Beijing Rail Transit Command Center (Phase II) Energy Dissipation Technology and Dynamic Elastoplastic Analysis

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SUMMARY:
Beijing Rail Transit Command Center (Phase II) is key project of Beijing. In order to ensure good seismic performance, design adopts complex structural system with reinforced concrete (reinforced concrete, and steel reinforced concrete) frame + steel support + buckling restrained brace. For energy dissipation technology used in this project, this article uses theoretical analysis and test methods to do research on the performance of buckling restrained braces, and dynamic elastoplastic analyzing technology to do research on the nonlinear response and seismic performance of the overall structure with the influence of rare earthquake, and, reveal the structure or existence of weak earthquake location (floor). Test and analytical investigation shows that buckling restrained braces of the soft steel core material used in this project have good energy performance, ensure the seismic performance of the overall structure, and have significance for similar projects in the future.

Keywords Buckling restrained braces; Elastoplastic; Seismic design; Seismic performance

1. OVERVIEW

Beijing Rail Transit Network Command Center Phase II project is located at Beijing Chaoyang District, North Camp area. The total construction area is 69,585 square meters, the ground floor area is 42,837 square meters, underground construction area is 26,748 square meters, and maximum building height is 51.100 meters, and they are mainly control center for the rail lines, AFC center, R & D and testing center, information center and associated supporting facilities (for architectural effect, see Figure 1). The whole structure is divided into underground structure, structure of the main building on the ground and structure of annex on the ground [Nonlinear dynamic time history analysis report of Beijing Rail Transit Command Center（Phase II)].

The main building is composed of 11-story building of the east and west two buildings which are basically symmetrical, middle 1-2 and 8 to 11 are of continuum structure. The structure is concrete frame - steel support structure (layer 10 and 11 adopt JY-SD buckling restrained braces), the structural plane is of L-shaped. The joints between the main building on the ground and wing are equipped with stitch to separate them, wing is a four-storey framework structure, and the main building is 12-storey concrete framework - steel support structure [Code for the aseismic design of building, China Building Industry Press, 2010].

2. THE ENERGY DISSIPATION PLAN

The buckling restrained braces need to be equipped with a glide plane or a layer without binding between the steel support of inner core and out concrete, so that the axial load is only borne by the steel core. Internal filling binding material and external steel pipe provide sufficient rigidity to prevent overall buckling of the support, making the hysteresis curve of the core steel brace full. Equip this support between the reinforced concrete frame columns, thus, the improved framework will not only have a certain stiffness, but the ductility and seismic capacity of the framework system can also be significantly improved.

Buckling support principle and the model figure, refer to Figure 2:

Figure 1. Beijing Rail Transit Network Command Center Phase II project architectural effect diagram

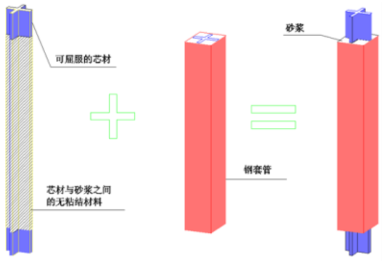


Figure 2. Schematic diagram of buckling restrained brace composition

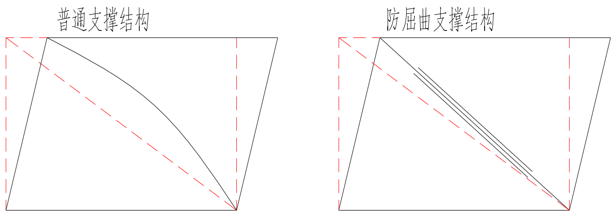


Figure 3. Transformation comparison of traditional brace and buckling restrained braces under seismic load

2.1 Experimental study on energy dissipation device core material

The mechanical properties of the buckling restrained braces is directly determined by core material, materials at low yield point can achieve displacement with greater rigidity and smaller yield, and also has good ductility performance. After calculation and analysis, finally adopt Q160 mild steel as the main core material.

