A New Type of SMA Self-reset Damper and Its Performance

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Abstract. This paper develops a new self-resetting energy-saving support of SMA based on the unique superelastic properties of shape memory alloy (SMA) through independent innovation in order to reduce the effect of earthquakes on engineering structures. Experiment and data analysis of the deformation, energy consumption and self-reset performance of this new structure are investigated shows that that the supporting device can stably exert the functions of energy consumption and self-reset under the tension and compression cyclic load;. This paper also explores the influence of loading rate and displacement amplitude on energy consumption of the supporting device, thus further expanding the application of SMA in civil engineering.

1. Background

Recent years have seen the wide concern for the damage of earthquakes to engineering structures, while structural vibration control technology can play a significant role in this regard. Traditional anti-seismic structures mainly rely on the increase of strength and deformability of structural components to achieve its due effects[1]. However, after the earthquake, the permanent residual deformation of the structure is large, leading to the difficulties and high costs in maintenance. In order to solve this, the structural vibration control technology has been developed, which aims to suppress the response of the structure under the external load by installing an energy-consuming damping device, thereby reducing the damage of shaking to buildings[1].

In the 1960s, the shape memory effect of SMA was discovered and applied to such fields as medicine, robotics, and aerospace. The past two decades have witnessed the innovative applications of SMA in civil engineering[2], including bridge limiters, special dampers, dissipative supports, basic isolation systems, special connectors, and reinforced concrete components with variable stiffness and strength.

At present, energy dampers widely used mainly include X-shaped and triangular metal dampers, friction dampers, viscous fluid dampers, viscoelastic solid dampers and magnetorheological dampers[3], which all have many limitations, including insufficient durability, complex maintenance and installation, and excessive structural residual deformation after strong earthquakes. SMA, with its sensing and driving functions[2][4], unique shape memory effect, superelastic effect (withstand 10% recoverable strain without exhibiting plasticity), high damping capacity, high resistance, high anti-fatigue property, durability, and thermal strain recovery ability, can be used to eliminate the aforementioned limitations.

The superelasticity of SMA means that when the temperature of material exceeds the transition temperature of martensite reverse phase Af (complete in austenite state) with the loading stress larger than the elastic limit, the inelastic strain is generated; the deformation disappears after removing the stress. The stress-strain relationship is obvious nonlinearity. The strain returns to zero when there is zero stress, showing the hysteresis cycle effect. The superelastic effect of SMA is a special performance of hysteretic energy dissipation, which can be used to develop energy absorbing devices with good performance based on the characteristics of SMA[5].
2. Model design

2.1. Self-resetting energy-consuming support structure and its working principle

The new SMA self-resetting energy-consuming support designed in this paper has the following characteristic: The Ni-Ti SMA wire inside the device is always in tension no matter the support is under tension or compression; in this way, the superelastic and high damping characteristics of SMA can be fully utilized to endow the support with a good self-resetting effect and energy consumption ability.

2.2. Structure of the new SMA self-resetting energy-consuming support

![Figure 1](image1.png)

(a) Side view of device

(b) Diagram of hole position of inner plate

The structure of the new SMA self-resetting energy-consuming support is shown in Figure 1, including two inner plates, two outer plates, six inner bars, two outer bars, and the SMA wire. The outer side plate has three holes while the inner side plate has six holes, all of which are symmetrically distributed around the circle center. The openings on the outer side plates are threaded while the six big holes of the inner side plate are coupled with three small holes for the SMA wire to pass through; meantime, the edge of the holes is chamfered to fit the SMA wire. The six inner bars are variable section bars, which can be divided into three sections according to the thickness (thin on the two sides and thick in the middle; one of the two thin ends are relatively longer than the other). The six bars are distributed in a regular hexagon shape, with the disjunction distribution of long and short sides. The long end of the inner bar is threaded with the bolt connected to the outer side plate; the short end is not treated like that. The outer bar and the outer side plate are bolted with the connection point at the center of the outer side plate, which is for applying the load during experiment. When the device is in operation, the tension of the SMA wire is achieved by separating the two inner side plates.

2.3. Working principle of the new SMA self-resetting energy-consuming support

Its working principle is shown in Figure 2. Tighten and anchor the SMA wire (consider prestressing); at this time, the two inner plates are pulled closer to each other until blocked by thin-thickness joint of the inner bar, and then the device becomes stable. It is assumed that the outer bar on the left side is fixed, and the external load on the right outer bar is applied in the axial direction of the device. When the tension is applied, the two outer plates move away from each other (as shown in Figure 2(a)), the long ends of the inner bar push the inner plates away, while the short ends are free to slide, thus elongated SMA wires; when the pressure is applied, the two outer plates move closer to each other (as shown in Figure 2(b)), the short ends of the inner bar push the inner plates away, while the long ends slide freely, thus elongated SMA wires.
3. Mechanical performance test of SMA self-reset energy dissipation support

3.1. Test overview
In order to study the mechanical properties of the new SMA self-reset energy-consuming support, this paper processes the specimen according to the drawing of the device. The total length of the test piece is 400 mm with the maximum displacement stroke of 12.8 mm (8% strain of SMA wire is taken). Prior to assembly, pre-stretch the SMA wire for 25 cycles with the strain amplitude and loading rate of 7% and 1.0%/min, respectively, thereby stabilizing its superelastic properties.

The mechanical performance test was completed in the Mechanics Laboratory of Southeast University using a 100kN universal testing machine, as shown in Figure 3.

