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Performance of segmental self-centering rubberized concrete columns under different loading directions

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ABSTRACT

Segmental self-centering columns are an advantageous construction choice in earthquake prone areas due to their minimal or even zero residual deformation and their low repair/downtime costs. This research investigated the behavior of segmental rectangular column members with a high cross-sectional length to width ratio under different loading directions, with the aim of potentially extending the concept of segmental self-centering columns to wall members, such as shear walls and retaining walls. The main parameters of this study were the direction of loading: in-plane (strong-axis bending) and out-of-plane (weak-axis bending), provision (or absence) of reinforcement, and the type of concrete material (conventional concrete or rubberized concrete). Eight concrete columns with a cross-sectional length to width ratio of 2.5 and consisting of three concrete segments with dry joints in between, were tested under reversed-cyclic lateral loading. A pre-stressing force of 100 kN, corresponding to a stress of 2.8 MPa on the column, was applied using unbonded post-tensioning (PT) bars. The results indicated that although in-plane loaded columns had a higher load capacity, they exhibited a less ductile response, higher level of damage and higher loss in the PT force, compared with the out-of-plane loaded columns. The total equivalent viscous damping and its variation was very small in all tested specimens, and it increased slightly as the drift ratio increased. Empirical equations were developed to express the damping as a function of drift ratio. It was also concluded that in the out-of-plane loaded specimens, the effect of reinforcement on the load-displacement response was insignificant. In rectangular columns with high length-to-width ratio, under out-of-plane loading, if a minimum level of axial pre-stressing is applied (to prevent shear or sliding failure), no structural reinforcement is required. In addition, the strength reduction due to using rubber in concrete at the structural level was much lower than that at the material level. The results of this study can potentially be applied to segmental concrete walls due to the high length-to-width ratios of the tested columns.

1. Introduction

Precast concrete members have become increasingly popular in the construction industry due to their fast and easy construction procedure. Segments of a structural member can be prefabricated in casting yards, and transferred to site for erection. In order to assemble the segments and maintain the integrity of the system, one of the popular construction methods is to apply a pre-stressing force using post tensioning tendons/bars. Self-centering behavior can also be introduced to the member if the tendons/bars are left unbonded. This results in a reduced residual deformation and limited level of damage experienced by structural members subjected to seismic loads. Under lateral loads, unbonded post-tensioning (PT) members are able to rock about their base, resulting in a lower level of damage compared with the bonded PT counterparts. This behavior is favorable due to the high cost and time consuming nature of repairs to a damaged structure with permanent residual deformations and can significantly reduce the repair and downtime costs [1,2]. A number of studies have been carried out recently to investigate the behavior of segmental self-centering columns [1,3–10]. They have shown that segmental PT columns withstand large nonlinear displacements without exhibiting significant or sudden loss of strength [1,3,4,11]. It has also been demonstrated that the use of multiple segments instead of one segment for the column system resulted in only a slight decrease in the lateral load capacity of the column [12]. Some previous studies have also focused on the behavior of self-centering walls [13–18] and similar to self-centering columns, they reported a ductile behavior, large displacement capacity and reduced damage extent [19]. The first aim of this study was to potentially

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extend the concept of segmental self-centering columns to wall members, and in particular, retaining walls. Previous research on self-centering precast walls has been focused on the in-plane behavior of those walls, mainly because such walls were intended to be used as structural wall members in building structures. This study examined the out-of-plane behavior, rather than in-plane behavior to extend the application to retaining wall members. The previous studies on self-centering walls consisted of walls with a single segment rather than multiple segments. In terms of construction, if segments are used, the assemblage of the wall is quick and easy and can potentially provide a cost-effective solution by reducing the labor and crane cost. Using lightweight materials (such as rubberized concrete or foam concrete) for the wall segments makes it easier for the laborers to put the segments together to construct the wall.

