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EXPERIMENTAL EVALUATION OF RC BRIDGE BENT UTILIZING BUCKLING RESTRAINED BRACES FOR SEISMIC RETROFIT

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ABSTRACT: Typical reinforced concrete bridge bents constructed in the 1950 to mid-1970 in the Pacific Northwest of the United States were lightly reinforced in the longitudinal as well as transverse directions and contained lap-splices with insufficient confinement in expected plastic hinge zones. In this study, the seismic performance of a deficient reinforced concrete bridge multi-column bent retrofitted using buckling restrained braces was experimentally studied. The buckling restrained brace was designed as a disposable element in order to dissipate energy during an earthquake event and protect the reinforced concrete elements which were designed to remain within the elastic range. A half-scale bridge bent was subjected to quasi-static cyclic loading protocols previously developed to reflect subduction zone earthquake demands. This paper presents the test setup, the loading protocol and discusses the experimental results of using buckling restrained braces as a retrofit measure for seismically vulnerable reinforced concrete bridge bents. The results showed that the overall bent was significantly stiffer than conventionally retrofitted, provided for ductile response without significant damage to the columns and could be a suitable retrofit measure for performance based dual-level design approaches.

1. Introduction

Over the years, earthquakes have exposed the vulnerability of reinforced concrete (RC) structures under seismic loads. The recent occurrence of highly devastating earthquakes near instrumented regions, e.g. 2010 Maule, Chile and 2011 Tohoku, Japan, has demonstrated the catastrophic impact of such natural force upon reinforced concrete structures. Typical reinforced concrete bridge bents constructed in the 1950 to mid-1970 in the Pacific Northwest were designed and built with minimum seismic considerations. This resulted in inadequate detailing within plastic hinge zones, leaving numerous RC bridge bents highly susceptible to damage following an earthquake. In order to overcome this deficiency, the present work presents experimental results of using buckling restrained braces (BRB) as a retrofit measure for multi-column reinforced concrete bridge bents.

Buckling restrained braces were introduce over two decades ago in the US and many experimental tests and post-earthquake reconnaissance in multi-story frame buildings have shown that these structures may be efficiently retrofitted using BRBs. However, the increasing use of this system for buildings has not been reflected in bridge structures.

The main characteristic of a BRB is its ability to have a stable hysteretic response through yielding in both tension and compression due to the prevention of global buckling (Clark, et al. 1999). This inherent property of stable hysteretic response, which may be translated to higher hysteretic energy dissipation, makes BRBs a good candidate in seismic retrofit applications. Fig. 1 illustrates a typical BRB anatomy.

This paper presents the experimental results of seismic performances of representative half-scale bridge bents retrofitted using buckling restrained braces in a diagonal configuration. Retrofitted and unretrofitted states were tested under subduction loading protocols in an effort to reflect the displacement demands in RC bridge bents subjected to subduction zone earthquakes. The braces were designed utilizing a structural fuse concept. In this concept, the main structural system is integrated with replaceable components in such a way to restrict the damage undergoing for the primary structure after a damaging earthquake (Connor, et al. 1997). The replaceable elements, which are the buckling restrained braces, were designed to take the earthquake-induced energy and dissipate it through nonlinear hysteretic behavior; meanwhile, the remaining structure is expected to behave elastically or with minor inelastic excursions.

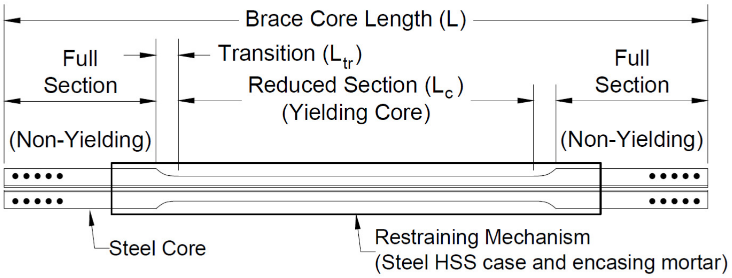


Fig. 1 – Anatomy of Buckling Restrained Braces (BRBs)

2. Experimental Program

2.1. General Description

In this study, the cyclic performance of a reinforced concrete bent retrofitted using buckling restrained braces (BRBs) was experimentally evaluated using quasi-static cyclic loading. The large-scale reinforced concrete bent specimen measured 3111 mm by 2997 mm and consisted of two circular cross section columns and a rectangular cap beam. The columns were subjected to constant axial load. The buckling restrained braces were designed as replaceable elements. The brace was secured to the frame using steel brackets (gusset plates) and post-installed adhesive anchors.

