Research Article

Numerical Analysis of the Structural Properties of Girdling Beam for a Square Column Used in Bridge Jacking Construction

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Abstract

As a key connecting structure of jacking construction, the load capacity of the girdling beam determines the safety of the jacking construction of bridges. The square cross-sectional column was held by the action of the girdling beam for jacking construction of the bridge and was studied with nonlinear analysis of its structural properties at different girdling heights, with different construction modes including integral cast and two-stage cast. The results, including the interface stress and internal stress, column, and girdling beam deformation and destruction features, were presented. The mechanical characteristics of girdling beam for the square column were summarized with the spatial strut-and-tie model. It has been proven that the slip failure mode of girdling beams is a kind of brittle failure that must have enough load resistance to ensure the safety of jacking construction.

1. Introduction

As a new bridge reconstruction technology, bridge jacking technology is increasingly applied in bridge reinforcement reconstruction engineering [1, 2]. The bridge jacking system consists of a jack system, jacking limit system, temporary jacking support system, jacking reaction system, and jacking monitoring system. The jacking reaction system refers to the structural system used to provide a support reaction for the jacking force application system, which is composed of the jacking chassis structural subsystem and the jacking tray structural subsystem (Figure 1). The jacking chassis structural subsystem is composed of pier and bottom girdling beam, and the jacking tray structural subsystem is composed of pier and top girdling beam. Common jacking reaction systems include bearing platforms, cap beams, steel brackets, vertical and horizontal connection beams, and girdling beams [3, 4]. The jacking chassis structural system refers to the structural system used to bear the load of bridge jacking and transfer the load to the foundation in jacking construction. The jacking tray structural system refers to the structural system used to support the upper jacking structure and lift up with it. Both the chassis system and the tray system can adopt the structural form of a girdling beam [5–9]. The girdling beam is widely used as a jacking reaction system in bridge and building construction because of its advantages of a simple structure system, flexible arrangement, and good applicability due to its insensitivity to bridge structures.

The girdling beam is a common form of jacking support system, it is also an important component as the role of force system conversion in the process of jacking, the stress condition of the girder under load is very complex, and its structure safety is directly related to the safety of the whole bridge jacking process [10–12]. At present, there are a few studies on the structural performance of girdling beams, and the solutions to some problems are only based on experience or refer to other related projects [13]. Therefore, it is necessary to study the structural performance of the girdling beam.

In this paper, numerical methods were used to study the mechanical properties of reinforced concrete girdling beams with different heights under load when columns are supported [14, 15]. The mechanical properties and failure
mechanism of the beam-column interface in the case of the contact interface between the girdling beam and column are studied. Thus, the stress characteristics, crack development, and failure mode of the common square column are obtained, which can provide a reference for the design of subsequent experimental research and for bridge jacking construction projects.

2. Numerical Model of the Girdling Beam Structure

This paper refers to the structure of the girdling beam in an actual jacking project [12]. The girdling beam is 1150 mm long and 850 mm wide (see Figure 2). The size and reinforcement are designed by the construction side based on experience and specification. According to the jacking specifications [4], girdling beam models of different section sizes were selected, and the flexural reinforcement design of deep beam members was carried out according to the maximum load of the column. The reinforcement design was based on the Technical Specifications for Bridge Jacking and Displacement [4], and the section size was constantly adjusted according to the requirements in the reinforcement design. Finally, the types of girdling beam models with reasonable bearing loads are designed. Because the interface parameters cannot be accurately determined for the gouging interface of the column, the effect of interface treatment on the mechanical properties of the interface cannot be effectively simulated. Since the calculation without gouging treatment is the most unfavorable case, the finite element simulation analysis of the model specimen on this contact interface with a two-stage cast model and the integral cast model specimen is carried out (see Table 1).

In this paper, the finite element solid model is used for nonlinear static analysis with Midas FEA software, which was developed for civil engineering structures. Using its powerful nonlinear function to carry out detailed analysis of the girdling beam joint, the stress, crack, deformation, and failure characteristics of girdling beam structures will be discussed.

