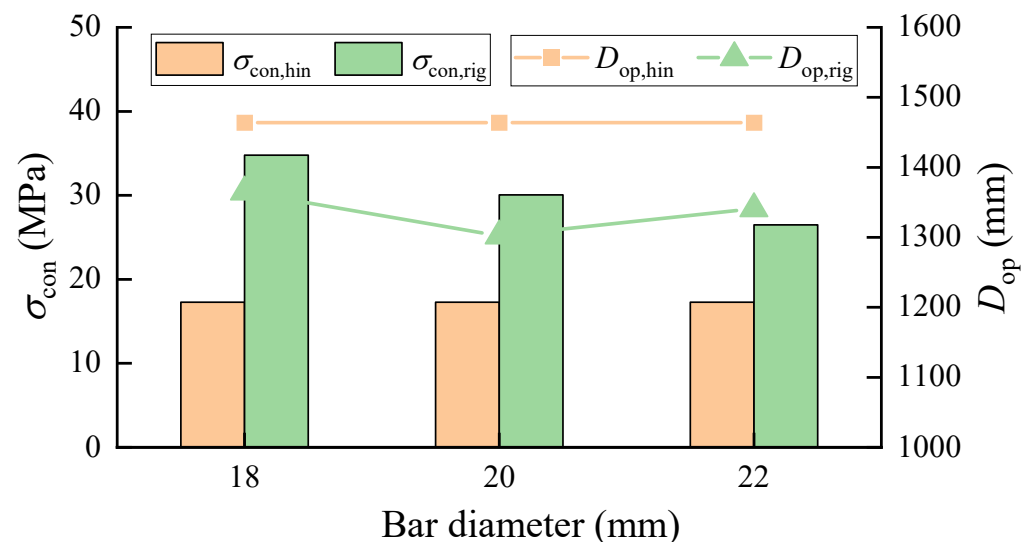


Figure 11. Optimization results of a cantilever scaffold with varying bar diameter.

5.3. Analytical Results with Varying Upper Suspension Point Positions

The upper suspension point of the diagonal bar is usually attached to the upper floor slab by a hinge. As the floor height varies, the position of the upper suspension point also changes. In this section, the effect of different upper suspension point positions on the optimal lower suspension point position was examined. The vertical distance between the upper suspension point of the diagonal bar and its connection with the end of the beam was considered at 3000 mm, 4500 mm, and 6000 mm. Figure 12 shows the variation in controlling stress with varying generations for different upper suspension point positions in both the hinged and rigid cases. The beam controlling stress starts to converge from the fourth generation when the beam is hinged but from the eighth generation when the beam is rigidly connected.

Figure 13 presents the optimization results of models with different upper suspension point positions. Here, the horizontal axis represents the different positions of the upper suspension point. When the beam is connected by a hinge, the beam controlling stress decreases slightly with an increasing upper suspension point because the beam is mainly subjected to axial force in this scenario. As the height of the upper suspension point increases, the horizontal component of the axial force of the diagonal bar decreases, thereby reducing the beam stress. Conversely, when the beam is rigidly connected, the beam controlling stress increases with increasing upper suspension point height. In this case, the beam acts as a beam-column member. The vertical component of the bar axial force increases as the upper suspension point increases, thereby increasing the internal force in the beam. Additionally, in the rigid connection case, the optimal lower suspension point position moves towards the free end of the beam as the upper suspension point becomes elevated.

