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## Application Study on Stress Optimization Design of Freeway PC Cast-in-situ Continuous Beam Bridge

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# Application Study on Stress Optimization Design of Freeway PC Cast-in-situ Continuous Beam Bridge

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**Abstract.** In the calculation of the superstructure of PC cast-in-place continuous beam bridge, the optimum degree of structural stress has a great influence on the performance of the structure. In this paper, the stress optimization process of the superstructure of PC cast-in-place continuous girder bridge is described in detail, and the parameter  $\theta$  of stress optimization index is put forward, and the validity of the parameter applied in engineering example is studied.

## 1. Introduction

Due to the advantages of reasonable distribution of internal force, small deformation, large stiffness and comfortable driving of PC cast-in-place continuous beam bridge, it occupies a large proportion in the design of expressway bridge. In the design of PC cast-in-place continuous beam bridge, the key problem is to calculate the internal force of the superstructure, especially the steel bundle arrangement and stress analysis. Whether the prestressing steel bundle is reasonable or not has great influence on the force and service performance of bridge structure. The same batch of prestressed structures has been tested for many years, some of them are intact, and some have been cracked or have other problems. In addition to the influence of external factors, the degree of optimization of structural stress regulation by the original designers has become the main internal factor affecting the performance of the structure. Therefore, in the design stage, it is particularly important to adjust the beam distribution and stress optimization of the superstructure of PC cast-in-place continuous girder bridge. The reasonable arrangement of prestressed steel bundles depends on the designer's rich design experience, repeatedly adjusting the beam shape and continuously carrying out the stress trial calculation. In order to quantitatively measure the degree of stress optimization, so as to play a guiding role in the selection of beam shape and stress test, the author will analyse the stress design of PC continuous beam bridge with equal cross-section below 50m span, which is widely used in expressway at present, and put forward the parameter  $\theta$ , which can be used to measure stress optimization index

## 2. Stress state analysis of PC continuous beam bridge superstructure design

The prestressed concrete structure can be divided into fully prestressed concrete structure and partially prestressed concrete structure [1] according to its stress state. In the stress design of the superstructure of PC cast-in-place beam bridge, it is usually designed as a fully prestressed concrete structure. However, for the continuous beam bridge with statically indeterminate structure, under the influence of the temperature and the settlement of foundation, the small tensile stress is easy to appear in some sections near the support. If the design of fully prestressed structure is blindly pursued, the prestressing tendons of the whole bridge will be deployed too much in order to eliminate the tensile stress at different points, and even the compressive stress reserve of some compression sections will



exceed the limit. Therefore, we can also allow small tensile stress of individual sections to be designed as partially prestressed concrete structures [2]. From the design experience, the allowable tensile stress in prestressed concrete beams should be controlled within 2MPa. The reason is that the standard value of axial tensile strength of C50 concrete is 2.65MPa [2], and the tensile stress does not exceed the standard value of tensile strength stipulated in the code, the concrete beam will not crack and can still meet the normal use of the structure. Secondly, the common steel bar in the structure can also bear part of the structural force. This is why we allow smaller tensile stresses to exist. Therefore, the conservative design controls the tensile stress within 2MPa.

In the Design Code of Highway reinforced concrete and Prestressed concrete Bridges and culverts, it is pointed out that the maximum compressive stress of normal section concrete of prestressed concrete members in use stage is less than 0.5 times of the standard value of axial compressive strength of concrete. For C50 grade PC cast-in-place continuous beam bridge, the standard value of axial compressive strength is 32.4MPa, so the compressive stress of concrete of each section should not exceed 16.2 MPa. In this way, the concrete will not be fractured.

Based on the analysis of the stress state of the superstructure of PC cast-in-situ continuous girder bridge, we can draw the following conclusion: For the design of the superstructure of PC continuous beam bridge marked C50 concrete, the stress of each section should be controlled between-2MPa~16.2MPa. According to the standard value of axial tensile strength and the standard value of axial compressive strength of the labelled concrete, the stress range of each section can be determined according to the standard value of axial tensile strength and the standard value of axial compressive strength of other graded concrete continuous girder bridges.

