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Experimental and numerical assessment of the effectiveness of FRP-based strengthening configurations for dapped-end RC beams

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ABSTRACT

This paper presents experimental and numerical assessments of the effectiveness of strengthening dapped-end reinforced concrete beams using externally bonded carbon fiber reinforced polymers (CFRPs). The research was prompted by a real application, in which the dapped-ends of several precast/prestressed concrete beams developed diagonal cracks due to errors during assembly. Hence, the dapped-ends were strengthened on-site using CFRP plates to limit further crack opening. In the empirical phase of the study, four similar specimens were tested: one unstrengthened reference specimen, two strengthened with high-strength CFRP plates, and one with high-modulus CFRP sheets. The specimens strengthened with plates had slightly higher load carrying capacity than the reference element, but failed by debonding, while the specimens strengthened with sheets showed no increase of capacity and failed by the fibers rupturing. Nonlinear finite element analysis of the specimens under the test conditions indicated that: (a) debonding is more likely to occur at the inner end of dapped-ends and (b) the capacity could have been increased by up to 20% if the plates had been mechanically anchored.

1. Introduction

Precast prestressed concrete (PC) structures have several advantages compared to cast-in-place structures; they can be constructed more rapidly and are generally more robust and durable. They are made of individual elements and assembled with various types of connections. For beams, these connections may require severe reductions of the cross-section at the ends, called dapped-ends. The abrupt change of cross-section in a beam results in a complex flow of internal stresses, which are typically highly concentrated at the re-entrant corner. Such regions in an element are called disturbed regions (D-regions) [1,2]. According to the PCI Design Handbook [2] dapped-end beams may fail in any of the five modes schematically represented in Fig. 1: (1) Flexure (cantilever bending) and axial tension in the extended end; (2) Direct shear at the junction between the dapped and undapped zone of the member; (3) Diagonal tension failure at the re-entrant corner; (4) Diagonal tension failure in the extended end; and (5) Diagonal tension failure in the undapped zone. Numerous researchers have analyzed and experimentally investigated these failure modes. Using the strut and tie method, Reynold [3], Mattock [4], Mattock and Theryo [5] and Hwang and Lee [6] have all proposed equations for predicting these failure modes and presented design criteria for dapped-end beams. Chen [7] tested four dapped-ends with identical geometry and reinforcement ratio, but different reinforcement layouts. The results showed that the reinforcement arrangement influences the capacity of the elements, and that the provisions given in the ACI 318-08 code [8] are conservative. Lu et al. [9] theoretically and experimentally investigated the shear resistance of 12 dapped-end beams, again finding that the PCI Design Handbook [2] provisions are conservative, and suggested new design proposals.

The load carrying capacity (hereafter capacity, for convenience) of dapped-end beams may be insufficient for reasons such as design errors, code changes, increases in loads, or structural damage. One option to increase the capacity of the dapped-end regions is to use fiber-reinforced polymers (FRPs) using the externally bonded reinforcement (EBR) technique. FRPs are viable solutions for strengthening or retrofitting reinforced concrete (RC) elements, and several guidelines for strengthening RC structures with FRPs have been published recently [10–12]. However, these guidelines

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Nomenclature

H	height of the experimental specimens
B	width of the web cross-section
h	height of the dapped-end
l_p	recess of the dapped-end
a	shear span according to PCI provisions
f_{ct}	tensile strength of concrete
G_f	mode I fracture energy of concrete
wc	crack opening at the complete release of stress
f_y	yield strength of reinforcement
f_u	tensile strength of reinforcement
ε_y	strain in reinforcement at yielding
ε_u	strain in reinforcement at maximum force
ε_{ult}	strain in reinforcement at failure (conventional value, adopted only for finite element modeling convenience)

