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# BENDING TEST OF A SHAPE MEMORY ALLOY BAR AND ITS SEISMIC APPLICATIONS[1]

## PRÓBA ZGINANIA PRĘTA Z PAMIĘCI KSZTAŁTU I JEGO ZASTOSOWANIA SEJSMICZNE

The goal of this study is to perform several bending tests on a shape memory alloy bar and to analyze the characteristics of the bending behavior. Single and double bending tests were conducted with varying loading speeds and maximum displacement. The loading and the unloading stiffness were estimated from the force-displacement curves and the equivalent damping ratio of each test was also assessed. The stress-induced-martensite hardening was observed from the SMA bar's bending behavior, however, the strength increment due to high loading speed appeared in tension was not observed in bending. This study introduced several seismic applications of SMA bending and showed their practicality. The significance of this study is to provide basic knowledge of SMA bending.
*Keywords*: shape memory alloy, bending, restrainer, loading stiffness, recentering

Celem badań było przeprowadzenie prób zginania pręta wykazującego efekt pamięci kształtu i analiza procesu zginania. Jednostronne i dwustronne próby przeprowadzono zmieniając szybkość obciążenia i maksimum odkształcenia. Obciążenie i odciążenie oceniano z wykresu siła-odkształcenie, a odpowiedni stopień tłumienia był każdorazowo określony. Tworzenie martenzytu odkształcenia obserwowano przy próbie zginania pręta, jakkolwiek jego przyrost obserwowany przy dużych szybkościach wzrostu naprężenia podczas rozciągania powodował umocnienie, którego nie obserwowano przy zginaniu. W niniejszych badaniach wykazano kilka sejsmicznych zastosowań stopów z pamięcią kształtu i wykazano praktyczność takich zastosowań. Ponadto badania te rozszerzyły wiedzę na temat zginania stopów z pamięcią kształtu.

## 1. Introduction

Shape memory alloys (SMA) show unique mechanical behaviors, such as shape memory effect and superelastic effect, and, thus, have potential for use in engineering application. One of the most fervently researched topics related to SMA, in civil engineering, is the seismic retrofit of bridges and buildings. The seismic applications of SMA for bridges are concentrated on dampers or restrainers; the shape memory effect is good for seismic dampers to dissipate seismic energy and the superelastic effect which allows large deformations to recover without residual deformation, is valuable for restrainers. In those applications, SMAs are activated in tension, compression, or both. Therefore, experimental tests on SMAs usually consist of tensile or compressive tests to support their applications.

Grasser and Cozzarelli [1991] developed a one-dimensional constitutive model to describe the force-deformation behavior of Nitinol (Ni-Ti alloy) SMA varied due to loading frequency and verified the model with experimental work. Dolce et al. [2000] developed a seismic damper for civil structures using SMA wires. The basic concept of their damper is the combination of martensite SMA wires for energy dissipation and austenite wires for recentering, and the effectiveness of the device was proved through experimental works. DesRoches and Delemont [2002] used SMA bars as restrainers instead of steel cable in bridges. They

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showed that the SMA bars are more effective to restrain relative deck displacement than the conventional steel cable restrainers. Wilde et al. [2000] also used SMA bars combining with elastomeric bearings for bridges. The SMA system was verified as an effective device to control relative deck displacement.

The above studies of seismic dampers or restrainers using SMA wires or bars were based on the tension or compression or both behavior. However, the bending of SMA bars may be more effectively used as dampers or restrainers in several cases. For example, Ocel et al. [2004] used the bending of SMA bars to dissipate seismic energy on the connection of beam-column in a steel frame. Also, Adachi and his colleagues [2000] attached an SMA plate as a damper or a restrainer to improve seismic bridge response. Ocel and Adachi used the bending behavior of SMA bars or plates. However, they did not show the mechanical bending behavior of the bars or plates.

Therefore, the understanding of the bending behavior of SMA bars was not addressed in their studies. This study performed single and double bending test of an SMA bar and discussed the mechanical bending behavior of the bar. This study suggests a basic understanding of SMA bars in bending and illustrated how to apply bending behavior in seismic applications.

## 2. Bending test of SMA bar

The 25.4 mm diameter Nitinol shape memory alloy rod shown in Figure 1 was tested. The bar had a length of 152 mm and was 25% cold-worked. The specimen was threaded at the ends and vacuum annealed at 450°C for 60 minutes, followed by water quenching. The composition of the alloy is 55.97% of Ni and 44.02% of Ti with weight ratio. The transformation temperature of $A_s$ is -11°C and, thus, it remains austenite state at room temperature.

