

# Development of Manufacturing Technology for Fe-Mn-Si Alloys with Excellent Low-Cycle Fatigue Properties and Application to Seismic Dampers for Buildings\*<sup>1</sup>

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The Fe-15Mn-10Cr-8Ni-4Si alloy, which has excellent low-cycle fatigue durability, was developed as a core material for steel-based vibration dampers that are effective against large-amplitude, long-period earthquake motions, and was put into practical use in 2014. However, manufacturing using small-scale equipment was expensive, so the authors tried manufacturing using stainless steel continuous casting facility and rolling facility, and succeeded in mass production. The authors also developed welding materials and welding techniques to assemble a buckling restraint brace damper with flat plasticizing section and one with cruciform plasticizing section, and successfully put these two types of brace dampers into practical use. The alloy plate has been recognized as an industrial product that can be manufactured with stable quality, and has been approved by the Minister of Land, Infrastructure, Transport and Tourism as a steel material for construction.

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## 1. Background and Development History

Needless to say, earthquake preparedness is important in Japan, a country with frequent earthquakes. As seismic countermeasures for buildings, seismic dampers that suppress damage to main structures by intensively undergoing deformation during earthquakes, especially steel system seismic dampers are often used from the viewpoint of cost, load capacity and productivity. In the Great East Japan Earthquake of 2011, long-period ground motions continued in skyscrapers in the Tokyo metropolitan area far from the epicenter, and in the Kumamoto Earthquake of 2016, aftershocks of the same seismic intensity occurred the day after the earthquake of seismic intensity 7. Therefore, the demand for steel dampers with excellent durability against repeated elastoplastic deformation has increased.

The authors developed Fe-15 Mn-10 Cr-8 Ni-4 Si alloy (mass%, thereafter FMS alloy), which drastically increased the low-cycle fatigue life by more than 10 times than conventional steels, by utilizing the reversible transformation of deformation-induced martensite in Fe-Mn-Si system shape memory alloys [1]. In 2014, shear panel steel dampers without welding structure using FMS alloy melted and rolled in a special steel manufacturing facility were applied to JP Tower Nagoya [2]. However, this facility had a small melting volume of 10 tons, and it was difficult to manufacture wide rolled plates. Therefore, it was necessary to establish a

manufacturing system using a continuous casting facility for stainless steels and a plate manufacturing facility as a manufacturing method capable of mass-producing wider rolled plates. In addition, in order to manufacture the most general buckling restraint brace damper whose plasticized cross section is flat or cruciform as a vibration control device, it was essential to develop welding materials and welding technology that enable welding between FMS alloy plates and ordinary architectural steel plates, and welding between FMS alloy plates to each other. It was also essential to obtain the approval by Minister of Land, Infrastructure, Transport and Tourism (standard strength is 270 N/mm<sup>2</sup>) for the rolled plates of the alloy in order to popularize it in the field of construction.

## 2. Production of FMS Alloy Rolled Plates from Continuous Casting

The FMS alloy has a high Cr content of 10 mass%, which is close to that of stainless steel. However, there was no steel type that contains a large amount of Mn and Si at the same time. Therefore, the strength and ductility of FMS alloy after melting and solidification were examined in order to judge the feasibility of continuous casting. As a result, it was determined that it could sufficiently withstand pullout during casting, so it was melted and cast in a 60-ton stainless steel continuous casting facility, and rolled plates of 8 to 34 mm in thickness × 1400 to 1600 mm in width × 6 to 10 m in length were successfully manufactured within the plate thickness standards of JIS G 4304 (Fig. 1, Fig. 2). Table 1 shows examples of the mechanical properties of typical rolled

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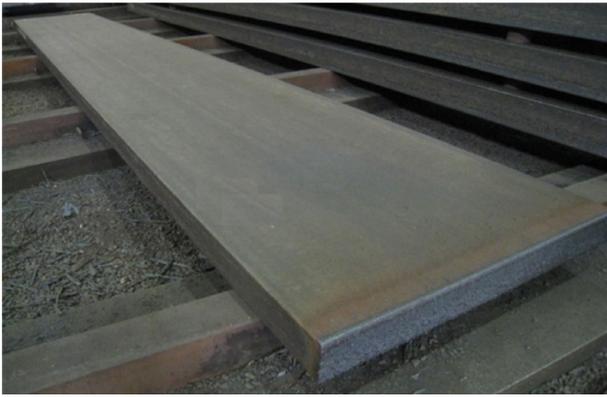


Fig. 1 A FMS alloy continuous casting slab with 140 mm in thickness, about 1300 mm in width, about 10 m in length.

