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ARTICLE

Hysteretic Performance of Ring-shaped Energy-dissipating Devices for Assembly of Steel Frame Structure with External Wall Panel

Yuliang Qi[1#], *Kewei Huang*[2#], *Jing Li*[3*], *Yixin Zeng*[3], *Keke Huang*[1]

[1] *Guangzhou Research Institute of Construction Industry Co., Ltd., Guangzhou, 510520, Guangdong, China*

[2] *Guangzhou Municipal Housing and Urban-Rural Construction Industry Monitoring and Research Center, Guangzhou, Guangdong, 510699, China*

[3] *School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, 510641, Guangdong, China*

ABSTRACT

To protect the external wall panel of the steel frame in prefabricated construction, a kind of ring-shaped energy-dissipating device (RSED) was proposed and further studied, which can connect the wall panel and steel frame. The hysteretic performance of steel frame-external wall panel system (SFEWPS) with RSED as the joint is analyzed via the finite element method, to quantify the protective effect of RSED on a wall panel. The results are that even under extremely rare earthquakes, RSED can still effectively control the energy consumption of wall panels, and play a protective role for it. In addition, combined with failure mechanism analysis, this paper proposes the best parameter selection for RSED.

Keywords: Assembly of steel frame; External wall panel; Energy-dissipating device; Hysteretic performance; Finite element analysis

1. Introduction

Owing to the characteristics of lightweight, high strength, high construction efficiency, and good seismic performance, prefabricated buildings have developed rapidly in recent years. However, there are still problems with the connection joints between the

*CORRESPONDING AUTHOR:
Jing Li, School of Civil Engineering and Transportation, South China University of Technology, Guangzhou, 510641, Guangdong, China; Email: cvjingli@scut.edu.cn
# Co-first authors, these first authors contributed equally to this work.

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external wall panels and the structural frame. Due to the variety of joint styles, the design standards of joints have not been unified at the moment [1]. It is not conducive to realizing the standardization and industrialization of the design and production of connecting joints.

The connection between the external wall panel and the steel frame is mainly in the form of four-point support, with connection types including rigid, flexible, semi-rigid, etc. Researchers attempt to use the above connection joints to reduce the interaction between the wall panel and steel frame to weaken the damage to the wall panel caused by the earthquake. However, relevant studies show that the wall panels have severe compressive failure near the connecting joints [2-4]. There is a new idea for energy dissipation and shock absorption of the structure that effectively utilizes the interaction between the two to provide additional damping to improve the overall seismic performance of the structure instead of reducing the interaction between external wall panels and steel frames [5]. And the metal energy dissipation device can be added between the steel frame and wall panel through the passive control method of structure to effectively utilize the interaction, leading to a better structure's seismic performance.

U-shaped energy-dissipating device is a kind of flexural displacement device made of mild steel, widely used in isolation systems. In view of the seismic performance of a U-shaped steel plate energy-dissipating device, finite element analysis and experiments have been done [6,7]. It is proved that the energy-dissipating device has good ductility, hysteretic performance, and energy dissipation capacity.

The authors proposed a kind of ring-shaped energy-dissipating device (RSED) (**Figure 1**) to connect the external wall panel and steel frame [8]. The RSED is going to perform a crawler motion under the earthquake and the displacement of the two straight segments of RSED can offset the inter-story drift, thus reducing the earthquake damage to the external wall panel. It's mentioned that the energy dissipation capacity of the RSED increases with the increase of thickness (t) and height (H) and decrease of diameter (D), and is related to the shape of the hole.

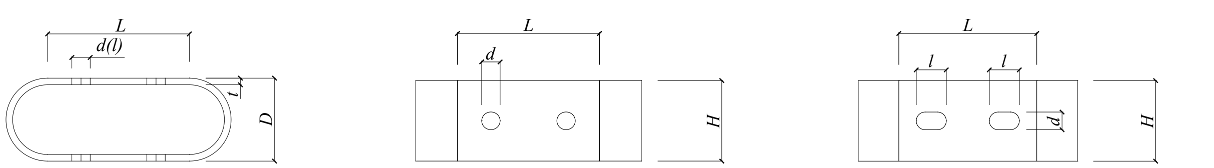
To further study the effect of RSED on a steel frame-external wall panel system (SFEWPS) and clear the protective effect of RSED on the wall panel, the hysteretic performance of SFEWPS with the RSED as the connection joint is analyzed in this paper, the protection effect of RSED on wall panel is quantified by calculating the energy dissipation contribution rate of RSED and failure mechanism analysis. Meanwhile, the protection trend of RSED with different parameters on the wall panel was obtained, and the optimal parameters of RSED were summarized.

