Analysis and comparison of the characteristics of two kinds of dampers

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Abstract. Low cycle reciprocating load tests were exerted to two new kinds of arc steel rod dampers which are suitable for latticed shell, and the finite element models of the two dampers were built, on the base of comparing experimental results and finite element calculation results, the influences to the characteristics of the two dampers of related parameters were analyzed. The resilience model of the two types of dampers were made on the basis of a large number of simulation calculations, and the stiffness degradation laws were researched too. Then the two kinds of dampers were arranged in latticed shell separately, and the influences to latticed shell were researched. Test and analysis indicate that the diameter of the arc steel rod has great influence on the characteristics of the two dampers, and the energy dissipation characteristics of double-layer arc steel rod damper are better than that of single layer arc steel rod damper.

1. The introduction

In order to reduce the damage of buildings under earthquakes, energy dissipation devices are often installed in building structures. The common dampers include viscous dampers, viscoelastic dampers, friction dampers, metal dampers [1]. Metal dampers are manufactured according to the characteristics that metal has good hysteretic characteristics after entering plastic state and can absorb excessive energy in the process of elastoplastic deformation. Because of the advantages of superior performance, simple manufacture and easy replacement, metal dampers have a good application prospect in practical engineering. At present, the theoretical and application researches on metal damper are gradually mature, and the research results are also very rich. Wu congxiao et al. [2] introduced the types and performance of metallic dampers in detail. There are many types of metal dampers, such as tapered Steel damper developed by Tyler et al [3], double-tube buckling Restrained Braces developed by Cai kequan et al [4], lead viscoelastic damper developed by Zhou yun et al [5]. Zhou yun et al. [6] also introduced the Shock absorption design methods of metal dampers. New types of metal dampers...
are developed with the Improvement of structure and material Innovation. Li hua et al.[7] developed a new type of metal variable friction damper, Xin yajun et al [8] proposed a combined steel lead damper, Ning xiangliang et al. [9] proposed a new type of buckling-restrained braces, but most of these dampers are used in frame structures, few of them are used in large-span structures such as latticed shell. Two arc steel rod dampers suitable for latticed shell structure were proposed by wenming[10][11], and static characteristics were analyzed. In this paper, Pseudo-dynamic tests on the two arc steel rod dampers were carried out firstly, then the Influences of parameter variation on energy dissipation characteristics were analyzed by finite element software, and relevant formulas were fitted. The resilience models of the two dampers were established on the basis of a large number of simulation calculation data, stiffness degradation laws were researched too. At last the two dampers were arranged in the lattic shell, and the influences of the two dampers on the stability of the reticulated shell were analyzed and compared.

2. Working principle and test Survey of the two dampers

The two kinds of arc steel rod dampers studied in this paper were developed by applying the good plastic properties of metal materials after buckling. The structure diagram of the two kinds dampers were shown in figure 1.

2.1. Working principle of the two dampers

Figure 1 (a) is a single-layer arc steel rod damper, hereinafter referred to as SSD, and figure 1 (b) is a double-layer arc steel rod damper, hereinafter referred to as DSD. DSD is an improvement on SSD. The two arc steel rod dampers are mainly composed of arc steel rod, conductive rod, disk, sleeve and actuator. Three arc steel rods with identical characteristics of SSD are distributed on one floor, the welding joints between steel rod and disc are distributed evenly on the disk, the angle with the center line of the disk is 120 degrees. The arc steel rods of DSD are distributed in the upper and lower layers, and the three arc steel rods of each layer are equally distributed on the disk. One end of the conductive rod is welded on the upper actuating disk, and the other end is gone through circular hole of the middle-plate and welded on the lower actuating disk.
When axial load is applied to the two dampers, the force is transferred to the lower actuator, and the lower actuator will be moved between the upper and lower limiter, the energy will be consumed with expansion and contraction of arc steel rod. The conductive rod can resist certain transverse load with the supporting of Disc Hole Wall. In practical application, steel pipe can be welded with both sides of actuator and chassis, and then steel pipe can be connected with the bolt ball (welded ball) of the grid frame (reticulated shell) structure, the same whole with structure and dampers can be formed. Therefore, the two dampers are suitable for Shock absorption of latticed Shell Structures.

