Pseudo-dynamic Tests on Pseudo-Elastic Bracing System made of Shape Memory Alloy

by

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Introduction

A research program is ongoing on a possible application of auto-adaptive media to make a structural system more smart/intelligent [1]. Many researchers are studying on possibilities of various kinds of new media, new material, and new devices. Among them, this paper deals with shape memory alloy. This alloy exhibits different properties depending on temperature, such as 1) shape memory effect, 2) pseudo-elasticity, and 3) these transitional state. While this kind of alloy has been already used in many aspects in everyday life, only few practical applications are found in structural system itself. As a first step to assess the applicability of this kind of alloy in a structural system, a tension bar made of this kind of alloy that exhibits pseudo-elasticity at room temperature is used herein as a passive bracing system.

Because of lack of practice, a constitutive modeling of this alloy suitable for structural analysis is not yet established. In such a situation, pseudo-dynamic testing technique is useful to study the non-linear behavior during earthquakes, because this technique does not require a mathematical constitutive modeling of structural element. Considering the present cost performance of this alloy, very limited amount may be used in a structural system so far. That means most portions of the whole structural system must be made of ordinary construction materials, such as steel or concrete, the behaviors of which have been well known. From these reasons, this paper applies a sub-structure pseudo-dynamic test technique to a hybrid model of structure, where only an element made of this alloy is chosen as a specimen and the remaining portions are fictitious or only exist in computer memory.

Preliminary Cyclic Loading Tests on Pseudo-elastic Tension Bars

The material used is a Ni-Ti-Co alloy. The mechanical properties of this kind of alloy depend on its chemical composition as well as production process. Table 1 shows the chemical composition of the alloy studied here. At a low temperature, the alloy consists of Martensite phase and exhibits shape memory effect, while it consists of Austenite phase and exhibits pseudo-elasticity at high temperature. At the intermediate temperature, each phase gradually transits to the other phase. An appropriate thermo-mechanical control production process, that is, forming and heat treatment conditions can control such a transition temperature. The heat treatment adopted here is 425°C for one hour followed by annealing and cold forming. A manner of cold forming is characterized by a reduction ratio of cross-sectional area, and it is taken 20% herein. As found in the following test results, the alloy produced exhibits stable pseudo-elasticity at the test temperature, 10 through 15°C during the tests.

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Originally 17mm diameter bars were mechanically shaped to 10mm diameter at body portions with the length of 100mm and screw-threaded portions with 31mm length were formed at both ends as shown in Figure 1. The loading test setup is shown in Figure 2. A loading column with pinned foot was installed on a steel base block, and an electro-hydraulic actuator supported by a reaction wall was connected at the loading column top. The tension bar specimen was installed at the half height of the loading column. During the following cyclic loading tests, one specimen was installed at one side of the loading column, while two specimens were inserted at both sides for a pseudo-dynamic test described in the next section. Each specimen was screwed into two interface blocks with pinned connections.

Quasi-static monotonic and cyclic loading tests and a dynamic cyclic loading test were performed. Actuator head speed was kept constant during each test, 0.002m/sec for quasi-static test and 0.1m/sec for dynamic test. As for cyclic loading program, gradually increased amplitude levels (0.004m, 0.08m, 0.012m, 0.016m, 0.02m at the actuator head) and two cycle reversals for each amplitude level were applied. Monitored signals were load and stroke read from the sensors installed in the actuator, two displacements read from two additional sensors installed at each specimen (*X1* for pin-to-pin distance and *X2* for tip distance of body portion), and two axial strains of body portion.