2. Finite element model

To explore the seismic performance of the RSED as a joint connecting steel frame and external wall panel, the finite element models of the SFEWPS were established for analysis.

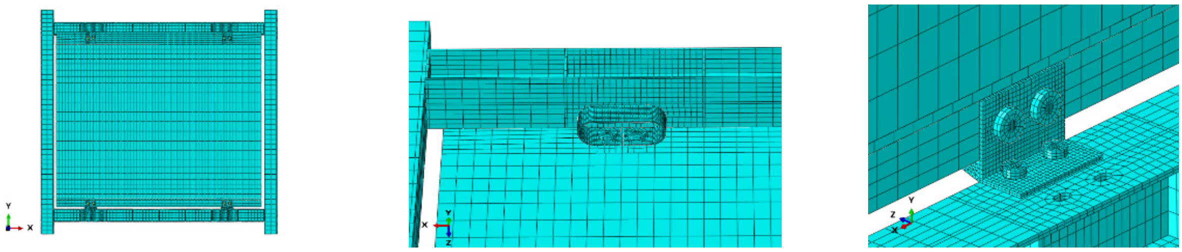
2.1 Model analysis

A steel frame model TX-0 without wall panels was established as a reference model, and SFEWPS finite element models TX-1~TX-9 with different specifications of RSED as upper joints were established. As shown in **Figure 2**, the RSED is adopted as the upper joint (**Figure 2(b)**) while the lower joint adopts a rigid connection (**Figure 2(c)**). The frame is



(a) Vertical view of RSED (b) Front view of RSED with a circular hole (c) Front view of RSED with a slotted hole

Figure 1. Ring-shaped energy-dissipating devices.



(a) The overall model (b) Model of upper joint (RSED) (c) Model of lower joint

Figure 2. Finite element model of SFEWPS.

4200 mm × 3600 mm (width × height). The specific information of each model is shown in **Table 1**.

Table 1. Information on SFEWPS models.

Model	*t*/mm	*D*/mm	*H*/mm	Shape of hole
TX-1	6	100	100	Slotted hole
TX-2	8	100	100	Slotted hole
TX-3	10	100	100	Slotted hole
TX-4	12	100	100	Slotted hole
TX-5	8	120	100	Slotted hole
TX-6	8	150	100	Slotted hole
TX-7	8	100	100	Slotted hole
TX-8	8	100	120	Slotted hole
TX-9	8	100	100	Circular hole

2.2 Element type, mesh discretization and material properties

ABAQUS is used for the finite element analysis, while the steel frame, wall panel, and joints adopted the C3D8R element, which is most widely used in the practical application of solid elements and with great speed and accuracy in calculation. And the steel bars configured inside the wall panel adopted the T3D2 element, which is focused on the axial tensile properties of the steel bars. For joints, it is necessary to analyze their strain under cyclic loading, so the mesh density is small, about 8 mm. For bolts, it is necessary to analyze the damage of bolts, so the mesh density is 5 mm, which is much smaller. For the wall panel around the bolt hole, it is necessary to focus on the interaction between the wall panel and joints and the damage to the wall panel there, so the mesh density is relatively small, about 30 mm. And the mesh density of the rest of the wall panel is ranging from 80 to 160 mm. The mesh density of the steel beam close to the joints is 20 mm, and the mesh density of the rest part is 50 mm. As for the number of elements, there are 33449 elements in the model.

The steel frame is made of Q355 with grade 10.9 bolts, and the RSED is made of 45# steel. The von Mises yield criterion was adopted in the steel model. The concrete grade of the wall panel is C30, and its constitutive model adopts the plastic damage model with the parameters of Guo [9] as shown in **Table 2**.

Table 2. Plastic damage parameters of concrete.

Expansion Angle/(°)	Eccentricity	f_{b0}/f_{c0}	K	Viscosity parameters
30	0.1	1.16	0.6667	0.005

2.3 Loading system

The loading system refers to the ATC-24 [10]. The loading method is to apply a reciprocating displacement load on the top of the column. Obtained by one-way loading, the yield displacement (△*y*) of the TX-0 is 30 mm. The loading system of TX-1~TX-9 uses reciprocal loading with two load cycles per load level of amplitude. The loading amplitude of each level is 0.25△*y*, 0.5△*y*, 0.7△*y*, 1.0△*y*, 1.5△*y*, 2.0△*y*, 3.0△ y, and 4.0△ y, respectively.

