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Experimental Study of the Behavior of Blind Bolted End Plate Connections

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Abstract

There is limited information on the behavior of connections between rectangular hollow section (RHS) columns and H-shaped beams. Since the RHS column has a closed section, it is difficult for ordinary bolts to be used in RHS column connections. However, application of blind bolts is a more feasible option for this. In order to investigate the seismic and shear behavior of the end plate connections of RHS columns with H-shaped beams using blind bolts, experimental tests were conducted in this paper to study the behavior of this kind of connection. Four full-scale specimens representing exterior beam-to-column connections were tested under monotonic loading and cyclic loading. The failure modes, shear capacity, moment-rotation relation curves, energy-dissipating capacity and connection classification of the joints were evaluated. The test results indicate that this new kind of connection exhibits excellent shear performance and very good rotational capacity which makes it beneficial in seismic zones.

Keywords: End plate connection; RHS column; blind bolt; static and cyclic loading; hysteretic behavior

1. Introduction

H-shaped columns are commonly used in conventional steel frames and there have been plenty of research on H-shaped beam-to-column end plate connections, while the study on connections between H-shaped beam to Rectangular hollow section (RHS) columns has been rarely reported. Actually H-shaped columns are not economic types due to significant stiffness difference between strong-axis and weak-axis[1], on the contrary, Rectangular hollow sections (RHS) are more suitable for structural applications, owing to their efficient structural performance and attractive appearance[2]. Currently most of the connections between H-shaped beam to Rectangular hollow section (RHS) columns are field welded connections which will slow down the construction schedule and make construction quality hard to be guaranteed. However, due to the lack of access inside the RHS column for bolting purposes, it has been difficult to develop a practical bolted end plate connection. With the need of a dry construction site and fast construction, also improvement of the construction quality, recently some blind fasteners are developed to be used in application which access for installation is from one side of the connection only, as in the case of connecting the end plate of a H-shaped beam to a RHS column, see figure 1. In the context of structural engineering, there are several commercially available blind bolts in the market. Each type of fastener differs in the bolt components, resistance mechanism and method of installation. In this paper, the blind bolts are provided by Lindapter company.

Although blind bolts have a lot of advantages, such as one-side fastening, quick construction, reliable behavior and good seismic performance, and are expected to be widely used in engineering projects[3], there have been few research reported about blind bolted connections, also the test data, calculation model and design methods of blind bolted connections are deficient[4].

Wang and Zhang[3] have carried out cyclic loading test on blind bolted beam-to-column end plate connections between concrete filled steel tube(CFST) columns and H-shaped beams, the joint shows excellent energy-dissipating capacity. Wang and Spencer[5] have tested the flexural capacity of blind bolted beam-to-column end plate connections between concrete filled steel tube(CFST) columns and H-shaped beams, the test indicates that this kind of connection has favorable rotational capacity. But the mechanical property of blind bolted beam-to-column end plate connections between RHS columns without filled concrete and H-shaped beams has been rarely reported. The design specification in British Standard[6] only gives suggestions about how to design this kind of connections but no specific design rules.

In this paper, experimental tests were conducted to study the behavior of the blind bolted end plate joint with RHS columns to H-shaped steel beam. Four full-scale specimens representing exterior beam-to-column joints were tested under monotonic loading and cyclic loading. A detailed description of the experimental program, loading scheme, mechanical properties of steel and the main results of the tests were presented. The failure modes, shear capacity, moment-rotation relation curves, energy-dissipating capacity and connection classification of the joints were evaluated.