Monotonic loading test result is shown in Figure 3 as axial restoring force versus axial deformation measured from tip distance of body portion (*X2*). Softening/yielding occurred at the deformation of about 1.1% of body portion length, and strain hardening began at about 5% strain. At about 11% strain, the specimen was suddenly broken in a brittle manner at the both side tips of body portion. Quasi-static cyclic loading test result is shown in Figure 4. The specimen was easily buckled between the pins when compressed, and then axial deformation measured from the pin-to-pin distance sensor (*X1*) is shown in Figure 4. Even an initial buckling resistance was found so small, and almost no post-buckling resistance was observed. The maximum tensile strain applied was almost the same with the strain level at strain-hardening initiation in the monotonic curve, that was, about 5% strain. Even after such a large strain level was experienced, the pin-to-pin distance came back to the original length when unloaded. As for the dynamic loading case with a constant actuator head speed of 0.1m/sec, load signal processed by 10Hz low-pass filter is shown in Figure 5(b) to eliminate high-cycle noise due to unfavorable oscillation of test setup itself as shown in Figure 5(a). Axial strain rate attained was as high as 0.5/sec, but no serious change was observed about basic restoring force characteristics.

Substructure Pseudo-dynamic Tests on Pseudo-elastic Bracing System

As shown in the cyclic loading test results, the specimen bar has almost no compressive axial resistance, and then a pair of bars should be used as a resisting system to alternative lateral loading. This section deals with a diagonal bracing system of pseudo-elastic tension bars combined with the other earthquake-resisting element such as a hysteretic damper. A hybrid structural model assumed in the following substructure pseudo-dynamic test is illustrated in Figure 6. Fictitious floor is supported by a fictitious pinned mechanism, and a pair of real specimen bars is installed with 45° angle from the horizontal axis as an earthquake-resisting element. Additionally, a fictitious hysteretic damper is also installed. Fictitious inertial mass concentrated at the floor level is denoted by m, and the lateral drift of floor is denoted by x. Lateral resistance carried by the bracing system is denoted by F_S, and the fictitious damper resistance is denoted by F_D. In the pseudo-dynamic test procedure herein, the following equation of motion is solved: $m\ddot{x} + F(x) = -m\ddot{y}$

where $F(x) = F_D + F_S$: hybrid restoring force, *m*: fictitious inertial mass floor, and $\ddot{y}$: ground acceleration