In the configuration of prestressed tendons in superstructure, the designers usually choose the basic beam type based on their own design experience, and try to calculate the stress values of the upper and lower edges of each section of the unit by the structural calculation program. In order to ensure that the stress values of each section of prestressed concrete structure meet the requirements, the spatial position of each section steel bundle is adjusted by comparing whether the stress of each section is in the range of-2MPa~16.2MPa stress. The beam adjusting process of the designer is actually the repeated adjustment of the space beam shape and position of the steel beam, as well as the repeated trial calculation process of the corresponding cross-section stress.

Generally speaking, the stress design value of the superstructure of PC continuous beam bridge is between-2MPa~16.2MPa, and the stress design of the structure meets the specifications. However, if the stress value of each section is close to the limit value-2MPa or 16.2MPa stress value, the more the stress weakness of the structure, the greater the probability of structural insecurity. If the stress state of the structure is beyond the design range due to accidental causes, these weak stress weaknesses will easily become the failure point of the structure. Therefore, if we want to reduce the probability of problems in the pre-stressed structure, the designer also needs to adjust the beam shape repeatedly to try out the stress to optimize the stress of the structure. The stress values of each section are kept away from the limit stress values-2MPa or 16.2MPa as far as possible, so that they are balanced in the middle region of-2MPa and 16.2MPa, and the stress weakness near the limit values is minimized as far as possible. This is the process of stress optimization. The following diagram shows that the stress values of each section of the ideal design state are normally distributed between-2Mpa~16.2Mpa.

In recent years, although the method of optimization theory has been gradually introduced into civil engineering, mechanical engineering, building engineering and other design fields, but in prestressed concrete structure stress optimization design plate has not been found on the basis of the code. The degree of stress optimization has not been clearly defined for the time being. Therefore, the optimal stress regulation of the superstructure of PC continuous girder bridge depends entirely on the design experience of the engineering designers.

### **3. The definition of Parameter $\theta$ for measuring stress Optimization Index**

In the process of optimizing the spatial position of the steel beam, the maximum tensile stress point and the maximum compressive stress point are corresponding to each movement of the steel beam

position. Of all the modulation states, a relative measure is needed for which beam type is better [3-5]. Based on the design experience of many years, the author thinks that the closer the maximum tensile stress point and the maximum compressive stress point are to the median mean value of the stress range -2MPa~16.2MPa (i.e.  $0.5 \times (16.2 - (-2)) = 7.1\text{MPa}$ ), the more balanced the stress distribution of the structure is. The closer the stress distribution of the upper and lower edges of each section of the structure is to the 7.1MPa curve, the better the selection of the beam shape will be.

The author puts forward the following concept: stress optimization index parameter  $\theta$ . Through this parameter, the degree of stress design of the prestressed structure can be clearly determined.

For prestressed structures with C<sub>50</sub> concrete, the reasonable stress range is -2MPa ~ (16.2MPa). The median mean is  $(0.5 \times (16.2 - (-2)) = 7.1\text{MPa})$ . It is assumed that the minimum value of stress and the maximum value of  $\sigma$  are the minimum and the maximum of the stress values of each section of the designed prestressed structure under various external forces. Then let  $\theta = 7.1 - \sigma_{\text{minimum}} / \sigma_{\text{maximum}} - 7.1$ , where  $\sigma_{\text{minimum}}$  is minimum,  $\sigma_{\text{maximum}}$  should meet the stress value interval requirements:  $-2\text{MPa} < \sigma_{\text{minimum}} < \sigma_{\text{maximum}} < 16.2\text{MPa}$ . Assuming that the optimal stress design state is that the stress values of all structures are very balanced and concentrated at 7.1MPa, that is,  $\sigma_{\text{minimum}} = \sigma_{\text{maximum}} = 7.1\text{MPa}$ , then  $\theta = 0$ ; Assuming that the worst stress design state, that is, the most disadvantageous point of structural stress, takes the extreme value, that is,  $\sigma_{\text{minimum}} = -2\text{MPa}$ ,  $\sigma_{\text{maximum}} = 16.2\text{MPa}$ ,  $\theta = 18.2$ . So the range of  $\theta$  is  $0 \sim 18.2$ . The smaller the  $\theta$  value, the more concentrated the stress value distribution is, the more reasonable the beam distribution is, and  $\theta$  can be called the parameter of stress optimization index, which can be regarded as the relative quantification standard of stress design optimization degree.

