Study on the Design of New Connectors for Steel-concrete Composite Beams

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Abstract. Steel-concrete composite beam structure has been widely used in the world because of its own advantages. The key to realize the combination of steel beam and concrete beam is the indirect connection of the contact interface between the two material components. With the diversification of the demand of steel-concrete composite structure and the continuous development of the design scheme, the traditional shear connection structure cannot meet the current composite structure design. Therefore, the research of new type connection gradually becomes the decisive factor of the continuous development of composite beam structure. In this paper, the research and application status and main development trend of steel-concrete composite structure connectors are first discussed. Then, the main development directions of several new connectors are presented. Finally, the relevant cases are analyzed. The results of this paper can provide some effective references for the design of steel-concrete composite structure connectors in the future.

Keywords: Shear connector; steel-concrete composite beam; new types.

1. Introduction

Steel-concrete composite beam structure has the advantages of excellent bearing capacity, good fire resistance and good ductility, which has been widely used in railway, highway and bridge, especially in long-span bridge at home and abroad. The steel-concrete composite beam structure makes full use of the characteristics of the material through reasonable design and construction. The compressive properties of concrete and tensile properties of steel are given full play in the structure, thus greatly improving the safety and reliability of the structure, which has a broad development prospect. The connection between steel beam and concrete determines the integrity of the structure and the stability of the force, while the force mechanism and environmental factors at the connection are relatively complex. Therefore, it is of great significance to study and improve the joint of steel - concrete structure.

Common traditional connectors can be divided into three types: rigid, elastic and combined. However, with the continuous development of construction technology, new materials and structural design, the traditional connectors have been unable to meet the needs of the contemporary steel-concrete structure. Scholars at home and abroad have developed many new connection schemes. In terms of construction, the channel connector greatly reduces the difficulty of construction with its easily weldable ability and good stress characteristics, and its optimal design shape has also been studied [1]. In order to cooperate with the construction of prefabricated steel-composite beam, some scholars studied the use of epoxy mortar to form shear pocket connector, and put forward the corresponding shear strength calculation formula for its new failure mode [2]. Two new shear connectors, π-type Perfobond and π-type Crestbond with smaller size and discontinuous arrangement, reduce the arrangement of connectors and reduce the construction cost. After the axial compression test, the researchers studied its influence on the bearing capacity and ductility of the SRC column, and analyzed the law of load shared by each material in the corresponding SRC column [3]. The new ultra-short stud connector meets the engineering needs of the steel-ultra-thin UHPC lightweight composite deck, and has excellent bearing capacity [4]. A new type of connector that inserts bolts from the outside and then welds the external bolt head to the steel pipe to transmit shear forces solves the problem of welding typical screws of composite members for small concrete-filled steel pipes [5]. For reducing the cracking in the negative moment zone of concrete structures, some domestic scholars have proposed the design of a new type of connector with low elastic modulus wrapped screw [6]. Later, some scholars studied the setting range of uplift and non-shear strength of railway steel-composite beams. To balance low fatigue strength of rigid connectors and large sliding and deformation of large flexible connectors as well as the variable stiffness of regional stress mutation phenomenon, a type of stud connectors based on the traditional design of pressing plate (ESP) shear connector, rubber - combinations of welding fittings, higher shear load delivering and resilient V-shaped shear connectors have been put forward [7-9]. In addition, some scholars have studied the mechanical properties of shear joints of detachable steel-concrete composite beams from the perspective of green environmental protection [10].

Relevant researchers bring forth the new from the old and put forward very effective improvement suggestions from various angles. To help put all these solutions into practice, this paper summarizes, compares and analyzes several typical new connector schemes, then sort out the feasibility and applicability of each scheme. Finally, the possibility of combining each scheme is analyzed to provide reference for the development of steel-mixed composite beam connectors.

