Structural Rationality Research on Integrated Prefabricated I-Shaped Steel-Concrete Composite Girder Bridges

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Abstract. In order to promote the use of steel-concrete composite bridges in small and medium span bridges, and improve industrial construction of bridge and assembling degree of the composite girder bridge, an integrated prefabricated steel-concrete composite girder bridge was proposed. Considering the requirements of small and medium span bridges and the condition of highway transportation, the basic unit of the integrated prefabricated steel-concrete composite girder was constructed, and the connection way of units was put forward so as to further form the whole bridge. According to the result of calculation and analysis, the mechanical behaviour of the integrated prefabricated steel-concrete composite girder is superior to the traditional separated prefabricated steel-concrete composite girder, and it also performs better than the existing prefabricated concrete box girder and prefabricated concrete T-shaped girder in economy from the prospective of cycle. Besides, by comparing with the existing prefabricated concrete box girder, the prefabricated concrete T-shaped girder and the separated prefabricated steel-concrete composite girder, the integrated prefabricated steel-concrete composite girder would significantly improve the construction efficiency and shorten the construction period, and the construction quality could be guaranteed. All in all, the integrated prefabricated steel-concrete composite girder is a rational structure with convenient construction for bridge engineering.

1. Introduction

With the development of China’s economy and the increase of steel structure production, in recent years, the national transportation industry has conducted the policy about promoting the use of steel structures and composite bridges. Steel and composite bridges are in an unprecedented period of development. However, due to the increasing labour cost in China and the increasing requirements for environmental protection and energy conservation, industrialization in civil engineering has become a new trend. The realization of prefabricated assembly in bridges has become one of the hot issues of the development of bridge structure technology at this stage. The steel-concrete composite bridge is a structural system in which steel and concrete are reasonably arranged in different parts, and the two are combined through shear connectors, which not only fully utilizes the material, but also can be quickly constructed, saving time and economic cost [1-2]. In the past, due to construction costs, concrete bridges were used extensively in small and medium span bridges, while steel-concrete composite beam bridges were less used. Liu et al. analysed the economy of small and medium span steel-concrete composite girder bridges, and obtained the T-shaped composite girder bridge with higher utilization, higher economy and easier assembly and construction than the concrete bridge with
the same span [3]. In addition, in developed countries such as European countries, the United States and Japan, fabricated steel-concrete composite bridges have developed for several years, and relevant design and construction guidelines and composite girder bridge standard drawings have been developed [4], such as the American I-shaped steel-concrete composite girder bridges standard drawings [5]. Therefore, in the background of China's current industrialization of bridge construction, the research on the design and construction technology of fabricated steel-concrete composite bridges plays a vital role in the realization of bridge prefabricated construction.

At present, the basic method for the construction of composite bridges in China is: firstly, the steel structures are manufactured in the factory. And then, they are transported to the sites and installed. Finally, the concrete deck is constructed. Concrete decks can be cast in situ or pre-fabricated as sections, and then hoisted and combined [6-11]. Due to the limitation of design, the construction method of these combined structural bridges has a large number of components, a large amount of lifting work on site, and a slow construction speed. Under the background of high-speed city tempo, the traditional construction method can’t fully meet the needs of key road construction. And there is a need for a more efficient construction structure of composite bridges. To this end, this paper proposes a new structure of steel-concrete composite girder bridge with higher construction efficiency and assembly degree. This structure is composed of I-shaped beam and concrete deck, and prefabricated a whole span length in the longitudinal direction, near one lane width. At present, there is no relevant literature about the research of this kind of structure and construction method. For this reason, this paper is to research the structural mechanical behaviour and construction methods. For the convenience of description, the composite bridge whose slab is prefabricated and installed block by block on the bridge is referred to as separated prefabricated steel-concrete composite girder bridge (Abbreviate it as SPCG), and the composite bridge which is prefabricated with concrete slabs and integrally hoisted is named as integrated prefabricated steel-concrete composite girder bridge(Abbreviate it as IPCG).

2. Structural Form of Integrated Prefabricated Steel-concrete Composite Girder Bridge

The most used small and medium span in bridges are taken as the basic research objects. The IPCG is proposed by taking the commonly used bridge with a span of 35m and a six-lane bridge width of 25m. Since the bridge has six lanes, it is divided into six unites breadthwise, each of which is about 4.17m. And the concrete slab is considered to be integrated prefabricated with the steel plate beam. The cross section of each unit is shown in figure1a. However, since the cross section of figure1a is merely supported by a single I-shaped beam, it is difficult to maintain balance, and the transverse span of the concrete deck is too large. Therefore, the π-shaped steel girder composed of one cross beam and two I-shaped beams is considered to take place of the single I-shaped girder. The cross section of π-shaped steel girder is shown in figure1b. The prefabricated steel cross beam is placed at a four-point position of the bridge span. As shown in figure 1b, the π-shaped steel girder fully guarantees the stability of the structure and facilitates the overall prefabrication and hoisting of the members.

