

Article

Effect of Shear Deformation at Segmental Joints on the Short-Term Deflection of Large-Span Cantilever Cast Prestressed Concrete Box Girders

Jie Liu ^{1,2}, Xiangyu Huang ^{1,2}, Juanjuan Chen ³ and Qiaoyun Wu ^{1,2,*} ¹ School of Civil Engineering and Architecture, Wuhan Institute of Technology, Wuhan 430074, China² Hubei Provincial Engineering Research Center for Green Civil Engineering Materials and Structures, Wuhan Institute of Technology, Wuhan 430074, China³ School of Architectural Engineering, The College of Post and Telecommunication of WIT, Wuhan 430074, China

* Correspondence: wuqiaoyun@wit.edu.cn

Abstract: The excessive deflection of large-span cantilever cast prestressed concrete (LCCPC) box girders has always been a complex problem to be solved in bridge engineering. To analyze the effect of shear deformation at segmental joints on the deflection of LCCPC box girders, comparison tests were carried out on three prestressed concrete (PC) I-girders with joints and a PC I-girder without joints, and a finite element simulation method of segmental joints was proposed based on the tests. Subsequently, finite element analysis was conducted on a test girder and the Assistant Shipping Channel Bridge of Humen Bridge (a PC continuous rigid frame bridge with a main span of 270 m) using this method. The experimental and theoretical analysis results showed that the effect of the shear deformation at joints compared to the deformation at midspan of the girder specimens was negligible. Deformation at midspan of the specimens would not significantly increase, even if shear rigidity at the joints was significantly reduced or there were more joints in the girder specimen. The effect of shear deformation at segmental joints on the deflection of LCCPC box girders was quite small and thus insignificant.



Citation: Liu, J.; Huang, X.; Chen, J.; Wu, Q. Effect of Shear Deformation at Segmental Joints on the Short-Term Deflection of Large-Span Cantilever Cast Prestressed Concrete Box Girders. *Buildings* **2023**, *13*, 219. <https://doi.org/10.3390/buildings13010219>

Academic Editor: Ahmed Senouci

Received: 26 November 2022

Revised: 7 January 2023

Accepted: 11 January 2023

Published: 12 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: large-span prestressed concrete box girder; joint; shear deformation; experimental investigation; finite element analysis; deflection

1. Introduction

Cantilever casting is a prevailing construction method for large-span PC box girders in China. In this way, vertical joints are formed between successively cast box girders and the continuity of the box-girder concrete is destroyed. In the design, box girders with segmental joints are usually analyzed based on ideal box girders without joints. The problem of excessive long-term deflection at the midspan of LCCPC box girders is widespread [1–4], and many researchers have attempted to determine the difference in deformation between box girders with and without joints. The accumulation of relative slip deformation at the segmental joints (i.e., shear deformation at segmental joints, see Figure 1) was listed as one of the main reasons for excessive deflection at the midspan of box girders [5–11], and some structural measures to control shear deformation at segmental joints have been proposed, such as inclined joints, stepped joints, etc.

Currently, the finite element method is mainly used for studying the influence of shear deformation at segmental joints on the deflection of the box girder, and the axial deformation of the linear spring element is devoted to simulating the shear deformation and shear creep deformation at segmental joints [8–11]. When shear forces are applied to the segmental joint, there is a small relative slip (that is, the shear deformation of segmental joints) in the section. The axial deformation of the linear spring element can be used to

simulate the slip. Accurately determining the stiffness of the linear element is key since the axial deformation is inversely proportional to the stiffness. However, existing studies report significant differences in determining the shear stiffness of segmental joints due to the lack of necessary theoretical derivation and experimental verification. He et al. [8] assumed that the shear modulus of a concrete segmental joint is 1/100–1 times that of C30, that is, 1.3×10^2 – 1.3×10^4 MPa. Wang [9] believed that the width of segmental joints is 0.1–0.2 mm, and the shear modulus of a concrete segmental joint was obtained through theoretical deduction. Du [10] concluded that the shear modulus of a concrete segmental joint is 1.4×10^4 MPa. Zhang [11] considered that the shear modulus of a concrete segmental joint is 0.2 times that of C50, which is 7.3×10^3 MPa. Due to great differences in the assumed shear stiffness of segmental joints and in calculation methods, the conclusions obtained were not consistent. He et al. [8] illustrated that when the shear modulus of a concrete segmental joint is taken as 1/100 of that of C30, the increment of midspan deflection of a bridge caused by shear deformation at the segmental joint will reach 12.76 cm. Wang [9] pointed out that the shear deformation at segmental joints has a certain influence on the construction deflection of the box girder, and the long-term deflection of the midspan will be increased by approximately one time. Du [10] insisted that the effect of shear deformation at segmental joints on the construction deflection of the box girder can be neglected but it has great influence on the long-term deflection of the box girder.

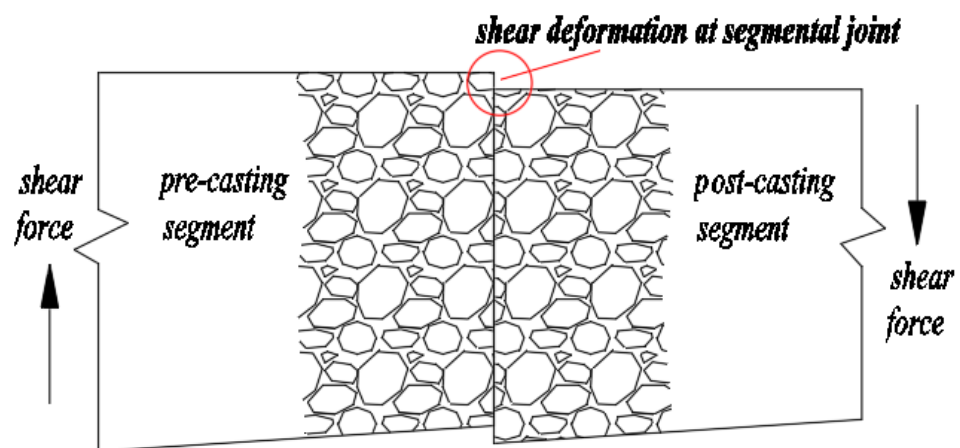


Figure 1. Schematic diagram of the shear deformation at segmental joints.

