

# Fatigue-Resistant Fe-Mn-Si Alloy Seismic Damper for Long-Period Ground Motion

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## 1. Background and Study Objectives

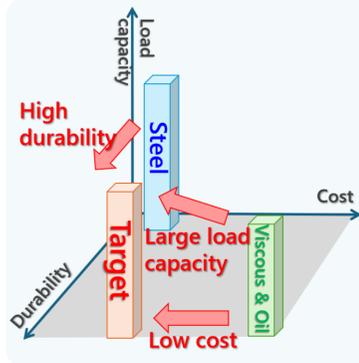
- In recent years, it has become clear that large-scale earthquakes such as the anticipated magnitude 8-9 Nankai Trough megathrust earthquake and the accompanying long-period ground motion have the potential to cause devastating damage to high-rise buildings nationwide in Japan. Due to these concerns, the durability requirements for seismic dampers in high-rise buildings with vibration control structures have dramatically increased.
- Steel dampers, which have been widely adopted as a general-purpose solution due to their high economic efficiency resulting from low cost, high load-bearing capacity, and stiffness, have become limited in application due to concerns about "metal fatigue failure" caused by large-amplitude and high-cycle deformation under such circumstances, leading to a demand for newly developed steel dampers with superior fatigue durability.
- To provide a new steel seismic damper with superior fatigue resistance against large-amplitude cyclic deformation, a new Fe-Mn-Si alloy with enhanced low-cycle fatigue resistance was developed in our work<sup>1)</sup>.

Mechanism	Major countermeasures for long-period seismic motion		
	Steel damper	Viscous damper	Oil damper
Mechanism	elastoplastic deformation of steel	viscous resistance of viscous body	viscous resistance of oil
Energy absorbance	○	◎	◎
Load Capacity	◎	△	△
Stiffness	○	×	×
Stability	○	△ (Temp. Dependency)	○
Cost	◎	△	△
Durability	△ (due to metal fatigue)	○	○

Large and long vibrations cause severe accumulated fatigue damage

Steel dampers are difficult to use against long-period seismic motion

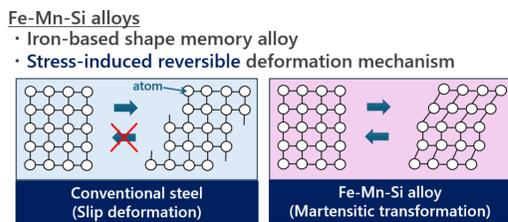
Features and problem of seismic dampers



Development concept of a new steel seismic damper

## 2. Fatigue-resistant Fe-Mn-Si alloy

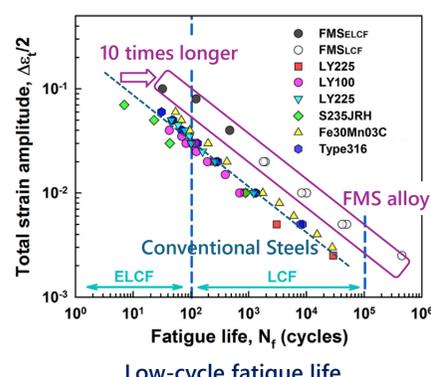
- Fe-Mn-Si alloys are a type of ferrous shape memory alloys that possess a reversible deformation mechanism through stress-induced martensitic transformation and its reverse transformation. In our study, reversible two-way martensitic transformation under cyclic tensile-compressive loading has been shown to improve low-cycle fatigue life<sup>1)</sup>. Based on these findings, a Fe-15Mn-4Si-10Cr-8Ni (wt.%) alloy (hereinafter called "FMS alloy") was developed for use in steel seismic dampers with superior fatigue resistance.
- While the fatigue life of conventional steel under identical strain conditions remains nearly constant regardless of steel grade, the FMS alloy is characterized by approximately 10 times longer low-cycle fatigue life compared to conventional steels under identical strain amplitude conditions<sup>2)</sup>.



Fe-Mn-Si alloys should be excellent in fatigue resistance

Development of a new Fe-Mn-Si alloy optimized for low-cycle fatigue properties and mass productivity

Fe-15Mn-4Si-10Cr-8Ni alloy (FMS alloy)

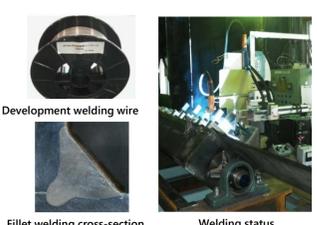


Low-cycle fatigue life

- To utilize the FMS alloy for seismic members, manufacturing technology for high-quality large-scale rolled plates using continuous casting processes, which are industrial manufacturing methods, has been established. Currently, with accumulated manufacturing experience, the alloy has been certified as a designated building material in Japan<sup>3)</sup>. Additionally, welding techniques for the FMS alloy were developed to diversify FMS alloy seismic damper design<sup>4)</sup>.



