

## A Study on Applicability of Hysteretic Damper to Existing Rail Way Viaduct Structure

Yuki NAKATA<sup>\*</sup>, Hajime OHUCHI<sup>\*\*</sup> and Hisao TSUNOKAKE<sup>\*\*\*</sup>

(Received September 30, 2008)

### Synopsis

When considering social function of railway viaduct as infrastructure, less damage control is expected even against significant earthquake such as the Tokai and the Tonankai Earthquake. Response control technique with damping device is highly expected as alternative solution. In responding, authors have developed Arc Shaped Dampers. In order to investigate applicability of proposed damper to rail way viaduct structures, seismic retrofit design and nonlinear analysis were conducted focusing on failure type and response control. Following results were obtained: the existing structure is failed in shear, while retrofitted structure assures flexural yielding ductile behavior.

**KEYWORDS:** Arc Shaped Damper, Rail Way Viaduct Structure, Response Control

### 1. Introduction

In the current seismic design standard for rail way viaduct structures, less damage is required against level 1 design seismic motion from less recovery aspect, while collapse prevention required against level two design seismic motion from life safety aspect. On the other hand, many existing structures designed by old specification are potentially shear failure type or have less ductility with less shear reinforcement. In the seismic retrofit of these structures, jacketing method has been commonly employed. However, when considering social function of these facility as infrastructure, early recovery and less damage is expected against level 2 seismic motion.

In these backgrounds, we have developed arc shaped steel damper and seismic retrofit method, which prevents brittle failure and assures damage control with appropriately corner arrangement into frame structure as shown in **Fig.1**. Advantageous points of the developed damper are 1) buckling prevention with its arc configuration and 2) wider distribution of plastic region into device. Next, with present dampers into corners, followings are assured; 1) strengthening of entire structure, 2) shear force decrease in the column end section, 3) shear capacity increase expected due to deep beam action in the column middle section and 4) seismic response reduction with high damping effect. In addition, corner arrangement of the present arc

---

\* Graduate Student, Div. of Structural & Concrete Engineering

\*\* Professor, Div. of Structural & Concrete Engineering

\*\*\* Research Associate, Div. of Structural & Concrete Engineering

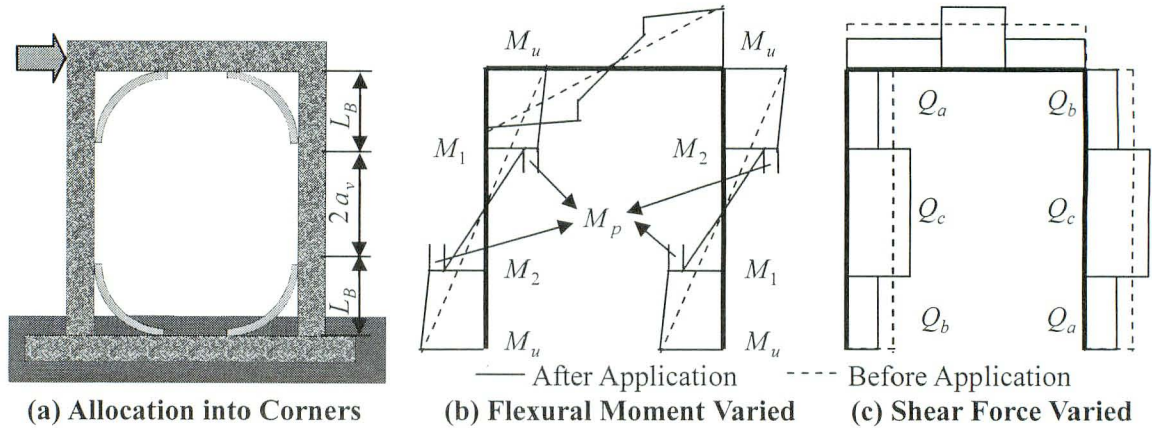


Fig.1 Retrofit by Arc Shaped Damper

shaped damper assures open space for usage.