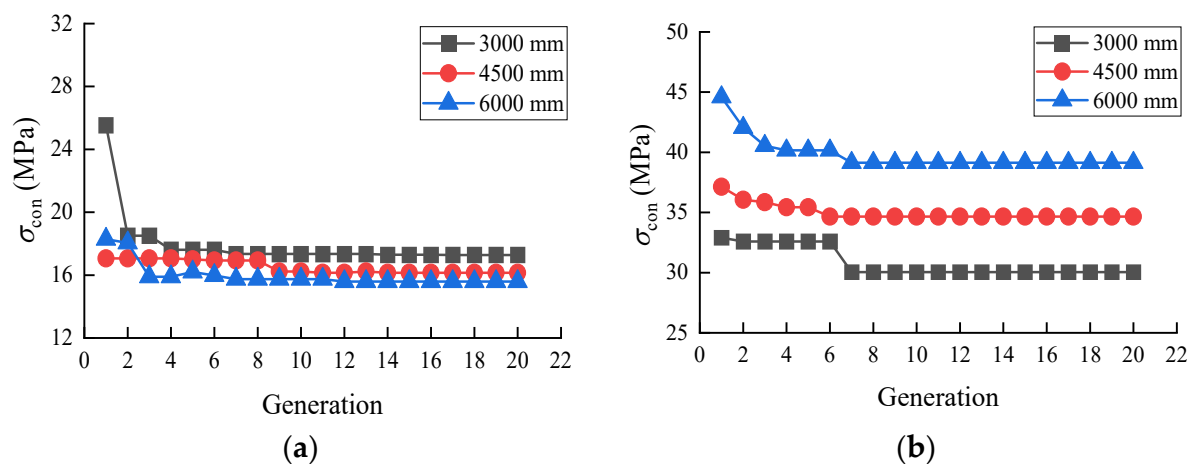


Figure 12. Optimization convergence processes with differ upper suspension point positions. (a) Hinged. (b) Rigid.

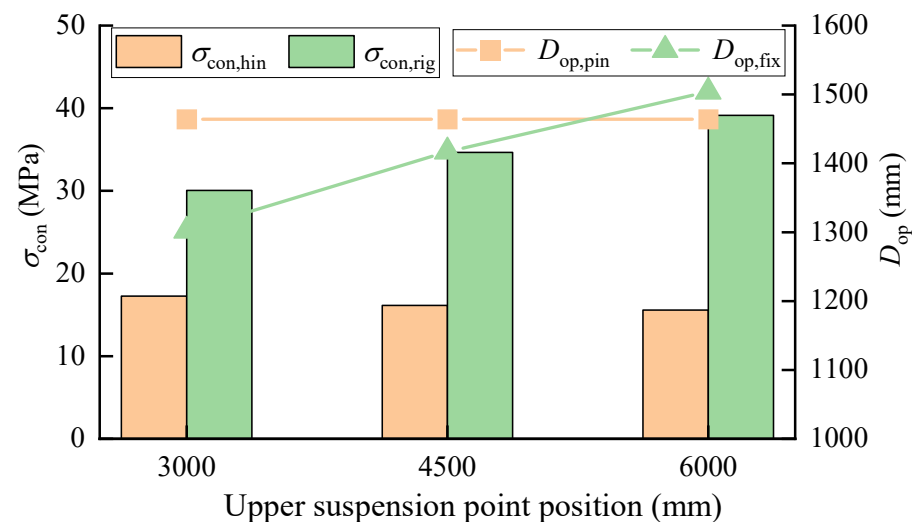


Figure 13. Optimization results of a cantilever scaffold with a varying upper suspension point position.

6. Optimization Result Evaluation

In Section 5, an optimization analysis was conducted to obtain the optimal lower suspension point position of an attached cantilever scaffold. This section aims to evaluate the optimization results by comparing the behavior of an optimized scaffold and one with the currently recommended specifications [30]. The difference between the optimized scaffold and the recommended specification is the lower suspension point position. For the recommended-specification scaffold, the lower suspension position is located at the end of the horizontal beam, i.e., D_s is 1800 mm (see Figure 2). However, the lower suspension position for the optimized scaffold is obtained by using the above optimal method. In addition, two concentrated loads (denoted by N_1 and N_2 in Figure 2) were applied to the scaffolds analyzed in this section, where the load positions were the same as those shown in Figure 2. The magnitude of the N_1 -to- N_2 ratio is 9:11.5 in this section.