Metal damper mainly selects soft steel, steel with low yield point, lead and memory alloy, because of defects of lead material and relatively expensive price of alloy material, soft steel and steel with low yield point become the optical choice for the construction industry damper material. According to requirements of damper, Japan specially developed SS400 (equivalent to the domestic Q235), LY225 and LY110, of which elongation of LY110 steel can reach up to 50%. Cumulative plastic deformation ability is very good. Chinese equivalent material is Q160. In contrast to Japanese materials, material stress-strain curve indicates that the Q160 materials has good elongation and elongation can reach 9% to 10% under maximum stress, more than 2 times of the traditional mild steel, and its elongation performance is equal to Japanese soft steel [Control of structural vibration – active, semi-active and intelligent control" Beijing, Science Press, 2003].

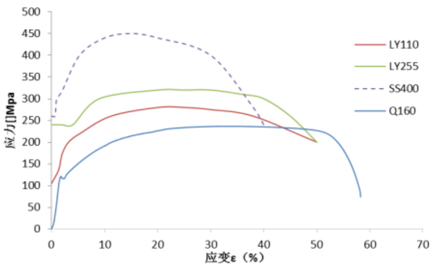


Figure 4. Steel stress mainly selects soft steel, steel

2.2 Damper selection and experimental study

To meet the requirement for using in large space, it is better to choose good frame structure, comprehensively consider building height and design classes to design the added core tube, and at the same time, as building plane is too long, there are problems of discontinuous plane, so the core tube is arranged at the north side of architectural center (command hall peripheral) to ensure uniform plane stiffness, but because the core tube takes up a smaller proportion of the total floor plane, the structure is of weak lateral stiffness and torsional deformation significantly, steel support is added at both ends of the structures. There are following disadvantages to simply adopting ordinary steel support for calculation analysis of the surface：

1) Steel brace performance index precautionary intensity does not yield， and component section size is relatively large;
2) If rare earthquake occurs, the steel brace shall become instable and deform;
3) Frame column is severely damaged under strong earthquakes.

For the above reasons, in the main structure, buckling restrained brace is equipped at some floors, in order to reduce the brace component size, reducing middle seisms, rare earthquakes, and internal force load of components connected with support, and plastic damage, and optimize the deformation performance of the overall structure during earthquake.

The buckling restrained braces select mild steel of low yield point as core material, after calculation, choose three types JY-SD [Gao Jie et al, 2011] type of buckling restrained braces with yield bearing capacity of 2500KN, 2000KN and 1000KN, and a series of experiments are carried out for this type of braces during this period. The experiments show that the performance of the model is stable, with good hysteretic energy performance. Experimental is repeatedly loaded under design displacement, that is, circulate three circles respectively under target displacement of L/500, L/300, L/200, L/150 and L/100. L/80 target displacement circulates 30 circles without obvious damage to component performance (reduced by 15% or more). From the hysteresis curve we can see, JY-SD-type low yield point mild steel buckling restrained braces has good plastic deformation, the hysteresis curve is full and stable, and is able to realize continuous work to meet the performance requirements in the rare earthquake.

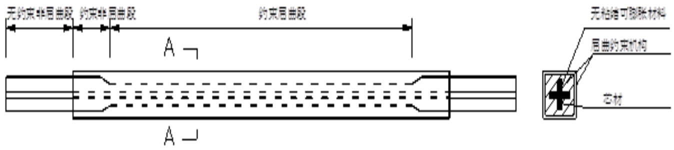


Figure 5. Buckling restrained braced construction

The hysteresis curve of buckling restrained braces test using low yield point is plump, and smooth with stable performance and component pull and pressure force are symmetrical without obvious deviation. JY-SD buckling restrained braces demonstrates very good hysteretic characteristics. Compared with traditional steel, hysteresis loop area is fuller, the yield stiffness accounts to 2% of the component elastic stiffness, making full use of the high elongation properties of the material [Gao Jie et al, 2011].