2.2. Reinforced Concrete Bent

The representative reinforced concrete bent corresponds to an existing RC multi-column bridge bent constructed in the 1950 to mid-1970 in Oregon. As many of the bridge structures built at that time in the Pacific Northwest, the bridge substructure was designed and built with minimum seismic considerations. This resulted in inadequate transverse reinforcement, no confinement, no seismic detailing, and lap-splices in the plastic hinge zone of the bent. The representative bridge bent consists of two circular columns per bent, a rectangular cap beam and rectangular pile cap footings. The column longitudinal reinforcement ratio is $\rho_L = 1.2\%$, which is barely above the minimum required by AASHTO ($\rho_L > 1\%$). Conversely, the column deficiencies are vast. The provided column shear reinforcement ($\rho_s = 0.2\%$) does not meet the code requirement ($\rho_s > 0.5\%$). The column confinement is almost inexistent since ϕ13 mm (#4) circular hoops spaced at 305 mm (12”) were provided. Moreover, lap splices can be found in expected plastic hinge zones and no seismic detailing was specified.

The RC bent used in the experimental program corresponds to a half scale model of the aforementioned representative bridge. Similitude laws were used in order to design the half scale RC bent hereinafter referred to As-built Bent. Table 1 illustrates the scaling process and includes relevant dimensions and reinforcement details for the test specimen. The RC bent specimen was constructed using concrete with a specified compressive strength (f'_c) of 23 MPa. However, an average measured compressive strength of 33 MPa was measured at the time of testing. The longitudinal steel was Grade 40 (276 MPa).

Table 1– Dimension of Representative Bridge and Test Specimen.

Parameter	Representative Bridge	Specimen
Column Diameter (mm)	914	457
Column Height (mm)	5689	2845
Beam Depth (mm)	1067	533
Beam Length (mm)	6096	2997
ρ_{Long} (%)	1.2	1.2
Hoop Spacing (mm)	305	152
ρ_{Trans} (%)	0.2	0.2
Lap splice (d_b) d_b: diameter of longitudinal reinf.	40	40
Concrete cover (mm)	50	25
Axial Load (% $A_g f'_c$)	10	10

2.3. Design of Buckling Restrained Braces

The design of BRBs followed the procedure described in Bazaez & Dusicka (2015), which uses a structural fuse concept as basis for design. The structural fuse concept states that the As-built bent would respond elastically under a damaging earthquake event. In order to fulfill this design concept and satisfy the dual performance criteria for existing bridges described in the FHWA (2006) guideline and in the Oregon Bridge Design and Drafting Manual (ODOT, 2014), the BRB needs to be designed in such way to reduce the displacement demands on the As-built bent under 500-year and 1000-year earthquake events. This reduction in displacement demand is called retrofit action and is illustrated in Fig. 2. In this figure, the BRB and the As-built RC bent responses are idealized through load-displacement curves. Relevant load-displacement parameters are the yield displacement (δ_y) and yield force (V_y) denoted by the superscripts BRB, B and R to designate the brace, As-built and retrofitted responses, respectively. The response of the retrofitted bent is no other than adding the contributions of the As-built bent and the BRB since both structural systems act in parallel. The design of BRBs is reduced to iterate until the BRB stiffness, the BRB steel core area and the length of the reduced section (L_c) are determined.