The above studies all hypothesized the shear stiffness without conducting relevant experimental studies. This paper fills the knowledge gap with experiments. To clarify the future direction of research, it is of great significance to explore the influence of shear deformation at segmental joints on the deflection of LCCPC box girders. Therefore, experimental studies were carried out in this paper to determine the decreasing degree of shear stiffness of segmental joints. On this basis, a finite element simulation method of segmental joints was suggested to overcome the limitations of quality and quantity of segmental joints. The influence of shear stiffness variation of segmental joints and the accumulation of shear deformation at multiple segmental joints on the deformation at midspan of the girder specimens was studied by numerical simulation. Finally, taking the Assistant Shipping Channel Bridge of Humen Bridge in the Guangdong province of China as an engineering example, the influence of shear deformation at segmental joints on the deflection of actual LCCPC box girders was analyzed.

2. Experimental Program

2.1. Overview of Girder Specimens

According to the hypothesis that the segmental joint stress of the girder specimens was similar to that of the Assistant Shipping Channel Bridge of Humen Bridge, four simply supported girder specimens (4700 mm in length and 550 mm in height) were

designed and manufactured, numbered B1 to B4, respectively. The materials, external dimensions, and prestressed reinforcement configuration were the same for all specimens (Figure 2). However, B1 was cast integrally, while girders B2 to B4 were cast segmentally to form segmental joints. In view of the influence of the interface roughness on the shear deformation at segmental joints, the interface of the segmental joints of girder B2 was artificially roughened, and the interface of the segmental joints of other girders was kept naturally smooth. In order to consider the influence of the shear reinforcement ratio, the reinforcement ratio of the web of girder B4 was reduced to half of that of the other girders. For girders B2 to B4, both sides of the segments were cast first, and the middle segments were cast after an interval of 28 days (Figure 3). The specimens were stored under laboratory environmental conditions for curing purposes.

The concrete for all girder specimens was designed to be grade C50, and the test showed that the 150 mm-cube compressive strengths of the pre-casting and post-casting concrete were 55.1 and 57.9 MPa, respectively. Grade HRB335 steel with a diameter of 8 mm was used for the ordinary steel bar. In addition, high-strength and low-relaxation steel strands with a diameter of 15.24 mm were applied to the prestressed bar. One bundle of strands was devoted to each girder, and each bundle was composed of 4 strands. The tested tensile strengths of the ordinary steel bar (grade HRB335) and prestressed steel bar with ϕ^s 15.24 were 341 and 1933 MPa, respectively, and the elastic moduli were 2.05×10^5 and 1.96×10^5 MPa, respectively.

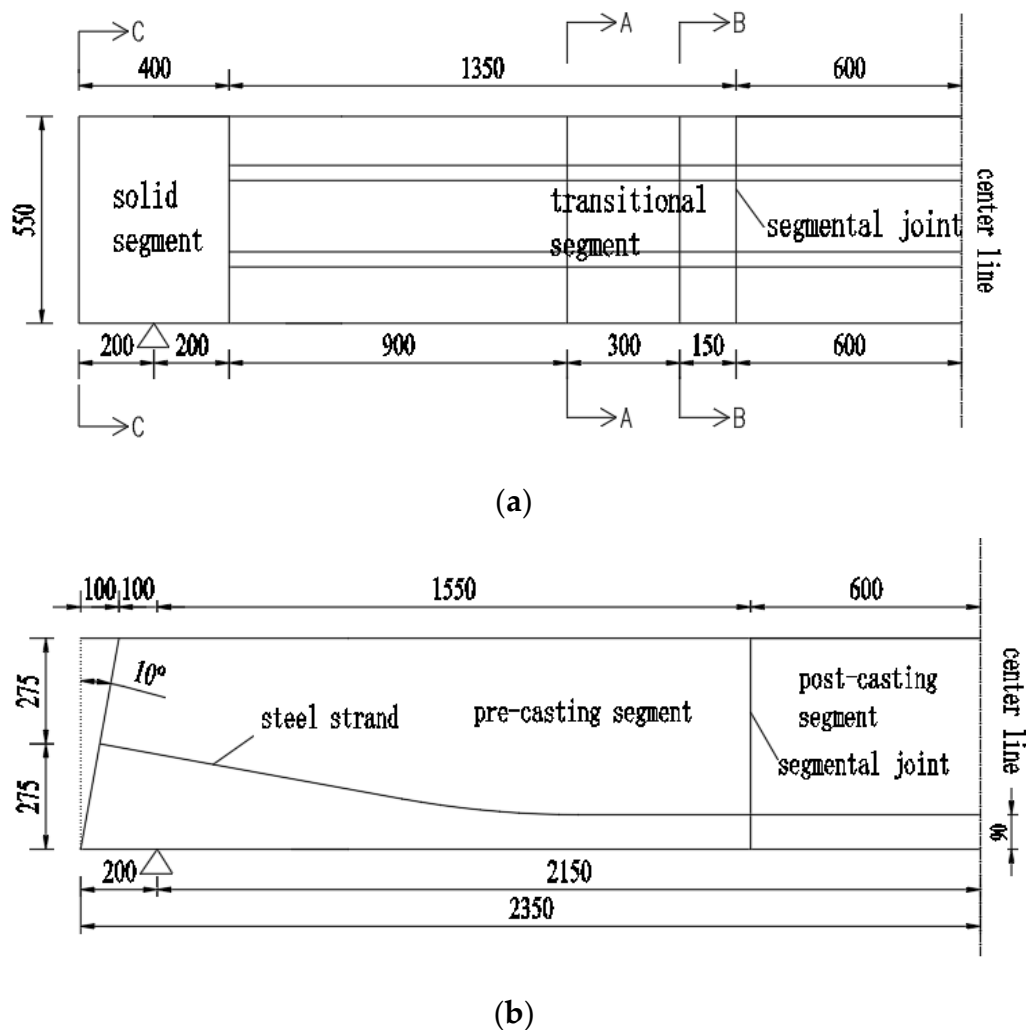


Figure 2. Cont.