Each adjustment of the steel beam will correspond to the minimum  $\sigma$  and the maximum  $\sigma$  of each time. At the same time, the corresponding  $\theta$  can be calculated. By comparing  $\theta$  value and selecting the optimum stress design state, the optimal beam shape is determined.

#### 4. Effectiveness Analysis of stress Optimization Index Parameter $\theta$ in Design example

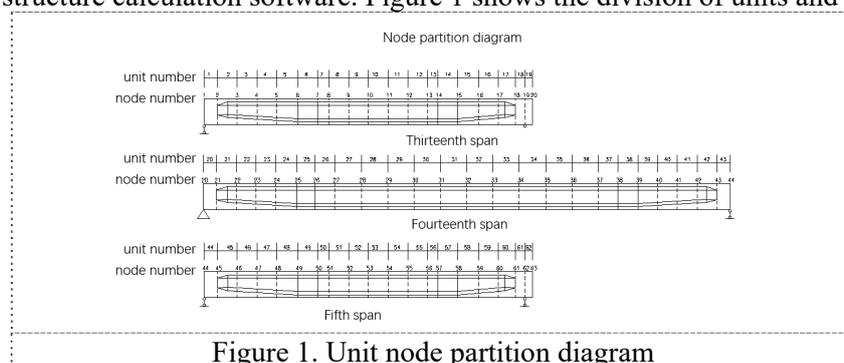
Taking the superstructure calculation of PC continuous beam bridge of an expressway as an example, the process of optimum design of structure stress by using stress optimization index parameter  $\theta$  in the design process is explained.

##### 4.1 Overview of bridge beam scheme

The main span of this bridge is 30 m 40 m 30 m PC continuous box girder, the bridge width is 16.75 m, the single box and double chamber section, the height of box girder is 2.0 m, the width of box beam is 16.75 m, the width of bottom plate is 12.0 m, the length of cantilever of flange plate is 2.375 m. The plane is located on the R2200m circular curve and the pier abutment is arranged in radial direction. The substructure consists of column platform and ribbed platform, column pier and pile foundation.

##### 4.2 Analysis and modeling of superstructure

In the analysis of superstructure, the bridge superstructure is discretized into 62 elements by using the general bridge structure calculation software. Figure 1 shows the division of units and nodes.



#### 4.3 Main technical standards and checking parameters

- Design load: automobile-super 20, trailer-120;
- Bearing settlement: 1.3 cm;

The remaining parameters are used according to the relevant specifications.

#### 4.4 Results of structural calculation and stress Optimization Design

The stress result diagram of the control section and the stress of the main node when the stress state of the control section reaches the stress range for the first time after many attempts to match the beam, as shown in Figure 2.

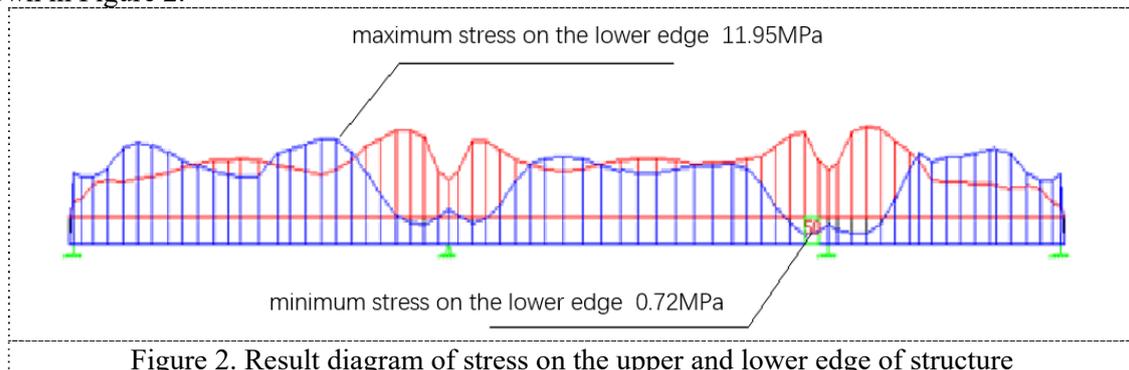


Figure 2. Result diagram of stress on the upper and lower edge of structure

According to the  $\theta$  concept of stress optimization parameter in this paper, the calculation of  $\theta$  value of the first structural design is as follows:

$$\theta_1 = |7.1 - 0.72| + |11.95 - 7.1| = 11.23$$

The most unfavorable section of the bridge is at the 16th node of unit 16 and the 41st node of unit 41. The maximum  $\sigma$  of stress is 11.95 MPa, the minimum  $\sigma$  of stress is 0.72 MPa, and  $-2 \text{ MPa} < \sigma_{\text{minimum}} < \sigma_{\text{maximum}} < 16.2 \text{ MPa}$  satisfies the range of stress values. The stress design is qualified.