2.1. Definition of Element Attributes. Concrete is simulated by a three-dimensional solid six-hedral element. The reinforcement element in FEA is not the element with nodes, but the reinforcement stiffness is directly added to the parent element of concrete, and there is no slip between the reinforcement and the parent element. The strain is also obtained by calculating the displacement of the parent element. The interface element in FEA is developed to simulate the contact between concave and convex surfaces of the same material or the contact between heterogeneous materials. In FEA software, there are four options to create interface, including “from element boundary,” “manual node ID input,” “convert element,” and “connect closest nodes.” Here, the option “from element boundary” was selected. Theoretical information can be obtained through the FEA software manual. It is mainly used to describe the uneven discrete cracks of concrete, the slip between steel and concrete, the contact between steel and concrete, or the contact surface of masonry structures. In this paper, a low-order quadrilateral interface element is adopted, which is composed of coordinate axes on the boundary plane and
### Table 1: Classification and dimensions of the model specimens.

| Group number | Specimens number | Height (mm) | Width (mm) | Length (mm) | Model type  |
|--------------|------------------|-------------|------------|-------------|-------------|
| 1            | 1-1              | 200         | 850        | 1150        | Two-stage   |
|              | 1-2              | 200         | 850        | 1150        | Integral    |
| 2            | 2-1              | 300         | 850        | 1150        | Two-stage   |
|              | 2-2              | 300         | 850        | 1150        | Integral    |
| 3            | 3-1              | 400         | 850        | 1150        | Two-stage   |
|              | 3-2              | 400         | 850        | 1150        | Integral    |
| 4            | 4-1              | 600         | 850        | 1150        | Two-stage   |
|              | 4-2              | 600         | 850        | 1150        | Integral    |

### 2.2. Material Properties

#### 2.2.1. Material Properties of the Concrete Element.

In combination with the concrete material characteristics selected in the test model of background engineering, the standard material JTG04 (RC) [16] C30 is selected. The specified elastic modulus is $3 \times (10^3 N/mm^2)$, the weight density is $2.5 \times (10^{-2} N/mm^3)$, Poisson’s ratio is 0.2, and the thermal expansion coefficient is $1 \times 10^{-5}$.

When concrete material enters the plastic stage, the model type selected is the total strain crack model. The Thorenhoff hardening model provided by the software is adopted for the compression model. The compressive strengths of the concrete column and the girdling beam are 28.5 MPa and 31.7 MPa, respectively, according to a real engineering project [11, 12]. The tensile model adopts the ideal failure model, and the input parameter is the 2.01 MPa tensile strength of concrete.

#### 2.2.2. Material Properties of Reinforcement Elements.

The reinforcement used in the model is HRB335 grade steel bars, whose elastic modulus is $2.0 \times (10^5 N/mm^2)$, weight density is $7.698 \times (10^{-2} N/mm^3)$, Poisson’s ratio is 0.3, and thermal expansion coefficient is $1.2 \times 10^{-5}$. The Van-Messeth model is used for the rebar, and the initial yield stress is 280 MPa. The hardening/softening function and temperature-dependent hardening/softening function are not considered.

#### 2.2.3. Attributes of Interface Elements.

In FEA, interface element attributes can be defined. To simulate the contact surfaces affected by friction between different materials or the same materials, the Coulomb friction model is selected in the program. The values were selected according to reference [17, 18] as follows: initial roughness $k_u = 3 \times (10^2 N/mm^2)$ and $k_i = 3 \times (10^3 N/mm^3)$, cohesion $c = (0.9 N/mm)^2$, angle of internal friction $\phi = 33^\circ$, “tension truncation” is selected without considering the effect of expansion angle, and the tensile strength is 0.9 MPa.

### 2.3. Finite Element Model Establishment

#### 2.3.1. Division of Elements Grid.

Due to the bidirectional symmetry of the test specimen, to reduce the computation time, and improve the calculation efficiency, only a 1/4 model is established in the finite element simulation. When dividing the grid, the size of the hexahedral element grid is 25 mm, and the size of the reinforcement element is 50 mm (Figure 3).

#### 2.3.2. Definition of Interface Elements.

It is an important work of finite element model analysis to establish the interface element on the beam-column contact interface and simulate the force and deformation of the interface. Only after the concrete elements of the column and the girdling beam are divided can the interface element of the beam-column joint be defined. The method in the software of “according to the element boundary” is adopted to establish the interface element, and the corresponding attributes are given to it. In addition to the beam-column interface, the interface element is also established at the contact surface between the steel bearing plate and the bottom of the girdling beam to accurately simulate the force situation near the bearing (see Figure 3).