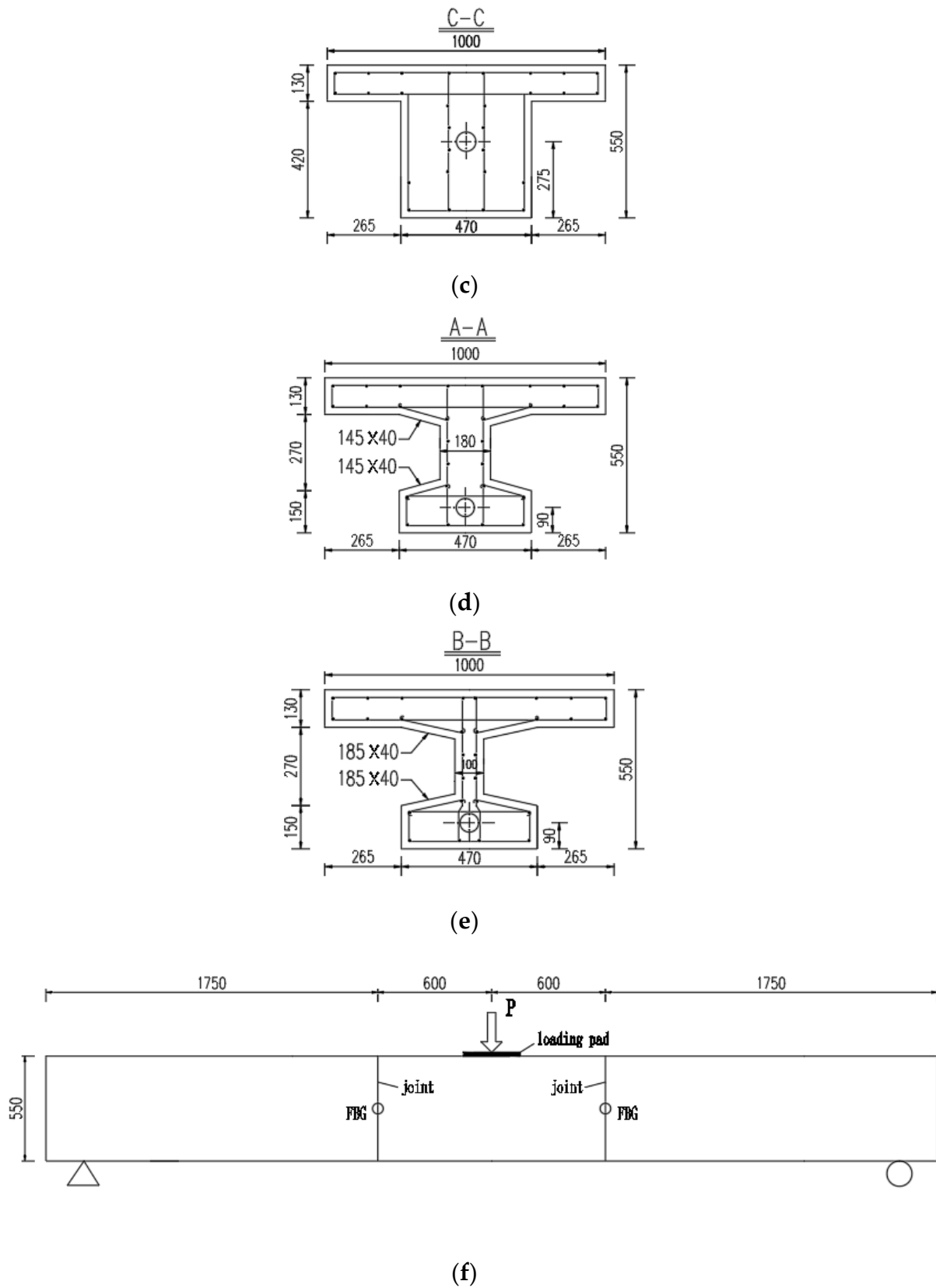


Figure 2. Schematic diagram of the girder specimen (unit: mm). (a) Dimensions of the girder specimen. (b) Layout of curved prestressed steel strands of the girder specimen. (c) C-C Section. (d) A-A Section. (e) B-B Section. (f) Loading and test system.

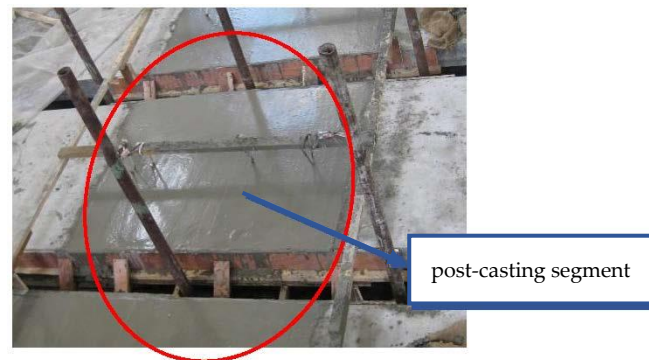


Figure 3. Casting of the middle segment of girders B2 to B4.

2.2. Measuring of Deflection of Girder and Shear Deformation at Segmental Joint

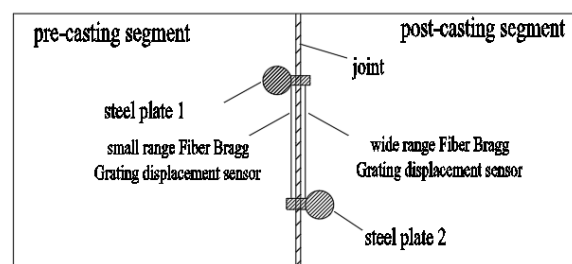
Deflection measuring points were arranged at the midspan and the two supporting sections, and an electronic digital dial gauge (measuring range of 5 cm, tolerance of 0.01 mm) was adopted to measure the deflection.

In view of the requirement of testing accuracy, a Fiber Bragg Grating (FBG) displacement sensor was applied to measure the shear deformation at the segmental joints. Due to the unknown magnitude of the shear deformation, wide-range (range of 3 mm, tolerance of $0.7\ \mu\text{m}$) and small-range (range of $100\ \mu\text{m}$, tolerance of $0.1\ \mu\text{m}$) sensors were installed and recorded at 60 Hz for each segmental joint during the test.

Before the test, the two ends of the sensor were respectively fixed on two steel plates along the segmental joint (Figure 4). The circular ends of the steel plates were bonded with the web using epoxy resin (steel plate 1 was bonded with the pre-casting section while steel plate 2 was bonded with the post-casting section). However, the rectangular ends of the steel plates were not bonded with the concrete. Therefore, the FBG displacement sensor would be elongated if shear deformation occurred, representing the shear deformation at the segmental joint.



(a)



(b)

Figure 4. Cont.

