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Behavior of unbonded post-tensioning monostrand anchorage systems under short duration, high amplitude cyclical loading

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ABSTRACT

This study evaluates the behavior of monostrand post-tensioning anchorages under both monotonic and short duration high amplitude (post-yield) cyclical loading representative of use in self-centering structural applications designed to provide seismic resistance. Anchorages from two different manufacturers were tested in coupled and uncoupled configurations. In addition, a modified wedge geometry was evaluated to determine if the performance of the system could be improved. Strain within the strand was recorded using extensometers and strain gages for different samples. A detailed evaluation of the relationship between the strain within the strand and the elongation measured by the testing frame was conducted to ensure that the strain within the strand was calculated accurately throughout the tests. The results of this research indicate that the strain within the strand is not linearly related to the elongation recorded by the testing frame, and a more accurate method was developed to allow for this conversion. Additionally, it was determined that couplers did not significantly affect the capacity of the system, but the capacity was affected by the manufacturer of the anchorage system and the loading regime used to test the sample. Based upon the observed variations in capacities, this study recommends the design of monostrand post tensioned systems using cast anchorages should be limited to a strain of 0.01 mm/mm.

1. Introduction

Since the mid-1990s, seismic design of precast structures has largely relied on utilizing unbonded post-tensioning to establish the connection between a precast member and an adjoining precast or cast-in-place concrete element [1–3]. This concept enables the precast systems to minimize structural damage and offer self-centering capability when they are subjected to earthquake lateral forces. Significant effort by multiple researchers has also been spent developing various design guidelines, procedures, and aids to allow for these systems to be incorporated into structures by the design engineers [4–7]. The desirable behavior and improved understanding of the design process for these precast concrete structural elements has promoted the use of unbonded post-tensioning in seismic-resistant design of structures designed with other construction materials (e.g., steel, masonry and timber). For all of these systems to perform as desired, the post-tensioning tendons should be anchored adequately and an appropriate ultimate strain limit should be established for the prestressing strands in consideration of anchorage condition. Low relaxation prestressing steel that is commonly used for prestressing self-centering structures has an ultimate strain capacity of at least 0.04. However, such large strains would not typically be reached due to strands failing prematurely near the anchorage.

In order to establish a reliable strain limit for prestressing steel used in self-centering applications, and in coordination with previously conducted related research, the objectives of this paper are to:

- Determine the ultimate strength and strain capacity of cast monostrand post-tensioned anchorages under monotonic and short duration high amplitude (post-yield) cyclical loads.
- Using monostrand anchorages, develop a dependable strain limit for prestressing strand for use in the design of structures with unbonded tendons.
- Determine the effect of couplers and modified wedge geometries on the ultimate strength and strain capacity of monostrand post-tensioned systems under monotonic and short duration high amplitude (post-yield) cyclical loads.

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- Evaluate the relationship between the elongation measured by the testing machine, anchorage seating, and elongation of the strand.

This paper is focused on the first part of a two part testing program designed to evaluate the behavior of both monostrand and multistrand anchorages. While this part was focused solely on monostrand anchorages, many of the objectives result in knowledge that informs the behavior of multi-strand systems, which are more commonly used in self-centering systems. These multi-strand systems are directly evaluated in the second part of the testing program.

2. Background

As part of a precast, self-centering rocking wall system project, the need for better understanding the strain limit on unbonded post-tensioning strands was identified. Previous research conducted by Walsh and Kurama [8] examined the monotonic and cyclical resistance of monostrand post-tensioning systems. Their research focused on monostrand testing of both cast and barrel anchorages. Monotonic testing showed a wide range of failure strains ranging from 0.01 mm/mm to 0.04 mm/mm, leading to the conclusion that design strains should be limited to 0.01 mm/mm (1% strain) for unbonded post-tensioning systems. Walsh and Kurama also found that cast anchors provided by the same manufacturer but with different casting date codes had significantly different capacities. Walsh and Kurama examined the accuracy of a 50 mm extensometer compared to a 900 mm extensometer as required by the International Code Council Evaluation Service (ICC-ES) [9]. They found that the 50 mm extensometer provided reliable results and the requirement for a 900 mm extensometer is not justified.