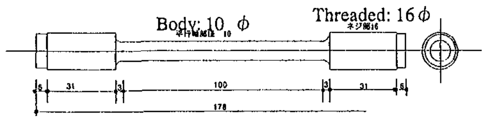


Figure 1 Specimen bar

Table 1: Chemical Composition

Metal element	Chemical Composition (% in weight)
Ni	54.66
Ti	Balance
Co	1.48

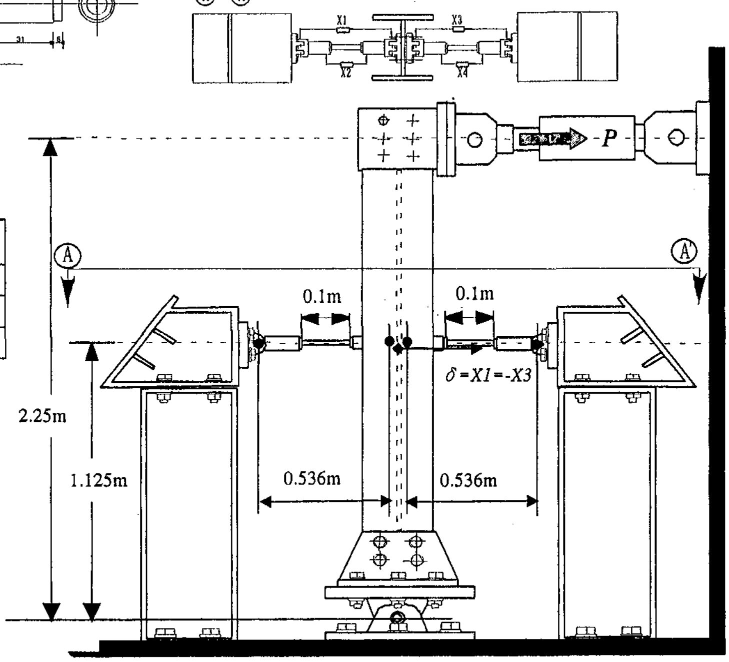


Figure 2 Loading test setup

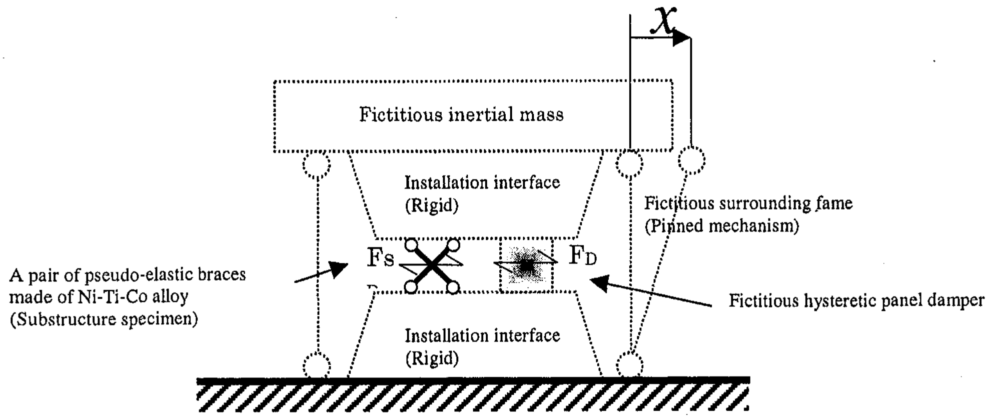


Figure 6: Hybrid model for substructure pseudo-dynamic test

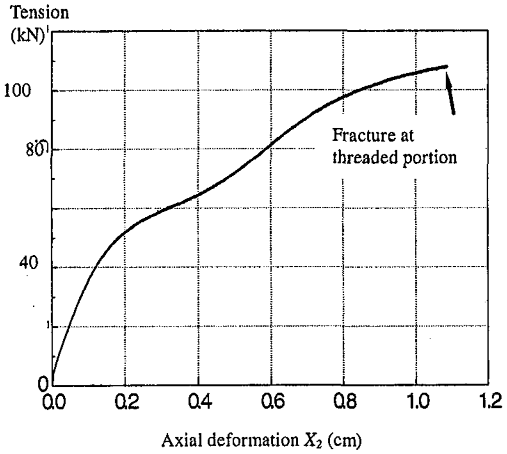


Figure 3: Monotonic loading test result

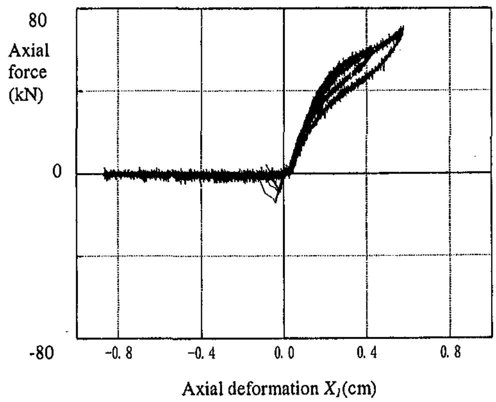
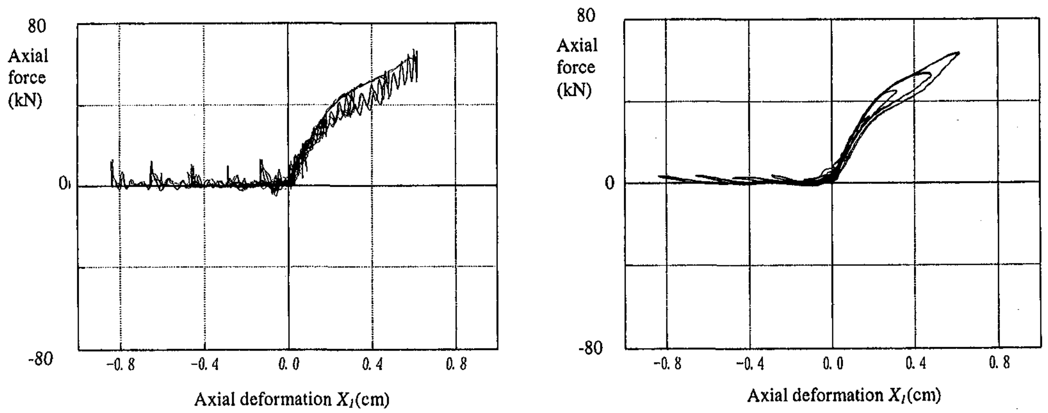