2.2. Pseudo-dynamic tests on the two dampers

The main parameters of the two dampers were shown in table 1. Three specimens of each damper were made (number of SSD is A1, A2, A3, number of DSD is B1, B2, B3). All materials was Q345, poisson's ratio was 0.3, material density was 7850 kg/m$^3$, yield strength was 345 MPa, ultimate strength was 510 MPa, and elastic modulus of material was 206 GPa. The performance curve of the material was shown in figure 2.

Table 1 Main Structural parameters of dampers

| Specimen number | Diameter of Arc Steel Bar/mm | Initial Bending of Arc Steel Bar/% | Actuator plate thickness/mm | Conducting rod diameter/mm |
|-----------------|-----------------------------|----------------------------------|-----------------------------|----------------------------|
| A               | 16                          | 15                               | 12                          | 25                         |
| B               | 16                          | 15                               | 12                          | 25                         |

![Fig 2 Material performance curve](image)

According to "Specification for seismic test of buildings " (JGJ/T 101-2015) $^{[12]}$, displacement loading mode was selected, downward elastic displacement $\Delta y=0.5$mm was exerted firstly, then upward displacement and downward displacement $\Delta y=0.5$mm were applied, thus one Pull-Pressure Cycle was finished, then Cyclic loading of $\Delta y$, $2\Delta y$…$24\Delta y$ was applied Continuously. The Number of cycles were shown in table 2. One Displacement meter connected with Static strain gauge DH3818 was set for each diagonal position of the force transfer beam. The measured displacement value was recorded by computer, and the average value read by the two displacement meters was used as the displacement of the damper. The performances under low-cycle reciprocating load of the two dampers were tested on a 10t self-reaction loading frame. The Actual loading diagram was shown in FIG. 3, and the hysteretic loop curve drawn according to experimental data was shown in FIG. 4 (due to space limitation, the hysteretic loop curve of samples A1 and B1 was drawn only).
Table 2 Loading scheme of test specimen

| Specimen number | Load step | Displacement /mm | Number of cycles |
|----------------|-----------|------------------|-----------------|
| A1             | 1         | ± 0.5Δy          | 1               |
| A2             | 2         | ± Δy             | 1               |
| A3             | 3         | ± 2Δy            | 3               |
| B1             | 4         | ± 4Δy            | 3               |
| B2             | 5         | ± 6Δy            | 3               |
| B3             | 6         | ± 8Δy            | 3               |
|                | 7         | ± 12Δy           | 3               |
|                | 8         | ± 16Δy           | 3               |
|                | 9         | ± 24Δy           | 3               |

Fig3 Actual loading diagram

(a) Hysteretic curve of SSD specimen  (b) Hysteretic curve of DSD specimen

Fig4 Hysteretic curve of two dampers

It can be seen from figure 4 (a) that the tensile and compressive properties of SSD under reciprocating load are not symmetrical, and the tensile properties are better than the compressive properties, while the tensile and compressive properties of DSD shown in figure 4 (b) are similar, the hysteretic curve is full and the energy dissipation ability is strong.

3. Effects on Energy Dissipation performances with the Variation of relevant parameters of the two dampers

In order to analyze the influences of relevant parameters on the performances of the two types of dampers, the finite element models of the two types of dampers were established firstly in ANSYS software. Element SOLID45 was selected. Miese yield criterion and Multilinear follow-up reinforcement criterion were chosen. The loading system was the same with the test. The finite element
model established in ANSYS was shown in figure 5 (in order to reduce the calculation amount, socket was not included in the calculation model).

![Finite element model of two damper](image)

**Fig5 Finite element model of two damper**

3.1. **Comparison of experimental and simulated results**

The comparison between the experimental results and the finite element calculation results about dampers A1 and B1 were shown in Fig 6.

![Comparison between experimental results and finite element calculation results](image)

**(a) Comparison between the experimental results and the finite element calculation results about SSD**

**(b) Comparison between the experimental results and the finite element calculation results about DSD**

**Fig6 Comparison between experiment results and finite element calculation results**

It can be seen from Fig6 that the results got by finite element calculation are in good agreement with the results got by experiment, the slope of hysteretic curve is basically the same, and the difference between extreme points is also within the range of error. The load displacement curve obtained by the test is more pinched, and the test data is relatively small. However, from the perspective of load displacement curve as a whole, the slope and shape of the whole curve are also similar, which indicate that if a finite element model based on the constitutive and material properties was established, the analysis data would be real and reliable.

