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Review of research on flexural properties of reconstituted bamboo-steel composite beams

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Abstract

As a big country of bamboo, bamboo resources occupy a quarter of the total area of bamboo resources in the world. Compared with wooden materials, bamboo materials as building materials, its longitudinal tensile property is about 2 times of it, the longitudinal compressive property is about 1.5 times of it; Compared with steel, its tensile property per unit weight is about 3~4 times of it, along the grain compressive property is about 1/5 ~ 1/4 of its. In the period of two five-year plan, the effective use of bamboo complex has been brought into the basic engineering of science and technology. During the 11th Five-Year Plan period, the Chinese high-tech research and development plan has been formally incorporated into the "high strength bamboo fiber composite material manufacturing technology". Bamboo composite and section steel have become the focus of the development of new materials in the future, they are organically combined into a complete material component, with outstanding functions and huge market prospects and development prospects.

Keywords

Bamboo, Section steel, Tensile property, Market prospects.

1. Background and significance of the research

With the development of high quality of Chinese economy and the continuous improvement of people's quality of life, people's demand for the housing is no longer only the function of shelter from wind and rain in the past, but more in green environmental protection sustainable development has new needs. In recent years, new policies have been implemented constantly, from the "Passive Ultra-low Energy Green Building Technical Guidance" issued by the Ministry of Housing and Urban-Rural Development in 2015, the "13th Five-Year Plan" Comprehensive Work Plan for Energy Conservation and Emission Reduction, the "13th Five-Year Plan" for Building Energy Conservation and Green Building Development, and the "Action Plan for Green Building Creation" issued in 2010, By the "14th Five-Year Plan for Building Energy Conservation and Green Building Development" issued by the Ministry of Housing and Urban-Rural Development this year, the state actively promoted the transformation of Chinese construction industry to green building, and continued to deeply promote the industrialization process of green building.

Green building people will think of wood, wood in history is the first used in the field of structural building materials. With the development of engineering construction, our specification of wood structure has been gradually improved. Our country invented mortise and tenon technology three thousand years ago, to be used in building the connection of beams and columns. Thanks to the maturity of mortise and tenon technology, many ancient wooden structures in China have been retained [1]. Based on the wood industry, the industrial modern prefabricated wood structure industry has gradually developed, which can meet the design needs of various building types. However, the prefabricated wood structure industry in China has a small scale and obvious gap in technical level, so it cannot become the main force of green building. China's forest area and savings rank top in the world, but its per capita area is small, 22% of the world average, and its per capita forest stock is even lower, only 14.6% of the world average. However, due to the mechanical properties of wood itself, the properties of materials in different regions are quite different, such as large wet growth, low flexor elastic modulus, poor impact toughness and other inevitable shortcomings, which can only be used in some specific structures. Since the financial crisis, the international forestry market is flagging, the import and export trade of Chinese wood fluctuates greatly, and the import of wood is more restricted. All these have produced great resistance to the development of Chinese wood structure.

Light steel structure, as a member of modern green building, has attracted more and more attention. Light steel structure generally has two kinds, one is composed of cold-formed thin-wall steel directly to form the skeleton, the other is composed of small section steel truss, truss frame. Cold-formed thin-wall steel was first used in automobile and aircraft manufacturing in the United States. After World War II, light steel structure was used in office and residential building systems in Britain and France. In the 1980s, cold-formed thin-wall steel structure was introduced in China, which was mostly used in low-rise residential buildings. The raw material of cold-formed thin-wall section steel is hot rolled or cold rolled strip steel, which is a variety of complex section steel made by pressure processing under normal temperature. At present, the current design specification of cold-formed thin-wall steel in China, Technical Specification for Cold-formed Thin-wall Steel Structure (GB50018-2002), has made specific requirements for the design of various sections and guaranteed the engineering quality and safety. Various forms of sections are shown in Figure 1. Because the section of thin-wall steel member is mostly open with large width and thickness, the member itself is easy to be affected by slenderness ratio and initial defects, etc., which is prone to local buckling in the process of stress, resulting in defects in the bearing capacity, stiffness and other performance indexes of the member. In order to solve the defect problem of cold-formed thin-wall steel, many scholars at home and abroad have carried out research on various combination forms of cold-formed thin-wall steel. Now the main combination forms are cold-formed thin-wall steel composite structure, cold-formed thin-wall steel concrete composite structure, cold-formed thin-wall steel and wood composite structure, cold-formed thin-wall steel and bamboo composite structure. The appearance of composite structure effectively improves the initial defects and local buckling problems of cold-formed thin-wall steel, avoids instability and failure of members before reaching the ultimate bearing capacity, and also reflects the excellent collaborative working ability of composite members.

