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Low-Cycle Fatigue Tests of a Type of Buckling Restrained Braces

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Abstract

In order to satisfy fatigue performance requirements of High Performance Seismic Dampers (HPSDs), which are expected to withstand Level 2 earthquakes three times without being replaced, a low-cycle fatigue experiment was carried out to address fatigue life problems about steel Buckling-Restrained Braces (BRBs). The results of fatigue tests under the constant and variable amplitude loadings show that all the specimens have good fatigue performance and the toe-finished method can effectively improve the fatigue performance of BRBs with relatively small strain amplitudes. But the BRB’s fatigue performance is affected by the in-plane gap width between filler members and the restraining member, which is verified by the comparative tests. Finally, fatigue curves are compared between these full-scale BRB tests and material tests presented in references.

Keywords: Damage Control Seismic Design, High Performance Seismic Damper, Buckling Restrained Braces, Low-cycle Fatigue, Steel Bridges.

1. INTRODUCTION

In the last few decades, damage control seismic design using damping devices has become popular in damage control design for bridge engineering as well as building engineering. Based on the design philosophy, damage is expected to concentrate in damping devices, exhibiting plasticity prior to other members, during a moderate to severe earthquake. Correspondingly the damage of the main structure, such as residual plastic deformation, can be controlled. Among many types of damping devices, more and more attentions are being paid to hysteretic dampers, because the inelastic deformation capability of
metallic substances represents an effective energy absorption mechanism for damping of engineering structures with low cost (Weber et al. 2006).

According to the yield mechanism, hysteretic dampers are divided into axial-type, shear-type, bending-type and torsion-type. So far, Buckling Restrained Braces (BRBs), as an axial-type damping device, are widely studied on component behavior and system applications in building (Iwata et al. 2006; Fahnestock et al. 2007) and bridge engineering (Usami et al. 2005). As an instance on component level, ductility capacity models for BRBs are developed to predict the cumulative plastic ductility (Andrews et al. 2009). Moreover, improved types of BRBs are in development, such as double steel cores encased in twin steel tubes and infill concrete tested by Lai and Tsai (2004). Besides test and analysis researches on component level, more investigations were conducted on systems under cyclic loadings (Uriz and Mahin 2008; Carden et al. 2006). It has been found from recent research series by the authors that light-weight BRBs were employed to replace insufficient lateral braces and cross diagonal braces for retrofitting an existing steel arch bridge, which leads to damage concentration in sacrificing damping devices and mitigates damage of main structures (Usami et al. 2005, 2008, 2009).

In this paper, an experimental study was carried out to address fatigue life problems about steel BRBs, in order to meet High Performance Seismic Dampers’ (HPSDs) performance requirements proposed by the author (Usami 2007). In particular, a method to improve low cycle fatigue strength of steel BRBs by smoothing the weld toes locating both ends of the brace member is introduced and comparatively verified by two series of fatigue tests.

2. Low cycle fatigue Testing Method

![Diagram](image)

**Figure 1: Configurations and dimensions of steel BRBs**

2.1. Specimens

As shown in Figure 1(a), a light-weight Buckling-Restrained Brace (BRB) mainly consists of a steel plate brace member, a pair of restraining members connected by high-strength bolts through two filler
members, and unbonding material stuck to the brace member. The twelve steel BRB specimens were divided into two series. The weld toes with a width of about 6 mm at both ends of BRB specimens in the S-I series were made by submerged arc welding, while no improving treatment was carried out, so the S-I specimens are called as-welded BRBs. The S-II specimens’ weld toes were modified by grinding to reduce the stress concentration and the S-II specimens are called toe-finished BRBs. This toe-finished method is represented by radius $r$ and depth $d$ of the finished groove as shown in Figure 1(d).

2.1.1. Brace member

A flat steel plate is used as the brace member shown in Figure 1(c) and geometric dimensions and structural properties are listed in Table 1. Aiming at well connection to experiment equipments, cruciform sections at both ends are expanded by welded 12mm thick rib stiffeners to each side of the plate. Material constants of the brace member are listed in Table 2. At the center of the brace member, two welded pins of 9 mm in diameter and 30 mm in height are used to prevent the relative movement between restraining members and the brace member in the longitudinal direction.