To conduct a bending test of a bar, a force at the top of a bar should be applied perpendicularly to the bar and the bottom of the bar is fixed. The top of the bar where a force is applied should have special boundary conditions for single and double bending; 1) lateral movement and rotation are permitted for a single bending and 2) lateral movement is permitted but restrained is the rotation of the top for a double bending. For this purpose, a specially manufactured ball, piston, and cylinder, which are shown in Figure 2, were used. Figure 3 shows the combined shape of the SMA bar and the ball or piston. In the combination of the ball and the cylinder in Figure 3(a), the ball permits the rotation of the SMA bar while the cylinder is moving laterally and, thus, it permits a single bending on an SMA bar. In the same manner, in the docking of the piston and the cylinder in Figure 3(b), the piston restrains the rotation at the bottom of an SMA bar even with lateral movement and, thus, it allows double bending on the SMA bar. In bending tests, two circular plates were located between the top and the bottom plate of the test machine to prevent the contact of the ball or the piston to the cylinder. This set-up confirms that there is not any compressive force on the SMA bar during its bending. Figure 3(c) and 3(d) show the whole set-up and the bended shape of an SMA bar in single and double bending test. In the bending tests, the displacement-control was performed. In the single bending test, the maximum displacements were varied form ±10 mm to ±40 mm with increasing ±5 mm. In all tests, 3 cycle loadings were applied.

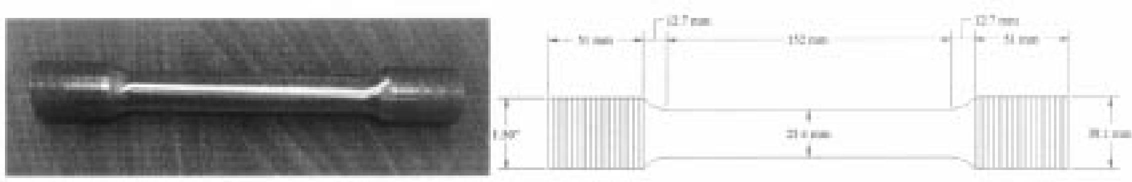
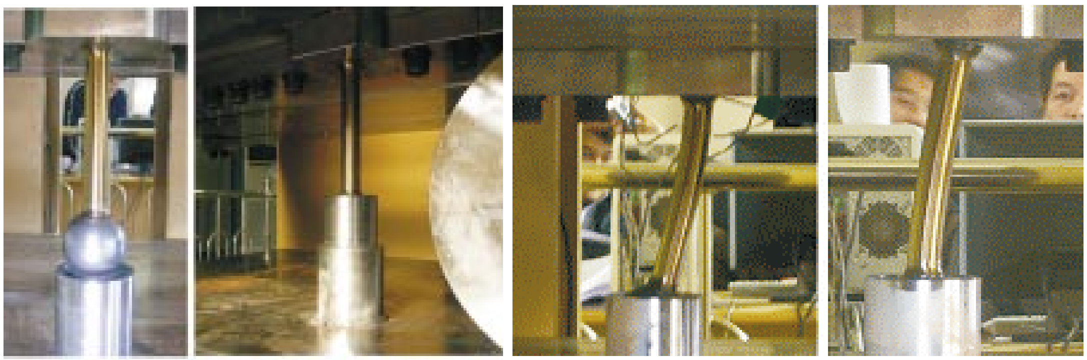


Fig. 1. Superelastic SMA bar (Right: Photo, Left: Schematic)

At the displacement of 40 mm, the tensile strain of the SMA bar at the fixed point was calculated as 6% over which the bar could be damaged. Therefore, the maximum displacement did not exceed the 40 mm. The loading speeds were 0.025 Hz for quasi-static loading and 0.5 Hz for dynamic loading. Since DesRoches [2004] mentioned the strength hardening of an SMA bar in tension due to the loading speed this study checked

Fig. 2. A ball, a piston and a cylinder to realize boundary conditions



(a) (b) (c) (d)

Fig. 3. Test set-up and bending shape of an SMA bar; (a) Docking of the ball to the cylinder for a single bending, (b) docking of the piston to the cylinder for a double bending, (c) SMA bar's single bended shape, and (d) a double bended shape

weather this phenomenon happens in bending of SMA bars. In double bending tests, the maximum displacements are varied from ±5 mm to ±20 mm with increasing ±5 mm.