3. THE STRUCTURAL DYNAMIC ELASTOPLASTIC ANALYSIS

3.1 Elastoplastic analysis summary

According to force and elastic-plastic behavior of structural components, the mainly selected unit forms include:

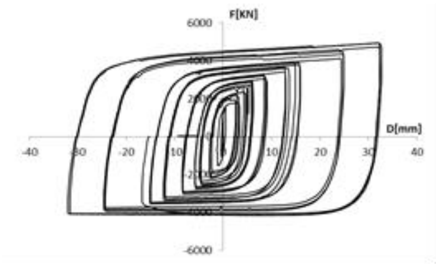


Figure 6. JY-SD buckling restrained braces hysteresis curve

✓ quadrilateral or triangle reduced integration shell elements: used for the simulation of the core tube shear walls, and even beams and floor slabs.

✓ Beam element: used for the simulated structural floor beams, columns and support. In Abaqus software, the unit is based on Timoshenko beam theory, can consider shear stiffness, and calculate the element stiffness in the cross-section and length of the two dynamic integral. For components connecting at both ends of gravity (during construction) (such as grid beams with the structure of the corner hexagonal, etc.), the release of degrees of freedom is used for simulation.

✓ Connector unit: used to simulate the buckling restrained braces.

This project has mainly two types of basic materials, namely, concrete and steel.

The constitutive model used in the calculation is as follows:

(A) Concrete

Elastoplastic damage model is adopted, and the model can consider the concrete material in tension and compression strength of differences in stiffness and strength degradation, recovery and other properties and the stiffness of the cycle of tension and compression fracture closure presented in concrete structure design regulations Table 4.13. It should be pointed out that the calculation of concrete does not consider cross-section within the constraints of the transverse stirrups enhancement effect. Use only the parameters of the proposed plain concrete specification. For concrete constitutive relation curve, see the following figure.

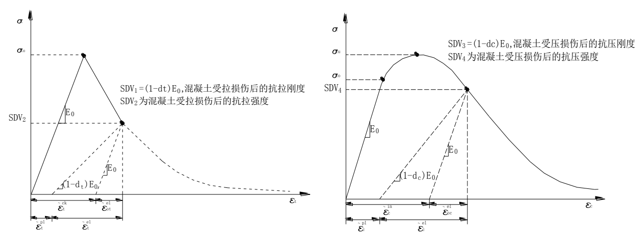


Figure 7. Concrete tension and compressive stress - strain curve and damage schematic

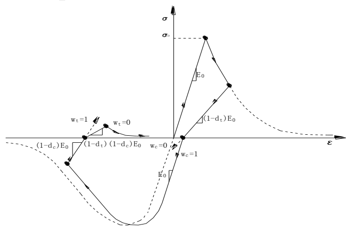


Figure 8. Concrete tension pressure stiffness recovery sketch map

The figure shows that when the load changes from tension into compression, the crack of the concrete material closes, the compressive stiffness is recovered to the original compressive stiffness; when load changes from compression into tension, the tensile stiffness of the concrete material is not recovered. It can be seen that, along with the concrete material into a plastic state, its stiffness decreases gradually. The reduction of the above in elastoplastic damage constitutive model. In damage theory with Najar, brittle solid material injury is defined as follows (see figure below):

$$D = \frac{W_0 - W_\varepsilon}{W_0}, \quad \text{where:} \quad \boldsymbol{W}_0 = \frac{1}{2}\boldsymbol{\varepsilon} : \boldsymbol{E}_0 : \boldsymbol{\varepsilon}, \quad \boldsymbol{W}_\varepsilon = \frac{1}{2}\boldsymbol{\varepsilon} : \boldsymbol{E} : \boldsymbol{\varepsilon}$$

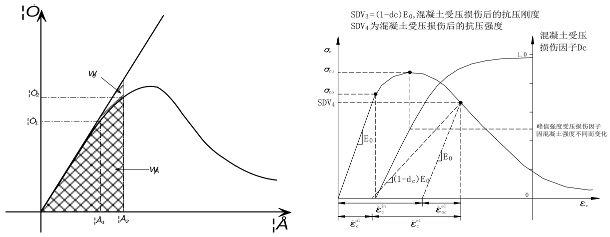


Figure 9. Damage of concrete subjected to uniaxial stress state definition schematic

(2) Steel

Bilinear kinematic hardening model (shown below) is adopted. Consider the Bauschinger effect, during the cycle, there is no stiffness degradation [Manual for design and construction of passive shock-absorbing structure, China Building Industry Press, 2008].