2. Status of the Connectors

2.1. Importance of Connectors

As the name implies, the connector is a component that plays a connecting role in the composite beam. As an intermediary between two entities, it is the basic component of composite structure. Shear connectors ensure the effective and stable transfer of shear force at the interface of steel-concrete composite structures, and play a leading role in the overall bearing capacity of composite members. They make the two materials to achieve integration and prevent the composite beam from premature vertical or horizontal separation of any form to complete the combined component force, especially in bending force. In addition, the study shows an appropriate design of shear connectors can play a relatively effective control effect on the seismic reaction of the composite structure.

2.2. Common Problems of Connectors

Common connectors in composite structures are headed studs, perfobond ribs, fibre reinforced polymer perfobonds, channels, pipes, Hilti X-HVB, composite dowels, demountable bolted shear connectors, shear connectors in composite column, etc. Among them, welding nail connector and perfobond connector (PBL connector) are the two most widely used connector forms at present [11]. However, with the development of composite beam structure, ordinary connectors are no longer able to meet the current needs. The main problems are as follows.

2.2.1. Construction difficulties

Common single-stud shear connectors require high voltage on-site, and the installation process is relatively complex. More and more geometric forms of the composite structure increase the construction pressure of the shear studs. When small concrete members are encountered, the welding of stud bolts could be extremely difficult. On the other hand, with the development of large composite beam structure, the traditional bolted shear connectors have been gradually unable to meet the needs of the project due to the large number of required joints, too dense installation, welding workload and other problems.

2.2.2. Rigid brittle and flexible fatigue failure

The joints with better stiffness are not easy to deform, with better bearing capacity and better fatigue resistance. However, the structural failure is usually manifested as the brittle collapse of the broken concrete, without prior warning, which is unfavorable to the safety of the structure.

On the contrary, the joints with better ductility deform greatly under the action of load, and the slip between components is relatively large. They show ductile collapse before breakdown, which is beneficial to the safety of the structure. However, when subjected load forms like oscillatory load, this kind of connectors show poor fatigue and durability. The most common form of flexible component is the shear studs, and fatigue is one of the biggest problems it faces.

2.2.3. Concrete cracking in negative moment zone

Recently, a large number of steel-concrete composite beams are covered with single welded nail connectors, but this method will produce great tensile stress in the concrete with negative bending moment area and lead to cracking, thus affecting the safety of the structure.

2.2.4. Environmental pollution

During the disassembly of traditional shear connectors, environmental problems such as construction waste and construction dust are being generated. In order to adapt to sustainable development, with the continuous popularization of composite structure and large-scale composite structure being gradually widely used, this problem needs to be solved urgently.

3. Classification of Shear Connectors

As mentioned above, the deformation capacity of a connector has a great impact on its bearing capacity, failure mode, and safety performance. Therefore, it is a common way to classify connectors according to their deformation ability. It can be roughly divided into three categories: rigid connector, elastic connector and combination connector [12].

3.1. Rigid Connectors

The deformation ability of rigid connectors is weak. Its bearing capacity is usually excellent, shear slip is small, and pressure stress distribution acting on the concrete is uniform. However, when the concrete strength is high, brittle failure is easy to occur at the contact surface between the joint and the steel beam. At the same time, the rigid connector needs to be arranged according to the shear diagram, which brings inconvenience to the construction [12].

Section steel and PBL connectors are typical rigid connectors [12].Common section steel connectors include C section steel connectors, U section steel connectors, V section steel connectors, etc. (Fig. 1). Many scholars are also committed to the study of the optimal shape of section steel. The section steel connector not only has strong shear resistance, but also its flange can resist lifting. During construction, the moment of inertia of the connected flange can be increased to reduce flange surface bulge and flexion. After concrete hardening, the section steel can also restrain the buckling of the steel plate under compression. What's more the section steel is easy to process and a wide variety of conducive to a wide range of application. However, the steel section cannot occlude the concrete completely in the plane perpendicular to the span direction, which is easy to form cracks and weaken the strength of the concrete flange plate.