Another method that has been evaluated in the literature for determining the strain within prestressing strand is through the use of strain gages. Strain gages are generally bonded to an individual wire of a 7-wire prestressing strand, oriented along the axis of the wire. In doing so, the strain gage measurement reflects the strain of the individual wire rather than that of the strand as a whole. Research conducted by Yates indicated that significantly different levels of strain could be observed amongst individual exterior wires at low load levels [10]. However, after a certain load is applied and each wire is fully anchored, the subsequent strain increases are relatively linear with near equivalent slopes. For this reason, Yates recommended that only strain readings corresponding to stresses higher than 345 MPa be considered for the preparation of a linear calibration curve. However, through extensive instrumentation and testing in a later study, Acosta concluded that when all strain gages are installed at one particular cross-section and at an equal distance of at least 600 mm from the anchorage ends, the gages measure similar values of strain even at low stress levels [11].

In a later study, Walsh and Kurama conducted testing on anchorage systems following the procedure outlined in the ICC-ES document, as well as modified loading procedures that included post-yield cyclical loading and loading with end eccentricities [12]. They found that the post-yield cyclical loading results in reduced wire fracture strains, and that this behavior is not captured in the ICC-ES procedure as the upper stress limit for the cyclical loading is too low. As with the previous testing, 0.01 mm/mm was recommended as the maximum design strain for unbonded post-tensioning systems. A variety of loading rates were used for the testing, with 0.056 mm/mm/minute being the maximum value. One recommendation for future research was to conduct additional tests at strain rates that are more representative of seismic applications [12].

The research described in this paper builds upon the research conducted by Walsh and Kurama to better understand the behavior of unbonded post-tensioning systems under both monotonic as well as high strain rate cyclical testing representative of use in a rocking wall system. Cast monostrand anchorages from two different U.S. manufacturers are examined under monotonic loads and cyclical loads simulating seismic effects. Continuous and coupled systems are examined to determine if the presence of a coupler has an effect on the capacity of the system. In addition, wedges with a modified geometry are evaluated. The standard wedge geometry is modified based upon two principles with the goal of producing a more uniform force distribution along the wedge length and allowing the strands to sustain large inelastic strains before experiencing fracture, which typically occurs at the anchor point.

The first principle used to modify the geometry is referred to as "angle differential" [13]. Standard wedges have a geometry in which the taper angle of the exterior surface of the wedge matches the taper angle of the wedge receiving bore, both of which are approximately 7°. This type of wedge geometry, which is the current industry standard, forces all of the wedge teeth to engage on the strand simultaneously when loading begins [14]. Once the entire wedge length has engaged, elongation of the strand within the anchorage is significantly restrained. Thus, the load along the length of the wedge is concentrated at the nose. This so-called "elongation nose loading" begins early in the loading and propagates as loading continues. Eventually, this stress concentration causes the premature failure of an individual wire within the anchorage at the nose of the wedge.

Alternatively, the wedges in this study with a modified geometry have an exterior surface taper angle that is 1°–2° greater than that of the wedge receiving bore. This angle differential allows the wedge to grip the strand sequentially from the "back" or wide end of the wedge to the "nose" or narrow end of the wedge as load increases. This fundamental change in the engagement of wedge teeth allows elongation of the strand to occur within the wedge throughout the majority of the loading. As a result, the normal force on the strand along the length of the wedge is more balanced as the load approaches the free-length failure strength of the strand, as shown in Fig. 1.

The second principle of the modified wedge geometry is referred to as "gap control" [15]. When wedges are placed around the strand prior to loading, an initial (uncompressed) gap exists between wedge pieces. As the prestressing force increases, the wedge pieces compress laterally, closing this initial gap. If the gap between wedge pieces is allowed to close completely, the wedges are no longer able to move inward and grip the strand as load increases. Unless designed carefully, the contact of the two wedge pieces can make the system potentially susceptible to a pull-out failure in which the gripping force of the wedge is no longer sufficient to restrain the tensile force of the strand.

The wedges denoted by the name "standard" have a geometry in which the wedge pieces will remain in "free float" (i.e., will never come in contact) throughout the loading sequence. Alternatively, the modified wedge developer has determined experimentally that allowing the wedge pieces to come into contact, with reasonable limitation, is actually beneficial to the operation of the anchor system overall. Therefore, the wedges with a "modified" geometry are manufactured to have a smaller uncompressed gap between wedge pieces. When this smaller initial gap is implemented, the centering movement of the wedges is stopped late in the loading sequence due to the wedge pieces coming into contact. This allows the wedges to penetrate the exterior strand wires only enough to avoid a pull-out failure without "over-penetrating" the strand and generating stress concentrations which reduce the capacity of the system.