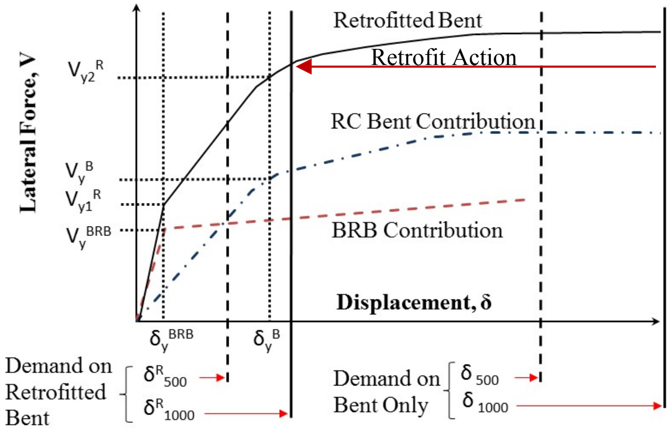


Fig. 2 – Retrofit design concept based on idealized load-displacement responses

Two BRB designs were considered in the study in an effort to assess the influence of BRB stiffness on the overall structural performance. The first BRB design, hereinafter referred to Model 1, was designed following the structural fuse concept. The second model, hereinafter referred to Model 2, was designed as a more flexible brace as compared to Model 1 in order to reflect a common industry practice where the reduced section is equivalent to two thirds of the total BRB length. For the braces, a yield stress of 305 MPa given by the BRB manufacturer, a brace angle (θ) of 48.7 degrees and BRB length of 3318 mm were considered appropriate for this application. The obtained parameters for the As built bent from pushover analysis were δ_y^B = 12 mm and V_i^B = 228 KN. A response spectrum with maximum spectrum acceleration (S_a) of 0.65g with a period at the end of constant design spectral acceleration plateau (T_s) equal to 0.49 sec for the 500-year event and 0.85g with Ts equal to 0.53 sec for the 1000-year event were considered. Such spectrum accelerations were assumed in an effort to represent acceleration demands of a vast number of bridges in the State of Oregon. The required BRB steel core areas and reduced section lengths (Lc) for both models are shown in Table 2. Table 2 also shows the displacement demands in the retrofitted bent.

Table 2– Results of BRB designs for Model 1 and 2.

Model	Steel area (mm^2)	Reduced Section (mm)	Displacement demand (mm)	
			δ^R_{500}	δ^R_{1000}
1	774	762	12	17
2	774	2250	19	27

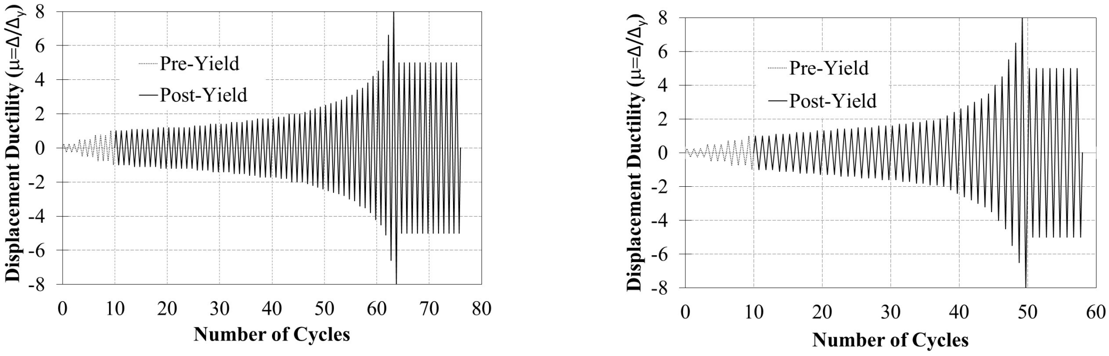
2.4. Connections

A novel gusset plate to RC bent connection was utilized in the experimental program. In this connection, the gusset plates were directly connected to horizontal RC elements without interfering with the columns. Post-installed adhesive anchors were designed for connecting the gusset plate to concrete elements. according ACI318 Appendix D (2011).

