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RETRACTED: Study on the design of composite beams under complex environment in mountainous areas

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The mountain area is faced with complex conditions such as vertical and horizontal valleys, complex geological topography, many earthquake fault zones, high seismic intensity, fragile ecology, and changeable climate. The traditional concrete bridges have a heavy weight, high consumption of sand and gravel materials, large structural dimensions of steel box composite bridges, high steel consumption, and poor overall horizontal performance of steel plate composite beams, which are not suitable for mountain construction conditions. Therefore, based on the construction environment and application requirements of highway bridges in mountainous areas, the structural scheme of steel box-steel plate composite beam is put forward in this paper, and the design of a 25 m–50 m standard-span steel box-steel plate composite beam is studied. The results show that the steel box-steel plate composite beam structure scheme is adopted, which has excellent mechanical characteristics of steel box girder and simple structure of steel plate girder. It has the mechanical characteristics of "balanced transverse force and excellent longitudinal force", so it is a reasonable choice for small radius curved beam bridge in a mountainous area, so it is a reasonable choice for small radius curved beam bridge in a mountainous area. The steel box-steel plate composite beam adopts the integrated technology of manufacture, transportation and installation, which can better meet the road transport conditions in the mountain area. The longitudinal assembly of the manufacturing unit as the installation unit can ensure the rapid and high-precision installation of the construction site, and the assembly construction of the bridge in the mountain area has been realized. The technical and economic comparison shows that the mechanical performance of steel box-steel plate composite beam is similar to that of steel box beam and obviously better than that of steel plate girder. The steel consumption and construction period of steel box-steel plate composite beam are similar to that of steel plate girder, and are significantly less than that of the steel box girder. Therefore, the steel box-steel plate composite beam is a good choice for mountain bridge construction.

KEYWORDS

mountainous areas, composite beam, standard span, stress characteristics, prefabricated

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1 Introduction

Although the steel bridge technology in China started relatively late, after more than 30 years of great-leap-forward development, steel bridge construction technology has made great progress. Since the beginning of the 21st century, the main bridges built in China are basically steel structure bridges. At present, as the two major rivers in China, the Yangtze River and the Yellow River run from east to west, the natural conditions make researchers pay more attention to and develop long-span bridges. As a result, the long-span steel cable-stayed bridges, suspension bridges and arch bridges built in China are at the leading level in the world. However, compared with the outstanding performance of steel bridges in the construction of river-crossing and sea-crossing bridges, highway standard-span bridges are still mainly concrete bridges, while standard-span steel bridges are seldom applied and studied in China. For many years, except for a few span bridges and long-span bridges with building height restrictions, concrete bridges are generally adopted. There are many reasons for this situation, and the main reason is that we do not have a good understanding of the advantages of steel bridges and the significance of popularization and application. From the perspective of the whole life cycle, the cost and durability advantages of steel bridges are more prominent. Ministry of Transport of the People's Republic of China reported that steel bridges with light weight, beautiful appearance, fast construction, environmental protection, energy saving and easy reconstruction are the inevitable choice for modern bridge construction (Ministry of Transport of the People's Republic of China, 2016).

The early standard-span steel bridge is not only complex in structure but also has some problems, such as dense transverse braces between steel beams, a large number of steel beam web stiffeners, small beam spacing of longitudinal beams and so on. It leads to a large number of components, tedious construction process, large welding workload, high construction cost, and the structural fatigue damage effect is more significant under long-term operation. Since the 1970s, standard-span steel bridges have developed rapidly in France and Japan. The structural system of the main beam has been greatly simplified, in which the number of transverse connections is reduced, the vertical arrangement of dense vertical stiffening ribs and transverse stiffening ribs is canceled, the distance between the main beams is increased, and gradually develops to the direction of less main beams or double main beams. At present, foreign standard-span steel bridge has developed into a mature prefabricated bridge product, which has a set of mature construction systems from factory manufacturing, transportation, on-site assembly, operation and management. According to the investigation and statistics, American Association of State Highway and Transportation Officials introduced that the main cross-section forms of foreign standard-span steel bridges are small-spaced steel plate composite beams represented by Japan and the United States (the style of Japan is similar to that of the United States) (Eurocode 4: Design of composite steel and concrete structures, 2004; AASHTO LRFD Bridge Design Specifications, 2020; Japan Road Association, 2012). The other is the large-spacing steel plate composite beam represented by Europe (mainly France). The French steel plate composite beam greatly simplifies the traditional structural system, taking the double main beam steel plate composite beam as the mainstream. Basically, investigated that there are no transverse braces and web longitudinal stiffeners, which are one of the most economical forms of bridges (Abdel-Basset Abdo and Abo El-Wafa Mohamed, 2006; Matteis et al., 2010; Sarraf et al., 2013; Buckler et al., 2000).

However, the technical development of standard-span steel bridges in China lags behind, and mature technical schemes suitable for large-scale construction have not been found in all parts of the country, especially those suitable for the western mountainous areas. The relatively mature technical scheme of steel plate composite beams with fewer longitudinal beams is basically only suitable for plain areas with good transport conditions and technical strength. In view of the special topography, geology, transportation and other conditions in the mountainous area of western China, whether the rationality, economy and construction efficiency of the foreign standard-span steel beam technical scheme can be guaranteed is worthy of further study.

In recent years, China's highway construction has gradually penetrated into the western mountainous areas, passing through mountains and valleys more frequently, and the proportion of Bridges continues to rise. According to the statistics of the projects under construction, such as Jinshajiang Expressway in Sichuan, Jiuzhaigou Expressway to Mianyang Expressway in Sichuan, and Luding Expressway to Asbestos Expressway in Sichuan, bridge and tunnel account for more than 85%, and over 90% of the total Bridges are 25 m–50 m standard-span Bridges. The standard-span bridge of the mountainous expressway has the characteristics of large overall scale, large number of individual projects and extremely dispersed distribution. Meanwhile, it also faces the harsh environment of high seismic intensity, complex terrain and climate conditions, inconvenient transportation and lack of sand and stone resources (Chen et al., 2008; Chen and Wang, 2013). Under the construction condition of the mountainous area, compared with steel beams, that the standard-span concrete beam has poor seismic performance due to its self-weight, and the large amount of concrete leads to the huge consumption of natural materials such as sand and stone. In addition, there are unfavorable factors such as large number of construction templates and large occupied area of the construction prefabricated site (NIE, 2011; ZHAO et al., 2018, 2019). The size of structural members of standard-span steel box girder is large, and the space requirement of segment transportation is high. In the mountainous areas where the transportation network and construction access roads are tight and narrow, it is difficult to transport and install. In addition, there are various factors, such as high steel consumption, and poor economy (NIE et al., 2007; LIU et al., 2017; LI, Z. 2021), which restrict the application of this type of bridge. Due to the poor lateral integrity and low lateral stiffness of the standard-span steel plate girder, the peak transverse stress of the main beam is high under the heavy and partial load vehicle load of the mountain highway with a small curve radius and large longitudinal slope. As a result, the transverse connection structure is difficult to meet the stress requirements (Culmo, 2011; LEBEL and Hirt, 2013; Wei et al., 2017; YANG and XIA, 2020). Therefore, based on the construction environment and application requirements of the standard-span beam bridge of a mountain highway, the structural

