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JSSI MANUAL FOR BUILDING PASSIVE CONTROL TECHNOLOGY PART-6 DESIGN OF STEEL DAMPER

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SUMMARY

In Japan, various types of steel damper, which are applied hysteretic energy absorption of steel, have been developed and used in passively controlled buildings. The steel dampers have been the most popular devices to control the seismic response of passively controlled buildings. This paper introduces the outline of design of steel dampers in the JSSI Manual for Building Passive Control Technology, which is compiled by the Response Control Committee of Japan Society of Seismic Isolation.
Following items of the manual are brought up.

(a) Principles of steel damper:
Mechanism, Variation of steel dampers / Characteristics of low-yield-point steels
(b) Dynamic characteristics of steel damper:
Fundamental characteristics in hysteresis / Dependency on frequency or displacement
(c) Performance tests and evaluation:
Inspection of the products / Performance tests for steel damper and evaluations

INTRODUCTION

Hysteretic energy absorption of beam or column members, which are composed of conventional steel, has been applied to safety limit of earthquake-proof design for steel building structures in Japan. Influenced by this design method, various types of steel dampers have been developed and applied in passively controlled buildings. The steel dampers have been the most popular devices to control the seismic response of passively controlled buildings. Recently, special steels for the steel damper, named low-yield-point steel have been developed and used for the steel damper. The low-yield-point steels which yield strength (YS) are 100 N/mm^2 (named LY100) or 225 N/mm^2 (LY225) have very narrow yield strength range (YS +/- 20 N/mm^2), and large elongation (LY100: 50% over, LY225: 40% over). This paper reports about the following items that constitute a part of the "JSSI Manual for Building Passive Control Technology" which is compiled by the Japan Society of Seismic Isolation: (a) Principles of damper:

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mechanism, variation. (b) Dynamic characteristics: fundamental characteristics in hysteresis, frequency or displacement dependency. (c) Performance tests and evaluation.

PRINCIPLE AND COMPOSITION OF STEEL DAMPER

The fundamental principle, mechanism and installing condition of steel damper shall be shown for the selection of the most applicable damper in the design of passively controlled structure.

Principle of steel damper

Steel dampers are consisted of steel as damping materials to absorb vibration energy by their plastic deformation. Hysteretic energy absorption of conventional steel members has been applied to safety limit of earthquake-proof design for steel building structures. Influenced by this design method, various types of steel dampers have been developed and applied for passively controlled building structures. Considering low or high cycle fatigue of steel material, the steel damper are applied mainly to absorb energy of seismic response vibration. For the usages as the damping material, the steel materials have to be furnished narrow dispersion of yield strength and large elongation capacity. Recently, special steels for the steel damper, named low-yield-point steel have been developed in Japan. The low-yield-point steels which yield strength (YS) are 100 N/mm^2 (named LY100) or 225 N/mm^2 (LY225) have very narrow yield strength range (YS +/- 20 N/mm^2), and large elongation (LY100: 50% over, LY225: 40% over). Figure 1 shows stress-strain relationship of low-yield-point steel compared with 400N/mm^2 class popular mild steel: JIS-SS400. LY100 shows no yield point. Thus, yield strength is defined by 0.2% offset strength. LY225 shows rather longer yield point elongation than mild steel. And both steel shows larger elongation than mild steel. Mechanism to yield steels as damping material can be classified to several deformation modes, which are axial, shear, bending or twisting. Since axial or shear type enables to consist larger capacity dampers, these types are rather popular as commercial products in Japan.