3.2. **Influence of radian and diameter on the skeleton curves of the two dampers**

It can be seen from the construction diagram of the two kinds of dampers that the main influence parameters to the energy dissipation characteristics of the two dampers are the diameter and radian of the arc steel rod.

When the arc steel rod radian was 15% or 20%, Keeping the thickness of the actuator and the diameter of the conductive rod showed in Table1 unchanged, the relationships between the energy...
dissipation characteristics of the two dampers and the diameter of the arc steel rod were researched. The corresponding skeleton curves were extracted from the hysteresis loop curves of each model. When the radian of arc steel rod was 15% or 20%, the relationship between skeleton curves and arc steel rod diameter about SSD were shown in FIG. 7, and the relationship between skeleton curves and arc steel rod diameter about DSD were shown in FIG. 8 (a-b showed in figure, a represented the radian of the arc steel rod, b represented the diameter of the arc steel rod, and the following representations were the same)

![Skeleton curves under different diameter when radian is 15%](image1)

![Skeleton curves under different diameter when radian is 20%](image2)

Fig7 The skeleton curves of SSD under different diameters

![Skeleton curves under different diameter when radian is 15%](image3)

![Skeleton curves under different diameter when radian is 20%](image4)

Fig8 The skeleton curves of DSD under different diameters

It can be seen from figs. 7 and 8 that the elastic strength and ultimate strength of SSD and DSD both increase with the increasing of diameter when the radian remains unchanged. And because of the asymmetry of the tension and compression properties of arc steel rod, the tensile limit of SSD is greater than its compression limit, and due to the average distribution of arc steel rods in the upper and lower layers, the tensile limit of DSD is similar to its compression limit.

When the diameter of arc steel bar was 14mm or 16mm, Keeping the thickness of the actuator and the diameter of the conductive rod showed in Table1 unchanged, the relationships between the energy dissipation characteristics of the energy dissipator and the radian of the arc steel rod were
researched. The corresponding skeleton curves were extracted from the hysteretic loop curves of each model. When the diameter of arc steel rod was 14mm or 16mm, the relationship between skeleton curves and arc steel rod radian about SSD were shown in FIG. 9, and the relationships between skeleton curves and arc steel rod radian about DSD were shown in FIG. 10.

![Skeleton curves under different radian when diameter was 14mm](image1)

![Skeleton curves under different radian when diameter was 16mm](image2)

**Fig 9** The skeleton curves of SSD under different radians

![Skeleton curves under different radian when diameter was 14mm](image3)

![Skeleton curves under different radian when diameter was 16mm](image4)

**Fig 10** The skeleton curves of DSD under different radians

It can be seen from figs. 9 and 10 that the skeleton curves about the two kinds of models are all close, the limit load decreases slightly with the increasing of diameter, the rigidity reflected by Slope of skeleton curves is no significant changed. When the diameter is 14mm, the skeleton curve under different radians is no significant change, the gap between curves increases slightly while diameter increases to 16mm, and the ultimate load decreases slightly with the increasing of radian.

### 4. Formula Fitting of Skeleton Curves of Two Kinds of Dampers

Keeping the thickness of the actuator and the diameter of the conductive rod showed in Table1 unchanged, the radiant of arc steel rod was selected from 10%, 15%, 20%, 25%, the diameter of arc steel rod was selected from 8mm, 10mm, 12mm, 14mm and 16mm, The energy dissipation characteristics of 16 different combinations of parameters were studied for each damper, and the related skeleton curves were extracted.
The yield point and failure load point in the skeleton curve were defined as the eigenvalue points. Dimensionless coordinates was adopted to deal with skeleton curves, namely the y axis was \( F/F_\mu \), the x axis was \( \Delta/\Delta\mu \), among which \( F_\mu \) was limit load and \( \Delta\mu \) was displacement corresponding to \( F_\mu \).