As a kind of building material with a long history, bamboo has been widely used by people in various fields of living and living. The bamboo resource is particularly rich, occupying about 1/4 of the total area of bamboo resource in the world. It is one of the origin centers of bamboo in the world. Bamboo is grass rather than wood, which has a short growth cycle and can be put into use in 3-5 years, so it has a broad development prospect and market. Bamboo material as the same kind of building materials, compared with wooden material, its longitudinal tensile property is about 2 times of it, the longitudinal compressive property is about 1.5 times of it; Compared with steel, its tensile performance per unit weight is about 3~4 times that of it, and its longitudinal compressive performance is about 1/5 ~ 1/4. In terms of durability, corrosion resistance and high temperature resistance, the heat treatment process of recombinant bamboo makes its performance better than that of wood, and the recombinant bamboo still maintains high strength at 150℃~200℃. The application of bamboo in engineering mainly includes reconstituted bamboo, bamboo plywood, bamboo particleboard, etc., among which bamboo integrated wood and reconstituted bamboo wood are widely used. After nearly 20

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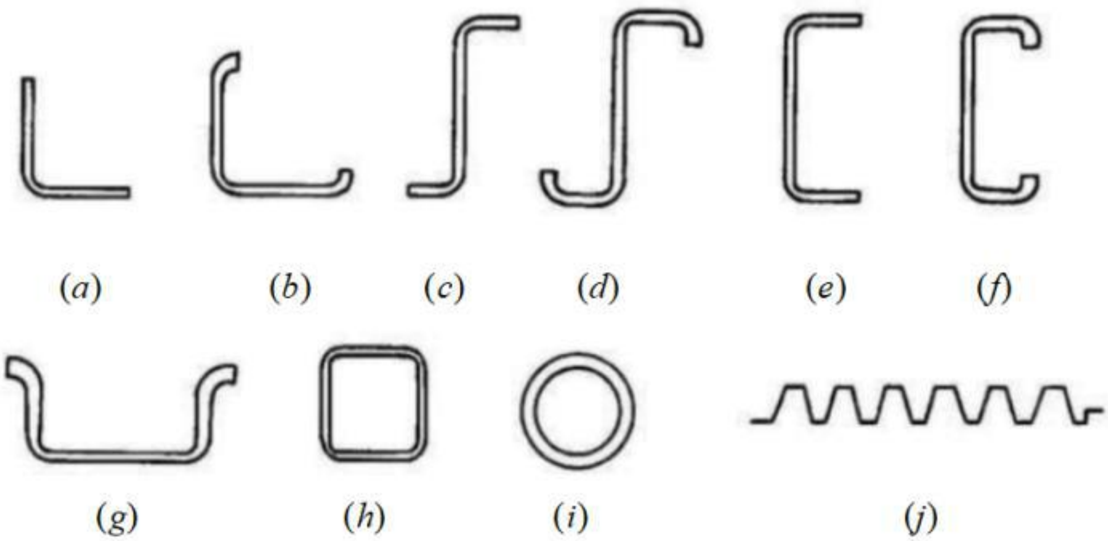
years of research, development and transformation of the reconstituted bamboo, the previous reconstituted bamboo used the leftover bamboo threads in daily life, and the bamboo bundles produced after dredding are the main raw materials. However, the emergence of a new production method developed by the Chinese Institute of Forestry Chemistry, bamboo based fiber material, has greatly improved the recycling efficiency and manufacturing quality of bamboo materials. It also enables the industrial production of reconstituted bamboo to be realized. The details are shown in Figure 2 and Figure 3. Domestic scholars and research institutes have done research on the basic mechanical properties of reconstituted bamboo. The research shows that the longitudinal tensile strength and tensile strength of reconstituted bamboo are relatively stable. Compared with wood, the longitudinal tensile strength is about 150% to 380%, and the longitudinal compressive strength is about 200%. The failure process of reconstituted bamboo is divided into three stages, showing good ductility.