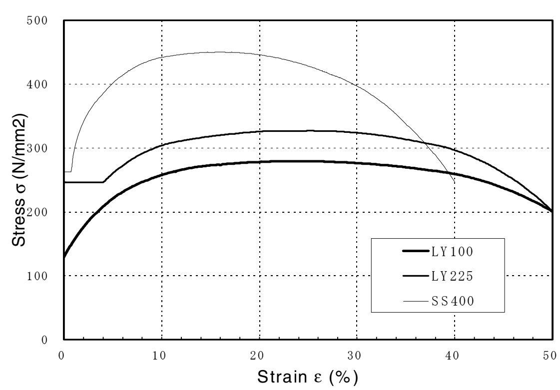


Figure 1: Stress-Strain Relationship of Low-Yield-Point Steel

Variation of steel damper

Figure 2 shows the variation of the steel dampers, which are widely supplied and used in Japan. Hatching zone of the figures shows the material for damping. Recently axial and shear types of the steel damper are more popular than other types.

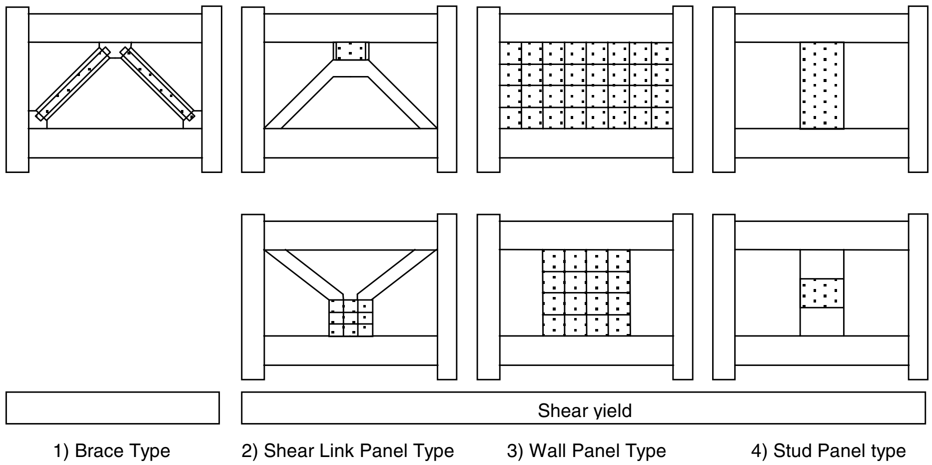


Figure 2: Variation of the steel damper

DYNAMIC CHARACTERISTICS OF THE STEEL DAMPER

The basic dynamic characteristics of the steel damper must be confirmed under the applicable conditions in advance by conducting the experiments, and the steel damper must be used within the verified conditions.

Basic properties

Figure 3 shows the example of the representative relationship between the load (stress) and displacement (strain) of the steel damper, which is made by LY100, under the static and progressive alternate loading. Even in the relationship between the load and displacement at the framework member, the basic characteristics of the damper steel under the static loading can be seen; After the elastic deformation, the LY100 damper starts yielding without showing any yield point, and as the strain amplitude increases, the maximum resisting force increases due to the strain hardening.

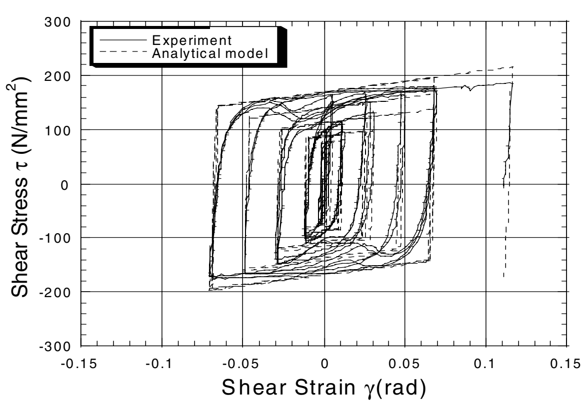


Figure 3: Examples of Hysteretic Behavior of Steel Damper
(Panel Type: LY100)