do not refer specifically to FRP strengthening of dapped-end beams, partly because the variations in geometry, material and loading conditions at their dapped ends hinder the establishment of clear criteria for robustly classified strengthening configurations. In a series of tests, Huang and Nanni [13] verified that FRPs can increase the capacity of dapped-end beams with "mild steel and no mild reinforcement" [13], and proposed a method for strengthening dapped-end beams with FRPs that was found to be "satisfactory and conservative" [13]. They too showed that dapped-end reinforcement designed according to the PCI Design Handbook [2] is very conservative. Gold et al. [14] strengthened dapped-end beams of a three-story parking garage that were deficient in shear resistance with FRP. Due to the lack of design provisions at that time, they carried out a series of tests to verify the effectiveness of the FRP strengthening and predictive performance of their design approach. The FRP strengthening systems doubled the resistance of the beams, confirming their effectiveness. Tan [15] experimentally investigated the efficiency of several FRP configurations for strengthening dapped-end beams with deficient shear resistance, varying in both fiber types and mechanical anchorage systems for the FRP. The results showed that glass fiber reinforced polymers (GFRPs) provided greater improvements in terms of ultimate load than carbon FRP plates and carbon fiber sheets, and the tested mechanical anchorage devices enhanced exploitation of the FRP systems' strengthening capacity by preventing their debonding. The empirically based strut and tie model they derived was applied to predict increases in the shear capacity of the dapped-end beams, and proved to be sufficiently accurate for the type of beams tested. More recently, in a large series of experiments Taher [16] assessed the effectiveness of the following techniques for improving the capacity of dapped-end beams: externally bonding steel angles; anchoring unbonded steel bolts in inclined, pre-drilled holes; externally applying steel plate jackets; and wrapping carbon fiber around the beam stem. Tests with 50 small-scale rectangular beams indicated that the FRPs were the most viable solution for strengthening/retrofitting applications. Using the strut and tie analogy, Taher also derived a regression model to estimate the capacity of the FRP-strengthened dapped-end beams, which reportedly provided "reasonable" predictions [16], but he did not consider any possible scale effects of the beams tested for deriving the model.

The current study presents an experimental program prompted by a real case application.

To the authors' knowledge, only four experimental investigations on dapped-end beams strengthened with FRPs have been reported [13–16]. The specimens tested in the previous four experimental programs and the research presented here are shown (at the same scale) in Fig. 2. Clearly, there are major differences in the specimens used in these research programs, in terms of the configuration of the dapped-end, position of the loading, shear spans, and size of the beams (see Table 1). Therefore, the work presented in this paper enriches the experimental database on FRP-strengthened dapped-end beams and provides both experimental and numerical assessments of the behavior of large, FRP-strengthened (and unstrengthened reference) dapped-end beams.

2. The context of this work

A single-storey industrial hall was constructed using 20 m long identical precast/prestressed beams, with 1800 × 660 mm cross-section, serving as supports for the roof purlins (Fig. 1). Immediately after assembly of the structure eight beams had diagonal cracks corresponding to the third mode of failure, see Fig. 1. The inclination of the crack angle varied between 40° and 50° with respect to the longitudinal axis of the beam. Initially the dapped-ends were designed using the strut and tie method according to the Romanian codes [17] and EC2 [18] for a reaction force of 800 kN positioned 400 mm from the re-entrant corner. An inspection revealed that the dapped-ends were not in full contact with the supporting columns. Consequently, the position of the reaction force was displaced by an additional 275 mm, resulting in the diagonal cracking. Hence, the dapped-end beams were re-assessed,

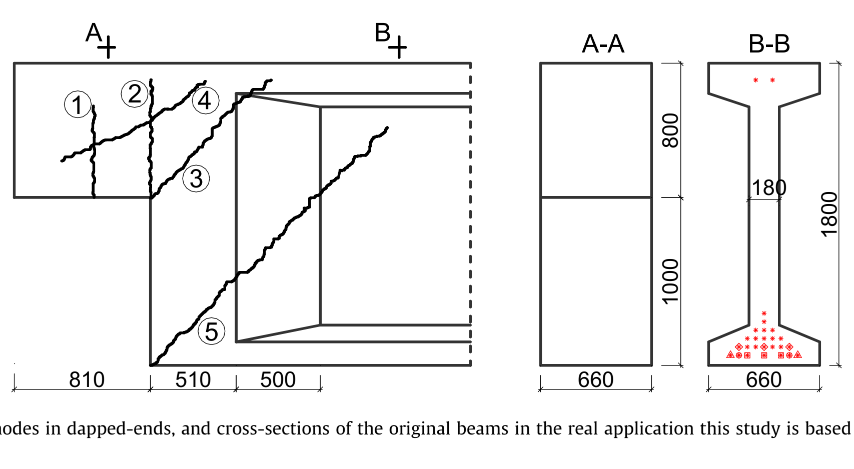

Fig. 1. Potential failure modes in dapped-ends, and cross-sections of the original beams in the real application this study is based upon (dimensions in mm).