(a) equilateral Angle steel; (b) rolled equal Angle steel; (c) Z-shaped steel; (d) Sawtooth steel; (e) channel steel;
(f) winding channel steel;(g) cap steel; (h) Welded square pipe; (i)Welded round pipe; (j) Molded plate

Fig 1 Common section shape of cold-bent thin-wall steel

Fig 2 Vedana Restaurant in Vietnam

Fig 3 Aman Convention Center

Both reconstituted bamboo and cold-formed thin-wall steel have their own competitive advantages and development potential. The organic combination of the two can become the development trend of the future construction industry and meet the national requirements of environmental protection and carbon neutrality. The reconstituted bamboo is added to the light steel structure, and the renewable raw materials, 100% recycling and dry treatment on the construction site eliminate the production of construction waste, and truly achieve green, low-carbon and environmental protection. This paper combines the reconstituted bamboo and the cold-formed thin-wall steel to form the cold-formed thin-wall steel-reconstituted bamboo composite beam, which can not only solve the flexural defects of the thin-wall steel members, but also make full use of the mechanical properties of the reconstituted bamboo, so that the two can work together better. Further research and discussion on the overall mechanical properties of reconstituted bamboo-cold-formed thin-wall steel composite beams are needed to provide valuable theoretical basis for application in practical engineering.

2. Research status at home and abroad

2.1. Research status of steel-concrete composite beams

In foreign research, at the beginning of the 20th century, reinforced concrete composite structure began to be paid attention by western scholars because of its high strength, excellent fire resistance and durability. After various tests, a series of design specifications were formulated. Later, the west has carried out more extensive and standard research on steel-concrete composite beams.

At the end of the 20th century, Elnashai et al. conducted mechanical properties tests under cyclic and transient dynamic loads on reinforced concrete composite beams with external concrete with lateral reinforcement, and the tests showed that the ductility and toughness of composite beams were significantly improved after modified section.

Nguyen et al. conducted a study on cold-formed thin-wall steel tubular concrete composite beams. The test showed that cold-formed thin-wall steel with the same section area as steel bars could replace traditional steel bars, making the composite beams reach the theoretical ultimate bearing capacity in flexural and shear. The empirical formula for shear bearing capacity of composite beams was preliminarily fitted, and the reliability of the equation was verified.

Hunaiti tested steel tubes with different sections filled with foam and lightweight aggregate to study the influence of concrete on the strength of composite structures. The test results show that the influence of foamed concrete on the compressive capacity of composite members can be ignored, and the tensile and flexural capacity of lightweight aggregate foamed concrete has significantly improved.

JG et al. derived the equivalent stiffness and elastic flexural strength of composite beams by conducting in-depth research on the dynamic stability of steel-cement composite beams with molded plates, and formed the theoretical equation of ultimate flexural strength. The experimental results show that the formula is correct and consistent with the experimental results.

In order to optimize the structure size, Tormen et al. established a mathematical model of steel-concrete composite beam through finite element software to control the size of steel and the thickness of concrete web. Based on the optimization proposed by Medeiros and Kripka, they improved the model. Tests showed that the composite beam had excellent performance and the optimized solution was effective. Composite beams can greatly reduce costs and obtain sufficient strength.

Subhani et al. studied the reinforcement of steel-concrete composite beams with profited steel plates, and compared and analyzed the flexural capacity, shear capacity, ductility and strain distribution of composite beams. The test showed that the properties of composite beams could be significantly improved by reinforcing the web of steel beams with carbon fiber reinforced polymer or steel plates. High strength bolt reinforcement can enhance the longitudinal shear strength of composite beams, but at the same time, the combined reinforcement will cause brittle failure and reduce the ductility of composite beams.

In the domestic research, in the 1920s, based on the consideration of fire performance, the study of steel beams outsourced concrete began. After the 1923 earthquake in Japan, it was found that the steel - concrete composite structure had excellent seismic performance, so a lot of research was carried out quickly. Steel-concrete composite structure of Wuhan Yangtze River Bridge was first used in China .

Nie Jianguo et al. have conducted a lot of research on the mechanical properties of steel-concrete composite beams. The tests show that the composite beams have excellent strength and ductility, and their bending strength is greatly affected by the slip effect. Based on the relative slip differential equation, the deformation formula and deflection formula of composite beams caused by the slip effect under different loads are derived. Based on the finite element program, the nonlinear stress analysis model of prestressed continuous composite beams and the calculation model of negative moment section bearing capacity of composite beams with different connections are established.