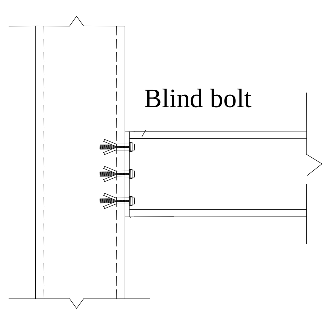


Fig.1 – End plate connection between RHS column and H-shaped beam using blind bolts

Fig.2 – blind bolts

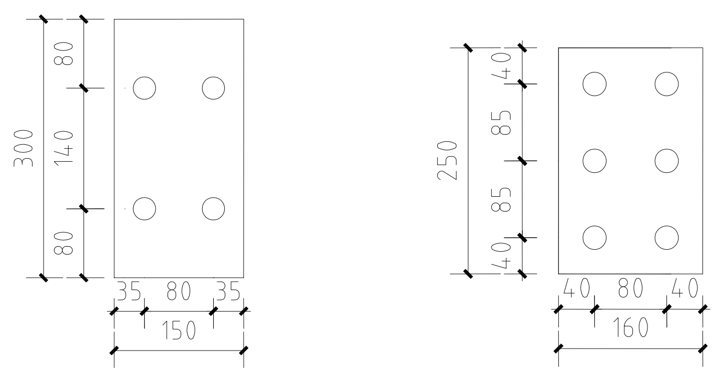
2. Experimental Study

2.1 Objective

In order to obtain the mechanical model, failure mode, ductility and energy-dissipating capacity of blind bolted end plate joint with RHS columns to H-shaped steel beam, a series of tests subjected to monotonic loading and cyclic loading were conducted.

2.2 Specimens

The specimens are divided into two groups, one group for monotonic loading and another group for cyclic loading. In the group for monotonic loading, the column is 1.4m high and the column section is □200×200×10, the beam is 1.1m long and the beam section is HN300×150×6.5×9, the thickness of the end plate is 10mm, all the components are made of Q345B. In the group for cyclic loading, the column is 1.4m high and the column section is □200×200×10, the beam is 1.1m long and made of Q235B, the beam section is HN250×125×6×9, the thickness of the end plate is 8mm, the other components are made of Q345B, the specific dimensions and opening location are shown in figure 3. All the specimens are flush end-plate connections, the end plate is connected with the beam flange by full penetration butt weld, and connected with the beam web by 8mm fillet weld. All the bolts are Grade 8.8 M16 blind bolts. The specific dimensions of specimens are illustrated in figure and table 1.

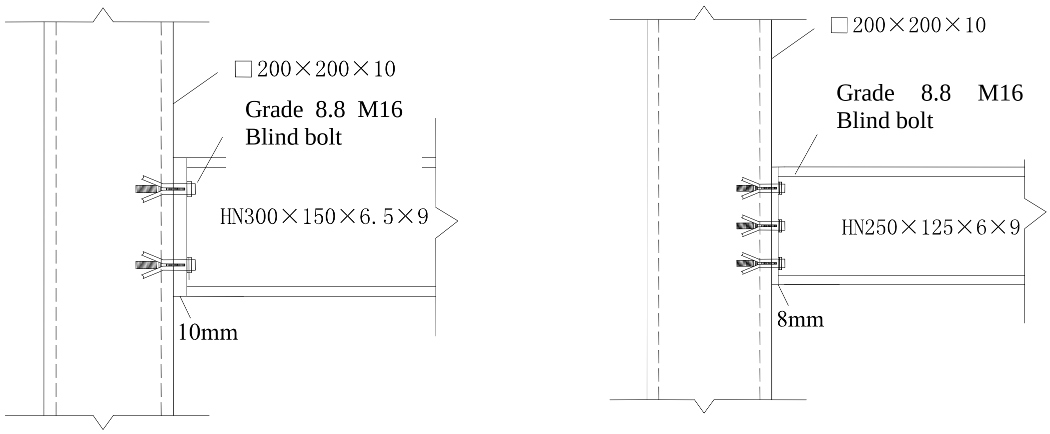


(1) monotonic loading (2) cyclic loading

Fig.3 – Dimensions of the end plate

Table 1 – Parameters of specimens

Loading scheme	Column section	Beam section	Thickness of end plate
monotonic loading	□200×200×10	HN300×150×6.5×9	10mm
cyclic loading	□200×200×10	HN250×125×6×9	8mm



(1) monotonic loading (2) cyclic loading

Fig.4 – Dimensions of specimens

The mechanical properties of specimens are obtained through material tests and the test results are shown in table 2.

