Engineering Structures 176 (2018) 632–651

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Evaluation of the behavior and ultimate capacity of unbonded monostrand-anchorage systems under concentric and eccentric inelastic cyclic loading

Luis Alberto Bedriñana[a,*], Kaiwei Zhang[b], Minehiro Nishiyama[c]

[a] *Department of Architecture and Architectural Engineering, Kyoto University, Kyotodaigaku-katsura, Nishikyo-ku, Kyoto 615-8540, Japan*
[b] *Kozo Keikaku Engineering Inc, Tokyo, Japan*
[c] *Department of Architecture and Architectural Engineering, Kyoto University, Japan*

ARTICLE INFO

Keywords:
Post-tensioning
Anchorages
Self-centering system
Strain capacity
Inelastic strain
Cyclic loading
Monostrand
Eccentric load

ABSTRACT

Unbonded post-tensioning (PT) monostrands have traditionally been used in buildings to sustain monotonic loads on members subjected mainly to gravity loads. As a result, most of the technical information on commercially available unbonded PT anchorage systems focused only on applications for gravity-loaded members. Despite the recent experimental research efforts on the behavior of PT anchorages under earthquake-simulated demands, this information has not been well quantified in design documentation. Consequently, further research is needed on unbonded PT anchorages for their use in members subjected to seismic loads. This paper presents the results of a comprehensive experimental evaluation on the ultimate capacity of monostrand anchorages subjected to high-amplitude concentric and eccentric cyclic loads. In addition, this paper addresses the influence of anchorage type, loading patterns and strand size on the ultimate deformation capacity of these anchorages. Specimens consisted of monostrands assembled with anchorages at both ends. Two types of anchorages were tested. Moreover, seven-wire, uncoated, low-relaxation PT monostrands in two sizes were considered. Several cyclic loading conditions were applied, in order to evaluate the behavior of anchorages under different scenarios. The ultimate capacity of the specimens was dominated by a premature fracture of one or few wires inside the wedges and two types of wire fractures were recognized: (1) with little reduction in the wire cross-sectional area and (2) with a notable reduction in the wire cross-sectional area prior the fracture. It was also observed that increased number of wire fractures correlated with larger strain capacity in some specimens. In addition, it was observed that eccentric loads reduced the strain capacity by about 18% for eccentricities of 6% in some cases. The fracture of the specimens occurred at relatively small strains, with values as low as 1.4%. Therefore, strains in unbonded post-tensioned strands should be limited to about 1.0% when designing for seismic loads. Furthermore, an analytical model was proposed to evaluate the influence of anchorages in unbonded post-tensioning precast structures.

1. Introduction

In the past few decades, the earthquake engineering community's attention has been drawn to assessing and controlling the damage produced in buildings after major earthquake events, with the purpose of mitigating economic losses and providing resilience. The motivation for this new approach was the occurrence of significant damage in code-compliant structures and the subsequent economic losses involved in repairing that damage after the seismic event [1]. For instance, it has been reported in recent earthquakes that code-compliant reinforced concrete (RC) buildings sustained major damage, leading to significant post-earthquake economic losses and business downtime [2–4]. Therefore, reducing residual damages and improving the post-earthquake structural performance remains an important challenge.

Self-centering rocking structures have been proposed to reduce the residual damage (damaged-controlled structures) and to improve the post-earthquake performance of RC buildings. One such type of structural systems was introduced in the mid-1990s, which consisted of precast concrete (PCa) elements connected by unbonded post-tensioning tendons [5]. Although different configurations have been proposed over the years, all of them share three basic components (Fig. 1): (1) precast structural elements not rigidly connected to allow gap opening, (2) a restoring force mechanism (unbonded post-tensioning tendons), and (3) additional energy-dissipation mechanism. These self-centering rocking systems proved to be very efficient in mitigating residual deformations and controlling the damage of RC structures in

* Corresponding author.
E-mail addresses: bedrinana.alberto.33x@st.kyoto-u.ac.jp (L.A. Bedriñana), kaiwei-zhang@kke.co.jp (K. Zhang), mn@archi.kyoto-u.ac.jp (M. Nishiyama).

https://doi.org/10.1016/j.engstruct.2018.09.036
Received 19 October 2017; Received in revised form 12 September 2018; Accepted 13 September 2018
0141-0296/

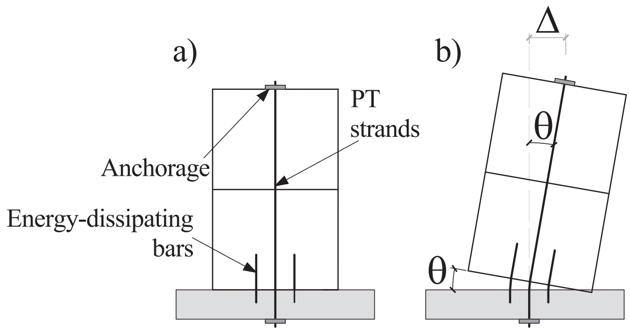

Fig. 1. Schematic figure of self-centering rocking walls. (a) Components. (b) Deformed condition.

large-scale experiments [5–8]. The superior performance shown experimentally later prompted the application of self-centering rocking mechanisms in the seismic-resistance design of structures with other materials such as timber [9], masonry [10] and steel [11].