Table 1: Geometric dimensions and structural properties of brace members

| Series        | Specimens | Steel grade | $L$(mm) | $B$(mm) | $t$(mm) | $A$(mm$^2$) | $\lambda$ | $P_y$(kN) | $\delta_y$(mm) |
|--------------|-----------|-------------|--------|--------|--------|-------------|----------|-----------|---------------|
| S-I:         | FE-1.0    | SM400A      | 99.9   | 10.5   | 1049   | 449        | 305      | 1.91      |
|              | FE-2.0    |             | 99.9   | 10.3   | 1029   | 457        | 299      | 1.91      |
|              | FE-3.0    |             | 99.7   | 10.7   | 1067   | 440        | 310      | 1.91      |
|              | FE-4.0    |             | 99.8   | 10.3   | 1028   | 457        | 299      | 1.91      |
|              | FE-R      |             | 99.8   | 10.3   | 1028   | 457        | 299      | 1.91      |
| S-II:        | FT-1.0    | SM400A      | 100.4  | 10.3   | 1037   | 452        | 260      | 1.91      |
| Toe-finished BRBs | FT-2.0    |             | 100.5  | 10.7   | 1071   | 435        | 269      | 1.91      |
|              | FT-3.0    |             | 100.3  | 10.3   | 1028   | 451        | 258      | 1.91      |
|              | FT-3.5    |             | 100.2  | 10.6   | 1060   | 438        | 266      | 1.91      |
|              | FT-3(6)   |             | 100.4  | 10.3   | 1029   | 451        | 258      | 1.91      |
|              | FT-R1     |             | 100.5  | 10.2   | 1028   | 456        | 258      | 1.91      |
|              | FT-R2     |             | 100.2  | 10.3   | 1032   | 450        | 259      | 1.91      |

Note: $L$ = length of brace member without cruciform part; $B$ = width; $t$ = thickness; $A$ = sectional area; $\lambda$ = slenderness ratio on weak axis; $P_y$ = yield axial load; $\delta_y$ = Nominal axial yield displacement.

2.1.2. Restraining member

Figure 1(b) shows the cross section details of the BRB. Geometric dimensions and structural properties of restraining members are listed in Table 3. The same SM400A mild steel is used for restraining members made of flat steel plates. Nominal values of gap widths between restraining members and the brace member are given together with measured material properties.

2.2. Testing setup and loading patterns

As shown in Figure 2, this experiment has the same testing setup as the reference’s (Usami and Sato 2010). A tensile and compressive alternative cyclic loading controlled by the axial strain of specimens is illustrated in Figure 3. Two cycles of the axial yield strain are firstly imposed as an evaluated procedure.
for testing the specimen and system. For this reason, counting of the cycles starts subsequently. The constant strain amplitude is cyclically imposed until the specimens’ failure, shown in Figure 3(a). The variable strain amplitude of the second pattern, shown in Figure 3(b), increases from \( \varepsilon_r \) to 1% at the start, then from 1% to 2% at \( n_1 \) cycles, then from 2% to 3% at \( n_1+n_2 \) cycles, and then keeps this amplitude till the specimen fails. The third pattern is almost the same as the second one except the strain amplitude gradually decreases. All the strain amplitudes are specified in Table 4. When the loading displacement becomes steady, the strain control equals to the displacement control. Therefore, we conducted the present fatigue tests by controlling the axial displacement.

Table 2: Material constants of brace members

| Series | Steel grade | \( E \) (GPa) | \( \sigma_y \) (Mpa) | \( \varepsilon_y \) (%) | \( \sigma_u \) (Mpa) | \( \varepsilon_u \) (%) | \( \nu \) |
|--------|-------------|--------------|-------------------|------------------|-----------------|-----------------|------|
| S-I    | SM400A      | 210          | 291               | 0.139            | 433             | 30.2            | 0.285 |
| S-II   | SM400A      | 209          | 251               | 0.130            | 409             | 29.2            | 0.280 |

Note: \( E \) = Young’s modulus; \( \sigma_y \) = yield stress; \( \varepsilon_y \) = yield strain; \( \sigma_u \) = tensile strength; \( \nu \) = Poisson ratio.

Table 3: Geometric dimensions and structural properties of restraining members

| Specimens        | Steel grade | \( E^s \) (Gpa) | \( \sigma_y^s \) (Mpa) | \( b_y \) (mm) | \( t_y \) (mm) | Gap width (mm) |
|------------------|-------------|-----------------|-----------------------|---------------|---------------|----------------|
| FE-1.0/2.0/3.0/4.0/R | SM400A      | 198             | 260                   | 201           | 14.3          | 1              | 2               |
| FT-1.0/2.0/3.0/3.5/R1/R2 | SM400A      | 212             | 264                   | 201           | 14.2          | 1              | 2               |
| FT-3(6)         | SM400A      | 212             | 264                   | 201           | 14.0          | 1              | 6               |

Note: \( E^s \) = Young’s modulus; \( \sigma_y^s \) = yield stress; Notations of \( b_y, t_y, d \) and \( d_0 \) refer to Figure 1(b).

