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NUMERICAL ANALYSIS ON SEISMIC BEHAVIOUR OF TIMBER FRAME STRUCTURE WITH HYBRID SCREWED-IN ROD CONNECTIONS

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ABSTRACT: A hybrid connection with steel bracket and screwed-in rods was developed for timber structures or hybrid steel-timber structures. Cyclic tests have been conducted upon the proposed connection and then compared it with the traditional bolted connections. Test results showed that the hybrid connection had better stiffness, energy dissipating capacity, and moment resisting capacity, compared with the bolted connection. The numerical models for the two types of connections were established. Bayesian parameter identification method was used to calibrate the parameters of the model. These two connection models were applied to a three-story frame numerical model in Open System for Earthquake Engineering Simulation (Opensees), and the seismic performances of the three-story frame with hybrid connection or bolted connections were evaluated, which can provide guidance for the application of the innovative connection hybrid connection. The results show that the hybrid connection can reduce the displacement response of the structure and improve the seismic performance of the structure, especially under rare earthquakes.

KEYWORDS: Steel bracket, Screwed rods, Bolted connection with steel plate, Three layers frame

1 INTRODUCTION

The bolted connections with steel plate are widely used in modern timber structures for convenient fabrication. However, bolted suffered lots of problems. Low initial stiffness may be caused by the space reserved for installation. Insufficient tensile and shear strength of timber results in low moment resisting capacity. Brittle failure mode of wood in tension and shear direction leads to brittle failure of joints [1-4]. In order to solve the above problems, screwed rods has been proposed to connect the beam and column. The joints connected by screwed rods have satisfactory initial stiffness and moment resisting capacity.

But the limitation in energy dissipating capacity restricts the ability of structures to reduce seismic response [5-7]. In this paper, screwed rods and steel bracket are used in beam-column connections. Cyclic loading test are implemented on bolted connection and hybrid connection to evaluate the initial stiffness, moment resisting capacity, and energy dissipating capacity. The connection numerical models are established in the OpenSees environment. Model parameters are identified by Bayesian method. The numerical models for bolted connection and hybrid connections are applied to a three-story structure model for nonlinear time history analysis. The interlayer displacement angles of the two structures are compared.

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2 NUMERICAL ANLYSIS OF BEAM-TO-COLUMN CONNECTION

2.1 NUMERICAL MODEL

Figure 1 show the specimen design of the hybrid connection. The specimen had a timber beam member (135 mm × 420 mm in cross section, 1500 mm in length), a steel column member (350mm × 160mm × 20mm in cross section, 1500 mm in length). The steel bracket was a replaceable ductile energy dissipation element. Steel bracket was connected by bolts to the steel column. Steel bracket was connected to the screwed rods at the end of the timber beam. The test data of bolted connection with steel plate were compared with the hybrid connection.

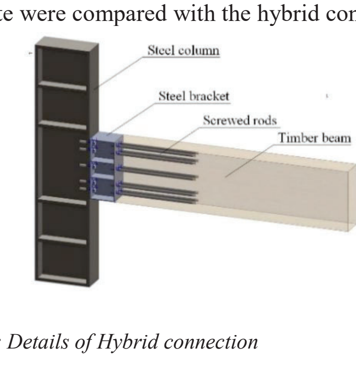

Figure 1: *Details of Hybrid connection*

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In order to meet the need of nonlinear time history analysis of the structure, fiber model is used for finite calculation of the structure. Figure 2 shows the model of the connection. The steel column was modelled by dispBeamColumn element with steel02 material. The model has high precision and high numerical stability, and can effectively simulate the Bauschinger effect of rebar. The glulam beam was modelled by dispBeamColumn element with Concrete02 material. The model parameters were determined according to results of the mechanical tests of glulam. The steel bracket was simplified to a rotational spring. Compared with the experimental data of the connection, the multi-parameter Pinching4 material model could better simulate the degradation and damage of the steel bracket, as shown in Figure 3. The model parameters are calibrated by Bayesian method. The method of parameter identification is referred to the literature [8]. Parameter identification results are shown in Table 1.