Zhou Qiliang et al. analyzed the equivalent bending stiffness of steel-concrete composite beams in a frame, and established the equivalent stiffness theory of composite beams under vertical loading with piecewise stiffness. The test shows that the rotational constraint stiffness of beam ends has a significant effect on the length of the negative bending moment zone and the equivalent bending stiffness of composite beams under vertical uniform load.

Compared with traditional steel-mixed beams, steel-concrete composite beams have lower dead weight and excellent seismic performance, which enhances the ductility of beams, reduces the section size of components, saves space and steel. Based on prefabricated construction, the construction period is shorter. However, most of the negative bending zone of composite beams will cause local distortion and yield due to the lateral bending instability of section steel and transverse deformation of web. The width and development range of cracks in the tensile zone of the beam span are larger than those of reinforced concrete beams.

2.2. Research status of cold-formed thin-wall steel - wood composite beams

In foreign studies, Issa CA et al. studied the reinforcement of wood beams, and conducted mechanical properties of wood beams reinforced by steel plate and carbon fiber reinforced polymer respectively. The tests showed that the bearing capacity of wood beams reinforced by steel plate increased more, and the failure mode of beams changed from brittleness to ductility.

Borri A et al. conducted a study on high-strength steel wire reinforced wooden beams, and carried out a flexural test on wooden beams with a four-point loading test device. The test showed that the external adhesion of steel wire significantly improved the flexural rigidity and ultimate bearing capacity of wooden beams, and derived the theoretical formula, showing that the error between the theoretical value and the test value was small.

Hassanieh A et al. conducted mechanical property tests on steel-wood composite beams with different connection forms. By analyzing the ultimate bearing capacity, failure mode, mid-span deflection and mid-span torsion of composite beams, they concluded that the combination of structural adhesive and mechanical connection could provide complete compound effect on composite beams and significantly increase the initial stiffness of composite beams. The composite beam with simple glued connection will have brittle failure when it is loaded in the same direction as the planks, and ductile failure when it is loaded perpendicular to the direction of the planks.

Borchani W et al. studied the flexural performance of I-beam composite beams with different sections. By analyzing the influence of parameters of web thickness, beam length and beam height, the test showed that the critical buckling load of composite I-beam was greatly affected by web thickness and beam height, and the increase of beam height was more likely to cause beam distortion. Increasing the thickness of web can increase the critical buckling load of beam. The roof of the Ghost Stone multi-function Hall in Japan adopts the steel-wood composite structure. Wood is used in the web, and steel is pasted on the outside of the web as the flange to form steel-wood composite beams. This is a practical case of steel-wood composite structure applied in engineering.

In domestic studies, Li Denghui, Li Tongtong et al. studied the mechanical characteristics of I-section steel-wood composite beams, set wood thickness, steel flange thickness and width, web height and other variables, compared and analyzed the stress and deflection curves of composite beams under different loading conditions, and studied the bearing capacity and flexural stiffness of composite beams. Based on the finite element software, the model of the composite beam is established, and the calculation formula of the mid-span deflection and bearing capacity of the composite beam is simplified. The test shows that the overall working performance of the composite beam is good, the mid-span cross section strain is proportional, the connection strength of steel and wood has a great influence on the bearing capacity and deformation of the composite beam. For the composite beam under shear, the flexural strength determines the failure of the composite beam with shear span ratio above 3.0. The shear strength determines the failure of composite beams with shear span ratio below 1.6.

Zhang Haiyan studied the flexural performance of box-type steel-wood composite beams, set parameters such as height-width ratio and width-thickness ratio, and calculated the flexural capacity and flexural rigidity of wood, steel and composite beams under different parameters. The test proved that the overall performance of composite beams was significantly improved, and the mid-span section deflection of components before yielding was proportional to the section height, conforming to the assumption of flat section. The ratio of width to thickness has a great influence on the ductility of composite beams. The increase of the ratio of height to width can improve the flexural bearing capacity and flexural rigidity of composite beams. In contrast, the ratio of height to width has a greater influence on the design of composite beams.