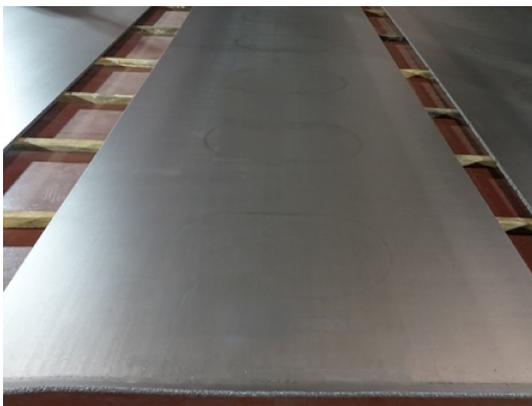


Fig. 2 A FMS alloy rolled plate with 22 mm in thickness, about 1600 mm in width, about 10 m in length.

plates, Charpy absorbed energies and low cycle fatigue lives with a strain amplitude of  $\pm 1.0\%$  [3].

The low cycle fatigue lives of 13 rolled plates of FMS alloy prepared by this method at the strain amplitude  $\pm 1.0\%$  were 10,730 to 17,711 cycles (average 13,556 cycles), which are equivalent to the fatigue lives of the same alloy prepared by a small amount of melting (several 10 kg).

Low cycle fatigue tests were carried out on 23 mm thick rolled plates manufactured at the same facility with strain values of  $\pm 0.5$  to  $\pm 5.0\%$ .

On the high-strain side ( $\pm 2.0$  to  $\pm 5.0\%$ ), the radial strain control was performed using an hourglass-shaped specimen to prevent the specimen from buckling, and on the low-strain

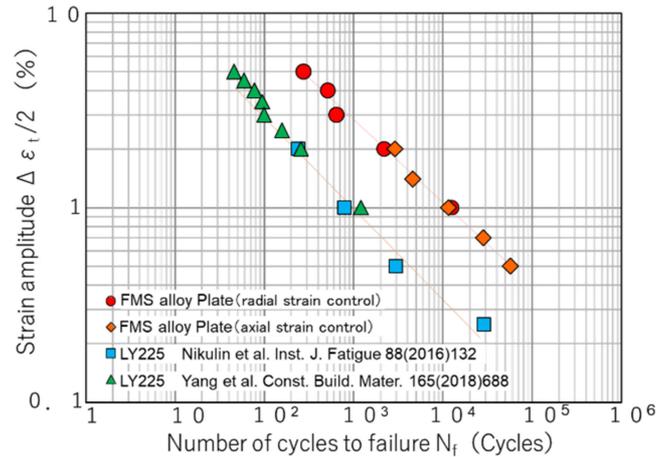


Fig. 3 Low cycle fatigue lives of FMS alloy plates in comparison with those of LY225 steel.

side ( $\pm 0.5$  to  $\pm 2.0\%$ ), the axial strain control was performed using a round bar specimen.

When the horizontal axis is the strain amplitude  $\Delta\epsilon_t/2$  and the vertical axis is the life  $N_f$ , a straight line is plotted on a double-logarithmic graph, and Manson-Coffin's law holds for both conventional LY225 (low yield point steel) and FMS alloys. FMS alloys have approximately 10 times longer fatigue lives than LY225 steels up to a high strain of  $\pm 5.0\%$  (Fig. 3).