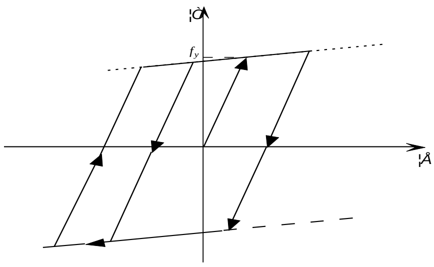


Figure 10. Steel bilinear kinematic hardening model diagram

In calculation analysis, set the steel ratio as 1.2, and the ultimate strain is 0.025.

3.2 Overall structure of the elastic-plastic analysis [Nonlinear dynamic time history analysis report of Beijing Rail Transit Command Center (Phase II)]

There are three groups of seismic records on the structure and three-dimensional input are alternately input into main direction (Figure 11), altogether six working conditions of the earthquake dynamic elastoplastic analysis, mainly examine the component response of the flexible design of the structure to take the performance of design parts, give the quantitative expression of major earthquake, assess the degree for them entering elastoplastic, and thus give design suggestions for improvement; examine the overall response of the structure and deformation, verify the seismic design of structure "earthquake inverted" fortification level standard, and further observe the weak partsof the structure.

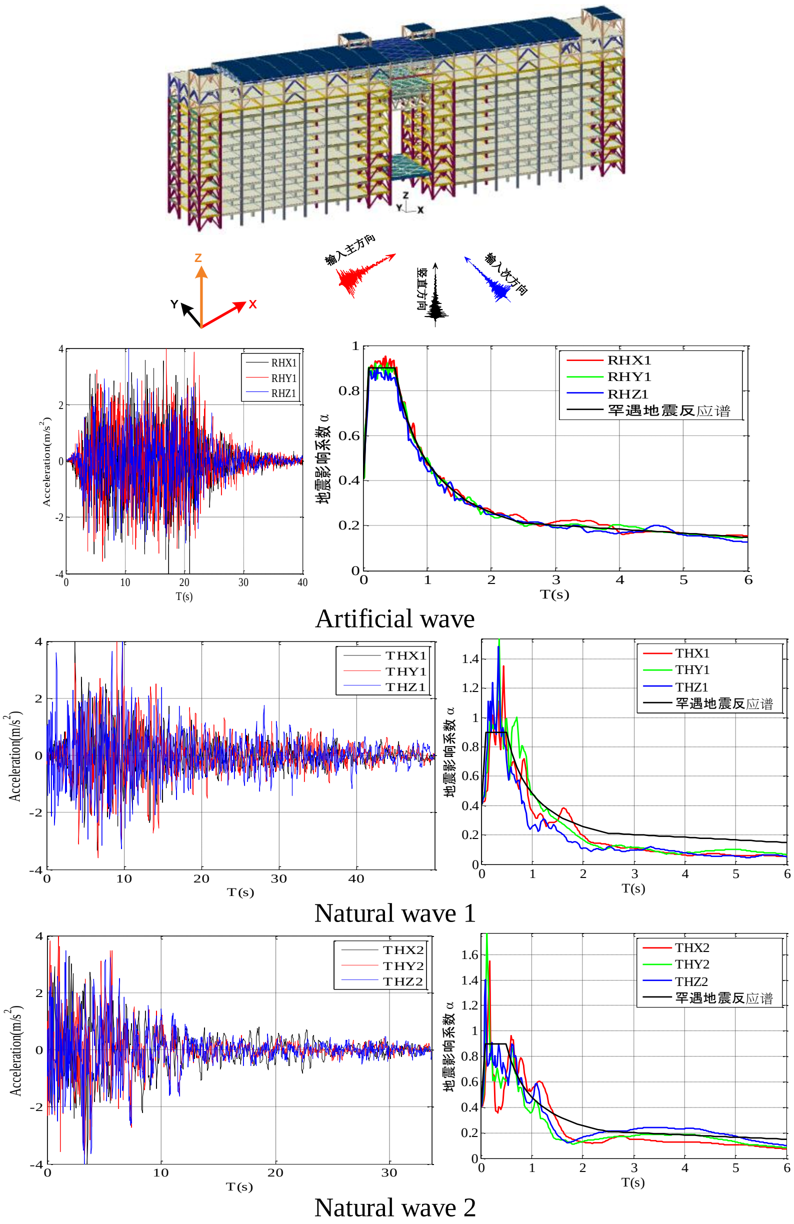


Figure 11. The input seismic waveform and spectral analysis

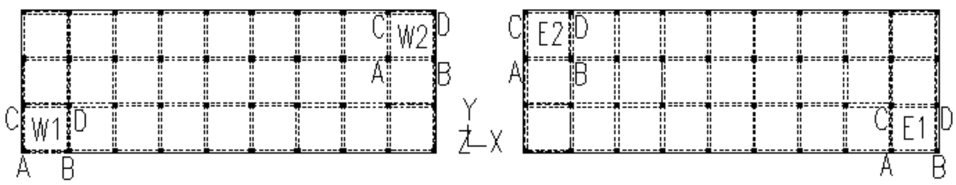


Figure 12. The frame tube position to take reference points

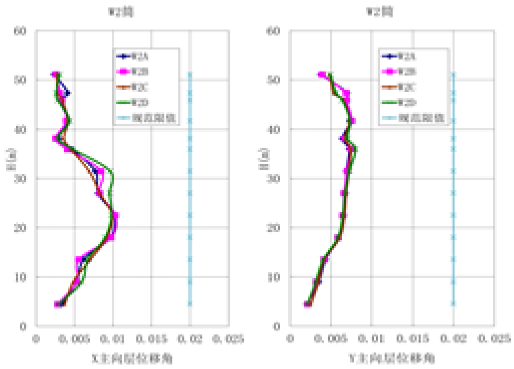


Figure 13. Node locations and artificial wave floors of the largest layer displacement angle response

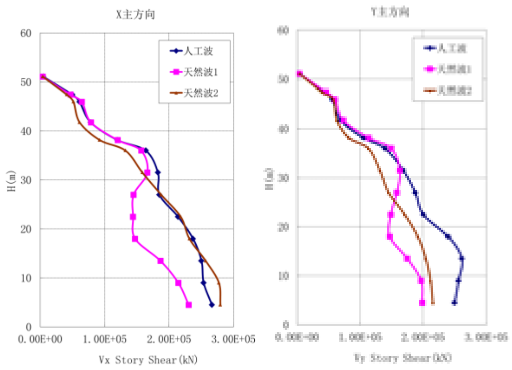


Figure 14. Maximum displacement and layer displacement angle response for artificial wave

