Experimental research on resilient performances of Fe-based SMA-reinforced concrete shear walls

S Yan¹, M Y Lin¹, Z F Xiao¹ and J Niu¹,²
¹ School of Civil Engineering, Shenyang Jianzhu University, Shenyang, Liaoning 110168, China.
² Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian Liaoning, 116024, China.

The corresponding author: cesyan@sjzu.edu.cn

Abstract. Earthquake-resilient structural system is a new kind of seismic vibration control structure, which has the characteristics of rapid recovery or with only a small amount of repair after earthquake. Using superelasticity of shape memory alloys (SMAs) can effectively increase the resilient performance of reinforced concrete (RC) shear wall structures, which have a wide application prospect in the seismic field of civil engineering. A pseudo static test of six Fe-based SMA-reinforced concrete shear walls is performed in the paper, aiming at investigating the influences of different SMA reinforcement ratio and steel stirrup ratio on their resilient performances and seismic capacities. By using the concept of the resilience-force-ratio at balance positions of the shear walls, resilient performances (e. g., deformation recoverability) of shear walls can be well represented. The experimental numerical results show that the resilient performances of SMA-RC shear walls can increase 21.7% compared with the ordinary steel reinforced ones, and the resilient performances of SMA-RC shear walls can be effectively improved by placing SMA reinforcements with an appropriate ratio. The steel stirrup ratio and SMA reinforcement ratio in the edge member have a great influence on the resilient performances of the shear wall structures.

1. Introduction
As important anti-lateral force components in high-rise building structures, concrete shear walls directly affect the seismic performance of the entire structure. For this reason, many scholars have adopted different methods to improve the deformation performance of shear wall members [1]. The use of resilient properties to improve the seismic performance of concrete shear wall structures is a new concept of structural seismic design [2-4], in order to achieve the purpose of resilient structures without repair or fewer repairs after the earthquake. Shape memory alloy (SMA) is a kind of functional material with many kinds of special mechanical properties, such as typical superelasticity and shape memory effect (SME). The superelasticity of SMA shows that the SMA material in the austenitic state is deformed by the force and when the external load disappears, the deformation can be restored, to a certain degree, and there is no large residual strain [5]. The application of the SMA superelasticity can improve, to a certain degree, the resilience of the structure. For example, the superelastic SMA-based concrete shear wall can solve the problem of weak self recovery ability in concrete structures.

Roh [6] used built-in SMA rods in the column structure, and the SMA structure has excellent self recovery function by using the superelasticity of the rod. Kuang et al. [7, 8] pre-buried SMA tendons
in the beam, and when the beam is loaded to a deformation and unloaded, the SMA reinforcement can restore the beam back to the original shape by using its excellent superelastic characteristics, so that the cracks of the beam are closed. However, the previous research on the resilience of SMA-based concrete structures is generally concentrated on beams, columns or joints [9-11], and most of the nickel titanium SMA is used. Although the effect of Ni-Ti-SMA is good, the cost is relatively high [12], which limit the application of Ni-Ti-SMA material in engineering. In this paper, the superelastic iron (Fe) based SMA is used in concrete shear walls, aiming at analyzing the seismic performance such as the hysteretic characteristics, bearing capacity and residual deformation, etc., by controlling the SMA reinforcement ratio and the steel stirrup ratio, and investigating the resilient performance of the Fe-SMA based shear walls, which lays a theoretical foundation for its application.

2. Experimental research

2.1. Test purpose and main parameters

The purpose of the experiment is to validate the resilient performance of Fe-SMA based shear walls under earthquakes. To this end, the pseudo static test scheme is used to study 6 groups of shear wall specimens for the dimension of 600mm×1000mm×140mm and concrete strength grade of C30, as shown in Table 1. The designed axial compression ratio of the shear walls is 0.4, and the specimen is designed according to the scale of 1/3 of a single-story shear wall. The dimension and reinforcement of the specimen are shown in Figure 1.

