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Subassemblage tests and finite element analyses of sandwiched buckling-restrained braces

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ABSTRACT

This study presents the experimental and finite element analysis results of a proposed steel buckling-restrained brace (BRB). The proposed BRB has two components: (1) a steel core plate that carries all axial forces during tension and compression, and (2) two identical restraining members that sandwich the core plate with fully tensioned high-strength A490 bolts to prevent core buckling. Instead of using unbonded material, a small air gap is provided between the core plate and the restraining members to allow for lateral expansion of the core plate under compression. Since two restraining members can be disassembled easily by removing the bolts, a damaged steel core can be replaced after a large earthquake. Thus, manufacturing new restraining members is not required. Four BRB subassemblages were tested to investigate the inelastic deformation capabilities and verify the stability predictions for the braces. Test results indicate that three BRBs with sufficient flexural rigidity of the restraining member develop (1) stable hysteretic responses up to core axial strains of 2.1%–2.6%, (2) maximum compressive loads of 1724–1951 kN (1.4–1.6 times the actual yield load), and (3) a cumulative plastic ductility that is much higher than that specified in AISC seismic provisions (2005). One BRB, intentionally designed with inadequate flexural rigidity of the restraining member, experienced global buckling as predicted. Nonlinear finite element analysis was conducted for each BRB for a correlation study. The objective of the analysis was to conduct a parametric study for different BRBs to further verify the effects of restraining member size, number of bolts, core plate length and cross-sectional area on buckling load evaluation. The design procedure for the sandwiched BRB was provided based on test and finite element analysis results.

1. Introduction

Buckling-restrained braced frames (BRBFs) for seismic load resistance have been increasingly used in recent years [1–3]. A BRBF differs from a conventionally braced frame because a buckling-restrained brace (BRB) yields under both tension and compression without significant buckling. Numerous tests have been applied to different BRBs [4–12]. A typical BRB has a steel core encased in a restraining member consisting of a steel tube filled with concrete or mortar. A thin layer of an unbonded material is provided between the steel core and the surrounding concrete interface to eliminate force transfer and allow for lateral expansion of the steel core under compression [4–8,10–14]. Thus, the surrounding restraining member behaves as a continuous lateral bracing for the steel core. Such a BRB with an unbonded material as an interface to prevent adherence between the steel core and concrete has problems associated with quality control during manufacturing and flexibility at both ends of the BRB [10].

This study proposes a sandwiched BRB (Fig. 1) that eliminates the use of unbonded material in the manufacturing process and increases the number of design alternatives at both ends of the core plate for gusset connections. Two identical restraining members are formed by welding a steel channel to a flat plate (face plate) and then filled with concrete or mortar. Unlike conventional BRBs [4–10,12–14] that have a steel core inserted into a restraining member, sandwiching a core plate between a pair of restraining members using fully tensioned high-strength A490 bolts expedites the assembly process. Adding additional washers or a thin plate between the side plate and the face plate provides a small air gap between the core plate and face plate, allowing for expansion of the core plate under compression. There are two advantages to the proposed BRB over other conventional braces [4–10,12–14]. The first is the ability to disassemble the brace, which not only means that the core plate can be replaced independently of the restraining members, but also provides an opportunity for inspection of the