Table 1 *Identified parameter*

Tag	Bolted connection	Hybrid connection
ePf1/kN·m	26.76	34.96
ePf2/kN·m	42.04	53.61
ePf3/kN·m	55.12	72.60
ePf4/kN·m	39.43	50.65
ePd1/rad	8.89E-03	6.25E03
ePd2/rad	2.02E-02	1.56E02
ePd3/rad	2.74E-02	3.86E02
ePd4/rad	6.00E-02	8.00E02
eNf1/kN·m	-35.51	-44.99
eNf2/kN·m	-45.45	-67.92
eNf3/kN·m	-70.29	-91.22
eNf4/kN·m	-51.70	-69.44
eNd1/rad	-8.86E-03	-6.25E03
eNd2/rad	-1.76E-02	-1.61E02
eNd3/rad	-3.52E-02	-3.80E02
eNd4/rad	-6.00E-02	-8.00E02
rDisP	3.50E-01	6.80E-01
rForceP	8.57E-02	2.73E-01
uForceP	2.01E-03	-3.01E-01
rDisN	1.67E-01	6.46E-01
rForceN	4.10E-02	5.50E-01
uForceN	3.03E-02	1.20E-01
gK1	9.50E-01	-5.15E-02
gK2	5.77E-01	1.29E-01
gK3	7.23E-01	1.62E-01
gK4	8.38E-01	8.67E-01
gKLim	4.01E-02	2.32E-02
gF1	9.31E-01	2.78E-01
gF2	8.40E-01	4.25E-01
gF3	6.09E-01	7.83E-01
gF4	5.13E-01	4.81E-01
gFLim	8.74E-03	1.19E-01
gD1	9.93E-01	-1.52E-03
gD2	4.01E-02	-1.58E-03
gD3	8.10E-01	4.71E-06
gD4	9.08E-01	4.78E-05
gDLim	8.46E-04	-1.64E-03

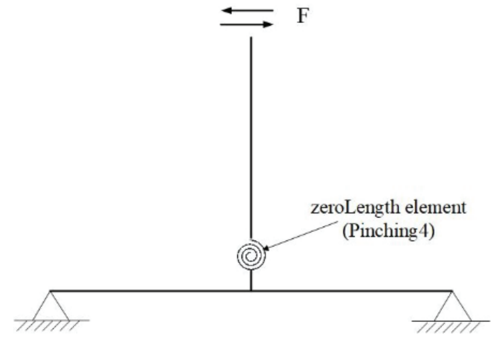

Figure 2: *Numerical mode of the connection.*

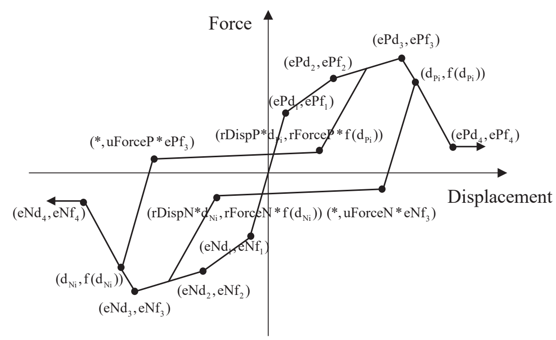

Figure 3: *Pinching4 constitutive model.*

2.2 CALIBRATION

In order to verify the accuracy of the numerical model, the simulation hysteresis curve of the connection model is compared with the experimental hysteresis curve. The hybrid connection test results are provided by the literatures [9]. Figure 4 and Figure 5 show the simulated result. The loading stiffness, bearing capacity and unloading stiffness obtained by numerical model are consistent with the experimental results, which proves that the model is effective and the parameter selection is reasonable.

