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# Numerical study on the seismic performance of precast segmental concrete columns under cyclic loading

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ABSTRACT

To accelerate construction speed, precast segmental column is becoming more and more popular in recent years due to its obvious advantages in saving construction time, reducing site disruption and controlling construction quality. However, the applications are still limited primarily in low seismic areas because its performance under earthquake loading is not well known yet. Many experimental studies have been carried out to investigate the seismic performance of segmental columns under cyclic loading. Due to the complexity in modelling such structures, numerical study of precast segmental columns subjected to seismic loads is limited. In this paper, three dimensional (3D) finite element (FE) models for two precast segmental columns are developed to predict the responses of such columns under lateral cyclic loading. The numerical models are first validated against the cyclic test results and then used to perform parametric studies. The influences of five parameters including bonding condition of the tendon, total initial axial forces level, confinement of the segments, number of segments, and energy dissipation (ED) bars on the performance of segmental columns are systematically investigated. Moreover, columns with shape memory alloy (SMA) bars are also investigated to increase the energy dissipation capacity and reduce the residual drift of the segmental columns. It is found that both mild steel and SMA bars can increase the energy absorption capacity of the column, but the SMA bars can minimize the residual drift due to its innate mechanical property. This study clearly identifies the influences of different factors on the performance of segmental columns. The developed numerical model can be used in the future studies to predict the seismic responses of structures with segmental columns.



## 1. Introduction

Precast construction has attracted a lot of research interests in recent years. Compared with traditional cast in situ construction method, the precast construction has many advantages. In the precast concrete systems, most of the structural elements are prefabricated in factories and then shipped to the construction site. With a few workers and lifting equipment, the structural system can be quickly erected. As a result, the on-site construction time can be significantly reduced and hence the environmental impact is less as compared to the traditional construction method. In addition, the quality of the structure and safety for workers can be improved since most of the construction activities are carried out in prefabrication factories. Precast segmental column is one the prefabricated systems which can be used as bridge piers to improve the construction efficiency in urban areas with heavy traffic. However, it should be noted that the applications of segmental columns are still limited to areas of low seismicity due to a lack of knowledge about its performance under seismic loading. To overcome this problem many important studies have been carried out to investigate the seismic behaviour of precast segmental columns recently [1–8]. Owing to the challenge in numerically modelling such columns formed up with discrete concrete blocks, most of the previous studies are based on the experimental tests.

In the precast segmental column system, the bonding condition of the prestress tendon is an important factor that has significant influence on the performance of the column. Both bonded and unbonded tendon systems have been reported in the previous studies. In the bonded tendon system, the tendon is placed in the corrugated tube and cementitious materials are injected into the corrugated tube after applying the prestressing force to the tendon. As a result, the tendon will deform together with the surrounding concrete. For the unbonded tendon system, no cementitious materials are filled in the tube. Previous studies [9,10] showed unbonded tendon system normally results in smaller residual drift. In comparison, bonded tendon will increase the strength of the column and yielding of the tendon can dissipate some energy [11].

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However, yielding of the tendon can also lead to a reduction of the axial force, which consequently decreases the friction force between the segments and thus reduces the shear resistance. Moreover, yielding of the bonded tendon is likely to result in larger residual deformation as compared to that of the unbonded tendon.

Since the segments of a segmental column are normally connected by prestress tendons, the level of prestressing force in the prestress tendon directly affects the performance of segmental column because it provides the lateral shear resistance through friction force and also the moment resistance for the column. Two specimens with different levels of prestressing forces under the same loading conditions were reported by Ou et al. [9]. The test results showed that the column with higher prestressing force had higher ultimate strength and smaller residual drift, therefore large prestressing force is desirable in these regards. On the other hand, increasing the posttensioning force increases the axial compressive stress in the concrete of the whole column. The toes of the segments therefore may experience large compressive stress when the segments rock with respect to each other. In other words, high axial compressive stress may lead to concrete crushing failure of the column and reduce the ductility of the column. Therefore, systematic studies are needed to determine the proper posttension force level that can be applied to the segmental column.

Previous studies showed that the segmental column normally experienced compression failure at the joints of the segments due to the large compressive stress when the segments rocked between each other under cyclic loading [4,12]. Thus different strengthening methods were used to mitigate the damage of the column, such as using high performance concrete [2], confining the segments with FRP [10], and confining the segments with steel jacket [1,3]. The confinement effectiveness directly affects the confined strength of the concrete and thus affects the performance of segmental column. Therefore, it is necessary to investigate the influence of confinement for the precast segments on the performance of segmental column.