Table 2 – Mechanical properties of steel

Loading scheme	**Component**	**Thickness (mm)**	**Yield strength (N/mm^2)**	**Ultimate strength (N/mm^2)**	**Elastic modulus (N/mm^2)**	**Elongation (%)**
Monotonic loading	Column	10	373	534	2.04×10^5	24.3
	Beam web	6.5	377	540	2.05×10^5	23.4
	End plate	10	381	542	2.09×10^5	22.7
Cyclic loading	Column	10	373	534	2.04×10^5	24.3
	Beam flange	9	283	450	2.04×10^5	27.2
	End plate	8	389	551	2.11×10^5	25.8

2.3 Test set-up and loading scheme

2.3.1 Monotonic static loading

In the tests, the column bottoms are rigidly connected and the other end of the beam is designed as pinned connection. Static load is exerted on the one third of the beam length location close to the beam-column connection, there is a pressure sensor on the other end of the beam. The shear force at beam-column connection can be calculated by deducting the pressure value of the pressure sensor from the exerting load. The distance between the loading point and the center of the bolts is 300mm, and the distance between the loading point and pressure sensor is 600mm, as seen in figure 5. The test set-up is shown in figure6. The loading is applied increasingly by stages, in each stage 30kN is increased until the specimen fails. When the following experiment phenomena occur, the specimens are identified as failure.

(1)Beam or column fails;
(2)Beam-column connection fails;
(3)The specimen loses the overall stability;

(4)The specimen fails to sustain the current loading, which means the load-displacement curve is descending[7].

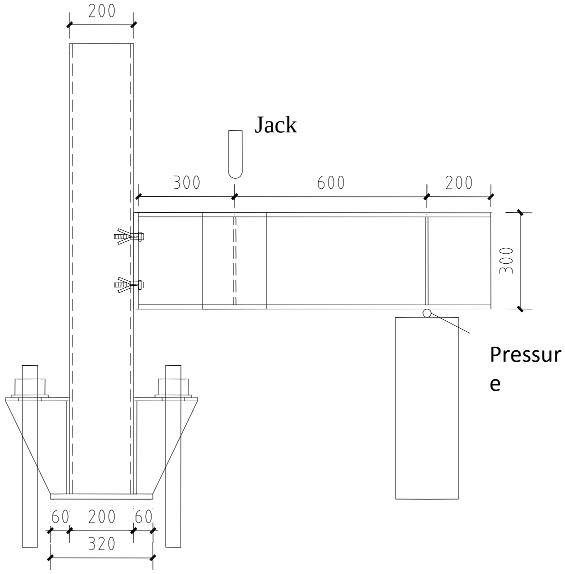


Fig.5 – Schematic diagram of loading and boundary conditions

Fig.6 – Test set-up

2.3.2 Cyclic loading

In the tests, the columns are placed horizontally and the beams are placed vertically. Lateral braces are arranged to avoid out-of-plane instability. The column is fixed by capping beam and anchor bolts in vertical direction, and the two ends of the column are pushed tightly to the reaction frame to prevent from slipping, as seen in figure 7. Also stiffeners are welded to the beam at loading location to prevent the beam from local buckling. The specific dimensions can be seen in figure 8 and the test set-up is shown in figure 9.