PBL connectors are perforated rectangular steel plates with round holes. The concrete or main steel bar runs through the upper hole, and the upper flange of the steel beam is welded to the lower steel plate, strengthening the connection between the connector and the concrete, and the connector and the steel plate. The concrete and steel bars in the holes act as pins. This construction makes the PBL connector have higher bearing capacity, higher stiffness and better fatigue resistance (Fig. 2). The final failure form is the shear failure of concrete in the hole. In recent years, to improve the corrosion resistance of PBL connector, many scholars devoted themselves to studying the FRP and PEL connector. Using FRP material as the support of shear splicer not only makes it obtain good corrosion resistance, but also improves the bending stiffness and bearing capacity of the structure, but also faces the problems of poor temperature resistance and aging. It is one of the main ways to develop shear connectors.

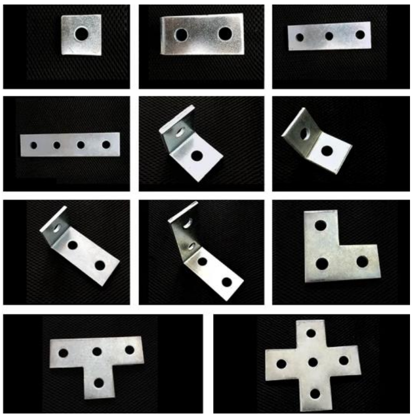

Fig. 1 Common types of section steel

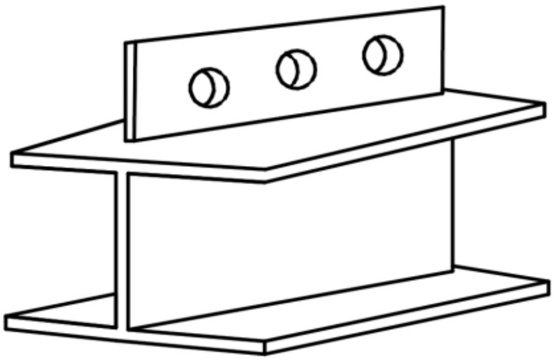

Fig. 2 PBL connector [3]

3.2. Elastic Connectors

Elastic connections have excellent ductility and maintain shear resistance while allowing relative slip at the concrete and steel interface. The main problems of this type of connection components are the control of relative slip and fatigue resistance.

The most common type of elastic connector is the weld nail. A weld nail consists of a longitudinal shear steel rod and an anchor head, which can resist the shear force between the steel plate and the concrete and is not directional. As a result of its simplicity of manufacturing and ability of effectively resisting shear force and slip in all directions, welded nail connectors are widely used in composite structures, especially composite Bridges. However, the strength of the weld between the joint and the steel beam should be higher than that of the stud, while the component is not resistant to fatigue. Therefore, the weld nail joint still has strength defects in long-term use (Fig. 3).

Another common type of elastic connector is a reinforced connector. The rebar connector is achieved by bending the threaded rebar and welding it to the steel beam to transfer shear force. This method is simple, effective and very economical. However, due to the shear force at the interface is mainly resisted by the tension of the bending steel bar, the connector is not suitable for the complex shear combination interface in different directions.

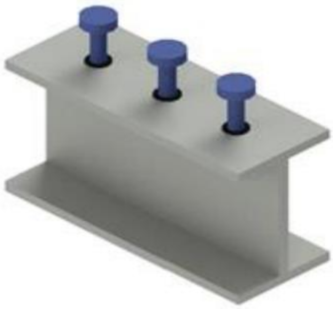

Fig. 3 Weld nail [11]

3.3. Combination Connectors

The combination connectors refer to connectors obtained by adding other organic materials on steel and making full use of the rigidity and ductility of the two materials. Common combination connectors are CL pin, PZ pin, welding pin root resin sponge and plastic foam, etc. The combination connectors are one of the main research directions of new type of connectors.