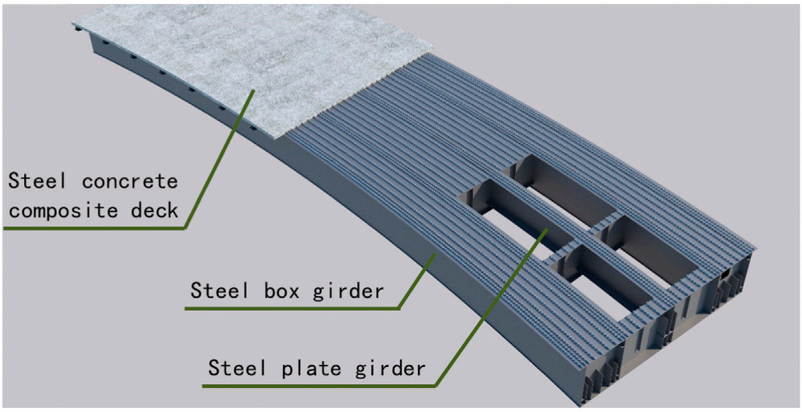

FIGURE 1
Structure of Steel box-Steel plate Composite Beam.

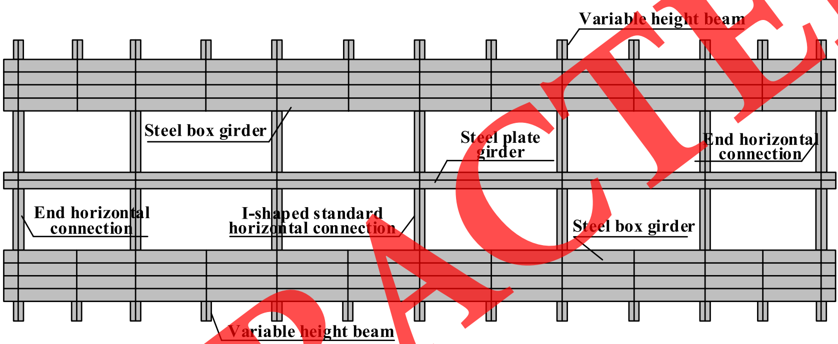

FIGURE 2
Plane of Steel box-Steel plate Composite Beam.

scheme of steel box-steel plate composite beam is put forward, and the related design and engineering application research are carried out in this paper.

2 Main beam structure

The steel box-steel plate composite beam adopts the structural form of "double steel side box + I-shaped steel plate girder added in the middle". The steel side box structure is symmetrically arranged on both sides of the main beam section, the I-shaped steel plate girder is added in the center of the section, and the I-shaped cantilevered beam is arranged on the outside of the top flange plate of the steel side box. In order to improve the lateral integrity of the structure of the steel side box and the steel plate girder on both sides, the I-shaped standard horizontal connection and the end horizontal connection are arranged at intervals along the length direction of the main beam. An integral cast-in-place steel-concrete composite bridge deck is arranged at the top of the main beam, and the overall structure of the main beam is shown in Figure 1 and Figure 2.

The economic span range of the steel box-steel plate composite beam is 25 m–50 m. The main structural parameters of the main beam are as follows: the height of the steel box girder is 1.8 m–2.3 m, the width is 1.8 m 2.2 m, the height of the I-shaped steel plate girder is 1.2 m 1.8 m, and the width of the upper and lower flange is 0.6–0.8 m (GB50917-2013, 2013), as shown in Table 1.

According to the forecast traffic volume and the long-term planning of social and economic development, expressways in mountainous areas of western China are usually designed as two-way four to six lanes, including ramp bridges of interchanges, and the single standard width range of highway bridges is usually 8.0 m–17.0 m (JTG D60-2015, 2015; ZHANG, 2017). To standardize the structural type of standard-span beam bridge, the force of main beam, the amount of material and the convenience of construction in the mountain area are considered in this paper. The structural classification system of double steel side box girder (B ≤ 12.5 m), double steel side box and composite main girder (B > 12.5 m) with an I-shaped steel plate girder in the middle of standard-span girder bridge is established, which provides a scientific and reasonable choice for the structural selection of standard-span girder bridge in the mountainous area. The details of the three main beam structures are as follows.

TABLE 1 Structural Parameters of Steel box-Steel plate Composite Beam.

Span (m)	Steel box girder		I-shaped steel plate girder		Horizontal quantity
	height/m	Thickness/mm	height/m	Thickness/mm	
25	1.8	12–16	1.4	12–14	5
30	1.8	14–20	1.4	14–20	6
35	2.1	14–20	1.6	14–20	7
40	2.3	14–20	1.8	14–20	8
50	2.3	14–24	1.8	14–24	9

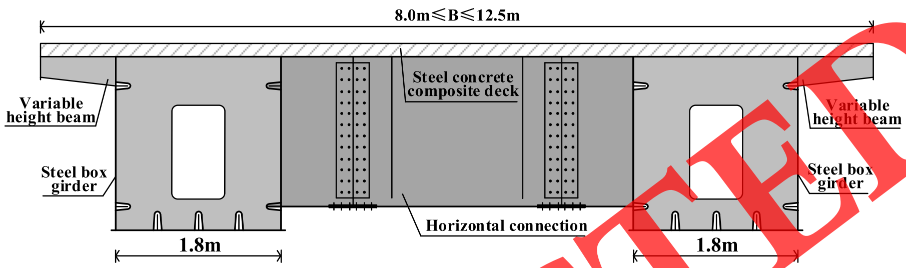

FIGURE 3
Double steel side box girder.

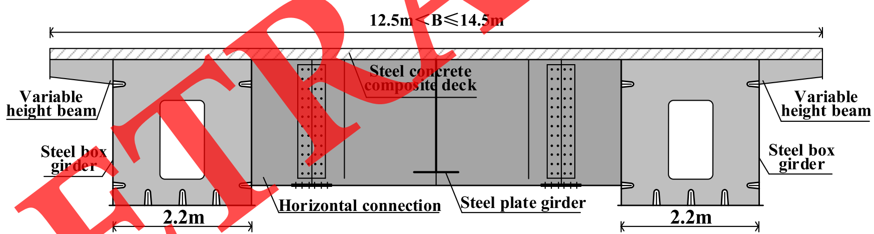

FIGURE 4
One I-shaped steel plate girder in the middle of double steel side box girder.

1) Double steel side box main beam

When the bridge width is 8.0 m ≤ B ≤ 12.5 m, a double steel side box main beam structure is adopted (Figure 3). Two steel side boxes are arranged symmetrically along the center of the section. The width of the box is 1.8 m. The I-shaped variable height beam is set outside the flange plate of the top of the steel side box.