Although some other means to provide self-centering capacity have been proposed, such as shape memory alloys [12,13] or fiber-based strands, the most common method used in RC building structures relies on unbonded post-tensioning steel strands. In unbonded post-tensioned structures, the strands transmit the tensioning forces to the main structure by means of anchorage systems inserted in the concrete. In consequence, the anchorage systems are essential to ensuring the restoring force and the safety of the overall structure. Unbonded post-tensioning (PT) monostrands have traditionally been used in buildings and bridges to sustain monotonic gravity service loads [14]. As a result, most of the technical information on commercially available unbonded PT anchorages focuses only on applications for gravity-loaded members [15]. Moreover, their design approach was based on research that has been conducted to evaluate PT stresses associated with the service and ultimate capacity of members subjected only to gravity loads [14,16,17]. When applying these conventional PT anchorages to members subjected to lateral loads a different condition is introduced, since strands are expected to be subjected to short-duration repeated stress variations during a seismic event. For instance, it has been reported in recent shaking table tests of unbonded post-tensioned precast concrete buildings that PT tendons underwent several cycles of large-amplitude elongations at moderate frequencies [7,8,18].

This paper describes the details and results of a comprehensive experimental program conducted to evaluate the behavior and ultimate capacity of unbonded monostrand PT anchorages subjected to cyclic loads. In addition, this paper discusses the influence of cyclic loading parameters on the deformation capacity of strand-anchorage systems. The development of an analytical model for the response of monostrand-anchorage systems is also discussed.

2. Background and previous research

The mechanical properties of 7-wire strands are ordinarily obtained from monotonic tensile tests in which special grips are used at the ends of the specimen to reduce relative slippage [19–21]. When an adequate gripping method is provided, the strands under monotonic tensile forces break around the middle of the test gauge length (free-length fracture), indicating a pure tension fracture [19,20]. The free-length fracture of strands has been commonly reported to occur at strains larger than 6% [22,23] when special gripping methods were provided; however, it is acknowledged that the fracture of strands occurs at lower strains when using commercially available anchorages [24], due principally to the different fracture pattern.

Currently, a restricted amount of studies on the deformation capacity of unbonded PT anchorages under earthquake-simulated loading are available in the literature. The initial research examined the ultimate behavior of monostrand anchorages (with different geometries and configurations) under monotonic tensile loading [21]. In this research, it was reported that most of the strand samples fractured prematurely close to the anchorages, not developing their full deformation capacity. Additionally, the fracture strain was found to be between 1 and 4%. Later on, Walsh and Kurama [24] tested about 400 monostrand anchorages, commercially available in the U.S., under different cyclic loading conditions (including one case with an eccentricity of 3.3% from the vertical axis) and reported that cyclic loading condition affected the strain capacity. Sideris et al. [25] further studied the post-yielding response of monostrand anchorages under cyclic loading and reported ultimate strains ranging from 1.5 to 4%. The residual capacity after the first strand wire fracture occurred was also evaluated in this study [25], indicating that additional wires fractured one after the other with increments of loading. In most of the previous tests, the ultimate capacity was dominated by the early fracture of one (or some) of the outer individual wires inside the anchorages at the wedge' nose (the narrow part of the wedges) [21,22,25,26].

It has been also highlighted that the anchorage's performance could be improved by modifying the wedge's geometry to reduce any stress concentration inside the anchorages. To evaluate possible improvements of the strain capacity, some tests were carried out on anchorages with modified wedges and it was noted that wedges with modified taper angle out-performed the standard ones [15,26,27]. Moreover, Bruce and Eatherton [16] conducted a test to evaluate the residual capacity of monostrand anchorages under cyclic loads, reporting a residual capacity of about 1.8 times larger than first wire fracture. Recently, monotonic and cyclic tests on multistrand anchorages, with standard and modified wedges, were also reported [28] and revealed that the strain capacity of standard multistrand anchorages was on average below 2%.

One important observation from the previous research is that many of the specimens did not meet the acceptance criteria for unbonded post-tensioning anchorages, especially the deformation capacity requirement. For instance, it is specified in the ICC-ES AC-303 that anchors under monotonic loads should develop at least 95% of the actual tensile strength, and the elongation at the ultimate load should be larger than 2% [29]; however, the Architectural Institute of Japan [30] specifies that anchorages should develop 95% of the nominal tensile strength with no specification for elongation. As it was previously discussed, several tested strand-anchorages showed fracture strains as low as 1%. In addition, cyclic loading at high stresses was found to reduce the deformation capacity [22] of PT anchorages and some test requirements are currently specified in that regard. For instance, Appendix B of the New Zealand Standard for Concrete Structures [31] requires that PT anchorages used in self-centering structures should be able to sustain more than 50 cycles at load levels of 50 to 80% of the nominal tensile strength of strands. Moreover, the International Code Council Evaluation Service [29] has a similar requirement for anchorages, indicating that they should be validated under cyclic loading levels between 40 and 80% of the nominal tensile strength with a frequency between 1 and 3 Hz. On the other hand, the Architectural Institute of Japan [30] specifies that anchorages should resist more than 200 loading cycles at load levels of 50 to 90% of the nominal tensile strength. However, these requirements were intended for low-cycle fatigue loading and do not necessarily simulate the loading condition of anchorages under seismic events, since post-yield cyclic loading was recommended to be used in the validation testing of unbonded post-tensioning strand-anchorage systems [22]. Then, cyclic loading patterns closer to seismic demands should be used when evaluating the ultimate capacity of PT anchorages.

One important issue to validate unbonded PT anchorages is the reliability of the measurement system. For instance, extensometers attached to the strand samples were used in some of the previous tests [21,22,26] to capture the fracture strain, whereas in other tests elongations were directly measured by potentiometers installed on either strand samples or loading equipment [15,25,26]. Nevertheless, due to