When the accumulated plastic deformation increases, the local buckling of the damper steel due to the residual strain causes the slip type hysteresis. The timing and the degree of this slip phenomenon vary depending on the local buckling stiffeners provided. Once the local buckling occurs, the resisting force of that portion rapidly drops and the low cycle fatigue damage is accumulated at and around the portion where the local buckling occurred. Therefore, generally the steel damper is used in the region that shows the spindle-shaped relationship between the load and displacement.
Generally, in the structural analysis of the vibration response analysis, etc., the relationship between the load and displacement of the steel damper is modeled following the hysteretic models of the conventional steel members and is used as the energy equivalent deformation dependent multi-linear (bi-linear or tri-linear) hysteretic model. The basic damping properties of the steel damper can be expressed by modeling the relationship between the load and displacement under the specified conditions such as static into the bi-linear model, and can be used as the reference values shown in Table 1 and Fig. 4.

Table-1: Performance Standard of Steel Damper

	Reference value
1	Elastic stiffness: K_d
2	Yield strength: F_y
3	Secondary stiffness: ${}_pK_d$
4	Maximum yield strength: F_{max}

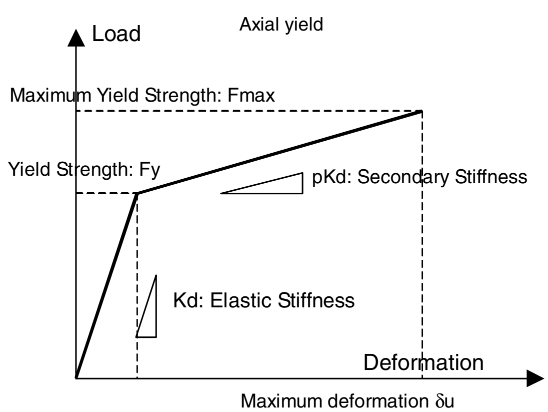


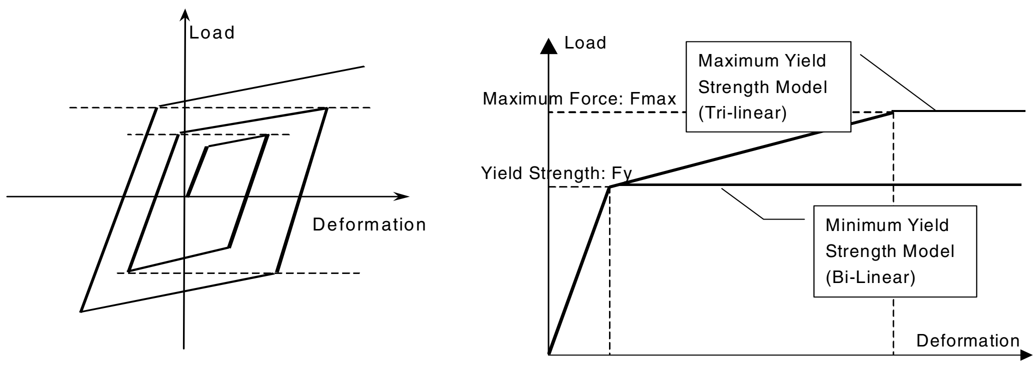
Figure 4: Performance Standard of Steel Damper

Similar to the characteristics generally found in the steel materials, these basic characteristic values of the steel damper change due to the velocity (strain speed) dependency or the displacement amplitude dependency. Therefore, in the hysteretic model used for the design of structure, the various kinds of analytical methods taking into account these changes in the characteristic values are proposed. The examples of the representative models being used include the following:

(a) An analytical method expressing the increase of the yield strength and the maximum yield strength of the hysteretic model by means of the strain dependent functional compensation or the equilateral hardening rule. (Fig. 5 a)
(b) A analytical method in which the increases of the yield strength and the maximum yield strength are regarded as the dispersion of the hysteretic property, and the two types of hysteretic models are

used; i.e., the bi-linear model covering the minimum yield strength and the tri-linear model representing the maximum yield strength taking into account the strain hardening by strain speed or displacement amplitude dependency. (Fig. 5 b)