3. Result analysis

From the finite element analysis, the hysteresis curve and energy dissipation of TX-0~TX-9 were obtained.

3.1 Hysteresis curve

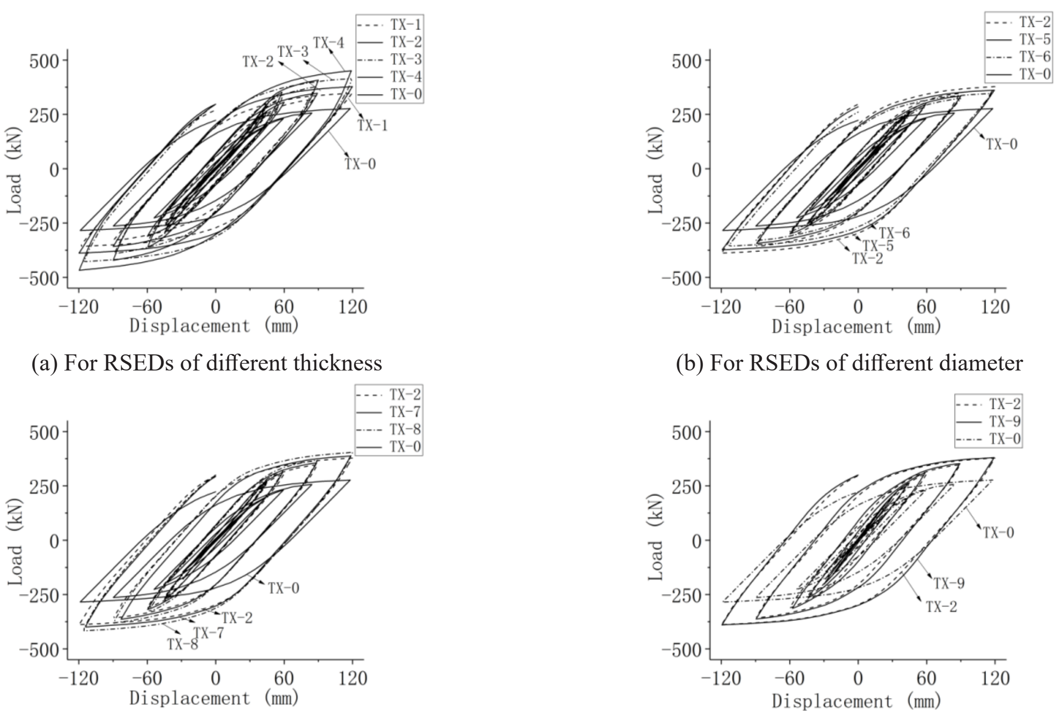
The hysteresis curves of TX-0~TX-9 are shown in **Figure 3**. It results that the SFEWPS with RSED has better energy dissipation capacity. The SFEWPS would dissipate more energy as the RSED becomes thicker and higher, and the diameter of the bent part becomes smaller. However, there is little difference in the energy consumption capacity of different SFEWPS with different types of holes of RSED.

3.2 Energy dissipation analysis

There are three main ways of energy dissipation in the system: plastic deformation of steel frame, cracking of external wall panel, friction slip, or plastic deformation of joints at the connection between the steel frame and external wall panel [11]. Studies [12,13] have shown that setting external wall panels can improve the energy dissipation capacity of the steel frame-external wall panels system, so researchers pay more attention to the safety of wall panels. Considering that the higher the energy consumption is, the more serious the damage to the wall panel will be [14], it is very important to control the energy consumption of the wall panel reasonably, especially in the case of small and moderate earthquakes, the energy consumption of the wall panel should be controlled as far as possible to give full play to the energy consumption capacity of the RSEDs.

To explore the contribution of RSED to the energy dissipation of the steel frame-external wall panel system, the energy dissipation value of RSED is calculated in each model by drawing the hysteresis curve of the RSED by extracting the displacement of the flat sections on both sides of the RSED from the SFEWPS analysis results (as shown in **Table 3**).