2) Add one I-steel beam in the middle of the double steel side box

When the width of the bridge is 12.5 m ≤ B ≤ 14.5 m, the main beam structure of a double steel side box and I-shaped steel plate girder is added in the middle (Figure 4). Two steel side boxes (2.2 m wide) are symmetrically arranged along the center of the section, and an I-shaped steel plate girder is arranged at the center of the section. The I-shaped high-rise beam is arranged on the outside of the top flange plate of the steel side box, and the I-shaped steel horizontal connection is adopted between the steel side box and the I-shaped steel plate girder.

3) Two I-shaped steel beams are added in the middle of the double steel side box

The main beam structure of a double steel side box and two I-shaped steel plate girders is added in the middle (Figure 5) when the width of the bridge is 14.5 m ≤ B ≤ 17.0 m. Two steel side boxes (with a width of 2.2 m) are arranged symmetrically along the center of the section on the outside, and two I-shaped steel beams are arranged symmetrically along the center of the section on the inside. The I-shaped high-rise beam is arranged on the outside of the top flange plate of the steel side box, and the I-shaped steel horizontal connection is adopted between the steel side box and the I-shaped steel plate girder.

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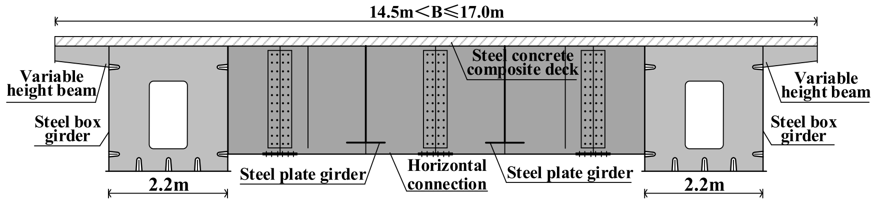

FIGURE 5
Two I-shaped steel plate girder in the middle of double steel side box girder.

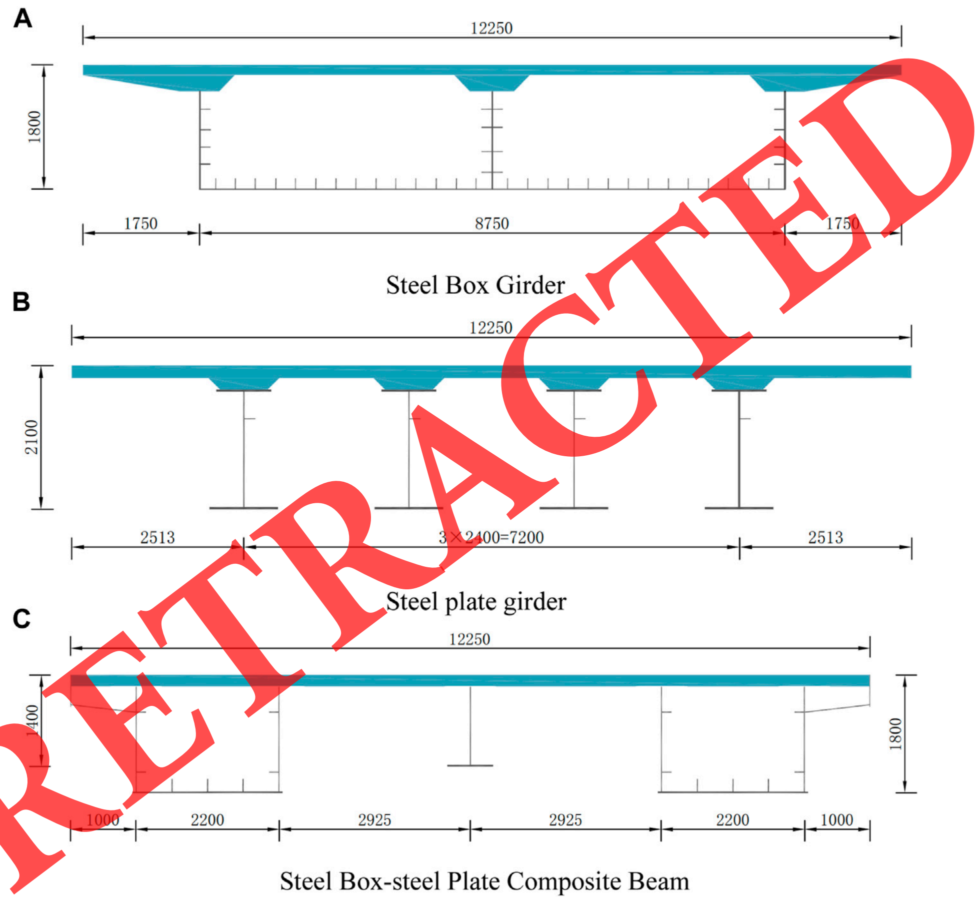

FIGURE 6
Calculation section of composite girder.

3 Analysis of mechanical behavior

3.1 Cross-section feature

In this paper, based on the same amount of steel used in the cross-section, the torsional section and bending section characteristics of the steel box girder, steel plate girder and steel box-steel plate composite beam with 30 m span and 12.25 m bridge width are calculated and analyzed. The section size parameters are calculated as given in Figure 6.

Figure 6A is the Steel Box Girder, Figure 6B is the Steel plate girder, Figure 6C is the Steel Box-Steel Plate Composite Beam.

3.1.1 Torsional cross-section characteristics

The cross-section of the standard-span steel box-steel plate composite beam is the combined section of the closed section of the steel box girder on both sides and the open section of the middle I-shaped steel plate girder. Considering it as a whole section, the sum of the torsional stiffness of steel plate girder and steel box girder is

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TABLE 2 Comparison of torsional characteristics.

Type of main beam	Torsional moment of inertia/mm4	Maximum shear stress/Unit moment	
		Steel box girder	I-shaped steel plate girder
Steel box girder	7.79×1011	543	-
Steel plate girder	1.83×1010	-	5465
Steel box-steel plate composite beam	2.58×1011	889	14

TABLE 3 Comparison of section bending characteristics.

Type of main beam	In-plane bending moment of inertia/mm4	Out of plane bending moment of inertia/mm4
Steel box girder	4.01×1011	9.42×1012
Steel plate girder	4.64×1011	8.49×1012
Steel box-steel plate Composite beam	3.08×1011	9.65×1012

the torsional stiffness of steel box-steel composite beam (HUANG, 1983; XU et al., 2004, 2007; NIE and TANG, 2006; NIE et al., 2008; LIU, 2019; ZHANG, 2019). Under the action of external torque, it is assumed that the circumference of the whole section rotates rigidly, then the middle I-beam under the whole section has the same torsion angle as the steel side box on both sides (i.e., the torsion angle per unit length of the closed thin-walled steel side box is equal to that of the open thin-walled steel plate girder). The torsional shear stresses of steel plate and steel box of steel box-steel plate composite beam section are obtained simultaneously according to the calculation formula of torsional shear stress of open section and closed section of material mechanics (Newmark, 1951; Batho et al., 1959; Viest and ASCE, 1960; Grant et al., 1977; Rotter and Ansourian, 1979; NIE et al., 1998; Fabbrocino et al., 1999; Amadio and Fragiacomo, 2002; JIANG et al., 2003).

