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Nonlinear finite element modeling of reinforced concrete haunched beams designed to develop a shear failure

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ABSTRACT

The results of different nonlinear finite element models for eight simply supported reinforced concrete haunched beams designed to develop a shear failure under static loading are presented and discussed in this paper. Simplified nonlinear models in which the participation of the longitudinal steel reinforcement and stirrups is indirectly included were assessed using SAP2000. More complex nonlinear finite element models were assessed with ANSYS, in which longitudinal steel reinforcement and stirrups were modeled as built. Softening of concrete due to deformation was taken into account in the selected constitutive models using a failure surface with different peak compressive and tension stresses. Strain hardening for the steel reinforcement was considered using the *Von Mises* yield criterion. Perfect bond between concrete and steel was assumed. Shear–displacement curves for a specific section located at midspan of the beams were obtained from the finite element models and compared to those obtained from experimental testing. Also, crack patterns associated to different loads steps were obtained from ANSYS finite element models. It can be concluded that it is possible to obtain a reasonable correlation between analytical and experimental load–deformation curves and the main developed arch mechanism for RCHBs failing in shear using both simplified and detailed finite element models, which for practical purposes is more than acceptable. However, only a medium correlation between cracking patterns numerically obtained with detailed finite element models and those experimentally identified were observed, particularly for beams with shear reinforcement.

1. Introduction

Reinforced concrete haunched beams (RCHBs) have been traditionally used around the world for the design of bridges and buildings (Fig. 1).

In order to insure the ductile behavior of RCHBs from a conceptual and capacity design viewpoint, it is necessary to understand how RCHBs resist shear forces under static and cyclic loadings in order to prevent potential shear failures, and then understand and insure ductile flexural behavior under static and cyclic loadings. For this reason, and as a first step, an experimental study on simply supported RCHBs designed to fail in shear was carried out using the geometries and practices observed in Mexico [1,2]. The geometry of prototype RCHB was defined according to a survey conducted in buildings of recent construction in Mexico City [1,2]. In such buildings, the most common dimensions were: (a) the haunched length was one-third the effective span of the beam (L), that is, $L/3$ and, (b) haunched angles varied from 6° to 12°.

Therefore, in this paper the first eight simply supported RCHBs reported to fail in shear under monotonic loading [1] were modeled using nonlinear finite elements. Four of the eight studied specimens do not have shear reinforcement whereas the remaining ones, identical in geometry, had minimum shear reinforcement. The considered angles of slope of the haunch from horizontal (or haunched angle, α) were 3.07°, 6.12°, 9.13° and 12.10°. The haunched length at both beam ends was one-third the effective span for the beam ($L/3$).

This study is focused on the numerical modeling of simply supported RCHBs designed to develop a shear failure under static loading. One of the principal purposes was to assess, based on a comparison of numerical and experimental results, the ability and limitations of simple and complex nonlinear modeling to predict the experimental behavior of the tested reinforced concrete haunched beams (RCHBs). For this purpose, simple models in which the failure is modeled using shear plastic hinges were

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(a) Bridges

(b) Buildings

Fig. 1. Structures with RCHBs used within the Metropolitan Area of Mexico City.

tested, as they may be appealing to design practice. More complex nonlinear finite element models were also assessed, where the concrete failure is distributed over the volume of the finite elements and steel plasticity is distributed in one-dimensional elements.

2. Description of the experimental study

2.1. Geometry, loads and boundary conditions

The geometry, loads and boundary conditions used in the experimental research program [2,3] are shown in Fig. 2, and were also used for the finite element models. All RCHBs elements have a total length $L = 330$ cm. The effective span for all RCHBs was $L = 2.80$ m and the width was $b = 22$ cm. The considered angles of slope of the haunch from horizontal were: 3.07°, 6.12°, 9.13° and 12.10°. The haunched length at both beam ends was one-third the effective span of the beam ($L_h = L/3 \approx 93.3$ cm). The bearing length at both beam ends was 25 cm. The linear tapering was obtained by keeping a constant depth $h_{\max} = 45$ cm at the beam ends while varying the depth of the beam at the central third from 45 cm (prismatic) to 25 cm, that is, $h_{\min} = 45$, 40, 35, 30 and 25 cm.