The present paper reports 1) hysteretic characteristic of the present damper, 2) seismic retrofit design, and for seismic performance evaluation and 3) nonlinear analysis of the retrofit designed structure under monotonic load and repeated lateral load.

## 2. Hysteretic Characteristic of Arc Shaped Damper

### 2.1 Experimental Test Procedure

Fig.2 (red line circle) illustrates proposed damper in which aluminum (JIS 1070-O) is utilized for the arc section. The damper ends are rotation free mild steel equipment product.

Fig.2 shows testing set up where repeated load application can be provided through L shaped loading frame of which both ends are connected to testing machine with actuator installed. Provided drift angles defined by  $\delta$  and  $L$  as shown in Fig.3 are 1/120, 1/60, 1/30, and 1/15 with three cycles for each. In addition, nonlinear analysis is conducted with general-purpose software FINAL.

### 2.2 Test Result

Fig.3 represents load-drift angle relationship which averaged in tension and compression on the assumption of the installation. During 1/15 drift angle, rapid load increase is observed in tension because elastic axial force dominates with the element linearly elongated. Moreover, tensile loading is larger than compressive due to variation in geometric configuration. The hysteresis is large spindle shape.

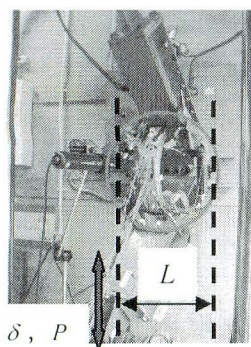


Fig.2 Test Scenery

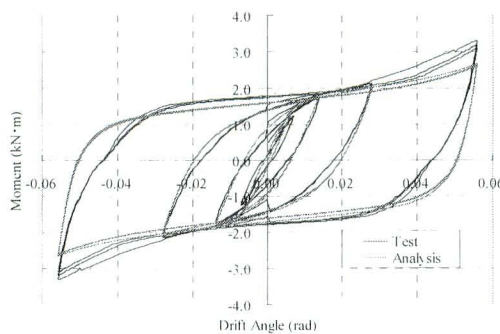


Fig.3 M-R Relationship

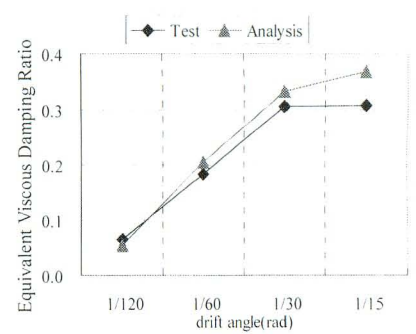


Fig.4 Equivalent Damping Ratio

**Fig.4** shows the obtained equivalent viscous damping ratio which is calculated from the second cycle hysteretic load-drift angle relationship. The Arc Shaped Damper has 30~40% damping in the larger drift angle range of  $R=0.03\sim 0.06$ . Equivalent viscous damping ratio at 1/15 of drift angle is less than that at 1/30 because of tensile axial force dominated in the larger displacement range.

### 3. Seismic Retrofit Design

Applicability of Arc Shaped Damper is considered for rail way viaduct structure model <sup>1)</sup> as shown in **Fig.5**. Here, relationships between strength of the damper and that of entire structure or shear force are leaded. The joining method between frame and damper is rigid.

Equilibrium of horizontal force (refer to **Fig.6**) in where the damper is installed as shown in **Fig.1 (a)** is considered. Horizontal components of damper's strength are  $P_{B2}$ (tension),  $P_{B1}$ (compression), strength of entire structure  $P_u$ , and the distribution of resultant force is shown **Fig.1 (b), (c)**.  $M_p$  in **Fig.1 (b)** is full plastic moment at the damper end. Shear force in when flexural moment at top and bottom end section of the column reach flexural capacity  $M_u$  is

$$Q_a = P_u / 2 - P_{B1}, \quad Q_c = P_u / 2 \quad \text{and} \quad Q_b = P_u / 2 - P_{B2} \quad (1)$$

