World Journal of Engineering and Technology, 2024, 12, 1046-1074
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

RC Frame-Prefabricated HPFRCC Energy Wall Structure System Energy Distribution Research

Yiting Chen

Department of Civil Engineering, Xijing University, Xi'an, China
Email: 787617255@qq.com

How to cite this paper: Chen, Y.T. (2024) RC Frame-Prefabricated HPFRCC Energy Wall Structure System Energy Distribution Research. *World Journal of Engineering and Technology*, **12**, 1046-1074.
https://doi.org/10.4236/wjet.2024.124066

Received: October 17, 2024
Accepted: November 11, 2024
Published: November 14, 2024

Abstract

The weak layer of steel concrete (RC) frame structure is easy to destroy under the action of the earthquake, the damage mechanism is more difficult to control. Severe damage to the building structure after the earthquake, resulting in too high repair costs or having to dismantle and rebuild. In order to improve and enhance the anti-seismic performance of the RC framework structure, energy consumption devices are added between the frame columns to achieve the effect of reducing the RC frame structure damage and improving the seismic performance of the RC frame structure. In this article, high-performance fiber-enhanced cement base composite materials fabricated energy consumption walls are prepared in the RC frame structure to form a new type of seismic structure system of RC frame-prefabricated HPFRCC energy consumption wall. This article uses the power timing analysis of the ABAQUS finite element software to study the anti-seismic performance, influencing factors and energy consumption distribution of the RC frame-prefabricated HPFRCC energy wall structural system.

Keywords

Reinforced Concrete Frame Construction, HPFRCC Material, Assembly Energy Dissipation Wall, Seismic Performance, Hysteresis Energy Dissipation Distribution

1. Introduction

The expected energy consumption distribution mode of the reinforced concrete frame structure under the seismic action is the plastic hinge formed by the frame beam to undertake most of the cumulative hysteresis energy consumption. The cumulative hysteresis energy consumption of a small number of frame columns should mainly concentrate in the underlying column bottom, the remaining parts of the column should try to avoid the appearance of plastic hinges. Under the action of earthquakes, the plastic hinge formed by components is used as a price hinge to absorb the energy released by the earthquake, while the stagnation energy consumption is one of the important indicators to measure the structural seismic performance. The total scattered energy of the structure includes energy such as stagnation energy, kinetic energy and strain energy. When the frame structure is affected by the earthquake, stagnation energy consumption refers to the energy consumed by all components in the structure when plastic deformation. The stagnation energy consumption can directly reflect the role of the earthquake, and the damage of the structure is also one of the indicators to measure the plastic damage of the structure and the component. RC frame-prefabricated HPFRCC energy consumption wall structure under the action of earthquake, the layer displacement gradually tends to be uniform. Compare with the ordinary reinforced concrete frame structure, the interlayer displacement is smaller. The HPFRCC energy wall is used as the main energy consumption component, which is responsible the role of the first line of defense. Influence RC frame—the distribution of total input seismic energy in the prefabricated HPFRCC energy consumption wall structure is affected by various factors, such as the number and location of the energy consumption wall.

2. Literature Review

Bora Gencturk [1] and others studied the seismic performance of a RC/HPFRCC frame with two layers and two spans under seismic action, the left column of the bottom floor was selected for static time history analysis, but the rest of the frame is analyzed by structural simulation technology under seismic action. The results show that the application of HPFRCC in RC frame structure can effectively improve the energy dissipation capacity of the structure under earthquake action.

Shuling Gao [2] and others studied the mechanical properties of HPFRCC materials through a biaxial dynamic compression test, and obtained its failure mode, peak strain, peak stress, elastic modulus, stress-strain curve and other indices. The results of the study suggest that, under the action of biaxial dynamic load, the ultimate compressive strength of HPFRCC is higher than ordinary concrete. It has good ductility property.

Hassan [3] and others study the compressive properties of HPFRCC at different ages. The results of the study suggest that the compressive properties of HPFRCC materials at different ages (7 days to 28 days) have no significant change.

Hiroshi Fukuyama [4] proposes a HPFRCC seismic response control device, set in a 1 × 2 span 3-layer steel frame and performing a shaking table test on it. The results show that the HPFRCC reaction control device can significantly reduce the stress deformation of steel frame and control the failure mechanism of the frame structure.

Hiroshi Fukayama [5] proposes a new technique for structural control of soft-layer reinforced concrete buildings. The HPFRCC device is installed next to an existing column on the ground floor. Through dynamic analysis, results show that the deformation ability of the structure is controlled successfully by HPFRCC device. The ductility and energy dissipation capacity of the specimen are greatly improved, and absorb more seismic energy. It has good plastic deformation ability and seismic performance.

Li [6] *et al.* studied the effect of fine aggregate on the strain-hardening performance of HPFRCC materials. The test results showed that the addition of fine aggregate to HPFRCC materials could improve its elastic modulus, and excessive fine aggregate content would inhibit the false strain hardening of the materials and reduce the ductility of the materials.

Matsumoto T [7] *et al.* tested the flexural fatigue characteristics of PVA-HPFRCC materials. The results show that the high ductility and steady-state fracture characteristics of HPFRCC have a great influence on the fatigue properties of the structure. In the macroscopic view, HPFRCC can be regarded as a kind of high-ductility cement matrix composite with metal characteristics and good fatigue resistance.

Through the experimental study, Maalej [8] and others found that the single fiber HPFRCC with high modulus has the characteristics of higher ultimate strength and lower strain capacity.

E.C. Olsen [9] proposed a method of seismic reinforcement, high ductility high-performance fiber reinforced concrete (HPFRCC) is prefabricated into filling plate for frame structure. The test shows that the structure has good cyclic properties in terms of hysteretic stability, ductility, energy dissipation and damage tolerance.

Qudah [10] and others used HPFRCC material instead of concrete in the middle node area to study its seismic performance. The results show that HPFRCC can effectively improve the seismic performance of the structure.

Zhang, X [11] and others proposed a new type of prestressed concrete composite shear wall, and studied the seismic performance of the composite shear wall for finite element analysis. The results show that the composite shear wall has good seismic performance.

Wang, YL [12] and others proposed an energy dissipation precast shear wall structure system with steel strip dampers, to study the seismic behavior of the shear wall structure, a low cycle repeated load test was carried out. The results show that the bearing capacity of the fabricated shear wall structure is slightly reduced, but the ductility is obviously improved. The energy dissipation of the shock absorber improves the seismic performance of the structure.

To sum up, HPFRCC material is used as energy dissipation damping device in frame structure, the seismic performance of the frame structure is improved. Most of the existing research is based on the influence of the seismic performance of steel frame structures, but there are few studies on the effect of HPFRCC energy dissipation wall in RC frame structure on the seismic performance of RC frame structure. This article uses a quantitative analysis method to analyze the power timing of the RC frame-prefabricated HPFRCC structure finite element model. By analyzing the plastic energy consumption distribution of the structural system in different earthquakes and the acceleration of different peak values, the principle of the energy consumption distribution of the RC frame-prefabricated HPFRCC energy wall structure system, discusses the factors that affect the distribution of structural energy, and analyze the stagnation of the structure between the distribution rules between the components and the distribution of energy consumption between the layers.

3. Methodology

3.1. Model Building

The model dimensions are shown in **Figure 1**. The reinforcement of the model is shown in **Figure 2**.

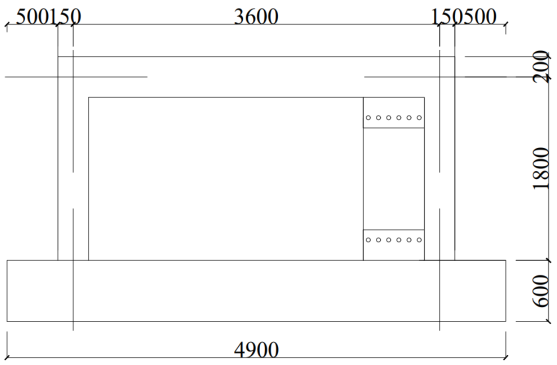
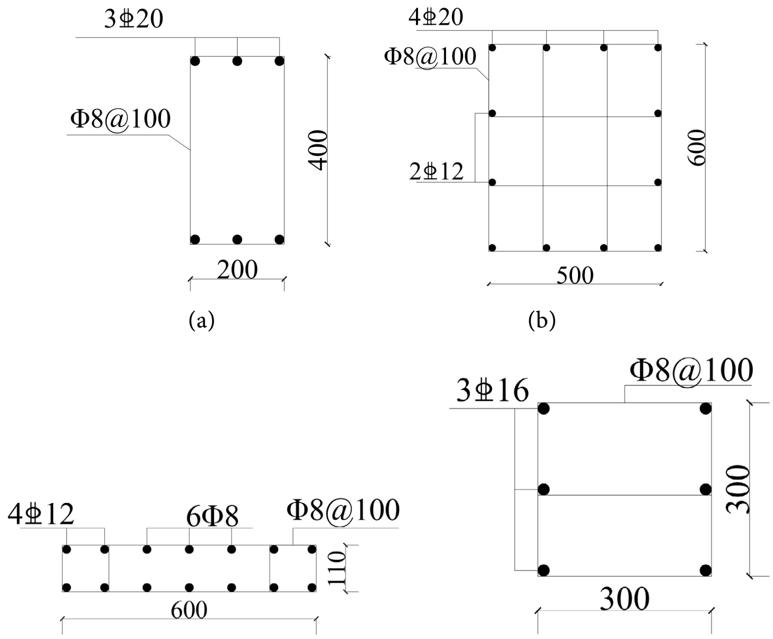


Figure 1. Size diagram of specimen FW-1.



(a) (b) (c) (d)

Figure 2. Reinforcement diagram of specimen. (a) Frame top beam reinforcement diagram; (b) Frame bottom beam reinforcement diagram; (c) FRC Energy dissipation wall reinforcement diagram; (d) Frame column reinforcement diagram.

The concrete strength grade of the frame structure of this model is C40, the wall adopts FC40 strength grade HPFRCC material, the thickness of the concrete protective layer of the test pieces is 10mm, the stress reinforcement adopts HRB400 reinforcement, and the beam, column and wall hoop adopts HPB300 reinforcement. The mechanical characteristics of the concrete and HPFRCC material are shown in Table 1. The model established by ABAQUS is shown in Figure 3. The mechanical parameters of reinforcement are shown in Table 2. The steel plate and bolt are connected by a binding connection. Displacement loading was adopted in the analysis, and the loading system was shown in Table 3. The loading system for grades 1 to 8 was used for one load cycle per stage, followed by three load cycles per stage.

Table 1. Mechanical properties of concrete and HPFRCC.

Parameter (test value)	Concrete	HPFRCC
Peak compressive strength f_c/MPa	44.19	45.56
Ultimate compressive strain	0.0033	0.008

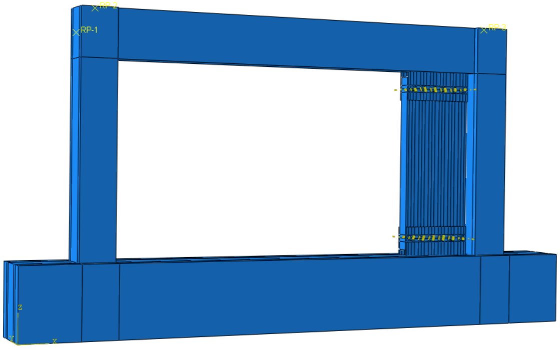


Figure 3. FW-1 model.

Table 2. Test results of reinforcement materials.

Grade of reinforcement	Diameter of reinforcement/mm	f_y (MPa)	f_u (MPa)
HPB300	8	380	505
HRB400	12	470	650
	16	533	710
	20	420	595

Table 3. Loading regime of specimen FW-1.

Specimen	Loading regime																
FW-1	Load level control displacement (mm)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		1	2	3	4	5	6	7	8	10	20	30	40	50	60	70	80

3.2. Unit Type and Unit Selection

The quasi-static analysis of the model is performed using the ABAQUS finite element analysis software. Both HPFRCC materials and concrete materials use the concrete plastic damage model provided by the software, and the reinforcement uses the strengthened elastic-plastic double-break line model. The energy-consuming wall, concrete, and steel bars are all modeled using solid modeling. The energy-consuming wall and concrete are modeled using hexahedral 8-node C3D8R linear reduced integration solid elements, and the steel bars are modeled using three-dimensional truss elements T3D2. The diameter of the steel bars is determined by defining the cross-sectional area of the element. As shown in Figure 4, the connection between the steel bar and the concrete is achieved using the EMBEDDED REGION constraint, where the steel bar is the embedded element and the concrete and PVA-HPFRCC are the main elements.

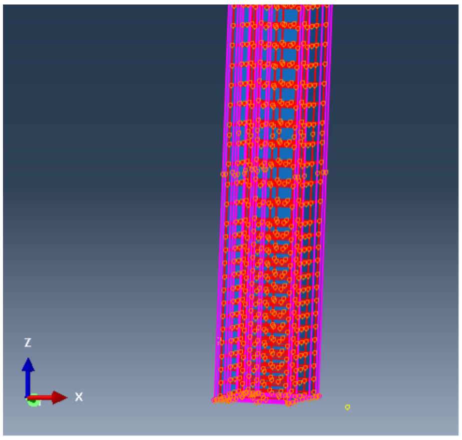


Figure 4. Reinforcement with concrete built-in definition.