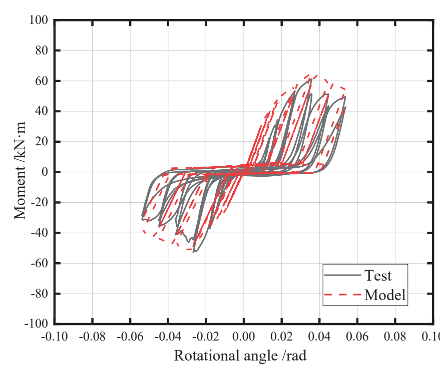

Figure 4: *Comparison of hysteretic curves (bolted connection)*

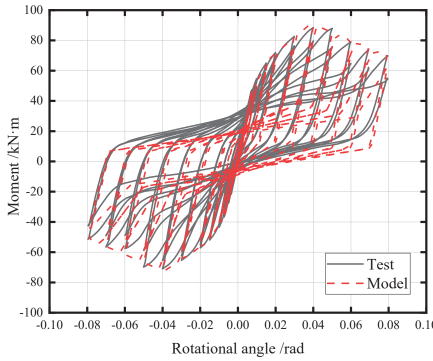

Figure 5: Comparison of hysteretic curves (hybrid connection)

3 NUMERICAL ANLYSIS OF FRAME STRUCTURE

3.1 NUMERICAL MODEL

According to Chinese code for seismic design of buildings (GB50011-2010) [10], a three-storey frame structure is designed. The structure is located in the 8 degree fortified area, the second group, the second site classification. As the structure is regular, the torsion effect can be ignored. Therefore, a longitudinal frame is proposed to reflect the longitudinal seismic performance of the whole structure. The frame consists of 3 spans of 5 meters each. Each layer of the frame is 4 meters in height, and the whole frame is 12 meters in height. Figure 6 shows the model of a three-story structure. A two dimensional three-storey frame was simulated. The model of beam, column and connection is established by the modelling method of Section 2. Spring elements using elastic materials with high stiffness were arranged at column base.

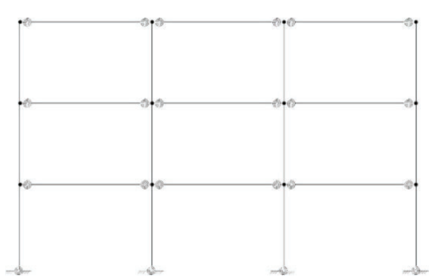

***Figure 6: 3.1** Numerical model for a three-story structure*

The modal analysis of the two frames is carried out respectively. The periods of the first two modes of the two frames are shown in the Table 2.

Table 2 Structural natural period of vibration

Specimen ID	First mode period /s	Second mode period /s
BC[a]	1.170	0.226
HC[b]	1.026	0.216

[a]BC (Bolted connection)
[b]HC (Hybrid connection)

Four natural ground motions were selected according to the site category of the structure, the design seismic grouping, the spectral characteristics of the standardized response spectrum and the first two natural vibration periods of the structure. The characteristics of each ground motion are shown in Table 3. The acceleration spectrum of each ground motion, the mean acceleration spectrum diagram and the target response spectrum are compared under the action of 8-degree frequent and 8-degree rare earthquakes as shown in Figure 7 and Figure 8.

Table 3 Main characteristics of selected earthquakes.

GM ID	Earthquake Name	Magnitude	PGA/g
GM1[a]	Imperial Valley-06	6.53	0.17
GM2	Coalinga-01	6.36	0.60
GM3	Chi-Chi_ Taiwan	7.62	0.21
GM4	San Simeon_ CA	6.52	0.44

[a]GM (Ground motion)