According to the calculation formula of torsional stiffness and maximum torsional shear stress of steel box-steel plate composite beam, the torsional characteristics and section stress are calculated. When the unit torque T =1 kN/m² is taken as the acting load, the calculated results are shown in Table 2.

The calculation results show that the torsional rigidity of the composite steel box-steel beam and steel box-girder section is more than 10 times that of the I-steel plate girder section, which is due to the contribution of the torsional rigidity of the steel box on both sides of the section. The steel plate girder at the center of the section of the steel box-steel plate composite beam only bears a small torque when each part of the whole section has the same torsion angle. The maximum shear stress of its section is less than that of a steel box, and far less than that of the conventional steel plate girder, which avoids the disadvantage of small torsional stiffness of steel plate girder and ensures that the section of steel box-steel plate composite beam has excellent torsional characteristics.

3.1.2 Bending section characteristics

The bending section characteristics are calculated by using the finite element solid analysis software, and the moment of inertia of the above steel box girder, steel plate girder and steel box-steel plate composite beam is obtained as shown in Table 3 (WANG and SHAO, 1997; LI, 1998; WANG, 2003; FAN et al., 2004; ZOU, 2006; JIANG et al., 2013; HE, 2017; HE et al., 2022; ZHANG and ZHOU, 2022).

The calculation results show that the bending stiffness of the steel box girder, steel plate girder and steel box-steel plate composite beam is similar. Among them, the in-plane bending stiffness of the I-shaped steel plate girder section is slightly larger than that of steel box-steel plate composite beam section and steel box beam section, while the out-of-plane bending stiffness of steel box-steel plate composite beam section is slightly higher than that of steel box beam section and steel plate girder section.

3.2 Mechanical characteristics

Based on the analysis of the section characteristics of steel box-steel plate composite beam, the finite element solid calculation and analysis models of steel box girder, steel plate girder and steel box-steel plate composite beam with the same amount of steel in a 30 m span are established. The mechanical characteristics of the straight line and small radius curve (R = 100 m) main beam under structural dead load and vehicle load are studied, the finite element calculation parameters are as follows:

1) Element: The main girder is simulated by rod element, and the bridge deck is simulated by plate element;
2) Material: The main girder is Q345 steel (Strength design value: 270–275Mpa), and the bridge deck is C40 concrete;
3) Boundaries: Adopt single-span simply-supported beam model;
4) Load: Dead load includes the self-weight of steel structure of main beam, bridge deck, guardrail and so on. The ve hicle partial load adopts 55t standard vehicle, which is applied to the mid-span section according to the vehicle load, and the loading diagram is shown in Figure 7 and Figure 8. Figure 8A is Plane layout, Figure 8B is Vertical layout.

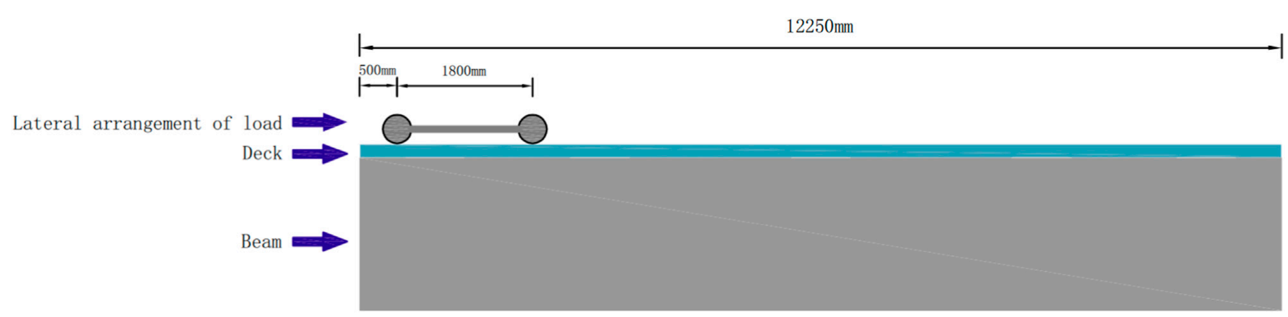

FIGURE 7
Schematic diagram of vehicle eccentric load.

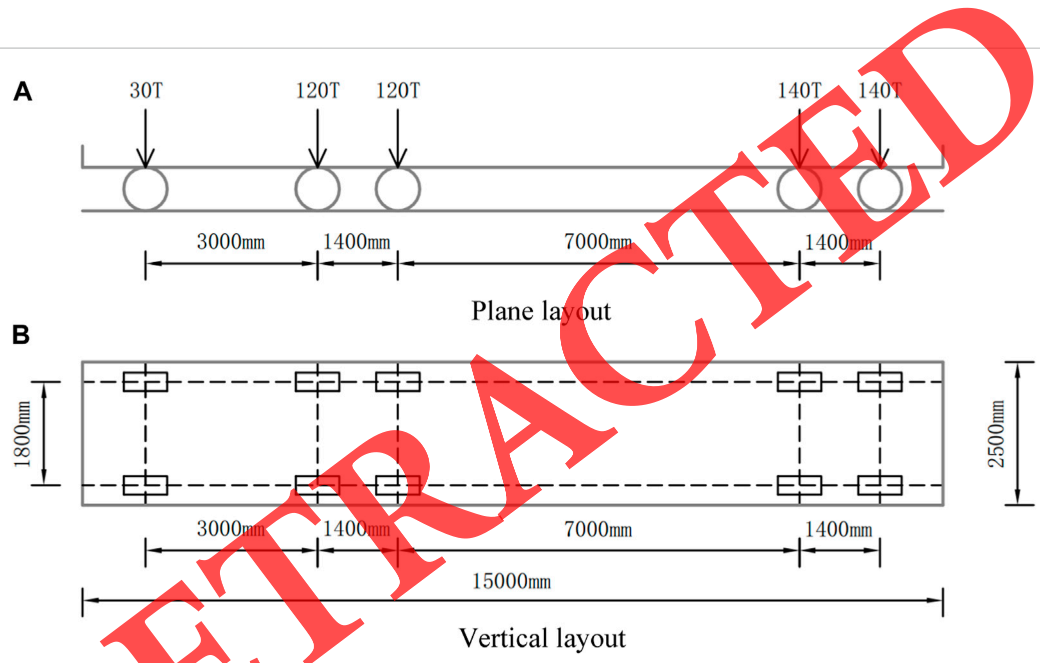

FIGURE 8
Vehicle load arrangement.