![Figure 1. Unit section form: (a)I-shaped; (b) π-shaped.](image)

The whole-span IPCG is divided into six units for overall prefabrication in transverse direction, and the transverse connection of the six prefabricated units needs to be considered. The connection
includes concrete slab members and the I-shaped steel beam members. The connection of concrete slabs can be connected by wet joints. In order to facilitate the transportation of prefabricated units, the bridge deck should be as small as possible to be single lane width, so the width of wet joints can be kept at 0.3-0.6m. The wet joints can be made of NC, and UHPC can be used to ensure the reliability of the overall mechanical behaviour of the bridge deck. The main steel beams are connected by steel cross beams to ensure the stability. A certain number of cross beams are required to ensure the stability of the beam when prefabrication, while no beam is required between the main beams as a stable structure has been formed during the hoisting construction. In addition, the cross beam will also participate in the lateral force transmission between the main beams, mainly to prevent the occurrence of uneven deformation. The lateral force transmission mainly relies on the concrete slabs at the mid-span, so the steel cross beam is only placed at the support. And the transverse connection of integrated prefabricated unit is shown as figure 2.

![Figure 2. Construction of transverse connection. (a) Support position; (b) Middle span position.](image)

When forming a multi-span continuous composite girder bridge, it is necessary to consider the longitudinal connection of simply supported composite beams. Since the prefabricated unit is placed on the support after hoisting, the cover beam of the middle pier of the multi-span continuous composite beam needs two rows of supports in the longitudinal direction, so as not to increase the longitudinal width of the cover beam. The centre line distance of the two rows of supports should be less than 1.4 m. The longitudinal wet joints between concrete slabs are cast in place, which are basically the same as the transverse connection. The longitudinal connection of the steel structure can be made by welding or bolting. Considering that the welding conditions on the site are difficult to guarantee, and in order to improve the construction efficiency, it is more feasible to use high-strength bolts. The splice plates are arranged on both sides of the web and flange plates for connection, which requires high processing precision. The details of longitudinal connection form for IPCG is shown as figure 3.

Considering the division of the transverse direction of IPCG to the prefabricated units and the transverse and longitudinal connections, the cross section form of the whole bridge is shown in figure 4, so that a span of composite girder bridge only needs 3 Prefabricated composite beam units.
3. Structural Rationality Analysis of Integrated Prefabricated I-shaped Steel-concrete Composite Girder Bridges

In order to research the structural rationality of the IPCG, the mechanical behaviour between the SPCG and IPCG is compared and analysed. The length and the width of the bridge are 5×35m and 25m respectively. The concrete deck has a net width of 24.7m and a thickness of 220mm; the upper flange of the main steel beam has a width of 400mm and a thickness of 16mm; the web plate has a height of 1439mm, a thickness of 16mm, and the web centre spacing of 2070mm; the bottom plate has a width of 500mm and a thickness of 25mm. The cross beam is placed at the support position and at the quarter point of the longitudinal direction. Since the two types of bridge structures are the same in size, the mechanical behaviour under the same load in the service stage is the same, and the comparison is unnecessary. But the difference between the two construction methods will lead to the different performance before the pavement stage. So only the difference between the two types of composite girder bridges before pavement is compared.

3.1. Mechanical behavior of Steel Beam on Construction

For the SPCG, the main steel beam is first erected, and then the concrete deck in the sagging moment area is constructed and combined with the steel beam through the studs. Finally, the concrete deck in the hogging moment area is constructed by combining the steel plate beam with studs. When constructing the concrete deck in the hogging moment area, the weight of the steel beam and concrete...
is completely born by the steel beam. At this time, the longitudinal compressive stress of the upper flange is large and which is easily buckled.

For the IPCG, the prefabricated steel beams are placed on the platform during prefabrication, and the concrete are directly casted into the formwork. At this time, the flanges of the steel beams do not have longitudinal stress. During construction, the prefabricated units are erected as a whole, and the weight of the steel beam and concrete are born by the composite beam. Because the concrete slab and the steel beam are born the dead load together, the longitudinal stress of the upper flange of the integrated prefabricated beam is less than that of the separated prefabricated beam. Since the concrete slab has a constraint effect to upper flange, the occurrence of buckling during construction is avoided.

For the SPCG, the most unfavourable state is the construction of the concrete deck in the sagging moment area after the erection of continuous steel beam. The finite element model is established as figure 5 for static analysis and buckling analysis. For the IPCG, the finite element model is shown in figure 6.

Figure 5. FEM of steel girder of the SPCG.  
Figure 6. FEM of prefabricated unit of the IPCG.

The calculation results are described as a half of the bridge in the longitudinal direction of the SPCG. The static analysis is carried out to obtain the curves of the longitudinal stress of the flanges along the distance to the beam end, as shown in figure 7 and figure 8 respectively. The maximum compressive stress of the upper flange is -80.6 MPa, and the maximum tensile stress is 102.9 Mpa. The maximum compressive stress of the bottom flange is -89.1 MPa, and the maximum tensile stress is 62.6 Mpa. The maximum shear stress of the web is 15.9 MPa. The elastic stability buckling analysis is carried out to obtain the first-order buckling mode, which is the overall bending and torsional buckling of the steel beam. The buckling mode is shown in figure 9 (only the side span steel beam is shown), which corresponding eigenvalue buckling coefficient is 4.4.