### 3. Result Analysis

#### 3.1. Deformation of the Square Column.

After reading the node’s results at the center of the column bottom, the displacement curve of the column varies with the height of the girdling beam, as shown in Figure 4. For the model with a low girdling beam height, the column displacement curve can be divided into two stages. In the first stage, the load-displacement curve is linear, and the displacement increases linearly with increasing load. Second, in the nonlinear displacement stage, the slope of the curve continues to increase; that is, with increasing load, the displacement increases faster and faster and is then suddenly destroyed. However, for the model with a high girdling beam height, the column curve basically has only one linear stage, and then, failure directly occurs.

The linear and nonlinear stages of the integral cast model specimen are much larger than those of the two-stage cast model specimen because the integral cast model has the best beam-column interface bonding performance. In fact, there
are no interfaces, so the cracking load and failure load are larger, and the fracture process has a relatively large ductility. While the linear stage of the two-stage cast model is relatively small and the nonlinear stage after cracking is very short, the ductility is very weak, and the failure process is very rapid. Because the shape and size of the square column beam model are the same as those of the integral cast model, the curve of its linear stage is similar to that of the integral cast model, but the cracking load of its interface is relatively low, and the nonlinear sliding failure process after cracking is very quick.

3.2. Deformation of the Girdling Beam. Taking the first group of model specimens as examples, Figures 5 and 6 show the stress and deformation of the girdling beam when it bears the load transmitted from the top of the column. Other model’s results are similar. In terms of the deformation in the X and Y directions, the top part of the beam compresses toward the column, while the bottom part expands to the outside, showing a deformation form of “squeezing at top and swelling at bottom.” In the Z direction (the height direction), except for the upward warping of the concrete at the outer corners of the four supports, the rest of the girdling beam deforms downward, and from the center to the outside, the vertical displacement gradually decreases, and the vertical displacement of the beam near the column is the largest. The column above the top surface of the girdling beam has vertical downward displacement and no other deformation. In addition to the downward slip displacement, the upper part of the column wrapped by the girdling beam deforms horizontally due to the extrusion of the girdling beam.

Before the sliding failure of the beam-column interface, the girdling beam at the bottom of the interface is separated from the column due to the effect of the “squeezing at top and swelling at bottom” of the girdling beam model. However, there is no separation phenomenon at the beam-column interface of the integral cast model under similar load coefficients (Figure 5). The maximum vertical deformation of the girdling beam occurs at the joint near the column on the top of the long-side span. The stress and deformation of the other groups were similar to those of the group.

By comparing the mid-span vertical displacement of each model, it can be found that for the same model, the mid-span vertical displacement of the long-side beam is larger than that of the short-side beam as a common beam member’s behaviors. Before the slip failure of the beam-column interface, the vertical displacement of the square column beam is basically the same as that of the integral cast beam under the same load (Figure 6). With increasing beam height, the vertical displacement of the mid-span gradually changes, and the deformation of the beam gradually becomes less obvious.

3.3. Stress Distribution at the Beam-Column Interface

3.3.1. Distribution of Interface Stress. During the loading process, the interface normal stress changes as follows: at the beginning of loading, the lower part of the interface is pulled,
while the upper part is compressed, and the normal stress line at each vertical point of the interface is approximately in a straight line form. As the load continues to increase, the tensile stress or compressive stress at each point increases linearly.

When the maximum tensile stress at the bottom of the interface reaches the limit tensile stress, the interface cracks, and with the increase in load and crack position gradually moves up, causing the position of the neutral axis deviation interface height center to move up. At the same time, the upper interface of the compressive stress exhibits a nonlinear increasing trend, and the nonlinear growth trend of compressive stress will be more obvious with the height (see Figure 7).

The above normal stress distribution diagram (Figure 7) shows that under the same load and at the same position, the normal stress level at the interface of the short-side beam is greater than that at the interface of the long-side beam. In addition, the stress at the same height of the interface is different.

The tensile stress decreases gradually at the bottom of the interface from the center of the interface to the angle of the square column. At the top of the interface, from the center of the interface to the column angle, the interface compressive stress increases gradually. The transverse growth trend of the compressive stress at the upper edge of the interface increases with increasing load. The transverse decreasing trend of the tensile stress at the lower edge of the interface before cracking at the bottom interface also increases with increasing load, but the decreasing trend is not as obvious as the increasing trend of the compressive stress at the upper edge. The maximum tensile stress point in the beam-column interface normal stress of the square-column model is located at the center of the bottom of the interface of the short-side beam, and the maximum compressive stress point is located at the corner of the top of the interface of the short-side beam.