If the results are not satisfactory enough, the beam shape of the structure can be debugged and the stress can be further optimized.

After many beam tests and stress tests, the final stress states determined by this bridge are as shown in Figure 3:

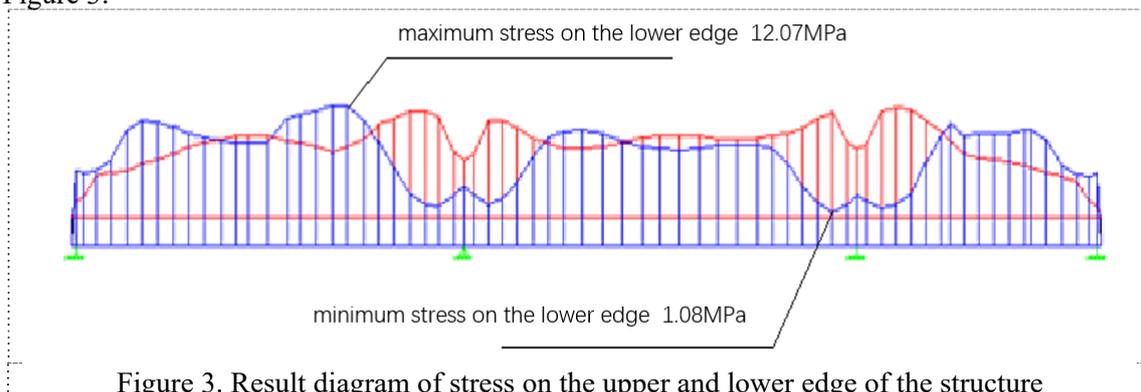


Figure 3. Result diagram of stress on the upper and lower edge of the structure

$$\theta_2 = |7.1 - 1.08| + |12.07 - 7.1| = 10.99$$

The maximum  $\sigma = 12.07 \text{ MPa}$  is at the 16th node in unit 16, and the minimum  $\sigma = 1.08 \text{ MPa}$  at the 41st node in unit 41.

It can be seen that  $\theta_2 (= 10.99) < \theta_1 (= 11.23)$ . Therefore, after the stress optimization design, the final stress state is better than the first design stress state. Therefore, the steel beam form corresponding to the stress state of  $\theta_2$  is the final result of this structural design.

The process of stress optimization is a multi-trial calculation process. When there is no parameter of stress optimization index as the relative quantitative measure of stress optimization degree, based on the designer's design experience and understanding of the stress state of the structure, the beam type can be regarded as a qualified structural design, such as the beam type corresponding to the  $\theta_i$

stress state, allowing it to reach the range of stress values specified in the code. Once we have the concept of stress optimization index parameter, as the criterion of stress optimization degree, the designer can select the optimal stress according to this standard in the adjustment of the stress state of the structure.

#### 4.5 Practical Test of stress Optimization

In the design of the superstructure of PC cast-in-place continuous girder bridge, the settlement of foundation will produce the secondary internal force in the upper beam structure, which must be taken into account in the design. The settlement value of foundation is generally chosen according to the maximum span of 1/3000, and the settlement value of continuous beam bridge with 40m span is 1.3 cm. When the dead load of the second stage of the bridge has not been loaded during the construction, the sudden and unexpected settlement of the large foundation at the two piers of 13#H14# has been observed. The settlement value has reached 10 cm, which is 7.7 times of the design value. The sinking state of the bridge appears, as shown in Figure 4.

