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Experimental study and numerical simulation of precast segmental bridge columns with semi-rigid connections

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ABSTRACT

To prevent the large axial prestressing forces that are typically necessary for a post-tensioned precast segmental column, a semi-rigid connection for a precast segmental bridge pier system is proposed. The proposed connection between segments is a hybrid connection containing bonded bar reinforcement that is spliced by bar couplers and shear keys to provide shear resistance between neighboring segments. Unbounded tendons with a small prestressing force can also be included to provide re-centering forces. Two types of connection between each prefabricated element, *i.e.*, a steel dowel shear key and a reinforced concrete (RC) shear key, are proposed and tested. From the experimental results and construction practices of the developed system, the high seismic resistance and the satisfactory constructability of the proposed pier are confirmed. Furthermore, to establish a proper analysis procedure for such a bridge column system, two finite-element models using solid elements and beam elements from the laboratory tests are also generated and both are shown to be appropriate and effective in capturing the seismic behavior of the proposed system.

1. Introduction

Since the introduction of precast segmental technology, allowing bridge engineers to reduce traffic disruptions, minimize environmental impact, and increase the speed of construction, it has been widely applied in bridge construction worldwide over the past few decades [1,2]. Nowadays, the most commonly used precast segmental technology for bridge substructures is the precast post-tensioned segmental column system. Many studies have confirmed that unbonded post-tensioned precast segmental bridge columns are capable of undergoing large lateral deformation with small residual drift because prestressing can provide a re-centering force [3–5]. In addition, shear keys do not need to be incorporated into the design of these segmental bridge columns because the prestressing force in the tendons is applied to enhance the axial force of the piers to increase between-segment friction [3]. Therefore, the main purpose of shear keys for many previous designs was to facilitate assembly rather than to provide shear resistance [5,6]. However, because of the lack of inelastic deformation for such unbonded post-tensioned precast segmental columns, it is also recognized that these post-tensioned columns without bonded reinforcement passing through segment joints have a lower hysteretic energy dissipation capacity compared with conventional monolithic columns and thus are not effective in reducing seismic energy [7].

In the literature, two types of precast bridge column systems have been investigated to overcome the above deficiency. One is a post-tensioned segmental column system equipped with some types of supplemental energy dissipation devices for increasing energy dissipation capacity [7]. The other is a precast column system that aims to emulate the behavior of a conventional monolithic column through the formation of plastic hinges at the column base. For the first body of research, supplemental energy dissipation devices that have been proposed include mild steel bars [8], internal steel tubes around the post-tensioned strands [9], elastomeric bearing pads [10–12], external energy dissipaters [10,13] and specially designed slip-dominant joints [14]. In addition, the integration of advanced materials, such as engineered cementitious composite, unidirectional carbon-fiber-reinforced polymer fabrics, or ductile fiber-reinforced cement-based composite segments, into the plastic hinging regions of the segmental precast bridge pier system was also proposed by some researchers

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[6,12] to enhance damage tolerance of large cyclic displacements. For the second body of research, most studies focused on the development of connections that closely resembled conventional cast-in-place systems. The emphasis of these studies was on either the connection details between column segments and the cap beam or foundation [15], or the connection details between segments or reinforcing bars [16]. Some proposed a partial precast segmental column system with a combination of several precast segment blocks and a cast-in-place column base to emulate current cast-in-place reinforced-concrete pier designs to ensure that plastic hinges can form at the ends of the columns during an earthquake [17,18].

Both of the abovementioned systems have been shown to possess a satisfactory energy dissipation capacity under proper design. However, for the first type of system with an unbound pre-stressed tendon, in most designs, to maintain and enhance the shear strength of precast segments, the pretension of tendons must be augmented to increase the axial force of bridge piers, thereby enhancing between-segment friction and enabling the segments to effectively resist the earthquake-induced shear force. As the bridge columns have to bear large axial forces even when no external forces are applied on them, this may cause adverse effects on the ductility of the bridge column and may result in excessive stress on the precast segments. In addition, the deficiency of prestress losses or non-uniformly distributed prestress that was hardly prevented in the process of exerting prestress on each tendon strand [19,20] may also be magnified as the prestressing forces are increased. On the other hand, for the second type of system, which is intended to emulate real cast-in-place technology, even though its advantage of achieving the same ductility as for a cast-in-place structure while reducing construction time has been confirmed, the large residual plastic deformation is also expected to be the same as for a cast-in-place column after a severe earthquake.