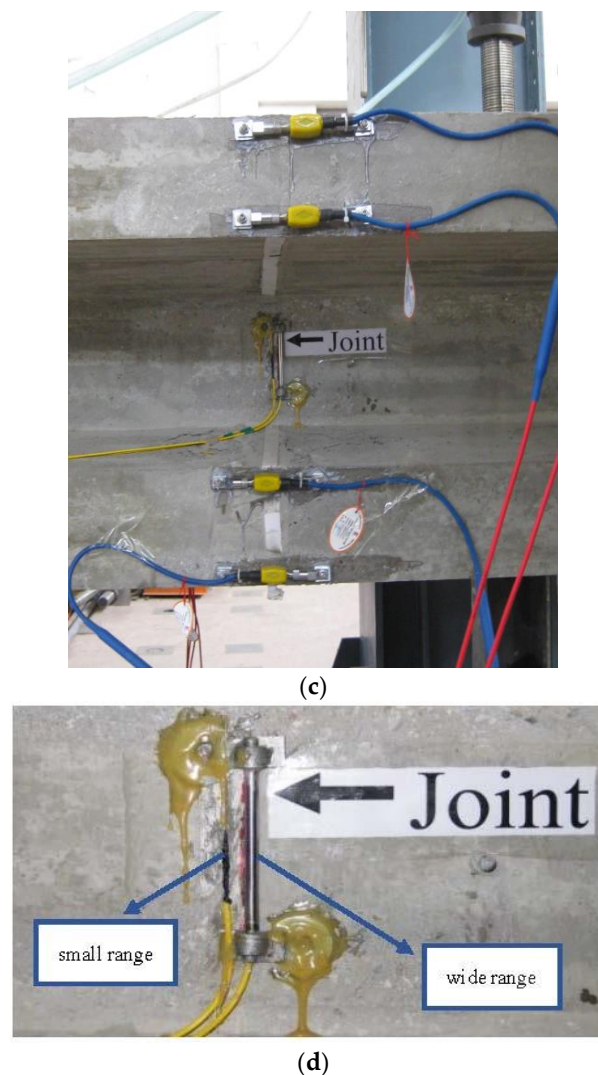


Figure 4. Loading of girders and measuring of shear deformation at the segmental joint. (a) Loading of girders. (b) Test plan. (c) Test pattern. (d) FBG details.

2.3. Loading Process and Test Phenomena

Tests were conducted using a servocontrolled actuator with a capacity of 1000 kN and a tolerance of 5 kN. Simply supported girder specimens were loaded with concentrated force at the midspan (Figure 4). The main purpose of the experiments was to test the shear deformation at segmental joints under compression-shear stress and tension-shear stress. To this end, the girders were loaded until bending cracks occurred. The force was loaded in nine stages to 250 kN during the test. At this time, a bending crack occurred near the midspan of the four girders (the distance between the crack and the section at the midspan was between 7 and 16 cm). Then, the force was loaded in two stages to 270 and 280 kN, respectively. The midspan crack under the maximum loading force (280 kN) extended through the bottom plate to the vicinity of the web plate. The crack at the joint was obvious in girders B2 to B4, as shown in Figure 5.



Figure 5. Crack at segmental joints of girders B2 to B4.

3. Test Results

The deformation at midspan of the main girder and the shear deformation at segmental joints were measured in the tests (Figures 6 and 7). The shear deformation was taken as the average value measured by wide-range and small-range FBG displacement sensors. The deformation at midspan and the shear deformation at segmental joints under the maximum load (280 kN) are listed in Table 1.

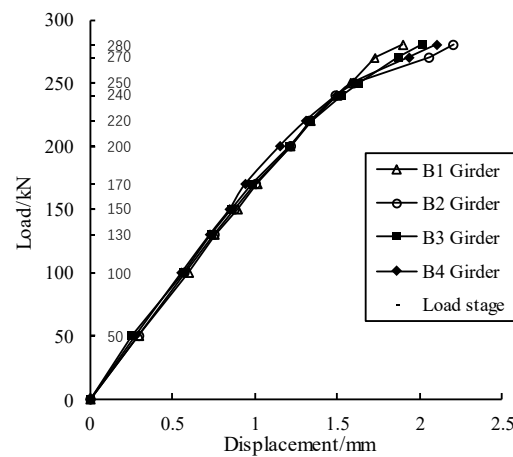


Figure 6. Deformation curve at the midspan of girder specimens.

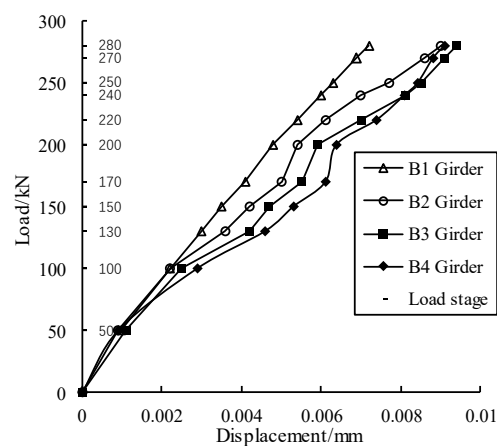


Figure 7. Shear deformation curve at joints of girder specimens.

Table 1. Maximum deformation test values of girder specimens (unit: mm).

Girder Specimens	B1	B2	B3	B4
Shear deformation at segmental joints	0.0072	0.0090	0.0094	0.0091
Deformation at midspan	1.90	2.21	2.02	2.11

It can be seen from Table 1 that the average maximum test value of the shear deformation at segmental joints of girders B2 to B4 was 0.0092 mm, while the average maximum deformation at midspan of these girders was 2.11 mm. The ratio of the shear deformation at segmental joints to the deformation at midspan was $0.0092/2.11 = 4\text{‰} < 1\%$. Thus, when calculating the deformation at midspan of girders B2 to B4, the shear deformation at segmental joints could be ignored.