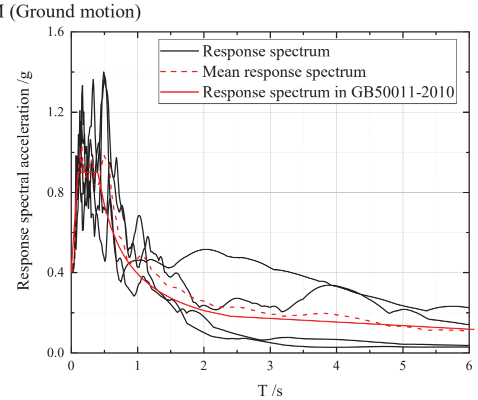

***Figure 7:** Rare earthquake response spectrum.*

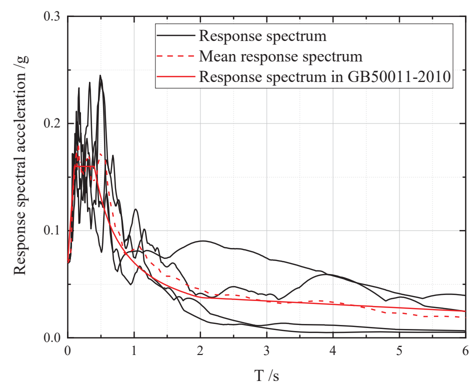

***Figure 8:** Frequent earthquake response spectrum.*

3.2 RESULT AND DISCUSSION

According to different fortification standards, the time history analysis after amplitude modulation is carried out on the four ground motions before time history analysis. The top-level displacement-time history curves of the two frames under different seismic waves are shown in the Figure 9-Figure 12 (Rare earthquake) and Figure 13-Figure 16 (Frequent earthquake). The maximum displacement response and maximum interlayer displacement Angle are shown in the Under rare

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earthquakes, hybrid connections can reduce the maximum displacement response by 19.62%, while under frequent earthquakes, hybrid connections can reduce the maximum displacement response by 9.38%. According to the simulation results, the hybrid connection can reduce the seismic response of the structure and improve the seismic performance of the structure. In rare earthquakes, the effect of lifting is more obvious.

Table ***4*** and Table 5.

By comparing the simulation results, it can be found that under rare earthquakes, the maximum displacement of the frame with hybrid connection is smaller than that with bolted connection. Under frequent earthquakes, the average maximum displacement of the frame with hybrid connection is smaller than that of the frame with bolted connection. However, the maximum displacement response of the frame with bolted connection is larger than that of the frame with hybrid connection under GM2.

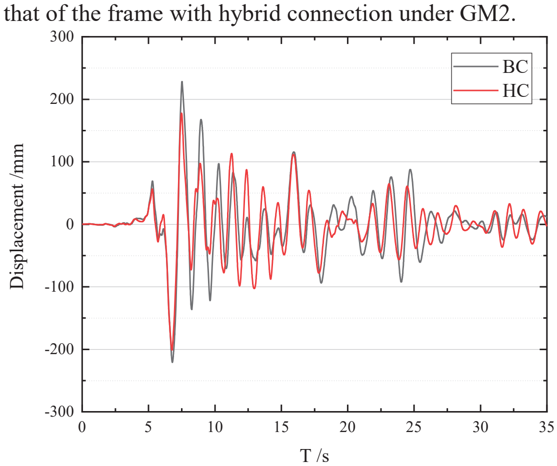

Figure 9: *Comparison of displacement time histories of the top layer of two frames under GM1 (Rare earthquake).*

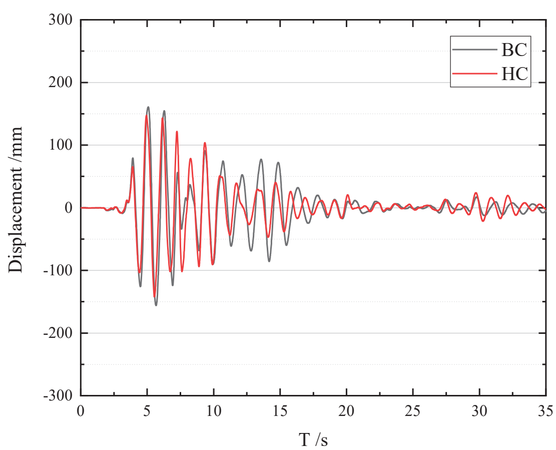

Figure 10: *Comparison of displacement time histories of the top layer of two frames under GM2 (Rare earthquake).*