Besides the above, the Ramberg-Osgood model or other modeling methods are also proposed, in order to give the detailed description of the curvilinear relationship between the load and displacement near the yield strength of LY100, as can be seen in Fig. 1, and the yield point disappearance phenomena (Bauschinger effect) of post yield steels. Depending on the installation method of the steel damper to the main structure, the additional bending stress or axial stress occurs due to the deformation of the main structure, which may have a large effect on the basic properties. Therefore, for those dampers, it is desirable to confirm their basic properties by conducting the experiments with due consideration for these effects, such as the frame experiments. In addition, depending on the type or arrangement of the steel damper, the additional load such as the long sustained load may be applied to the damper. On such occasion, it is anticipated that the damping performance may deteriorate due to the occurrence of the entire buckling of the stiffener.



(a) Equilateral Hardening Model (b) Analysis Using Two Models

Figure 5: Examples of Hysteresis Model

Therefore, the effects of the additional axial stress on the damping performance have been confirmed by experiments conducted using the panel type dampers, and in many cases, the load such as the long sustained loading is permitted as the continuously added load. However, except for the case in which the effects of these additional loads have been confirmed, care must be exercised on the additional loads such as the long sustained loading; for example, the timing of full tightening of the steel damper should be staggered from that of the main structural frame.

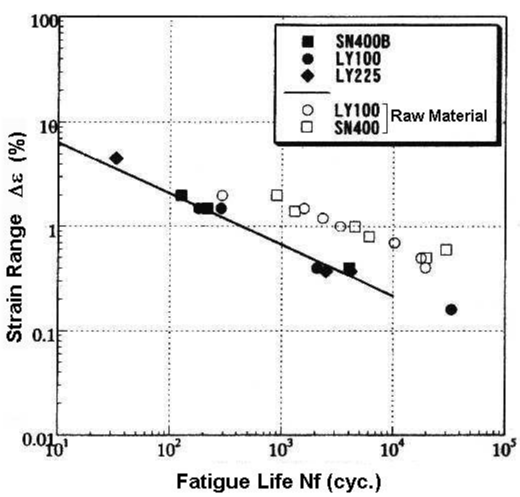
Performance at ultimate stage

As shown in Table 2, the performance of the steel damper at the ultimate stage can be classified into the item concerning the deformation ability under the unidirectional displacement such as the breakage or buckling of the steel, mutual interference of the component parts, etc. and the item concerning the deformation ability under the repetitive displacement related to the accumulation of the fatigue damages.

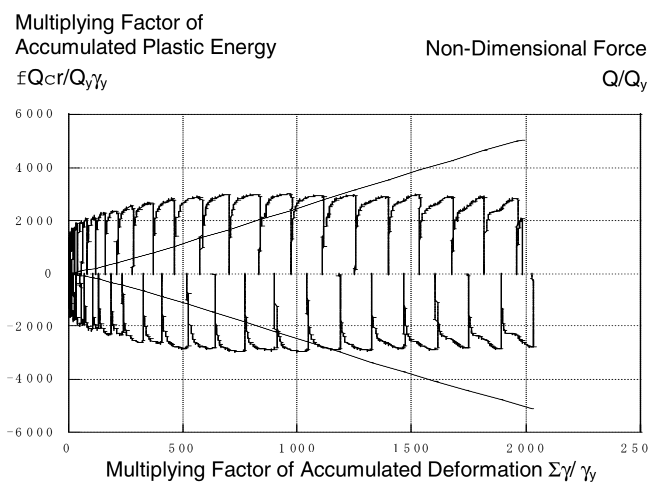
Among others, the deformation ability at the ultimate stage under the unidirectional displacement is important in order to clarify the minimum energy absorption performance under the ultimate deformation stage. And, the critical deformation that the steel damper can absorb the energy by the plastic deformation is made clear through the experiments, etc. As the methods for evaluating the critical deformation ability under the repetitive displacement, the following two types have been used: An evaluation method using the limit of the accumulated value of the multiplying factor of the plastic deformation or the multiplying factor of the plastic energy, and an evaluation method using the low cycle fatigue characteristics. In the design stage, the vibration whose repetitive cycle involving the plastic deformation is small such as earthquakes is often evaluated using the accumulated plastic value (multiplying factor) and, therefore, conventionally the criticality evaluation using the accumulated value has been widely carried out. In the recent years, however, the low cycle fatigue characteristics has come to be used widely for the evaluation under the repetitive displacement, because it is possible to obtain the accumulated value limit under the various amplitudes using the fatigue characteristics easily and because this method can be applied widely, since the vibrations of higher repetitive cycles such as wind can be reviewed. Figure 6 (a) shows the example of the fatigue characteristics for the total strain amplitude Δε (= maximum strain – minimum strain). The fatigue characteristics at the material level are also shown. Figure 6 (b) shows the examples of the multiplying factor of the accumulated plastic deformation.