3.3.2. Distribution of Shear Stress at the Interface. Figure 8 is the diagram of the shear stress at the column interface of the girdling beam models (3-1 and 4-1).

It can be found from the stress diagram that for the girdling beam for the square column, the maximum principal tensile stress appears at the edge of the short-span beam interface of the center of the bottom edge, and the maximum principal compressive stress and maximum shear stress appear on the interface at the top edge of the column corner position and decrease from the angle to the column on both sides of the interface.

It can be seen from the principal tensile stress of each model that the transverse distribution of the principal tensile stress at the interface of the square-column model is similar to that of the normal stress at the interface and decreases gradually from the center of the interface to the corner of the column. In addition, the relative position of the maximum principal tensile stress at the bottom of the interface gradually decreases with increasing height of the girdling beam. This is because the relative crack height at the bottom of the interface gradually decreases with increasing beam height before the phenomenon of slip failure appears in the model.
3.4. Concrete Stress of the Girdled Beam. In the support system, the load-bearing surface of the girdling beam does not rely on the top part surface, and this is different from the general reinforced concrete beam. There is the bond friction between the side surface of the girdling beam and the column surface to bear the shear, which is equivalent to the vertical shear force applied to the inner side of the girdling beam. Therefore, in the analysis of the girdling beam, except for the general longitudinal flexural shear action, the difference between the inner and outer forces caused by the partial load should be considered.

3.4.1. Longitudinal Distribution of the Normal Stress of the Girdling Beam. For the model specimen of the same height, the trend of the normal stress at the top and bottom of the mid-span section changing with the load is shown in Figure 9 (the first group models). When the load is small, at the top of the beam cross section of all girdling beams, there is compressive stress, while at the bottom, there is tensile stress, and the stress linearly increase with increasing load. When the tensile stress at the bottom of the beam reaches the limit tensile stress of concrete, the concrete cracked, in accordance with the procedures set
the tensile constitutive model of concrete, the concrete tensile stress no longer increases, and the tensile stress does not change. When the load value exceeds a certain value, the compressive stress at the top begins to show a nonlinear growth trend. The load value with inflection point significance can be found by comparing the curves of each model in the figure. For the same height of the girdling beam model, under the same load level, whether in the linear growth stage or in the nonlinear growth stage, the top and bottom stresses of the long-side beam are greater than those of the short-side beam.

Under the same load level, with the increase in the height of the model specimen, the compressive stress at the top of the mid-span section and the tensile stress at the bottom of the girdling beam decrease continuously. When the tensile stress at the bottom of the mid-span section reaches the ultimate tensile stress of concrete, the load level increases with the increase in the height of the specimen. Similarly, the compressive stress increases with increasing height of the model specimen when the top compressive stress exhibits nonlinear growth. In addition, under the maximum load, the value of compressive stress at the top of the mid-span section decreases obviously with increasing model specimen height.

3.4.2. Transverse Distribution of the Normal Stress of the Girdling Beam. When the structure is loaded, the vertical load on the top of the column is transferred to the girdling beam through the interface adhesion force and friction force. For the girdling beam, the vertical shear force is applied on the inner surface of the beam, which inevitably causes an uneven stress distribution on the inner and outer sides. The normal stress at the upper and lower edges of the mid-span section of the long- and short-side beams is analyzed in the following ways, as well as the change in the normal stress in the process of load increase.

The analysis of the first group of models shows that the main tensile stress of the girdling beam reaches the ultimate tensile stress in the maximum area, and the crack area of the beam is the largest. The corresponding maximum principal compressive stress on the top surface of the beam also decreases in this order. The distribution forms of the principal stress of the beam body of the model specimen are consistent with the development of load, but the main stress distribution of the beam in the figure is at different statuses due to the different loads that were applied to the girdling beam.

By comparing the main tensile stress diagrams of all models at their respective maximum load coefficients, it can be found that the distribution forms and variation rules of the main tensile stress on the bottom surface are consistent, but there are some differences on the side and the top surface.