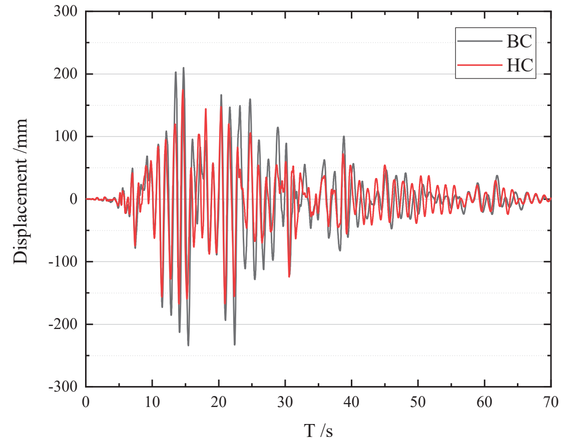

Figure 11: *Comparison of displacement time histories of the top layer of two frames under GM3 (Rare earthquake).*

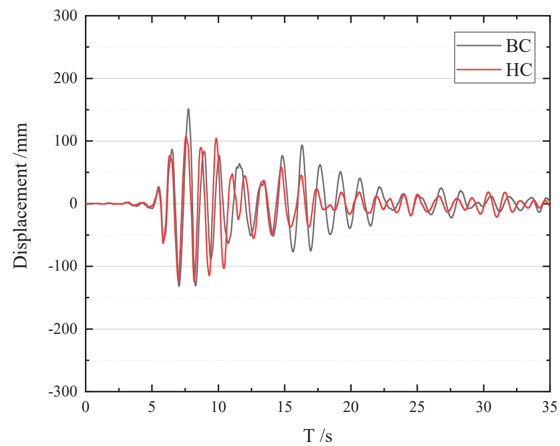

Figure 12: *Comparison of displacement time histories of the top layer of two frames under GM4 (Rare earthquake).*

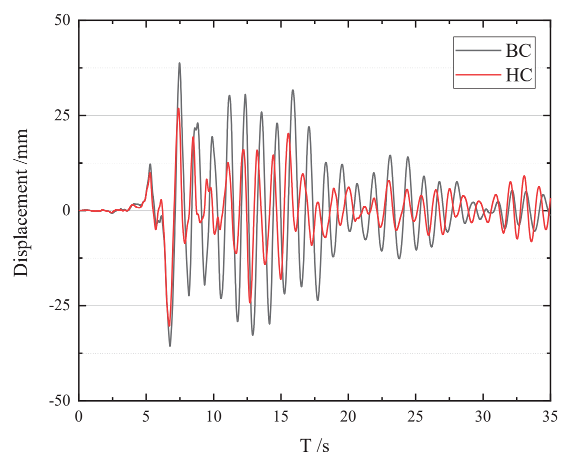

Figure 13: *Comparison of displacement time histories of the top layer of two frames under GM1 (Frequent earthquake).*

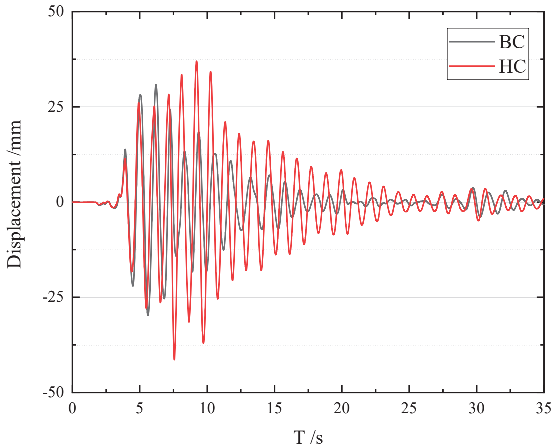

Figure 14: *Comparison of displacement time histories of the top layer of two frames under GM2 (Frequent earthquake).*