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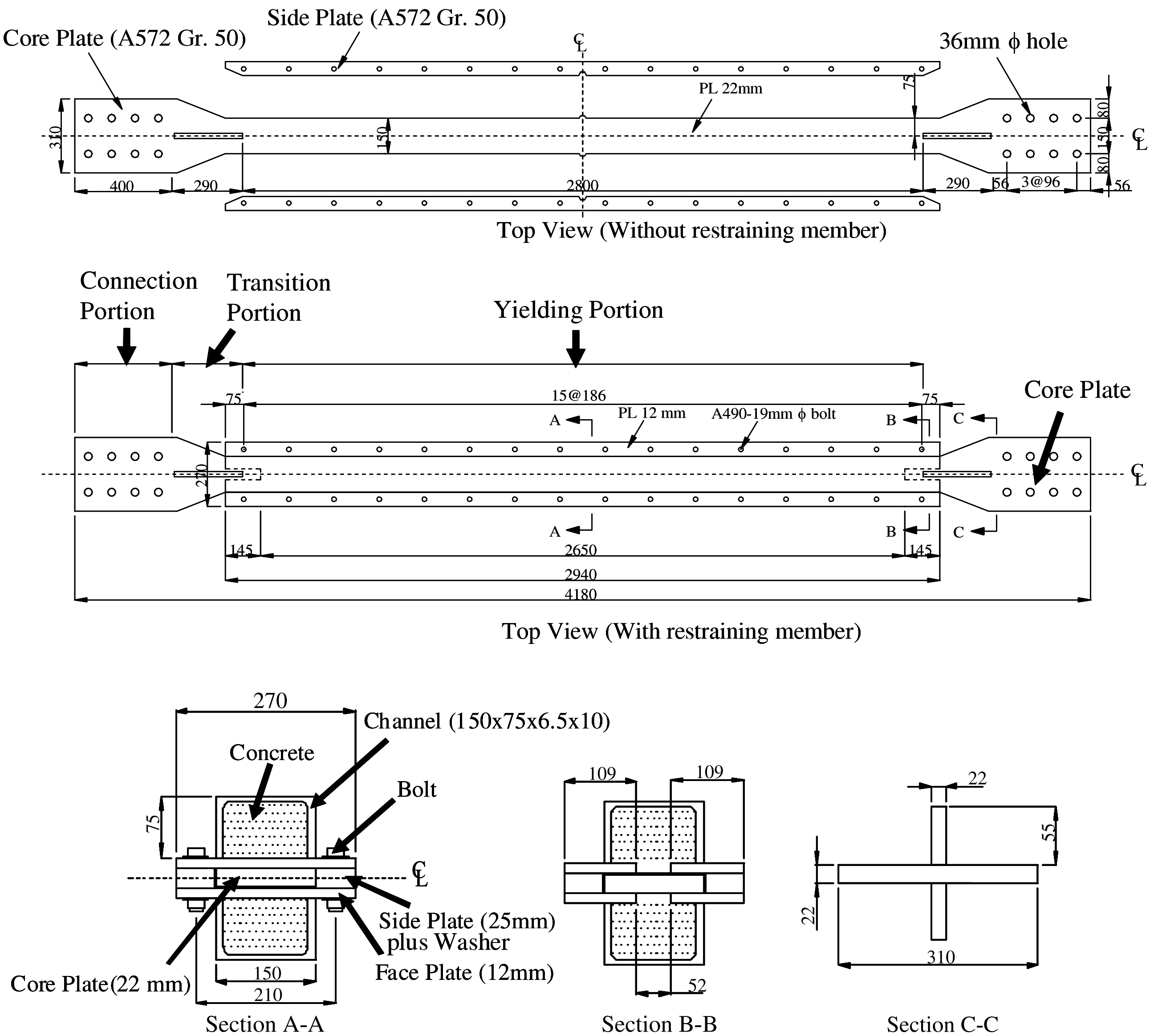

Fig. 1. Proposed buckling-restrained brace.

core. This is beneficial after a large earthquake or if used in an application such as a bridge superstructure [15] where high cycle fatigue is a concern. In case the core plate is damaged, replacing the core plate with recycle of restraining members of the proposed BRB is much cheaper than other conventional BRBs. The second is that in using conventional materials and providing a rational design basis, it opens up the opportunity for more widespread usage of BRBs, reducing the need for specialized design or fabrication. This, in the past, has limited the use of BRBFs unfairly over other poorer performing systems that require less performance verification. Furthermore, the core plate and restraining members can be delivered separately for on-site erection. A semi-circular tube may substitute for a rectangular channel to enhance architecturally appealing of the restraining member. A potential disadvantage of the proposed BRB is that it is slightly expensive with more parts (i.e. bolts) to assemble than some others in the first application.

Tests were conducted on four proposed BRBs designed with three performance parameters—moment of inertia of the restraining member and number and spacing of bolts. The test program investigated (1) the deformation capability of the proposed BRBs based on AISC loading protocol [16], (2) whether buckling load of the BRB could be estimated based on the proposed methodology, and (3) the effects of restraining member size and number of bolts on BRB cyclic behavior. Nonlinear finite element analysis was conducted for each BRB for correlation analysis. The objective of the analysis was (1) to conduct a parametric study of different BRBs to verify the effectiveness of the restraining member and number of bolts in preventing steel core buckling, and (2) to study the effects of BRB length and cross-sectional area on buckling load variation. This work presents the behavior of the sandwiched BRB experimentally and analytically, and provides a design procedure for this BRB [17,18].

2. Buckling-restrained brace design

Global stability of the BRB is estimated using the Euler theory of buckling. Fig. 2(a) shows the schematic of the proposed BRB in compression; the bending moment at the center of the restraining member is

$$M_{cent} = \frac{i + g + e}{1 - \frac{P_{\max,g}}{P_e}} P_{\max,g} \quad (1)$$

where i $(= L/1000)$ is the initial imperfection at the center of the BRB, g is the gap between the core plate and restraining