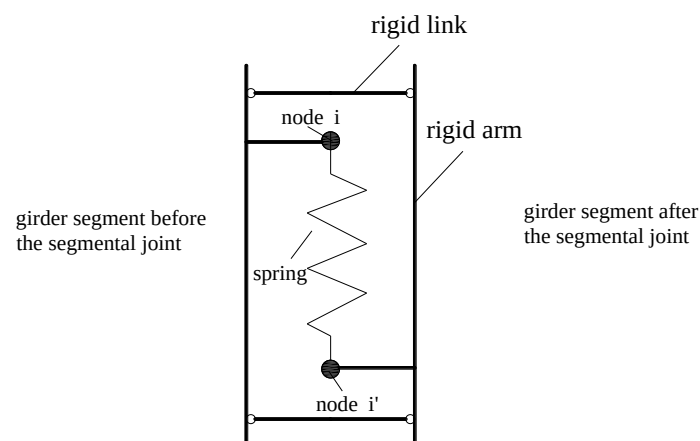
The average shear deformation of girders B2 to B4 was 0.0092 mm, and the shear stiffness of the corresponding joint was denoted as k_j . The test value of the shear deformation at the segmental joint of girder B1 was 0.0072 mm, and the shear stiffness of the corresponding segmental joint was denoted as k_t . According to the inverse ratio between deflection and stiffness, it was inferred that $k_j = (0.0072/0.0092) k_t = 0.783 k_t$. In conclusion, compared with the corresponding section of the integrally cast girder, the shear stiffness of the segmental joint section was virtually reduced by segmental casting, but the degree was limited. When the concentrated force of 280 kN was applied at the midspan of the girder specimen in this paper, the shear stiffness reduction coefficient of the segmental joint section was $1 - 0.783 = 0.217$.

4. Finite Element Analysis on Test Girders

To develop the theoretical analysis system of the shear deformation at segmental joints, and to study the changes in shear stiffness and the influence of possible multiple segmental joints on the deformation at midspan of the girder, finite element analysis on the stress and deformation of girders in the linear elastic stage was carried out. The following analysis is based on the finite element simulation method of segmental joints, avoiding the tedious nonlinear analysis without affecting the purpose.

4.1. Simulation Method and Principle of Segmental Joints

Two overlapping sections were established at the segmental joint during simulation. The nodes on the joint sections were coincident and corresponding. To avoid changing the transmission of axial force and bending moment in the model, and to conveniently simulate the shear deformation at two sections of the segmental joint, the constraint relationship shown in Figure 8 was applied to each pair of coincident nodes. To illustrate the constraint relationship between nodes i and i' , they were drawn at different although coincident positions.

**Figure 8.** Constraint relationship between coincident nodes at the segmental joint.

The following theoretical derivations determine the stiffness of the spring at the segmental joint (Figure 8). For two adjacent sections with longitudinal horizontal distance δ [12], the vertical relative displacement (shear displacement) under shear force Q_P is given by:

$$\Delta y = \gamma \times \delta = \frac{Q_P}{kGA} \times \delta \quad (1)$$

where γ is the shear strain, k is the shear correction factor of the section, G is the shear modulus of the material, and A is the area of the section.

If this shear displacement (Δy) is equivalent to the spring with axial stiffness K , the following equation shall be satisfied:

$$\Delta y = \frac{Q_P}{K} \quad (2)$$

Contrasting Equation (1) with Equation (2) gives:

$$K = \frac{kGA}{\delta} \quad (3)$$

The interfaces of the concrete cast at different times are coincident in the model, that is, the segmental joint only represents one section in the longitudinal direction. As a result, the stiffness of the segmental joint spring element is equivalent to the shear stiffness in unit width. Letting δ in Equation (3) equal 1 gives:

$$K = kGA \quad (4)$$

4.2. Verification

To verify the rationality of the method in this paper, the whole model and the model with segmental joints of the girder specimens were established by 3D 8-node isoparametric elements (SOLID45 element) in ANSYS [13] (Figure 9). The geometrical dimensions, boundary constraints, element partition, material characteristics, and load size of the two models were all the same. The only difference between them is that the segmented modeling method was used in the segmental joint model, so that there were two coincident sections at the joint. Coupling the longitudinal and transverse linear displacements of all overlapping nodes of these two coincident sections, the vertical spring element COMBIN14 was established at the overlapping nodes of the web, and the compression deformation of the element was applied to simulate the shear deformation at the segmental joints.

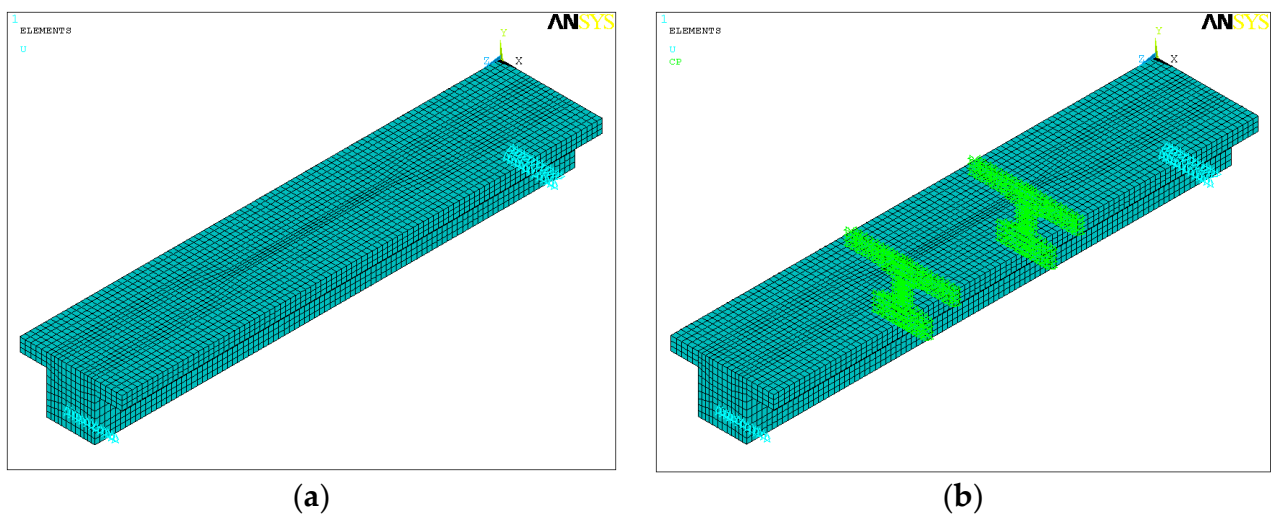


Figure 9. ANSYS finite element models of the girder specimen. (a) whole model of the girder specimen. (b) model with joints in the girder specimen.

The stiffness of the spring element is calculated by Equation (4). At this time, the stiffness of the spring element is in line with the shear stiffness of the corresponding section at the segmental joints in the whole model. If the results calculated using the whole model and the model with segmental joints were consistent under the same loading condition, the method would be proven to be credible. The results of these two models under self-weight are shown in Table 2. It can be seen that the results at the midspan section were consistent, indicating that the simulation analysis in this paper was reasonable.