2.5. Loading Protocols

Loading of the test specimens was slowly applied using quasi-static cyclic loading protocols aiming to reflect subduction zone earthquake demands up to displacement ductility 8 as shown in Fig. 3 (Bazaez & Dusicka, 2014). The horizontal loads were applied under displacement control based on a pattern of progressively increasing displacements, referenced to the horizontal displacement to cause first yield (Δ_y) in the brace for the Bent/BRB structural system (Model 1 & 2) and in the columns for the as-built RC bent. The protocols subjected the Bent/BRB system and the as-built bent to cumulative inelastic deformations equal to 351 and 257 times the yield deformation Δ_y, respectively. These values of cumulative inelastic deformations are greater than that required in cyclic test for qualification of BRBs, which requires a cumulative inelastic deformation of at least $200\Delta_y$ (AISC, 2010).

Failure was defined as a 20% drop in peak lateral load for each specimen except for Model 1, which was tested up to the expected displacement demand under the 1000-year event, δ^R_{1000} = 17mm. Δ_y was theoretically determined from material properties for Models 1 and 2 and from pushover analysis for the As-built RC bent. Values of actual yield displacement were then corrected during each test.



(a) (b)

Fig. 3 – Loading Protocol for: (a) Bent/BRB structural system. (b) As-Built RC Bent

2.6. Experimental Setup and Instrumentation

The experimental setup consists of a half scale model of a typical RC bride bent retrofitted using buckling restrained braces in a diagonal configuration, namely Model 1 and Model 2. The braces in both models have the same material properties and cross-sectional area of steel core within the reduced section. However, they differ in length of the reduced section (L_c). The cyclic lateral loading was applied through a horizontal hydraulic actuator capable of applying a maximum load of 980 KN in tension and 1330 KN in compression. The actuator was connected to a steel beam on the cap beam. The lateral force was applied under displacement control and load cells were used to monitor the applied load during testing. To simulate the gravity load on bridge columns, 10% of the column axial capacity (0.10f'cAg) was applied through two high-strength rods and hydraulic rams attached to a horizontal steel beam located on top of each column. A six degree of freedom (6DOF) load cell was connected at midspan of the cap beam in order to measure the internal forces that are transmitted from one side of the bent to the other. The footing was secured to the laboratory floor with post-tensioning rods. A schematic representation of the test setup is shown in Fig. 4.

Strain gages were used to measure the strain at specific points in the specimens. All strain gauges were installed at expected plastic hinge zones. LVDTs were used to measure displacements of specified points on the specimen.

