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Numerical Simulation Study of Non-standard Prestressed Concrete Continuous Box Girder Bridge

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***Abstract*—This paper summarizes the stress characteristics of non-standard box girders and the grillage method, and according to the engineering practice experience, summarizes the characteristics of the grillage method in the stress analysis of non-standard box girders, and draws the corresponding conclusions. On this basis, the finite element models of the special-shaped bifurcated box girder and the widened box girder are established respectively. According to the analysis results and the operation of the bridge after completion, the grillage model can meet the needs of design checking calculation, provide theoretical basis for bridge construction, and it is worthy of reference for similar projects.**

Keywords—non-standard box girder; grillage method; finite element;midas civil

I. Introduction

Since the construction of municipal overpasses should satisfy the requirement of aesthetics and environmental harmony at the same time. Because of its requirements for designed alignment, there will inevitably be many curved ramps, curved ramps will also be connected with the main girder, so there will be a variety of non-standard structure at the junction of the main girder and ramp, such as widening, heightening, skew and curves may all be the same Occasionally or partially coexisting. Box girder is the most commonly used form of urban overpass. Its overall stiffness is large, the flange plate is elongated, the shape is beautiful, and most of them are large. The number of applications in large span, curved girder and special-shaped bridge structures, the current span is more than 20 m. Based on the above characteristics, the prestressed concrete continuous box girder can meet the needs of non-standard structure in terms of spanning capacity, alignment, stress and construction, so it is very suitable for the construction of urban overpass. At present, the analysis theories of straight and curved beams at home and abroad are relatively mature, but the calculation methods and analysis theories of special-shaped bridges are still backward, and there is no complete, systematic analysis theory and practical calculation methods, and lack of relevant experience. In view of the in-depth research on the stress analysis method and the law of structural effect are insufficiency, it is necessary to study the practical calculation method and mechanical behavior principle of the bifurcated special-shaped continuous girder bridge. In this paper, some non-standard prestressed concrete continuous box girders with widening, heightening or pier top with oblique crossbeam are analyzed by special finite element programs, and their simulation methods and application are discussed.

II. Overview of Non-standard Structure and ITS Analytical Methods

A. Characteristics of Non-standard Structure

The spans of Non-standard bridges (also known as heteromorphy bridge or special-shaped structure) are generally 20-40m. Cast-in-place continuous special-shaped multi-compartment box structure is commonly used in urban viaducts and highway overpasses. It has small self-weight, large flexural and torsion rigidity, good overall performance, large span capacity, small building height, flange plate elongation, neat appearance, good visual effect under the bridge, and can adapt to complex linear deformation changes of overpasses. According to the structural characteristics of the large extension arm of the special-shaped multi-chamber box girder and the load requirement of bearing eccentric torsion load, the thickness of the web of the special-shaped box girder is thicker on the outer side, while the thickness of the web on the inner side and the web connected with the box girder of the turnout is thinner [1,2].

The structural forms of box-shaped structural bridges can be divided into the following two categories [3]:

- Special-shaped Bifurcated Box Girder Bridge: The main bridge widens gradually and divided into two independent structures. The two independent branches influence each other and restrict each other. At the fork point, small radius curved webs and connected beams with larger stiffness will generally appear, because the structure before the fork becomes wider gradually. At the bifurcation point, the structure is suddenly divided into two relatively narrow independent structures. At the bifurcation point, there is a large sudden change in stiffness and continuity. It is not as good as the wide bridge with different deformation as the whole bridge, but the division of main line and branch line bridge is clearer after bifurcation. This kind of structure is

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generally used. Bridges with not too wide deck and not too large bifurcation angle.

- Widening Special-shaped Box Girder Bridge: The middle web is in the form of curves or broken lines, and the box chamber exists at the same time when the width of the box girder varies in the wide section with the variation of the width of the box girder. In the case of widening or increasing compartments, there are common webs and diaphragms and overlapping reinforcing bars in the bifurcation of the main and ramp bridges. The prestressing tendons have bifurcation and obvious flat bending at the bifurcation, the anchorage space is narrow, the arrangement of tooth blocks and the anchorage of prestressing tendons are more difficult. This structure will produce sudden change in stiffness at the widening section and the stress is very complicated. It is suitable for the case that the bridge deck is relatively wide and the intersection angle of the two branches is relatively large.