3.2.1 Transverse mechanical properties of linear main beams

In a straight line, the web stress calculation results of steel box girder, steel plate girder and steel box-steel plate composite beam under dead load and partial load are shown in Figure 9. Figure 9A is web stress of steel box girder, Figure 9B is web stress of steel girder, Figure 9C is web stress of steel box-steel plate composite beam.

The calculation results show that under the action of dead load, the equivalent stress index of each web of the straight main beam is more uniform, but there is a stress difference between the transverse webs under the action of vehicle partial load. Under the action of eccentric load, the stress difference ratio of the inner and outer web is regarded as the transverse transfer efficiency of the force, and the stress of each web of the steel box girder is more uniform. The maximum stress difference between the inner and outer webs is 3 MPa, and the lateral transfer efficiency is about 96.6%. The force acting on each web of the steel plate girder is extremely uneven, which causes the equivalent force of the web to fall rapidly along the transverse direction. The maximum stress difference between the medial and lateral webs is 29 MPa, and the lateral transfer efficiency is about 64.8%. The equivalent force of the steel box web of the steel box-steel plate composite beam decreases slowly along the partial load position to the other end of the transverse direction, the maximum stress difference between the inner and outer webs is 15 MPa, and the transverse transfer efficiency is about 82.0%. On the other hand, the stress of the web of the middle I-beam is obviously less than that of the side box. The above results show that under the action of automobile eccentric load, the outer web of steel plate girder with low torsional stiffness bears more load, and the stress index of the outer web is much higher than that of the inner web. The transverse torsion effect of the main beam makes the stress

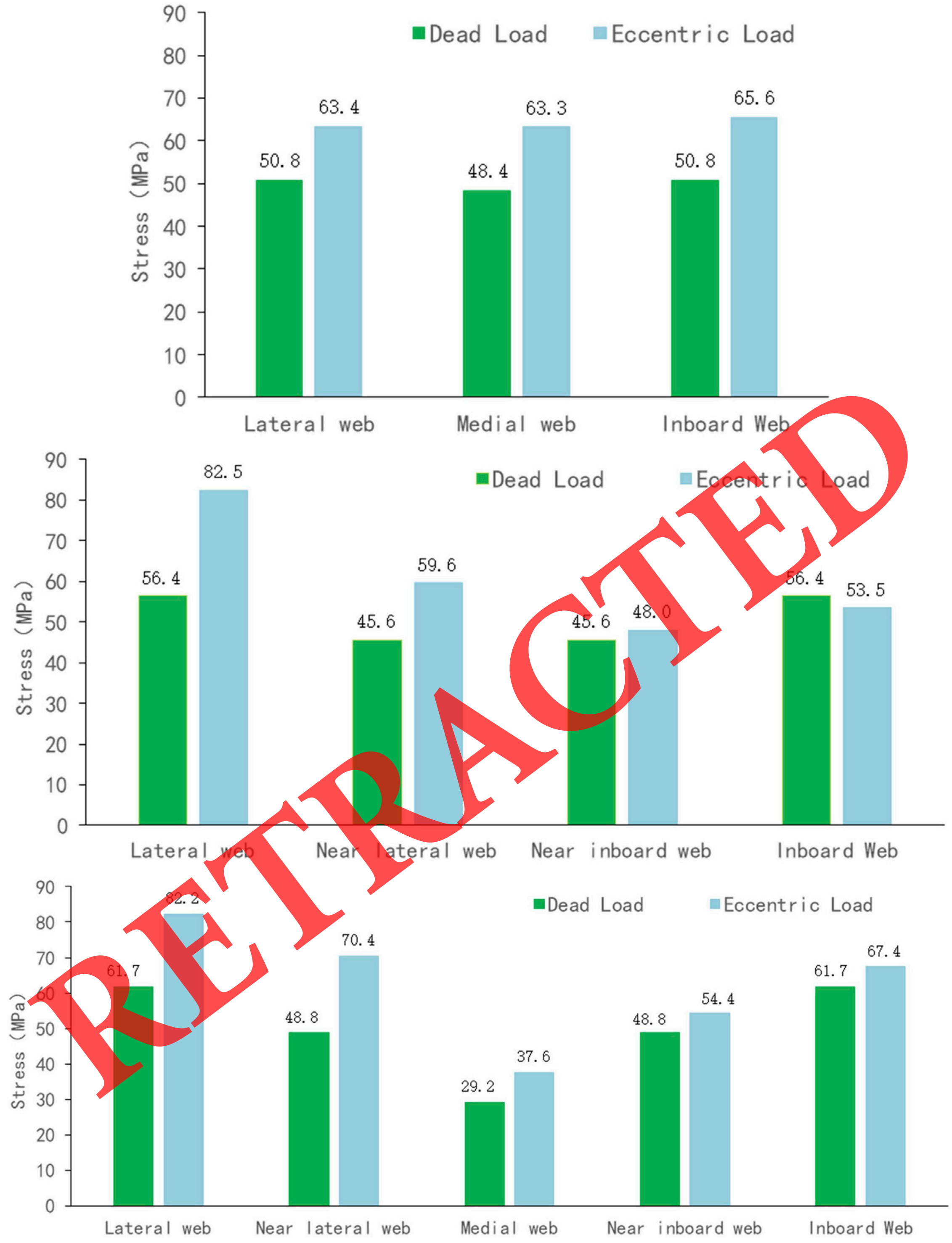

FIGURE 9
Comparison of web stress of straight girder.

of the inner web of the steel plate girder even lower than that of the dead load, and the phenomenon of "overloading of the outer beam and unloading of the inner beam" occurs. Because the torsional stiffness of steel box girder is much larger than that of steel plate girder, the cooperative force capacity between steel box-steel plate composite beam and steel box girder web is stronger, and the transverse stress transfer efficiency is higher. However, compared with the stress state of dead load, the stress of each web increases along the transverse direction under partial load, but the extreme stress condition of "overloading of outer beam and unloading of the inner beam" will not occur.

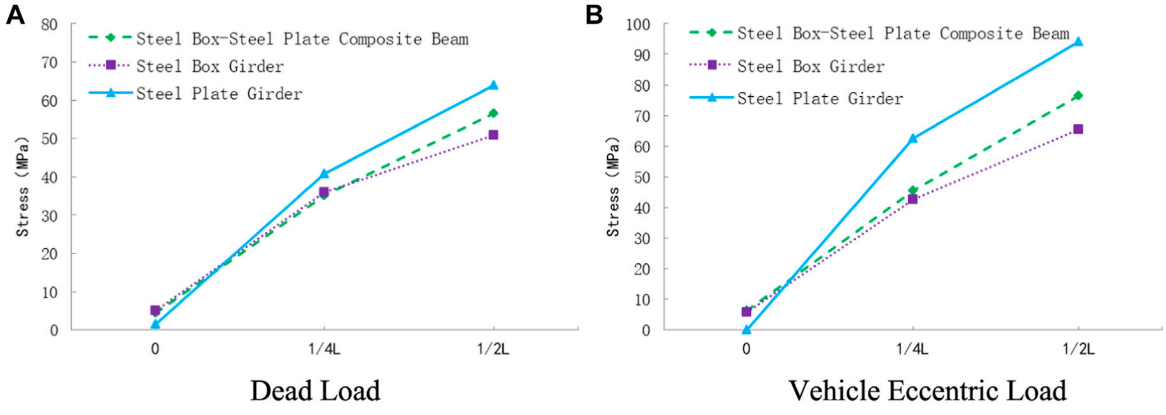

FIGURE 10
Comparison of normal stress of bottom of straight girder.

