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Experimental study on the structural behavior of concrete dapped-end beams

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ABSTRACT

A common structural system in precast pre-stressed concrete girders with dapped ends has been intensively used in elevated viaducts recently built in Mexico City. A critical aspect of this solution resides in the possibility of a premature cracking in the reentrant corner of the dapped-end beam. An experimental research program was carried out to evaluate the performance of the present solution of the dapped end, both under service loading and ultimate design loads, and also to explore other solutions that could improve the performance in terms of the cracking of the reentrant corner.

Four dapped-end beams models at a 1:3.6 scale were built and tested under vertical loads. The first specimen reproduced the solution adopted in the prototype, which was designed and reinforced according to the recommendations of the PCI Design Handbook. To the second one a longitudinal post-tension was applied, in the third specimen diagonal bars replaced part of the hangers, and the fourth was provided with both diagonal bars and post-tensioning.

Experimental results allowed to conclude that, the specimens with longitudinal post-tensioning at the dapped, performed within the code requirements both under the service and ultimate loads, showed the best behavior in terms of cracking control. The strut-and-tie model proposed by Mattock provides a good prediction of the load capacity attained in the experimental specimens.

1. Introduction

In the last two decades, for the elevated viaducts in Mexico City, a construction system based on precast/pre-stressed concrete elements has been used. In this system, the bridge girders are divided into two parts by imposing a hinged support in sections where the bending moments that are originated by the gravity loads in a continuous beam are minimal (Fig. 1). One critical aspect of this solution is the transmission of the shear force at the joint, where the two parts of the girders have dapped ends, and thus only one half of the girder depth can be relied on to withstand the reaction at the support. To counteract this shortcoming, both dapped ends are solid, whereas the rest of the girders have a box-like section. Nonetheless, the steel reinforcement becomes very dense at the dapped ends, and its detailing is rather complicated.

The design procedures for the ends of the dapped girders are well established and are based primarily on experimental tests performed for different configurations of reinforcement. The critical failure modes that can govern the design have been identified, and for each of them, the methods for computing the reinforcing steel that is needed to achieve adequate safety against failure have been proposed (PCI, 1999). Nevertheless, the design recommendations do not include procedures for controlling diagonal cracking at the entrant corner under service loading. These cracks could cause water penetration and degradation because of the corrosion of the steel reinforcement. The lack of visual access to the area makes it difficult to detect this damage and take timely corrective actions.

Practitioners of the structural design of bridges in Mexico commonly follow the AASHTO code [1] but, with incorporates several items from the American Concrete Institute (ACI) and the Pre-stressed Concrete Institute (PCI) codes for specific requirements on the reinforced and pre-stressed concrete structures, respectively. In particular, the dapped beam ends of the viaduct were designed using the PCI rules.

2. Objectives and scope of the research project

To validate the criteria and procedures that are presently used for the design of the ends of the dapped girders for the

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aforementioned viaducts, a research program was performed that included an experimental portion and a numerical portion. The experimental study was mainly devoted to the verification of the predicted performance of the different reinforcement configurations, specifically in terms of their ability to control the diagonal crack starting at the entrant corner. The numerical study validated the present practice for estimating cracking under the service loads and how to control it. This paper addresses the experimental part of the program. The authors of the present study have previously reported parts of the work performed for this issue [2]. The results of the numerical studies will be presented in a future article.

Four scaled-down specimens of the end zone of the main girder being used in one of the elevated viaducts recently completed in Mexico City were built and tested in the laboratory. The first specimen reproduced a typical solution based on vertical stirrups (hangers) and on vertical and horizontal hoops. In the other three specimens, modifications were made to control the cracking behavior of the reentrant corner. These modifications included the longitudinal post-tensioning of the beam end and the substitution of parts of the vertical hangers with diagonal bars, which approximately followed the path of the principal stresses.

The four specimens were subjected to increasing vertical loads that were applied symmetrically or eccentrically in small increments up to the cracking of the reentrant corner and continued for the ultimate design load until they reached near-failure conditions. The specific objectives of this study were to:

- Evaluate the four types of reinforcement adopted in the laboratory specimens in terms of their suitability for the future construction of similar bridges.
- Verify the behavior of the four specimens in terms of safety against failure and in terms of the cracking performance under service loads.
- Gather experimental evidence to calibrate different methods for the numerical simulation of the cracking of the dapped ends.