As for the mechanical properties, as a result of the investigation of 59 rolled plates manufactured so far, it was confirmed that the average value of 0.2% proof stress in the rolling direction is 286 MPa, and that each data is normally distributed in the range of approximately  $\pm 3\sigma$  within the standard value, and that it is possible to manufacture rolled plates with stable mechanical properties, and to manufacture products of stable quality as industrial products necessary for the Minister of Land, Infrastructure, Transport and Tourism's certification as designated building materials. Similar results were obtained for tensile strength and Charpy absorption energy.

### 3. Development of Welding Technology and Production of Dampers

Buckling restraint brace dampers, which are most commonly used as vibration control devices, have flat or cruciform plasticizing section. The respective design

Table 1 Mechanical properties and fatigue lives of FMS alloy plates produced from stainless steel continuous casting process.

Thickness	Standard <sup>a</sup>	0.2% proof stress	Tensile strength	Elongation	Charpy absorbed energy(0°C)	Fatigue life (strain amplitude $\pm 1.0\%$ )
8 mm	Type 5	295 N/mm <sup>2</sup>	655 N/mm <sup>2</sup>	67 %	143 J <sup>b</sup>	13,780 cycles
12 mm	Type 5	284 N/mm <sup>2</sup>	671 N/mm <sup>2</sup>	66 %	354 J	13,344 cycles
16 mm	Type 5	283 N/mm <sup>2</sup>	678 N/mm <sup>2</sup>	67 %	386 J	14,230 cycles
23 mm	Type 1A	285 N/mm <sup>2</sup>	661 N/mm <sup>2</sup>	54 %	371 J	12,556 cycles
28 mm	Type 1A	290 N/mm <sup>2</sup>	673 N/mm <sup>2</sup>	60 %	354 J	12,039 cycles
34 mm	Type 1A	289 N/mm <sup>2</sup>	652 N/mm <sup>2</sup>	58 %	347 J	11,670 cycles

<sup>a</sup> The specimens were fabricated in compliance with JIS Z 2241

<sup>b</sup> Using subsize specimen

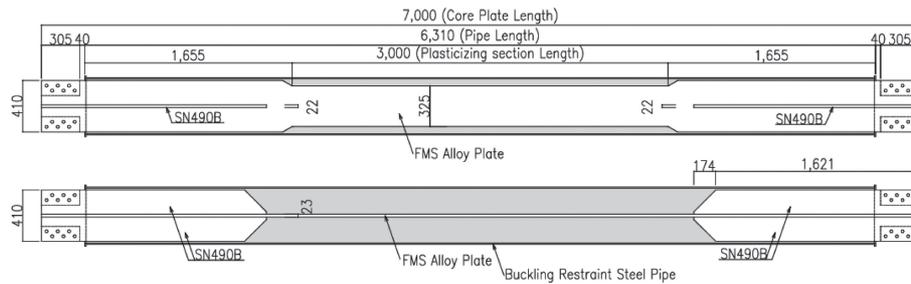


Fig. 4 A design example of FMS alloy flat plasticizing section brace damper [4].

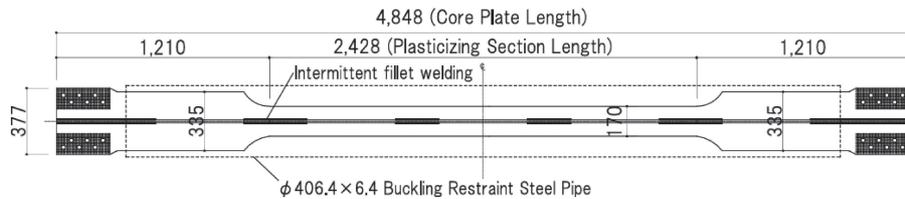


Fig. 5 A design example of FMS alloy cruciform plasticizing section brace damper [5].

drawings are shown in Fig. 4 [4] and Fig. 5 [5]. In both braces, the core plate consists of a plasticizing section (center parallel section) and joint sections (widening sections) at both ends. In the case of a flat plasticizing section brace, ribs of structural steel plates (SN 490 B) are fillet welded to the joints. On the other hand, in a cruciform plasticizing section brace, it is necessary to fillet weld core plates (FMS alloy) to each other, and since the fatigue durability of the plasticizing section is required similar to that of the core plate, the fatigue durability of the welded part is required similar to that of the FMS alloy.