Table 1. Parameters of Fe-SMA based shear wall specimen.

| Sample number | Reinforcement in edge member of the shear wall | Longitudinal tendons | Stirrup | Reinforcement ratio | Stirrup ratio |
|---------------|-----------------------------------------------|----------------------|--------|---------------------|--------------|
| GJ10-120      | 4Φ8 ordinary steel bars                       | Φ6@120               | 0.32   | 0.72                |
| GJ8-120       | 4Φ10 ordinary steel bars                      | Φ6@120               | 0.21   | 0.72                |
| SMA8-120      | 4Φ8 SMA bars                                  | Φ6@120               | 0.21   | 0.72                |
| SMA10-120     | 4Φ10 SMA bars                                 | Φ6@120               | 0.21   | 0.72                |
| SMA8-80       | 4Φ8 SMA bars                                  | Φ6@80                | 0.32   | 1.02                |
| SMA10-80      | 4Φ10 SMA bars                                 | Φ6@80                | 0.32   | 1.02                |

Figure 1. Shear wall specimens. (a) main view; (b) 1-1 cross-section; (c) 2-2 cross-section.

2.2. Loading equipment and measurement scheme
The pseudo static loading scheme is adopted in the experiment. First, the vertical load is applied by a 100 t hydraulic jack on the top of the specimen to meet the requirement of the axial compression ratio of 0.4; then a 150 t electro-hydraulic servo dynamic loading system is used to apply the horizontal low cyclic loading, and the test equipment and the photos in the site are shown in Figure 2. The mixed loading system is adopted in the test. The vertical load of 500 kN is kept during the loading and unloading process, and the force control theme is adopted before the horizontal load reaches the yield load. After the yield displacement is reached, the displacement control theme and two cycles at the stage are adopted until the bearing capacity of the concrete shear wall is reduced to 85% ultimate bearing capacity or failure of the shear wall. Load and deformation are measured by load sensors and displacement meters, respectively.

3. Experimental analysis on resilient properties of SMA shear walls

3.1. Load-displacement hysteretic curves

During the experiment, the horizontal displacements and external forces at the top of the tested shear walls are measured. The displacement-load hysteresis curves of the 6 sets of specimens obtained from the test are shown in Figure 3.

For the force control stage, before cracking of concrete, all the specimens are in the elastic working state, that is, the loading paths in the hysteresis curves are basically coincided with the unloading ones, and there is a linear relationship between the load and the displacement, whether in the positive direction or negative one. From the cracking of concrete to the yield stage of steel rebars, the stiffness of the specimen has not changed obviously with the very small residual deformation, and the corresponding resilient force at the balance point (the horizontal displacement is zero) is also very small. After reaching the yield load, the hysteresis curves begin to tilt to the displacement axis with the degradation of the stiffness and gradually increasing area of the hysteresis loop.

For the displacement control stage, the external force and stiffness of the specimens at the latter cycle are lower than the previous cycle, indicating obvious strength and stiffness degradation. After reaching the ultimate load, the stiffness of the specimen continues decreasing, and the hysteresis loop area continues increasing. The "kneading" phenomenon of the Fe-SMA shear wall is more obvious than that of the ordinary shear wall. The self-centering property produced by the SMA superelasticity makes the residual deformation of the component smaller than before and shows a good resilient property. Generally speaking, the more obvious the phenomenon of "kneading" is, the stronger the corresponding resilience is.
Figure 3. Experimental hysteretic curves for 6 Fe-SMA concrete shear walls.