As shown in Figure 12, take a few reference points at each location of the frame tube, such as A, B, C and D (W stands for west side of the frame tube, E on behalf of the east side of frame tube), according to the displacement and the time course of output, during the clearing process of the results, and obtain data layer displacement and the maximum story displacement angle. It should be stated out that because there are too much working conditions for calculation, the following results only give the max reference points. Under the influence of 8 degrees rare earthquake waves, select the structure of the maximum value of all reference points, X is the input of the main direction, the roof of the maximum displacement is 282mm, and the displacement angle between the floors of the largest layer is 1/96, at the 6th floor; Y is the main input direction, the maximum roof displacement is 285mm, and maximum story displacement angle is 1/102 at the 11th floor. It can be found that the difference of the displacement angle results between each tube reference point layer is very small, indicating that each reverse effect of each tube is not obvious. Lateral stiffness changes uniformly.

3.3 Buckling-Restrained buckling restrained braces earthquake elastoplastic analysis results

The study shows that common support and buckling restrained braces hybrid arrangement can mostly save cost on the basis of improving the seismic performance. Ordinary support and buckling restrained braces under seismic action form framework support system, support provides lateral stiffness, part of buckling restrained braces enters into the yield energy consumption under the influence of fortification intensity. With rare earthquake, most of the buckling restrained braces enter into the energy consumption stage but does not cause damage, and deformation and instability does not occur to ordinary steel support.