Table-2: Performance Standard of Steel Damper at Ultimate Stage

	Classification	Reference value
1	Deformation ability under the unidirectional displacement	Maximum deformation
2	Deformation ability under the repetitive displacement	Multiplying factor of the accumulated plastic deformation, multiplying factor of the accumulated plastic energy or the fatigue characteristics



(a) Example of the fatigue characteristics of the brace type damper



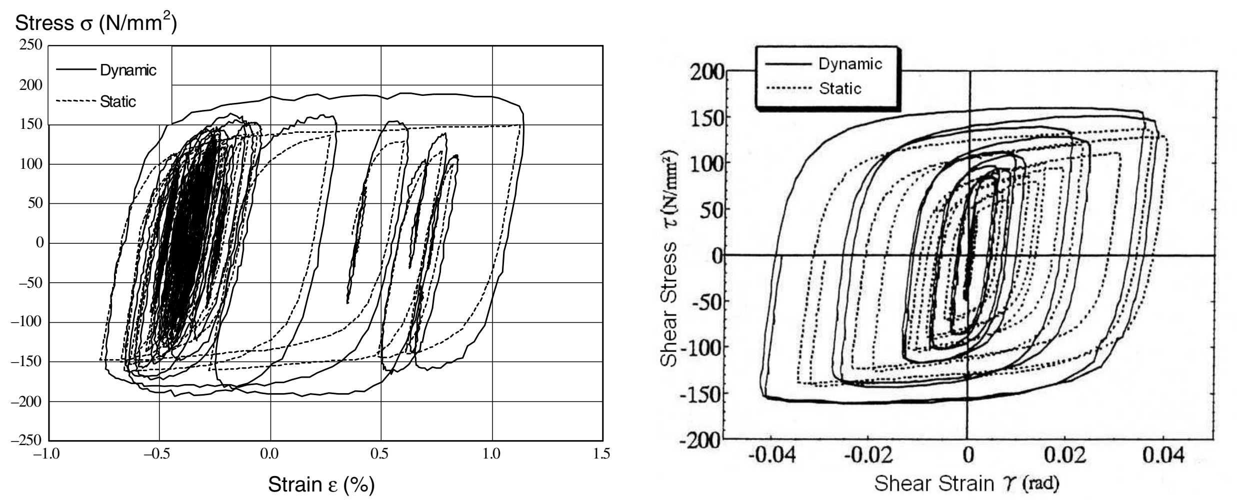
(b) Examples of the accumulated deformation and accumulated plastic energy multiplying factor

Figure 6: Example of Deformation Ability under The Repetitive Displacement

Velocity (vibration frequency) dependency

Of the steel dampers, LY100 exhibits the relatively significant velocity dependency. Figure 7 (a) shows the experimental results concerning the relationship between the stress and the strain of the brace type steel dampers using LY100 under the static and the dynamic random loadings (max. 11%/sec.), and figure 7 (b) shows panel type steel damper under the static and the dynamic random loading (1Hz). As the strain speed increases, the yield strength and the maximum yield strength increase. Especially, in such case that the plastic region is smaller when compared to the floor height, the strain speed of the damper during the earthquake is amplified by more than several times of the interlayer displacement velocity, and the strain speed dependency becomes distinctive, so that care must be exercised when preparing the hysteretic models.