3.2. Experimental analysis of resilient performance
In order to better describe the resilient performance of the Fe-SMA concrete shear walls, a concept corresponding to the resilience for each loading cycle $n$, which is a special external load $F_r(n)$ at the point corresponding to zero displacement (the balance point), is defined as the resilient force at the
balance position. The ratio of the resilient force $F_r(n)$ of each cycle to the ultimate load $F_u$ is defined as the resilience ration at the balance point. The meaning of the variables is shown in Figure 4, and the calculation formula is shown in Equation (1),

$$k_r(n) = \frac{F_r(n)}{F_u}$$

in which, $F_r(n)$ is the resilient force at the cycle $n$; $F_u$ represents the ultimate load of the shear wall. The small value of the ratio of the resilient force means the small restoring force is required to drive the shear wall to the balance position, indicating the good resilience of the shear wall under earthquakes. Otherwise, the shear wall has a weak resilience. In order to compare the resilience performance of Fe-SMA concrete shear wall with the RC one at different loading stages, each skeleton curve of the hysteresis curve and the curve of the resilient force ratio at each balance position is drawn in the same figure, as shown in Figure 5, in which the transverse coordinate represents the number of cycles for the loading step of $\Delta y$; the left and right ordinates represent the resilient force ratio and the external load, respectively. The cracking load, yield load and resilient-force-ratio of the shear walls at the ultimate balance points are shown in Table 2. Through comparison in Figure 5, the following general rules can be found.

3.2.1. The basic characteristics of resilient force ratio curves. For Fe-SMA concrete shear walls or ordinary RC shear walls, the resilient-force-ratio $k_r(n)$ curve is consistent with the skeleton curve of the hysteretic curve. The resilient capacity of the Fe-SMA concrete shear wall is closely associated with the loading cycle number $n$ and varied for different loading stage. When the cyclic load amplitude is small and the resilient-force-ratio $k_r(n)$ is also small, indicating good resilience for shear walls. With the increase of the cyclic load amplitude, the resilient-force-ratio increases gradually, representing the resilient capacity of the shear wall is reduced, and the resilient-force-ratio $k_r(n)$ gets the maximum value when the cyclic load amplitude reaches the peak value. The strength and stiffness degradation of the shear wall become more obvious than the initial stage. The skeleton curve goes decreasing, accompanying the decrease of the resilient-force-ratio $k_r(n)$, and the resilient ability of shear wall can be slowly increased with the increase of the resilient-force-ratio $k_r(n)$. 

Figure 4. Definition of recoverable force at balance positions.
3.2.2. Comparison of resilient ability between Fe-SMA shear wall and ordinary RC shear wall. It can be seen from Figure 5 that the maximum resilient-force-ratios $k_r(n)$ at the balance position for the ultimate bearing capacity state for SMA8-120, GJ8-120, SMA10-120 and GJ10-120 shear walls are 0.18, 0.23, 0.30 and 0.34, respectively, indicating that the maximum resilient capacity of the Fe-SMA shear wall is 21.7% higher than that of the ordinary RC shear wall. In addition, the cracking load and yield load of the shear wall can be significantly improved by placing the Fe-SMA reinforcement in the...
edge element of the shear wall. The experimental results of other shear walls are shown in Table 2. The resilient-force-ratio $k_r(n)$ at the balance position of the Fe-SMA shear wall is less than that of the ordinary shear wall, indicating that the resilient capacity of the Fe-SMA shear wall is better than that of the ordinary steel shear wall.

3.2.3. The influence of the diameter of the longitudinal SMA reinforcement. From the comparison of SMA8-120 shear wall and SMA10-120 shear wall, SMA8-80 shear wall and SMA10-80 shear wall, the maximum resilient-force-ratios at balance points will increase with the increase of the diameters of the SMA reinforcements, that is, the resilient capacity of the shear wall is reduced. This is because the superelasticity of SMA is closely related to the material property. In general, the superelasticity of SMA decreases slightly with the increase of the rebar diameter. Therefore, the SMA for a small bar diameter will have superior superelasticity, and it should be used as far as possible under the same reinforcement ratio.