Zhao Yuting studied the mechanical properties and connection characteristics of H-shaped steel-wood composite beams. The tests showed that the final displacement, ductility coefficient, energy dissipation and maximum tensile strain of the specimens were proportional to the shear span ratio, and the initial stiffness and maximum pressure should be inversely proportional. With the increase of bolt spacing, the initial stiffness of the specimen increases. The performance of composite steel and wood beams is better than that of pure steel beams, and the calculation formulas of flexural stiffness and flexural capacity are simplified. The average error between theoretical and experimental values is less than 5%.

Liu Degui et al. studied the flexural performance and interface connection performance of built-up H-section steel and wood composite beams, discussed the composite beams with parameters such as board thickness, H-section thickness, bolt spacing, height of web boards and different connection forms, and proposed the calculation formulas of mid-span deflection and flexural capacity of composite beams and shear capacity of connection interfaces. The results show that the height of web board, bolt spacing, flange plate width and thickness have significant effects on the flexural performance of composite beams, while the influence of web board thickness can be ignored. The connection mode of screw plus epoxy resin adhesive can effectively avoid the brittle failure characteristics of simple screw connection and simple resin adhesive connection. The theoretical values calculated by the formula are in good agreement with the experimental values.

2.3. Research status of cold-formed thin-wall steel - bamboo composite beams

In foreign studies, Al-Fasih et Al. studied the mechanical properties of bam-reinforced concrete beams, and discussed the bearing capacity, failure form and failure mechanism of composite beams by comparing and analyzing parameters such as bamboo section size, bamboo type and water content. The tests showed that the type of bamboo has a significant impact on the tensile strength of bamboo. The optimum water content of bamboo is 12%. The bearing capacity of bamboo-reinforced concrete composite beams is proportional to the cross-section size of bamboo boards. The deflection of composite beams is controlled by the ultimate tensile strength of bamboo boards.

Ghavami and Tsutsumoto et al studied bamboo reinforced concrete beams and compared and analyzed the linear stiffness, ultimate load, shear strength and bending strength of beams strengthened with bamboo boards. The test shows that the reinforced concrete beams reinforced with bamboo can effectively improve the flexural performance of the beams and reduce the amount of reinforcement, but the bearing capacity of the beams will not be reduced. The reinforcement of bamboo boards will not change the failure form of the beams.

Haryanto Y et al. studied the mechanical properties of bamboo-concrete slabs under concentrated loads. By determining the ultimate load, stiffness, cracking mode and toughness of composite slabs, they evaluated the influence of bamboo-reinforced concrete slabs on structural properties. Tests showed that the mechanical properties of bamboo-concrete and reinforced concrete slabs were comparable. The strength of reinforced concrete slab is 82% and the ductility is 92%. Bamboo can be further studied as an alternative to steel.

Quaranta G et al. studied steel-bamboo composite truss beams, analyzed the dynamic response of the truss beams and the free attenuation response of the structure under environmental vibration, and estimated its modal characteristics. The tests showed that the composite truss had excellent seismic performance and bearing capacity, and the combined connection of bolts and structural adhesive significantly improved the bearing capacity of the truss.

In the domestic research, Shen Huangying et al. conducted a bending test on the I-section cold-formed thin-walled bamboo plywood composite beam, set the thickness of the bamboo plate, the thickness of the section steel and the section size as parameters, and comprehensively compared the strain of the steel plate and bamboo plate under various loads, the development of the deflection and the failure process of the composite beam. The test showed that the composite beam worked well together and had significant combined effect. The bearing capacity of composite beam increases with the increase of steel plate thickness, bamboo plate thickness and section size.

Zhao Jiayao studied the flexural properties of rectangular steel tubular and bamboo plywood composite beams, set the section size, thickness of section steel and screw connection variables, and comprehensively compared the strain and deflection curves of the composite beams under different loads. The tests showed that the overall working performance and strength of the composite beams were significantly improved after the structural adhesive connection and screw reinforcement. Its bearing capacity is proportional to the calculated deflection, and the ultimate bearing capacity is far beyond the normal use limit state, with excellent safety.

