**cycLIC LoaDING TESTS of FaTIGUE-RESISTANT**

**Fe–Mn–Si-based Alloy Seismic Damper**

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**ABSTRACT**

The importance of implementing damage control measures against the long-period, long-duration seismic events in high-rise buildings has been increasingly recognized in recent years. Therefore, the performance requirements for seismic dampers installed in vibration-controlled buildings have increased dramatically; in particular, the requirement for durability against cyclic deformation have been deemed essential. In this context, we proposed a novel fatigue-resistant seismic dampers that are made of a Fe–15Mn–4Si–10Cr–8Ni damping alloy and designed to counteract long-period ground motion. In this study, we aim to verify the deformation behavior and fatigue endurance of the proposed seismic damper using cyclic loading tests. The results revealed that the developed damper has a significantly better fatigue life than conventional steel dampers and offers outstanding deformation performance and durability under low-cycle fatigue. In addition, shear-panel-type and brace-type seismic dampers made of this alloy were installed on steel-structure buildings in Japan. The proposed fatigue-resistant seismic dampers make it possible to allow the buildings to withstand long-period, long-duration ground motion and repeated after-quakes.

*Keywords: Fe-Mn-Si-based alloy; Seismic damper; Long-period ground motion; Dynamic loading tests*

**1. INTRODUCTION**

Vibration-control structures are employed in many high-rise buildings to preferentially absorb seismic energy in the event of an earthquake and reduce the swaying of the building to minimize the damage to the principal structural members (columns and beams). Common types of seismic damping devices include steel dampers and viscous dampers. In the former type, a low-yield-point steel that has lower strength than the standard architectural steel undergoes elastoplastic deformation. The latter type relies on the viscous resistance of viscous bodies or oil. In high-rise buildings, numerous damping devices are used to ensure the redundancy and robustness of quake-resistance performance; in the design process, it is important to consider the characteristics and optimal locations for each type of damping device.

Recently, the importance of damage-control measures against long-period, long-duration seismic activity in high-rise buildings has been realized. High-rise buildings undergo vibrations of larger amplitude and longer period than shorter buildings because they experience resonance with seismic ground motion with predominantly long-period components. In cases where the durability may be compromised because of metal fatigue, the conventional low-yield-point steel dampers are not suitable for use in maintenance-free countermeasure technologies for long-period, long-duration seismic motion. However, steel dampers are indispensable for economical vibration control structures. Therefore, it is necessary to increase considerably the durability of steel seismic dampers.

From these backgrounds, we used a Fe–15Mn–4Si–10Cr–8Ni damping alloy to fabricate novel fatigue-resistant seismic dampers to counteract long-period ground motion (Sawaguchi et al. 2015). This alloy offers a low-cycle fatigue life that is approximately ten times that of conventional low-yield-point steel, LY225. In this study, we aim to verify the deformation performance and fatigue resistance of this novel seismic damper. Loading tests on shear-panel-type and brace-type seismic dampers were conducted to characterize their fatigue endurance.

**2. FATIGUE RESISTANT FE-MN-SI-BASED ALLOY seismic damper**

***2.1 Shear-panel-type seismic damper***

The Fe–15Mn–4Si–10Cr–8Ni damping alloy used here is described in detail in our previous report (Sawaguchi et al. 2015). Here, we present a shear-panel-type seismic damper made of this damping alloy (Sawaguchi et al. 2016). Figure 1 shows photographs of the developed seismic damper and the alloy panel used as the energy-absorbing member in the damper. The damper exhibits a hysteretic damping effect due to the elastoplastic deformation of the alloy panel. Under a maximum rated deformation angle of 1/25 rad, the damper can bear loads up to approximately 4,000 kN, placing it in the highest class of steel dampers.

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Figure 1. (a) Shear-panel-type Fe–15Mn–4Si–10Cr–8Ni alloy seismic damper and (b) the alloy panel

Figure 2 shows the configuration of the shear-panel-type seismic damper. In order to make the best use of the superior fatigue properties of the alloy, a buckling-stiffening system that does not require welding of the alloy was implemented. In addition, the R-shape of the alloy panel was designed to control the load and reduce the strain concentration on the bolt-joint region.