For a segmental column, the joints will open and the segments will rock between each other under seismic loading, so a segmental column with the same height but with different number of segments may have different responses due to the different locations and the different amount of openings. Thus the number of segments is another factor which may affect the seismic performance of the segmental column. However, only very limited studies have investigated the influence of this factor. ElGawady and Sha'lan carried out an experimental study on a series of precast segmental bridge bents confined with FRP [12]. Among the five specimens, F-FRP1 and F-FRP3 had the same dimensions and the same designs except that specimen F-FRP1 had only one segment while specimen F-FRP3 had three segments. The test result showed that these two specimens behaved similarly. Further studies are however necessary to confirm this observation and its validity to segmental columns with other number of segments.

For a segmental column in an earthquake event, the rocking behaviour between the segmental joints reduces the damage of the whole column and the posttensioned tendons pull the column back to its original position which minimize the residual displacement of the column. Therefore the segmental column has better self-centring ability in comparison with the traditional monolithic column. Nevertheless, many previous studies also showed that precast segmental columns that connected only with prestress tendons dissipated very limited energy (e.g. [9]). A variety of energy dissipation devices have been proposed to increase the energy dissipation capability of segmental columns. These devices can generally be divided into two categories, i.e. the internal energy dissipation bars [5,9] and the external energy dissipation devices [3,13,14]. According to these studies, the use of energy dissipation devices increases the energy dissipation of the columns, but may also introduce more damage to the column and increase the residual displacement.

The above review reveals that many factors can affect the performance of segmental column under seismic load. To systematically investigate the influences of these factors on the behaviour of segmental columns, ideally numerical simulation is a better alterative since laboratory testing is not only time consuming but also costly. Some numerical models have been developed and reported in the literature to investigate the influences of particular factors on the performance of segmental columns. These models include fibre based model [8], two dimensional (2D) FE model [11], and three dimensional (3D) FE model [15–18]. Among them, Ou et al. [15] investigated the influence of energy dissipation bar ratios, Dawood et al. [18] focused on predicting the backbone curves of segmental columns, and Leitner and Hao [17] investigated the influence of different options to increase the energy dissipation capacity of the columns. However, studies on the influences of different designs on the cyclic performance of segmental columns are limited. The present study aims to develop an accurate numerical model and then systematically investigate the influences of different design parameters on the performance of segmental columns. Three dimensional (3D) FE models are first developed by using the ABAQUS/Standard program and the models are validated against the experimental results reported by Hewes and Priestley [1]. Comprehensive parametric studies, including the influences of bonding condition of the tendon, total axial force level, confinement for the segments, number of the segments, and energy dissipation (ED) bars on the cyclic response of the segmental columns are then carried out to better understand the behaviour of segmental columns. Finally, shape memory alloy (SMA) bars are also used and investigated to increase the energy dissipation capacity and reduce the residual drift of segmental columns.

## 2. Numerical modelling

Three dimensional (3D) FE models of two segmental columns are developed by using the commercial finite element software ABAQUS/Standard [19]. In this part, a brief description of the models and the detailed modelling methods and procedures will be presented.

### 2.1. Model description

Three-dimensional (3D) FE models are developed based on the experimental tests performed by Hewes and Priestley [1]. A tall column JH1 with an aspect ratio of six and a short column JH3 with an aspect ratio of three are modelled and validated in this study. Fig. 1 shows the design details of the two columns. For column JH1, a base segment and another three segments are connected by an unbonded prestress tendon at the centre of the column. For column JH3, the base segment is the same as JH1 while only one segment is stacked on the base segment. All the segments have a circular cross section with a diameter of 610 mm. To minimize the damage of the concrete segments, the base segments of JH1 and JH3 are confined by steel jackets with the thickness of 6 mm and 2.8 mm, respectively. No steel bars are placed in the base segments. The upper segments are transversely confined by transverse reinforcement with a diameter of 9.5 mm and a spacing of 75 mm. Eight longitudinal steel bars with a diameter of 12.7 mm are also placed around the section evenly in the upper segments. The tendons used in the columns are ASTM A779 Grade 270 prestressing strands. The total cross section area of the tendons for each column is 2665 $mm^2$.