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Bond-slip responses of stainless reinforcing bars in grouted ducts

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ABSTRACT

To promote prefabricated segmental bridges in regions of moderate or high seismicity, stainless energy dissipation bars (ED bars) are used continuously across the column segment critical joints to increase the hysteretic energy dissipation. However, the bond response and the design development length of the anchored ED bars were not well understood for hollow thin-wall segmental bridge columns. In this paper, an experimental program was conducted to investigate the influence of bar embedment length and ratio of duct diameter to bar diameter on monotonic bond-slip response of stainless ED bars. Phenomenological nonlinear bond-slip and end-slip models were developed to simulate the loaded bar end force-displacement relationship. The results of the experimental study were used to establish preliminary design equations for A706 and stainless Talley S24100.

1. Introduction

Prefabricated concrete bridge elements and system construction have attracted growing attention in the past decades. Conventional cast-in-place (CIP) bridge construction practice requires that concrete substructures be built on site. At most bridge construction sites, workers spend long periods of time in potentially dangerous locations, such as close to moving traffic, over water, near power lines, or at high elevations [1]. Precast concrete bridge construction, compared to conventional CIP technology, has the advantages of minimizing traffic disruption, improving worker safety, mitigating environmental impact, reducing accidents in work zone, and maintaining construction quality. For bridges, precast segmental practice has been mainly used in non-seismic or low seismic regions [2,3]. For buildings, precast components have been used to resist seismic loads in buildings [4]. However, recent post-earthquake field investigation and experimental study in laboratory in Europe [5,6] reported inadequate seismic performance of existing precast reinforced concrete framed building structures. The structural failure was primarily due to the critical connection failure, such as beam-to-column, panel-to-structure, and column-to-socket foundation connection systems. These connections were found to be lack of shear and ductility capacity. Therefore, connection detailing in the precast reinforced concrete structures really needs more systematic and careful investigation to confidently propose their engineering practice in seismic zones.

As mentioned above, connection details are crucially important for precast construction practice to ensure its competent structural performance compared to traditional monolithic CIP method. Grouted sleeve couplers, grouted pockets, grouted ducts and bolted connection are the four types of connection details commonly used in prefabricated construction practice. Among the four connection details, grouted ducts have acceptable construction tolerances and usually their cost is low. They can minimize interference with the reinforcement and easily confine connection reinforcement. Grouted ducts are viable for various types of connection reinforcement. Generally, grouted ducts are capable of developing good anchorage and superior ductility, and the design approach is relatively simple. Matsumoto et al. [7] reported that grouted ducts used in precast construction demand more difficult grouting operations, and the major factor that can produce a difference in structural behavior for a precast vs. CIP system is the number and location of connectors. Using a small number of connectors would result in a small rotational stiffness of the connection.

Recent research has been focused on the development and application of precast segmental concrete bridge columns in moderate or high seismicity zones [4,8]. In the previous research program conducted by Ou et al. [9], mild steel energy dissipation bars (ED bars), which were continuous across the column segment joints, were added into the segmental column. Opening of the critical segment joints was used to mobilize the plastic deformation of the ED bar to increase the hysteretic energy dissipation. To avoid

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Notation

The following symbols are used in this paper

A	nominal bar area, mm^2
A_{tr}	transverse reinforcement area within distance S, mm^2
c	neutral axis depth on the compression side of the hollow section, mm
c_b	distance of the center of a bar to the nearest concrete surface, mm
D	accumulated damage index
d_b	nominal bar diameter, mm
d_t	distance from the ED bar to the compression face (760 mm or 29.9 in.)
f'_c	designated concrete compressive strength, MPa
f'_g	actual grout compressive strength, MPa
f_y	specified yield strength of reinforcing bar, MPa
h	column height, mm
l_{au}	additional unbonded length, mm
l_d	development length, mm
l_e	embedment length, mm
l_e/d_b	normalized embedment length
L_e	effective bonded length, mm
n	number of bars being spliced or developed at the plane of splitting
n_i	number of cycles at a certain stress/strain level
N_f	fatigue life (cycles to failure)
N_{fi}	fatigue life cycles at the corresponding stress/strain level
P	maximum axial force on bar, kN
s	normalized slip value at one side of the joint
S	spacing of the transverse reinforcement, mm
S_E	slip from two sides of the joint, mm
$u(x)$	displacement at location x
V	model tuning parameter for A706;
x	embedment direction
Δ	column top displacement, mm
ε	bar strain
ε_m	maximum bar strain
Π	bar circumference, mm
σ_m	bar stress at maximum bar strain, MPa
$\sigma(x)$	bar stress at location x
τ_{an}	average normalized bond stress
$\tau(x)$	bond stress at location x