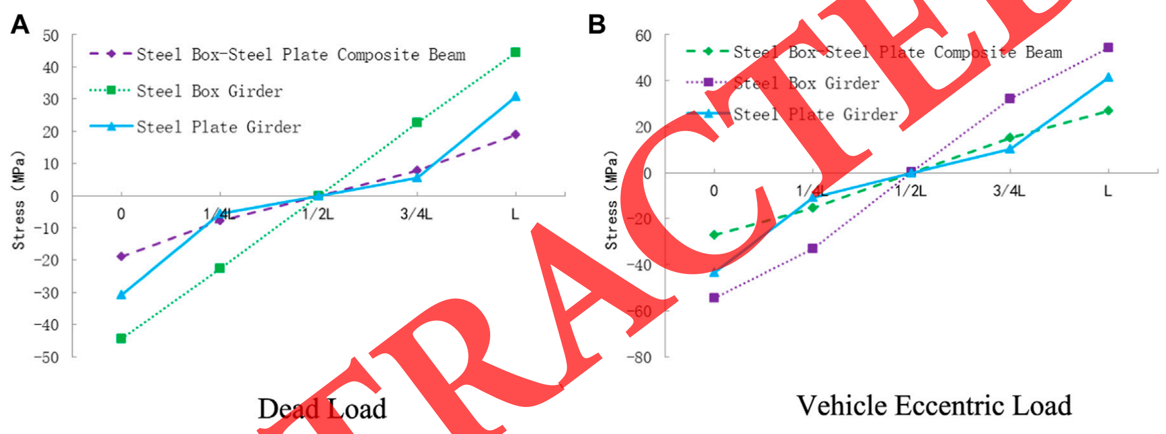

FIGURE 11
Comparison of web shear stress of straight girder.

3.2.2 Longitudinal stress characteristics of straight main girder

The calculation results of normal stress and web shear stress of steel box girder, steel plate girder and steel box-steel plate composite beam under dead load and partial load are shown in Figure 10 and Figure 11. Figure 10A is dead load, Figure 10B is vehicle eccentric load. Figure 11A is dead load, Figure 10B is vehicle eccentric load.

Under the action of dead load, the normal stress index of the linear steel box girder is the lowest, the steel plate girder is the highest, and the steel box-steel plate composite beam is in the middle. The shear stress index of steel box-steel plate composite beam is the lowest, steel plate girder is the second, and steel box girder is the highest. Under the action of vehicle partial load, the above force characteristics show a magnifying trend. The above results show that the bending force in the longitudinal direction of the main beam is mainly under the action of dead load. When the amount of steel used in the section is the same, the in-plane bending stiffness of the steel box section is slightly larger than that of the steel box-steel plate composite section, and the in-plane bending stiffness of the steel plate girder section is slightly higher than that of the former two. However, the weight of the bridge deck of the steel plate composite beam is larger than that of the other two kinds of the main beam. Therefore, the normal stress of steel box-steel plate composite beam is different from that of steel box beam and steel plate girder under dead load, but the index is close. The shear stress of single webs is significantly lower than that of steel box girder with 3 webs and steel plate girder with four webs due to the composite section of steel box and steel plate having five webs. Moreover, the stress of the three types of main beams increases under the action of the partial load, but the increase of the stress index of steel plate girder is larger than that of steel box-steel composite beam and steel box beam.

3.2.3 Transverse stress characteristics of curved main beam

In the curve state (R=100 m), the web stress calculation results of steel box girder, steel plate girder, and steel box-steel plate composite beam under dead load and partial load are shown in Figure 12. Figure 12A is web stress of steel box girder, Figure 12B is web stress of steel girder, Figure 12C is web stress of steel box-steel plate composite beam.

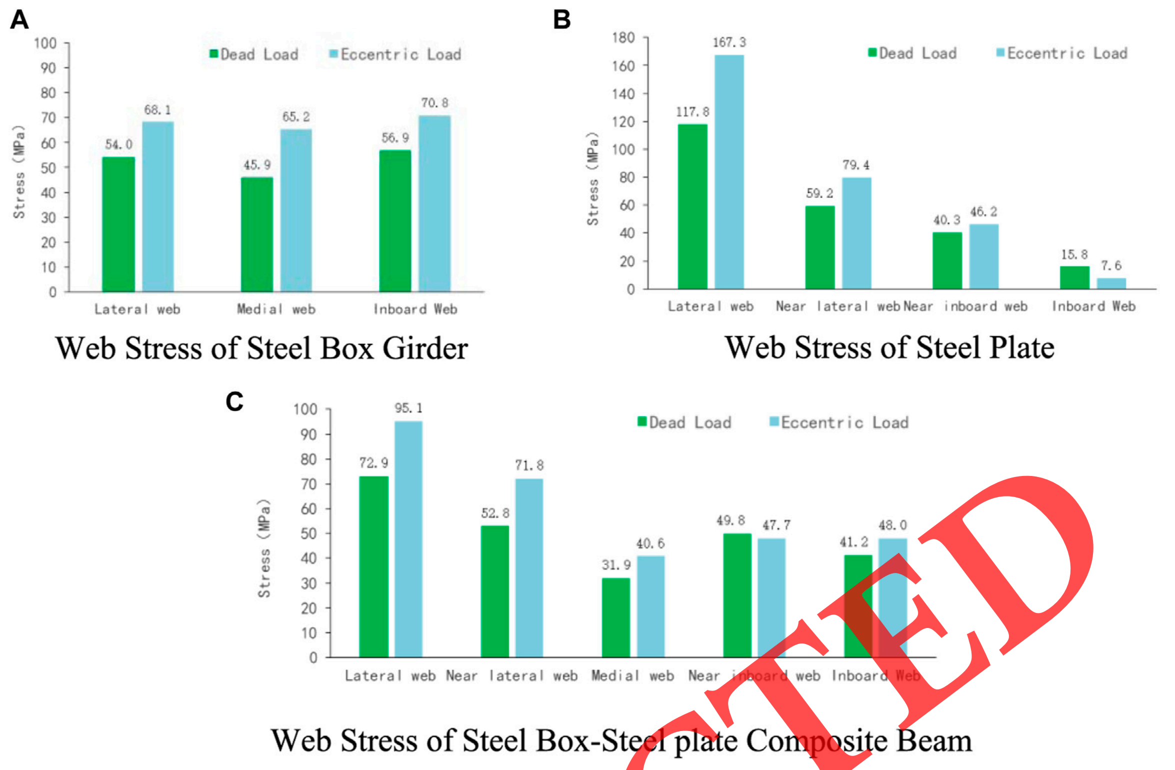

FIGURE 12
Comparison of web stress of curved girder.