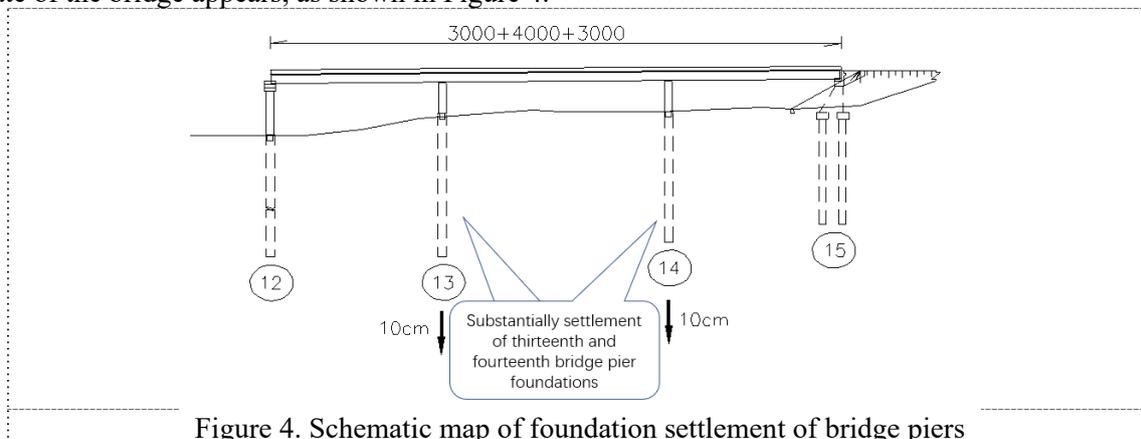


Figure 4. Schematic map of foundation settlement of bridge piers

The design unit carries on the stress analysis to the superstructure system in the state of the sinking bridge. The results are showed in Figure 5.

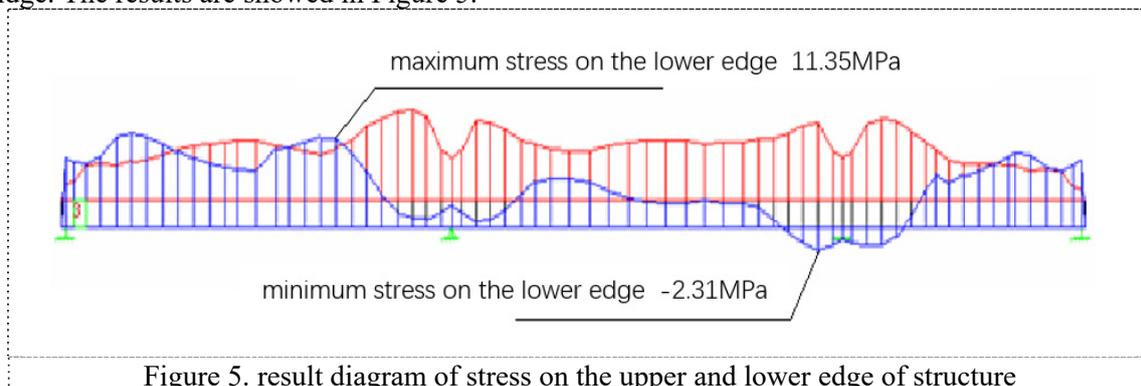
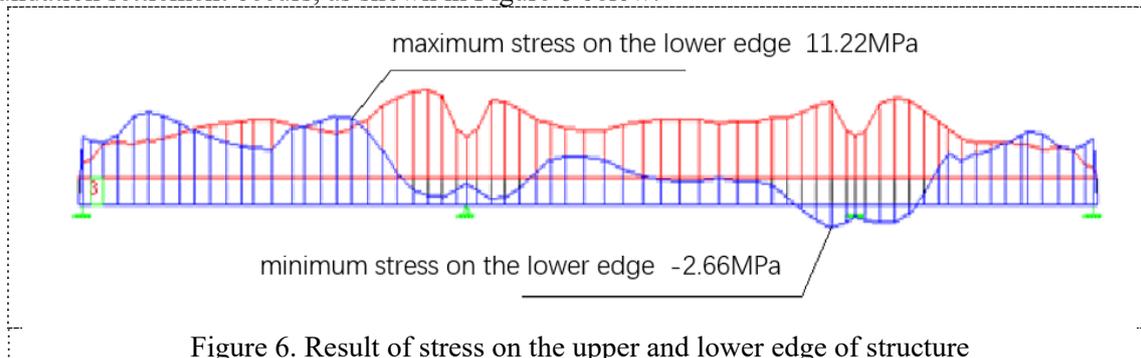