With the increase in the height of the girdling beam, the distribution of the principal tensile stress on the side changes, and the angle of the main compressive stress increases continuously; that is, similar to the shear-span ratio, it decreases and finally almost reaches a right angle and is connected with the principal tensile stress trace at the support, forming two peak shapes on both sides of the mid-span section. When the model is close to failure, the cracks are concentrated in the “peak” and extend up to the top of the beam. In addition, with increasing beam height, the principal tensile stress concentration on the top surface region corresponding to the support center will gradually disappear.
3.5. Stress of Reinforcement of the Girdling Beam

3.5.1. Longitudinal Stress Distribution. When the girdling beam is supported for the top load to be underpinned, the stress distribution of the reinforcement in the beam is that the longitudinal reinforcement at the bottom of the beam bears greater tensile stress, while the longitudinal reinforcement at the top (i.e., the horizontal reinforcement at the top) bears greater compressive stress, and the stress value in the middle of the span is greater than that on both sides. The longitudinal variation trend of the bottom longitudinal reinforcement stress is that it decreases gradually from the maximum of the mid-span section to both sides, and when it reaches the edge of the column, the tensile stress decreases to zero. Continuing to develop on both sides, the longitudinal bar stress becomes compressive stress and gradually increases to the inner edge of the support when the compressive stress reaches the maximum, and then, the compressive stress gradually decreases. To the center of the support, the compressive stress decreases to zero. Then, it develops continuously to both sides, and the reinforcement stress is restored to tensile stress and begins to gradually increase, reaching the edge of the support when the tensile stress reaches the maximum. Then, the tensile stress gradually decreases until the beam ends on both sides, and the reinforcement stress is restored to zero.

In addition, by comparing the stress distribution patterns of transverse longitudinal bars at the bottom, it can be found that the distribution length of the larger tensile stress near the column is longer than that far from the column. Similarly, for the longitudinal reinforcement at the top of the girdling beam, the longitudinal variation trend of stress is relatively simple; that is, the maximum compressive stress of the mid-span section gradually decreases to both sides, and the compressive stress decreases to zero at approximately the center of the support.

Figure 10 and 11 show the stress-load curves of the longitudinal bars at the top and bottom edges of the girdling beam at middle span, respectively, for the integral cast model and the other phased cast models. It can be seen from the figures that the stress of the integral cast model shows a certain nonlinear linear increase, while that of the phased models shows an almost linear increase. Under the same load stage, with the increase in the beam height, the reinforcement stress of the interior at the top and bottom edges of the beam decreases gradually. Before the cracking of the concrete at the bottom of the beam, with the increase in the load, the reinforcement stress at the top and bottom edge increases in a linear form. After the cracking of the bottom concrete, the section stiffness is reduced, and the deformation of the beam body is accelerated due to the decrease in the section height so that the reinforcement stress at the top and bottom increases with the increase in the load in a nonlinear trend. In addition, the reinforcement stress of each model did not yield under the maximum load factor. This shows that the reinforcement has a large load capacity, and the load capacity of the girdling beam has not been fully utilized.

3.5.2. Transverse Stress Distribution. At the bottom of the short edge of the girdling beam, the lateral longitudinal reinforcement tensile stress is greater than the medial stress, known from the analysis of the previous, because when the model carries load, the long-side direction deformation is greater than the short edge direction. On the short edge beam interface, the normal stress is greater than that on the long-side edge when the first short edge beam cracks, and the upper interface of the short beam lateral extrusion effect is greater than that of the long beam.

This is equivalent to applying an outward horizontal force on the inner side of the short-side beam, and the resultant force of the horizontal force and the friction on the inner side of the short-side beam points diagonally downward. From the direction of the resultant force, the position of the bottom lateral longitudinal reinforcement is “lower” than that of the inside longitudinal reinforcement, so the tensile stress of the bottom lateral longitudinal reinforcement of the short-side beam is greater than that of the inside.

In addition, for the top longitudinal reinforcement of all models, the compressive stress of the lateral longitudinal reinforcement of the long-side beam is greater than that of the inner one, while that of the short-side beam is the opposite. By comparing the difference in tensile stress between the inner and outer longitudinal reinforcements, it can be found that the difference in tensile stress between the inner and outer longitudinal reinforcements of the long-side beam is not as obvious as that of the short-side beam.

3.6. Crack and Failure Mode. Because the bond of concrete at the beam-column interface is obviously lower than the tensile strength of concrete, the bonding interface is the weak layer of the model structure and easily cracks. It can be seen that the first crack occurs at the column angle, and then, the cracks extend from the column angle to the interface center at the long and short sides of the square to run through the whole interface laterally. At the same time, the cracks on the interface will also extend vertically upward with increasing load.