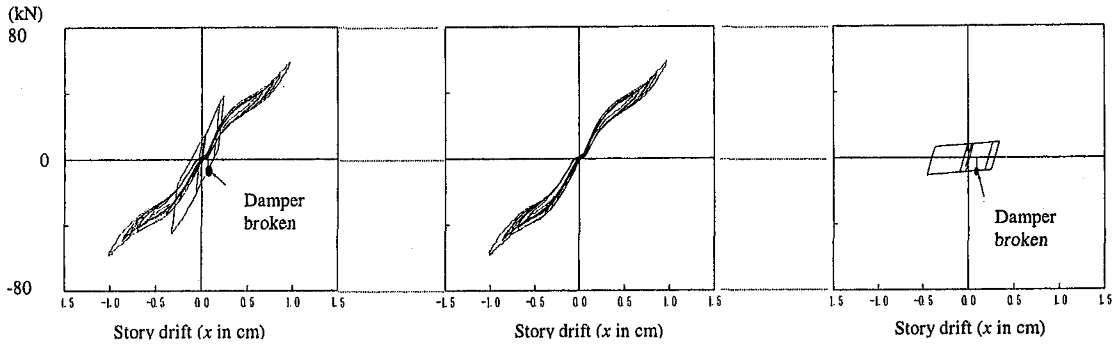
Figure 4: Cyclic loading test result (Quasi-static)



(a) Raw data including high-cycle noise

(b) 10 Hz low-pass filtered data

Figure 5: Cyclic loading test result (Dynamic, strain rate: 0.5/sec)



(a) The whole story shear

(b) Contribution of pseudo-elastic braces

(c) Contribution of a damper

Figure 7: Pseudo-dynamic test result (Hysteresis loop, combined system-P1)

The following formulas are used according to the geometry of test setup:

$$F_S = 2P/\sqrt{2}, \quad x = \sqrt{2}\,\delta$$

where P : Load measured by the load cell of actuator

δ : Lateral displacement at the specimen level, which is regarded identical to the displacement on the pin-to-pin distance of body portion ($X1 \fallingdotseq -X3$) and controlled by the actuator during pseudo-dynamic test

All the pseudo-dynamic tests were performed on the hybrid structural system mentioned above subjected to the ground acceleration record of El Centro NS, 1940, the PGA of which was scaled to 0.5m/sec^2 considering the specimen resistance level. In the simulation of a bracing system combined with a damper (P1), the fictitious damper was assumed to follow a normal bi-linear model until it lost its resistance due to a certain reason, e.g. interface/connection failure, and such a failure was assumed to occur at the time 2.5 sec. For the comparison, a pseudo-dynamic test was performed on another structural system that had only a pair of specimen braces to resist earthquakes (P2). The latter system (P2) is identical to the system where a fictitious hysteretic damper is removed from the former system (P1). Basic parameters on the hybrid models tested are summarized in Table 2.

The test results are shown in Figures 7 and 8 for the combined case (P1), and Figures 9 and 10 for the case of bracing system only (P2), respectively. Even after the braking of damper in the combined case, the pseudo-elastic bracing system worked well as back-up/fail-safe system and the whole system survived after all. On the other hand, the brace-only system experienced a large displacement because of lower stiffness and lack of energy dissipation within small amplitude levels. And finally after 2 seconds from the start of ground motion, the brace was broken in a brittle manner at its screw-threaded portion, and the test was terminated.