Figure 5. result diagram of stress on the upper and lower edge of structure

By comparison with Figure 3, we can see that the maximum  $\sigma = 12.07\text{MPa}$  (16-unit 16 node) and  $\sigma$  minimum =  $1.08\text{MPa}$  (41 element 41 node) in normal state are still the most disadvantageous points of the bridge in abnormal sinking state.  $\sigma$  maximum =  $11.35\text{MPa}$  (16 units 16 nodes),  $\sigma$  minimum =  $-2.31\text{MPa}$  (41 unit 41 nodes). It can be seen that the stress value of abnormal state caused by settlement is weakened as a whole. Due to the minimum  $\sigma = -2.31\text{MPa}$  of the lower edge of abnormal state structure, the cracking value of concrete- $2.65\text{MPa}$  (tensile ultimate strength of concrete) is not reached. Therefore, the superstructure in the state of sinking bridge has not been cracked, although it has already appeared tensile stress, and the external structure of beam body is still intact. The bridge can still be used in the original design state after the bridge reinforcement unit uplift maintenance to the original design state, thus the huge loss has been recovered for the whole project construction. At present, the construction of the bridge has been successfully completed and opened to traffic.

The superstructure stress optimization is successful in the design of the bridge. After stress optimization, the stress control of beam body is balanced and concentrated, there is no obvious stress weakness, and the stress reserve is sufficient. When the bridge pier settles suddenly and unintentionally, the stress in the beam decreases uniformly, although there is tensile stress, but it is not destroyed, it can still be used after maintenance.

If stress optimization is not carried out in the design of superstructure, if the stress state corresponding to  $\theta_1$  of the bridge is taken as the final design result, the stress state after the abnormal foundation settlement occurs, as shown in Figure 6 below.



It can be seen that  $\sigma$  minimum  $= -2.66\text{MPa}$ , exceeding the ultimate tensile strength of concrete  $-2.65\text{MPa}$ , the beam body must crack the superstructure failure. The loss caused by this result is incalculable, which further verifies the importance of stress optimization design.

Therefore, the author concludes as follows: when the design of superstructure of PC cast-in-place continuous girder bridge, when the stress design state reaches the range of stress value specified in the code, it is only defined as qualified design. At the same time, stress optimization index parameter  $\theta$  should be used as the index to evaluate the merits of stress optimization design, and the stress design should be reoptimized by adjusting the stress design of the structure. The most unfavourable stress point near the extreme value range of stress is eliminated as far as possible, and the probability that these weak points cause damage to the structure is reduced. Finally, a better stress optimization scheme is selected as the final result of the design.

## 5. The Prospect of stress Optimization Design

The author has consulted a lot of literature, and the theory and research on stress optimization design are few, so stress optimization design has a very broad development prospect. The parameter  $\theta$ , which measures the degree of stress optimization, also needs to be improved. At present, the beam adjusting process of the superstructure of PC cast-in-place continuous beam bridge by designers is an attempt process to calculate the structural stress continuously. According to the concept of stress optimization index parameter  $\theta$ , the designer can select the stress state with relatively small  $\theta$  value as the optimal state of the structural design. But the artificial trial calculation process must be finite. If we give the concept of stress optimization index parameter  $\theta$  to the structure calculation program, as the condition of judging the stress state, So we can use the computer technology to adjust the beam shape infinitely and try to calculate the stress value, so as to be as close as possible to our ideal optimal beam shape optimal stress state, and at the same time, we can also provide some ideas for the intelligent structure design program. It also reduces the workload of engineering designers to adjust the stress.

## 6. Conclusion

In the design of PC cast-in-place continuous beam bridge, the stress balance of superstructure is the key point of design. In this paper, the stress design state of PC cast-in-place continuous beam bridge is analysed in detail, and the concept of parameter  $\theta$ , which can measure the degree of stress optimization, is put forward, and the process of stress optimization design is expounded with a design example and the function of stress optimization is verified. For prestressed concrete cast-in-place

structure, stress optimization design can play an important role either in improving the service life of the structure or in enhancing the adaptability of the structure in the case of accidental occurrence.

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