The bilinear model of stiffness degradation was used, the skeleton curves obtained by the simulation through dimensionless treatment were regressed, and the results were shown in FIG. 11. The slope and equation of each line segment in SSD and DSD models were shown in table 2 and table 3 respectively.

(a) Skeleton curve model of SSD  
(b) Skeleton curve model of DSD

Fig11 Two fold line skeleton curve models of two kinds of dampers

In FIG. 11, A and C were the yield points of tension and compression respectively; D and B were the load value points. In the curve model, OA and OC of line segment were respectively regressed by Unloading stiffness before yielding under reciprocating compressive and tensile loads of the damper, and the slope represented the relative elastic stiffness of the damper. Line segment CD and AB were respectively regressed by Unloading stiffness gotten from yield to maximum load under the action of tension and compression load, and the slope represents the plastic stiffness of the energy dissipator after yielding. The trend of skeleton curves of the two types of dampers are roughly similar, but the initial stiffness of the DSD energy dissipator is larger than that of SSD. The slopes and equations of the two models are listed in table 2 and 3. and the initial stiffness of DSD is about 4% larger than that of SSD. By comparison, the reverse stiffness of DSD is 40% larger than that of SSD, which is caused by the imbalance of SSD tension and pressure, while the DSD is significantly improved, and the differences in plastic stiffness between the two dampers are not obvious.

| line segment | regression equation | \( \Delta/\Delta\mu \) range | Angle with X-axis | Slope |
|--------------|---------------------|-----------------------------|------------------|------|
| OA           | \( \frac{F}{F_\mu}=2.895(\Delta/\Delta\mu) \) | [0,0.297]                   | 70.94            | 2.895|
| AB           | \( \frac{F}{F_\mu}=0.22(\Delta/\Delta\mu)+0.781 \) | [0.297,1]                  | 12.41            | 0.22 |
| OC           | \( \frac{F}{F_\mu}=4.62(\Delta/\Delta\mu) \) | [-0.131,0]                 | 77.78            | 4.62 |
| CD           | \( \frac{F}{F_\mu}=0.089(\Delta/\Delta\mu)-0.594 \) | [-1,-0.131]               | 5.08             | 0.089|
Table 4 Relevant Parameters of Bifolded Skeleton Curve of DSD

| line segment | regression equation               | $\Delta/\Delta \mu$ range | Angle with X-axis | Slope |
|--------------|-----------------------------------|---------------------------|------------------|-------|
| OA           | $F/F_\mu = 3.005(\Delta/\Delta \mu)$ | [0,0.267]                 | 71.59            | 3.005 |
| AB           | $F/F_\mu = 0.269(\Delta/\Delta \mu) + 0.731$ | [0.267,1]                 | 15.05            | 0.269 |
| OC           | $F/F_\mu = 8.567(\Delta/\Delta \mu)$ | [-0.204,0]                | 83.34            | 8.567 |
| CD           | $F/F_\mu = 0.220(\Delta/\Delta \mu) - 0.763$ | [-1,-0.204]               | 12.41            | 0.220 |

5. Stiffness degradation law of the two dampers

The resilience models of the two dampers were described based on the previous simulation calculation data, and the resilience models of the two dampers were shown in figure 12.

Dimensionless coordinates were adopted uniformly. Point A was the positive yield point and AB was the positive reinforcement stage. Point C was the reverse yield point and CD was the reverse reinforcement stage. The unloading line developed along the AO segment when the energy dissipator was unloaded before loading to point A; and when the energy dissipator was unloaded after loading to point A, the stiffness degenerates and the unloading line develops along the BF segment. Similarly, if the load was unloaded before point C, the unloading line was CD; and if the load was unloaded after point C, the unloading line was DE.

In the figure, $K_0^+$ represented the positive initial stiffness, $K_0^-$ represented the reverse unloading stiffness, $K_1$ represented the forward unloading stiffness, $K_2$ represented the reverse loading stiffness, $K_3$ represented the reverse unloading stiffness, and $K_4$ represented the forward loading stiffness.