Beams were simply supported and tested under monotonic loads (V) that were applied 10 cm (3.937 in.) from the vertex formed by the intersection of tapered sections with the prismatic section, as depicted in Fig. 2.

The cryptogram used for the identification for the RCHBs corresponds to the originally proposed by Archundia [3], TASCαi-Rj, where i is an index that indicates the considered haunched angle: $i = 0 = 0°$, $i = 1 = 3.07°$, $i = 2 = 6.12°$, $i = 3 = 9.13°$ and $i = 4 = 12.10°$; j is an index that identifies the shear reinforcement: $j = 0$ indicates the absence of shear reinforcement whereas $j = 1$ indicates the use of minimum shear reinforcement as requested in NTCC-04 [4] guidelines.

Complete details on how the specimens were designed to insure that they failed in shear while following general NTCC-04 guidelines, as well as construction details process of all beams used to develop the numerical models in this study can be found elsewhere [1,3].

2.2. Flexural and shear steel reinforcement

Flexural and shear reinforcement details for each beam considered in this study are shown in Fig. 3. Also, the corresponding typical cross sections are shown in Fig. 4. As commented, the studied specimens were classified into two groups: (1) R0 elements, in which no shear reinforcement is used along the haunched length (Fig. 3a–d) and, (2) R1 elements, where minimum shear reinforcement, equal to the one required by NTCC-04 [4] for prismatic beams is provided along the haunched length (Fig. 3e–h).

3. Simplified modeling using SAP2000

As a first step, nonlinear static analyses were performed using SAP2000 [5]. To do this, simple models using tapered beam-elements were developed. A lumped plasticity modeling was used through shear plastic hinges. Average mechanical properties for the reinforced concrete were used for the tapered elements.

3.1. Modeling considerations

Force–displacement relationships were defined and assigned for each plastic shear hinges, which were obtained from experimental results. These curves were defined based upon the experimental data recorded. The purpose of this modeling was to explore the usefulness of using a simple analytical approach to represent the behavior of RCHBs failing in shear by taking into account the experimental information that was already available. The procedures to define the shear plastic hinges, as well as the obtaining of the pushover curve, are illustrated in Fig. 5.

The location of shear plastic hinges (L_{crit}), measured from the supports, it is associated to the effective equivalent depth at the critical haunched section (d_{crit}, Figs. 6 and 7) and computed using Eq. (1), in which d_{crit} represents the depth that must be used to compute the shear resistance in RCHBs according to Tena-Colunga et al. [1], which can be obtained using Eq. (2):

$$L_{\text{crit}} = \frac{d_{\max} - d_{\text{crit}}}{\left(\frac{h_{\max} - h_{\min}}{l_c}\right)} \tag{1}$$

$$d_{\text{crit}} = d_{\min}(1 + 1.35\tan\alpha) \leqslant \left[\left(\frac{h_{\max}h_{\min} - h_{\max}^2}{2l_c} + h_{\max}\right) - r\right] \tag{2}$$

where $h_{\max}$ and $h_{\min}$ have been defined previously, and $d_{\max} = (h_{\max} - r)$, $d_{\min} = (h_{\min} - r)$, l_c is the haunched length and r is the concrete cover for the longitudinal reinforcement.

The location of plastic shear hinges used in the simplified RCHBs modeling with SAP2000 is schematically shown in Figs. 5a and 7. This modeling was used based upon the observed damage during experimental tests [1,3]. All variables used to define the location of plastic shear hinges are shown in Table 1.

3.2. Results of nonlinear static analysis

In order to assess the usefulness of simplified analytical models to reproduce the experimental behavior of RCHBs, applied shear force versus displacement curves at midspan obtained