6.1. Varying Beam Cross-Section

Figure 14 shows a comparison of the bearing capacities for optimized and recommended-specification scaffolds with different beam cross-sections. In Figure 14, the symbol $P_{0,hin}$ represents the bearing capacity of recommended-specification scaffolds when the beam is connected by a hinge and $P_{op,hin}$ denotes the bearing capacity of optimized scaffolds also when the beam is connected by a hinge. Similarly, the symbols $P_{0,rig}$ and $P_{op,rig}$, respectively,

represent the bearing capacities of the recommended-specification and optimized scaffolds when the beam is rigidly connected. Evidently, the bearing capacities keep increasing when the section dimension increases for all cases. Additionally, the bearing capacities were significantly enhanced when the scaffold type changed from the scaffold with currently recommended specifications to the optimized one. However, the degree of enhancement notably depends on the connection type. When the horizontal beam connection is hinged, the enhancement increases with increasing beam section dimension. In contrast, the enhancement decreases with increasing beam section dimension when the beam connection is rigid.

To illustrate why the capacity of the optimized scaffold is greater than that of a recommended-specification one, a stress nephogram of the horizontal beam corresponding to the instant when the material just enters plasticity is shown in Figure 15. The titles of all the sub-figures in Figure 15 are named with the following convention: “section dimension-scaffold type-connection type”. For example, the title “I14-specification-hinged” denotes that the section dimension of the horizontal beam is I14, the analyzed scaffold type is the one with the currently recommended specifications, and the connection with the horizontal beam is a hinge. As can be seen, the positions of the material yield were changed according to the lower suspension point position optimization. Thus, the bearing capacity of the optimized scaffold is always higher than that of the recommended-specification one.

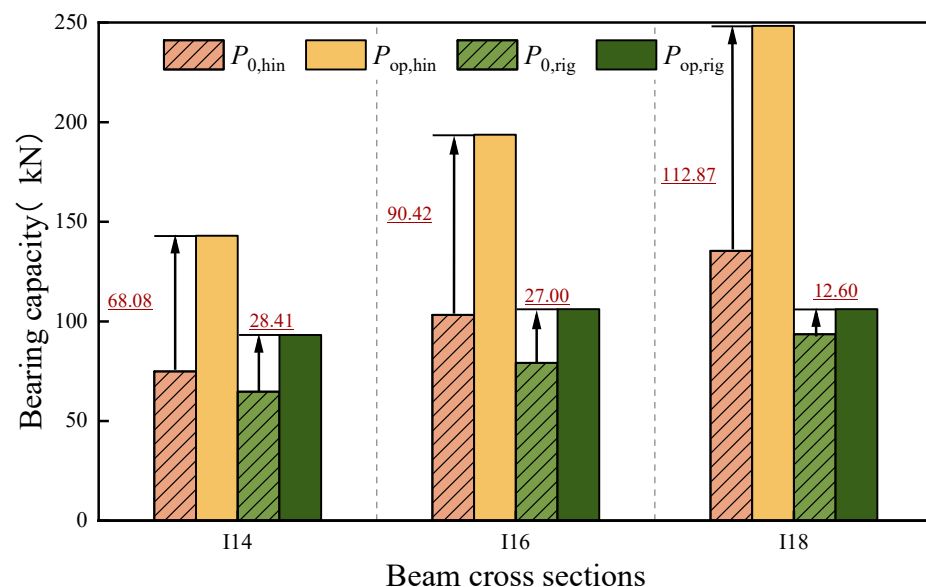


Figure 14. Bearing capacity of a cantilever scaffold with a varying beam cross-section.

6.2. Varying Bar Diameter

Figure 16 presents a comparison of the bearing capacities of the optimized and recommended-specification scaffolds with different bar diameters. As can be seen, lower suspension position optimization improves the bearing capacity for both the hinged and rigidly connected horizontal beams. However, this improvement effect is correlated with the beam connection type. For the hinged connection, the bearing capacity improved by around 90 kN when the bar diameter increased from 18 mm to 22 mm. However, this improvement changed from 16.20 kN to 36 kN for the rigid connection because the rigidly connected beam rotation can be effectively decreased by increasing the bar diameter.