3.3. Partitioning of Grids

The quality of mesh division in ABAQUS directly affects the time of calculation and analysis as well as the accuracy of the analysis results. Due to the complexity of the model and the long analysis time, in order to reduce the analysis time and ensure the accuracy of the analysis results, multiple grid accuracy divisions are performed and the results are analyzed. In the end, the overall grid division accuracy is set to 300mm for this simulation, and the grid division accuracy at the beam-column nodes is set to 150 mm.

3.4. Formulating Establishment Model Overview

Basic model reinforced concrete frame structure formulating finite element model is taken from actual engineering, select the one floor 6-layer three spans for power timing analysis, and calculate the brief diagram as shown in Figure 5. Earthquake fortification intensity is 7 degrees, and at the class II site, the design earthquake is grouped into the first group, structural seismic grade 2. Model parameters are shown in Table 4. The prefabricated HPFRCC energy consumption wall is arranged according to research needs, establish 4 RC framework-prefabricated HPFRCC energy wall structure finite element model, according to the design of the different rigidity and strength ratio of the HPFRCC energy wall and frame column, HPFRCC energy consumption wall is arranged as: First layer of side cloth; First layer of middle cloth; First or second layer of side cloth; First or second layers of middle cloth. The basic parameters of the HPFRCC energy consumption wall are shown in Table 5, and the model diagram is shown in Figure 6. The connection part of the RC frame and HPFRCC energy wall consumption wall use steel plates to connect. All steel plates are Q235 grade 20mm thick steel plates. The connection structure of the frame beam and energy consumption wall is shown in Figure 7.

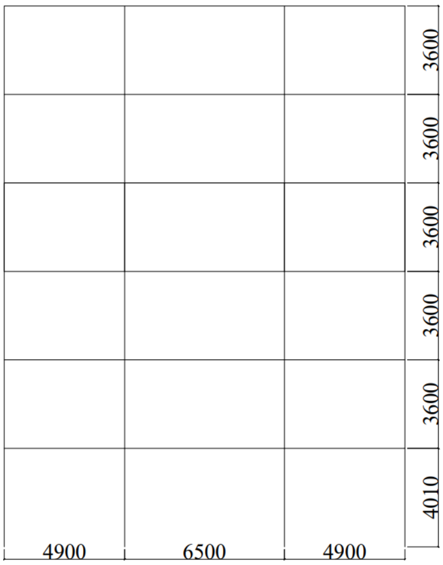


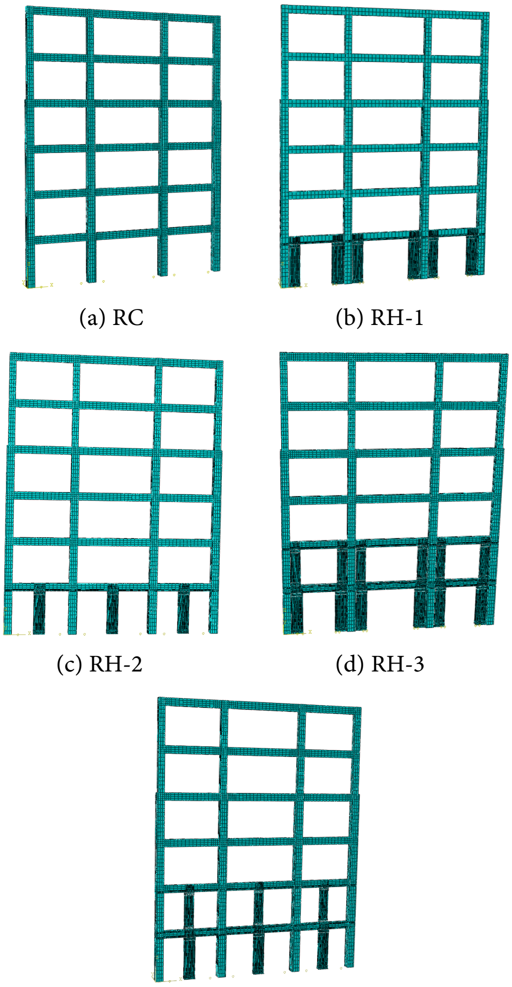
Figure 5. Calculation diagram.

Table 4. RC frame dimensions and reinforcement table.

Number		1	2	3	4	5	6
Height (mm)		4010	3600	3600	3600	3600	3600
Column size (mm)		650 × 650 (middle) 600 × 600 (side)	600 × 600	600 × 600	600 × 600	500 × 500	500 × 500
Column reinforcement (Unilateral)		2C22 + 2C20	4C20	4C20	4C20	4C20	4C20
Beam size (mm)		250 × 600	250 × 600	250 × 600	250 × 600	250 × 600	250 × 600
Reinforcement	Top	8C22	8C22	8C22	8C22	7C22	8C20
	Bottom	5C22	5C22	5C22	5C22	5C22	5C22
Column stirrup		Φ10@100/150 (middle) Φ8@100/150 (side)	Φ8@100/150	Φ8@100/150	Φ8@100/150	Φ8@100/150	Φ8@100/150
Beam stirrup		Φ8@100	Φ8@100	Φ8@100	Φ8@100	Φ8@100	Φ8@100

Table 5. Basic parameters of an HPFRCC energy consumption wall.

	First energy consumption wall			Second energy consumption wall			Stiffness ratio of the wall to the column	Strength ratio of the wall to the column	Layout position
	Size	Force	Distributed tendon	Size	Force	Distributed tendon			
RH-1	900 × 150 × 3310	Φ8@100	Φ8@100	-	-	-	1.17	0.84	Side cloth
RH-2	900 × 150 × 3310	Φ8@100	Φ8@100	-	-	-	1.17	0.84	Middle cloth
RH-3	900 × 150 × 3310	Φ8@100	Φ8@100	750 × 150 × 2900	Φ8@100	Φ8@100	First floor1.17 second floor1.07	First floor1.07 second floor0.82	Side cloth
RH-4	900 × 150 × 3310	Φ8@100	Φ8@100	750 × 150 × 2900	Φ8@100	Φ8@100	First floor1.17 second floor1.07	First floor1.07 second floor0.82	Middle cloth



(a) RC (b) RH-1

(c) RH-2 (d) RH-3

(e) RH-4

Figure 6. Finite element model diagram.

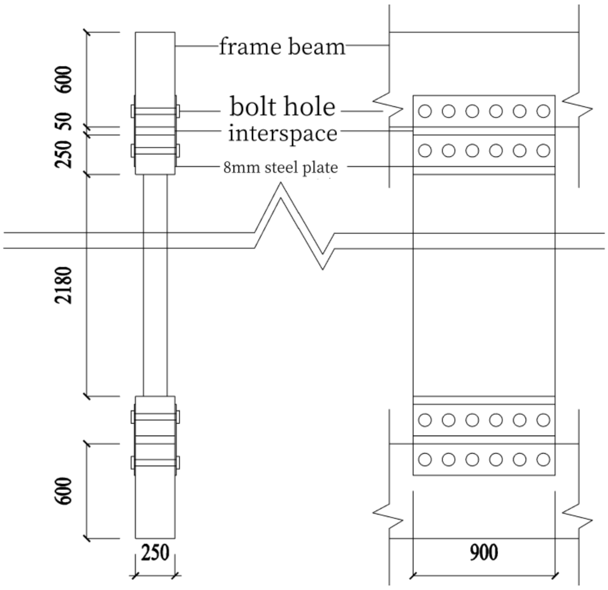


Figure 7. Connection construction of energy consumption wall and frame beam.

The concrete strength level adopts C35, HPFRCC strength level adopts C30, beam, column, energy consumption wall longitudinal reinforcement and stirrup adopt HRB400, the intensity of the concrete and reinforcement adopts the intensity of the material strength specified in the specification, the mechanical property parameters of HPFRCC materials are determined according to the test data, the relevant material parameters are shown in Table 6 and Table 7.

Table 6. Mechanical properties of reinforcement.

Reinforcement model	f_y/MPa	Ultimate tensile strain
HRB400	432	0.01

Table 7. Mechanical properties of concrete and HPFRCC.

Parameter (average)	Concrete	HPFRCC
Peak tensile strength f_t/MPa	3.1	4.5
Ultimate tensile strain	0.0001	0.015
Peak pressure strength f_c/MPa	32.01	29.6
Ultimate pressure strain	0.0033	0.008

3.5. Selection of Seismic Waves

Choose 11 seismic wave, respectively for five dynamic time history analysis of plasticity finite element model, selection of seismic parameters shown in Table 8. According to the research needs, the amplitude modulation of 11 seismic wave peak acceleration is carried out according to 0.1 g, 0.2 g, 0.3 g, 0.4 g and 0.5 g.

Table 8. Seismic wave parameter.

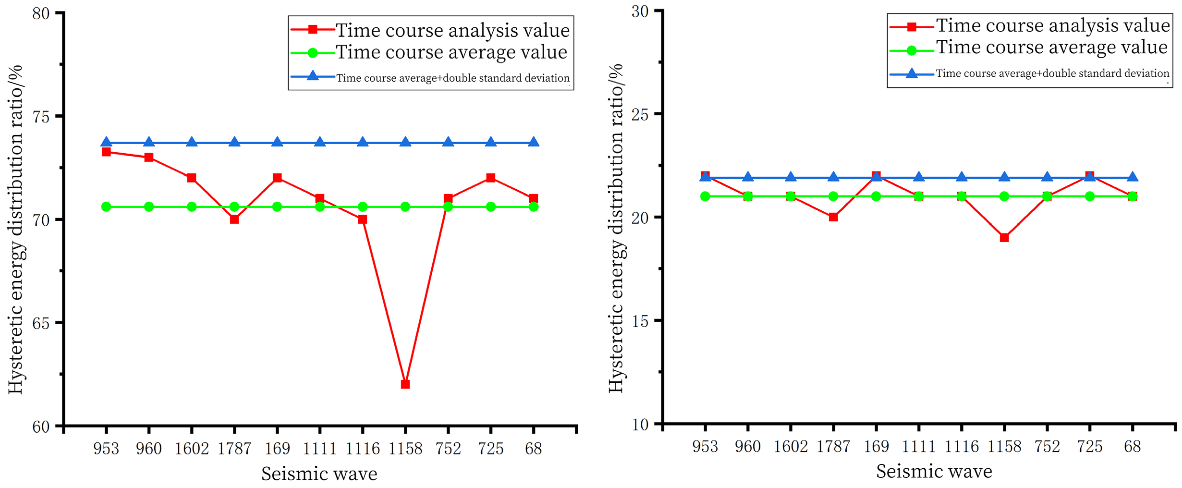
No.	Magnitude	Time	Name	Recording station	PGA max (g)	PGA max (cm/s)
1-953	6.7	1994	Northridge	Beverly Hills-Mulhol	0.52	63
2-960	6.7	1997	Northridge	Canyon Country-WLC	0.48	45
3-1602	7.1	1999	Duzce, Turkey	Bolu	0.82	62
4-1787	7.1	1999	Hector Mine	Hector	0.34	42
5-169	6.5	1979	Imperial Valley	Delta	0.35	33
6-1111	6.9	1995	Kobe, Japan	Nishi-Akshi	0.51	37
7-1116	6.9	1995	Kobe, Japan	Shin-Osaka	0.24	38
8-1158	7.5	1999	Kocaeli, Turkey	Duzce	0.36	59
9-752	6.9	1989	Loma Prieta	Capitola	0.53	35
10-725	6.5	1987	Superstition Hills	Poe Road	0.45	36
11-68	6.6	1971	San Femando	LA-Hoollywood Stor	0.21	19

4. Research Results

Hysteresis energy consumption is an important parameter to reflect the state or damage degree of the seismic structural system. The energy consumption of the different peak acceleration is calculated in 11 seismic waves from the five structural models, studying the dissipative distribution of horizontal seismic energy along structural components and layers.

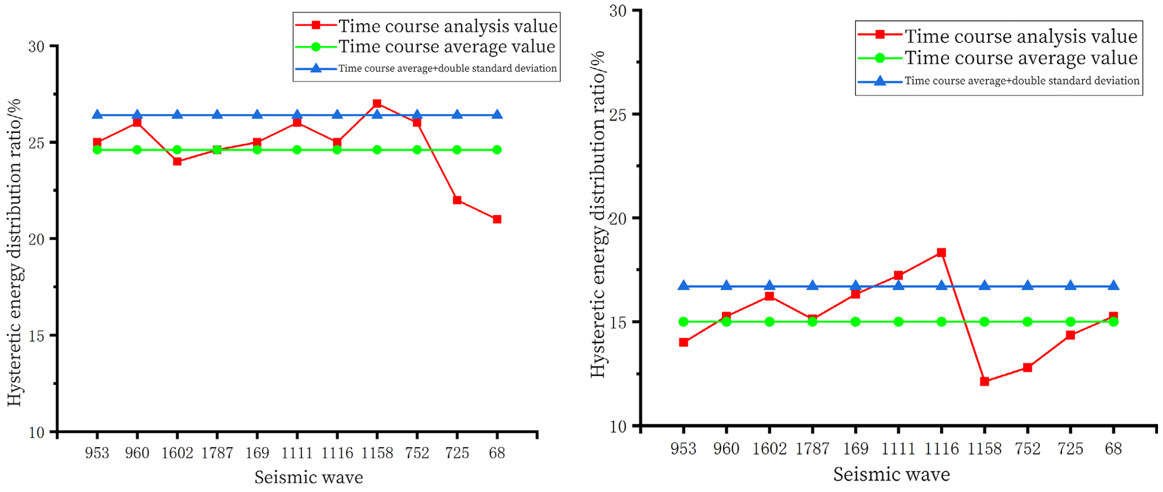
4.1. Analysis of Beam Energy Consumption Ratio

According to the component type, the hysteresis energy consumption of RC frame-prefabricated HPFRCC energy consumption wall structure can be divided into frame beam, frame column and HPFRCC energy consumption wall (**Figure 8**).