thus,

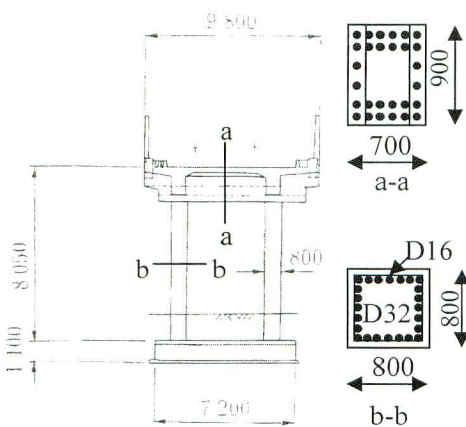
$$M_1 = M_u - Q_a L_B \quad \text{and} \quad M_2 = M_u - Q_b L_B \quad (2)$$

From flexural moment, shear force of the column middle section is given as follows.

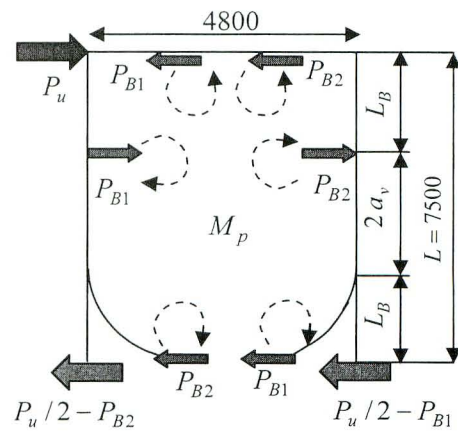
$$Q_c = \frac{(M_1 - M_p) + (M_2 - M_p)}{L - 2L_B} = \frac{2M_u - (P_u - P_{B1} - P_{B2})L_B - 2M_p}{L - 2L_B} \quad (3)$$

From eq. (1) and eq. (3), eq. (4) is obtained.

$$P_u = \frac{4M_u + 2(P_{B1} + P_{B2})L_B - 4M_p}{L} \quad (4)$$



**Fig.5 Model Structure**



**Fig.6 Equilibrium of Horizontal Force**

The first term is strength of entire structure before retrofit, and other terms that by retrofit.

Next, the condition that frame not shear failure is determined. In order to prevent shear failure, because shear force is simply smaller than shear capacity,

$$Q_b < V_d \text{ and } Q_c < V_{dd} \quad (5)$$

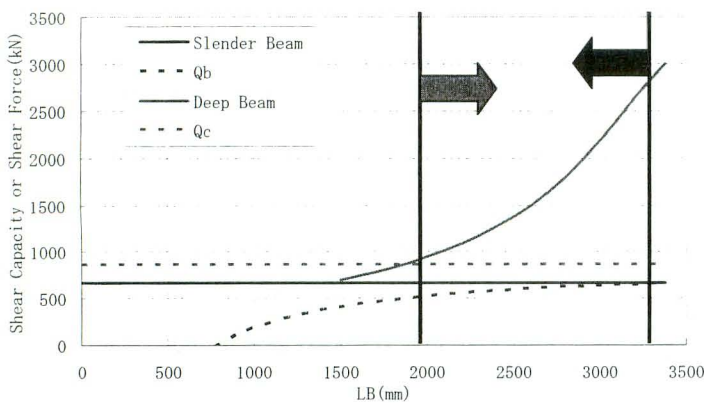
$V_d$  : Shear Capacity of Slender Beam ( $a/d > 2.5$ )<sup>2)</sup>, where  $a/d$  is shear span ratio.