4. New Type of Shear Connectors

4.1. Ease Construction Difficulties

4.1.1. New channel shear connector

The channel shear connector is easy to be welded and has good availability. At present, it is easy to perforate and cut the shape of the channel shear connector, so it is one of the research directions of new connectors of steel-concrete composite beams. However, the shape and size of the channel shear connector will affect the concrete slab. Too long joints will cause difficulties in the construction of longitudinal reinforcement. Bilal et al. studied five new shear connector shapeto determine the shape that provided the best performance (Fig. 4) [1].

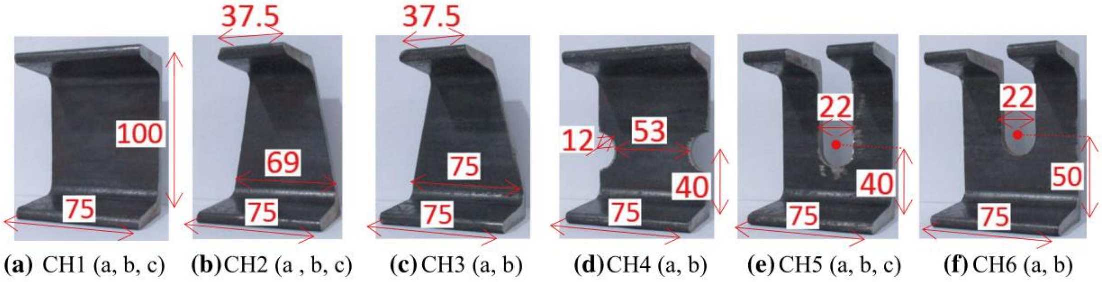

Fig. 4 The geometric details of ordinary and new channel connector shapes for each group（unit：mm） [1]

In this experiment, CH1 (common channel connector shape specimen) in Fig. 4 was used as the control group, and the other five shapes were used as the experimental group for 12 push-out experiments.CH2 studies the effect of reducing the top flange length on concrete and the effect of reducing the web width between two plastic hinges on connector behavior. Research shows that the cost of this shape is reduced by 25% compared with the ordinary shape (Fig. 5). The width between the two plastic hinges of CH3 is the same as that of CH1, and the other shapes and sizes are the same as that of CH2. The purpose is to provide a comparison for studying the influence of the width between the two plastic hinges on the connector performance.CH4 evaluated the perforation diameter of 24mm on the first plastic hinge to study the influence of web reduction at the first plastic hinge on the deformation ability of the connector. CH5 was perforated with a 22mm hole in the middle of the first plastic hinge and cut out at the edge of the hole to evaluate the effect of reducing the width between the top flange and the plastic hinge on the denaturation ability of the connector. The perforation position of CH6 is 10mm higher than that of CH5, and other features are the same as those of CH5.

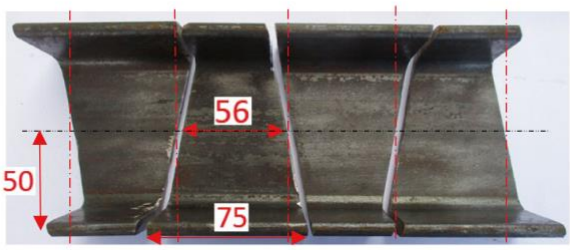

Fig. 5 Transversal cutting of CH2 shape [1]

In this test, the failure mode, load-slip behavior and ductility coefficient of the specimens were studied. In the push-out experiment, the failure mode of CH1 is concrete cracking - splitting, and the rest of the specimens are concrete cracking. In addition, the specimens in group CH1 were greatly affected by concrete cracking. Compared with the common channel shear connector, the new type of channel shear connector has higher load bearing at the same slip in the plastic stage, but has little effect at the other stages. The new connectors show better ductility, especially CH3, CH4, and CH6.

The research shows that the longer flange will have a negative effect on the concrete, and the ductility of the short channel connector is decreased. Combined with the partial shear connection, support structure and slip requirements in the case of large span, the CH6 and CH2 shape channel shear connectors have more practical engineering performance.