B. Overview of Grillages Method

The grillage method is an effective and practical method to analyze the superstructure of bridges by means of computer. It is easy to understand and use, and has been widely used in bridge structure calculation [5,6]. This method was first proposed by Sawkole[6]. It is suitable for slab, beam, box girder superstructure and various composite system bridges.

The main idea of the grillage method is to simulate the superstructure of the bridge with an equivalent grillage. The flexural and torsion stiffness scattered in each section of the slab or box girder is concentrated in the nearest equivalent grillage member, while the transverse stiffness is concentrated in the transverse grillage member. From the point of view of fully satisfying the boundary conditions, the grillage must satisfy the following equivalent principles; when the prototype actual structure and the corresponding equivalent grillage bear the same load, the flexure of both should be equal at all points, and the bending moment, shear force and torsion in any grillage should be equal to the internal force of the actual structural part represented by the grillage. However, due to the different structural characteristics between the actual structural system and the beam-lattice system, the ideal state of "equivalence" mentioned above is difficult to achieve, and the equivalence is only approximate.

This characteristic is manifested in the following aspects:

- The bending moment of any beam in the grillage method is strictly proportional to its curvature. In the original plate structure, the bending moment in any direction is related to the curvature in that direction and its orthogonal direction. For reinforced concrete members or pre-stressed concrete members, the longitudinal and transverse two-way reinforcement is generally adopted, and the Poisson ratio of concrete is small (μ=-0.15-0.16). Therefore, the longitudinal and transverse bending moments derived by the grillage method are sufficiently accurate for structural design [5,6].
- In the actual plate structure, the balance of any element requires that the torsion is equal in the orthogonal direction, and the torsion is the same in the orthogonal direction. In the equivalent grillage, because of the different structural characteristics of the two types, it is impossible to make the torque and torsion equal at the nodes in the orthogonal direction. However, when the grillage is fairly fine, the grillage becomes a surface with the deflection, it can be approximately equal in the orthogonal direction.

For the special-shaped box girder structure in urban interchange engineering, since the bridge structure is variable in width, slope and curvature, there may be bifurcation and sudden change in stiffness. If single beam element analysis is adopted it can't meet the accuracy of calculation always. And if plate and shell element and solid element analysis method is taken, although the accuracy is high, but the workload is too large, the calculation efficiency is not high. The grillage method is an ideal method for the analysis of this kind of structural bridge because of its clear thinking and high computational efficiency.

C. Basic Principles of Grillage Division with Non-standard Box Bridge Structure

In the analysis of bifurcated special-shaped structure bridges by grillage method, the key point is the division of grillage members, especially at bifurcation, widening and curvature. The density of grillage partition will directly affect the equivalent degree and calculation accuracy of grillage member and original structure. Generally, the finer grillage division, the higher calculation accuracy, and the more the calculation amount will be, which will lead to the decrease of calculation efficiency. Therefore, it is necessary to divide the grillage reasonably, which is not only simple and efficient, but also can accurately reflect the mechanical characteristics of the structure. Due to the diversity of bridge structure and support forms, it is difficult to generalize the unified principle for all types of bridge grillage division. For box girder bridge grillage division, domestic and foreign researchers have done a lot of research, and obtained the corresponding division principle, summarized as follows [7-9]:

- For box girders with oblique webs, the position of longitudinal members should coincide with that of webs. For box girders with oblique webs, the position of longitudinal members is generally the middle position of oblique webs. In order to facilitate the application of automobile loads, virtual beams are usually added to the outer flange of the side webs to transfer loads.
- The partition of transverse members should be dense. If the partition is too sparse to accurately simulate the mechanical performance of the original structure, it will affect the calculation efficiency. Generally, each span is divided into at least eight sections. The position

of supports and diaphragms should consider the arrangement of transverse members, and the spacing between transverse members and longitudinal members should be as close as possible to ensure the rational distribution of load static force.