The amplitude of 45 mm corresponds to an inter-story drift of 1/80 (45 mm/3600 mm), which corresponds to the inter-story drift of steel structures under moderate earthquakes specified in code [15]. The energy dissipation contribution of each type of RSED is greater than 83%, indicating that the energy dissipation capacity of the RSED is fully utilized. The inter-story drift corresponding to the amplitude of 90 mm is 1/40, exceeding the limit of inter-story drift under rare earthquakes. When the displacement amplitude continues to increase to 120 mm, the energy dissipation contribution of the RSED continues to decrease, but the energy dissipation contribution is above 65%, much higher than that of the wall panel.



(a) For RSEDs of different thickness

(b) For RSEDs of different diameter

(c) For RSEDs of different height

(d) For RSEDs with different holes

Figure 3. Hysteretic loops for SFEWPS with different RSEDs.

It results that even under the extremely rare large earthquake, the RSED can still give full play to the energy dissipation capacity so that the wall panel in the system is always in a state of low energy consumption. The use of RSED has an excellent protective effect on the wall panel.

4. Failure mechanism analysis

By analyzing the stress, strain, tension, and compression damage of the energy dissipator and external wall panel in each stage, the failure mechanism of the RSED and external wall panel is clarified. According to the failure mechanism, the optimal selection of RSED component parameters is provided.

4.1 Failure process analysis

In order to explore the influence of different RSEDs on the failure of wall panels, the percentage of integral points P_T that the tensile strain is greater than the limit strain (0.0001), and the percentage P_C that the compressive strain is greater than the peak compressive strain (0.002) with displacement amplitude is analyzed to reflect the wallboard failure process [16], as shown in **Figure 4**.

The influence of the thickness of the RSED

As shown in **Figure 4(a)** and **Figure 4(b)**, when the displacement amplitude exceeds 7.5 mm, TX-1~TX4 begin to show tensile damage, when the displacement amplitude exceeds 30 mm, TX-2~TX-4 wall panels begin to show compressive damage, and when the displacement is loaded to 45 mm, TX-1 wall panels begin to show compressive damage. When the displacement amplitude of the wall plate with different thicknesses of dissipator increases, the damage to the wall plate will also increase, and the larger the thickness of the dissipator, the more serious the damage to the wall plate. It means that when the thickness of the energy dissipator is too large, it is not conducive to the protection of the wall plate.

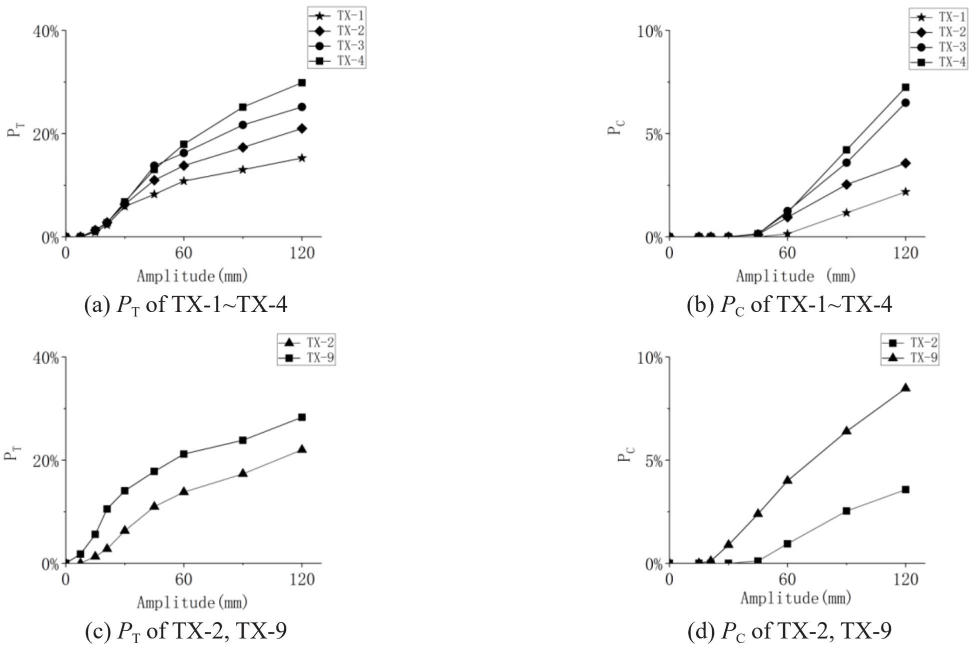
Slotted hole and circular hole

The wall panel of the TX-9 model with circular hole RSED began to fail earlier, tensile failure began to occur when the displacement load was 7.5 mm, and compressive failure began to occur when the displacement load was 15 mm. Under all levels of load, the wall panel failure degree of the TX-9 model with circular hole RSED was more serious than that of the TX-2 model with slotted hole RSED.