4.1.2. New channel shear connector

The ultimate strength of shear connector is related to the elastic modulus, compressive strength and screw tensile strength of concrete material. Therefore, a new type of shear connector with pocket shear, mainly characterized by coating epoxy mortar layer on the concrete surface, is under study [2]. This connector is coated with epoxy mortar layer in the reserved hole of concrete slab, which changes the failure mode of the stud shear connector, and increases its shear strength and shear stiffness compared with the ordinary shear pocket connector (Fig. 6).

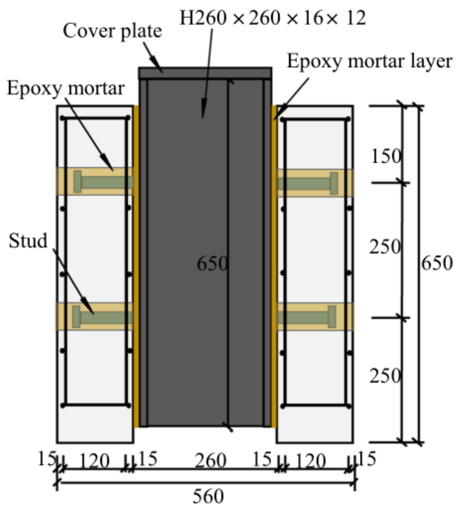

Fig. 6 Shear connector with epoxy mortar [2]

The effect of the diameter of the reserved hole on the performance of the new shear joint was studied by the push-out test. The results show that with the increase of the diameter of the reserved hole, two different failure modes appear in the epoxy mortar layer. The epoxy mortar layer of the specimen with smaller reserved hole breaks above the upper stud, while the specimen with larger reserved hole breaks in the upper half of the stud.

The experimental results show that the epoxy mortar layer can not only resist the separation of concrete slab and steel beam by bonding, but also that the epoxy mortar flowing into the reserved hole can share the shear load of the stud to a certain extent, and the shear bearing capacity increases with the increase of the diameter of the reserved hole. This has a very benign effect on the performance of shear connectors.

However, this test only considers the shear state of the epoxy mortar layer. The stress state of shear connectors in practical engineering application is very complex, and there are many factors that affect their performance. More tests and studies are needed for this new connector mode.

4.1.3. New short post connector

Some scholars have studied new short column connectors under axial compression to reduce the relative slip of section steel and concrete and ensure the overall working performance of composite members [3]. Two new shear connectors, π-shaped perforated plate and π-shaped CR with small size and discontinuous arrangement, were studied by push-out tests. They carried out axial compression tests on one common and five steel reinforced concrete short columns with shear connectors, compared and analyzed the influence of connectors on bearing capacity and ductility of steel reinforced concrete columns, and then analyzed the law of load shared by each material in steel reinforced concrete columns.

It is found that the ductility of SRC with shear connectors (stud, π-shaped perforated plate, π-shaped CR shear connector) is improved. Srcdc-1 with π-shaped CR shear connector has the best ductility, and its ductility coefficient is increased by 8. 4% compared with the specimen without shear connector.

4.1.4. Small CFT bolt shear connector

It is very difficult to weld common stud bolt in small size concrete composite construction. As a result, a new type of small connector with external bolt heads that is also solderable at the CFT size was developed [5].

This is a structure with a diameter of less than 200mm. This construction requires the bolt to be inserted into the bolt hole on the steel pipe from the outside, and then the bolt head to be welded to the steel pipe from the outside (Fig. 7).

