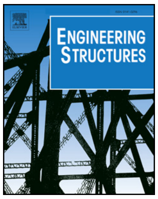
Engineering Structures 174 (2018) 126–138

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct



Core behavior and low-cycle fatigue estimation of the Perforated Core Buckling-Restrained Brace

X. Cahís[a,*], E. Simon[a], D. Piedrafita[a], A. Catalan[b]

[a] Department of Mechanical and Construction Engineering, University of Girona, Girona, Spain
[b] Department of Construction, University of Oviedo, Gijón, Spain

ARTICLE INFO

Keywords:
Buckling-restrained brace
Hysteresis damper
Energy dissipation
Low-cycle fatigue
High-mode buckling
Buckling wavelength

ABSTRACT

The Perforated Core Buckling-Restrained Brace (PCBRB) is an all-steel BRB whose core has been split into two lateral bands connected by stabilizing bridges. The core, with a constant cross-section perimeter, can slide along the restrainer so that it can be inspected or replaced by simply removing a centering pin. We analyzed the behavior of two different Perforated Core (PC) geometries which we tested to failure with different load protocols of several maximum deformation amplitudes. The main difference between both geometries was the radius of the lateral band connections. The experimental results show how a low radius, despite offering a higher constant cross-section yielding length, leads to a lower dissipation capacity and to a closer distance between stabilizing bridges. The results also show a gradual drift of the internal and the external lateral band segments into permanent negative and positive elongations, respectively, which increases the minimum gap required between the core and the restrainer. We also analyzed the in-plane and the out-of-plane wavelength of the high-mode buckling of the PC and validated two wavelength prediction equations that would prevent the uncontrolled second-order deformations and the buckling failure of the PC. Finally, based on experimental data, we propose two low-cycle fatigue relationships for the PCBRB that would be valid for elastoplastic devices with uniform uniaxial strain distribution, such as BRBs and TADAS devices.

1. Introduction

Unexpected and severe earthquake damage in structures in the early seventies prompted research into exchangeable dissipation energy devices [1]. Of such devices, Buckling-Restrained Braces (BRBs) are some of the most widely investigated and fitted. These devices were first installed in Japan in the late eighties and their use has since expanded all over the world [2–4] thanks to their simplicity and reliable energy dissipating capacity [5–7]. BRBs have mostly been fitted as part of Buckling-Restrained Braced Frames (BRBF) – a concentrically brace frame system with BRBs as braces – although they have also been used to upgrade bridges [8] and retrofit existing structures [4,9].

BRBs are elastoplastic energy dissipation devices composed of a steel core, which resists the axial load and dissipates energy through plastic deformation, and a restraining unit, which wraps around the core thus preventing it buckling under compression. BRBs can be classified as conventional or all-steel BRBs. Conventional BRBs have a buckling-restraining unit (referred to as a restrainer from here on) comprised of a hollow steel tube filled with concrete, and their core is coated with a debonding material which allows for their transversal expansion in compression and guarantees a constant gap between the core and the concrete. A tight gap (less than 2 mm) has been found to reduce the high-mode buckling outward forces between the core and the restrainer, thus allowing for higher strains on the core [10]. All-steel BRBs have neither a concrete filling (making them lighter than conventional BRBs) nor a debonding coat, as these are replaced with an air gap. While this undoubtedly simplifies manufacturing and quality control processes, all-steel BRBs must assure a tight gap which is not easy to achieve with standard steel profiles.

Another advantage to all-steel BRBs over conventional BRBs is that, if required, some of them can have their core inspected or even replaced. That said, these ‘inspectable’ all-steel BRBs do require a detachable restrainer, usually clamped with bolts, as they have a dog-bone shaped core installed inside them [10–14]. The Perforated Core Buckling-Restrained Brace (PCBRB) [15] on the other hand, substitutes the dog-bone shaped core with one of a constant rectangular cross-section perimeter whose yielding part has been split into two lateral bands connected by stabilizing bridges (Fig. 1). This new design permits a non-detachable restrainer – as an assembly of welded parts - which enables the core to be inspected or replaced by simply removing a

---

[*] Corresponding author.
E-mail address: xavier.cahis@udg.edu (X. Cahís).

https://doi.org/10.1016/j.engstruct.2018.07.044
Received 5 February 2018; Received in revised form 9 June 2018; Accepted 16 July 2018

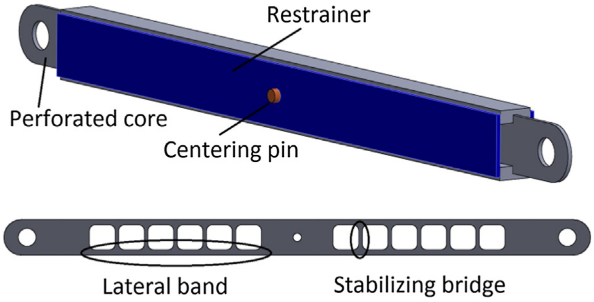


Fig. 1. The Perforated Core Buckling-Restrained Brace (PCBRB).

centering pin and sliding the core along the restrainer guides, i.e. without the need to unbolt any of the restrainer components.

Despite the vast amount of research into BRBs, (e.g. global and local buckling prevention [11,16–18], high-mode buckling effects [11,12,19–21] and equivalent elastic stiffness and specific hysteretic models for numerical structural analysis [22–24]), the low-cycle fatigue of BRBs has been related to the classic Manson-Coffin formula [14,25] originally proposed for constant stress amplitude cycling. Using this model for random amplitude cycling requires counting algorithms, such as the rain flow method [2,26], to obtain equivalent blocks of cycles of constant amplitude to ultimately assess the damage. Miner's cumulative damage index is typically used for this [27]. In these cases, the use of the dissipated energy and the cumulative plastic deformation becomes more direct and easier to implement than cycle counting [28,29]. In considering this approach, Benavent [30,31] proposed that the ultimate energy dissipation capacity of elastoplastic energy dissipators is determined by the consumption of the skeleton curve, understood as the part of the hysteretic response that increases the force response by steel hardening. Through experimental tests on BRBs, Tsai et al. [22] determined that that the cumulative plastic deformation could be related to the maximum plastic deformation in a potential function.