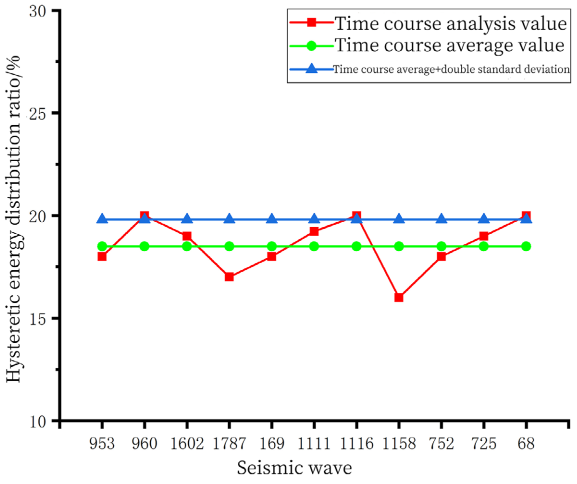


(a) RC

(b) RH-1



(c) RH-2 (d) RH-3

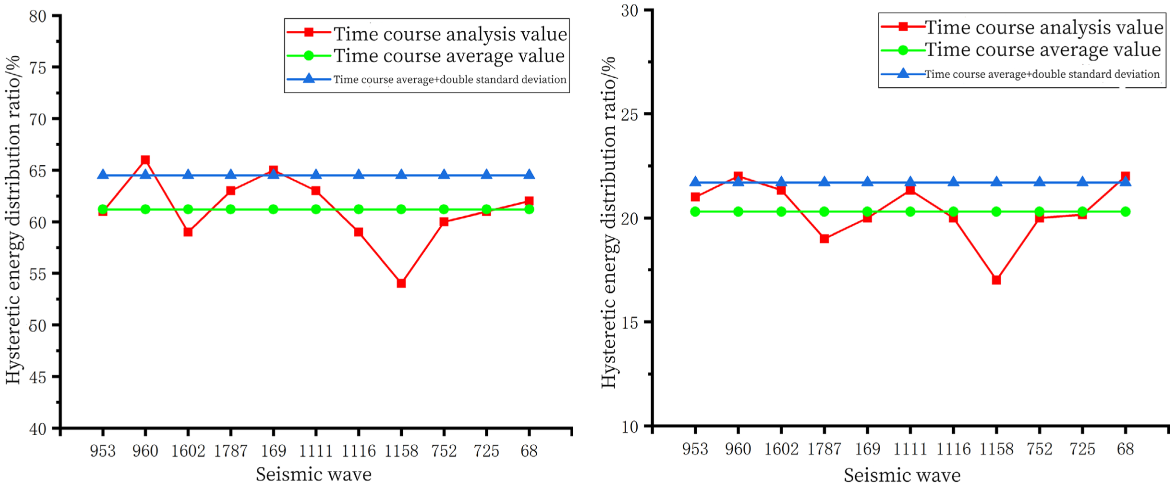


(e) RH-4

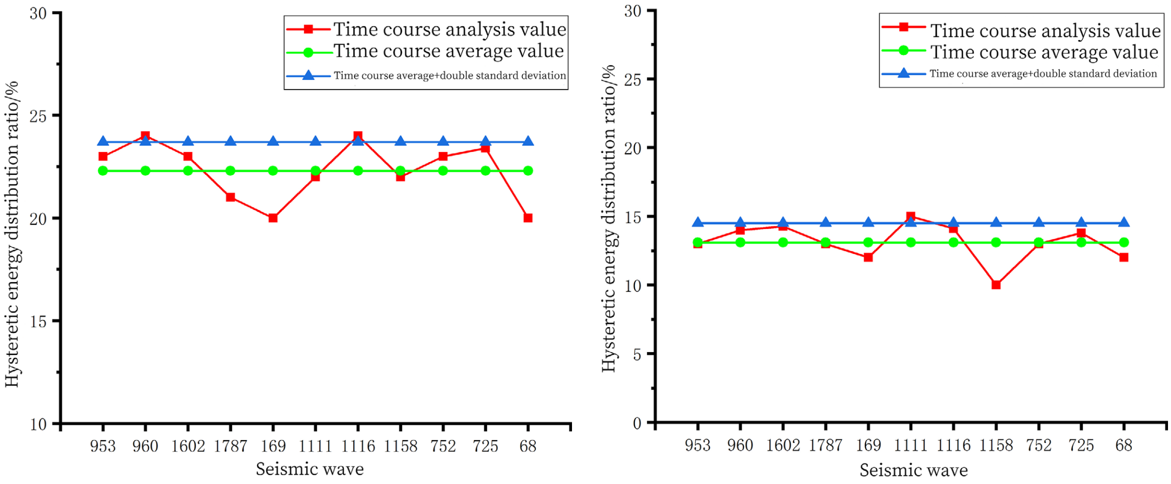
Figure 8. Beam hysteresis energy consumption.

1) When the peak acceleration of the seismic wave is 0.1 g, the average hysteresis energy consumption of the model reinforced concrete frame beam is about 70.6%, and the mean plus the twice standard deviation is 73.7%. The results show that the control of hysteresis energy consumption ratio of RC frame is better than that of RC frame wall. The data show that the hysteresis energy consumption ratio of frame beams can be reduced by increasing the number of dissipating wall layers.

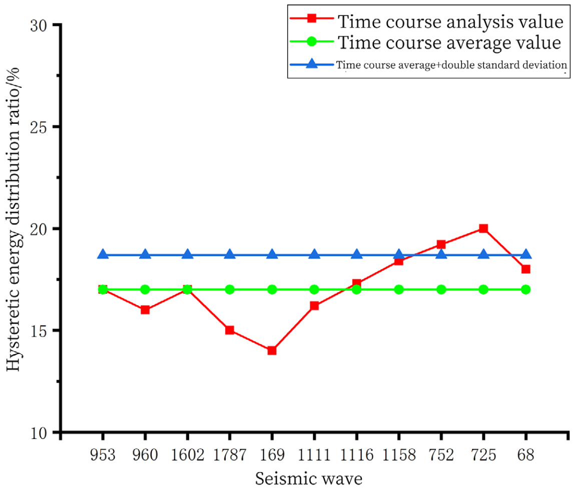
2) As shown in Figure 9, when the peak acceleration of the seismic wave is 0.2 g, the average hysteresis energy consumption of RC frame beam is about 61.2%, the mean plus the twice standard deviation is 64.5%. The data show that HPFRCC components fabricated in RC frames can reduce the proportion of hysteresis energy consumption of the frame beams. The hysteresis energy consumption of the frame beam of model RH-1 is 35% less than that of model RH-3. It shows that the more layers of the energy consumption wall, the smaller the hysteresis energy consumption ratio of the frame beam.



(a) RC (b) RH-1



(c) RH-2 (d) RH-3



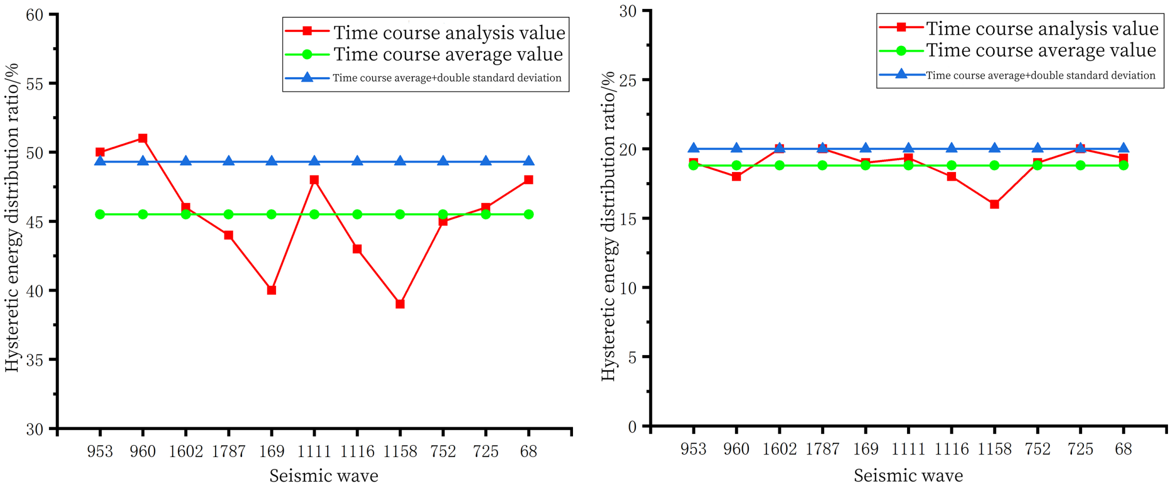
(e) RH-4

Figure 9. Beam hysteresis energy consumption.

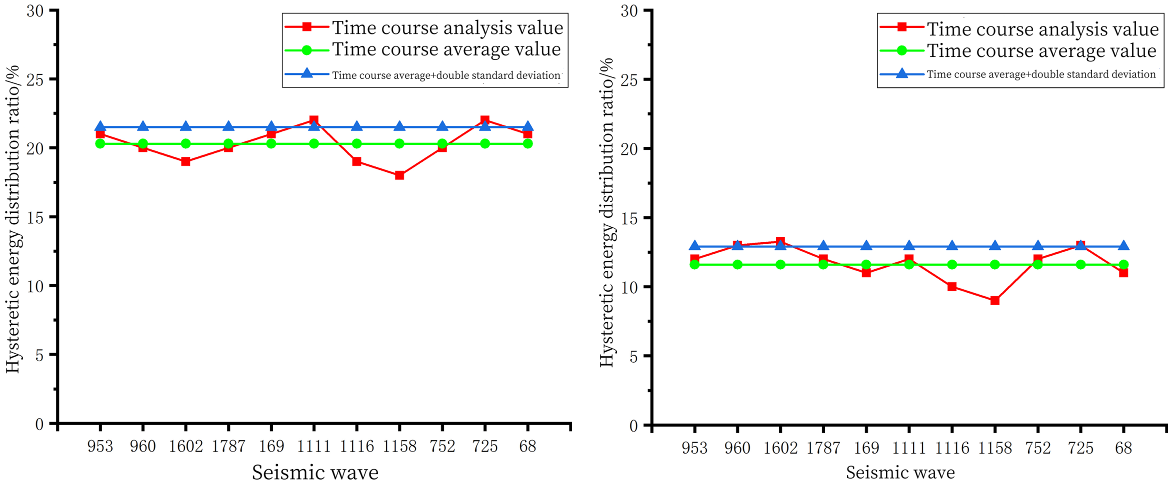
3) As shown in **Figure 10**, when the peak acceleration of the seismic wave is 0.3

g, the average hysteresis energy consumption of RC frame beam is about 45.5%, and the mean plus the twice standard deviation is 49.3%. The hysteresis energy consumption of the frame beam of model RH-3 is 38% less than that of model RH-1, the results show that the control effect of the two-floor wall on the hysteresis energy consumption ratio of the original reinforced concrete frame is better than that of the first-floor wall.

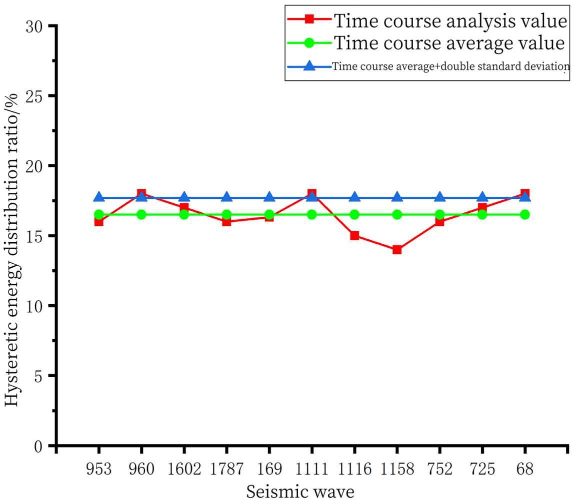
4) As shown in **Figure 11**, when the peak acceleration of the seismic wave is 0.4g, the average hysteresis energy consumption of RC frame beam is about 36%, the mean plus the twice standard deviation is 39.8%. Contrast and analyze the above data. It can be seen that, in the model RH, the proportion of hysteresis energy consumption of the frame beam will be different depending on the location of energy consumption wall, energy consumption wall side cloth is better than the energy consumption wall middle cloth. With the increase of the layers of energy consumption wall, the proportion of the hysteresis energy consumption of the frame beam decreases.