This experiment focuses on the effects of two variables, namely, deformation amplitude and loading rate, on the mechanical properties of the specimen. The test was carried out at room temperature of about 5 °C. Due to the limitations of the test conditions, the influence of temperature on the properties of the SMA wire was not taken into consideration. Three different loading conditions are set based on the purpose of the test, as shown in Table 1.
Table 1 Test Loading Conditions and Test Processes

| Test condition | Loading mode/mm               | loading rate/ (mm/min) | Explain                          |
|---------------|--------------------------------|------------------------|----------------------------------|
| I             | 0→12.8→12.8→12.8→12.8→12.8→12.8→12.8→12.8→12.8→12.8→12.8→0          | 1.6                    | Tension-compression cycle, 5 cycles |
| II            | 0→3.2→3.2→6.4→6.4→9.6→9.6→9.6→12.8→12.8→0 | 1.6                    | Variable-amplitude tension-compression cycle, 4 cycles |
| III           | 0→11.6→11.6→11.6→11.6→11.6→11.6→11.6→0   | 8, 40, 80              | Variable-speed tension-compression cycle, three cycles |

3.2. Selection of mechanical parameters
To investigate the hysteretic performance of SMA self-resetting energy-consuming support, the following parameters [1] are selected for research:
- $W_D$, single-turn energy consumption, or the area enclosed by the hysteresis curve in a single cycle;
- $\eta$, Energy dissipation coefficient, or the energy dissipation efficiency of the support, which is expressed as:
  $$\eta = \frac{W_D}{W_e}$$
  ($W_e$ is the total energy input for the loading phase);
- $K_0$, initial stiffness, or the slope at the initial elastic section of the load-displacement curve;
- $F_y$, yield load.

3.3. Experimental result and analysis
The load-displacement curves of the specimens under three different working conditions are shown in Figure 4. The experimental results are as expected, showing that the specimens have good hysteretic performance.

According to the data in Figure 5(b), the mechanical parameters of SMA self-resetting energy dissipation under different displacement amplitudes are obtained and shown in Table 2. For the relationship between the displacement amplitude and the single-cycle energy dissipation and energy dissipation coefficient, see Figure 5.
Table 2 Mechanical properties of specimens under different displacement amplitudes

| Displacement amplitude (mm) | Initial stiffness $K_0$ (kN/mm) | Yield load $F_y$ (kN) | Single cycle energy dissipation $W_D$ (J) | Energy Dissipation Coefficient $\eta$ |
|-----------------------------|---------------------------------|-----------------------|----------------------------------------|----------------------------------|
| 3.2                         | 1.24                            | 4.41                  | 0.46                                   | 0.196                            |
| 6.4                         | 1.24                            | 4.41                  | 7.50                                   | 0.511                            |
| 9.6                         | 1.24                            | 4.41                  | 20.02                                  | 0.672                            |
| 12.8                        | 1.24                            | 4.41                  | 30.09                                  | 0.728                            |

• As shown in Figure 5(a), the load-displacement curves of the test pieces are basically coincident in several cycles, indicating that the performance of the test piece is stable. Rare residual deformation indicates that the test piece has outstanding self-resetting performance. Flag type hysteresis curve shows that the test piece has good energy consumption effect.

• As the displacement amplitude changes, $K_0$ and $F_y$ remain unchanged, showing that these two mechanical parameters are not related to the displacement amplitude. Calculation shows that for the new SMA self-resetting energy-consuming support, $K_0$ = 1.24 kN/mm, $F_y$ = 4.41 kN. Since the SMA wire is the main force-bearing component, $K_0$ and $F_y$ of the test piece can be adjusted by changing the number of turns of the SMA wire.

• As shown in Figure 5(b), the SMA wire can fully exert the energy consumption function after it enters the yield state; with the increase of the displacement amplitude, the energy consumption of the test piece obviously increases. It can be seen from Table 2, taking 6.4 mm as a reference, the displacement amplitude of 9.6 mm and 12.8 mm lead to the increase of the energy consumption of the single ring of the component by 1.63 and 3.01 times, respectively, and the increase of the energy dissipation coefficient by 0.32, and 0.42 times, respectively. Combined with Figure 6, it can be seen that single-turn energy consumption is approximately in a linear relationship with the displacement amplitude; the energy dissipation coefficient changes approximately linearly when the displacement amplitude is small, and changes gradually more gentle when the displacement is large.

• As shown in Figure 5(c), as the loading rate increases, the hysteresis curve becomes narrower with less the area enclosed, thus lower capacity of the energy consumption of the device.
Due to the error in the fabrication and installation of the test piece, a horizontal section with less rigidity appears when the test piece is subjected to the conversion of tension and compression (i.e., the load is 0), as shown in Figure 5(a). This condition can be improved by applying pre-stress to the SMA wire, which, however, was not verified in this paper due to the limitations of experimental conditions.

4. Conclusion
This paper develops a new SMA self-reset energy-consuming support, illustrate its structure and working principle, and test its main mechanical properties and influencing factors through experiments. The conclusions are as follows:

- In the working state of the device, no matter whether the device is pulled or pressed, the inner plates can be farther away from each other using the inner bar, thus elongated SMA wires, which is a full utilization of the superelastic capacity of the SMA wire. The device is fully bolted to avoid mechanical properties change in the SMA wire during welding. The device is assembled using the plates and bars, making it easy to process and produce in scale.
- Under cyclic compression load, the device shows stable hysteresis performance. The single-turn energy consumption and energy dissipation coefficient are positively correlated with the displacement amplitude and negatively correlated with the loading rate.
- Due to the error in manufacturing and installation of the device, the SMA wire is slack in the initial state, leading to the appearance of a large horizontal section near the zero point of the load-displacement curve. For further research, pre-stress can be applied to the SMA wire during installation to optimize the performance of the damper.

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