6.3. Varying Upper Suspension Point Position

Figure 17 presents a comparison of the bearing capacities of the optimized and recommended-specification scaffolds with different upper suspension points. Evidently, in the hinged cases, changing the upper suspension point position has almost no effect on the bearing capacity. However, in the rigid cases, the bearing capacity decreases as the upper

suspension point is elevated because, with a rigid connection, lifting the upper suspension point increases the vertical component of the bar axial force. This results in a higher beam stress when subjected to the same load, thereby reducing the ultimate bearing capacity. Notably, the bearing capacity corresponding to the optimized scaffold is always higher than that of the recommended-specification one, especially for the hinged connection horizontal beam case.

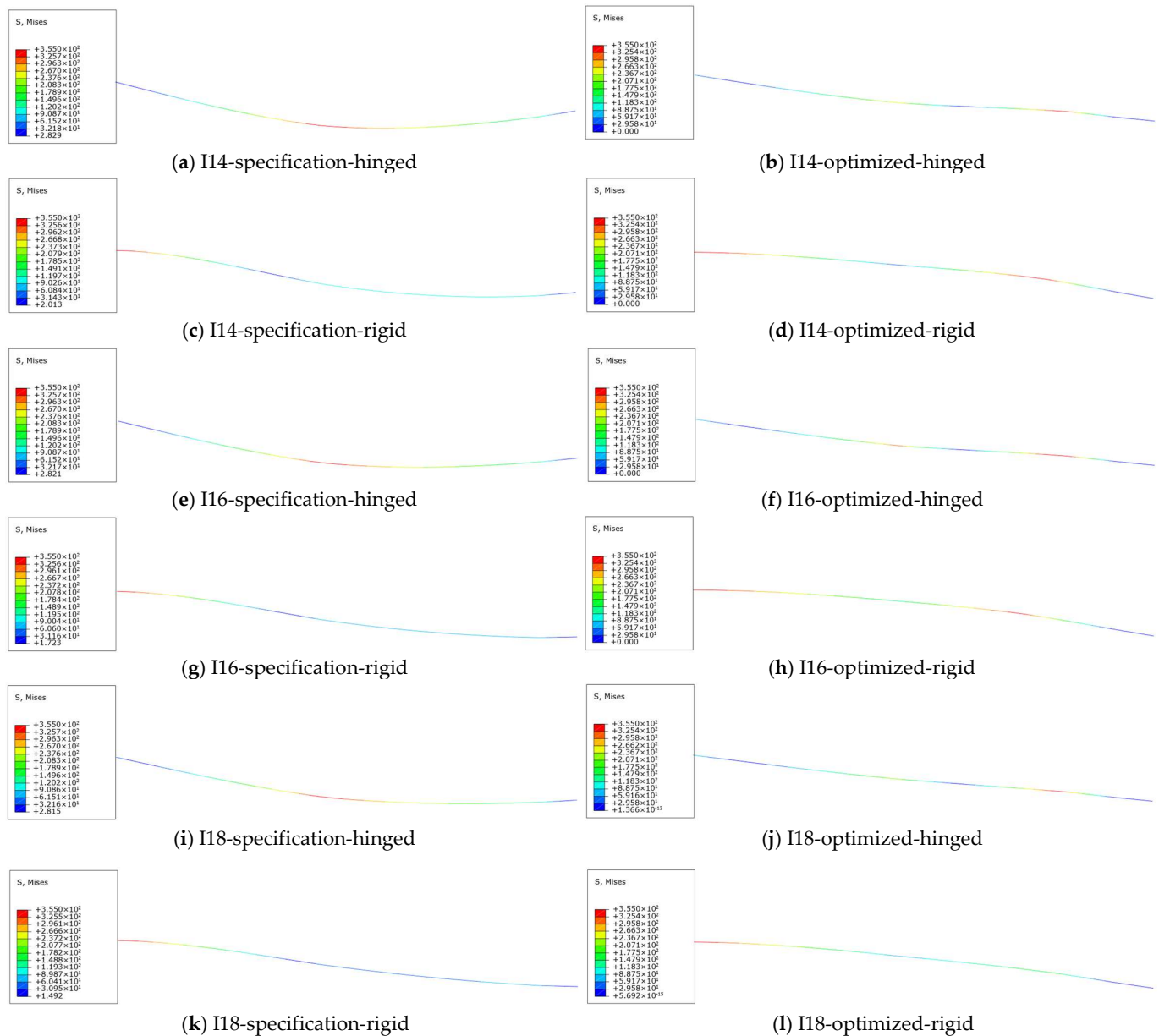


Figure 15. Stress contour plots of horizontal beam with varying beam cross-section.