### Table 2. Experimental parameters of shear wall specimens.

| Sample number | Cracking load / kN | Cracking displacement / mm | Yield load / kN | Yield displacement / mm | Equilibrium resilient ratio |
|---------------|--------------------|----------------------------|----------------|-------------------------|---------------------------|
| GJ10-120      | 60                 | 1.45                       | 75             | 2.2                     | 0.23                      |
| GJ8-120       | 60                 | 1.34                       | 95             | 2.8                     | 0.34                      |
| SMA8-120      | 75                 | 1.8                        | 103            | 3.6                     | 0.18                      |
| SMA10-120     | 75                 | 2.4                        | 110            | 4.0                     | 0.30                      |
| SMA8-80       | 75                 | 1.7                        | 105            | 3.7                     | 0.12                      |
| SMA10-80      | 90                 | 2.3                        | 120            | 4.8                     | 0.25                      |

3.2.4. The influence of the ratio of stirrup in the edge element of shear walls. From the comparison of SMA8-120 shear wall and SMA8-80 shear wall, SMA10-120 shear wall and SMA10-80 shear wall, respectively, it can be found that the ratio of the resilient force ratios at the balance positions of the Fe-SMA shear wall decreases with the increase of the ratio of the stirrup in the edge region, which indicates that the increase of the stirrup ratio at the edge members of the shear wall can provide good confinements to the core concrete at the edge region. The resilient capacities of shear walls are increased by about 30%.

4. Conclusions
(1) The iron (Fe) based superelastic SMA in the shear wall edge components can improve its resilient capacity, which is about 21.7% higher than that of ordinary reinforcement shear wall, accompanying with the increases of cracking load, yield load and ultimate load, etc.

(2) The resilient capacity of Fe-SMA shear walls is related to the amplitude and cycle number of cyclic loading. The resilient-force-ratio $k_r(n)$ at the balance position has the peak value and the corresponding resilient capacity is the lowest when the amplitude of cyclic load reaches the largest (corresponding to the ultimate load).

(3) The reduction of the diameter of the SMA reinforcement, for a certain degree, can increase the resilient capacity of the Fe-SMA shear wall under the same reinforcement ratio.

(4) The ratio of the stirrup at the edge element of the shear wall has a certain effect on the resilient capacity of the shear wall. The maximum increasing amplitude for the two sets of shear walls in this test is about 30%.
Acknowledgments
This work was partially funded by the Liaoning University Fundamental Science Research Key Project grant LJZ2017002; the Liaoning Provincial Department of Education Science Research Project grant LJZ2016029.

References
[1] Abdulridha A and Palermo D 2017 *Engineering Structures* **147** 77-89
[2] Lv X L, Zhou Y and Chen C 2014 *Earthquake Engineering and Engineering Dynamics* **34** 4 130-139 (in Chinese)
[3] Zhou Y and Lv X L 2011 *Journal of Building Structures* **32** 9 1-10 (in Chinese)
[4] Fang C, Wang W, He C and Chen Y Y 2017 *Engineering Structures* **150** 390-408
[5] Ren W J, Li H N and Song G B 2016 *Journal of Dalian University of Technology* **46** S1 157-61 (in Chinese)
[6] Roh H and Andrei M R 2010 *Engineering Structures* **32** 3394-403
[7] OU J P and Kuang Y C 2007 *Journal of Architecture and Civil Engineering* **24** 3 1-6 (in Chinese)
[8] Kuang Y C and Ou J P 2008 *Smart Materials and Structures* **17** 2 25020
[9] Fang C, Yam M C H, Lam A C C and Xie L K 2014 *Journal of Constructional Steel Research* **94** 122-36
[10] Wang W, Chan T-M and Shao H L 2015 *Journal of Constructional Steel Research* **109** 61-71
[11] Speicher M S, DesRoches R and Leon R T 2011 *Engineering Structures* **33** 2448-57
[12] Zheng Y, Dong Y and Li Y H 2018 *Construction and Building Materials* **158** 389-400