Lv Bo, Li Zhuolin studied the mechanical properties of steel-bamboo composite box beams, and compared the flexural and shear properties of composite beams by controlling the thickness of steel plate, the thickness of bamboo plate and the section size of composite beams. The formulas for calculating the flexural and shear capacity and mid-span deflection of composite box beams under the limit state were deduced. The error between the theoretical and experimental values was small. The results show that the failure of the composite beam is ductile failure, and there is no obvious slip at the interface joint. The bearing capacity of the composite beam increases with the increase of the thickness of the steel plate, the thickness of the bamboo plate and the section size of the composite beam, and the section size has a significant effect. Most of the cross section forms in the study are shown in Figure 4.

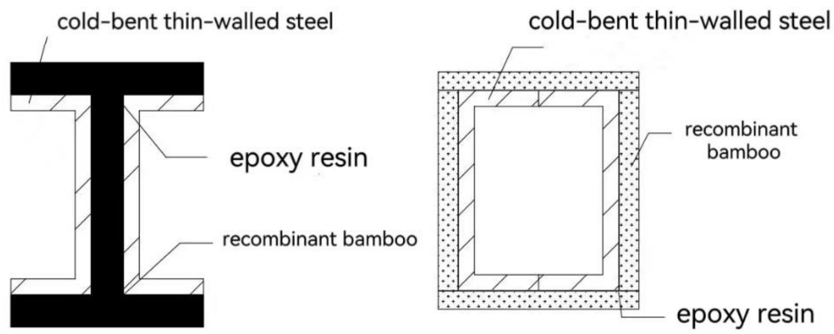
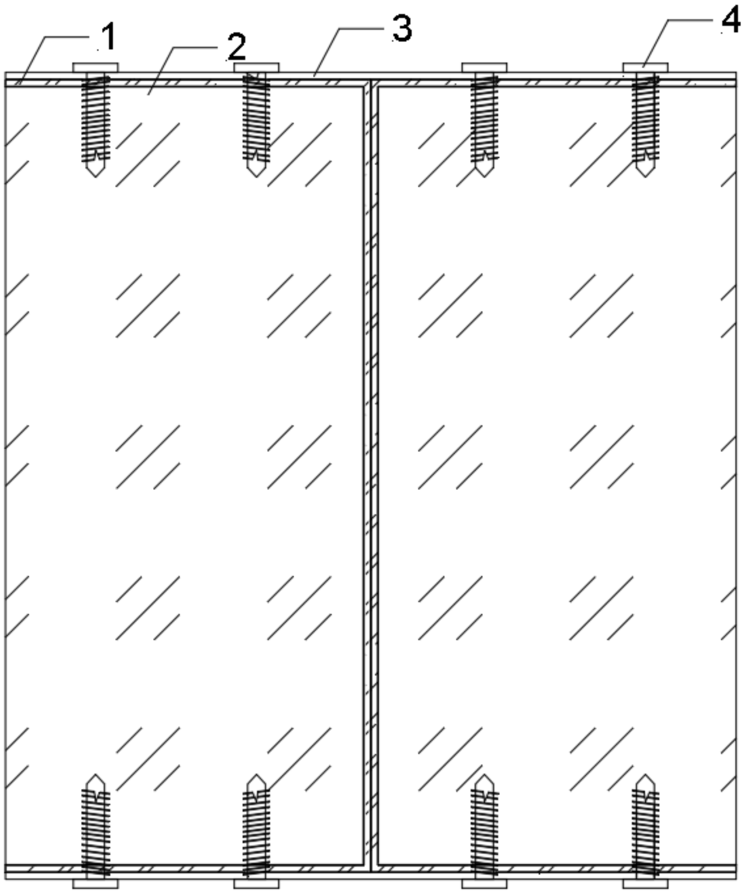


Fig 4 Section of the composite beam



1. Cold formed thin wall U-section steel 2. Reconstituted bamboo 3. Steel plate connectors 4. Tapping screws

Fig 5 Section of recombinant bamboo-cold-bent thin-wall steel composite beam

Bai Wenkui studied the flexural properties of cold-formed thin-wall steel-reconstituted bamboo box composite beams, set the parameters of beam net span, thickness of section steel and reconstituted bamboo, height of section steel, span height ratio and height-thickness ratio to create a finite element model of composite beams, and proposed a single variable formula. The simulated values were in good agreement with the theoretical values. The results show that the thickness of the reconstituted bamboo and the height of the cold-formed thin-wall steel significantly affect the bearing capacity of the composite beam, and the maximum increase is 58.59% and 49.10%, respectively. The ratio of span to height and height to thickness is proportional to the bending capacity of the composite beam.