The main structure consists of two towers at left and right, connected together through the bottom to the top area, while the top of the region is weak due to the large space requirements of the lateral stiffness, buckling restrained for support is mainly set in the top of the connecting area (Figure 10, Figure 11).

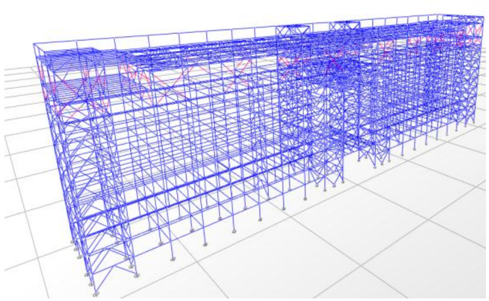


Figure 15. Buckling Restrained Braced layout

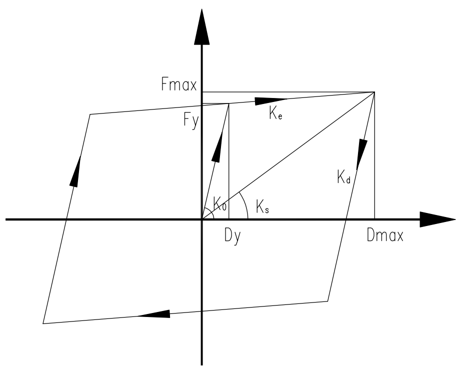


Figure 16. Buckling Restrained Braced ideal elastoplastic model

The buckling restrained braces adopts ideal elastoplastic model, and considers the slight increase in yield stiffness. With eight degree rare earthquake, select four typical buckling restrained braces for hysteresis curve analysis along the corner, peripheral and core barrel, the JY-SD-1000 maximum axial deformation is 15mm, maximum axial deformation of JY-SD-2000 type is 13mm, maximum axial deformation of the JY-SD-2500-type is 15mm, and three buckling restrained braces deformation rate do not exceed 1%, hysteresis curve is full, indicating that the buckling restrained braces enters into the yield energy consumption to a greater extent under seismic action whilemain structure is intact.

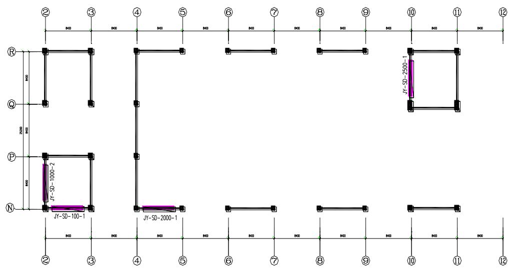


Figure 17. Buckling Restrained Braced layout

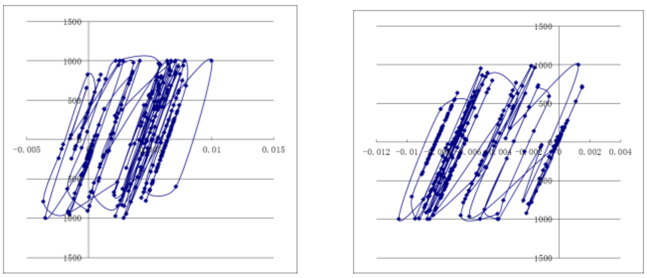


Figure 18. Artificial wave JY-SD-1000-1 buckling restrained braces hysteresis curve

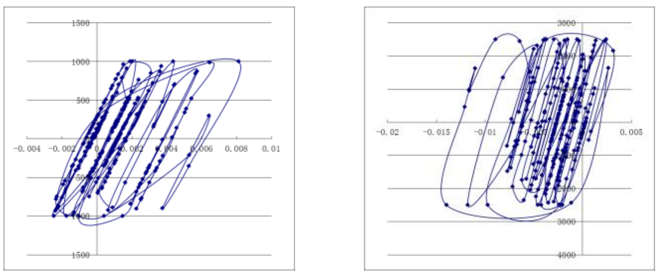


Figure 19. Artificial wave JY-SD-1000-2 buckling restrained braces hysteresis curve