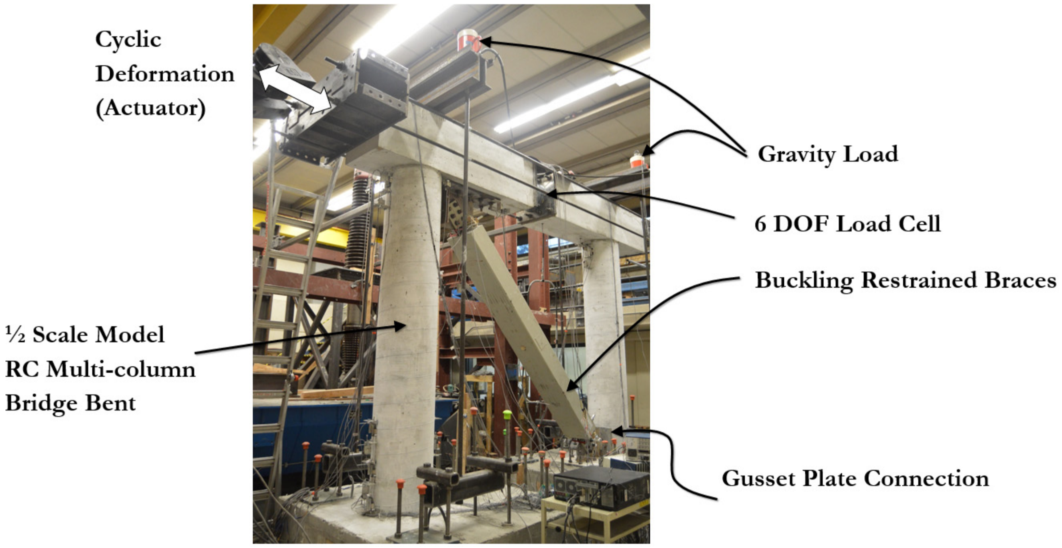


Fig. 4 – Experimental Test Setup

3. Test Results

3.1. RC Bent/BRB Model 1

The lateral load vs. displacement hysteresis curve (shown in Fig. 5) for this specimen indicates high ductile behavior and energy dissipation. Model 1 exhibited a ductile behavior up to a ductility value of 8, which was the maximum ductility considered in this case. The theoretical yield displacement of the brace was computed as 1.8 mm. However, this yield displacement was corrected during the test in an effort to accommodate the actual response of the test specimen. The experimental yield displacement was 2.1 mm, which is a 17% increase with respect to the theoretical value. The first horizontal crack of width less than 0.05mm occurred at a displacement of 6.3 mm and a lateral load of 350 kip approximately. The peak lateral load was 503 KN and occurred at a lateral displacement of approximately 17 mm. The specimen did not exhibited a significant decrease in lateral strength. At the end of the test, only horizontal hairline cracks of width 0.05mm were observed at the base and top of columns as shown in Fig. 6. Once the BRB was removed from the RC bent, it was observed that the gusset plates did not present any trace of damage. The brace was opened in order to observe the damage presented in the steel core. Fig. 7 shows the damage undergoes by the steel core, in which is observed little damage in the intersection between the transition section (L_{tr}) and the reduced section (L_c). This damage is attributed to high stress concentrations from changing the cross sectional shape of the steel core.

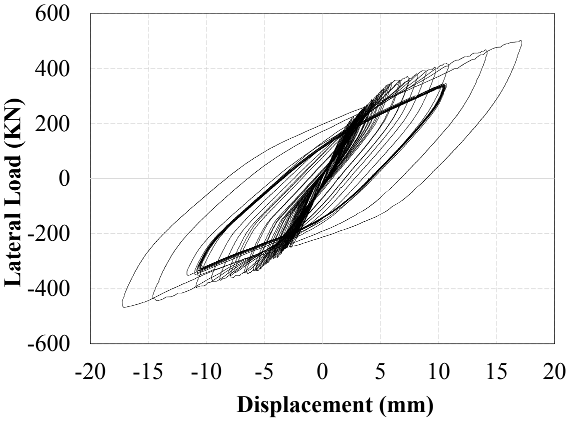
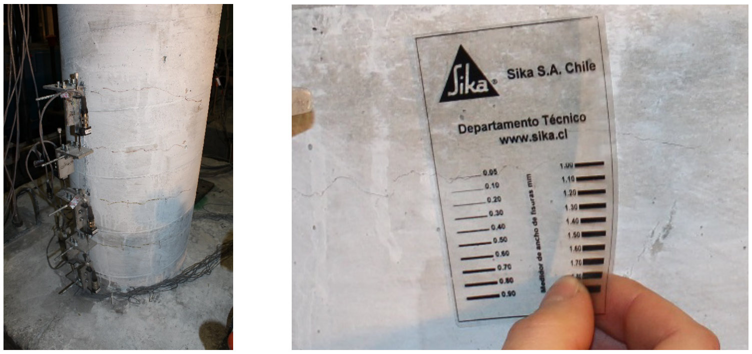


Fig. 5 – Load vs Displacement response of RC Bent/BRB Model 1



(a) (b)

Fig. 6 –Damage in RC Bent Model 1. (a) Horizontal crack pattern. (b) Crack width.