- For the bearing, bifurcation and sudden change of stiffness of the bifurcated special-shaped bridge structure, the mesh should be refined.
- For bifurcated special-shaped structure bridges, the longitudinal girder lattice is generally orthogonal to the transverse, and for the main line bridge and ramp bridge, skew transition can be used at the junction, and the skew angle generally does not exceed 20 degrees.

To sum up, there is no uniform standard for the division of grillage, and flexible division should be carried out according to the principle of reflecting the structure and actual stress state of the structure.

III. Numerical simulation study of Special-shaped Bifurcated Box Girder Bridge

A. Brief Introduction of Structure

The research object is based on a urban overpass bridge engineering in Dongguan city at China, The whole structure includes the main branch and the ramp branch, in which the mainline bridge span combination is (34+33+30.5) meter, and the ramp is in 25 meter span (FIGURE I). It's a typical special-shaped bifurcated box girder structure.

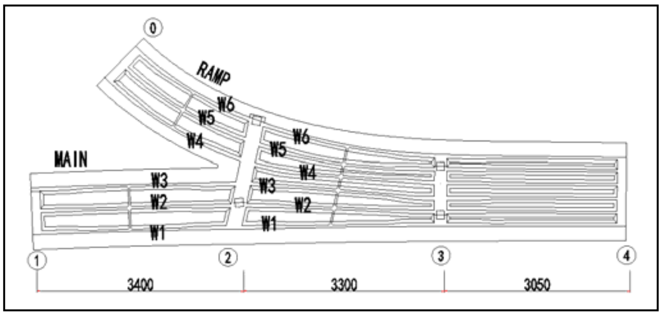

FIGURE I. THE PLAN DRAWING OF SPECIAL-SHAPED BOX GIRDER (UNIT: CM)

The structure type is a prestressed concrete continuous box girder bridge.The widest section of this structure is with a size where the width is 22.724 meters and the height 2.1 meters. The narrowest section of this structure is with a size where the width is 16.104 meters and the both side heights are 2.422 and 2.218 meters.The section of main girder branch structure (near Pier 1 in Fig.I) is with a size where the width is 12.6 meters and the height is 1.8 meters. The section of ramp girder branch structure (near Pier 0) is with a size where the width is 11 meters and the height is 1.8 meters.

B. Establishment of Finite Element Analysis Model

In view of the special-shaped box girder mentioned above, the finite element analysis model is established based on the theory of grillage method. There are six webs in the whole bridge according to Fig.1, so the whole structure is divided into six longitudinal grillages according to the weds of the box girder (from W1 to W6 shown in Fig.I). In addition, two virtual beams are added to facilitate loading. These two virtual beams do not affect the stiffness and force of the structure. 50 transverse grillages are set in the transverse direction. The cross-sectional characteristics of the longitudinal and transverse grillages are calculated according to Hamberley's theory [4], all the resistant bending moment inertias of the longitudinal sections are relative to the cross section center of mass. The calculation of torsion stiffness of grillages is spread out on the longitudinal beams according to the free torsion stiffness of the whole box section[10].The numerical model will be built with Midas Civil[11] which is a professional finite element analysis software for bridge structure. The main materials of this bridge are C50 concrete whose bulk density is 26 and low relaxation steel strand with standard strength 1860MPa, relaxation coefficient 0.3, pipeline friction coefficient 0.17, friction influence coefficient of local deviation of pipeline per meter 0.0015 and anchor deformation parameter 0.006. All of these condition will be taken account for the analysis model shown in FIGURE II.

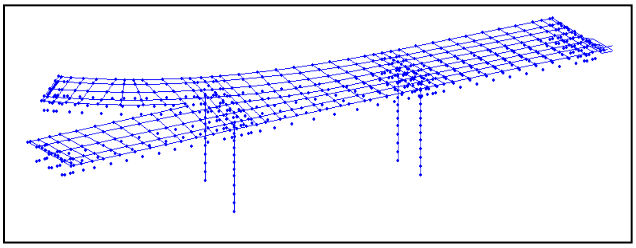

FIGURE II. THE FINITE ELEMENT MODEL OF THE WHOLE BRIDGE BASED ON BRILLAGE MENTHOD

After applying the boundary conditions and various design loads, the static analysis of the structure can be carried out in Midas Civil. The corresponding calculation results can be read by the post-processing module, and then checked according to the design specifications [12,13].