(a) Resilience model of SSD

(b) Resilience model of DSD

Fig12 Bilinear resilience model for two kinds of dampers

According to the comparison between fig.12 (a) and (b), it can be seen that the trends of the resilience model of the two dampers are roughly similar, but the resilience model of the DSD is fuller, the tensile and compression performance of the SSD is poorer, and the performance of DSD is significantly improved.

Stiffness degradation laws of the two dampers were fitted, the stiffness degradation rules of SSD were shown in table 3, and the stiffness degradation rules of DSD were shown in table 4.
Table 5 Stiffness degradation laws of SSD

| Rigidity | Degradation law |
|----------|-----------------|
| K1       | $F / F_o = 5.194(\Delta / \Delta_o)^2 - 4.479(\Delta / \Delta_o) + 1.053$ |
| K2       | $F / F_o = 0.456(\Delta / \Delta_o)^2 - 0.071(\Delta / \Delta_o) + 0.228$ |
| K3       | $F / F_o = 11.6(\Delta / \Delta_o)^2 - 23.147(\Delta / \Delta_o) + 11.43$ |
| K4       | $F / F_o = 1.413(\Delta / \Delta_o)^2 - 2.27(\Delta / \Delta_o) + 0.973$ |

Table 6 Stiffness degradation laws of DSD

| Rigidity | Degradation law |
|----------|-----------------|
| K1       | $F / F_o = 0.436(\Delta / \Delta_o)^2 - 0.432(\Delta / \Delta_o) + 0.122$ |
| K2       | $F / F_o = 0.707(\Delta / \Delta_o)^2 - 0.650(\Delta / \Delta_o) + 0.601$ |
| K3       | $F / F_o = 4.456(\Delta / \Delta_o)^2 - 1.699(\Delta / \Delta_o) + 0.636$ |
| K4       | $F / F_o = 2.086(\Delta / \Delta_o)^2 - 2.478(\Delta / \Delta_o) + 0.758$ |

6. Application of two dampers in latticed shell

In order to analyze the influences of the two dampers on the dynamic characteristics and stability of the latticed shell, a finite element model of single-layer cylindrical reticulated shell was established, and the two dampers were placed in the reticulated shell separately. The reticulated shell model was shown in FIG. 13, and the arrangement of dampers was shown in FIG. 14. (The bold lines in the figure represent dampers)

Fig 13 Finite element model of lattice shell       Fig 14 Arrangement of dampers

The reticulated shell were supported by four sides, constraints were imposed on four sides. Eigenvalue buckling analysis was performed on reticulated shells with the two types of dampers separately, and the first six order buckling coefficients were extracted respectively, which were shown in table 5.
Table 7 Buckling coefficient of reticulated shell

| Buckling order | Initial latticed shell | latticed shell mixed with SSD | latticed shell mixed with DSD |
|---------------|------------------------|------------------------------|------------------------------|
| 1             | 2.804                  | 2.822                        | 2.837                        |
| 2             | 3.188                  | 3.217                        | 3.233                        |
| 3             | 5.197                  | 5.236                        | 5.263                        |
| 4             | 5.275                  | 5.289                        | 5.399                        |
| 5             | 5.628                  | 5.691                        | 5.793                        |
| 6             | 6.859                  | 6.897                        | 6.996                        |

The analysis results show that the buckling coefficient of the reticulated shell significantly improves with the addition of dampers, because the stiffness of the reticulated shell structure is increased with the addition of dampers. While the performances of the DSD are superior. Each buckling coefficient of reticulated shell mixed with DSD is higher than that of reticulated shell mixed with SSD, which indicate that the performance of DSD is more stable.

The critical load of the latticed shell instability was analyzed by characteristic value got by eigenvalue buckling analysis, the nonlinear stability of the reticulated shell was analyzed. In order to track the instability of the reticulated shell, load-displacement curve of the whole process was extracted. Due to limited space, the load-displacement curves of no448 node was extracted only, which was shown in figure 15, and the position of node 448 in the reticulated shell was shown in figure 15.

Fig 15 Load-displacement curves of No 448 node

It can be seen from figure 15 that the extreme point of reticulated shell with dampers is much higher than that of initial reticulated shell, and the stability of the reticulated shell mixed with DSD is significantly better than that of reticulated shell mixed with SSD. It shows that the two kinds of dampers can improve the structural stability, and the improved double layer arc steel damper has better performances, and can be considered to add this damper in practical engineering.