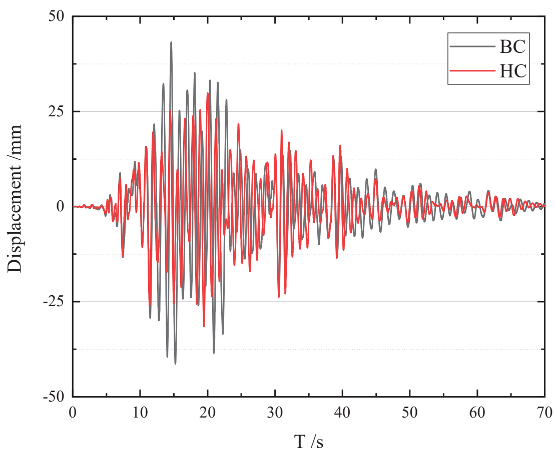

Figure 15: *Comparison of displacement time histories of the top layer of two frames under GM3 (Frequent earthquake).*

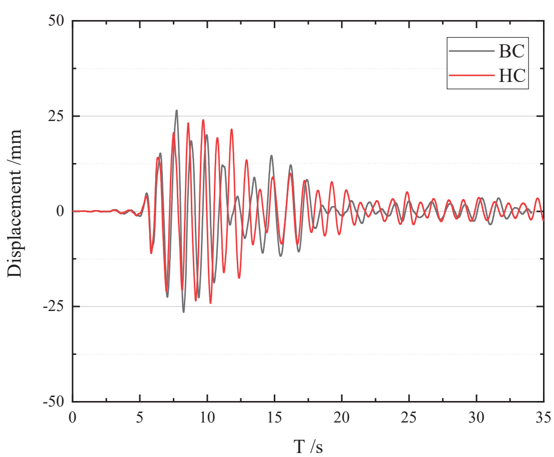

Figure 16: *Comparison of displacement time histories of the top layer of two frames under GM4 (Frequent earthquake).*

Under rare earthquakes, hybrid connections can reduce the maximum displacement response by 19.62%, while under frequent earthquakes, hybrid connections can reduce the maximum displacement response by 9.38%. According to the simulation results, the hybrid connection can reduce the seismic response of the structure and improve the seismic performance of the structure. In rare earthquakes, the effect of lifting is more obvious.

Table 4 Comparison of maximum deformation under rare earthquakes

GM ID	Maximum displacement /mm		Maximum displacement Angle /%		Difference ratio /%
	BC	HC	BC	HC	
GM1	228.37	201.34	1.90	1.68	13.42
GM2	160.83	147.06	1.34	1.23	9.36
GM3	234.05	174.59	1.95	1.45	34.06
GM4	151.40	124.60	1.26	1.04	21.51
Total	193.66	161.90	1.61	1.35	19.62

Table 5 Comparison of maximum deformation under frequent earthquakes

GM ID	Maximum displacement /mm		Maximum displacement Angle /%		Difference ratio /%
	BC	HC	BC	HC	
GM1	38.78	30.31	0.32	0.25	27.96
GM2	30.83	41.40	0.26	0.35	25.54
GM3	43.14	31.50	0.36	0.26	36.96
GM4	26.54	24.13	0.22	0.20	9.97
Total	34.82	31.84	0.29	0.27	9.38

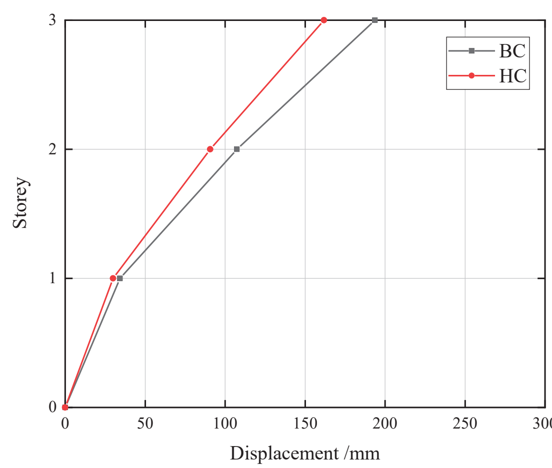

Figure 17: *Comparison of displacement between layers of the two frames (Rare earthquake).*