TABLE 4 Deflection of girder under eccentric load on the outside of curve.

Type of main beam	Inner mid span deflection/mm	Lateral mid span deflection/mm	Deflection difference/mm
Straight steel box-steel plate composite beam	-2	-7	5
Curved steel box-steel plate composite beam	-2	-9	7
Straight steel box girder	-2	-7	5
Curved steel box girder	-2	-9	7
Straight steel plate girder	2	-8	10
Curved steel plate girder	1	-14	15

Under the action of dead load, the equivalent stress of the curved main beam is different between the lateral web and the medial web, and the force on each web is no longer balanced. The stress of each web of steel box girder is more uniform under the action of automobile partial load. The maximum stress difference between the webs is only 3 MPa, and the lateral transfer efficiency is about 96.2%. The force acting on each web of the steel plate girder is extremely uneven, and the equivalent stress of the web falls rapidly along the transverse direction. The maximum stress difference between the webs is 160 MPa, and the lateral transfer efficiency is about 4.5%. The difference in web stress distribution of steel box-steel plate composite beam is 45 MPa, and the transverse transfer efficiency is about 50.5%. The above results show that the phenomenon of "outer beam overloading and inner beam unloading" will occur in curved steel plate girders regardless of partial load or not. However, the transverse stress transfer efficiency of steel box-steel plate composite beam and steel box girder is high, and the transverse force is more balanced. This balanced transverse force characteristic is also reflected in the web deformation. Under the same lateral eccentric vehicle load, the deformation of the webs of three kinds of steel main beams is shown in Table 4. It can be seen that the deflection of steel box-steel plate composite beam and steel box beam is significantly smaller than that of steel box beam, and this law of curved beam is more obvious than that of the straight beam. These results show that the steel box-steel plate composite beam has obvious characteristics of lateral equilibrium force under the condition of a typical small curve radius route in the mountainous area.

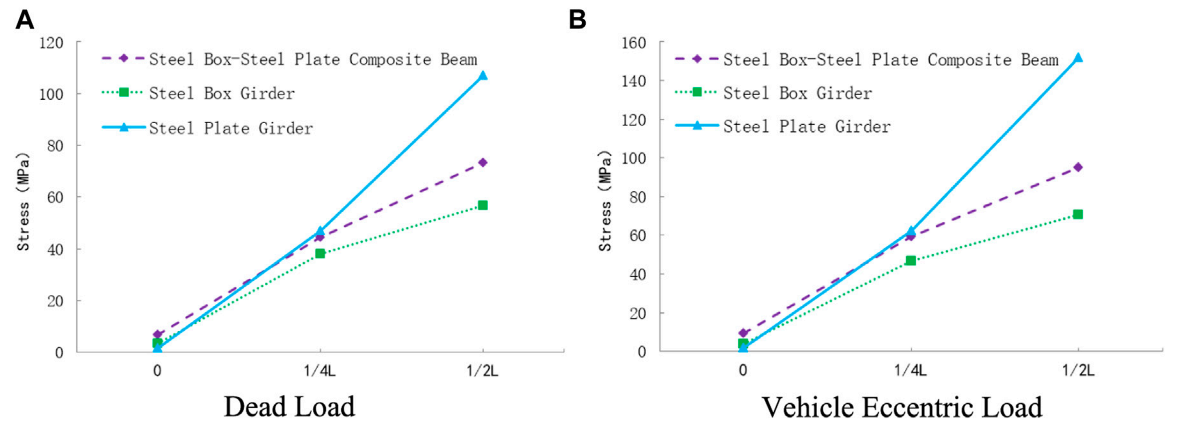

FIGURE 13
Comparison of longitudinal normal stress of curved girder.

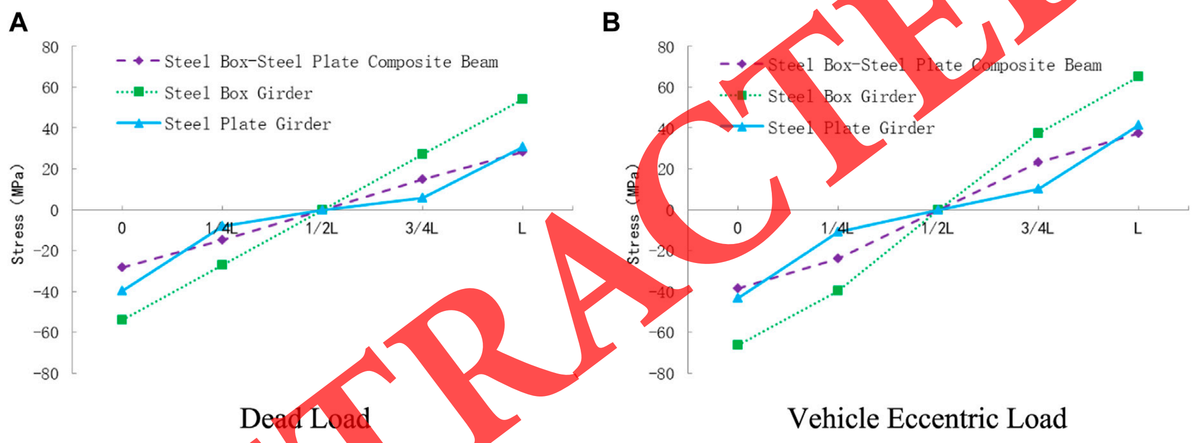

FIGURE 14
Comparison of shear stress of curved girder.

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3.2.4 Longitudinal stress characteristics of curved main girder

In the curve state (R=100 m), the calculation results of normal stress and web shear stress of steel box girder, steel plate girder, and steel box-steel plate composite beam under dead load and partial load are shown in Figure 13 and Figure 14. Figure 13A is dead load, Figure 13B is vehicle eccentric load. Figure 14A is dead load, Figure 14B is vehicle eccentric load.

Under the action of dead load, the normal stress index and shear stress index of curved steel box girder are the same as those of linear steel box girder. Through the analysis results, it is found that under the action of dead load, the main beam not only produces the longitudinal bridge bending moment, but also the curve arrangement of the main beam makes the main beam produce lateral eccentric force. Due to the difference in out-of-plane bending and torsional stiffness of the three kinds of steel main beams, the normal stress of steel plate girders is much higher than that of the other two kinds of steel girders. The bending and torsional force effect of the curved main beam under the eccentric load on the outside of the curve are further increased. The normal stress and shear stress of three kinds of steel girders have increased, in which the stress index of steel plate girder increases sharply, and the stress difference between steel box-steel composite beam and steel box girder is further enlarged. In addition, the section shear stress of steel box-steel composite beams with five webs is still lower than that of steel girders with four webs and steel box girders with 3 webs. The above results prove that the steel box-steel plate composite beam and steel box girder have excellent longitudinal stress states under the common curve radius in the mountain area.

