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Local buckling behavior of steel angle core members in buckling-restrained braces: Cyclic tests, theoretical analysis, and design recommendations

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ABSTRACT

The local stability of buckling-restrained braces (BRBs) is one of the most concerned issues. However, few discussions were conducted on the BRBs using section steel or welded cruciform core members, and the currently proposed methods concentrated on the design of casing only. In this study, incremental cyclic tests were conducted on eight BRB specimens using steel angle core members. Key parameters included the core width-to-thickness (b/t) ratio and the gap between the core and the casing. The test results show that two types of local buckling modes of the core were observed, while no local failure of the casing induced by local buckling was found. Significant local buckling and cyclic deterioration behavior were observed for the specimens with the b/t ratio of around 8.5 when the axial core strain reached 1.4%, causing 13% reduction in energy dissipation. Local buckling waves tended to concentrate near the core ends with enlarged buckling amplitudes due to the friction and uneven gap. The ratio between buckling amplitude and buckling half-wave length is found to be a governing parameter for BRB seismic performance. This ratio is recommended to be smaller than 0.04 to ensure stable cyclic behavior. The analytical model for the local stability of steel angle core members is proposed and the inelastic local buckling critical load is obtained. The analytical results show good agreement with experiment. Three re-defined general requirements for BRB local stability design are proposed, and the design recommendations for the steel angle core members are provided. Several implications of this study to other BRB configurations are presented finally.

1. Introduction

Buckling-restrained braces (BRBs) have been widely implemented into engineering structures in seismic-prone areas to minimize structural damage under severe earthquakes. With the restraining effect of the outer buckling–restraining mechanism (hereafter called casing), the inner steel core can yield both in tension and compression, thus exhibiting stable cyclic behavior. To realize this goal, preventing significant buckling of steel core members is of crucial importance.

Four types of cross-sections, i.e., rectangular core plate (see Fig. 1(a)), welded sections (see Fig. 1(b)), section steels (see Fig. 1(c)–(e)) and solid circular sections [1] (see Fig. 1(f)), can be used as typical BRB core members in engineering applications. Based on previous studies, it was often found that local buckling of the core plate in the weak or strong axis direction (see Fig. 1(a)) was prone to occur due to the local failure of casing [2–6]. Numerous researches on the local buckling condition of core plate and the design criteria to prevent the local failure of casing were reported [2,4,5,7–9]. Recent researches [10,11] showed that significant local buckling of the core plate would deteriorate the low-cycle fatigue performance of BRBs due to strain concentration even though the local failure of casing was successfully avoided. Ensuring even strain distribution along the core yielding portion by limiting the gap or core width-to-thickness ratio is important to avoid significant local buckling of the core plate [12–14]. These findings highlighted the importance to limit the local buckling amplitudes of the core plate and the necessity to consider this effect into design. This is especially important for the BRBs used as energy dissipation fuses to the structures.

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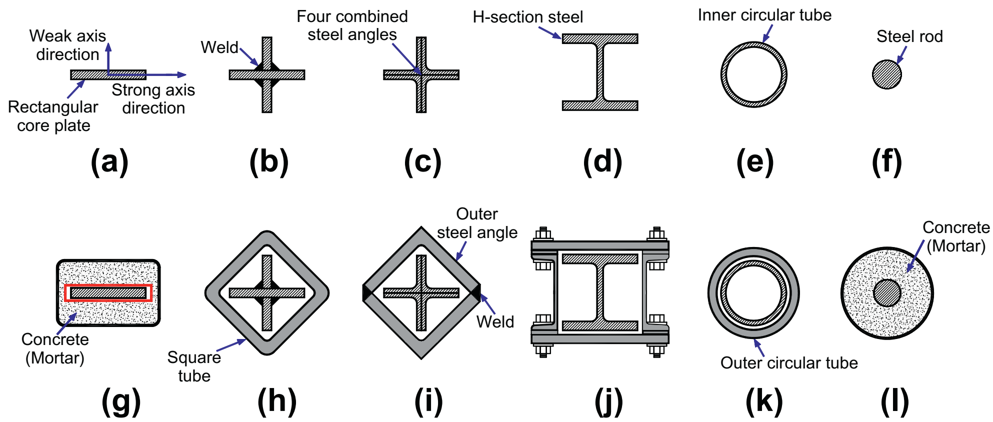

Fig. 1. Typical BRB sections.

