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Cyclic behavior of continuous reinforced concrete haunched beams with transverse reinforcement designed to fail in shear

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HIGHLIGHTS

- Reports the cyclic testing of continuous RCHBs failing in shear.
- Cracking is more widespread and distributed in RCHBs than in prismatic beams.
- Strength degradation in RCHBs is less abrupt than in prismatic beams.
- In RCHBs, stiffness degradation decreases as the haunched angle increases.
- Dissipated hysteretic energy per unit volume is larger in RCHBs.

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ABSTRACT

Research results and interpretations of the testing of five prototype continuous reinforced concrete beams (four haunched and one prismatic) designed to develop a shear failure under increasing cyclic loading are presented. Subject beams were tested with minimum shear reinforcement. The studied haunched length was one-third the effective span of the beam. The considered angles of slope of haunch from horizontal vary from 0° (prismatic) to 10°. Increasing cyclic tests were displacement-controlled, and two cycles at the same displacement were set in the displacement history which considers a geometrical increment of target displacements. Differences in the cyclic shear behavior of haunched beams with respect to prismatic beams were monitored in terms of cracking patterns, stiffness and strength degradation and energy dissipation. The obtained results from the increasing cyclic testing in continuity conditions allow one to corroborate what it was observed in previous testing for simply supported beams: reinforced concrete haunched beams seem to be more efficient than reinforced concrete prismatic beams, even when they fail in shear.

1. Introduction

Reinforced concrete haunched beams (RCHBs) are often used in buildings (Fig. 1) and bridges (Fig. 2) worldwide. Despite their common use, there are still few experimental research studies for this structural element. Most of the available experimental research has focused to study their shear behavior under static loading [1–10]. Before presenting this research study, there were only two studies reported in journals for RCHBs failing in shear under a continuity condition [11,12], but with the limitations of using static loading and without providing shear reinforcement. To the authors' knowledge, the only cyclic testing available for a shear failure are the ones conducted by this research team for simply-supported RCHBs with and without shear reinforcement [13–17].

Due to the aforesaid, it is not surprising that the design of RCHBs is not addressed in most specialized reinforced concrete textbooks; only few of them include brief sections [18–21]. In these books, it is considered the contribution of inclined steel reinforcement in the shear resisting mechanism, which it is correct. However, this contribution is considered under the assumption that RCHBs develop shear cracks at a 45° angle (extrapolation of classical shear design for prismatic beams using the critical section method), which it is not precise based upon experimental evidence [1–8,10,11,16,17]. Another consequence of having limited experimental information for RCHBs is that there are no specific recommendations for haunched beams in the reinforced concrete guidelines most commonly used in Mexico [22,23] that would

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Fig. 1. Examples of buildings with reinforced concrete haunched beams in Mexico City.

(a) Mexico City (b) Lisbon

Fig. 2. Examples of bridges with reinforced or prestressed concrete haunched beams.

ensure a proper shear and flexural design. Besides, to the authors' knowledge, there a few nonlinear finite element simulations of tested haunched beams failing in shear [10,24,25].

In order to ensure the desirable ductile behavior of RCHBs according to capacity-design rules, it is necessary first to understand how sudden failures under monotonic and cyclic loads occur, for example, the shear failure. Once this goal is achieved, it can be possible to study how to warrant a ductile flexural failure. Therefore, in this paper, experimental results of RCHBs designed to develop shear failure and tested under cyclic loading under a continuity condition are presented. This paper is devoted to discuss in-depth the results related to the observed cyclic behavior. An in-depth discussion of the shear-resisting mechanism assessed experimentally and their relation to proposed design equations are reported elsewhere [26,27].

2. Survey of existing RC haunched beams in buildings and bridges

This research team conducted a survey since the early 2000s to document Mexican design practices for reinforced concrete haunched beams used in buildings and bridges, which it is reported in greater detail elsewhere [17]. The survey took into account information used by practicing engineers and available in some predesign guidelines [28], elastic analysis aids [29–31], plus the information obtained from studies of old existing buildings [32], field observations, and information shared by some leaders of design firms. Among other issues, it was found that, historically, reinforced concrete haunched beams used in Mexico City have the following geometric ranges: a) haunched length (L_h): $0.2L \leq L_h \leq 0.4L$ and, b) haunched angle (α): $3^\circ \leq \alpha \leq 15^\circ$. In recent buildings, the most common haunched length that has been used is $L_h \approx 0.33L$ and the following range for the haunched angle: $4^\circ \leq \alpha \leq 10^\circ$.

3. Description of test specimens

The geometry of prototypes RCHBs was defined according to the described survey conducted in existing bridges and buildings in Mexico City (i.e., Fig. 2). A double-cantilever setup was chosen (Fig. 3), similar to the one used by MacLeod and Houmsi [8] in their smaller-size specimens. The width (b) for all beams was 25 cm, the effective span (L) was 370 cm, and the shear span (a) was 150 cm. The haunched length (L_h) at both beam ends was very close to one-third the effective span ($L_h = L/3 \approx 125$ cm). Five different linear tapering geometries were obtained by keeping constant the overall depth at each beam end ($h_{max} = 45$ cm) and reducing the overall depth at the central prismatic section to $h_{min} = 45$ (prismatic control element), 38, 31, 27 and 23 cm. Therefore, haunched angles from the horizontal (α) were 0°, 3.21°, 6.39°, 8.19° and 9.98° respectively (Table 1).

The geometry of all prototypes satisfied the requirement $L/h > 5$ to be considered as slender beams by the Mexican code [18]. In addition, with the purpose of not magnifying the characteristic arching mechanism observed experimentally and analytically in haunched beams [1,2,10,17], all prototypes were checked to fulfill the well-known a/d limiting ratio between slender beams and