4 Assembling construction

Based on the goal of integration of manufacture, transportation, and installation of the main beam, the steel box-steel plate composite beam is divided into steel side box element and I-steel plate girder element to realize the assembly and efficient construction of steel box-steel plate composite beam. The two types of units are composed of a

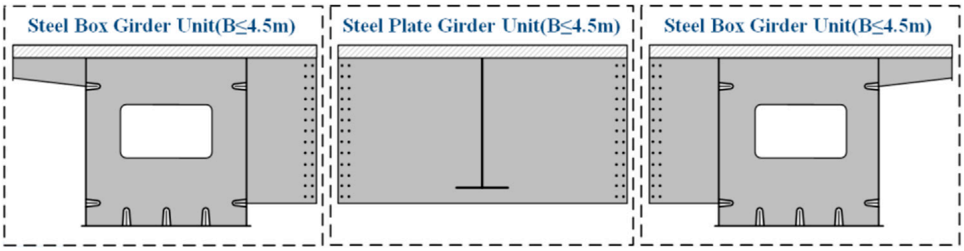

FIGURE 15
Standardized Manufacturing Unit of Steel box-Steel plate Composite Beam.

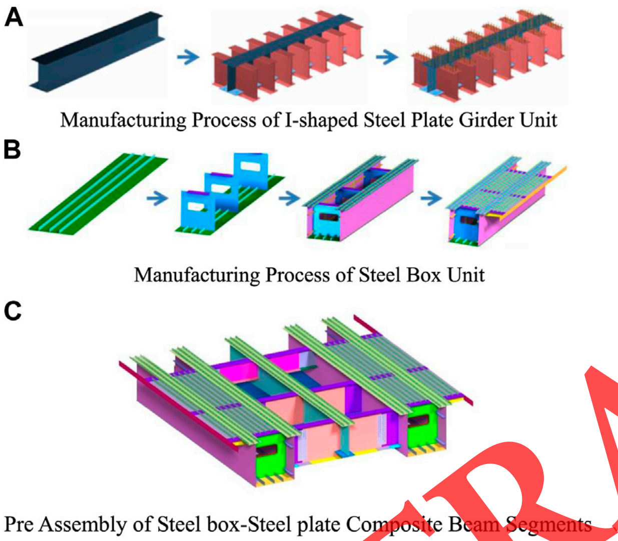

FIGURE 16
Manufacturing Diagram of Steel box-Steel plate Composite Beam Unit.

FIGURE 17
Transportation and Hoisting Construction of Steel box-Steel plate Composite Beam.

bottom plate, web, stiffening plate and splicing plate. The unit size is less than 4.5 m × 2.5 m × 15 m. After high-precision maching, manufacturing, assembly and pre-assembly are completed in the factory, the reduction manufacturing unit is transported as a transport unit to the bridge site, and the segment assembly and installation are completed. The assembly construction group is shown in Figure 15 and Figure 16. Figure 16A is manufacturing process of I-shaped steel plate girder unit. Figure 16B is manufacturing process of steel box unit. Figure 16C is assembly of steel box-steel plate composite beam segments.

The application of the Yakang highway lift interchange steel structure bridge shows that the manufacturing unit is used as the transport unit to meet the road transport conditions in mountainous areas. After the longitudinal assembly of the manufacturing unit, the installation unit is formed, and the installation of the beam section is quickly completed by a car crane of bridge erection machine. Figure 17A is standardized manufacturing transportation, Figure 17B is hoisting of steel box, Figure 17C is hoisting of steel plate girder. The integrated construction technology of manufacturing, transportation and installation reduces the temporary structural engineering in the process of manufacturing, transportation and installation. On average, it takes only 6 days to complete the

TABLE 5 Comparison of technical indexes of 30 m span girder.

Type of main beam	Concrete consumption	Steel consumption	Weight	Peak stress	Construction period	Construction cost
	/m3·m−2	/Kg·m−2	/kN·m	/MPa	/day	
Steel box girder	0.21	442	127.0	151	8	High
Steel plate girder	0.22	333	121.5	205	6	Low
Steel box-steel plate composite beam	0.21	311	111.4	160	6	Middle

transportation, secondary assembly and high-precision erection of the single-span main beam, and the geometric accuracy error of the main beam is less than 5 mm.

Taking the simply supported beam with a 30 m span and 12.25 m width in Sichuan Yakang Expressway as an example, the technical indexes of the steel box girder, steel plate girder, steel box-steel plate composite beam and prestressed concrete beam are compared, as shown in Table 5. The comparative analysis shows that the steel consumption, average construction period and seismic internal force of steel box-steel composite girder are less than those of steel box girder and steel box girder. The stress index of the main girder is similar to that of the steel box girder and obviously smaller than that of the steel plate girder, so it has excellent technical and economic indexes.

5 Conclusion

Based on the results obtained from this study, we can draw the following conclusions:

1) The integration of steel box-steel plate composite beam makes use of the excellent stiffness characteristics of steel box girder section and the simple structural characteristics of steel plate girder. Compared with the steel plate girder, the section stiffness and structural strength of the main girder are better, which avoids the stress problems of weak transverse stiffness and high stress index of the steel plate girder. The above good advantages are also similar to the mechanical properties of steel box girders.
2) The transverse mechanical properties of steel box-steel plate composite beams are good, and the torsional stiffness of its section is more than 10 times that of I-shaped steel plate girders. The lateral transfer efficiency of the force in the straight-line state is 1.26 times that of the steel plate girder, and the transverse force transfer efficiency in the curve state is 11.1 times that of the steel plate girder.
3) Based on the narrow road transportation conditions in the mountain area, an integrated unit of manufacture, transportation and installation is established, which takes the main beam as the main body and the total width of the component is not more than 4.5 m. It can realize the efficient assembly manufacture, transportation and installation of the steel structure main beam, overcome the construction problems of large transport components, on-site assembly and hoisting of the steel box girder, and make it have excellent adaptability in mountain construction.
4) In terms of mechanical behavior, the steel box girder is the best, but the three main girders can meet the structural stress requirements. For the construction of standard-span beam bridges in mountainous areas with many curved bridges, lack of sand and gravel resources and inconvenient transportation, steel box-steel plate composite beam is a competitive prefabricated main beam structure scheme.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YZ and CS proposed a new type of steel box-steel plate composite beam which is suitable for mountain construction. YZ was responsible for the research of technical route and calculation analysis, collected and analyzed data for various steel-concrete composite bridges, and wrote papers. CS carried out the structural design of steel box-steel plate composite beam structure, and applied the structure to bridge construction. SL has made contributions to the collection of existing research data and the field research of the project.

Conflict of interest

Author CS was employed by the company Sichuan Highway Planning, Survey, Design And Research Institute Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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