On the other hand, local buckling was also reported for the section steel or welded core members in BRBs (see Fig. 2) [15–20] even though the flexural stiffness of the whole core section is significantly enlarged compared with that of the core plate section. However, the low-cycle fatigue performance of the BRBs using welded cruciform core section (see Fig. 1(h)) was only concerned [15,21]. Discussion on the local stability of the cruciform core member has not been reported. A simplified formula governing the interrelationship among the brace ductility, the ratio of maximum compressive force to yield force, and the width-to-thickness ratio of the flange plate in H-section steel core member was obtained by Usami et al. [17] based on multiple regression of experimental results. However, the local buckling condition from theoretical view and the effect of buckling amplitude on the BRB seismic performance have not yet been examined. A series of researches on the local stability of circular tube core member restrained by an outer tube (see Fig. 1(k)) were conducted by Suzuki et al. [19] and Takeuchi et al. [20]. It was suggested that to avoid local failure of the outer tube, the maximum gap should be smaller than 7% of the inelastic buckling half-wave length of the inner tube [20].

From the above summary, it is clear that most of the researches focused on the local stability of the BRBs using core plate or circular tube core member, and the currently used local stability design criteria concentrated on the design of casing only. Few discussions on the welded or section steel core members in BRBs have been reported. Particularly, the issues regarding the local buckling conditions of welded or section steel core members, the characteristics of local buckling behavior, and the effect of local buckling amplitudes on BRB seismic performance have seldom been discussed. These are key issues that need to be resolved prior to the practical use of these BRB members as energy dissipation fuses to the structures.

2. Research objectives

Angle steel BRB (ABRB), as shown in Fig. 1(c) and (i), is a new type of all-steel BRBs proposed by the authors to minimize the negative effect of welding on the seismic performance of welded cruciform core section [22]. A series of cyclic tests of sixteen ABRB specimens were conducted [22,23] and the test results showed that the ABRB exhibited stable cyclic behavior with a maximum core strain of 3% and a cumulative plastic ductility capacity of 1068. The design criteria and practical design methods for the core end stability and global stability of ABRBs were also proposed [24–26]. These studies verified the feasibility of the practical use of ABRB as energy dissipation fuses.

This paper, as an extension of the authors' previous work [22–27], aims to further investigate experimentally and theoretically the local buckling behavior of steel angle core members in ABRB. The local buckling condition and the effect of local buckling amplitudes on BRB seismic performance are two concerned issues in this study. To this end, eight ABRB specimens were tested under incremental cyclic loading, in which the effect of core width-to-thickness ratio, the gap between the core and the casing, and the thickness of the casing were considered. In the following sections, the test results regarding the cyclic behavior, the failure modes, and the local buckling behavior of the core members are first presented. The key factors affecting the core local buckling and the effect of local buckling amplitudes on BRB seismic performance are discussed. The local buckling condition of steel angle core members is derived theoretically and verified by experiment. Three re-defined design requirements for the BRB local stability are proposed and the corresponding design recommendations for steel angle core members are presented. Implications of this study to other BRB configurations are discussed finally.

3. Test program

3.1. Specimens

Eight ABRB specimens labeled ABRB-1 to ABRB-8 were designed. The specimen configurations are shown in Fig. 3. The material properties and parameters of the specimens are presented in Tables 1 and 2, respectively. All the steel angle components were cut from commercially supplied section steel angles by cold

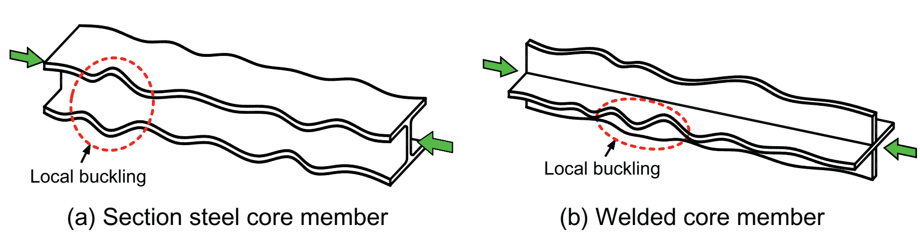

Fig. 2. Typical local buckling configurations for section steel and welded core members.