FMS alloy rolled plate (10,000mmL × 1,600mmW × 22mmT)



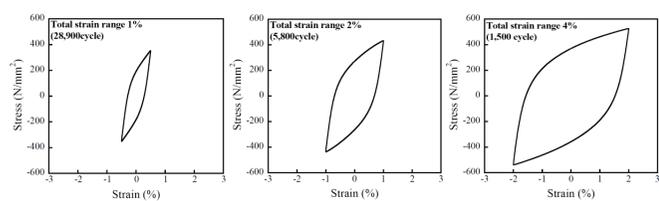
Welding technology for FMS alloy

Mechanical properties of FMS alloy (For example)

Standard <sup>a)</sup>	0.2% proof stress	Tensile Strength	Yield-tensile ratio	Elongation
Type 1A	285 N/mm <sup>2</sup>	661 N/mm <sup>2</sup>	43.1 %	54 %

a) The specimen was fabricated in compliance with JIS Z 2241.

The design allowable strength  $F = 270 \text{ N/mm}^2$  was established considering the scatter range of tensile test results from multiple melting charges for FMS alloy rolled plates.



Stress-strain hysteresis of FMS alloy in fatigue tests

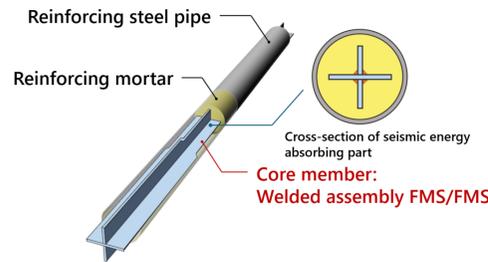
※Each hysteresis loop is plotted over approximately half the fatigue life ( $N_f/2$ )

## 5. Conclusion

- A high-strength type FMS alloy BRB with excellent fatigue durability and load capacity required for super-high-rise buildings was developed as a countermeasure against long-period ground motion.
- The practical applications to the Chunichi Building and The Landmark Nagoya Sakae validated the effectiveness of the developed technology.
- This development expands the application range of FMS alloy dampers, enabling enhanced design flexibility and long-term reliability for vibration control systems in super-high-rise buildings.

## 3. Design and Loading tests

- Previously, shear panel-type dampers and buckling-restrained braces (BRB) with flat plate core members using FMS alloy have been developed and applied to buildings in Japan<sup>5)</sup>.
- Furthermore, to accommodate higher load capacities for super-high-rise buildings and expand design flexibility, a high-strength FMS alloy BRB was developed with a cruciform cross-section core formed by welded assembly. The welding used a specially developed filler wire with superior fatigue durability that can follow FMS alloy deformation, and intermittent MIG welding was adopted to reduce oxides that cause fatigue cracks. The specification also included grinding of weld bead toes.
- This core member was then made into a buckling-restrained member by inserting it into a steel pipe and filling the surrounding space with mortar.



Design specifications

Yield axial force of core member,  $N_y$   
 $N_y = A_c \cdot F = 2,661 \text{ kN}$

$A_c: 2 \times 235 \times 22 - 22^2 = 9,856 \text{ mm}^2$   
 $F: \text{Design standard strength} = 270 \text{ N/mm}^2$

Maximum axial force of core member,  $N_{max}$   
 $N_{max} = A_c \cdot \sigma_{max} = 4,928 \text{ kN}$

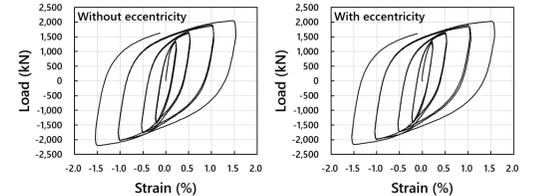
$\sigma_{max}: \text{Maximum stress during fatigue testing at } \pm 1.5\% = 500 \text{ N/mm}^2$