$V_{dd}$  : Shear Capacity of Deep Beam ( $0 < a/d < 2.5$ )<sup>2)</sup>

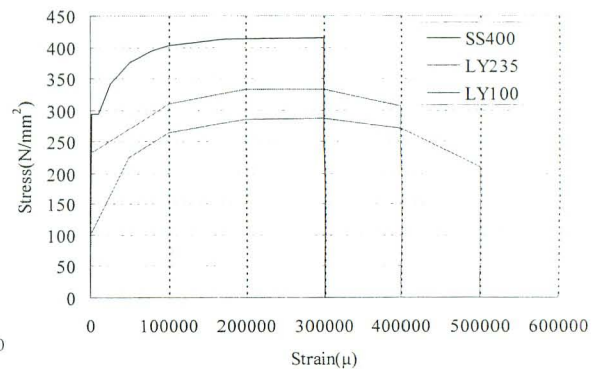
Here, increase in strength of entire structure is 30% considering pile's strength. Moreover, the ratio to  $P_{B1}$  and  $P_{B2}$  is assumed as 1.2:1.0 considering the test result. Then, if shear reinforcement ratio is 0.15% (then, ratio of shear capacity to shear force in flexural capacity is 0.94), relationship between  $L_B$  (refer to **Fig.1 (a)**) and shear force or shear capacity is given **Fig.7** from eq. (4), (5). Note, however, that  $M_p$  is disregarded because calculation of  $M_p$  is difficult and disregard of  $M_p$  is conservative side. In **Fig.7**, vertical axis is shear force or shear capacity, and abscissa axis  $L_B$ . Full line is shear force, and dash line shear capacity. In order to prevent shear failure at the column middle section, it must be that red full line is above red dash line, and at the column end section, blue full line above blue dash line. The region which implements red arrow and blue arrow coincidentally is, that is, the condition that frame not shear failure. Thus,  $1850 < L_B < 3200$  implements the condition.

#### 4. Numerical Analysis

From 3 chapter,  $L_B$  is determined as 2100 (mm). Then,  $P_{B1} + P_{B2}$  is also determined by eq. (4). Materials of the damper are 1) mild steel (SS400), 2) low yield point steel (LY235) and 3) extreme yield point steel (LY100). **Fig.8** illustrates stress-strain relationship<sup>3)</sup>. Elastic modulus of each is  $2.0 \times 10^5$  (N/mm<sup>2</sup>). The section sizes which implement strength are determined from specification size of H-section steel. Note, however, that those moment of inertia is largest are selected though there are some sections which implement strength.