Table 2. Results at midspan of the girder specimen under self-weight.

Computation Model	Normal Stress of Lower Edge/MPa	Vertical Displacement/mm
ANSYS whole model	0.573	0.1075
ANSYS model with joints	0.573	0.1075

4.3. Results and Analysis

According to the finite element analysis and test results, finite element simulation analysis on the girder specimen was carried out when the loading force at midspan was 200 kN, which corresponded to the measured displacement at midspan of 1.24 mm. Since the purpose of the finite element analysis was to obtain the deformation of test girders (midspan displacement and shear deformation at segmental joints) under the load of 200 kN, geometric nonlinear and prestress forces were not considered in the analysis. The details of the model are listed in Table 3. The methods provided by He et al. [8] and Wang [9] were adopted for comparison. The whole model had 15,537 nodes and 11,604 SOLID45 elements, and the model with segmental joints had 15,855 nodes and 12,132 elements (including 11,604 elements of SOLID45 and 528 elements of COMBIN14). The solid element SOLID45 was used to simulate the girder, and spring element COMBIN14 was applied to simulate the segmental joint. The results are shown in Table 4.

Table 3. Details of the models under the action of 200 kN.

Computation Model	Number of Elements	Meshing Size of SOLID45	Loading Method
ANSYS whole model	11604 SOLID45	50 mm	Steel pad (200 mm × 200 mm) at midspan
ANSYS model with joints	11604 SOLID45 and 528 COMBIN14		

Table 4. Results at midspan of girder specimens under the action of 200 kN.

Method	Spring Stiffness N/mm	Vertical Displacement /mm	Relative Error to the Measured Displacement	Lower Edge Normal Stress /MPa
1. Whole model	—	1.2422	—	8.902
2. Verification Model with Joints	7.846×10^8	1.2422	0.18%	8.898
3. Curve measured from FBG	1.182×10^7	1.2530	1.05%	8.895
4. From He et al. [8]	2.795×10^6	1.3138	5.95%	8.893
5. From Wang [9]	7.846×10^9	1.2416	0.13%	8.889

It should be noted that the model with segmental joints was applied to Methods 2–5 in Table 4, and the difference lies in their values of spring stiffness. Method 2 was proposed in this paper and Equation (4) was devoted to calculating the spring stiffness, in which $G = 3.65 \times 10^4$ MPa. Method 3 was used to calculate the spring stiffness by Equation (2), in which $\Delta y = 0.0055$ mm (i.e., the measured average value of shear deformation at the segmental joints of girders B2–B4). Method 4 was used to calculate the spring stiffness by Equation (4), where $G = 1.3 \times 10^2$ MPa (the value was based on the eighth-grade concrete shear modulus by He et al. [8]). Method 5 was adopted to calculate the spring stiffness by Equation (3), where $\delta = 0.1$ mm, $G = 3.65 \times 10^4$ MPa.

As can be seen from Table 4, the results calculated by Methods 1 and 2 were almost the same. In addition, the shear deformation at a segmental joint obtained by Method 3 was

$(1.2530 - 1.2422)/2 = 0.0054$ mm, which was almost the same as the value measured by the FBG displacement sensor (0.0055 mm). The correctness of the simulation analysis was verified in this paper one more time, showing that the values of spring stiffness calculated by Methods 2 and 3 were reasonable.

The results of normal stress at the lower edge were almost identical in Table 4, and the calculated vertical displacement results were also close. Therefore, it was difficult to judge the correctness of the various methods from only the error value, so it was necessary to judge the correctness of the methods using the determination principle of spring stiffness.

The spring stiffness obtained by Method 2 represents the shear stiffness of the section corresponding to the segmental joint in the whole model. Because segmental casting can reduce the shear stiffness of the segmental joint section relative to the corresponding section of the integral casting girder, the rational spring stiffness at the segmental joint should be less than that in Method 2. In contrast, the spring stiffness obtained by Method 5 is ten times of that in Method 2, which obviously does not conform to common sense.

He et al. [8] reduced the shear modulus of a concrete segmental joint, and the spring stiffness obtained using this method was only 0.0036 times that obtained by Method 2. Although the spring stiffness was less than that of Method 2, the theoretical basis of this method was insufficient, and Method 4 was not reasonable. The relative error between 1.3138 mm (the midspan displacement obtained by Method 4) and 1.24 mm (the measured value) was only 5.95%, while the relative error between the result of Method 4 and 1.2422 mm calculated by Method 2 was only 5.76%. This result showed that although the girder had only two segmental joints, infinitely reducing the shear stiffness of the segmental joint section (such as 0.36% of the ideal section shear stiffness) would have a non-negligible effect on the displacement at midspan. Thus, the shear stiffness of the segmental joints would not be greatly reduced, according to the test results.

It should be pointed out that although Method 3 was correct according to the calculation principle, some errors must have occurred between the results of Method 3 and the measured values. This is because when Equation (2) was used to calculate the spring stiffness at the joint section in the finite element analysis, Δy represented the shear deformation of the section of the joint. However, it is difficult to accurately test the shear deformation of a section using existing test methods, and the actual test often measures the shear deformation of a part of the main beam with a very small length, which will result in a large Δy value and small spring stiffness. Inevitably, the test method proposed in this paper also had similar shortcomings, resulting in the spring stiffness obtained by Method 3 being smaller, which was only 0.0232 times that obtained by Method 2 (i.e., the shear stiffness of the section corresponding to segmental joints in the whole model). However, the relative error between 1.2530 mm (the midspan displacement obtained by Method 3) and 1.24 mm (the measured value) was only 1.05%. In comparison, the relative error between the result of Method 3 and 1.2422 mm calculated by Method 2 was only 0.87%. It can be concluded from these results that significantly reducing the shear stiffness of the segmental joint section to a certain extent (such as reducing the shear stiffness to 2.3% of that of ideal section) would not cause a significant increase in the displacement at midspan.

The main reason for the above phenomena is that the reduction of the shear strength of segmental joints occurs only at joint sections. In general, the ratio of the shear deformation of the PC girder to the total deformation is relatively small; thus, significantly reducing the shear stiffness of the segmental joint section to a certain extent does not cause a significant increase in the displacement at midspan. It can be further explained that the shear deformation at segmental joints of the girder specimens could also be ignored even if there were multiple segmental joints.