3. Fatigue test results

3.1. Experimental stress-strain relation of BRBs

Some of experimental stress-strain curves of BRB specimens are given in Figure 4. The tensile state of BRBs is displayed in the positive direction. The abscissa is the engineering strain, \( \varepsilon \), while the ordinate is the engineering stress, \( \sigma \). The test results of all the specimens are summarized in Table 4. In addition,
stable stress-strain curves were obtained without overall buckling occurrence in the whole loading history of all the specimens even though the maximum strain amplitude was as large as 4% in the FE-4.0’s test. It is shown in the hysteretic curve of the FE-1.0 specimen that the first loop is hardly affected by the strain hardening effect while the others are remarkably influenced by the strain hardening effect. At the last loop, the strength decreases rapidly in the tensile state and then unloading is applied when the axial force falls down by over 10% of the maximum axial force. The same results can be observed in other specimens with the constant strain amplitude. The hysteretic behavior of the specimens with the comparatively large strain amplitude, such as FE-3.0, FT-3.0 and FT-3.0G etc, is unsymmetric in tension and compression, and the maximum absolute compressive stress is 15% to 30% larger than the maximum tensile stress. On the other hand, under the comparatively small strain amplitude condition, the hysteretic behavior is almost symmetric in tension and compression. The reason for this behavior is explained as follows: with the strain amplitude increasing in the compressive state, the contact force and the friction between restraining members and the brace member increased.

![Stress-strain behavior of low cycle tests of BRBs](image)

Figure 4: Stress-strain behavior of low cycle tests of BRBs

The failure cycle number $N_f$ is given in Table 4 for each specimen. The toe-finished specimens show better fatigue performance than as-welded specimens with the same 1% or 2% strain amplitude. From the values of Cumulative Inelastic Deformation ($CID$) listed in the table, it is clear that all the test specimens, especially toe-finished specimens, possess good cumulative inelastic deformation properties and greatly satisfy the performance requirement for HPSDs. Although the in-plane gap width of the FT-3(6) specimen is set at 6mm, this specimen can still meet the demand of the cumulative deformation, whereas its $CID$ value decreased by 17% and the number of fatigue failure cycles reduced by 14% in contrast with the FT-3.0 specimen. Therefore, it is thought that the in-plane gap width, as one of the key parameters, should be 1-2mm during the fabrication.

### 3.2. Rupture of specimens

Failure positions of all the test specimens are listed in Table 4 and sketched out in Figure 5. Crack initiating from the weld toes of the rip stiffener’s end induced the failure of specimens (FE-1.0 and FE-2.0) with a comparatively small strain amplitude, shown in Figure 6(a), but the initiation of crack around the welded pins caused the failure of specimens (FT-1.0 and FT-2.0) with the same strain amplitude, shown in Figure 6(b), because the toe-finished method can effectively smooth the weld toes and reduce the stress concentration. The reason why the FT-1.0 specimen broke not cracked at the base of welded pins is that unloading was not applied in time when the strength of the brace member began to decrease and the crack had formed.
### Table 4: Test results of all the BRB specimens

| Series | Test specimen | $\Delta e/2$ | $\Delta e$ | $\Delta e_e$ | $\Delta e_p$ | $N_f$ | $n_i$ | CID | Failure position | Loading pattern |
|--------|---------------|--------------|-------------|--------------|-------------|-------|-------|-----|-----------------|----------------|
| S-I    | FE-1.0        | 0.01         | 0.02        | 0.003        | 0.017       | 111   | —     | 3.62 | Rib end         | Constant strain amplitude |
|        | FE-2.0        | 0.02         | 0.04        | 0.004        | 0.036       | 29    | —     | 1.99 | Rib end         | Constant strain amplitude |
|        | FE-3.0        | 0.03         | 0.06        | 0.005        | 0.055       | 14    | —     | 1.42 | At pin          | Plastic strain amplitude |
|        | FE-4.0        | 0.04         | 0.08        | 0.006        | 0.074       | 7     | —     | 0.96 | Near pin        | Plastic strain amplitude |
|        | FE-R          | 0.015        | 0.03        | 0.004        | 0.026       | —     | 5     | 2.04 | Near pin        | Variable strain amplitude |
|        |               | 0.025        | 0.05        | 0.004        | 0.046       | —     | 8     |      |                 |                             |
|        |               | 0.035        | 0.07        | 0.006        | 0.064       | —     | 1     |      |                 |                             |
|        |               | 0.03         | 0.06        | 0.005        | 0.055       | —     | 10    |      |                 | Variable strain amplitude |
|        | FT-1.0        | 0.01         | 0.02        | 0.004        | 0.016       | 168   | —     | 5.45 | At pin          | Constant strain amplitude |
|        | FT-2.0        | 0.02         | 0.04        | 0.004        | 0.036       | 42    | —     | 2.96 | Near pin        | Constant strain amplitude |
|        | FT-3.0        | 0.03         | 0.06        | 0.005        | 0.055       | 14    | —     | 1.52 | Near pin        | Plastic strain amplitude |
|        | FT-3.5        | 0.035        | 0.07        | 0.005        | 0.065       | 9     | —     | 1.18 | Near pin        | Plastic strain amplitude |
|        | FT-3(6)       | 0.03         | 0.06        | 0.005        | 0.055       | 12    | —     | 1.26 | Near pin        | Plastic strain amplitude |
| S-II   | FT-R1         | 0.01         | 0.02        | 0.004        | 0.016       | —     | 5     | 2.21 | Near pin        | Variable strain amplitude |
|        |               | 0.03         | 0.06        | 0.005        | 0.055       | —     | 10    |      |                 |                             |
|        | FT-R2         | 0.02         | 0.04        | 0.005        | 0.035       | —     | 8     | 2.60 | Near pin        | Variable strain amplitude |
|        |               | 0.01         | 0.02        | 0.004        | 0.016       | —     | 32    |      |                 |                             |