The machine used for these tests has the capacity of 20,000 kN in horizontal and ±1500 kN in vertical direction. The maximum strokes are ±250 mm in horizontal and 200 mm in vertical direction. The maximum loading speed is 130 mm/sec.

### 3. Results and discussion

The test results are shown in Figures 4-6. From the hysteretic curves, the loading and the unloading stiffness and the equivalent damping ratio are estimated. In each figure, the loading stiffness and the equivalent damping ratio are shown up.

In the single bending tests, the loading stiffness was close to the unloading one. The dynamic test results were similar to the quasi-static results. The strength increment appeared in a tensile test of an SMA bar with a dynamic loading that was not observed in the bending test (D e s R o c h e s et al., [2004]). Heat of transformation is not released from samples because of a high strain rate, and thus samples are deformed adiabatically, which raises the temperature of samples. The stress for inducing martensitic transformation increases with increasing temperature. Therefore, the flow stress increases with increasing strain rate. In a tensile test, the tensile stress was developed uniformly for the whole SMA bar. Thus, a large area can be exposed to a high stress. However, in the bending test, the developed high tensile stress was concentrated on the small area at the fixed point of the SMA bar. Since the phenomenon appeared in a small area in a bending test, the strength-increment effect was negligible.

In Figure 4(f), the stiffness increment at the displacement of 32 mm in loading curve is observed, whose reason is not clear from the test. Further study is required to seek for the reason. However, the bar's stiffer behavior can be helpful to improve seismic response of bridges with using the bar as a restrainer.

The estimated loading and unloading stiffness and equivalent damping ratios are arranged in Table 1 and 2 for the single bending tests. The average loading and unloading stiffness are 0.223 kN/mm and 0.212 kN/mm. The unloading stiffness was similar to the loading stiffness to 25 mm; however, the unloading stiffness was less than the loading ones after the displacement of 30 mm. This is assumed to be caused by SIM hardening at the fixed point of the specimen. The average damping ratio is 6.7% that is larger 67% than that in tension.

In the single bending tests with dynamic loadings, the average loading and unloading stiffness are 0.208 kN/mm and 0.207 kN/mm, and the average damping ratio is 6.69%. Although the loading stiffness with dynamic loadings is less than that of the quasi-static loadings, the general trend of the double bending behavior is similar to the single bending.

TABLE 1
Loading and unloading stiffness and equivalent damping ratio of the single bending tests with quasi-static loadings

| Max. displacement (mm) | Loading stiffness (kN/mm) | Unloading stiffness (kN/mm) | Damping ratio (%) | Residual deformation (mm) |
|---|---|---|---|---|
| 10 | 0.246 | 0.255 | 5.98 | 1.755 |
| 15 | 0.234 | 0.238 | 5.82 | 2.808 |
| 20 | 0.227 | 0.233 | 6.43 | 4.388 |
| 25 | 0.221 | 0.231 | 6.82 | 5.867 |
| 30 | 0.217 | 0.173 | 7.56 | 8.249 |
| 35 | 0.210 | 0.168 | 7.26 | 10.61 |
| 40 | 0.207 | 0.137 | 7.06 | 12.79 |
| **Average** | **0.223** | **0.212** | **6.70** | |

The double bending test results are listed in Table 3. The average loading and unloading stiffness are 1.104 kN/mm and 1.263 kN/mm that are approximately 5 times larger than those from the single bending.

TABLE 2
Loading and unloading stiffness and equivalent damping ratio of the single bending test with dynamic loadings

| Max. displacement (mm) | Loading stiffness (kN/mm) | Unloading stiffness (kN/mm) | Damping ratio (%) | Residual deformation (mm) |
|---|---|---|---|---|
| 10 | 0.209 | 0.279 | 5.37 | 2.006 |
| 20 | 0.202 | 0.220 | 7.10 | 4.889 |
| 30 | 0.196 | 0.189 | 7.67 | 8.425 |
| 40 | 0.223 | 0.138 | 6.64 | 12.787 |
| **Average** | **0.208** | **0.207** | **6.69** | |