In the square column, the crack development is not obvious. Even under the ultimate load, the crack distribution range is very small, and the cracking stress has not been reached in most areas of the girdling beam. This shows that the failure mode of the square column model is a simple slip failure at the interface between the girdling beam and column, and the girdling beam and column are not obviously cracked.

By analyzing the crack distribution and development of all models, it can be found that for the same group of models, the crack distribution range of the integral cast model is larger. The crack development rule is basically the same as the increase in load, but the crack development of each model is different; that is, under the same load, with the increase in the height of the model specimen, the crack distribution range and extension height in the model decrease successively.
3.7. Summary of Mechanical Characteristics. When the structure is under load, the upper part of the interface is compressed, and the lower part is pulled. The closer it is to the top surface, the greater the compressive stress is. When the axial pressure is small, the vertical distribution of the compressive stress at the interface is an inverted triangle. The position of the neutral axis moves up gradually with increasing load. For the square column, the transverse distribution of compressive stress in the interface of the even load is small and increases with the load, and the large stress position moves from the interface center to the column angular. Therefore, near the column, the angular position of the compressive stress is gradually greater than that of the interface center. The distribution of the interface compressive stress and strain is shown in Figure 12.

Based on the above results, including deformation, stress, failure mode, and cracking behavior, the mechanical characteristics of the girdling beam with a column show a typical spatial strut-and-tie model. In other words, the shear resistance of the interface is mainly provided by the bonding and friction of the upper contact surface, and the axial pressure on the top of the column is transmitted by the oblique concrete pressure bar between the support and the interface. At the same time, the concrete at the bottom of the
girdling beam cracks, and the cracking range expands with increasing load, so it can be assumed that the concrete in the tension zone exits the work, and the longitudinal tension of the bottom of the columned beam is borne by the reinforcement. The inclined angle of the compressive member depends on the girdling beam height and reinforcements in the two directions of the girdling beam with different layouts. The application of the model needs to be verified by more tests because it involves the force on the beam-column contact surface for the member connection. The spatial strut-and-tie model is shown in Figure 13.

4. Conclusion

(1) In the failure process of the girdling beam, the column displacement curve can be divided into three stages, namely, the linear stage, nonlinear displacement stage, and failure stage. The linear and nonlinear stages of the integral cast model are larger than those of the two-stage cast model, which proves that the interface of the girdling beam will reduce the cracking load and failure load, and the ductility of the two-stage cast model is obviously reduced for the column sliding out.

(2) For the same group model, the mid-span vertical displacement of the long-side beam is larger than that of the short-side beam. The slip failure at the beam-column interface is mainly characterized by vertical displacement and bending deformation at the long side. With the increase in the beam height, the vertical displacement of the mid-span decreases while the bearing capacity increases, and the deformation of the beam decreases.

(3) Before the sliding failure of the beam-column interface, the stage cast model shows the effect of “squeezing at the top and swelling at the bottom” of the girdling beam. The lower part of the interface is separated from the column under the girdling beam, but the upper part is extruded with the column, which delays the interface slip failure to a certain extent.

(4) As the column support system in the girdling beam structure, the force-bearing behavior is not like ordinary reinforced concrete beam under the bending load, because it is bonded at the inside surface with column, and the surface friction overcomes the shear, equivalent to embracing the surface of the column to overcome the vertical shear, so the
girdling beam stress analysis in addition to considering the general longitudinal bending moment, the difference between the inner and outer forces caused by eccentric load should also be considered.

(5) For the girdling beam with a square column, the interface at the corner of the column cracks first, and then, the cracks extend from the corner to the center of the interface at the long- and short-side beams. With the increase in the height of the beam, the distribution range and extension height of cracks also decrease successively with the ultimate load decrease. Even under the ultimate load, the crack distribution is in a small range. It is proven that the failure mode of the square column model is slip failure at the beam-column interface.

(6) In view of the importance of the girdling beam to support the column, even if the performance of the girdling beam is not fully utilized, it should not be designed too economically and should be safe enough. The successful experience is to increase the interaction force between the column and the inside of the girdling beam by means of shaving the surface of the column or even planting the rib on the column's surface.

(7) A typical spatial strut-and-tie model can be used to analyze the mechanical behavior of girdling beams with square columns, the relevant parameters of the model need to be verified by more tests.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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