To address the above issues, the purpose of this study is to propose a precast column system lying in between the above two systems. To prevent the large axial prestressing forces that are typically necessary for a post-tensioned precast segmental column, this study adopts shear keys as the major contributors of shear resistance. In addition, to develop a system for potential use in seismic regions, a semi-rigid connection for the precast segmental bridge pier system is proposed by employing the concept of a human spinal column. The bones in the human spine can deform in various ways to complete an action and provide support because the connection is not totally rigid. In addition, because providing reliable connections to ensure ductile performance is essential for design in earthquake-prone areas [21], the proposed connection between segments is a hybrid connection containing bonded bar reinforcement that is spliced by bar couplers and shear keys to provide shear resistance between neighboring segments. Unbounded tendons with a small prestressing force can also be included to provide re-centering forces. For the proposed system, the bearing elements of bonded reinforcing bars can provide strength and energy dissipation capacity, and the prestressing elements can provide re-centering force upon column deformation. Only a small amount of prestress force is required for the column, owing to the provision of the shear keys for the precast segments against shear stress induced by an external force. Compared to the conventional methodology for a post-tensioned precast column, the present design can resolve the issue of large axial pressure loading on the column caused by excessive prestressing. In particular, the precast segments of this design can be stacked by mortise-and-tenon joints so as to prevent lateral displacement. In this study, two types of connection between two adjoining prefabricated elements, *i.e.*, a steel dowel shear key and an RC shear key, were proposed and tested at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan.

To provide a clear guideline for practicing engineers and researchers, precast post-tensioned segmental columns have been investigated analytically by many researchers over the past few years. Dawood et al. [22] presented a detailed three-dimensional finite-element model that was developed using the ABAQUS platform. Nikbakht et al. [23] analytically evaluated the hysteretic performance of precast self-centering segmental columns at different post-tensioning force levels using a three-dimensional finite-element program. Chou et al. [24] developed a simplified two-dimensional finite-element model using truss and beam-column elements to predict the cyclic behavior of post-tensioned segmental columns. Ou et al. [25] proposed a detailed three-dimensional finite-element model utilizing solid elements in segments and contact elements between segment interfaces to predict the cyclic response of post-tensioned segmental columns in testing. Similarly, to establish a proper design and analysis procedure for the bridge pier system proposed in the current study, numerical simulations of the proposed specimens using two different finite-element models were also conducted. One was a sophisticated finite-element model using solid elements by ANSYS [26], and the other was a simple analytical model for which the columns were simulated with beam-column elements using SAP2000 [27]. Both analytical results were compared with the experimental measurements and confirmed the experimental observations.

2. Specimens

2.1. Specimen design

In this study, two types of connection between each prefabricated element were proposed. One was a steel dowel shear key and the other was an RC shear key, as given in Fig. 1. The steel dowel shear key was made of JIS G4051 S45C steel bar with a diameter of 40 mm. The RC shear key was made of reinforced concrete with a diameter of 266 mm and integrated with the segment. Both connections were designed based on the concept of mortise-and-tenon joints. For conservative purpose, the design of the shear keys was only based on pure shear capacity of the section of steel bars or RC shear keys to sustain the shear forces generated from the lateral forces. Each connecting set includes a shear key and a joint hole, wherein the shear key protrudes from one surface to serve as a tenon tongue and the second surface has a joint hole to serve as a mortise hole. Thus, the precast segments of this design can be stacked by mortise-and-tenon joints so as to prevent lateral displacement and address the issue of high prestress force required for prestressed tendons. In addition, a small gap exists between the shear key and the inner surface of the joint hole to enable the protruded key to rotate inside the joint hole.

To investigate the seismic performance of both types of connection, three precast segmental column specimens with different prestressing forces for each type were constructed and tested at NCREE. For the columns adopting steel dowel shear keys, the specimens were denoted as SSK-P0, SSK-P1, and SSK-P2. For the columns with RC shear keys, the specimens were denoted as RCSK-P0, RCSK-P1, and RCSK-P2, where P0 represents zero prestressing force, and P1 and P2 represent prestressing forces of 0.025 $f_c'A_g$ and 0.05 $f_c'A_g$, respectively. Herein, A_g is the gross cross-sectional area of the column and f_c' is the design concrete compressive strength. For comparison, a conventional cast-in-place monolithic column specimen without connections (specimen BM01) was also constructed and tested. Thus, a total of seven specimens, as given in Fig. 2, were constructed and tested at NCREE. As can be observed in Fig. 2, all these specimens were 3.6 m in effective height with a