Displacement amplitude dependency
The repetitive hysteretic characteristics and the fatigue characteristics in the plastic region of the damper steels depend on the magnitude of the displacement amplitude. LY100 exhibits the strain hardening as early as the initial loading stage, and such tendency becomes distinctive as the strain amplitude becomes larger. Although LY225 shows smaller displacement amplitude dependency near yield strain revel, if the strain amplitude is more than (+/-) 2%, LY225 also exhibits the strain hardening as early as the initial loading stage. Therefore, when modeling the hysteretic characteristics of the steel dampers, it is necessary to take into account the expected displacement amplitude during the big earthquakes.



(a) Brace Type: LY100 (b) Panel (Stud) Type: LY100

Figure 7: Hysteretic Behavior of Steel Damper in Dynamic and Static Loading Tests

Dependency on environmental conditions
Under the ambient temperature of 0 ~ 40 Celsius Degree in which the steels are normally used in the buildings, the level of the temperature dependency which influences the mechanical properties related to the hysteretic damping performance of the steel such as the yield strength is very low so that it can be ignored. Therefore, similar to the conventional structural steels, in the case of the steel dampers, too, it is not necessary to take into account the temperature dependency. In addition, since the humidity does not directly influence the hysteretic damping performance of the steel, in the case of the steel dampers, it is not necessary to take into account the humidity dependency.

Time dependency
Under the ambient temperature, the steels do not exhibit the deformation with age such as creep. Therefore, it is not necessary to take into account the time dependency

Durability
Under the ambient temperature, the steels do not exhibit the performance changes with age. Therefore, it is not necessary to take into account the changes of characteristics concerning the durability, provided that the sufficient rust prevention treatment is applied such as coating, etc. However, when the plastic deformation occurs on the steel, the rust prevention coating may peel off, so that the repainting must be considered depending on the applied environment.

Fire resistance
When the steel damper is exposed to the high temperature environment such as fire for a long period of time, the quality of material and the mechanical properties may change. Therefore, it is desirable to conduct the appearance inspection after the fire and change the damper as necessary, although the detailed procedures should be as per specified in the exchange criteria for each damper.

PERFORMANCE TEST AND EVALUATION METHOD

When setting the basic dynamic performance of the steel damper, the performance test must be conducted under the various expected conditions, and the evaluation must be conducted in accordance with the appropriate evaluation method, taking into account the variations among products.

During the test for confirming the basic performance, etc. of the steel damper, generally the plastic deformation of the product, i.e., the permanent deformation occurs, so that in order to secure the dimensional accuracy and to maintain the energy absorption performance of the product, it is not desirable to conduct the performance test using the product itself to be shipped. Therefore, in the case of the steel dampers, it is a common practice to guarantee that the products to be shipped have the same basic performance with the representative products manufactured by the same production methods and quality control system, and that the products to be shipped are proved to have the same quality with those representative products by the material testing, dimensional inspections, nondestructive inspections, etc.

Material characteristics
As the material inspection of steels to be used for the dampers, mainly the tests to confirm the mechanical properties shown in Table 3 are conducted. For some types of steel, these tests accord to the inspection certificate. In these cases, the values of certificates are substitutable.

Table-3: Inspection of Steel Material

	Test item	Details of test	Test method	Remarks
1	Chemical component	Major elements	Method specified at the material certification or in accordance with the similar JIS standard.	Each production lot
2	Mechanical properties	Yield strength YS (N/mm^2), Tensile strength TS (N/mm^2), Elongation EL (%), etc.		Each plate thickness / product lot

* For some types of steel, the values specified in Inspection Certificate may be used.