7. Conclusions

The energy consumption characteristics of the two arc steel rod dampers were analyzed and compared in this article. On the base of experiment, finite element model was established by using ANSYS software. The influences of related parameters on the characteristics of dampers were analyzed, Skeleton Curves and Stiffness Degradation Performances of the two dampers were researched too. The influences on the stability of reticulated shells was further analyzed. The conclusions were drawn as follows:
(1) The tensile and compressive properties of SDS under the action of reciprocating load are not symmetrical, and the tensile properties is better than the compressive properties. The tensile and compressive properties of DSD are similar, the hysteretic curve is relatively full and the energy dissipation ability is better.

(2) Under the condition of constant radian, the elastic strength and ultimate strength of SSD and DSD both increase with the increasing of diameter. The tensile limit of SSD is greater than the compression limit due to the asymmetric tensile and compression performance of the arc steel rod. Due to the average distribution of arc steel rods in the upper and lower layers, the tensile and compression limit of DSD are similar.

(3) Under the condition of keeping diameter unchanged, the skeleton curves of SSD and DSD are close with the increasing of radian. The ultimate load decreases slightly with the increasing of radian, and the stiffness named by the slope of the skeleton curve is no significant changed. Compared with the influence of diameter on the skeleton curve, it is not so intuitive.

(4) The ultimate load of reticulated shell is significantly increased after the dampers are added, and the promotion effect mixed with DSD is more remarkable.

Reference

[1] Zhou yun, Deng xuesong, Tang tongbi, Wu congxtiao, Nie yiheng, Ding kun. State of the Art and prospect of energy dissipation technology in China (mainland) [J]. Earthquake resistant engineering and retrofitting 2006(28),6:1-15.

[2] Wu congxtiao, Zhou yun, Wang tingyan. Types and performance of metallic dampers and their engineering applications[J]. Earthquake resistant Engineering and retrofitting, 2006(28)1:87-94. (in Chinese)

[3] Tyler R G. Tapered Steel Energy Dissipators for Earthquake Resistant Structures[J]. Bulletin of New Zealand National Society for Earthquake Engineering ,1978,11(4):282-294.

[4] TSAI keh-Chyuan, HWang yean-chih, Weng chungshing. Seismic performance and applications of double-tube buckling Restrained Braces [J]. Progress in steel Building structures,2005,7(03):1-8.

[5] Zhou yun, Wu zongxiao, Deng xuesong. Development, research and application of lead viscoelastic damper [J]. Engineering mechanics,2009,26(S2):80-90.

[6] Zhou yun, Qian hongtao, Chu hongmin, Zou zhengmin. A study on the design principle and performance of a new type of Buckling-Resistant Brace[J]. CHINA CIVIL ENGINEERING JOURNAL ,2009,42(04):64-71.

[7] Li hua, Zhang zhongen, Tang ermei. Research and application of new metal damper of variable friction[J]. Journal of disaster prevent and Mitigation engineering,2012,32(04):459-462.

[8] Xin yanjun, Wang huanding, Cheng shuliang. Experimental study on new combined steel lead damper [J]. Engineering mechanics,2007,24(03):126-130.

[9] Ning xiangliang , Liu jun, Zhang ying, Li wenbin, Xu mingjie, Hu yuxin. Design, testing and seismic mitigation performance research of a new type of buckling-restrained braces[J]. Journal of Earthquake engineering and engineering vibration,2012,32(01):49-53.

[10] Wen ming, Huang haowen, Wang limin, etc. Parameter analysis and practical application research of a new steel damper [J]. Journal of nanchang university, 2016,38 (3) : 272-275
[11] Wen ming, Huang chunmei, Huang haowen, etc. Characteristics Analysis of New energy dissipation [J]. Journal of nanchang university, 2008, 40(1):41-45

[12] Ministry of housing and urban-rural development of the People's Republic of China, Specification for seismic test of buildings (JGJ 101-2015). [S]. Beijing: China architecture & building press, 2015.

[13] Wang xinmin. Numerical analysis of ANSYS engineering structure [M]. Beijing: people's communications press, 2007