TABLE 3
Loading and unloading stiffness and equivalent damping ratio of the double bending test with quasi-static loadings

| Max. displacement (mm) | Loading stiffness (kN/mm) | Unloading stiffness (kN/mm) | Damping ratio (%) | Residual deformation (mm) |
|---|---|---|---|---|
| 10 | 1.327 | 1.459 | 4.53 | 1.038 |
| 20 | 1.161 | 1.343 | 6.03 | 2.501 |
| 30 | 1.036 | 1.167 | 8.30 | 4.599 |
| 40 | 0.893 | 1.083 | 8.77 | 6.367 |
| **Average** | **1.104** | **1.263** | **6.91** | |

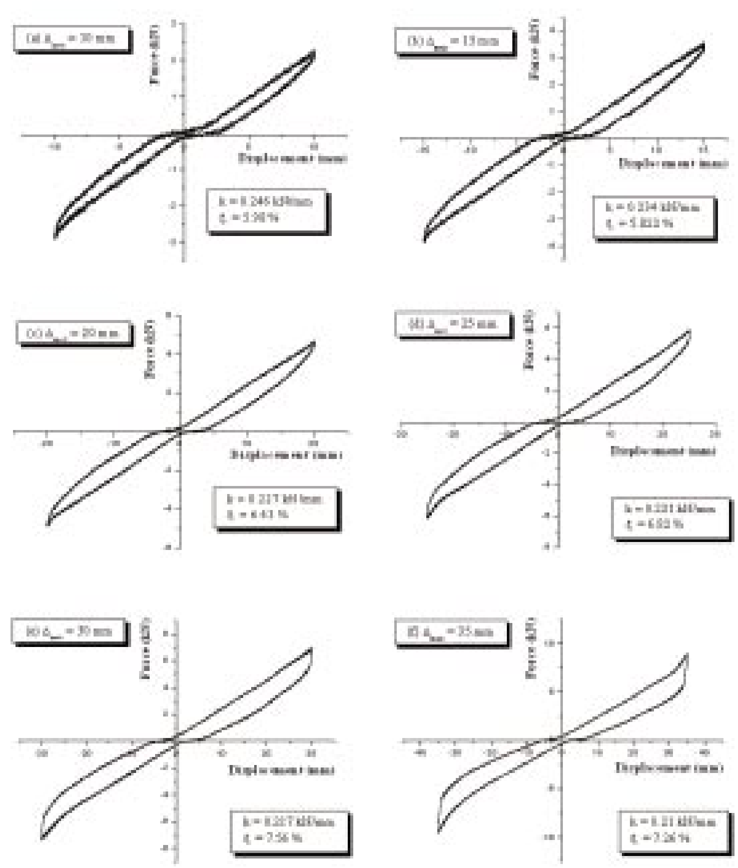


Fig. 4. Force-displacement curves of the single bending with a quasi-static loading (loading speed = 0.025 Hz)

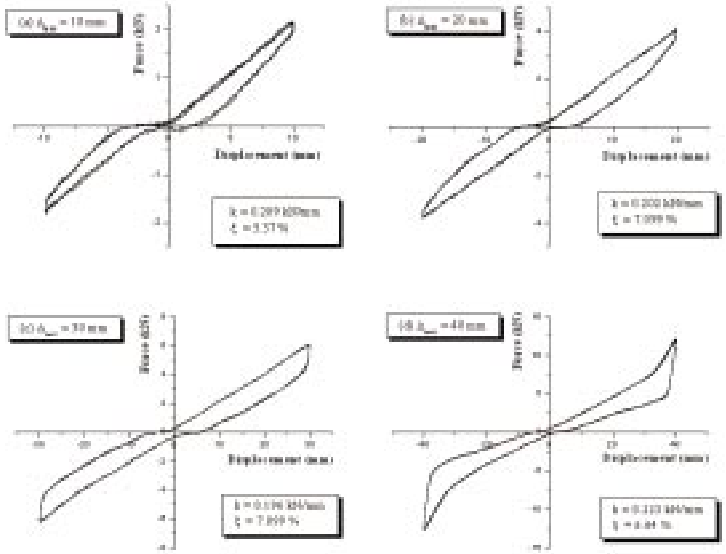


Fig. 5. Force-displacement curves of the single bending with a dynamic loading (loading speed = 0.5 Hz)