Configuration of the high-strength type FMS alloy BRB

- To understand the deformation characteristics and fatigue performance of the developed brace, structural tests were conducted using FMS alloy BRB specimens.
- Loading steps were performed with gradually increasing loads of  $\pm 0.2 \sim \pm 1.5\%$  and a strain amplitude of  $\pm 1.5\%$  for low-cycle fatigue tests. To confirm buckling stability, the presence or absence of eccentricity was tested as a parameter. The external eccentricity was set to 49 mm, which is 1/100 of the total core member length.
- It was confirmed that regardless of the presence or absence of eccentricity, there was no disturbance in the load-strain loops due to local buckling, and the peak load variation was also stable. The fatigue life exceeded 300 cycles at  $\pm 1.5\%$  strain amplitude, demonstrating sufficient performance for maintenance-free seismic damper use even after multiple large earthquakes.



Structural test status



Load-strain relationship (gradually increasing loads)

Design specifications for specimen

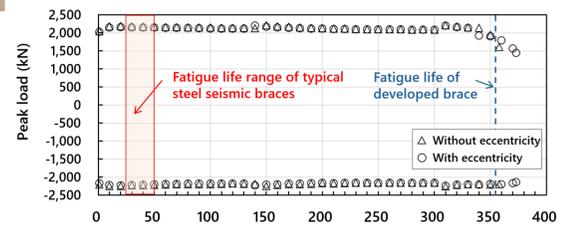
Plastic deformation cross-section reduced to approximately 70% of actual size,  $A_c$

$A_c = 2 \times 170 \times 16 - 16^2 = 5,184 \text{ mm}^2$

Plastic deformation length of Core member,  $L_d$

$L_d = 2,484 \text{ mm}$

, assuming equivalence with the actual brace.



Fatigue life of developed brace ( $\pm 1.5\%$ )

## 4. Applications

- The developed FMS alloy seismic braces have been installed in the Chunichi Building and The Landmark Nagoya Sakae. These super-high-rise buildings are mixed-use complexes with offices, hotels, and retail facilities as landmarks in Sakae, Nagoya-City, Aichi, Japan. The region is predicted to experience major earthquakes of seismic intensity 6-lower or higher, such as the Nankai Trough megathrust earthquake, with the main motion lasting several minutes. Additionally, numerous aftershocks are highly likely to occur following such earthquakes.
- Against this background, vibration control performance in these buildings was required to ensure seismic device performance would not deteriorate under long-period ground motion and multiple large earthquakes, enabling business continuity plans (BCP) after disasters.
- By installing the developed braces on floors with large deformation amounts, structural limitations against repeated deformation were eliminated, improving the design allowable capacity and contributing to BCP enhancement. Additionally, the realization of high-strength type steel dampers with high durability enabled a reduction in the number of control devices installed and was also effective in improving design flexibility.



Developed brace

Chunichi Building  
 Total Floor Area: 117,293.1 m<sup>2</sup>  
 Structural Scale: B5F, 33F, P1F / S, SRC, RC / Height: 158m  
 Design & Construction: Takenaka Corporation  
 Completion: July 2023

The Landmark Nagoya Sakae  
 Total Floor Area: 109,700 m<sup>2</sup>  
 Structural Scale: B4F, 41F, P1F / S, SRC / Height: 211m  
 Design: Mitsubishi Jisho Design Inc., Takenaka Corporation  
 Construction: Takenaka Corporation  
 Completion: March 2026 (schedule)



Chunichi Building



The Landmark Nagoya Sakae

## References

- T. Sawaguchi *et al.*, Designing Fe-Mn-Si alloys with improved low-cycle fatigue lives, *Scripta Materialia*, 99, pp.49-52, 2015.
- I. Nikulin *et al.*, Effect of strain amplitude on the low-cycle fatigue behavior of a new Fe-15Mn-10Cr-8Ni-4Si seismic damping alloy, *International Journal of Fatigue*, 88, pp. 132-141, 2016.
- Y. Chiba *et al.*, Development of manufacturing technology for Fe-Mn-Si alloys with excellent low-cycle fatigue properties and application to seismic dampers for buildings, *Materials Transactions*, 65, pp. 1583-1587, 2024.
- T. Nakamura and T. Sawaguchi, Tensile and low-cycle fatigue properties of weld metal using fatigue-resistance Fe-Mn-Si-based alloy, *Journal of Structural Engineering*, 67B, pp.633-641, 2021. (In Japanese)
- Y. Inoue *et al.*, Fatigue-resistant Fe-Mn-Si-based alloy seismic dampers to counteract long-period ground motion, *Japan Architectural Review*, 4, pp.76-87, 2021.