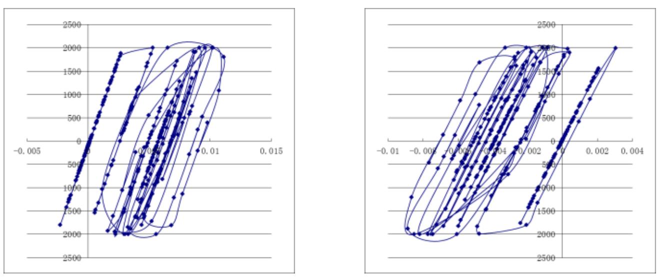


Figure 20. Artificial waves, JY-SD-2000 Buckling Restrained Braced hysteresis curve

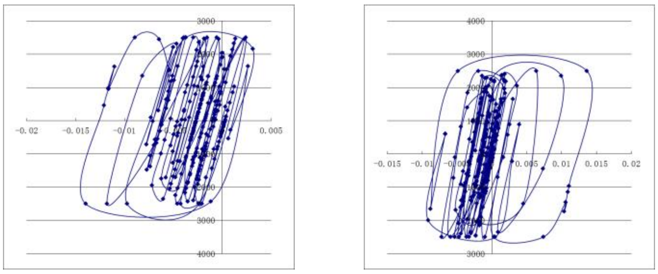


Figure 21. Artificial waves JY-SD-2500 Buckling Restrained Braced hysteresis curve

According to 'herringbone' or 'V-shaped' component hysteresis curve, buckling restrained braces is divided into two components, and the hysteresis curve of the same performance is consist of two parts of the left arrel, parts, both with good hysteretic performance, at the same time, to verify if components meet the design target of the project, actually measure the selected JY-SD buckling restrained braces component, typical hysteresis curve is shown in Figure 22 and Figure 23, experimental load is in accordance with component length of 1/500, 1/300, 1/200, 1/150, 1/100, circulate three circles under target displacement, circulate 30 circles with 1/80 component length or design goals displacement in great earthquake. the component is required to have a positive growing stiffness, the carrying capacity is not significantly reduced, and the phenomenon of low-cycle fatigue does not occur.

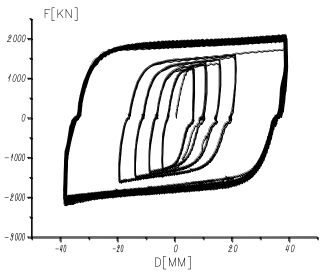


Figure 22. JY-SD-1000-4000 Buckling Restrained BracedBraced experimental hysteresis curve

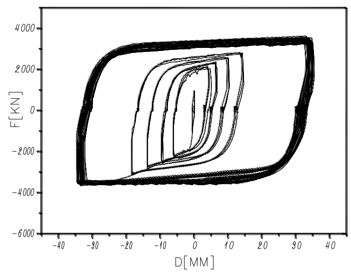


Figure 23 .JY-SD-2000-3600 Buckling Restrained experimental hysteresis curve

Note: JY-SD represents the CABR series, 2000KN and 3600mm is length

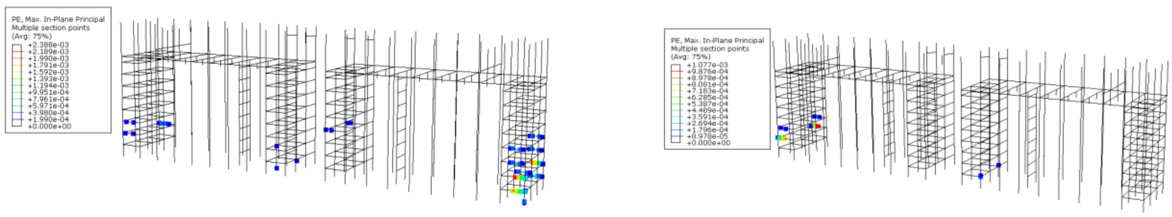
In the experiment, component is symmetrically loaded along the axial symmetry tension and compression, component yield displacement is about 2.3mm. The measured yield carrying capacity of 1000KN components is approximately 1004KN, and the ultimate bearing capacity is 2005KN (pressure); 2000KN component yield bears 2094KN, with ultimate bearing capacity of 3680KN (pressure). As JY-the SD component perfectly controls the bonding layer of air gap size, the maximum carrying capacity difference of the two components tension and compression is about 6 percent, two-way bearing capacity is very symmetrical.