Therefore, to ensure the energy dissipation capac-

Table 3. Energy dissipation coefficients with 45, 90, and 120 mm displacement.

	Total energy consumption/ kN·mm			Energy consumed by an RSED/kN·mm			RSED energy dissipation contribution		
Displacement	45 mm	90 mm	120 mm	45 mm	90 mm	120 mm	45 mm	90 mm	120 mm
TX-0	12095	41681	103487						
TX-1	14278	49367	124533	1023	3135	7394	93.72%	81.58%	70.27%
TX-2	15116	53355	136551	1374	4367	11652	90.96%	74.82%	70.48%
TX-3	16036	55430	140406	1827	5308	12593	92.72%	77.21%	68.22%
TX-4	16411	56042	149059	2013	5510	16795	93.28%	76.74%	73.71%
TX-5	14341	50658	129443	989	3307	8635	88.07%	73.68%	66.54%
TX-6	14111	49713	123593	900	3059	6869	89.29%	76.17%	68.33%
TX-7	15248	54363	137987	1316	4479	12196	83.48%	70.64%	70.70%
TX-8	15597	55300	140177	1484	4813	12816	84.75%	70.68%	69.86%
TX-9	19276	59292	147182	3216	6713	15890	89.57%	76.24%	72.73%



(a) P_T of TX-1~TX-4

(b) P_C of TX-1~TX-4

(c) P_T of TX-2, TX-9

(d) P_C of TX-2, TX-9

Figure 4. The number of integration points where the strain of the external wall panel exceeds the limit.

ity of the system as a whole and reduce the damage to the wall panel caused by the earthquake the thickness of the RSED should be controlled, and the slotted hole should be adopted.

4.2 Stress and strain analysis

According to the constitutive curve, the ultimate tensile strength of concrete is 2.7 MPa, and the ultimate compressive strength is 23.4 MPa. Whether the concrete is damaged under tension or compression will be comprehensively judged according to the cloud diagram of finite element analysis [17]. From the results of the previous analysis, the excessive thickness of the RSED or the use of circular holes will cause more serious damage to the external wall panels. Therefore, this section takes TX-2 and TX-3 models with moderate thickness of the RSED and slotted holes as examples to conduct micro-stress and strain analysis.

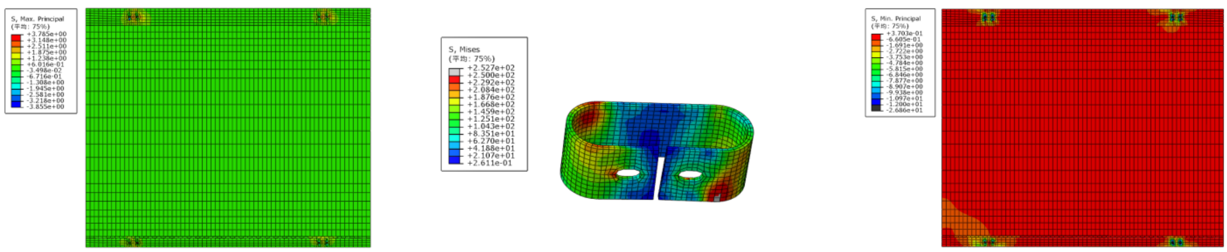
TX-2 analysis

When the displacement was loaded to 15 mm, the maximum principal tensile stress of the wall panels at the upper and lower joints was 3.78 MPa. Combined with the equivalent plastic strain of concrete and the tensile damage cloud diagram, it illustrated that local cracking occurred in the wall panels near the joints. The cracking area was mainly concentrated on the left and right sides of the bolt holes, but other areas of the wall panels remained intact, as shown in **Figure 5(a)**.

When the displacement is loaded to 30 mm, the maximum stress value of the energy eliminator the RSED of TX-2 is 253 MPa, which exceeds the yield strength of 250 MPa, and it is judged that the energy eliminator begins to yield. The yield position is mainly concentrated at the connection between the straight section and the bending section, as shown in **Figure 5(b)**.