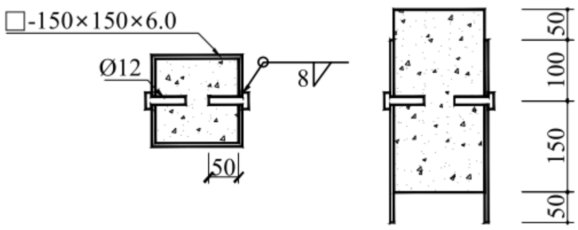

Fig. 7 Installation of small CFT bolt shear connectors [5]

The scholar conducted basic shear tests on a small CFT bolt-type shear connector, and the results showed that the shear force of the connector exceeded the Korean shear force standard. However, when mounting bolts are inserted from the outside, the absence of an attachment head may cause problems that cannot resist drawing loads. Therefore, more stress tests are needed to further analyze and improve the specimen.

4.1.5. New ultra short stud connector

A UHPC lightweight composite bridge deck structure solves the problems of fatigue cracking, pavement damage and sensitivity to dead weight and thickness of orthotropic steel bridge deck. However, the ultra-thin UHPC layer is only 35mm thick, compared with the conventional minimum height of 35mm, which is obviously not enough to meet its requirements. Therefore, some scholars proposed a new type of ultra-short stud connector with a height of only 24mm and an aspect ratio of only about 1.8 (the aspect ratio of conventional stud is no less than 4) (Fig.8), and conducted mechanical research through static push-out test [4].

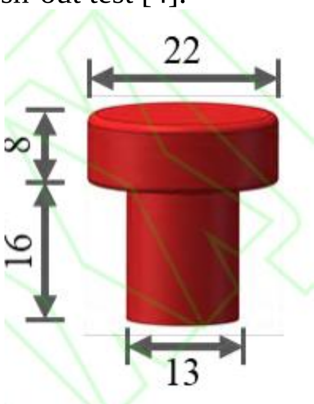

Fig. 8 Size of ultra short stud connector [4]

The scholar conducted basic shear tests on a small CFT bolt-type shear connector, and the results showed that the shear force of the connector exceeded the Korean shear force standard. However, when mounting bolts are inserted from the outside, the absence of an attachment head may cause problems that cannot resist drawing loads. Therefore, more stress tests are needed to further analyze and improve the specimen.

These scholars analyzed the influence of stud diameter and UHPC strength on shear performance of connectors. It was found that the failure mode was bolt shear, and the damage scope of UHPC was only at the root of the bolt. The UHPC strength has a slight effect on the shear strength of the connectors, while the ultra-short stud diameter has a significant effect on the shear strength.

4.2. The Balance between Rigidity and Flexibility of connectors

4.2.1. Embossed steel plate connector

The layout of a new embossed steel plate connector (ESP) is shown in Fig. 9. In this composite member, all connections are welded to the rigid section and embedded into the floor slab after pouring concrete.

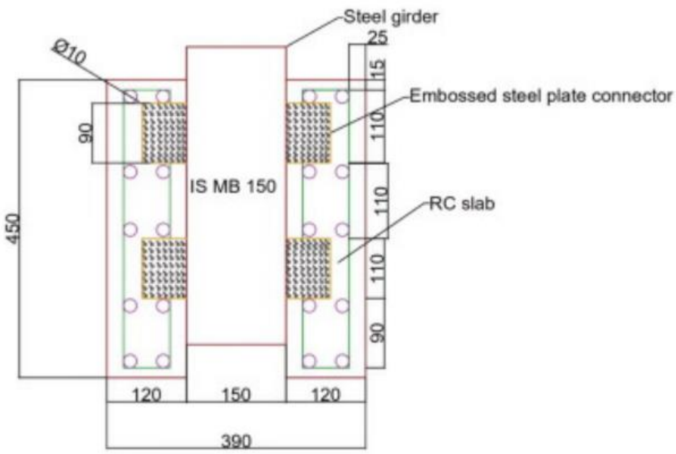

Fig. 9 Construction of ESP [7]

Some scholars have carried out push-out tests on this kind of connector [2]. The test results show that the ESP shear joint is very robust in design, has good bond strength with concrete, and has higher shear strength than the specimens with nails. The ESP connector is also very durable and can withstand high impact loads. In addition, the maximum shear load of ESP increases with increasing plate thickness.