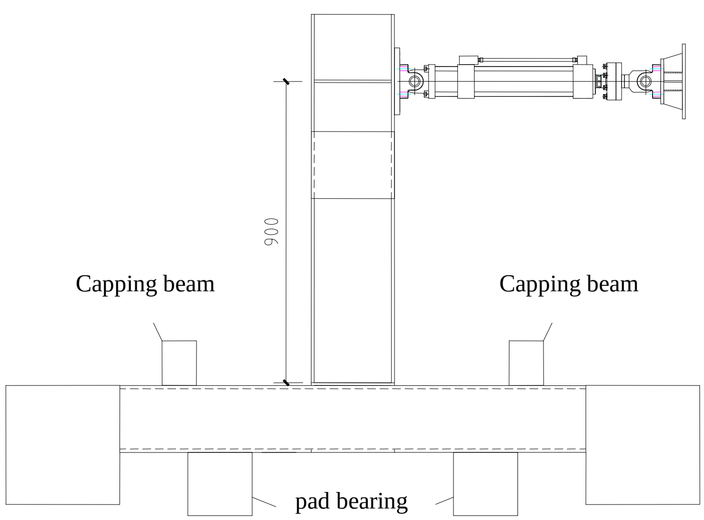


Fig.7 – Schematic diagram of loading and boundary conditions.

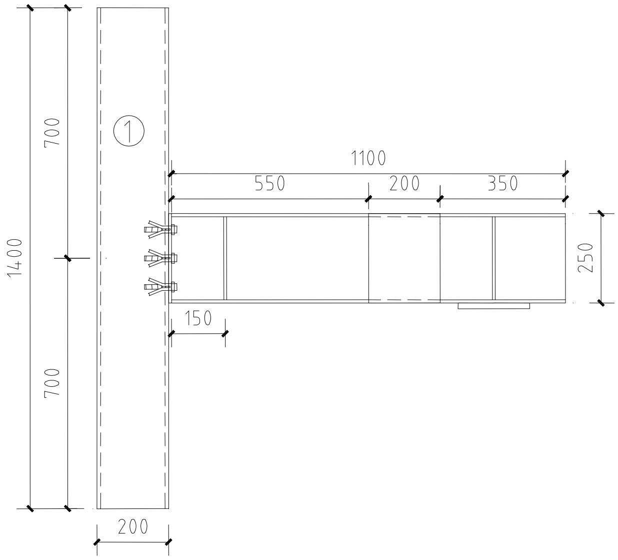


Fig.8 – Schematic diagram of connection

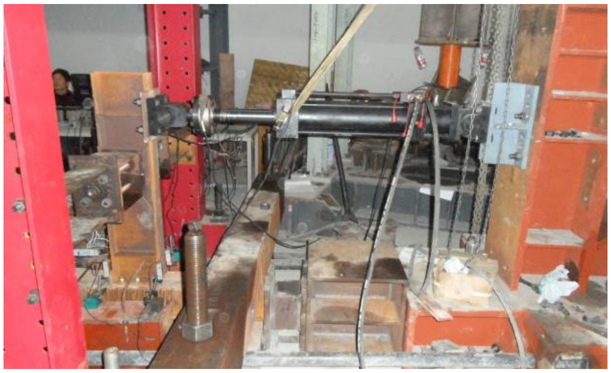


Fig.9 – Test set-up

2.4 Test process and failure characteristic

2.4.1 Monotonic static loading

During the early stages of the loading process, there is no evident deformation on the specimen. With the load increasing gradually, blind bolts began to incline and the end plate on the beam started to separate from the column wall, as seen in figure 10. But in general, the whole specimen had no obvious deformation until the ultimate load were reached. When the load reached 900kN, shear yielding occurred on the beam web and finally the beam failed, as shown in figure 11. There is no damage on beam-column connection during the whole loading process, only the bottom of the end plate separated a little bit from the column wall because of the effect of additional bending moment on the end plate and it barely had any influence on the shear capacity of the beam-column connection. The screws of the blind bolts deformed apparently under shear force, so did the sleeves of the blind bolts, which can be seen in figure 12, although the blind bolts kept undamaged. The end plate of the beam and the column wall also kept no evident deformation, as shown in figure 13.