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Figure 2. Schematic of the buckling-stiffening system of the shear-panel-type seismic damper

***2.2 Brace-type seismic damper***

Recently, it has become possible to produce rolled alloy plates by using continuous casting, which a common industrial method for producing rolled stainless-steel plates. This industrial mass-production technique has made available large rolled plates with excellent dimensional accuracy at a low cost. Large rolled plates of Fe–15Mn–4Si–10Cr–8Ni alloy were used to fabricate the most versatile brace-type seismic dampers.

By using these large rolled plates, we have developed the most versatile brace-type Fe–15Mn–4Si–10Cr–8Ni alloy seismic dampers. Figure 3 shows a photograph of the developed brace-type seismic damper and Figure 4 shows its configuration. This damper was designed with a buckling-restrained brace with an energy-absorbing core plate made of the Fe–15Mn–4Si–10Cr–8Ni alloy with a cross-section of 325 mm (width) by 23 mm (thickness). Rib plates of an ordinary architectural steel (SN490B) were joined with the core plate by welding. High-strength bolts were used for the joints with the steel building frame. Buckling of the seismic damper was restrained by covering the core plate with mortar and steel pipe.

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Figure 3. Brace-type Fe–15Mn–4Si–10Cr–8Ni alloy seismic damper

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Figure 4. Schematic of the buckling-stiffening system of the brace-type seismic damper

**3. LOADING TESTS**

***3.1 Dynamic loading tests of shear-panel-type seismic damper***

Dynamic loading tests were carried out to confirm the deformation performance and fatigue resistance of the developed shear-panel-type Fe–15Mn–4Si–10Cr–8Ni alloy seismic damper. Because of the load limit of the applied-force actuator, the test samples were fabricated such that their shapes were similar to the shape of a seismic damper, but the height, width, and thickness of the movable portion of the alloy panels were scaled to half the actual values. Figure 5 shows the force-application system (a large dynamic actuator with a maximum load capacity of 2,000 kN) and the test sample for the dynamic loading tests. Shear deformation was applied to the test sample by the horizontal displacement of a steel beam. Using this setup, three types of tests were conducted: progressive strain increase and decrease tests (involving three cycles of sinusoidal waves with various amplitudes at a period of 5 s, which is the natural period of the vibration of a typical high-rise steel building), a low-cycle fatigue tests (sinusoidal waves of constant strain amplitude with a period of 5 s applied with a representative share deformation angle of ±1/100, ±1/50, or ±1/25 rad), and random-wave loading tests (random wave of about 300 seconds including many long-period components, mimicking a medium-intensity and very large earthquakes).

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Figure 5. Force-application system and test sample

Figure 6 shows the relationship between the load and deformation angle during the progressive strain increase and decrease test. The relationship between the load and deformation angle was stable over a range of deformation angles, resulting in stable hysteresis loops. No discontinuous load decreases due to buckling or failure were observed during these tests.

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Figure 6. Relationship between the load and rotation angle with

gradually (a) increasing and (b) decreasing displacement

Figure 7 shows the results of the strain-controlled low-cycle fatigue tests demonstrating the fatigue endurance of the seismic damper. The test results show that the proposed damper offers outstanding deformation performance and durability under low-cycle fatigue. Further, it has significantly better fatigue life than conventional steel dampers. Figure 8 shows that the peak load was consistent over all cycles until just before failure. Figure 9 shows the load–deformation angle hysteresis loops at each strain amplitude, each plotted from a different test over roughly half of the fatigue lifetime (*Nf*/2). The developed seismic damper exhibited stable hysteresis loops across a range of strains from small to large.

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Figure 7. Low-cycle fatigue characteristics

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Figure 8. Evolution of the cyclic load with the number of cycles

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Figure 9. Load-deformation angle hysteresis loops of the seismic damper during low-cycle fatigue tests

The random-wave loading tests that simulated long-period and long-duration earthquake waves were performed to examine the seismic response performance the developed seismic dampers. Figure 10 shows a random wave about 300 seconds including many long-period components simulated very rare, very large earthquakes (Level 2). The random-wave loading tests were conducted in the order shown in Table 1; the tests included simulated very rare, very large earthquakes (Level 2) and rare medium-intensity earthquakes with 50% reduced intensity (Level 1).