When the displacement was loaded to 45 mm, the maximum principal compressive stress of the wall panels at the upper and lower joints was 26.86 MPa. According to the cloud diagram, it was judged that compressive failure occurred in the wall panels near the joints, mainly concentrated on the upper and lower sides of the bolt holes, but most other areas of the wall panels remained intact, as shown in **Figure 5(c)**.

It proved that the failure sequence of TX-2 is as follows: Local cracks appear at bolt holes of the wallboard; local yield of RSED steel plate; the wall



(a) Main tensile stress of wall panel at cracking load

(b) RSED stress distribution at yielding load

(c) Main compressive stress of wall panel at crushing load

Figure 5. Cloud diagram of TX-2.

panel near the joint appeared to have compression failure. Before the failure of the wall panel, the steel plate of the RSED enters the plastic yield stage to meet the expected effect and avoid premature failure of the wall panel.

TX-3 analysis

When the displacement was loaded to 15 mm, the maximum tensile stress of the wall panels at the upper and lower joints was 3.15 MPa. it can be concluded from **Figure 6(a)** that there is local cracking of the wall panels near the joints.

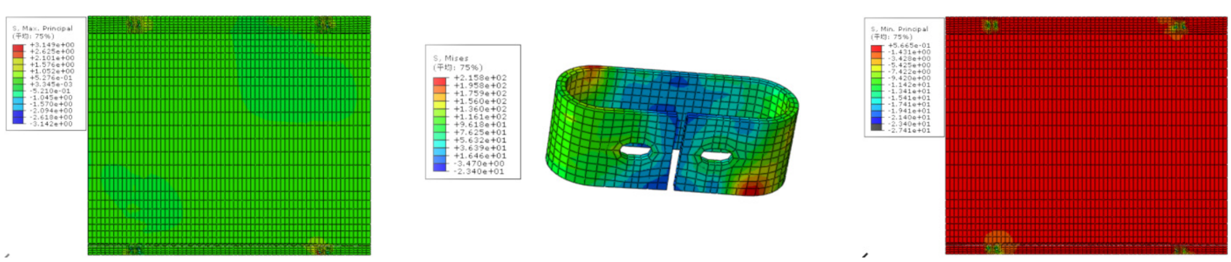
When the displacement was loaded to 30 mm, the maximum principal compressive stress of the wall panels at the upper and lower joints was 27.41 MPa, the compressive failure of the wall panels near the joints, as shown in **Figure 6(c)**.

However, the maximum stress of energy eliminator RSED of TX-3 is only 215.8 MPa at this time, failing to reach the yield stress, as shown in **Figure 6(b)**. It shows that the wall panels have been damaged under pressure before the RSED enters the yield stage, and the protective effect of the RSED on the wall panels is not obvious, which does not meet the expected effect of the RSED.

According to the above analysis of the failure mechanism of each model, the overall energy dissipation capacity of model TX-2 is strong, and the damage degree to the wall panel is small. The RSED can enter the plastic yield state before the wall panel is crushed. Therefore, TX-2 is the best model with both the energy dissipation effect and the wall panel protection effect.

5. Conclusions

(1) RSED can give full play to its energy dissipation capacity in SFEWPS. The energy dissipation contribution of RSED decreases with the increase of displacement amplitude. When the load amplitude reaches 120 mm, which is greater than the equivalent load amplitude of 90 mm in rare earthquakes, the contribution of RSED to energy consumption is still greater than 65%, and the energy consumption of the wall panel is effectively controlled, which shows the excellent protection effect of RSED on the wall panel.



(a) Main tensile stress of wall panel at cracking load

(b) RSED stress distribution when the wall begins to crush

(c) Main compressive stress of wall panel at crushing load

Figure 6. Cloud diagram of TX-3.

(2) According to failure process analysis, the large thickness of RSED leads to serious damage to the wall panel, and the RSED with the circular hole will cause a greater damage degree to the wall panel than that of the slotted hole. Therefore, the RSED with moderate thickness and the slotted hole should be selected, which can not only ensure the energy dissipation capacity of the structure as a whole but also reduce the damage to the wall panel due to the sliding action of bolts in the slotted hole.

(3) According to stress and strain analysis, when the thickness of the RSED is 8 mm, and the slotted hole is adopted, the stress-strain analysis of the SFEWPS shows that the RSED enters the plastic yield stage before the wall panel is destroyed, and the expected effect of protecting the wall panel can be achieved.

Conflict of Interest

There is no conflict of interest.

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