(a) RC (b) RH-1

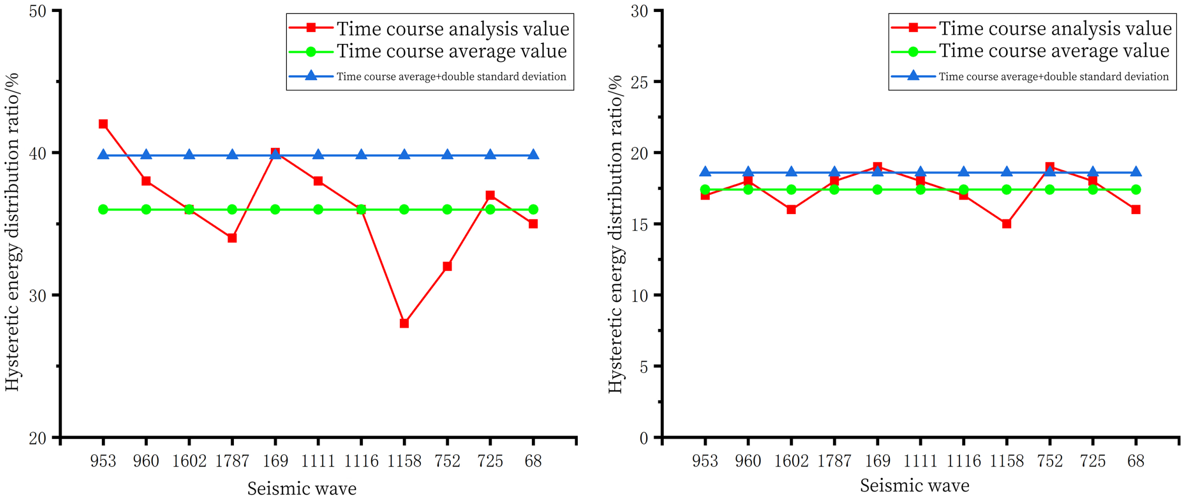


(c) RH-2 (d) RH-3



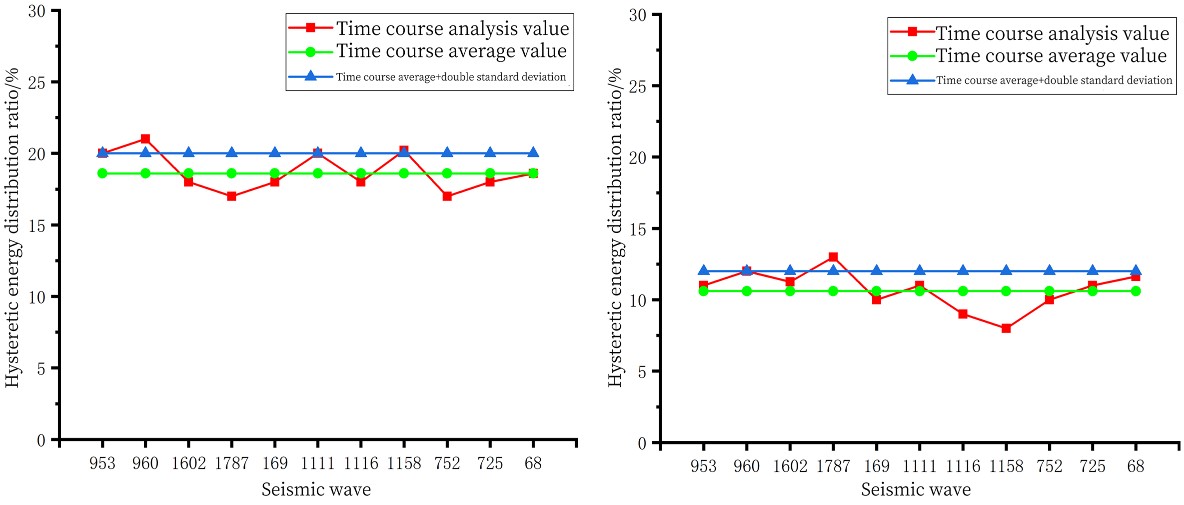
(e) RH-4

Figure 10. Beam hysteresis energy consumption.



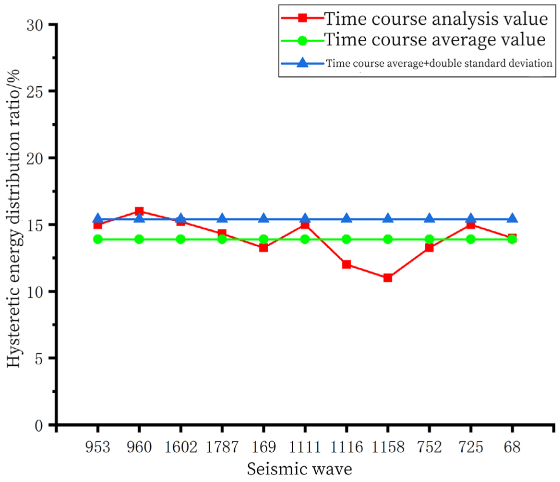
(a) RC

(b) RH-1



(c) RH-2

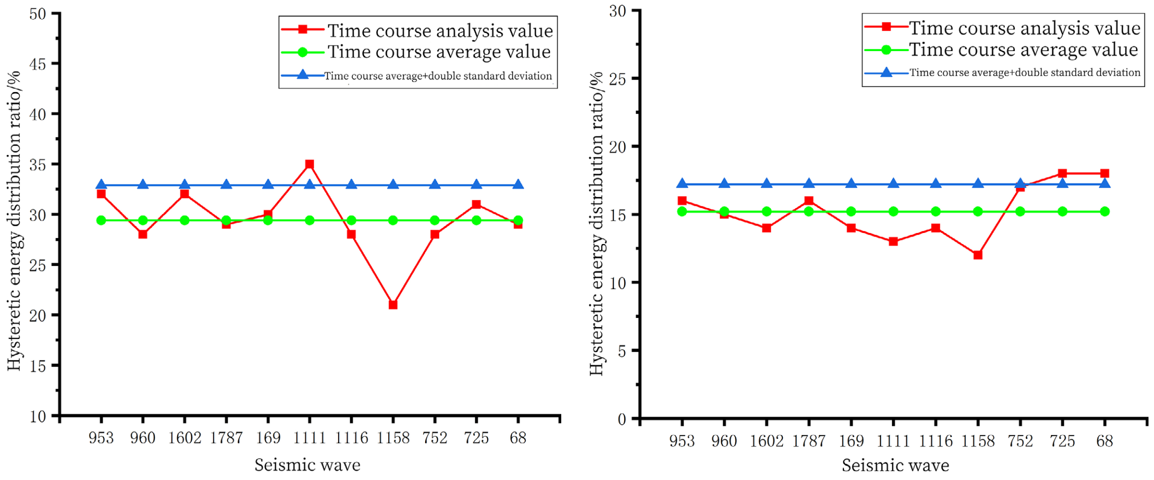
(d) RH-3



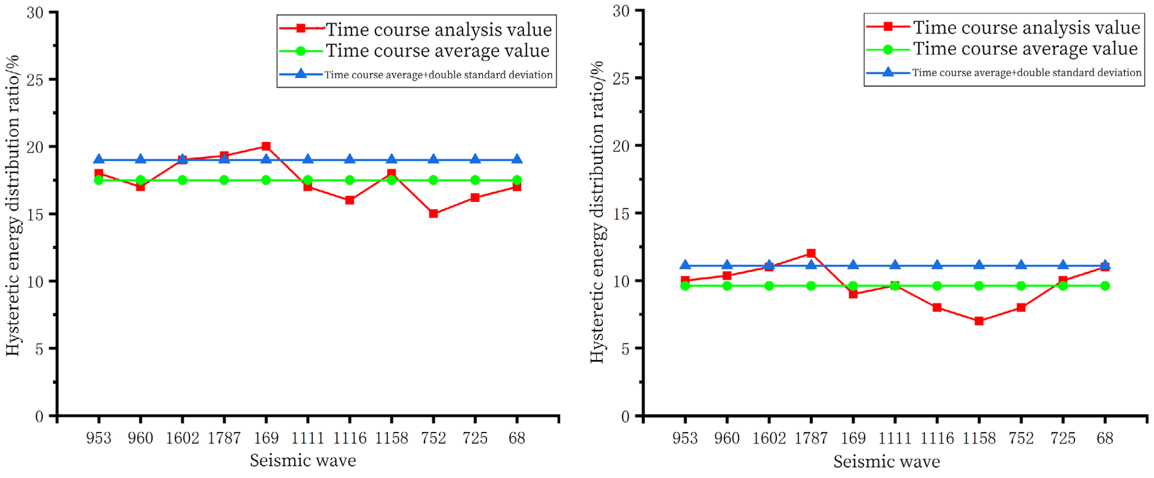
(e) RH-4

Figure 11. Beam hysteresis energy consumption.

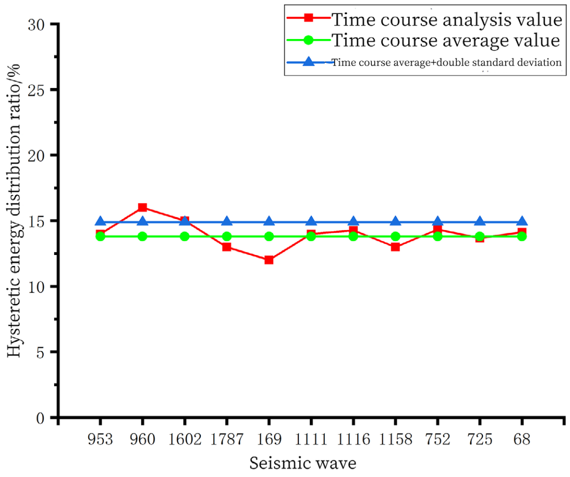
5) As shown in Figure 12, when the peak acceleration of the seismic wave is



(a) RC (b) RH-1



(c) RH-2 (d) RH-3



(e) RH-4

Figure 12. Beam hysteresis energy consumption.

0.5 g, the average hysteresis energy consumption of RC frame beam is about 29.4%, and the mean plus the twice standard deviation is 32.9%. These data show that the effect of controlling the hysteresis energy consumption ratio of the frame beam is better in the way of laying energy consumption walls at the side of the RC frame. The hysteresis energy consumption of the frame beam of model RH-3 is 37% lower than that of model RH-1, and model RH-4 is 21% lower than model RH-2. It can be seen that the hysteresis energy ratio of the control frame beam with two layers of energy consumption wall is better.

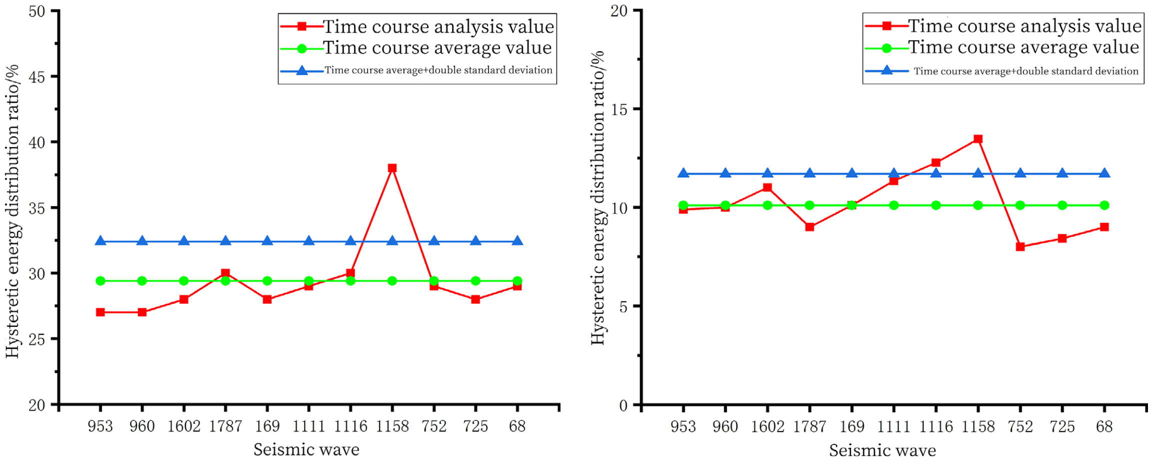
4.2. Analysis of Column Energy Consumption Ratio

Figure 13-17 show the distribution ratio of hysteresis energy consumption of the frame column under different peak accelerations in different working conditions. The data in the figure is the ratio of hysteresis energy consumption of the frame column to the total hysteresis energy consumption under each working condition.