The calculation results of the IPCG are described by a whole span. The static analysis is carried out to obtain the curves of the longitudinal stress of the flanges along the distance to beam end, as shown in figure 7 and figure 8 respectively. The upper flange has only compressive stress, the maximum value is -15.2 Mpa. The bottom flange has only tensile stress; the maximum of it is 64.3 Mpa. The maximum shear stress of the web is 13.2 MPa. The first-order buckling mode of elastic stability buckling analysis is overall out-of-plane buckling, which is shown in Fig.10. The corresponding eigenvalue buckling coefficient is 31.8.
As we can see from figure 7 and figure 8, the longitudinal stress of the upper flange of the SPCG is much larger than that of the IPCG. The SPCG also generates more compressive stress on the bottom flange, while the IPCG not. The bottom flange tensile stresses of the two are relatively close. Therefore, the IPCG has a significantly better mechanical behaviour than the SPCG with the same structural dimensions. It is further explained that the use of the IPCG can greatly reduce the amount of steel in the case where the steel structural stress levels of the two are comparable.

In addition, as can be seen from figure 9 and figure 10, the steel girders of the two have different buckling modes during construction. The SPCG is unstable, because the buckling coefficient is small during construction. While the IPCG has a large buckling coefficient, and merely no instability failure occurs during construction.

In summary, under the action of one-stage dead load, not only the flanges of the IPCG have reasonable stress, but also the maximum shear stress of the web is relatively reduced. The restraining effect of the concrete slab effectively prevents the buckling of the upper flange of the steel beam from occurring.

3.2. Stress Analysis of Influence of Support Arrangement on Concrete Deck in Hogging Moment Area

Since the prefabrication unit needs to be integrally hoisted during construction, the support is required at both ends of the prefabrication unit. A double supports structure is designed at the hogging moment
area, forming a longitudinal connection shown in figure 3. And the steel beam is first erected and then the concrete bridge deck is constructed for the SPCG, a single support is designed at the same area, which is shown in figure 11. Therefore, under the same load, the double-support structure of the IPCG at the hogging moment area will cause less longitudinal stress of the concrete slab. Considering the action of the second-stage dead load, the finite element model is established to compare the stress in the hogging moment area of the two prefabrication methods.

Under the second-stage dead load, the concrete slab of the two prefabricated methods both have maximum longitudinal tensile stress at the hogging moment of the side span. Take the concrete slabs on the mid-support with a length of 4m and a width of 24.7 m. The longitudinal stresses of the concrete decks of the two structures are shown in figures 12 (a) and (b) respectively. For the SPCG, the maximum longitudinal tensile stress is 3.99 MPa. For the IPCG, the maximum tensile stress in the longitudinal direction is 3.10 MPa, and the latter reduces the stress by 0.89 MPa, which is 22.3%. There is a similar law for the concrete stress of the two forms under the action of vehicle loads.

4. Prospect of the IPCG
In order to realize the industrialized construction of the IPCG, it is necessary to further optimize the cross-sectional form, material and component size and form a standard design drawing.

(a) Optimize the cross-section form. In addition to the IPCG described in this paper, other cross section forms with high utilization of materials can be selected, such as U-shaped cross sections and truss cross sections.
(2) Optimize the materials, and select high-performance steel and concrete. For steel beams of composite bridges, weathering steel can be one of the directions of development. For concrete decks, high-performance concrete can be used.

(3) Optimize the component size. Based on the selection of reasonable cross section forms and materials, optimize the structure of the bridge for a variety of length of spans and widths to reduce the amount of materials. Making the structure optimal and forming a standard design to fully meets the actual needs of the integrated prefabricated steel-concrete composite girder bridges.

5. Conclusion
According to the actual situation of commonly used small and medium span bridges, the structural form of the integrated prefabricated steel-concrete composite girder bridge is proposed. And mechanical behaviors of the IPCG and the SPCG are compared, the following conclusions are obtained:

(1) Compared with the SPCG, the compressive stress of the upper flange of the IPCG can be significantly reduced under the action of first stage dead load, and the bottom flange will not produce compressive stress. The stress on the flanges is more reasonable, and the maximum shear stress of the web is also reduced. During the construction, the restraint effect of the concrete slab can effectively prevent the upper flange of the steel beam in the sagging moment area from buckling. In the service stage, due to the arrangements of the support, the longitudinal tension stress of the concrete slab in the hogging moment area is reduced to a certain degree.

(2) The construction costs of the IPCG will be higher than that of precast concrete box girders and precast concrete T-shaped beams. However, from the perspective of sustainable development, the IPCG has certain economic advantages considering whole-life cycle.

(3) The dead load of the IPCG is basically the same as that of precast concrete box girders and precast concrete T-shaped beams. The IPCG are feasible on construction, because the number of beams and wet joints are reduced significantly, which can effectively improve construction efficiency and reduce construction time.

(4) It is necessary to further optimize the cross-section forms, materials, and component dimensions of the IPCG and achieve a standard design drawing to meet the needs of large-scale application.

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