Fig.10 – The end plate separating from the column wall

Fig.11 – The shear failure of beam

Fig.12 – The deformation of blind bolt

(1) bolt opening on the end plate (2) bolt opening on the column wall

Fig.13 – The deformation of bolt opening on the end plate and column wall

2.4.2 Cyclic loading

During the early stages of the loading process, the bending moment at the beam-column connection is relatively small, there is no evident deformation on the specimen. When the bending moment reached 40kN·m, the end plate began to yield, revealed obvious deformation and separated from the column wall. Blind bolts had been pulled out from the column due to large tension force, as shown in figure 14. With the load increasing gradually, when the bending moment reached 52kN·m, the end plate deformed severely due to yield, sleeves of the blind bolts were cut through under shear force and the blind bolts were pulled out, in the mean time, apparent deformation occurred on the column wall, as seen in figure 15. Then the test stopped after blind bolts failed.

Fig.14 – Blind bolts pulled out from the column

Fig.15 – The deformation of the connection

2.5 Test results and analysis

2.5.1 Monotonic static loading

From the test results we can see that, it is the shear capacity of the beam that dominates the failure of the specimen. During the whole loading process, the beam-column connnection showed no evident deformation or damage. In the design process of the test, we intended to let the beam-column connnection fail first, so the dimensions of the beam are relatively big to make the beam much stronger. While the actural results did not happen as expected, the beam failed before the connection. Thus it can be seen that for this kind of blind bolted beam-column connections, the connection is usually stronger than the beam.
According to the load-carrying capacity tables of the blind bolts provided by the Lindapter company, the characteristic value of each blind bolt under shear force is 139kN. From the test (see figure 16)we can see that the ultimate load-carrying capacity for four blind bolts under shear force is 600kN, that makes the ultimate load-carrying capacity for each blind bolt under shear force is 150kN, higher than the characteristic value provided by the company, which means it can meet the strength requirement of beam-column connnections in steel buildings.

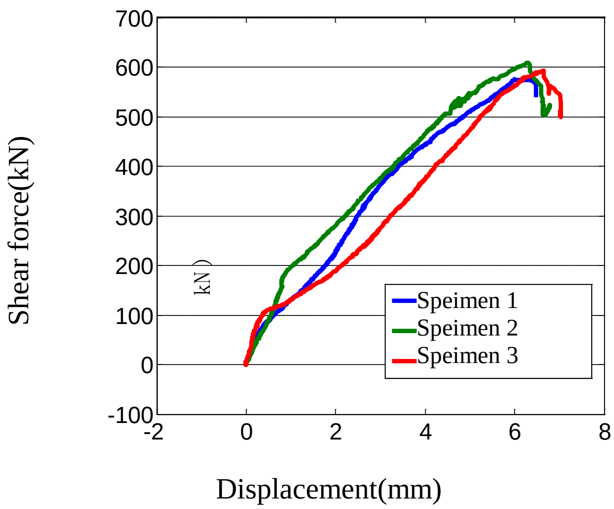


Fig.16 – Shear resistance-displacement curve of the beam-end

From figure 5 we can see that the distance between the loading point and the center of the bolts is 300mm, and the distance between the loading point and pressure sensor is 600mm, and the connnection is assumed as semi-rigid. So we can simplify the schematic diagram of loading as the mathematical model (see figure 17), where *F* stands for the load of jack, *N* stands for the reaction force of the pressure sensor, so the shear force at the connection *Q* can be calculated by $Q=F-N$.

If the stiffness of the connection $k=0$, then $Q=2N$, otherwise, $Q=\beta\cdot N$, according to the knowlodge of structural mechanics, we know that $\beta>2$. The relationship between β and the shear force of the connection is shown in figure 18, we can see that when the load is relatively small, the shear force of the connection is relatively big due to the initial stiffness of the connection, when the shear force of the connection reaches 300kN, the proportion of the load undertaken by the connection tends to be stable and the ratio of *Q* over *N* is close 2.0. At this time, we can basically ignore the effect of initial stiffness of the connection on the distribution of load, and the connection can be identified as pinned connection.