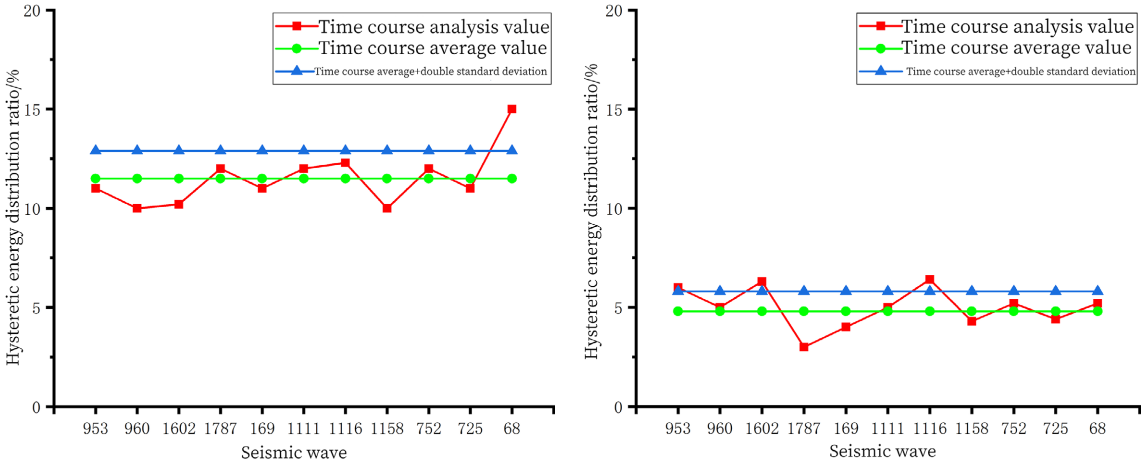
1) By the calculation data of Figure 13, when the peak acceleration of the seismic wave is 0.1g, the hysteresis energy consumption of model RH-1 is 12% lower than that of model RH-2. It shows that the control effect of the first energy consumption wall side cloth on the hysteresis energy dissipation of the frame column of the original frame structure is better than that of the first energy consumption wall middle cloth. It can be seen that the control effect of two layers of energy consumption wall side cloth on the hysteresis energy consumption of frame column is better than that of two layers of energy consumption wall middle cloth.

2) As shown in Figure 14, when the peak acceleration of the seismic wave is 0.2 g, the average hysteresis energy consumption of RC frame column is about 38.8%, and the mean plus the twice standard deviation is 42.1%. After the ordinary RC frame is equipped with HPFRCC energy consumption wall, the hysteresis energy consumption ratio of frame column decreases obviously. It can be seen that, compared with the energy consumption wall in the middle of the span, the energy consumption wall arranged in the column end attachment can effectively control

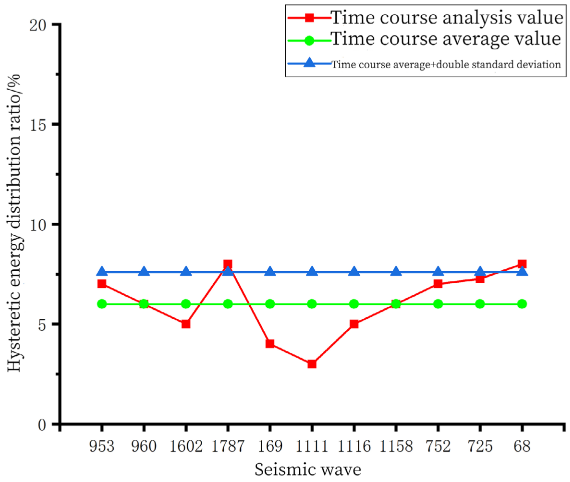
the hysteresis energy consumption of the frame column of the original RC frame structure. With the increase of the number of energy-consumption wall layers, the hysteresis energy consumption of frame columns decreases gradually.



(a) RC (b) RH-1

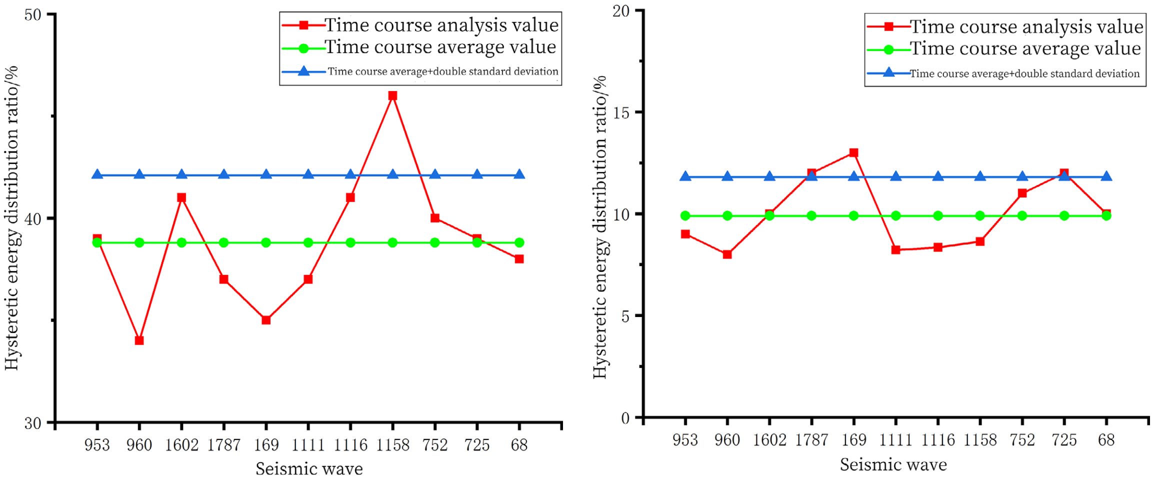


(c) RH-2 (d) RH-3

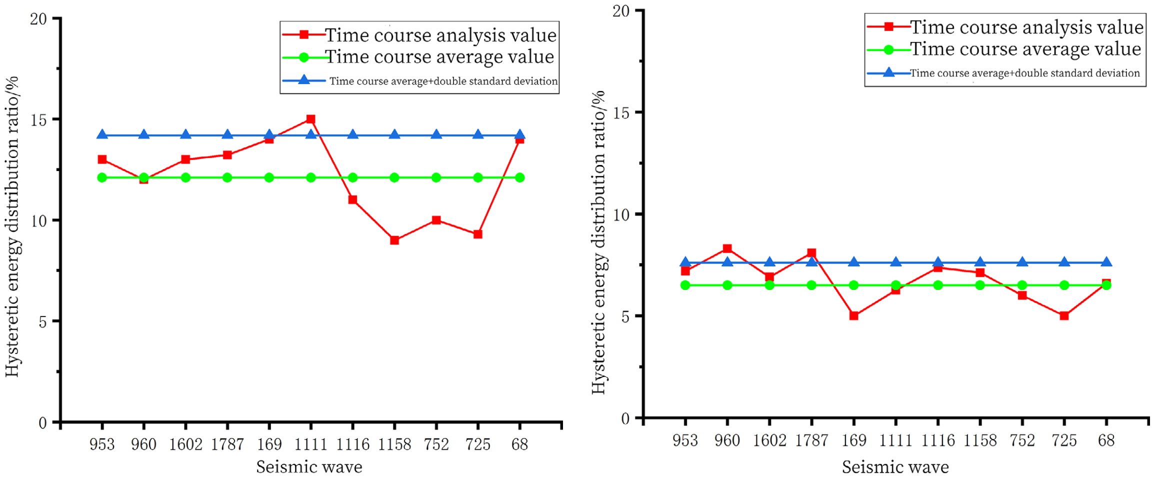


(e) RH-4

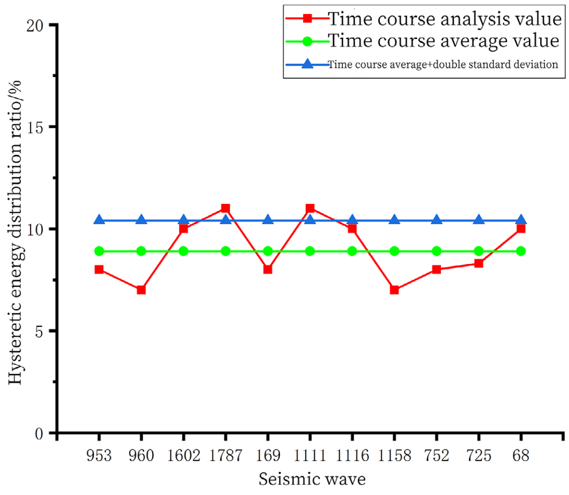
Figure 13. Column hysteresis energy consumption.



(a) RC (b) RH-1



(c) RH-2 (d) RH-3

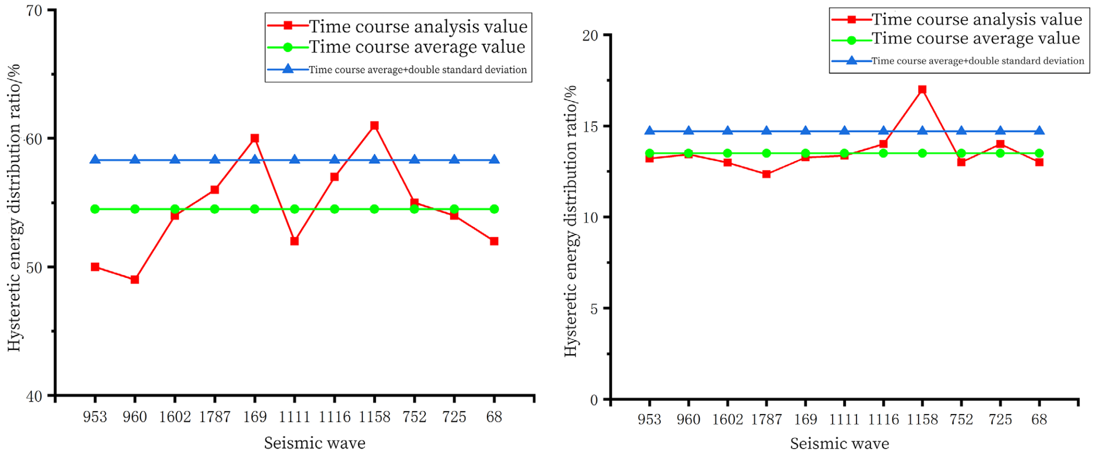


(e) RH-4

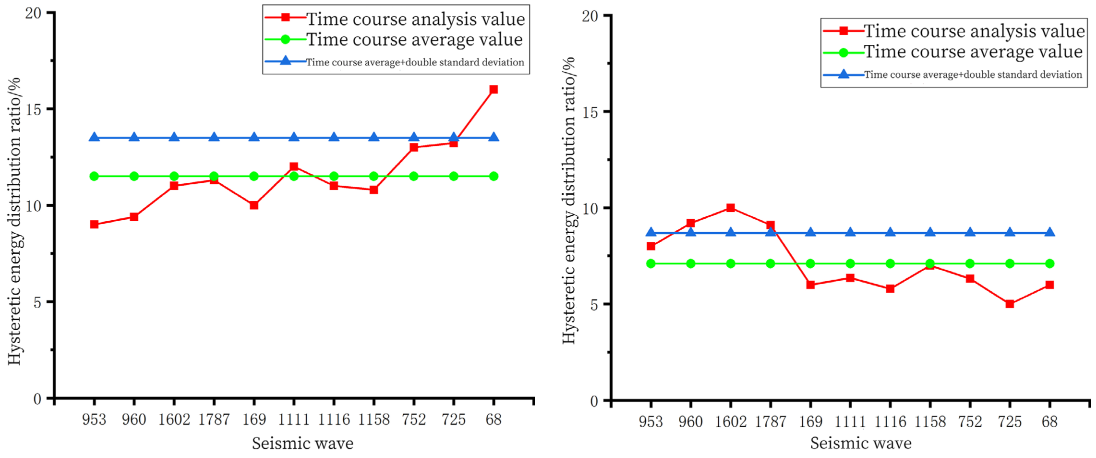
Figure 14. Column hysteresis energy consumption.

3) As shown in **Figure 15**, when the peak acceleration of the seismic wave is 0.3 g, the average hysteresis energy consumption of RC frame column is about 54.5%,

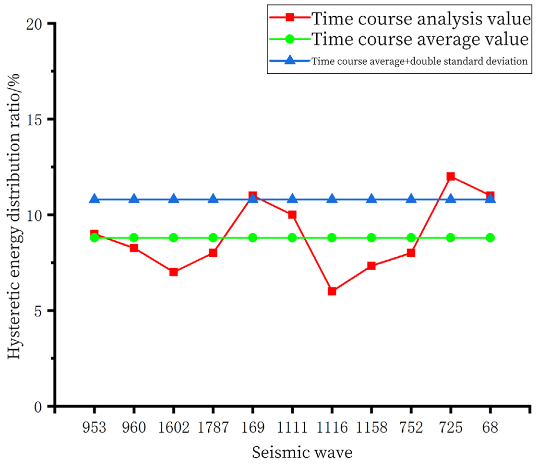
the average hysteresis energy consumption of the frame columns of RH-1, RH-2, RH-3 and RH-4 are 13.5%, 11.5%, 7.1% and 8.8%. It can be seen that when the HPFRCC energy consumption wall component is assembled in the RC frame, the hysteresis energy consumption of the frame column is reduced significantly.