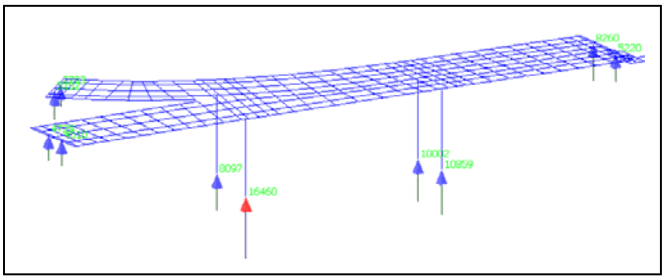

FIGURE III. THE VERTICAL REACTION FORCE OF THE FINITE ELEMENT SIMULATION MODEL

The vertical reaction force of the structure is checked which is the key to check out if the overall force of the model is balanced and statically determinate. The reaction force result in standard value combination at unfavorable condition with both live load and dead load is shown as FIGURE.III. According to the Figure, the maximum vertical reaction occurs on the support in Pier 2 outside of the plan curve, the value is about 16460kN, other vertical reaction value in supports are showed in Fig.8. According to these reactions result, the suitable tonnage support can be selected. After checking, the sum of vertical reaction and the sum of vertical load are equal in general, which shows that the finite analysis model of the bridge is feasible.

IV. NUMERICAL SIMULATION STUDY OF WIDENING SPECIAL-SHAPED BOX GIRDER BRIDGE

A. Brief Introduction of Structure

The research object is based on a urban overpass bridge engineering in Dongguan city at China too. The span combination of the structure is 15.735+1783m. The beam height is 1.25m and the bridge width is gradually changed from 38.19m to 20.8m. In order to conform to the skew relationship under the bridge, the skew mid-beam is designed. The elevation and plan of the structure are shown in FIGURE IV.

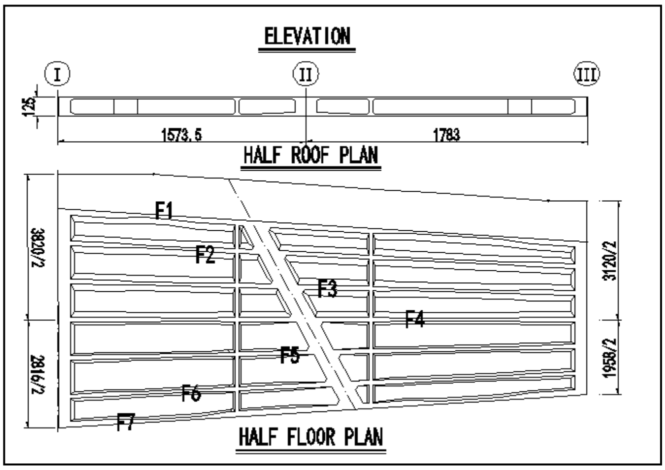

FIGURE IV. THE DIAGRAMMATIC SKETCH OF WIDENING BOX GIRDER (UNIT: CM)

The cross sections at both ends of the structure are shown in FIGURE V. In order to prevent the distortion and warping of box girder, a stiffening beam is arranged at both ends of the oblique middle beam.