The authors developed welding materials and welding technology suitable for welding between the FMS alloy and the ordinary architectural steel, and welding between FMS alloys to each other [6]. The former is required to be strong as a joint, the latter is required to follow plastic deformation, and both are required to prevent high-temperature cracking of the weld metal. The former is a weld material with a component such that the solidification mode of the weld metal is the FA mode in which the primary ferrite crystallizes, the austenite crystallizes in the eutectic reaction, and the solidification is completed in the two phases of ferrite and austenite. As for the latter, while solidifying in the A mode, high-temperature cracking was successfully suppressed by optimizing the welding conditions, and it became possible to manufacture the core member of damper shown in Fig. 6 (flat plasticizing section) and Fig. 7 (cruciform plasticizing section), respectively.

#### 4. Loading Test of Actual-Scale Brace Damper

The cyclic loading test of the flat plasticizing section brace damper shown in Fig. 4 was carried out using a uniaxial loading device with a maximum load capacity of 3000 kN at a strain amplitude of  $\pm 0.5\%$ , and the fatigue durability was confirmed. The test was carried out at a maximum loading rate of about 1 mm/sec with an upper limit of 1000 cycles, which is about twice the fatigue life of conventional steel brace. As shown in Fig. 8, the change of the maximum load

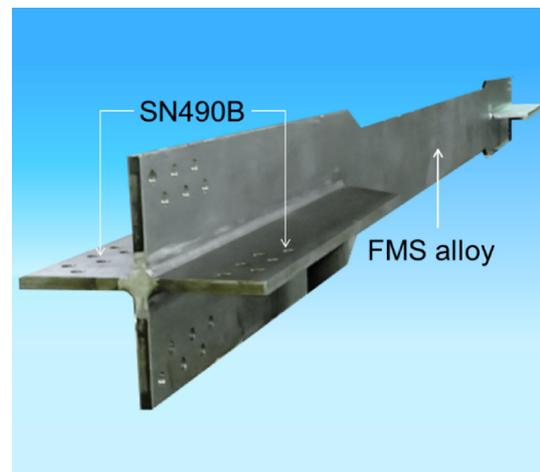


Fig. 6 A Core member of a flat plasticizing section brace damper.

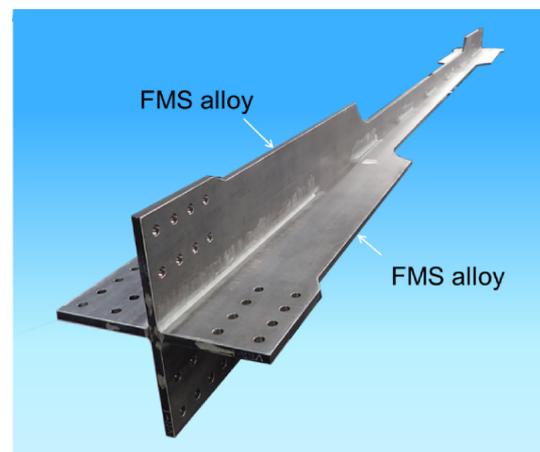


Fig. 7 A Core member of cruciform plasticizing section brace damper.

due to the repetition of the flat plasticizing section brace damper is very gradual and has hardly changed up to 1000 cycles, and it is confirmed that it has excellent durability and stability of the generated load [4, 7].