premature fracture, the ED bar was deliberately debonded in the vicinity of the joint over a specified length by wrapping the bar with duct tape. Alternatively, stainless steel bars with superior ductility and low-cycle fatigue performance [10] can be used for ED bars. Highly alloyed materials like stainless steel exhibit a high corrosion resistance [11,12]. Furthermore, the use of stainless steel bars can also address the potential corrosion problem associated with opening of the critical joint.

There has been plenty of research work on the bond-slip response and anchorage issue of conventional steel reinforcing steel bars in grouted ducts [13–15]. Brenes et al. [13] found that the duct material has an important influence on the behavior and failure mode of connections. The formation of splitting cracks in the concrete represents a critical mode of response. Steuck et al. [15] found that the bar size effect was small compared to the scatter among the test results. Parallel tests with polypropylene fibers showed that fibers generally decreased the pullout resistance, although this is likely attributed to the result of reduced grout strength. In the absence of ducts, Darwin and Zavaregh [16] investigated the bond strength of grouted reinforcing bar in concrete. The effects of hole preparation method, grout type, hole diameter, bar size and embedment length were the research focus. It was found that the grouts which provide strong bond at the grout-concrete interface provide higher bond strengths than the grouts which undergo failure at the grout-concrete interface. Bond strength increases with increasing embedment length, cover, and bar size. Wu and Zhao [4] developed a unified bond stress-slip model that is suitable for numerical simulations. By tuning the major parameters, the proposed mathematically continuous model can simulate the unconfined concrete conditions without transverse reinforcement and the confined concrete conditions with stirrups which failed in both the splitting mode and pullout mode.

However, concerns rise when stainless steel ED bars are embedded into critical regions in segmental bridge columns, especially the required additional unbonded length (l_{au}) to ensure the ductile performance of the columns in earthquakes. Various factors affect bond stress development, such as transverse rib geometry and bar surface treatment, confinement, reinforcing bar yield stress, bar embedment length, ratio of duct diameter to bar diameter, concrete properties and reinforcement corrosion condition. For ED bars used in segmental bridge columns, the selection of the duct diameter is restricted by construction tolerances and by interference with segment reinforcement. An efficient design would choose smaller diameter ducts, which can accommodate ED bars to reduce the amount of grout needed in the connection and meantime minimize reinforcement congestion. However, on the other hand, practical engineers are prone to use reasonably larger ducts to facilitate construction with the concern that larger ducts may impair bond stress development between the bar and surrounding grout. Matsumoto et al. [7] recommended that duct diameters be 2–3 times that bar diameter and providing a horizontal tolerance of at least 1 in. (25.4 mm). The effect of the ratio of duct diameter to bar diameter attracts a lot of attention recently but remains uncertain in this particular design scheme. This research work concentrates on the influence of bar embedment length and ratio of duct diameter to bar diameter on monotonic bond-slip responses of stainless steel ED bars.

2. Experimental program

2.1. Test specimens and setup

An experimental program was conducted to investigate the influence of bar embedment length and ratio of duct diameter to bar diameter on monotonic bond-slip responses of stainless steel ED bars. Due to the excellent performance in previous research [10], stainless Talley S24100 reinforcing bars were the focus of the test program. Carbon A706 reinforcing bars were also tested as a benchmark. The lug patterns and deformations of carbon A706 and stainless Talley S24100 bars are slightly different (shown in Fig. 1), but they both satisfy ASTM A706 and ASTM A955 [3], respectively. The different bar deformations and different monotonic tensile test behaviors (shown in Fig. 6) contribute to the different local bar bond-slip behaviors in concrete blocks with grouted ducts. Predictions of local bar bond-slip behavior of other reinforcing bar deformations and monotonic tensile behaviors need more research efforts and should be examined with cautions.