Design and Performance Tests of Buckling Restrained Braces for Seismic Retrofit of a Long-span Bridge

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ABSTRACT: Described in this paper is a retrofitting method of long-span bridges using a buckling restrained bracing, BRB, with the emphasis on the reduction of the weight during the retrofitting and its mechanical characteristics including the effect of the hysteretic damping are discussed. Five types of BRB members are compared: one uses the flat plates while the other uses crucified plates as the core member. In addition to these types, the third type is also considered by using the existing member with an intentional cut and with a buckling restraining sleeve. In the tests, models of the scale factor of 1/6 were made and they were subjected to repetitive tests to find the load-displacement relationship, hysteretic damping effect, yielding strength and the stiffness. From the test results, different characteristics were observed among different types of specimens. Furthermore, BRBs incorporated into a frame were tested in order to confirm the same damping performance as unit tests.

1 INTRODUCTION

The Minato Bridge with a total length of 980m was completed in 1974 and is the third longest truss bridge in the world. In the assessment of the seismic safety of this bridge, the seismic design load was reviewed considering extremely large earthquakes whose return period exceeds 1000 years. By using these earthquake motions, a large number of dynamic analyses have been performed and it is found that a lot of truss members cannot remain in elastic condition. To deal with this fact, the damage-controlled design has been applied.

This concept has been already employed in the field of high-rise buildings in Japan. The application of this concept in the damage control design of the long-span truss bridge treated herein will allow the bridge to have only small residual deformation which would permit to open the traffic even after an extreme large earthquake. In order to support this, buckling restrained brace, BRB which provide adequate damping, have been selected. BRB restrained with mortal, which is called unbonded brace, have been used for buildings in Japan. However such BRB is not suitable for the existing long span bridge considering its construction. To put it plainly, lighter BRB has been required.

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2 OUTLINE OF THE BRIDGE AND BUCKLING RESTRIED BRACE

Object bridge is shown in Figure 1 and the type of bridge is a cantilever truss bridge. Steel hysteretic dampers for retrofitting this bridge treated herein, consist of core steel using low yield-point (LY225: $\sigma_y=225$ N/mm²) and outer restraining steel. This is called buckling restrained brace, BRB, shown in Figure 2, and will provide large damping without buckling. Buckling strength of a normal steel brace is lower than its yield strength so, hysteretic damping due to cyclic loading cannot be expected. Figure 3 shows the sway-braces of towers as well as lateral-braces of the lower part of the superstructure near towers that buckle under compression force caused by design earthquakes acting in the transverse direction of the bridge. In order to provide adequate damping to the entire bridge and also to avoid buckling or yielding of main members, some existing braces should be replaced by BRBs that satisfy the seismic design requirements of the retrofitting method applied herein.



Figure 1 Structural and geometrical characteristics of the Minato Bridge



Figure 2 Buckling restrained brace (BRB)



Figure 3 Optimal layout of members to be replaced with BRBs

3 TESTS OF BUCKLING RESTRAINED BRACE SCALE-MODELS

3.1 *Considerations and outline of the test*

Results of the dynamic analysis show that BRBs reduce the seismic response of the whole bridge. However there are several facts to investigate yet for retrofitting existing long-span bridges such as the effect of core types in dampers hysteretic behavior, and their stability and fatigue response during cyclic loading which are some of the reasons of the tests conducted in this study.

Although many BRBs have been developed for retrofitting of buildings, it is necessary to modify them for retrofitting of bridges to make them lighter members and suitable to be coupled with the existing gussets. Several types of scale-models of buckling restrained braces, BRBs, were tested to investigate their hysteretic characteristics. The test-specimens were designed for the upper lateral sway braces of towers shown in Figure 1 with their connection portion fitting the gusset details. The specimens were one-sixth models of 1.5m-length considering the size of the test facility. A hydraulic actuator of 200tf of capacity was used.

3.2 BRB scale-models and test setup

The characteristics of five test-specimens numbered from 1 to 5 are described in Table 1. A cross-type core made of low yield-point steel was used for Specimen 1 (see Figure 4). As shown in Figure 5, the core of Specimen 2 consisted of a parallel BRB composed by two cross-type cores identical to the used in Specimen 1. Specimen 3 had a core composed by two flat plates restrained transversally by a box-section beam (see Figure 6). The core of Specimen 4 shown in Figure 7 is a parallel BRB composed by two cores (four plates)

identical to the used in Specimen 3. Specimen 5 as indicated Figure 8 in is also considered by using the existing member with an intentional cut and with a buckling restraining sleeve.

The gap between faces of core member and the buckling restraining member is 2mm; a PTFE sheet together with a rubber sheet is installed inside the 2mm gap to reduce the friction force between them. Figure 9 illustrates the test setup characteristics and the cyclic loading pattern used to control the tests.