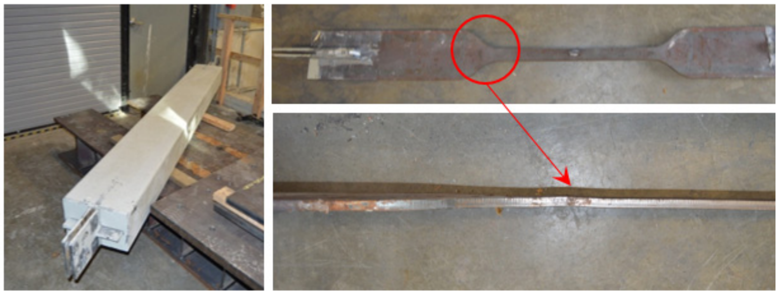


Fig. 7 –Damage in BRB Model 1

3.2. RC Bent/BRB Model 2

Fig. 8 shows the lateral load vs. displacement hysteresis curve for this specimen. The curve indicates high ductile behavior and energy dissipation up to a ductility value of 4.5, which is equivalent to a displacement of 33 mm. The theoretical yield displacement of the brace was computed as 5.2 mm and the experimental one was 7.3 mm, which is a 40% increase with respect to the theoretical value. The horizontal cracks during the test formed throughout the expected plastic hinge zones of the columns and progressed in length and width as shown in Fig. 9(a). The maximum horizontal crack width was 0.4mm. Vertical cracks (width less than 0.6mm) were registered in the cap beam in negative moment areas. As the progressively increasing displacements were applied, the lateral load increased up to 463 KN for the brace compression direction. From that displacement forward, the specimen exhibited a significant decrease in lateral strength during the compression half-cycles. Presumably, buckling of the steel core started developing at this point giving place to fracture of the steel core once the BRB was tensioned after a cycle in compression as shown in Fig. 8. Once the BRB failed, all the load capacity was carried by the As-built RC bent capacity without considering the BRB contribution.

The peak lateral load was 511 KN and occurred at a lateral displacement of approximately 30 mm. At the end of the test, minimal spalling of concrete at the base of the columns was observed as illustrated in Fig. 9(b). Once the BRB was removed from the RC bent, the gusset plates were inspected and did not exhibit any trace of damage. The brace was opened in order to observe the damage presented in the steel core. Fig. 10 shows the damage undergoes by the steel core, in which is observed the fracture of the steel core. Even though, this specimen was designed to sustain a maximum displacement of 68.5 mm, the fracture of the steel core occurred at a lateral displacement of 30 mm. This mode of failure was attributed to poor confinement in the transition section (L_{tr}) within the brace.

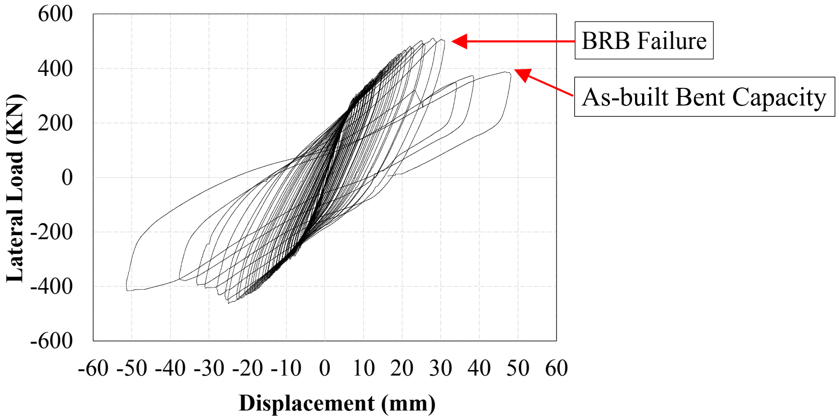


Fig. 8 – Load vs Displacement response of RC Bent/BRB Model 2

(a) (b)

Fig. 9 –Damage in RC Bent Model 2. (a) Horizontal cracks. (b) Spalling of concrete.