(a) RC (b) RH-1



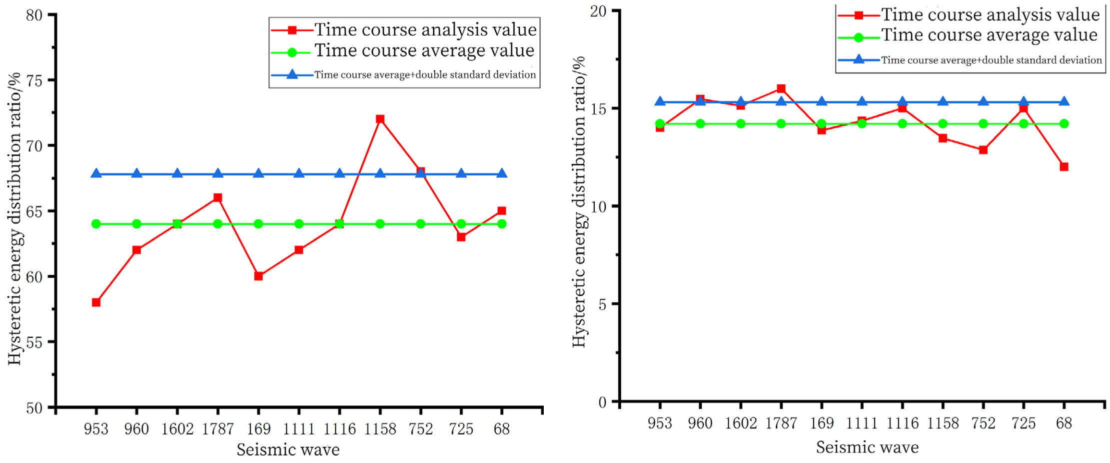
(c) RH-2 (d) RH-3



(e) RH-4

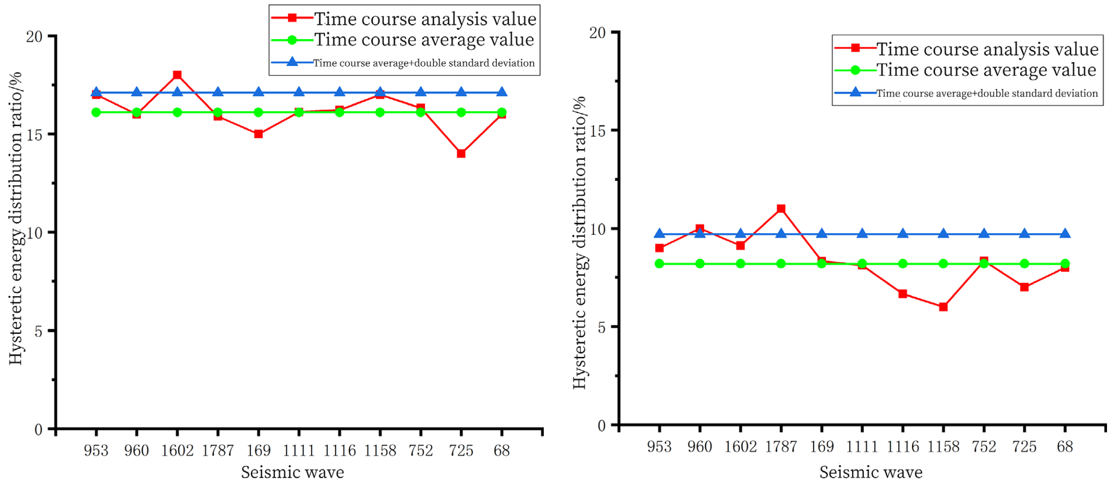
Figure 15. Column hysteresis energy consumption.

4) As shown in **Figure 16**, when the peak acceleration of the seismic wave is 0.4 g, the average hysteresis energy consumption of RC frame column is about 64.0%, and the mean plus the twice standard deviation is 67.8%.



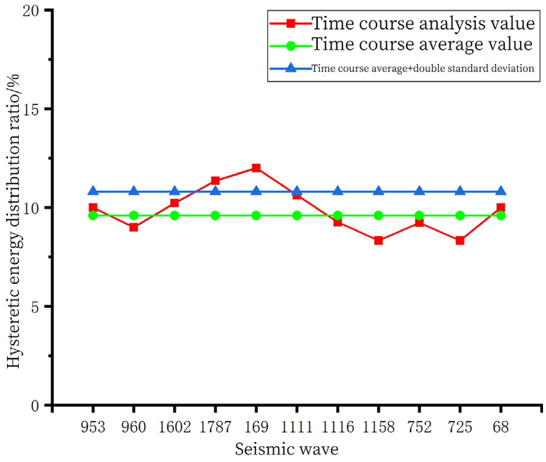
(a) RC

(b) RH-1



(c) RH-2

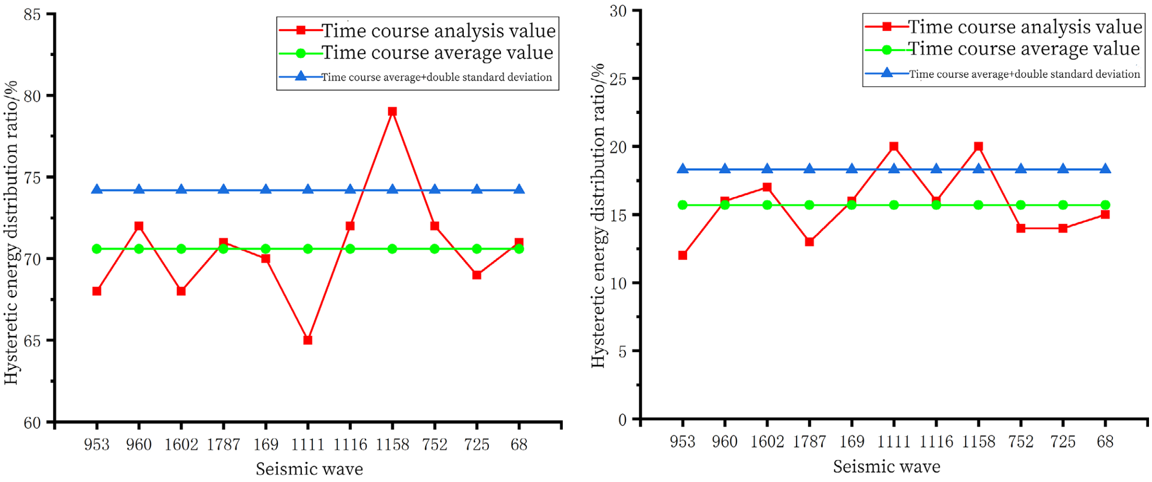
(d) RH-3



(e) RH-4

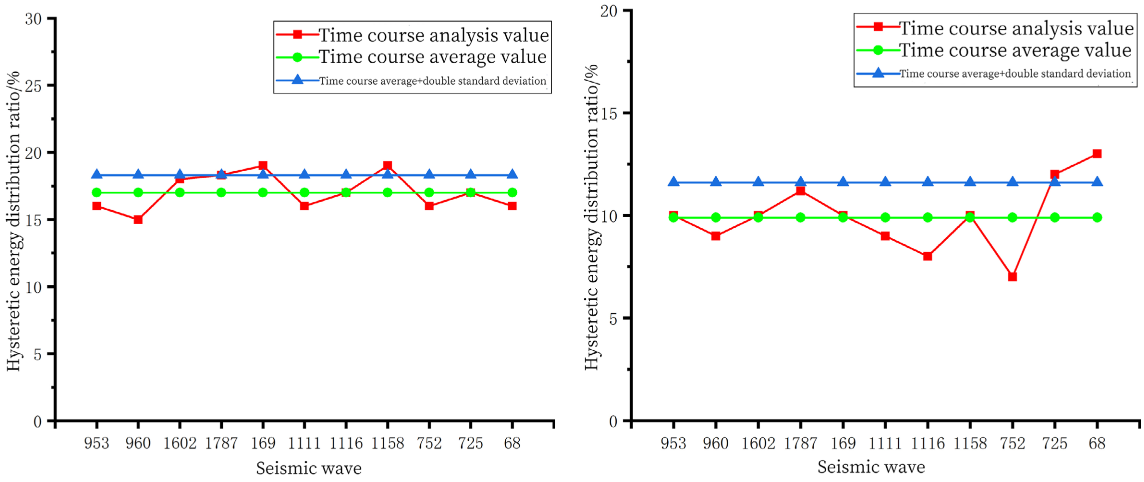
Figure 16. Column hysteresis energy consumption.

5) As shown in **Figure 17**, when the peak acceleration of the seismic wave is 0.5 g, the average hysteresis energy consumption of RC frame column is about 70.6%,



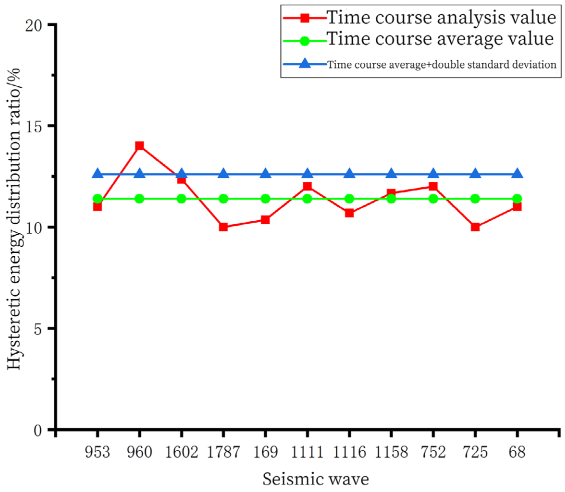
(a) RC

(b) RH-1



(c) RH-2

(d) RH-3



(e) RH-4

Figure 17. Column hysteresis energy consumption.

The mean plus the twice standard deviation is 74.2%. The results show that the hysteresis energy consumption of the first layer side cloth is better than that of the first layer middle cloth. The hysteresis energy consumption of the frame column of model RH-3 is reduced by 13% compared with model RH-4. It indicates that the two-layer side cloth of the energy consumption wall is better than the two-layer middle cloth of the energy consumption wall. The hysteresis energy consumption of the frame column of model RH-3 is 37% lower than that of model RH-1. It can be seen that the two layers of side cloth of the energy consumption wall is better than the first layer of side cloth. The result shows that the control effect of the two layers of the consumption wall on the proportion of hysteresis energy consumption of the original RC frame column is better than that of the first layer of the consumption wall.

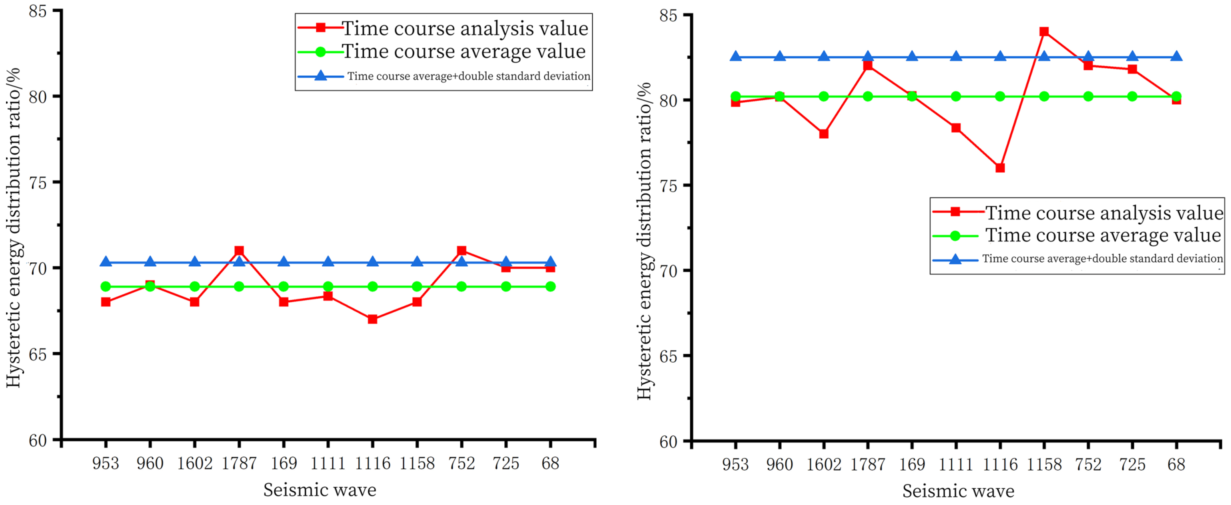
As can be seen from the above data analysis, the RC frame-prefabricated HPFRCC energy consumption wall structure is under seismic action with different peak accelerations, and the total energy consumption of the frame column is much smaller than the ratio of the frame column of model RC. The energy consumption of the RC frame-prefabricated HPFRCC energy consumption wall structure accounts for about 8% - 12% of the total energy consumption. With increasing earthquake intensity, under the different peak acceleration of the seismic, the proportion of hysteresis energy allocation of ordinary RC framework is changed. The hysteresis energy consumption of the frame column is gradually greater than that of the frame beam. This indicates a substantial emergence of plastic hinges in the RC frame, and a weak layer also appeared.