Test-specimen	Core shape	Single/ Parallel	Plastic portion	Steel grade	Core-area
Specimen 1	Cross	Single	1468 mm	LY225	2432 mm^2
Specimen 2	Cross	Parallel	1468 mm	LY225	2326 mm ²
Specimen 3	Flat-plate	Single	1225 mm	LY225	2460 mm ²
Specimen 4	Flat-plate	Parallel	1225 mm	LY225	2296 mm ²
Specimen 5	I- shape	Single	1468 mm	SM490	1644 mm ²

Table 1 Characteristics of test-specimens



















Figure 8 Specimen 5



Figure 9 Test setup characteristics and the deformation protocol

3.3 *Experimental Hysteretic curves*

The load-deformation relationship of Specimen 1 with a cross-type core exhibited a stable hysteretic behavior as shown in

Figure 10, and experienced 20 cycles, its strain was 2% before fracture in tension. The parallel BRBs with cross-type core corresponding to Specimen 2 showed almost the same hysteretic behavior as Specimen 1; however, its strain hardening was noticeable at a deformation corresponding to 2% of strain. The Specimen 2 finally broke in tension after experience of 10 cycles; its strain was 2%. On the other hand, Specimen 3 exhibited an asymmetric load-deformation curve in both tension and compression. The Specimen 4 also has a stable behavior. An equivalent damping coefficient obtained at 1% strain showed that damping of the cross-type core damper and the flat-type are almost same value, 50%. However that of Specimen 5 is 37% which is less than those of Specimen 1-4.

3.4 *Failure pattern*

Figure 11, Figure 12 and Figure 13 indicate the failure pattern of Specimen 2, 4 and 5 respectively. Core steel was broken near the center portion by tension load in Specimen 2. On the other hand, local bucking occurred at edge of Specimen 4. This is because the strength of the outer restraining steel was inadequate to prevent the bucking of the core steel. The failure mode of Specimen 5 was fracture of existing web plate at the corner cut position. This would be related to stress concentration.

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Test-specimen	Turne	Equivalent damping	Cumulative plastic		
	Туре	coefficient	deformation ratio		
Specimen 1	Single cross-type	48%	1879		
Specimen 2	Parallel cross-type	47%	1052		
Specimen 3	Single flat-plate-type	50%	1298		
Specimen 4	Parallel flat-plate-type	50%	611		
Specimen 5	Existing-brace-modification-type	37%	196		

Table 2 Equivalent damping coefficient and cumulative plastic deformation ratio



a) Single cross-type (Specimen 1)



c) Flat- plate-type (Specimen 3)



e) Existing-brace-modification-type (Specimen 5)





b) Parallel cross-type (Specimen 2)



d) Parallel flat- plate- type (Specimen 4)



Figure 11 Failure Pattern of Specimen 2



Figure 12 Failure Pattern of Specimen 4



Figure 13 Failure Pattern of Specimen 5

4 TESTS OF BUCKLING RESTRAINED BRACES INCORPORATED INTO A FREME

4.1 *Considerations and outline of the test*

It was validated that the hysteretic performance of BRBs is enough for the damping for the bridge. However there is a great lack of data for performances of BRB incorporated in a flame. Especially, it is important to confirm the relationship between the lower beam and BRBs because strength and stiffness of the existing lower beam of the bridge are not so large. Therefore we carried out the flame test with BRBs in order to confirm the damping property and deformation characteristics of column, beam and gusset of the flame.

4.2 Frame scale-models and test setup

Figure 14 shows the test specimen and setup. The flame specimens were tested using a one-sixth-scale model and it targeted at the panel of tower of the bridge in shown Figure 15. Tests were executed by using reaction wall and the hydraulic actuator with a 300tf capacity, which creates relative story displacement. The frame was pin connected with the reaction floor and the connection beam, which was pin connected with the actuator. BRBs as shown in Figure 5 and Figure 7 were selected considering practical construction.

The experiments were controlled using the relative story displacement and the target displacement is 21.8mm, which corresponds to the design value of the bride. The deformation protocols are shown in Figure 16.



Figure 14 Test setup

Figure 15 Object



Figure 16 Deformation Protocol

4.3 *Test results*

The recorded hysteretic loops for the two types of BRBs are shown in Figure 17. Both types provide stable hysteretic performance up to the target drift displacement. Figure 18 provides the hysteric area and the equivalent damping coefficient for the frame with flat-plate-type BRBs and the cross-type BRBs. Equivalent damping coefficients of the flat-plate-type and the cross-type are 27% and 32% respectively. From these results, it can be stated that the cross-type BRB is more effective than the flat-plat-type BRB.



Figure 17 Load-displacement Loops for the Flame



The residual displacement of the lower beam is shown in Figure 19. As previously mentioned, the bending strength of the lower beam is quite small. For this reason, it yielded at the both ends and the residual deformation occurred. The tests were finished before BRBs would fail, because the residual deformation of the lower beam dramatically increased in the same cyclic load. Up to this point, the cumulative plastic deformation ratios of flat-type and cross-type BRBs are 522 and 1955, respectively. These values perform the design criteria of the bridge.



Figure 19 Residual Displacements of the Lower Beam

5 CONCLUSIONS

The results of this study make possible the following conclusions:

1. Several types of the weight saving BRBs are proposed and they show stable hysteretic properties. The cross-type BRB and the flat-plate-type BRB provide around 50% of

the equivalent damping coefficient. That of the existing-brace-modification-type BRB is 37%.

- 2. Failure pattern of each BRB are different. The parallel cross-type BRB and the existing-brace-modification-type BRB broke by tension load. However the local buckling was found in the parallel-flat-type BRB. The cumulative plastic deformation ratio of the cross-type BRB shows larger value than those of others, which satisfy the design criteria.
- 3. Frame tests indicate the cross-type BRB is better than the flat-plate-type BRB, because the latter difference in tension and compression strength causes the residual deformation of the lower beam.

ACKNOWLEDGEMENTS

The authors are very grateful to Professor Emeritus Eiichi Watanabe of Kyoto University, Professor Kazuo Inoue of Kyoto University, Professor Yozo Fujino of Tokyo University, and Professor Tsutom Usami of Nagoya University for their valuable suggestions and helpful recommendations for improving this study.

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