Table 2: Summary of Pseudo-dynamic Test Parameters

Test parameters \ Test cases	P1 Bracing plus damper	P2 Bracing only
Pseudo-elastic bracing system (specimen) • Linear-elastic lateral stiffness • Softening (yield) lateral resistance	A pair of Ni-Ti-Co Alloy tension bars 15400 kN/m (tension-side only) 31 kN	
Hysteretic Damper (fictitious) • Initial lateral stiffness • Yield lateral resistance	Normal bi-linear model (broken at time 2.5 sec) 39200 kN/m 12 kN	None
Fictitious inertial mass	70,000 kg	
Fictitious viscous damping	None	
Natural period (in linear-elastic range)	0.22 sec	0.42 sec
Yield or softening shear coefficient	0.024 (damper yield) 0.062(brace softening)	0.045
Input ground motion • Scaled PGA • Duration	El Centro N-S, 1940 0.5 m/sec^2 10 sec	

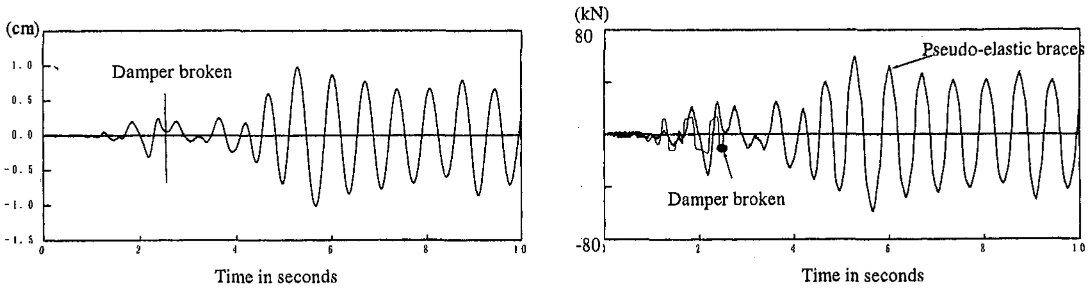
Numerical Simulation on Related Situations

The following related situations were analyzed by completely numerical simulation:

(A) A system consists of a hysteretic damper only, which is not broken.

(B) A system consists of a hysteretic damper only, which is broken at the time 2.5 sec

(C) A system consists of a hysteretic damper and linear-elastic bracing system, which has the same initial stiffness with the pseudo-elastic bracing system tested.



(a) Time history of story drift (cm)   (b) Time history of restoring force (kN)

Figure 8: Pseudo-dynamic test result (Time histories, combined system-P1)