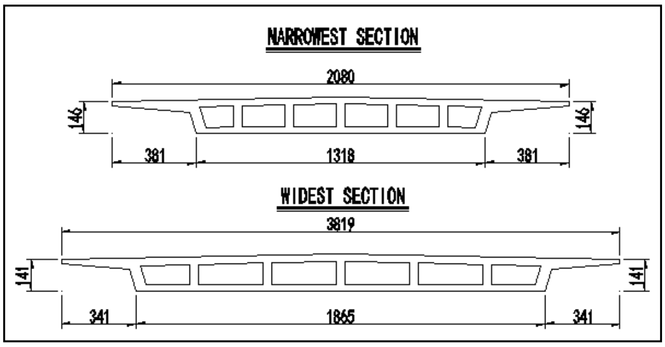

FIGURE V. THE BOTH END SECTIONS OF WIDENING BOX GIRDER (UNIT: CM)

B. Establishment of Finite Element Analysis Model

According to the widening box girder mentioned above, the finite element analysis model is established based on the theory of grillage method. Longitudinal girder grid number is numbered 1-7 which is F1-F7 shown in Fig IV. from bottom to top in accordance with the calculation model sketch. The bottom and top two longitudinal girders are imaginary beams, which are not included in the calculation. The finite element model of the widened bridge is shown in FIGURE VI.

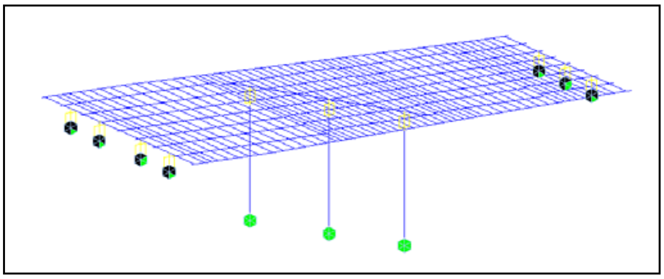

FIGURE VI. THE FINITE ELEMENT SIMULATION MODEL OF WIDENING BOX GIRDER BRIDGE

After all the boundary conditions and various design loads are set up in the finite element model, the static analysis of this widening bridge can be carried out in Midas Civil. The relative calculation results can be obtained by the post-processing module in Midas Civil, and then put the checking calculation into effect refer to the design code [12,13].

Similar to the example of special-shaped box girders above, the reaction force of the structure is the key to check out whether the overall outer force of the simulation model is balanced and statically determinate or not. The calculation results of reaction force show that the model of the widened bridge is correct, and the reaction force of the structure under the combined action of standard values is shown in the FIGURE VII.

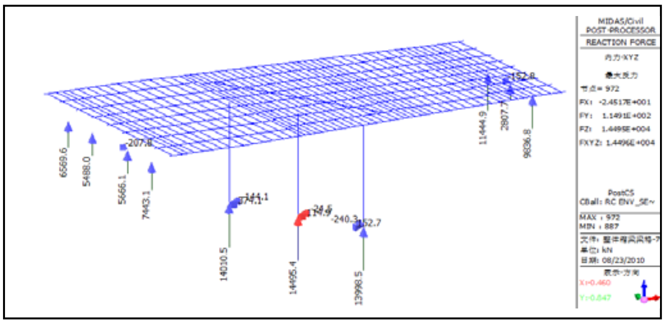

FIGURE VII. THE3D REATION FORCE OF THE FINITE ELEMENT SIMULATION MODEL OF WIDENING BRIDGE

According to the reaction on the graph, the maximum support reaction appears at the middle pier of the middle fulcrum. This is because the horizontal curve of the widened structure is straight line, so the maximum support reaction is different from the bifurcation structure mentioned above.

V. SUMMARY

Based on the theory of grillage method, two non-standard box girder structures are simulated by finite element method in Midas, and the following conclusions are drawn.

- The grillage method seems to be inherently compatible with non-standard box girder structures. Whether it is bifurcation, skew, curve, widening or heightening, the method has great adaptability. At the same time, this method is also very convenient for prestressing concrete structures with steel bundles on webs. Especially in structural design, it can directly correspond to the checking calculation of the code.
- The above two examples have successfully solved the stress problem of this kind of bridge by using the grillage method as the means of design checking. The safe operation for more than ten years shows that the method is very effective and it is recommended to be popularized in similar engineering.
- Although the grillage method is convenient and practical, it solves many problems for people in bridge construction, but it also has some shortcomings. For example, the determination of mechanical properties of grillage has great subjectivity, and the calculation results are greatly influenced by human factors. If it can be compared and revised by solid model and experiment, it can achieve better application.

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