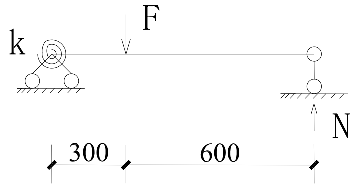


Fig.17 – Simplified mathematical model

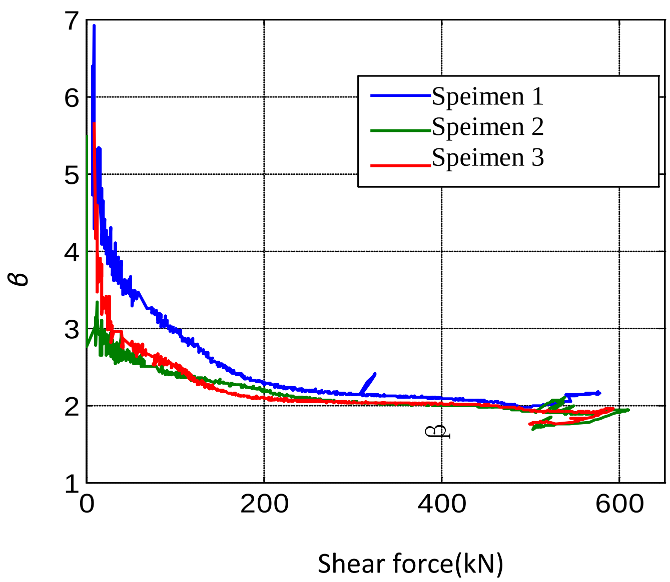


Fig.18 – The relationship between β and shear resistance of connection

2.5.2 Cyclic loading

(1) Stress pattern

Tests of blind bolts for tensile capacity were conducted before the specimen test, the ultimate tensile capacity for grade 8.8 M16 blind bolts is around 121kN, the tests ended with the failure of the sleeves of blind bolts. The load-displacement curve and failure photo can be seen in figure 19. In the specimen tests, when the bending moment of the connnection reached 52kN·m, the blind bolts in edge row failed and could not bear the additional load, as seen in figure 14. According to the test results of tensile capacity, the ultimate tensile capacity for each grade 8.8 M16 blind bolt is around 121kN, centering around the flange of the beam, so the ultimate bending moment of blind bolts in edge row can bear is 51kN·m, very close to the test results. According to provisions in Code for design of steel structures[8] in China, the end plate is rigid plate that will not deform locally, only rotate globally and the stress pattern of bolts is linearlly distributed. But actually in the tests, only the blind bolts in edge rows contribute to the resisting bending moment.

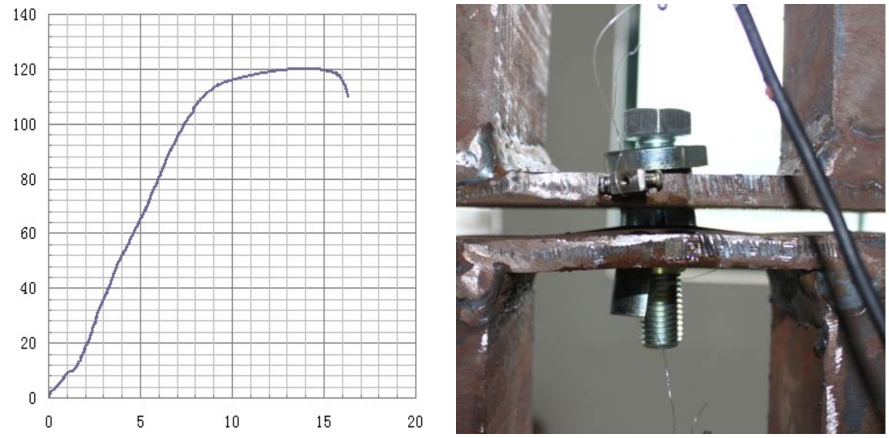


Fig.19 – Tensile capacity test result of blind bolts

(2) Hysteretic performance

Hysteretic curve of the connection can be seen in figure 20. It shows that the connection has good ductility, the ultimate rotation of the connection reaches 0.2rad, far beyond the limit value of 0.03rad required by American seismic standard.