**Fig.7 Condition for Failure**



**Fig.8 Stress-Strain Relationship**

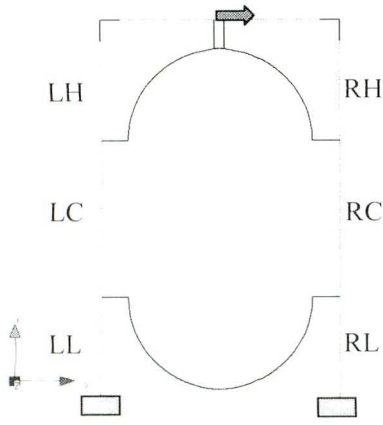


Fig.9 Analysis Model

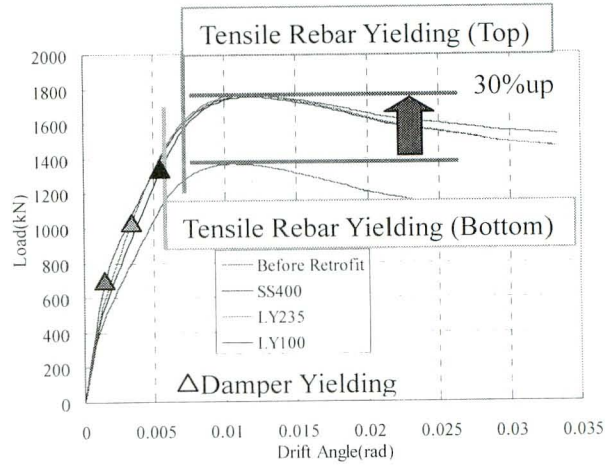


Fig.10 Load-Drift Angle Relationship under Monotonic Load

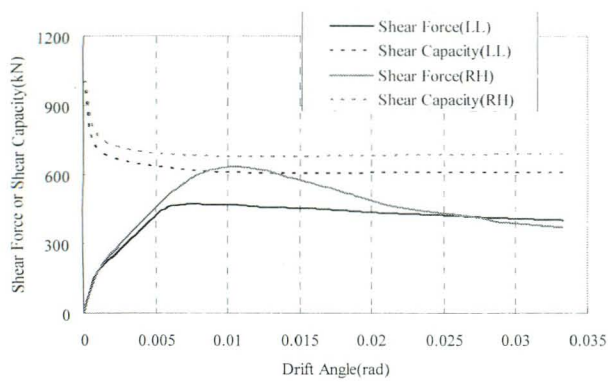
#### 4.1 Static Nonlinear Analysis

##### 4.1.1 Monotonic Load

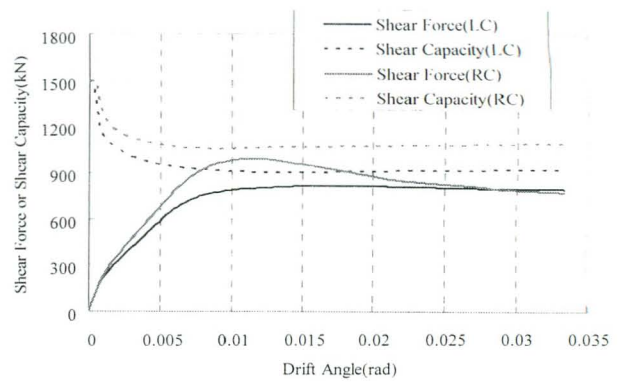
Nonlinear Analysis is conducted with the model as shown in Fig.9. In addition, the name of each members defined as shown in Fig.9. Displacement boundary condition is shown in Fig.9, and all elements are beam. Moreover, black line is stiff elastic elements considering the width of frame and damper. With this model, material and geometric nonlinear analysis is conducted. Load-drift angle relationships are shown in Fig.10. The frame before retrofit is assumed as flexural failure though shear failure. Strength of entire structure all increase 30% as design. On yielding of longitudinal rebar, it yields at the same drift angle in all cases unaffected by the dampers. The all dampers yield before tensile rebar yielding. Moreover, displacement in damper's yielding is smaller according to smallness each damper's yielding, and initial stiffness of frame larger according to that of damper.

##### 4.1.2 Checking of Shear

Fig.11 illustrates hysteresis of shear force. Note, however, that only the results of SS400 damper is shown because shear force and shear capacity are almost consistent from material to material. And as is obvious from eq. (1) and  $P_{B1} > P_{B2}$ , only the results of LL and RH is shown at the column end section because LH and RL is not also shear failure if LL and RH not it. Compared left column with right, force moves to right due to variation of axial force and vertical components of damper's reaction. But shear force is smaller than shear capacity in all members. So this can prevent shear failure.



(a) LL and RH



(b) LC and RC

**Fig.11 Shear Force and Shear Strength**

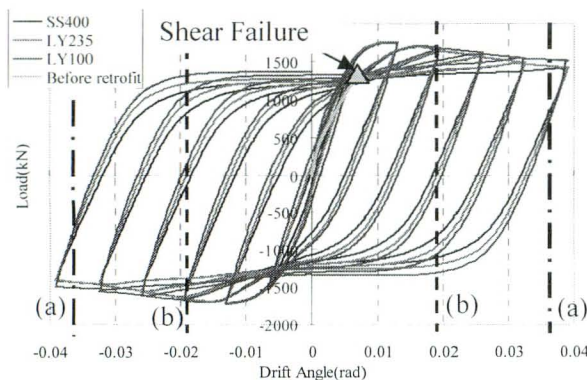
#### 4.1.3 Repeated Lateral Load

Nonlinear analysis is conducted under repeated lateral load. Provided displacements are  $\delta_y \cdot 2\delta_y \cdot 3\delta_y \cdot 4\delta_y \cdot 5\delta_y \cdot 6\delta_y$ , where  $\delta_y$  is yielding displacement of the frame. **Fig.12** illustrates load-drift angle relationship, and dash lines (a) show limiting drift angle by formula of deformation performance for railway viaduct structures <sup>2)</sup>. In addition, dash lines (b) is shown from following formula <sup>4)</sup>, because (a) is unassured for structures with low shear reinforcement ratio.