3. Background

3.1. Previous experimental research on the ends of the dapped beams

The first important study conducted on the ends of the dapped beams was made by Reynolds [3] who proposed the detailing of the reinforcement and a procedure based on the equilibrium of the bending moments for quantifying the strength contribution of each type of reinforcement. Mattock and Chan [4] carried out a comprehensive experimental program. Their results allowed them to develop a rational procedure for computing the amount of the horizontal and vertical reinforcing bars and the longitudinal anchoring reinforcement.

Regarding the analytical research work, Werner and Dilger [5] used the finite element method to determine the load that originated the first crack at the reentrant corner. Hamoudi et al. [6] defined the diagonal cracking mechanisms for determining the resistance of the dapped girders based on linear elastic analyses. Khan [7] made recommendations for extending the procedures proposed in previous studies for beam ends with span-to-depth ratios greater than 1.0. Lu et al. [8] used experimental evidence and suggested a softened strut-and-tie model to predict the resisting load of beam ends. Herzinger and Elbadry [9] investigated the efficiency of incorporating studs with single or double heads for reinforcing the dapped end. The shear friction and diagonal bending method was employed to determine the location of the critical crack at failure. Recently, Mattock [10] examined and compared the behavior observed in tests of 16 dapped ends that were subjected to a variety of combined vertical and outward horizontal reactions. The study showed that the strut-and-tie models included in ACI SP-208 [11] and ACI SP-273 [12] are not consistent with the observed behavior of the dapped-end beams because they overestimate the force to be carried by the hanger reinforcement. On the other hand, the FIP recommendations [13] correctly estimate the required amount of hanger reinforcement but require additional reinforcement to carry the force in the tie identified as DF in Fig. 2b. The simplified strut-and-tie truss model proposed by Mattock showed good correlation with the observed behavior of the dapped ends and will lead to the minimum required amount of reinforcement.

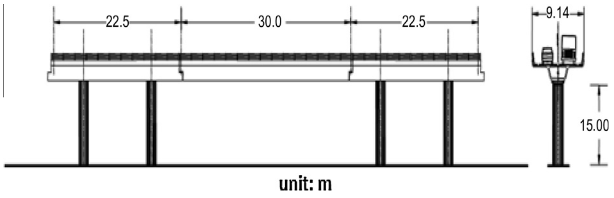

Fig. 1. Gerber-type girders for the elevated viaducts in Mexico City.

Nagrodzca-Godycka and Piotrkowski [14] presented the results of an experimental investigation of the reinforced concrete dapped-end beams loaded with inclined forces compared to the identical ones loaded with vertical force only. This type of load may occur in the Gerber beam joints or in the dapped-end beams supported on corbels (Fig. 3). The authors adopted the inclined force resulting from the horizontal force-vertical force ratio $H/Fvu = 0.5$, which was similar to the value used in Mattock and Chan's studies [4].

The experimental program showed that the crack patterns were different in the dapped-end beams loaded with inclined forces compared to those observed with a vertical force. A 25% decrease in the load capacity occurred when an additional horizontal force equal to one half of the vertical force was imposed. The failure of the dapped ends with high amounts of reinforcement most often occurred after both the horizontal reinforcement and the vertical stirrups yielded.

3.2. Design criteria for the dapped-end beams

The present practice for designing dapped-end beams is based on the equilibrium conditions at failure. The Pre-stressed Concrete Institute (PCI) Handbook [15] requires the investigation of several potential failure modes (see Fig. 4) and defines the calculations to be performed to determine the reinforcement required for each of them. The design equations are based on the studies of Mattock and Chan [4] and are suitable for short dapped ends ($a/d \leqslant 1$), where a is the shear span and d is the effective depth of the dapped end. The main modes of failure to be considered are characterized by cracks 1–5 in Fig. 4.

The necessary main reinforcement to avoid each failure is as follows:

1. Bending and axial tension require horizontal hoops capable of withstanding the sum of the tensile forces induced by the two effects.
2. Direct shear is taken through a combination of horizontal and vertical hoops (A_s and A_h).
3. Diagonal tension causing the inclined crack at the reentrant corner: vertical hoops (hangers) or diagonal bars must counteract the total applied shear.