This project buckling restrained braces core material adopts Q160 low yield point mild steel, components ultimate deformation capacity and ductility is superior to the core material of the traditional materials to a great extent. Figure 22 and Figure 23 low yield point soft steel core material support shows full hysteresis curve after yielding, the flexural rigidity curve slightly and positively grows, and the curve is flat, in contrast to the common core material curve, low yield point of the soft steel core material curve shows more "flat".

The overall structure of the elastoplastic analysis indicates the need to support the maximum deformation of 18mm (yield displacement to 7.8-fold), the components measured displacement of more than 32mm (yield displacement 14.8 times), the actually measured deformation of component is 1.9 times or more.

3.4 Damage to structure in the rare earthquake

Figure 24 shows, plastic strain distribution of beams and columns inner structural steel with the influence of natural wave 2.. We can see that, X and Y are main input directions, structural steel with plastic strain occurring in its structure (including structural steel concrete components middle structural steel) is mainly focused at the local steel components on the first floor of the frame tube structure, where plastic under strain is 2338 with X as the input principal direction, and; maximum plastic strain is only 1077 with Y as main direction.



X direction Y direction

Figure 24. Beam and column steel plastic strain distribution with the influence of natural wave 2 the role of the lower

To sum up, the great plastic deformation of the main buckling restrained braces structure in the rare earthquake decreases the main structural damage, and protects the safety of the main structure.

4. CONCLUSION

This project introduces energy dissipation technology, carry out hybrid arrangement in the building through energy consumption support and ordinary support, and constitute framework support system with concrete components, alternatively change primary and secondary directions through three sets of seismic records of the main building structure (each earthquake record consists of two horizontal and vertical components) and three-dimensional input and the rotation of the primary and secondary direction, totally 6 calculation analysis working conditions VIII grade (0.20g) rare earthquake (peak acceleration 400gal) influenced dynamic elastoplastic analysis, and the seismic performance evaluation of the project structure in VIII degree (0.20g) rare earthquake (peak acceleration of 400gal) are as follows:

1) With buckling restrained brace system three-dimensional input influenced elastoplastic time interval analysis, max displacement of structure top is 285mm, the maximum story displacement angle is 1/96, not exceeding 1/50. During the whole calculation process, the structure is always upright, meeting the regulation requirements of "inverted" earthquake.

2) Dynamic elastoplastic analysis shows, low yield point core material buckling restrained braces provides elastic lateral stiffness in most earthquakes, energy consumption support begins to yield after the middle earthquake, the stiffness of the whole structure reduces, the damping ratio increases, the earthquake force is significantly reduced compared with traditional "pure anti" structure. In rare earthquake, energy consumption support can well play yield and energy consumption function, invalidation does not occur with continuous and stable work, and certain security reserve is preserved.
Dynamic elastoplastic analysis result of three-dimensional function and preliminary and secondary directions alternatively changing shows that plastic stress only occurs to structural steel concrete columns inner structural steel, indicating that in the rare case of earthquake, structural steel reinforced concrete columns has good seismic performance.

REFERENCES

Code for the aseismic design of building (GB50011-2010)", Beijing: *China Building Industry Press*, **2010**.

"Control of structural vibration – active, semi-active and intelligent control" *Beijing, Science Press*, **2003**.

Gao Jie, Xue Yantao, et al, Research on metallic mild steel damper of JY-SS-I type by test, *Journal of Civil Engineering and Management*，**2011.9, Volume 28 issue 3**.

"Manual for design and construction of passive shock-absorbing structure", Beijing, *China Building Industry Press*, **2008.**

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