From figure 20, we can also see that during the early stages of loading, the pinch effect of hysteretic curves is relatively evident, mainly because there were initial imperfections on end plate and column wall and there was gap exsisted between end plate and column wall. In addition, the relatively bigger deformation of blind bolts in early stages of loading process is also one of the reasons for the pinch effect.

With the increase of the load, the end plate and column wall started to yield, the hysteretic curve of the connection became more and more plump. In a hysteretic circle, when the jack is applying load in one direction, the column wall started to bulge, as seen in figure 21, when the jack is applying load in another direction, the end plate will push back the bulge on the column wall in the flange side under compression first, then pull out the column wall in the flange side under tension. The connection dissipates the energy mainly through the yield of end plate and column wall.

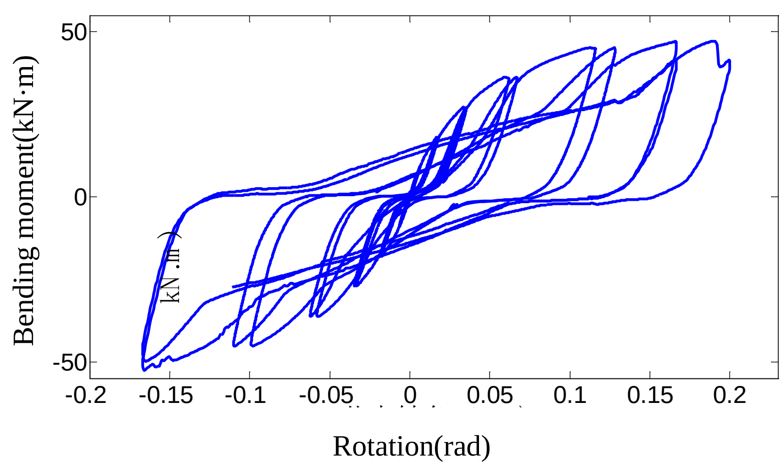


Fig.20 – Hysteretic curve of the connection

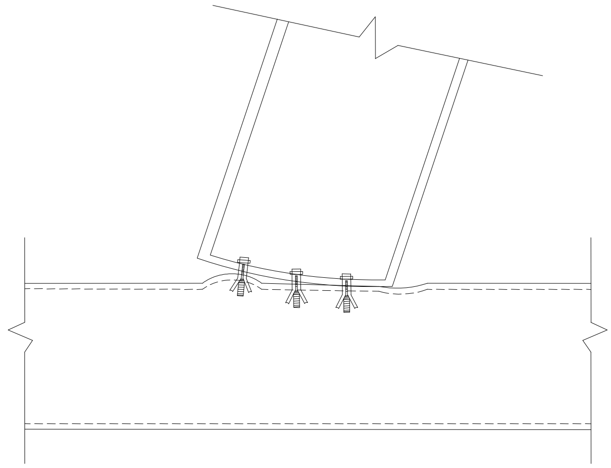


Fig.21 – Deformation of the column wall

3. Conclusions

(1) The connections between H-shaped beams to Rectangular hollow section (RHS) columns can be classified as semi-rigid connections, which possess a certain degree of resistance of shear, bending moment and deformation. While from the perspective of conservative, we can assume this connection as pinned connection.

(2) The shear capacity of this kind of connection is relatively high, usually higher than the shear capacity of the beam, makes this kind of connection a reliable connection.

(3) The stress pattern of this kind of connection is that the bolts in edge row undertake almost all the bending moment, centering around the flange of the beam.

(4) During the early stages of loading, the pinch effect of hysteretic curves is relatively evident, but with the increase of the load, the end plate and column wall started to yield, the hysteretic curve of the connection became more and more plump. The connection dissipates the energy mainly through the yield of end plate and column wall.

(5) This kind of connection has good ductility, the ultimate rotation of the connection reaches 0.2rad, far beyond the limit value of 0.03rad required by American seismic standard.

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