5. Influence of Shear Deformation at Segmental Joints on the Deflection of an Actual Box Girder

The finite element method was used to analyze the influence of shear deformation at segmental joints on the deflection of the box girder of the Assistant Shipping Channel

Bridge of Humen Bridge, which is a PC continuous rigid frame bridge with a span of 150 m + 270 m + 150 m constructed by cantilever casting. Inspection after seven years of service showed that the deflection at midspan reached 22.2 cm, which far exceeded the designed maximum creep deflection of 11.2 cm. To simplify the analysis, this paper only considered the most unfavorable case according to the test results. When the maximum load was applied at the midspan of the test girder, the reduction coefficient of shear stiffness was 0.217. Therefore, the reduction coefficient of 0.217 was considered as the worst case and adopted in the FEM model.

Two analysis models of the Assistant Shipping Channel Bridge of Humen Bridge in construction stages were established using ANSYS. One is the whole model and the other is the model with joints. The model with joints reduced the shear stiffness by 0.217. The loads were composed with gravity and longitudinal prestress of the box girder. To reduce the difficulty of calculation, only half of the bridge model along the transverse direction was established due to the symmetry of the structure. The models are shown in Figure 10, in which the whole model had 42,732 nodes and 32,636 SOLID45 elements, and the model with joints had 45,372 nodes and 34,556 elements (including 32,636 SOLID45 elements and 1920 COMBIN14 elements).

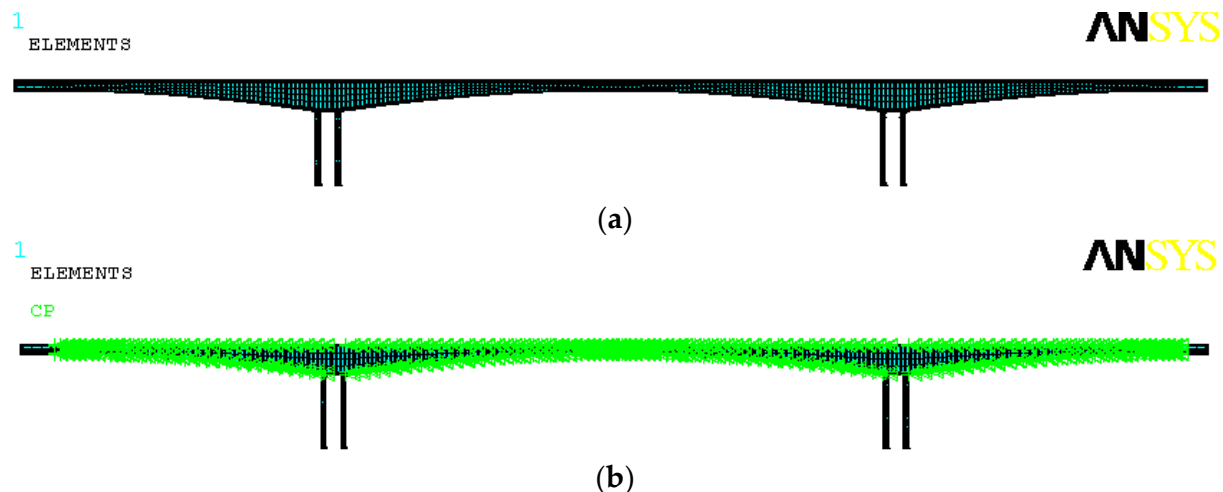


Figure 10. ANSYS finite element models of the Assistant Shipping Channel Bridge of Humen Bridge. (a) Whole model of the Assistant Shipping Channel Bridge of Humen Bridge. (b) Model with joints of the Assistant Shipping Channel Bridge of Humen Bridge.

In these two models, the displacement of each segment after the completion of the bridge was extracted, respectively. The displacement of the whole model was subtracted from that of the model with joints, and the influence value of the shear stiffness reduction of the segmental joints on the displacement of the girder (hereinafter referred to as the influence value) was obtained. Taking the junction of 0[#] and 1[#] segments of the pier top as the origin, the longitudinal distribution of the influence value along the box girder was drawn, as shown in Figure 11 (only half of the midspan is drawn due to symmetry), in which specifying the upward displacement was the positive direction.

It can be seen from Figure 11 that the decrease in joint shear stiffness slightly increased the displacement of the main girder, and the maximum and minimum influence values were 0.0103 and 0.0001 mm, respectively. In addition, the maximum and minimum displacements of the segment extracted from the whole model were 147.25 and 8.28 mm, respectively, indicating that the influence value was a different order of magnitude from the displacement. Further analysis showed that the maximum ratio of the influence value to the displacement of the corresponding segment was $0.0048/8.28 = 0.06\% < 1\%$. Therefore, the shear deformation at segmental joints only had a slight influence on the deformation of the box girder and could be neglected.

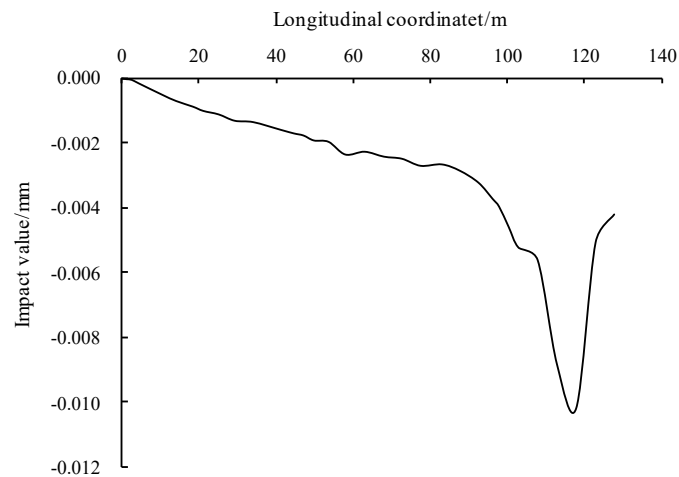


Figure 11. Longitudinal distribution of additional deflection caused by shear deformation at segmental joints.

The LCCPC box girder is dominated by bending, and the segmental joints are generally under bending and shear loading conditions. Whether in the form of compression shear or tensile shear, parts of or all of sections bear the major compressive stress in the normal direction. In addition, a large number of prestressed steel bars and ordinary steel bars cross the joint section, which makes a great contribution to resist shear deformation at joints [14,15]. Additionally, the ratio of PC girder shear deformation to total deformation is relatively small. Therefore, the shear deformation at segmental joints has a slight influence on the deformation of LCCPC box girders, which can be ignored.