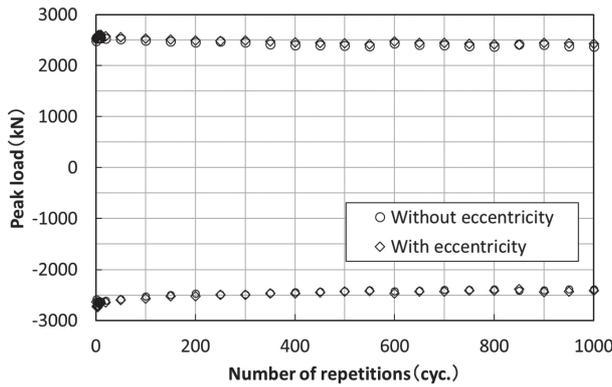


Fig. 8 Change of the maximum load due to the repetition of the flat plasticizing section brace damper at a strain amplitude of  $\pm 0.5\%$  (The test was completed after 1000 cycles) [4].

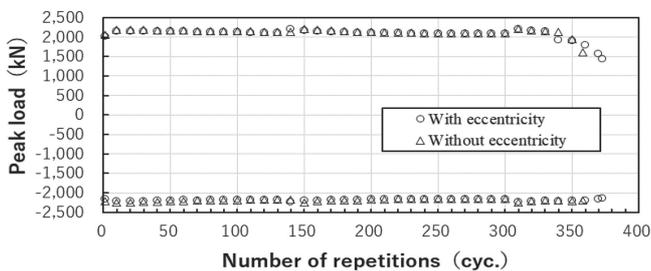


Fig. 9 Change of the maximum load due to the repetition of the cruciform plasticizing section brace damper at a strain amplitude of  $\pm 1.5\%$  [5].

Next, a low cycle fatigue test of the cruciform plasticizing section brace damper shown in Fig. 5 at a strain amplitude of  $\pm 1.5\%$  was carried out using the same machine as above. The change in the maximum load due to the repetition is shown in Fig. 9, and the fatigue life was 356 cycles (the number of cycles when the load decreased to 80% of the maximum load), which was more than 7 times the average value of the conventional steel brace.

## 5. Application Status

16 flat plasticizing section brace FMS alloy dampers (core length approx. 6 m) with joints welded to structural steel were mounted at the Aichi International Exhibition Center, completed in 2019 (Fig. 10) [8], and 32 cruciform plasticizing section brace dampers (core length 5~6 m) with FMS alloys welded to each other were mounted at the Chunichi Building, completed in 2023 (Fig. 11). In the latter case, the maximum applied load was increased due to the increase in the cross-sectional area, which contributed to the reduction in the number of installations compared with the conventional steel dampers [9].

## 6. Material Approval, Patents, and New Developments

In recent years, due to the increase in the number of applications and the increase in the production results of continuous casting, the authors applied for general material certification of this alloy, and in November 2022, the Minister of Land, Infrastructure, Transport and Tourism approved it as a building material designated under Article 37 (ii) of the



Fig. 10 Flat plasticizing section FMS alloy brace dampers mounted at the Aichi International Exhibition Center.



Fig. 11 Cruciform plasticizing section FMS alloy brace dampers mounted at the Chunichi Building.

Building Standards Act (MSTL-0584, Reference value  $270 \text{ N/mm}^2$ ). As for the patents of this alloy, Japanese No. 6182725 and 6887642, European EP 2940175 and Korea 10-2144708 have been registered. For lens dampers<sup>®</sup> using this alloy, Japan ERI Co., Ltd. issued a structural performance evaluation report (ERI-K 21006) [10], and in addition, various types of vibration control dampers such as Hourglass-shaped damper [11], H-section buckling restrained brace [12], and U-shaped damper [13] have been actively developed.

## 7. Summary, Future Prospects

In order to popularize FMS alloys, which have a remarkable low cycle fatigue life of 10 times that of conventional materials, as seismic dampers for long-period ground motions and large earthquakes, the authors established mass-production manufacturing technology for the plates, welding technology with ordinary architectural steel, and welding technology between FMS alloys, and obtained the approval by Minister of Land, Infrastructure, Transport and Tourism for the plates. As a result, construction companies and designers can select various types of seismic dampers such as shear panel type and brace type using FMS alloy. In the future, it is expected that not only large brace

dampers for skyscrapers, but also panel dampers for mid- and low-rise buildings, condominiums, and general housing will be widely used. Moreover, it is expected that they will be used for civil engineering, bridges, and other industries.

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