4.2.2. New steel connector

A modified V-shaped steel connector is under research, and scholars are adjusting its shape to improve its bearing capacity and ductility, while simplifying its production process [9]. In the future, the new connector can also start from the improvement of the geometric shape of the section steel, so that the connector can find the balance of rigidity and flexibility at the contact surface of the composite beam.

4.2.3. Rubber and nail combination connector

Recently, a new type of connector that wraps a material with a low elastic modulus around a rigid screw has also become popular. This joint not only contributes to the balance between rigidity and flexibility, but more importantly, it reduces the cracking in the negative moment zone of concrete. It will be described in more detail later.

4.3. Reduce Concrete Cracking in Negative Moment Zone

If the concrete and steel beams in the composite beam form a complete composite section with almost no relative displacement, the negative moment zone of the concrete beam will produce great tensile stress and lead to its cracking. Therefore, scholars put forward a kind of composite beam that keeps the positive moment area fully combined, and adopts flexible connectors in the negative moment area to make it a flexible composite structure, so as to reduce the tensile stress in the concrete in the negative moment area [8]. However, this will increase the stress of the steel beam and the overall deflection of the beam, and may lead to the phenomenon of connector pulling out and interface slip [8].

The rubber-pin combination connector is a flexible connector with a rubber sleeve wrapped around the root of the common connector to reduce the initial stiffness of the connector (Fig. 10). The pull-out action of the rigid material in the middle of the joint ensures that the steel bars are not separated from the bridge panel, while the non-shear behavior of the low elastic modulus material outside allows the panel to slide longitudinally, reducing the tensile stress of the concrete.

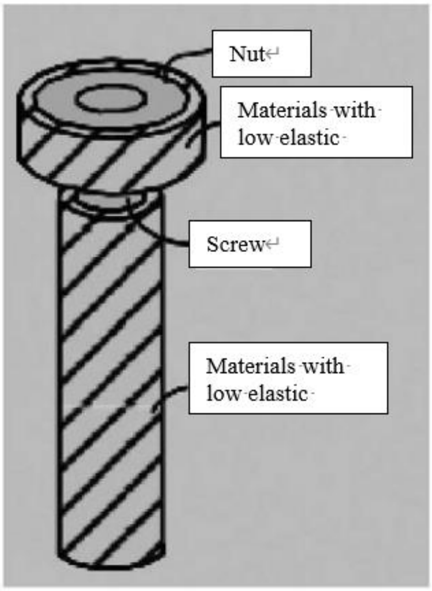

Fig. 10 New combination connector [6]

Scholars have done push-out tests on this new type of connector [8]. The experimental results show that the combined joints not only effectively reduce the shear stiffness of the joints and the tensile stress of the concrete in the negative moment area, but also improve the stress mutation phenomenon in the variable stiffness area. In the experiment, setting a transition area of 2 m at the junction of the positive and negative moment areas can reduce the stress mutation size by 30% [8].

This specimen also has the advantages of light weight, sound absorption and corrosion resistance. It is worth mentioning that it is a very economical new design of shear connector.

4.4. Green Shear Connector

Due to the environmental problems such as construction waste and construction dust in the demolition process of traditional building structure, disassembly is a development direction of the current building structure system. Therefore, some scholars selected the structural form of shear connector of high-strength bolt with built-in single nut, and made the shear connector detachable after specific construction procedures [10].

Due to the environmental problems such as construction waste and construction dust in the Scholars also carried out a push-out test [10] on the shear resistance of the removable composite beam bolt connection, and analyzed the influence of different bolt diameters (M20, M24) and material strengths (C50, C60) on the shear resistance of the removable composite beam bolt connection. The results show that the new shear connector is easy to disassemble after reaching the ultimate bearing capacity, and the steel beam and bolt are not deformed much, and the disassembly performance is good.