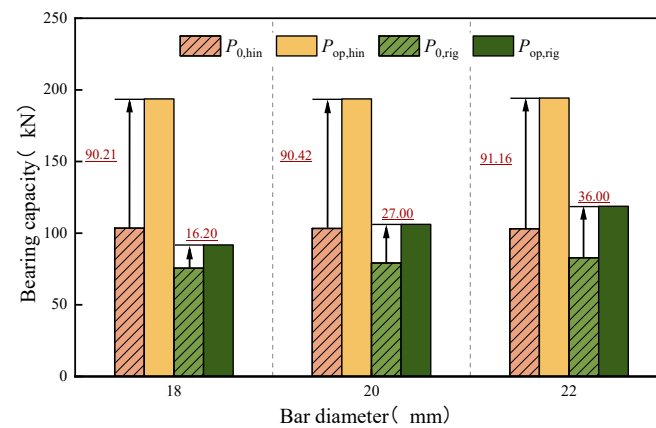


Figure 16. Bearing capacity of cantilever scaffolds with varying bar diameter.

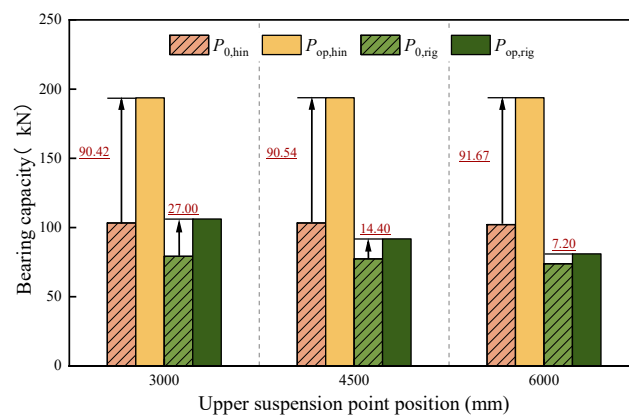


Figure 17. Bearing capacity of a cantilever scaffold with a varying upper suspension point position.

7. Conclusions

Based on the GA, an optimization method to determine the optimal lower suspension point position of attached cantilever scaffolds is proposed and, using this method, the behavior of attached cantilever scaffolds is examined. The effects of different structural parameters are also investigated. The following conclusions can be drawn:

1. The proposed optimization methodology is demonstrated to be an efficient and accurate way to obtain superior behavior for an attached cantilever scaffold. The convergence speed of the rigidly connected beam controlling stress is always slower than that of the beam connected by a hinge. In addition, the convergence speed could also be affected by the beam sections and upper suspension point position, especially for rigidly connected cantilever scaffolds.
2. According to a parametrical analysis of the proposed optimization methodology, the optimal lower suspension point position corresponding to the hinged cantilever scaffold cannot be affected by the beam section or bar diameter. However, for a rigidly attached cantilever scaffold, it is significantly affected by the beam section and bar diameter.
3. Compared to the specification-recommended attached cantilever scaffold, the bearing capacity of the optimized ones could be significantly enhanced. The enhancement is correlated to the attached cantilever scaffold connection types. When the attached cantilever scaffold is rigidly connected, the maximum bearing capacity enhancement could reach about 100%. In contrast, the maximum enhancement is about 40% for the case when the scaffold is connected by a hinge.
4. The controlling stress of the rigidly connected beam is always greater than that of the hinged connection beams. In other words, the bearing capacity of a hinged cantilever

scaffold is higher than that of a rigid one when the amount of consumed material is the same.

Note that theoretical and numerical analyses were primarily performed in this study. Therefore, an experimental investigation on the behavior of attached cantilever scaffolds is essential because construction imperfections may differ between experiments.

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