Tests to confirm the performance
Outline of the tests to confirm the basic (static/dynamic) characteristics of the steel dampers are shown in Table 4. Considering the capacity of the testing facility, partial or miniature test specimens are acceptable. Substantial attentions to the scale effect should be paid to design miniature test specimen that stress concentration such as welding notch etc. is incomplete to miniature or some regions such as bolted connection of damper are complicated to miniature. Although partial model requires no attention to scale effect, also substantial attention should be paid to the modelization of fracture mode at ultimate stage, etc. Besides, loading system should be considered carefully that steel damper installed into the main structure experience such as additional bending moment from connection according to lateral displacement of the structure, which affect to the performance of damper.

Table-4: Performance Tests for Steel Damper

Classification	Basic performance item	Test method	Details of test and evaluation method
1 Standard characteristics	(a) Hysteretic curve (Under the major displacement up to the critical deformation) (b) Basic characteristics - Elastic stiffness: K_d - Secondary stiffness: $_pK_d$ - Yield strength: F_y (c) Critical deformation (fracture mode)	Gradual increase of maximum displacement due to alternate loading	(a) Test equipment The static loading: Acceptable * The additional bending/axial stress on the installation portion: Should be considered, if necessary. (b) Test specimen The partial/scaled specimen: Acceptable. (c) Basic characteristics Confirmed geometrically from the combination of material and the shape of damper considering hysteretic curve, or settled directory from the hysteretic curve. (d) Critical displacement (CD) At which the fracture occurs or the load holding becomes impossible. * Deformation exceeds the test equipment capacity: The recorded displacement shall be the CD
2 Dependencies	(a) Displacement velocity (strain speed) dependency	Constant maximum displacement due to alternate loading	(a) Test specimen The partial/scaled specimen: Acceptable. (b) Test conditions The displacement velocity: Shall be determined considering the dynamic characteristics of the building.
	(b) Repetitive cycle dependency	Constant maximum displacement due to alternate loading * Remarks: This test may be conducted as the low cycle fatigue test.	(a) Test equipment The static loading: Acceptable (b) Test specimen The partial/scaled specimen: Acceptable. The testing on the bare steel of the damper: Acceptable (only in the case that the deformation mechanism can be modelized)
3 Accumulated energy absorption performance	(a) Low Cycle Fatigue curve (Relationship between strain and cycle) * The accumulated energy absorption performance shall be confirmed at least by either one of the following tests: (i) Fatigue curve (ii) Accumulated plastic deformation	Constant maximum displacement due to alternate loading	(a) Test equipment The static test: Acceptable (b) Test specimen The shape/dimension: Determined to reflect properly the causes of the product fatigue failure. Usage of the partial test specimen: Acceptable (in case that the fatigue fracture mode is clarified) (c) Test method The fatigue curve: Fatigue life shall be clarified from several hundreds cycle to 5.

	Remarks) The Critical status of fatigue fracture (i) Rupture occurred, (ii) The maximum yield strength deteriorated*1), (iii) The quantity of energy absorption dropped*1), (iv) The loss of the stable hysteretic nature. *1) Drop by 90% or 75% to the standard value.		
	(b) Accumulated plastic deformation	Gradual increase of displacement due to alternate loading test (static)	(a) Test specimen and conditions, etc. Same as above standard characteristics test
	* This performance test may be omitted when the fatigue curve has been obtained.		
4 Durability	-----	-----	-----
5 Fire resistance	-----	-----	-----

CONCLUSION

The outline of the part of design of steel dampers in the JSSI Manual for Building passive control Technology, which is compiled by the Response Control Committee of Japan Society of Seismic Isolation, is introduced.

REFERENCES

1. Nakata Y., Uemura K., Iida T., Hirota M., "Performance and Quality Control of Steel Hysteretic Damper", Symposium Proceedings of Passive Controlled Structure 2001, Japan: Tokyo Institute of Technology, 2001, 87-100
2. Editor: Japan Society of Seismic Isolation. "The Manual for Design and Construction of Passively Controlled Structure." Japan: Japan Society of Seismic Isolation, 2003, 185-200