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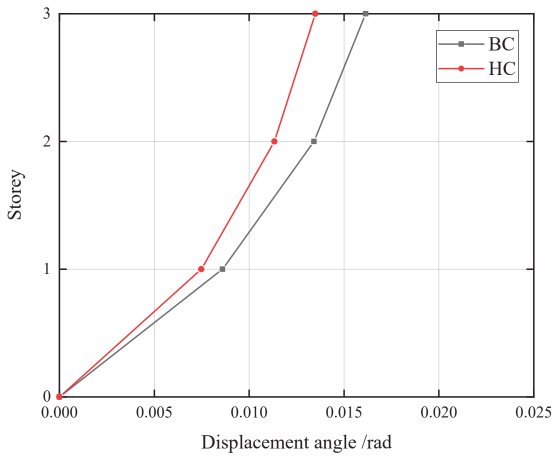

Figure 18: *Comparison of displacement angle between layers of the two frames (Rare earthquake).*

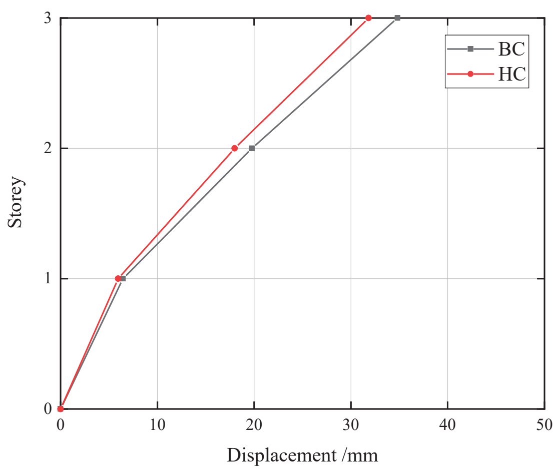

Figure 19: *Comparison of displacement between layers of the two frames (Frequent earthquake).*

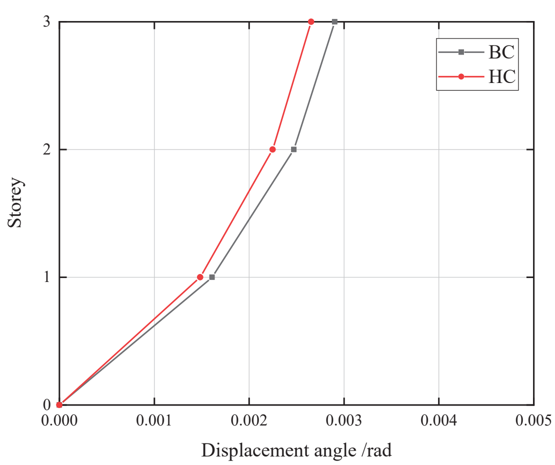

Figure 20: *Comparison of displacement angle between layers of the two frames (Frequent earthquake).*

Figure 17- Figure 20 shows the mean displacement and the mean displacement angle of each layer under different ground motions according to different fortification standards. The displacement response of each floor of the mixed connected frame is smaller than that of the traditional connected frame

4 CONCLUSIONS

In this paper, a ductile beam-column connection, named as hybrid connection, was proposed and investigated. Compared with the traditional bolted connection, hybrid connection has higher stiffness, moment resisting capacity, and energy dissipating capacity. The joint models are established and compared with the experimental results to verify the accuracy of the model. Also, these two kinds of connections are applied to a three-story structure model. The interlayer displacement angles and interlayer displacement are compared. The following conclusions can be drawn:

1. The connection modelling method has been verified by experimental data with accuracy and can be used for connection modelling.
2. The frame with hybrid connection can reduce the displacement response of each layer of the structure and improve the seismic performance of the structure under the ground motions according to different fortification standards.
3. It is more obvious that the frame with hybrid connection can improve the seismic performance of the structure under rare earthquakes.

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