From this research, we further tested and analyzed the behavior of the Perforated Core (PC) of the PCBRB [15]. We compared the high-mode buckling wavelength obtained from the numerical and the experimental responses as well as the influence the strain has on the wavelength. Besides this, and departing from the low cycle relationship obtained by Tsai et al. [22], we propose two low-cycle fatigue models for the PCBRB.

2. Experimental tests

2.1. Specimen geometry and materials

Fig. 2 and Table 1 define the geometry and dimensions of the newly and formerly tested [15] PC specimens. The two series of specimens, whose steel mechanical characteristics are detailed in Table 2, were manufactured from a single steel sheet using a habitual laser cutting process.

As part of this study, we aimed to obtain an as general as possible, low-cycle fatigue expression for mild steel yielding cores, so we selected a new steel grade for the new specimens. We also wanted to study the effect of decreasing the radius between the lateral bands and the stabilizing bridges while maintaining similar lateral band lengths L_{lb}. This would mean, on the one hand, that the new specimens would have a higher ratio of the constant cross-section length to the lateral band length nL_a/L_{lb}, where n is the number of windows (perforations) between the lateral bands, which might result in a higher energy dissipation capacity. On the other hand, decreasing the radius might increase the strain concentration effect and have a contrary effect on the energy dissipation capacity. Furthermore, an increase in the radius would increase the total laser-cut window length to the lateral band length nL_s/L_{lb}. This would also increase manufacturing costs.

To define the gap between the core and the restrainer, we assumed that all-steel BRBs with gaps between 1 and 2 mm offered good hysteretic responses [10,22]. We also considered that a gap larger than the required would increase the normal thrust on the restrainer and thus the friction forces [21,32]. Something which was not at all desirable. Finally, the gap had to allow the core to freely expand transversally under compression. The design and manufacturing of the PCBRB tested allowed for tight mounting tolerances because the core was laser-cut and guided by milled slots in the restrainer. To define the gap, we first estimated the maximum compressive strains of both PC specimens [22]:

$$\varepsilon_c \cong \theta \frac{\sin 2\phi}{2}\frac{L_{wp}}{L_c} \tag{1}$$

where θ is the interstory drift ratio, ϕ is the BRB inclination, L_c is the core length and L_{wp} is the work-point-to-work-point length of the brace. Considering our test setup and loading conditions (Section 2.2), the maximum θ was 1% and $\phi = 45^\circ$. We considered $L_c = nL_a$, as we considered the plastic strain to be mainly concentrated in the constant cross section length of the lateral bands, and $L_{wp} = L_b = 3533$ mm, where L_b was the length of the PCBRB between its pinned connections [33]. From Eq. (1) we obtained an estimation on the average maximum compressive strain of 3.4% and 5.4% for specimens PC-r5 and PC-r45, respectively. From these values we then obtained the transversal deformation for both directions:

$$g_{i,min} = \varepsilon_c \nu t_i \tag{2}$$

where ν is the Poisson ratio (0.5 in plastic deformation) and t_i is the thickness of the yielding core cross-section in the i-direction. In the case of the PCBRB (see Fig. 2), $t_i = 2b$ on the plane of the core and $t_i = t$ in its normal direction. Expression (2) offered values of $g_{i,\min} = 0.68$ mm and $g_{o,\min} = 0.17$ for PC-r5, and $g_{i,\min} = 1.08$ mm and $g_{o,\min} = 0.27$ for PC-r45. We provided a 1 mm gap in both directions, (mainly because of manufacturing and mounting considerations), which gives enough room for expansion in the out-of-plane core direction. We considered that slightly overpassing the in-plane gap requirements would not be an issue as the lateral bands could freely expand except in the stabilizing bridge zones, where strains were expected to remain much lower than those in the constant cross-section lateral band segments.

2.2. Test setup and instrumentation

The test setup, the BRB restraining unit, the auxiliary testing components and the instrumentation that were used to test the new PC geometry are the same as those used on the previously tested core specimens and their precise details are described elsewhere [15]. As a PCBRB (Fig. 1) is expected to behave symmetrically we tested the PCBRB specimens with half of their usual core (Fig. 2). Before the brace was assembled, the lateral bands of the core were greased by hand with KP2P-30 grease lubricant as DIN 51502. The PCBRB was pinned to a strong floor and to a column (Fig. 3). A servo-controlled hydraulic jack equipped with a load cell and a displacement transducer applied the horizontal displacement loads to the column-to-brace joint. The main parameters recorded were the load applied by the hydraulic jack and the global deformation of the lateral bands. The total deformation of the lateral bands was measured by the transducer IDT-1, which was fixed to the solid core as shown in Fig. 4b. We used two additional internal displacement transducers on specimen PC-r5-1 (identified as IDT-2 and IDT-3 in Fig. 4) to measure the local deformation of the outermost and innermost lateral band segments of the core. The specimens PC-r5-1 and PC-r45-1 were tested with the AISC 341-16 [36] qualifying protocol (Fig. 5a) considering the minimum design interstory drift ratio (1%) and a 3 m-high floor. The rest of specimens were tested under consecutive sequences of the EN 15129 [37] qualifying protocol (Fig. 5b), where different maximum displacement values were assigned (see Table 3) in order to calibrate the low-cycle fatigue models.