In order to put this type of detachable composite connector into engineering application, more tests and mechanical properties analysis are needed. However, the contribution of removable shear connectors to sustainable development cannot be ignored.

5. Conclusion

This paper summarizes the current situation and development trend of connectors, and generally classifies the current research on new connectors into four directions. Finally, the following conclusions are drawn.

(1) The connector plays a vital role in the combined structure. However, the rapid development of the combined structure and the problems existing in the structure are the most important reasons for the urgent improvement of the connector.

(2) Connectors can be roughly divided into rigid connectors, elastic connectors and combined connectors according to their deformation ability. Rigidity and flexibility have their own advantages and disadvantages. The combination of the two forms is one of the main research directions of new connectors.

(3) Nowadays, the research of various new connectors has made a lot of progress, which can be roughly divided into Easing construction difficulties, rigidity and flexibility balancing, Reducing concrete cracking in negative moment zone and 4.4Green shear connector, four improvement directions according to their effects. However, most of these connectors have not been put into engineering applications, and the current combination structure is still dominated by using the traditional connectors such as bolts. The new connector needs to carry out more tests on mechanical properties, environmental factors, manufacturing and other aspects of the proposed scheme, and on the basis of continuous improvement, the final design scheme to meet the actual engineering application.

References

[1] Bilal Maghaghi, Messaoud Titoum, Aida Mazoz. Experimental evaluation of new channel shear connector shapes. International Journal of Steel Structures, 2021, 21(3): 883-900.

[2] Senqiang Lu, We Zhao, Zhenzhu Guo. Experimental study of the new type stud shear connector for assembled steel-concrete beams. Iranian Journal of Science and Technology, Transactions of Civil Engineering, 2022, 46: 3119-3130.

[3] Guochang Li, Kaiqi Cao, Zhijian Yang, Zengmei Qiu. Experimental study on axial compression performance of steel reinforced concrete columns with new shear joints. Industrial Building, 2020, 52(05): 106-112+139.

[4] Shixiang Zhang, Meng Li, Xudong Shao, Junhui Cao, Yongquan Lu, Qinggang Zheng. Jianqiang Zhang. Experimental study and finite element analysis of new ultra-short stud connector. Highway Engineering: 1-10.

[5] Kim, Cheol Hwan, Yun, Yan Wang et al. Load transfer capacity of bolt type shear connectors for small sized CFT member. Journal of Korean Society of Steel Construction, 2021, 33(5): 327-335.

[6] Yang Minli. Application of new connector in negative bending moment zone of composite beam of rail transit. Railway Construction Technology, 2020(08): 120-124.

[7] Vijayakumar, N.Pannirselvam. Behaviour of a new type of shear connector for steel-concrete composite construction. Materials Today: Proceedings, 2021, 40(1): 154-160.

[8] Qingtian Su, Hang Su, Fei Wu. Analysis of the influence of rubber-welded nail joint on the mechanical performance of steel-mixed composite beam. Journal of Tongji University (natural science edition), 2021, 49(08): 1079-1087.

[9] Hussein Al-kroom, Mujahed Thneibat, Yassin Alghrir, Volker Schmid. An experimental investigation of new bent V-shaped shear connector. Latin American Journal of Solids and Structures, 2021,18(5):1-9.

[10] Huiyong Ban, Jiawei Luo, Yuanqing Wang, Lu Yang. Research on mechanical behavior of Shear joints of detachable steel-concrete composite beams. Progress in Steel Structures in Buildings, 2022, 24(08): 35-46.

[11] Rahul Tarachand Pardeshi and Yogesh Deoram Patil. Review of various shear connectors in composite structures. Advanced Steel Construction, 2021, 17(4): 394-402.

[12] Yibo Wang, Shizhong Liu, ZhenFeng Li, Zhe Wang, Xuyang Bai, Dongyun Li. Research on the development trend of steel-mixed structure bridge connectors. Highway and transportation technology, 2021, 37(02): 45-52.