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Figure 10. Waveform input to the damper (at level 2 wave)

Table 1 Order of the random-wave loading tests

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| **Step** | **Step 1** | **Step 2** | **Step 3** | **Step 4** | **Step 5** | **Step 6** |
| Input wave | Level 1  (50 %) | Level 2  (100 %) | Level 2  (100 %) | Level 1  (50 %) | Level 1  (50 %) | Level 2  (100 %) |

Figure 11 shows the load–deformation angle relationship observed during the first and third random-wave tests mimicking earthquakes of Level 2 and Level 1, respectively. The results show that the seismic dampers exhibit stable energy absorption from small to large deformation angles, even with random wave inputs. In addition, it can be seen that the load- and energy-absorption performance at the third tests (Step 5 and 6) hardly change compared to that of the first tests (Step 1 and 2). These results confirm that the seismic dampers have excellent seismic wave response performance and superior fatigue durability, implying that this damper is a sufficient countermeasure technology for long-period, long-duration earthquakes.

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Figure 11. Load–deformation angle hysteresis loops of the seismic damper during random wave loading tests

Figure 12 shows photographs of the alloy panel after the tests were completed. The alloy panels do not exhibit cracks and significant buckling. This result further demonstrates the excellent effect of the developed buckling-stiffening system and confirms the outstanding deformation performance and outstanding durability of the shear-panel-type Fe–15Mn–4Si–10Cr–8Ni seismic damper.

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Figure 12. Photographs of the alloy panel after all the tests were completed

***3.2.Brace-type seismic damper***

Cyclic loading tests were conducted on the developed brace-type seismic damper to evaluate its deformation performance and fatigue resistance. Figure 13 shows the dimensions of the full-scale test sample. The length of the plastically deformed region of the test sample was 3,000 mm and its cross section was 325 mm in width by 23 mm in thickness. The force-application device was a uniaxial static loading device with a maximum load capacity of 3,000 kN. The loads were measured by the load cell of the device and the displacement was measured by displacement sensors mounted in the longitudinal direction of the samples. In addition, the axial strain of the plasticized region of the test sample was measured by a strain gauge attached to the center of the test sample.

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Figure 13. Dimensions of the full-scale test sample used in the cyclic loading tests

Using this force-application system, cyclic loading tests were performed with a strain amplitude of ±0.5% (±18 mm based on the lengths of the plasticized and elastic regions) according to the loading pattern shown in Figure 14. The cyclic loading tests were conducted up to the fatigue limit (defined at which the cyclic load decreases to 80 % of the maximum load or the sample breaks) or until a maximum of 1,000 cycles (which is about twice the fatigue lifetime of conventional steel seismic dampers). The loading rate was about 1 mm/sec at maximum. To confirm the stability of the load and the usefulness of the buckling-stiffening system, the cyclic loading tests were done with and without eccentricity of about 47 mm (which is 1/150 of the 7,000 mm length of the test sample).

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Figure 14. Loading order for the cyclic loading tests

Figure 15 shows the load–strain relationship obtained as the strain was progressively increased to the target strain amplitude of ±0.5%. The load–strain relationship was stable regardless of the presence of eccentricity. Figure 16 shows the load–strain relationship in cycles 2–10 cycles at a strain amplitude of ±0.5%. No significant changes were observed in the hysteresis characteristics of these cycles.

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Figure 15. Load–strain relationship while progressively increasing the strain to the target amplitude of ±0.5%

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Figure 16. Load–strain relationship during the first 2–10 cycles

Figure 17 shows the evolution of the peak load over progressive cycles for each cyclic loading test. As shown in Figure 17, the peak load hardly changes up to 1,000 cycles regardless of the presence of eccentricity; neither maximum load capacity reduction nor discontinuous load reduction was observed before the number of cycles reached 1,000. These results confirm the stability of the peak load and the superior fatigue durability of the proposed damper. In addition, the damper exhibited sufficient stability against buckling and acceptable joint strength at a strain amplitude of ±0.5%. Finally, upon observing the core plate after the test, no fatigue cracks were observed in the plastic deformation region or the weld tip (i.e., where the strain was concentrated).

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Figure 17. Evolution of the cyclic load with the number of cycles

**4. Conclusions**

Here, we designed fatigue-resistant seismic dampers, including both shear-panel-type and brace-type dampers, that were made of a Fe–15Mn–4Si–10Cr–8Ni damping alloy and designed to counteract long-period ground motion. The outstanding deformation performance and durability under low-cycle fatigue were demonstrated experimentally. The developed fatigue-resistant seismic dampers made of this alloy were installed on steel structure buildings in Japan. Consequently, the dampers made it possible to allow the buildings to withstand long-period, long-duration ground motion and repeated after-quakes.

**5. Acknowledgments**

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