As the calculation of shear creep of concrete is not clear at present, the shrinkage and creep effect of concrete were not considered in this paper. In addition, few studies have reported the shear creep coefficient of concrete. If the shear creep coefficient and compression creep coefficient are calculated using the same expression [16], the shear creep deformation of joints and total deformation of the box girder would increase in equal proportion with time.

6. Conclusions

- The ratio of the shear deformation at segmental joints to the deformation at midspan of the girder specimens was less than 1%, indicating that the shear deformation at segmental joints can be ignored.
- The finite element analysis on the girder specimen showed that even if the shear stiffness of the joint section was significantly reduced, such as 2.3% of that of the ideal section, the deformation at midspan would not significantly increase. If the shear stiffness of the joint section continued to decrease to 0.36% of that of the ideal section, the deformation at midspan would be significant. Since the measured shear stiffness of the joint section of the girder specimen in this paper could only be reduced up to 78.3% of the stiffness of the ideal section, the deformation at midspan would not obviously increase even if there was an accumulation of shear deformation in multiple segmental joints.
- The finite element analysis on the Assistant Shipping Channel Bridge of Humen Bridge showed that the influence of the shear deformation at segmental joints on the deflection of LCCPC box girders was less than 1%, which could be ignored.
- In this paper, experiments were adopted to fill the knowledge gap in deducing shear stiffness only by hypothesis. In addition, experimental research on the shear creep of concrete is crucial to determine the long-term deflection of LCCPC box girders. Thus, it is recommended that relevant research be conducted to elucidate the effect of shear creep deformation.

Author Contributions: Conceptualization, J.L.; methodology, J.L.; software, J.L.; validation, J.L.; investigation, X.H. and J.C.; data curation, X.H.; writing—original draft preparation, X.H. and J.C.; writing—review and editing, J.L. and Q.W.; visualization, X.H. and J.C.; supervision, Q.W.; Funding Acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The National Natural Science Foundation of China (grant number 52278210), the Science and Technology Research Project of Department of Education of Hubei Province (grant number D20221506), and the Science Foundation Research Project of Wuhan Institute of Technology (grant number K202223).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available, as the data also forms part of an ongoing study.

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

References

1. Bažant, Z.P.; Li, G.; Yu, Q.; Klein, G.; Křístek, V. Explanation of Excessive Long-Time Deflections of Collapsed Record-Span Box Girder Bridge in Palau. In Proceedings of the 8th International Conference on Creep, Shrinkage and Durability of Concrete and Concrete Structures, Ise-Shima, Japan, 30 September 2008.
2. Bažant, Z.P.; Yu, Q.; Li, G. Excessive Long-Time Deflections of Prestressed Box Girders. I: Record-Span Bridge in Palau and Other Paradigms. *J. Struct. Eng.* **2012**, *138*, 676–686. [\[CrossRef\]](#)
3. Bažant, Z.P.; Yu, Q.; Li, G. Excessive Long-Time Deflections of Prestressed Box Girders. II: Numerical Analysis and Lessons Learned. *J. Struct. Eng.* **2012**, *138*, 687–696. [\[CrossRef\]](#)
4. Ferro, G.A.; Restuccia, L.; Falliano, D.; Devitofranceschi, A.; Gemelli, A. Collapse of Existing Bridges: From the Lesson of La Reale Viaduct to the Definition of a Partial Safety Coefficient of Variable Traffic Loads. *J. Struct. Eng.* **2022**, *148*, 04022181. [\[CrossRef\]](#)
5. Liu, J.; YE, J.; CHEN, J. Study of the effect of segmental joint weak layers on deformation of long span cantilever-casting PC box girders. *Ind. Constr.* **2015**, *45*, 70–75. (In Chinese)
6. Zhu, F. Calculation Theory of Structure and Supervision under Construction of Continuous Rigid Frame Bridge. Master's Thesis, Dalian University of Technology, Dalian, China, 2003. (In Chinese).
7. He, C. Influence of vertical joints on the post-construction deflection of continuous rigid frame bridges. *J. Chongqing Jiaotong Univ. (Nat. Sci.)* **2009**, *28*, 480–483. (In Chinese)
8. He, P.; Zhou, Z.; Ji, G.; Fan, L. Quality of vertical joints in continuous rigid bridges and its Influence on the post-construction deflection of the bridges. *J. Chongqing Jiaotong Univ.* **2004**, *23*, 6–9. (In Chinese)
9. Wang, R. Study on Shear Deformation of Segmental Joint and Its Influence on Pile-Soil-Bridge System. Ph.D. Thesis, Tianjin University, Tianjin, China, 2009. (In Chinese).
10. Du, J. Study on Shear Deformation of Segmental Joint and Its Influence to Deflection of Continuous Rigid Bridge. Master's Thesis, Southwest Jiaotong University, Chengdu, China, 2012. (In Chinese).
11. Zhang, W. Effect of Segmental Joints in Cantilever Casting Concrete Bridges on Deflection. Ph.D. Thesis, Harbin Institute of Technology, Harbin, China, 2012. (In Chinese).
12. Carpinteri, A. *Structural Mechanics—A Unified Approach*, 1st ed.; CRC Press: London, UK, 2017; pp. 394–423.
13. Ansys. Available online: <https://www.ansys.com/zh-cn> (accessed on 25 November 2022).
14. Bonopera, M.; Chang, K.C.; Lin, T.K.; Tullini, N. Influence of Prestressing on the Behavior of Uncracked Concrete Beams with a Parabolic Bonded Tendon. *Struct. Eng. Mech.* **2021**, *77*, 1–17. [\[CrossRef\]](#)
15. Limongelli, M.P.; Siegert, D.; Merliot, E.; Waeytens, J.; Bourquin, F.; Vidal, R.; Le Corvec, V.; Gueguen, I.; Cottineau, L.M. Damage Detection in a Post Tensioned Concrete Beam—Experimental Investigation. *Eng. Struct.* **2016**, *128*, 15–25. [\[CrossRef\]](#)
16. Li, S.; Yang, Y.; Pu, Q.; Yang, D.; Sun, B.; Li, X. Three-Dimensional Nonlinear Creep and Shrinkage Effects of a Long-Span Prestressed Concrete Box Girder Bridge. *Struct. Concr.* **2019**, *20*, 638–649. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.