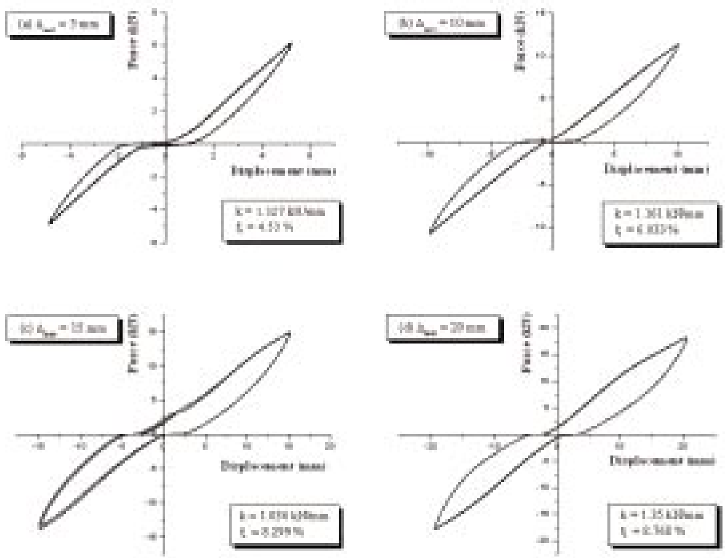


Fig. 6. Force-displacement curves of the double bending with a quasi-static loading (loading speed = 0.025 Hz)

The average damping ratio is 6.91% which is close to that of the single bending. In the single bending, the loading and the unloading stiffness are similar before the SIM hardening is developed. However, in double bending, the unloading stiffness is larger from 9% to 17% than the loading stiffness.

The residual deformations after the bending increase with increasing the displacement; which means that the recentering capability decreased with large bending displacement. The residual deformations of the double bending are larger than those of the single bending since the developed strains of the double bending are larger than those of the single bending.

## 4. Seismic applications of SMA bending

Use of SMA in bending appears to have many benefits that could be applied to their use as seismic mitigation devices. The recentering capability and increased damping could all improve the response of bridges in earthquakes. In use of SMA bars in tension, compression, or both, a connection would have to be designed that would allow an SMA bar to be used in tension and compression without buckling, and which would still allow thermal movement of the bridge. However, such a connection is not easy to be realized. For example, Wilde's study requires 2 m long SMA bar in tension and compression to mitigate the seismic response of a bridge in transverse direction (W i l d e et al., [2000]). Therefore, any device is necessary to prevent the bar's buckling.

When the bending of SMA bars is used in seismic applications, the bars are located perpendicular to the developed inertial force due to an earthquake in bridges. This makes their installation easier. With a lock-up device, the thermal expansion of bridges can be absorbed easily shown in Figure 7; the device could be a damper or seismic restrainer during an earthquake. Also, SMA bars can be used in an elastomeric or frictional bearing to increase recentering capability and damping to compensate the week points of conventional elastomeric or frictional bearings. An elastomeric bearing has relatively small damping and a frictional bearing does not any recentering capability. The SMA bars in bridge bearings also can provide the resistance to up-lifting force.

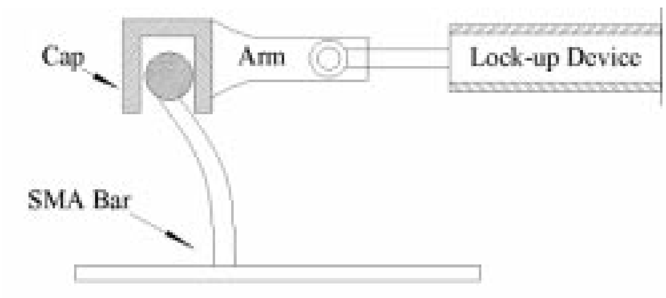



Fig. 7. Combination of a lock-up device and an SMA bar

## 5. Conclusions

This study conducted several bending tests of an superelastic SMA bar and discussed the results of single and double bending with varying loading speed and maximum displacement. From the force-displacement curves of the single bending, the loading and the unloading stiffness were estimated and they showed similar values. The equivalent damping ratio is 6.7% averagely which is larger 67% than that in tension. Thus, it can say that the bending has more energy dissipation capacity. The loading speed can not change the single bending behavior of the specimen significantly different from the tensile behavior. The loading stiffness of the double bending is approximately 5 times larger than that of the single bending. Thus, the double bending is more applicable to restrain seismic displacement of bridges, however, it has smaller moving tolerance comparing to the single bending. The SIM hardening was also observed in bending as the same as in tension. The stiffness increment due to SIM hardening probably would be helpful to prevent unseating of bridge decks.

As W i l d e mentioned in his study, a long SMA bar in tension and compression needs some additional method to install stably and prevent buckling. The application of SMA bending is more practical and easily combined with other devices.

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