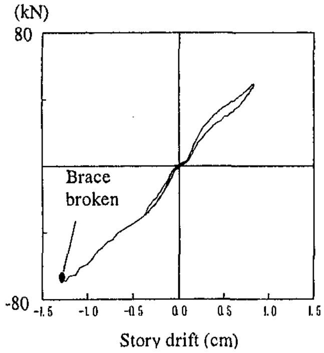
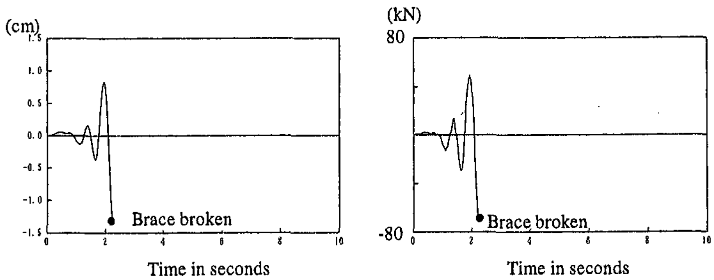
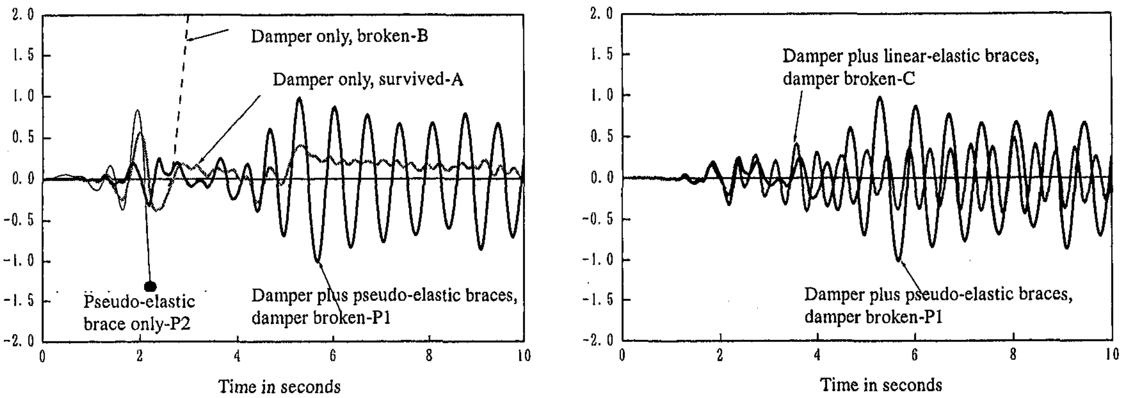


Figure 9: Hysteresis loop (Brace-only system-P2)



(a) Time history of story drift (cm)   (b) Time history of restoring force (kN)

Figure 10: Time histories (Brace-only system-P2)



(a) Sole versus combined   (b) Pseudo-elastic versus linear-elastic

Figure 11: Comparison with numerically simulated responses in other related situations

Time histories of response displacement of the situations (A) and (B) are shown in Figure 11(a) together with the test cases. A damper-only system remained within small displacement level (A) so far as it was not broken during the earthquake. But once it was broken due to an accidental reason, the structural system was driven to the final collapse (B). When a pseudo-elastic bracing system was added, it worked well as back-up/fail-safe system, and the system survived even after an accidental failure of damper (P1). As for permanent set/residual displacement after earthquake, some amount of permanent set was inevitable for a damper-only system (A), while the pseudo-elastic bracing system had no permanent set, as shown in the test case (P1), also resulted from the disappearance of hysteretic damper in this case. When a damper survives with the pseudo-elastic bracing system, the system will return also to the original position by uninstalling the damaged damper. The situation (C) is compared with the test case (P1) in Figure 11(b). Completely linear-elastic bracing system behaved also well as a back-up system, and the response displacement was even smaller than that in the pseudo-elastic case (P1). This means that the energy dissipation of specimen brace is not sufficient so far to compensate the effect of softening in pseudo-elastic range. Further efforts in the production process may be needed to obtain an optimal amount of energy dissipation in pseudo-elastic range.

Concluding Remarks

A Ni-Ti-Co alloy exhibits shape memory effect, pseudo-elasticity, and these transition properties depending on the temperature when used. This paper examined a first-step application of such an alloy to an earthquake resistant structural system by making and testing a pseudo-elastic bracing system. Substructure pseudo-dynamic tests were performed to examine the behavior of pseudo-elastic bracing system during an earthquake when combined with fictitious hysteretic dampers.

(1) Cyclic loading test shows that a pseudo-elastic brace can return to the original length even after subjected to 5% strain reversals, and also a certain amount of hysteretic energy dissipation is expected for the strain range grater than 1%. Such a property is unable to be attained by a single member made of ordinary steel.
(2) A pseudo-elastic bracing system is better to be used with other hysteretic elements such as a hysteretic damper. A damper provides energy dissipation within small displacement levels, and a pseudo-elastic bracing system works in turn as a back-up/fail-safe system when an accidental failure of damper or damper interface occurs, and also it helps to pull back the structure to the original position by uninstalling the damper after earthquake.

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References

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