4.3. Analysis of Energy Consumption Ratio of Energy Consumption Wall

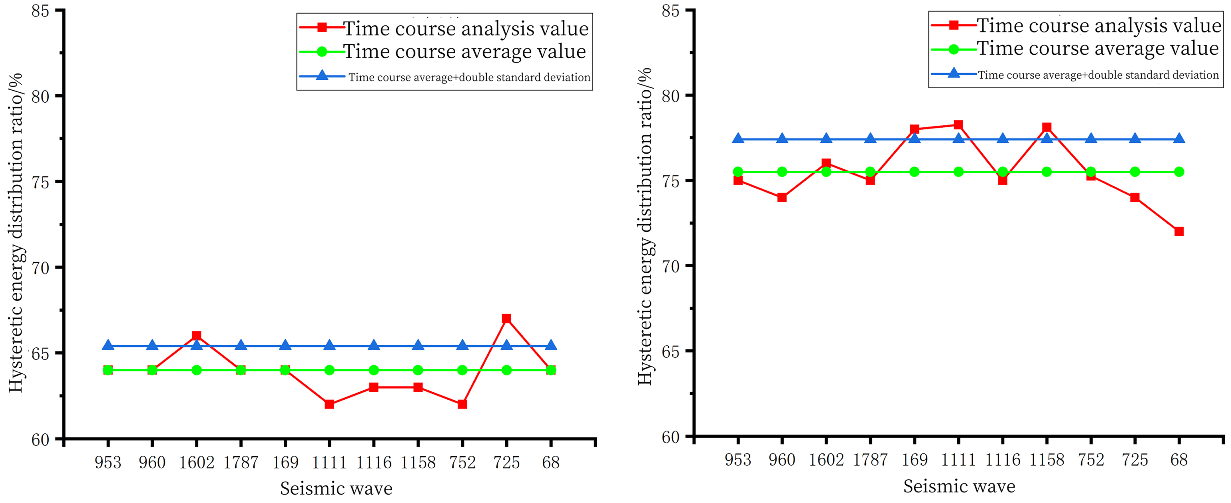
Figures 18-22 show the distribution of the hysteresis energy consumption of the energy consumption wall under each working condition. The data in the figure is the ratio of hysteresis energy consumption to total hysteresis energy consumption under different seismic action.

1) As shown in **Figure 18**, when the peak acceleration of the seismic wave is 0.1 g, the average energy consumption of the energy consumption wall of models RH-1, RH-2, RH-3 and RH-4 accounted for 68.8%, 64.0%, 80.2% and 75.5% of the total energy consumption.

2) As shown in **Figure 19**, when the peak acceleration of the seismic wave is 0.2 g, the average energy consumption of the model RH-1 energy consumption wall is 69.8% of the total energy consumption, and the mean plus the twice standard deviation is 72%. The proportion of the energy consumption wall of model RH-1 increased by 6% over that of model RH-2. The control effect of the energy consumption ratio of the first layer of the energy consumption wall is better than that of the cloth in the first layer of the energy consumption wall. The proportion of the energy consumption wall of model RH-3 increased by 9% over that of model RH-4. It shows that the effect of two layers of the energy consumption wall on the proportion of the energy consumption wall is better than the layout of two layers

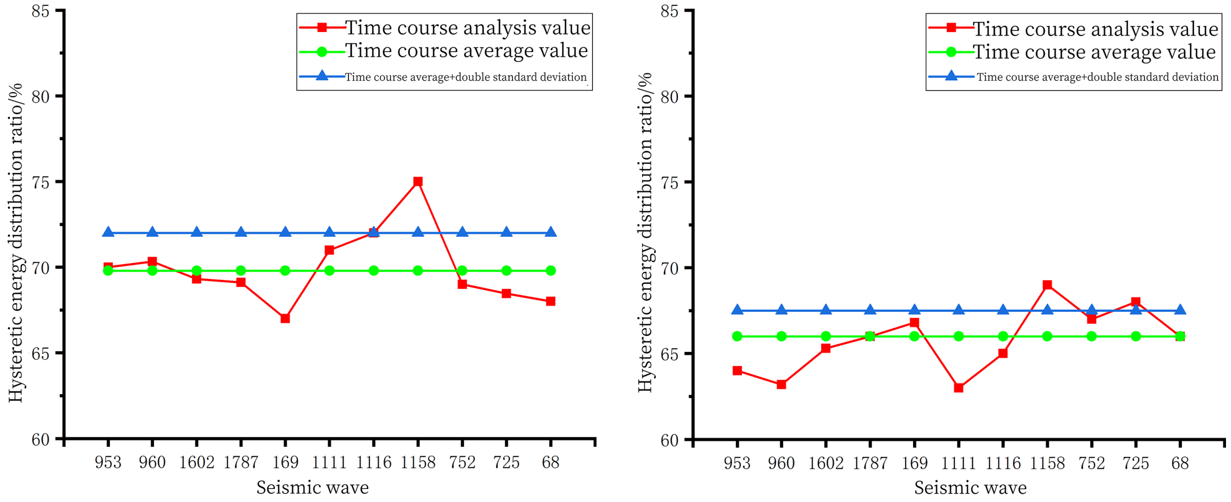


(a) RH-1 (b) RH-2

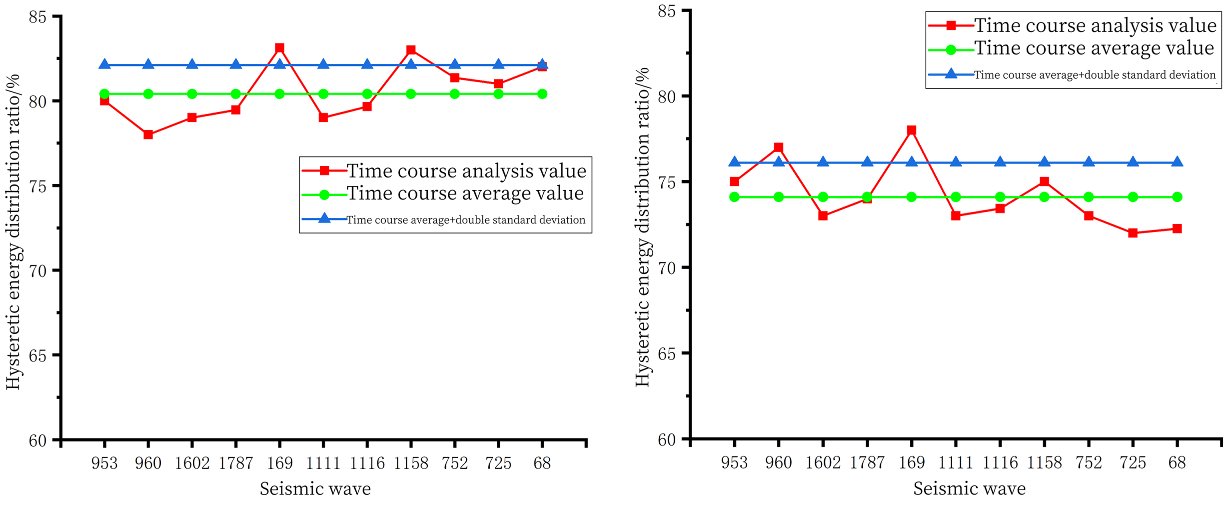


(c) RH-3 (d) RH-4

Figure 18. Wall energy consumption.



(a) RH-1 (b) RH-2



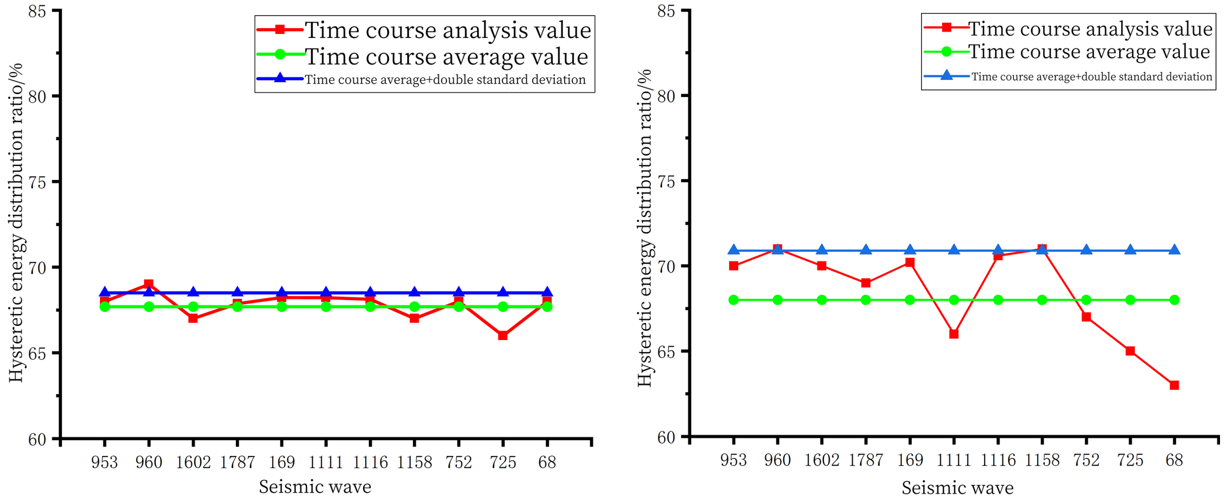
(c) RH-3

(d) RH-4

Figure 19. Wall energy consumption.

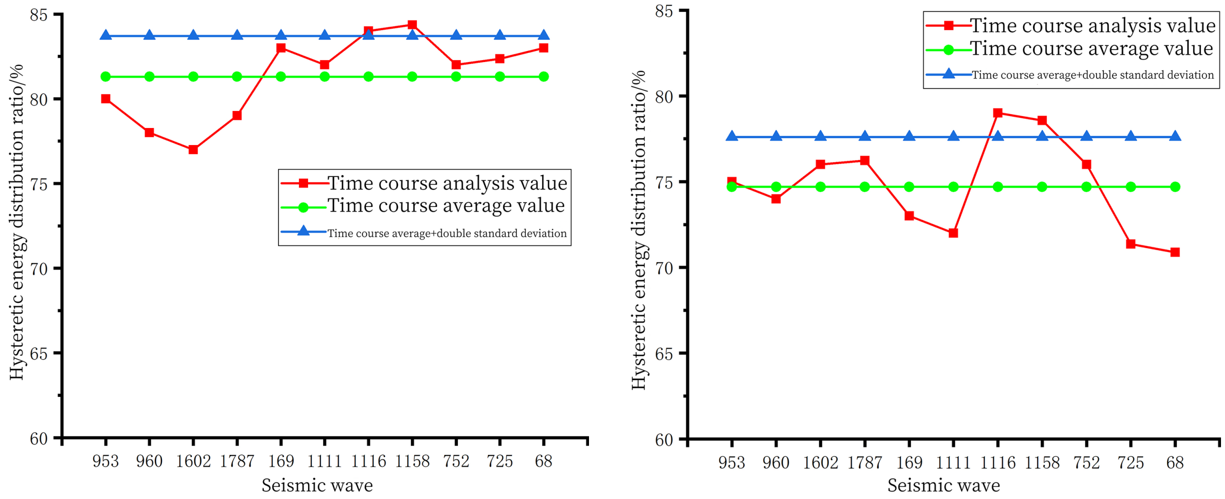
of the energy consumption wall. Compared to model RH-1, the average value of the energy consumption wall of model RH-3 is increased by 15%, and the control effect of two layers of the energy consumption wall is better than the side cloth of the first layer of the energy consumption wall. The proportion of the energy consumption wall of model RH-4 increased by 12% over that of model RH-2. The control effect of the cloth of the energy consumption wall in the two layers of the energy consuming wall is better than that of cloth in the first layer of the energy consumption wall.

3) As shown in Figure 20, when the peak acceleration of the seismic wave is 0.3 g, the average energy consumption of the energy consumption wall of models RH-1, RH-2, RH-3 and RH-4 accounted for 68.0%, 67.7%, 81.3% and 74.7% of the total energy consumption. It shows that the displacement of the energy consumption wall layout is different, the proportion of its hysteresis energy consumption changes, side cloth of the first layer is better than the middle cloth of the first layer.



(a) RH-1

(b) RH-2



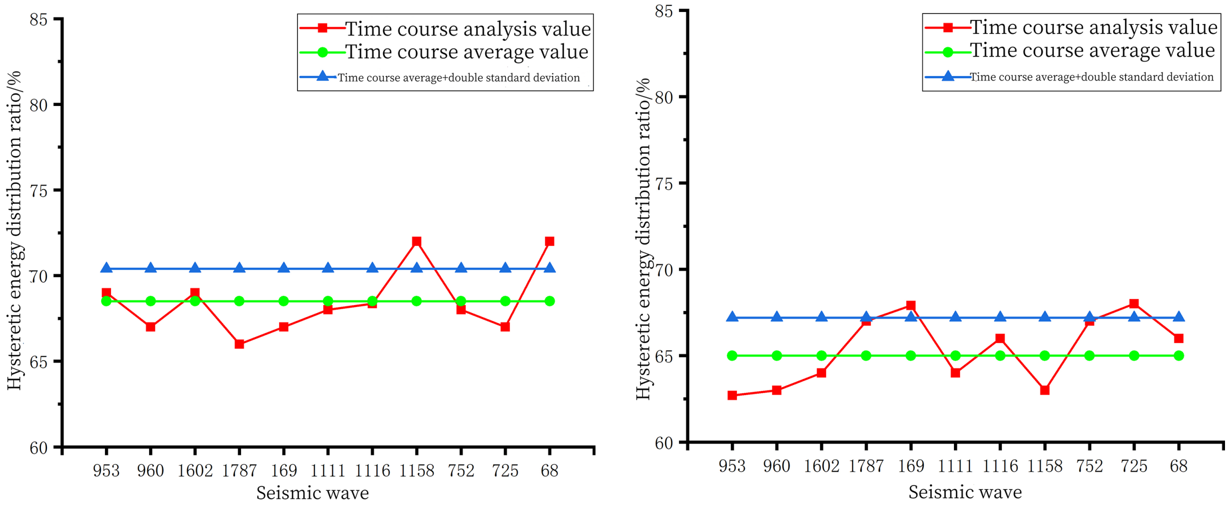
(c) RH-3 (d) RH-4

Figure 20. Wall energy consumption.