To sum up: Compared with pure steel beams, the mechanical properties such as flexural shear strength and flexural stiffness of steel-concrete composite beams, steel-wood composite beams and steel-bamboo composite beams have been improved to varying degrees. The combined bamboo and steel beams have similar mechanical properties, and the overall working performance and cooperative working ability of the two are excellent. The composite beams can significantly improve the local buckling failure of cold-formed thin-wall steel. Combined with the research results at home and abroad, this paper proposes a new type of recombinant bamboo-cold-formed thin-wall steel composite beam structure: after drying in the cold-formed thin-wall U-section steel, embed the recombinant bamboo, and then fix the treated two U-sections back-to-back with steel plate bonding and self-tapping screws, namely, the recombinant bamboo-cold-formed thin-wall steel composite beam structure, as shown in Figure 5. This structure positively responds to our country to promote the industrialization of assembly-type building and green building, and satisfy the need of practical engineering effectively. Therefore further in-depth study on test and numerical simulation of this composite beam is necessary.

3. Conclusion

There are few researches on the reconstituted bamboo and cold-formed thin-wall steel composite structure at home and abroad, only the related mechanical properties of this new structure have been studied. This study is a supplement to the cold-formed thin-wall steel and reconstituted bamboo structural system.

References

[1] Chaves I A, Beck A T , Malite M . Reliability-based evaluation of design guidelines for cold-formed steel-concrete composite beams[J]. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2010, 32(SPE):442-449.

[2] Wu S , Shan Q , Zhang J , et al. Shear behavior of I-shaped wood-steel composite beam[J]. Bioresources, 2020, 16(1):583-596.

[3] Ran L I , Yushun L I, Jiawei H E , et al. Experimental study on shear behavior of box section bamboo-steel composite beams[J]. Journal of Building Structures, 2017.

[4] Skuratov S, Danilova-Volkovskaya G, Yanukyan E, Beilin M. Bamboo as a Unique Ecological Building Material of the XXI Century: Bamboo Description, Bamboo Physical and Mechanical Properties Studies. MSF 2021;1043:149–54.

[5] Nie J G , Cai C S , Wu H , et al. Experimental and theoretical study of steel–concrete composite beams with openings in concrete flange[J]. Engineering Structures, 2006, 28(7):992-1000.

[6] Mohammad, R, Salari, et al. Finite element formulations of one-dimensional elements with bond-slip[J]. Engineering Structures, 2001, 23(7):815-826.

[7] Issa C A , Kmeid Z . Advanced wood engineering: glulam beams[J]. Construction & Building Materials, 2005, 19(2):99-106.

[8] Borri A, Corradi M. Strengthening of timber beams with high strength steel cords[J]. Composites, 2011, 42B(6):p.1480-1491.

[9] Hassanieh A, Valipour H R, Bradford M A. Experimental and numerical study of steel-timber composite (STC) beams[J]. Journal of Constructional Steel Research, 2016, 122:367-378.

[10] Jiao P , Borchani W , Soleimani S , et al. Lateral-torsional buckling analysis of wood composite I-beams with sinusoidal corrugated web[J]. Thin-Walled Structures, 2017, 119(oct.):72-82.

[11] Al-Fasih M Y, Hamzah S, Ahmad Y, et al. Tensile properties of bamboo strips and flexural behaviour of the bamboo reinforced concrete beams[J]. European Journal of Environmental and Civil Engineering, 2021(12):1-17.

ISSN: 1813-4890

[12] Ghavami K. Ultimate load behaviour of bamboo-reinforced lightweight concrete beams[J]. Cement & Concrete Composites, 1995, 17(4):281-288.

[13] Tsutsumoto N Y, Fazzan J V, Melges J, et al. Structural behavior of reinforced concrete beams strengthened with bamboo splints[J]. Acta Scientiarum Technology, 2019, 41(1):36989.

[14] Haryanto Y , Wariyatno N G , Hu H T , et al. Investigation on Structural Behavior of Bamboo Reinforced Concrete Slabs under Concentrated Load[J]. Sains Malaysiana, 2021, 50(1):227-238.

[15] Quaranta G, Demartino C, Xiao Y. Experimental dynamic characterization of a new composite glubam-steel truss structure[J]. Journal of Building Engineering, 2019.