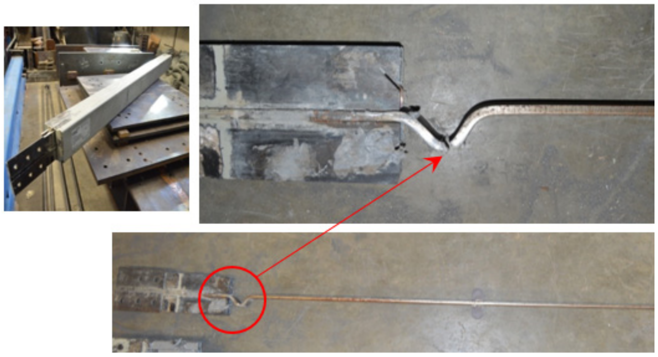


Fig. 10 –Damage in BRB Model 2

3.3. As-Built RC Bent

Despite all the deficiencies of the As-built RC bent, this bent exhibited a moderately ductile behavior. The initial damage consisted of horizontal cracks that were propagated throughout the height of expected plastic hinge zones to give place to spalling of concrete in early stages. Vertical cracks in the beam increased in width up to 0.8 mm. The ultimate mode of failure was crushing of concrete and buckling of steel reinforcement at the end of testing. Crushing of the concrete at the base and top of the columns began due to flexural loading, exposing the column reinforcement. Once the concrete cover was lost, the longitudinal bars in those regions began to buckle and finally facture as shown in Fig. 12(a) and Fig. 12(b), respectively.

The theoretical yield displacement of the bent was computed using a pushover analysis, which resulted in a yield displacement equal to 12.2 mm. However, this yield displacement was then corrected during the test. The experimental yield displacement was 13.7 mm, which is a 12% increase with respect to the theoretical value. The experimental yield displacement was determined by using strain gauge measurements at the base and top of the columns.

The lateral load vs. displacement hysteresis curve (shown in Fig. 11) for this specimen indicates reasonable ductile behavior and energy dissipation. The As-built RC bent was able to attain a maximum displacement of 125 mm before the applied load dropped below 80% of the peak load. The peak lateral load was 311 kips and occurred at a lateral displacement of approximately 62 mm. It is worth mentioning that the initial stiffness of the As-built bent is lower since stiffness degradation occurred when the bent was previously tested in a retrofitted state.

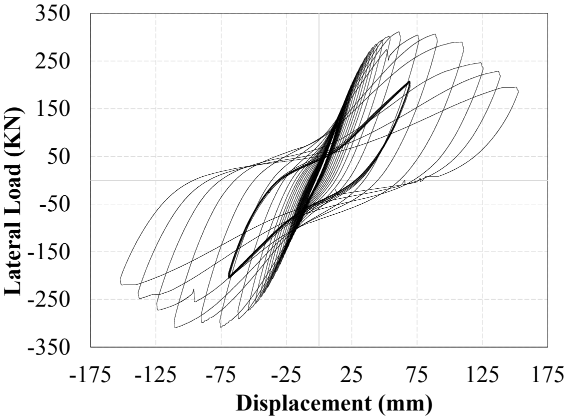


Fig. 11 – Load vs Displacement response of As-built RC Bent

(a) (b)

Fig. 12 –Damage in As-built RC Bent. (a) Buckling of steel. (b) Rupture of steel.

4. Conclusions

This contribution presents the experimental results of seismic performances of seismically deficient bridge bents retrofitted using buckling restrained braces in a diagonal configuration. Retrofitted and unretrofitted cases were tested using cyclic loading protocols representative of the displacement demands in RC bridge bents subjected to subduction zone earthquakes. The retrofitted RC bridge bent was designed to perform elastically or with minor inelastic excursions within the original bent throughout the different seismic hazard design levels. Two BRB designs were considered in this study in an effort to assess the influence of BRB stiffness on the overall structural performance. A novel gusset plate to RC bent connection was used, in which the gusset plates were directly connected to the horizontal RC elements without interfering with the columns.

The results of these large-scale experiments successfully demonstrated the effectiveness of utilizing buckling restrained braces for achieving high displacement ductility of the retrofitted structure, while also controlling the damage of the existing vulnerable reinforced concrete bent up to the design performance levels. No damage was observed in the connection regions of the brace throughout the loading history, leaving the potential for replaceability of the sacrificial BRB element. The potential for improving the overall seismic behavior and the design performance levels with BRBs offers bridge design professionals a viable method for performance driven retrofit of multi-column reinforced concrete bridge bents.

The results also indicated that despite the detailing deficiencies of the multi-column RC bridge bents built before 1970 in the Pacific Northwest, the cyclic response of the unretrofitted bent exhibited moderately ductile performance. The moderately ductile performance is likely a result of a relatively long lap splice length ($40d_b$), and low axial column loads (0.1 f'c Ag).

5. Acknowledgements

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