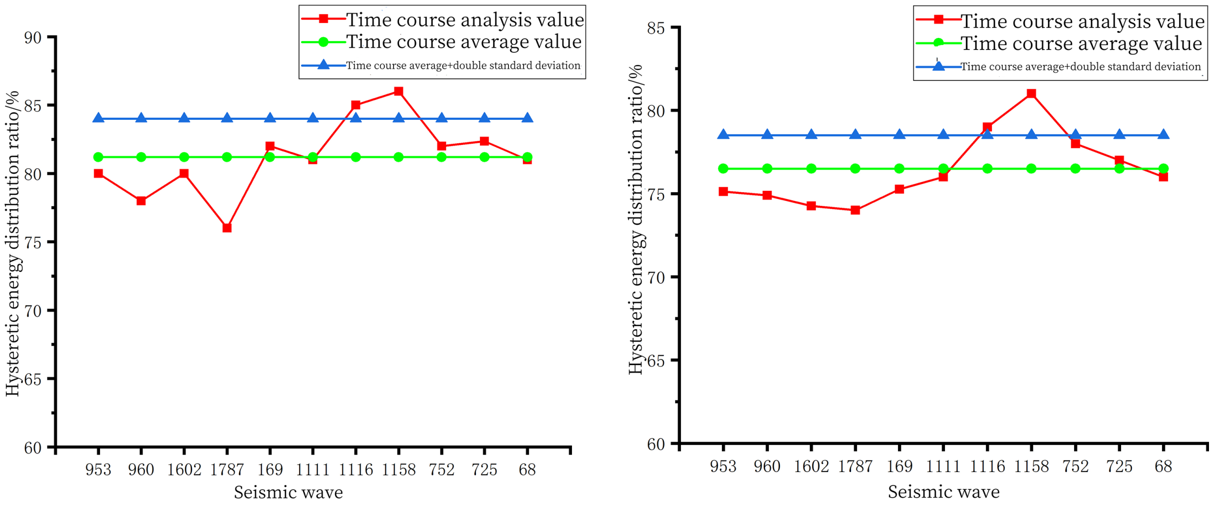
The number of layers arranged by the energy consumption wall is different, and the proportion of the energy consumption is also different, two layers are better than the first layer.

4) As shown in **Figure 21**, when the peak acceleration of the seismic wave is 0.4 g, the side cloth of the first layer of the energy consumption wall controls the ratio of the energy consumption wall better than the middle cloth of the first layer of the energy consumption wall. The proportion of the energy consumption wall of model RH-3 increased by 6% compared to model RH-4. The side cloth of the energy consumption wall is better than the control ratio of two layers of the energy consumption wall.

5) As shown in **Figure 22**, when the peak acceleration of the seismic wave is 0.5 g, the proportion of energy consumption of model RH-1 is reduced by 16% compared to model RH-3. It shows that the side cloth of energy consumption wall is better than controlling the ratio of energy consumption in the two layers of energy

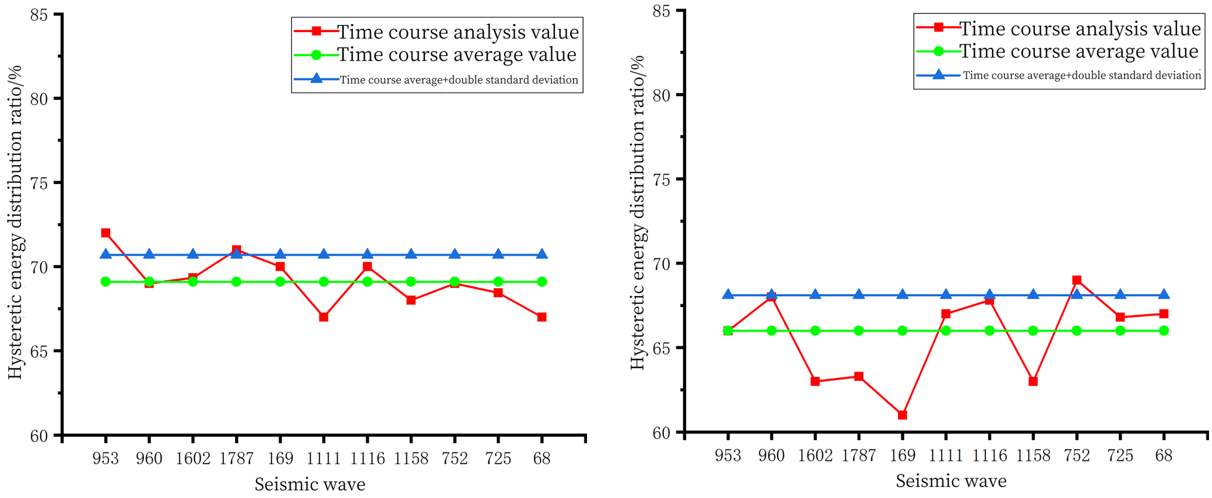


(a) RH-1 (b) RH-2

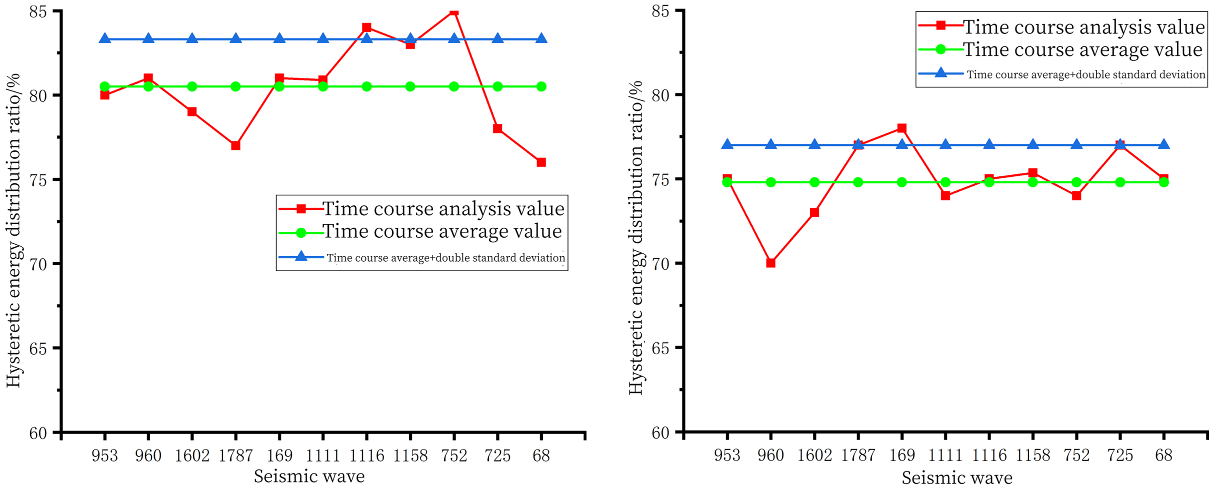


(c) RH-3 (d) RH-4

Figure 21. Wall energy consumption.



(a) RH-1 (b) RH-2



(c) RH-3 (d) RH-4

Figure 22. Wall energy consumption.

consumption wall. Therefore, when the energy consumption wall in the RC frame, the number of layers will affect the proportion of energy consumption wall in the lagging energy consumption. The proportion of the energy consumption wall of model RH-3 increased by 8% compared to model RH-4. It shows that the ratio control of the hysteresis of the energy consumption wall in the two layers of the energy consumption wall is better than that in the first layer of the energy consumption wall.

The size of the energy consumption can reflect the energy consumption capacity of the component. Under the different seismic conditions, the average energy consumption of the model RH-3 is the largest, reaching 83.1%, framework energy consumption is 16.9%. The energy consumption capacity of model RH-1 is 3.8% higher than that of model RH-2. It shows that the energy consumption wall side cloth is better than the middle cloth in the energy consumption wall. The energy consumption capacity of model RH-3 is increased by 18% over model RH-1. It shows that the multi-layer arrangement of the energy consumption wall is more energy consumption than the single-layer arrangement.

From the above data, after the ordinary RC frame assembly of HPFRCC energy consumption wall structure, its seismic performance can be significantly improved and enhance the retardation energy consumption capacity of the structure, more reflects the energy consumption wall as the first line of defense and frame for the second line of defense “two lines of defense” seismic design thought.

5. Conclusions

By considering different seismic action and different energy consumption wall layout mode factors, analyze the total input energy of the structure and its distribution rules, obtain the interlayer distribution and overall distribution of the hysteresis energy consumption in model RC and model RH, discuss the distribution law of hysteresis energy consumption between the components and layers under different modes of the energy consumption walls. Get the following conclusions:

1) Under the action of different seismic waves, the energy consumption distribution of the RC frame-prefabricated HPFRCC energy consumption wall structure is obviously concentrated, it is stable in the first layer of the arranged energy consumption wall, so this energy consumption distribution is stable and controllable.

2) The arrangement of different energy consumption walls has great influence on the distribution of the energy consumption between layers and components. When the energy consumption wall is distributed, the energy consumption distribution of the structure is most reasonable. The diapause energy consumption is distributed in the vertical shape of large and small in the structure. When the structure is in a weak layer, the energy is concentrated in this layer.

6. Implications

The arrangement of energy-dissipating walls has a significant impact on the total energy consumption and the distribution of hysteretic energy dissipation among stories and components within the structure. Both the number of energy-dissipating walls and the number of stories in which they are arranged significantly influence the hysteretic energy dissipation of the structure and its distribution pattern among stories and components.

Funding

Xijing High-level Talent Fund XJ20B08; Research on energy dissipation mechanism and seismic performance control method of ECC energy dissipation wall; Shaanxi Provincial Department of Education 2021 Annual Youth Innovation Team Construction Research Program Project: Research on seismic performance and damage mechanism control of RC frame-ECC energy dissipation wall structure; Project Number: 21JP140.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Gencturk, B., Elnashai, A.S., Lepech, M.D. and Billington, S. (2013) Behavior of Concrete and ECC Structures under Simulated Earthquake Motion. *Journal of Structural Engineering*, **139**, 389-399. https://doi.org/10.1061/(asce)st.1943-541x.0000667

[2] Gao, S. and Hu, G. (2021) Experimental Study on Biaxial Dynamic Compressive Properties of ECC. *Materials*, **14**, Article 1257. https://doi.org/10.3390/ma14051257

[3] Hassan, A.M.T., Jones, S.W. and Mahmud, G.H. (2012) Experimental Test Methods to Determine the Uniaxial Tensile and Compressive Behaviour of Ultra High Performance Fibre Reinforced Concrete (UHPFRC). *Construction and Building Materials*, **37**, 874-882. https://doi.org/10.1016/j.conbuildmat.2012.04.030

[4] Fukuyama, H., Iwabuchi, K. and Suwada, H. (2004) HPFRCC Device for Structural Control of RC Buildings with Soft Story. 6*th RILEM Symposium on Fiber-Reinforced Concretes*, Varenna, 20-22 September 2004, 20-22.

[5] Fukuyama, H., Tesshigawara, M., Suwada, H., *et al.* (2004) HPFRCC Device for Seismic Response Control. 13*th World Conference on Earthquake Engineering*, Vancouver, 1-6 August 2004, Article No. 425.

[6] Li, V.C., Mishra, D.K. and Wu, H. (1995) Matrix Design for Pseudo-Strain-Hardening Fibre Reinforced Cementitious Composites. *Materials and Structures*, **28**, 586-595. https://doi.org/10.1007/bf02473191

[7] Matsumoto, T., Suthiwarapirak, P. and Kanda, T. (2003) Mechanisms of Multiple Cracking and Fracture of DFRCC under Fatigue Flexure. *Journal of Advanced Concrete Technology*, **1**, 299-306. https://doi.org/10.3151/jact.1.299

[8] Maalej, M., Zhang, J., Quek, S.T., *et al.* (2018) High-Velocity Impact Resistance of Hybrid-Fiber-Engineered Cementitious Composites. *Fracture Mechanics of Concrete Structure*, **21**, 589-597.

[9] Olsen, E.C. and Billington, S.L. (2011) Cyclic Response of Precast High-Performance Fiber-Reinforced Concrete Infill Panels. *ACI Structural Journal*, **108**, 51-60.

[10] Qudah, S. and Maalej, M. (2014) Application of Engineered Cementitious Composites

(ECC) in Interior Beam–Column Connections for Enhanced Seismic Resistance. *Engineering Structures*, **69**, 235-245. https://doi.org/10.1016/j.engstruct.2014.03.026

[11] Zhang, X., Zhou, G., Li, S., Zhang, F. and Zhang, S. (2022) Experimental and Numerical Study on Seismic Behavior of Prestressed Concrete Composite Shear Wall. *Engineering Structures*, **266**, Article 114546. https://doi.org/10.1016/j.engstruct.2022.114546

[12] Wang, Y., Zhang, Y., Cui, H., Cai, Z. and Xu, L. (2020) Experimental Study on Fabricated Shear Wall Structure with Energy-Dissipating Vertical Joint. *Structural Concrete*, **21**, 2654-2668. https://doi.org/10.1002/suco.202000229