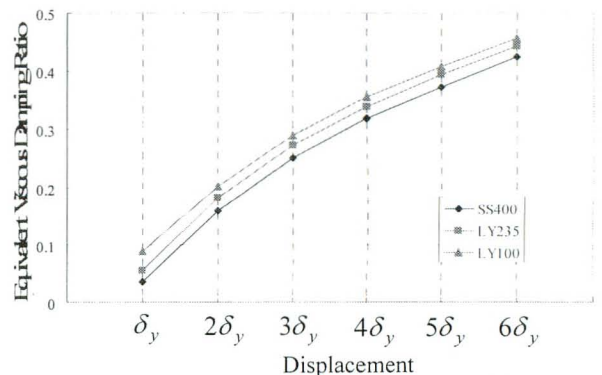
$$\mu = (V_c + V_s - V_{my}) / (0.18V_c) + 3 \geq 3 \quad (6)$$

$V_c$  : Shear force contributed to concrete,  $V_s$  : Shear force contributed to hoop,  $V_{my}$  : Yield load

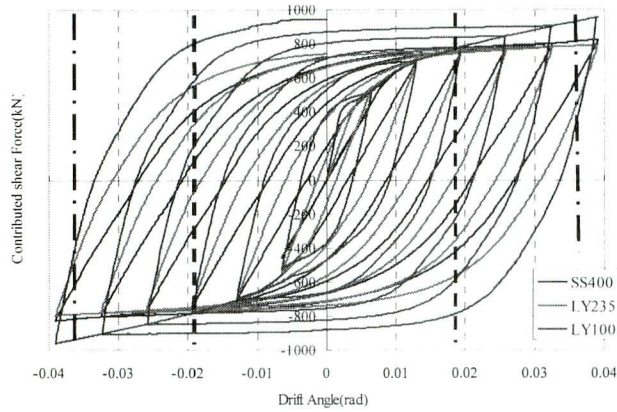
LY100 damper has spindle hysteresis which is the largest absorbed energy. Next, equivalent viscous damping ratio is shown in **Fig.13**. Equivalent viscous damping ratio is larger as larger drift angle in all cases, and LY100 damper is the most at all drift angles. So, LY100 damper is most effective from the viewpoint of damping effect.



**Fig.12 Load-Drift Angle Relationship under Repeated Lateral Load**



**Fig.13 Equivalent Viscous Damping Ratio**



**Fig.14 Shear Force Contributed to Damper**

**Fig.14** illustrates shear force contributed to the dampers of each. LY100 damper has the largest hysteresis and load due to strain hardening and difference among each yielding points. And from **Fig.12** and **Fig.14**, the ratio to shear force contributed to the dampers and that to the frame is almost equal.

#### 4. Concluding Remark

Followings are concluded.

- 1) The present arc shaped damper assures 30~40% damping in the larger drift angle range of  $R=0.03\sim 0.06$ .
- 2) In the nonlinear analysis against monotonic load and repeated lateral load, retrofitted structure provides flexural yielding ductile behavior as expected in the present design.
- 3) Appropriate arrangement of present damper has possibility to lead high ductile yielding in the existing frame structure with brittle failure expected.

Mr.T.Shimabata and Dr.I.Shimada are acknowledged for their significant contribution in the arc shaped damper development.

#### 5. References

- 1) Japan Society of Civil Engineers, STANDARD SPECIFICATIONS FOR CONCRETE STRUCTURES -1996 Seismic Design (1996)
- 2) Railway Technical Research Institute, The Model Code for Design of Concrete Railway Structures (2004)
- 3) Railway Technical Research Institute and OBAYASHI CORPORATION, The Code for Design of Railway Viaduct Structures with Damper Brace (2000)
- 4) Japan Society of Civil Engineers, Seismic Capacity Checking Technique of Concrete Structures –Actual State and future perspective– (2002)