Note: $\Delta e/2$ = strain amplitude; $\Delta e$ = strain range; $\Delta e_e$ = elastic strain range; $\Delta e_p$ = plastic strain range; $N_f$ = number of failure cycles; $n_i$ = number of cycles at $\Delta e_i$ range; CID = Cumulative Inelastic Deformation.

Under the comparatively large strain amplitude condition, crack occurrence near the welded pins can be observed after the specimen tests (FE-3.0, FT-3.0 and FE-R etc), because of peak stress occurring in these areas caused by high-order buckling modes in the core plate weak-axis direction. It is shown in Figure 5: Crack positions of test specimens.

Figure 5: Crack positions of test specimens
Figures 6(c) and 6(d) that the cracks began to propagate at three places but the longest crack induced the specimens’ failure.

4. Fatigue curve For brbs

The strain-based evaluation of fatigue problems is widely used at present. The total strain range can be divided into elastic and plastic strain components, each of which has been shown to be correlated with fatigue life in a linear fashion using a log-log scale based on most metals’ experimental results. Manson-Coffin equations indicating the relationship between the number of failure cycles $N_f$ and the total strain range $\Delta \varepsilon$ can be obtained as follows (Stephens et al. 2001)

$$\Delta \varepsilon = C_e \cdot (N_f)^{-k_e} + C_p \cdot (N_f)^{-k_p}$$

(1)

Where $C_e$ and $k_e$ = constants that depend on the material. Considering that the elastic strain becomes small compared with the plastic strain and the total strain range is directly measured. Equation (1) can be approximately given by

$$\Delta \varepsilon = C \cdot (N_f)^{-k}$$

(2)

Figure 6: Photos of failure positions

Figure 7: Comparison of fatigue curves

Figure 7 compares fatigue curves obtained in the present tests with those obtained in BRB tests (Nakamura, 2000) and steel material tests (Nishimura 1978; Tateishi 2005; Saeki 1995). The fatigue curve of as-welded BRBs is almost consistent with that provided in the reference (Nakamura, 2000). The values of the failure cycle in the BRB tests are consistently smaller than those in the material tests at the same strain range. For example, the fatigue performance of the toe-finished BRBs is about 1/3 of that in the material tests conducted by Saeki (1995), probably because of influences of stress concentration around the welded pins, also mentioned in the reference (Nakamura, 2000). But it is obvious that the fatigue performance of the BRB specimens at the comparatively small strain range is improved by the toe-finished method and verified by the present tests.
5. Conclusions

In this study, experiments were carried out to address fatigue life problems about steel BRBs satisfying the performance requirements of HPSDs. The main results are summarized as follows:

1. Low-cycle fatigue tests were conducted to verify that all the specimens possess good fatigue performance and all the $CID$ values are far larger than the $CID$ limit value of the HPSD.
2. It was experimentally confirmed that the toe-finished method can effectively improve the fatigue performance of the steel BRBs under the comparatively small strain amplitude condition. The number of failure cycles of the FT-1.0 specimen with 1% strain amplitude increased by 50%.
3. The in-plane gap width between filler members and the brace member, as a key parameter, was experimentally confirmed to have an influence on the cumulative inelastic deformation performance. The $CID$ value of the FT-3(6) specimen decreased by 17% in contrast with the FT-3.0 specimen.
4. The comparison of fatigue curves between the full-scale BRB tests and the material tests shows that the values of $N_f$ in BRB tests are consistently smaller than those in the material tests at the same strain range.

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