The second aim of this research was to attempt to use a lighter material than conventional concrete, hence, crumbed rubber from waste tires was used in concrete and its effects were investigated. Due to the increasing number of vehicles, each year a huge amount of tires are dumped in landfill or stockpiled worldwide. For example, Australia produces more than 18 million waste tires (~ 51 million passenger car tire unit) each year weighing over 200,000 t [20,21]. The civil engineering and construction industries can potentially recycle a significant amount of waste tires [22]. Recycling of used rubber conserves valuable natural resources and reduces the amount of tires disposed of in landfills [23,24]. One of the methods to reduce the tire waste, is to cut them in small pieces, in the form of tire chips or crumb rubber and reuse them in building products, such as concrete. Studies have shown that using rubber in concrete reduces the weight of concrete and improves its ductility, toughness, impact resistance, and damping ratio [25–28], even though it adversely affects the strength [29–34]. Limited studies have been carried out so far to investigate the behavior of rubberized concrete at the structural level. Son et al. [35] showed that the ductility of the column specimens tested under pure axial loading improves by 45–90% depending on the rubber size and content. Ganesan et al. [36] indicated that the addition of shredded rubber significantly enhances the beam-column joint energy dissipation, ultimate deflection and ductility, but reduces the load carrying capacities of the specimens. Using shaking table test results of columns, Xue and Shinozuka [37] reported an increased damping ratio and decreased peak strength in rubberized concrete compared to conventional concrete. On the other hand, based on experimental testing of two large-scale footbridges, Bowland [38] indicated that the crumb rubber does not significantly affect the damping and can even sometimes reduce the damping. Al-Tayeb et al. [39] showed that by increasing the rubber content, while the impact bending capacity of beam specimens increases, the static bending capacity decreases. Youssf et al. [40] reported that by increasing rubber content in column members, the hysteretic damping ratio and energy dissipation increases, however, the viscous damping ratio decreases. Using experimental results of segmental columns, Hassanli et al. [41] reported that the damping was similar in rubberized concrete and conventional concrete, however, when concrete was confined by fiber reinforced polymer (FRP), rubberized concrete showed a slightly higher damping ratio compared to conventional concrete. Youssf et al. [42,43] showed that for both conventional and rubberized concrete columns, increasing the FRP-confinement thickness increases the column plastic hinge length.

To the authors' knowledge, no study has yet been carried out on segmental self-centering walls or columns with high cross-sectional length to width ratios. Similar to columns, the segmental construction technique integrated with unbonded post-tensioning technique can potentially be applied to wall members such as shear walls and retaining walls. While for shear walls the in-plane behavior is of more concern, for retaining walls out-of-plane loading is important. No study to date has been conducted to examine self-centering segmental retaining walls. Additional research is also required to better understand the behavior of rubberized concrete at the structural level, to demonstrate its potential use in engineering applications. Similarly, the information about the effect of reinforcement confinement on the force displacement behavior of segmental columns is very limited. While previous studies showed that confining the bottom segment using FRP wraps could significantly improve the ductility, the effect of confinement using reinforcement is not clear.

In this study, eight segmental concrete columns were post-tensioned and tested laterally under reversed-cyclic lateral loading. The main parameters were the loading direction, the provision of rubber in concrete, and the provision of reinforcement. The objective of this research was to; a) understand the behavior of segmental columns having high cross-sectional length to width ratios to potentially extend the idea of self-centering construction to wall members, b) to explore the possible future use of rubber in concrete at a structural level, and c) to better understand the effect of reinforcement in segmental members. The conclusions provided in this study, will be used for the next stage of the research which is testing of segmental wall members under in-plane and out-of-plane loading.

2. Experimental program

Eight rectangular segmental concrete columns were manufactured and tested under incrementally displacement increasing reverse cyclic loading. Fig. 1 shows the geometry of the tested specimens. The columns had cross-sectional dimensions of 120 mm by 300 mm and a cantilever height of 1425 mm (from the center of the column head to the surface of the footing). Each column specimen consisted of three concrete segments, a column head at the top and a footing at the bottom, and all were connected together using a central PT bar (Fig. 1). The column head was a concrete cube with an edge length of 350 mm, through which the lateral load was applied using a horizontal actuator. The concrete footing was 1200 mm in length, 400 mm in width, and

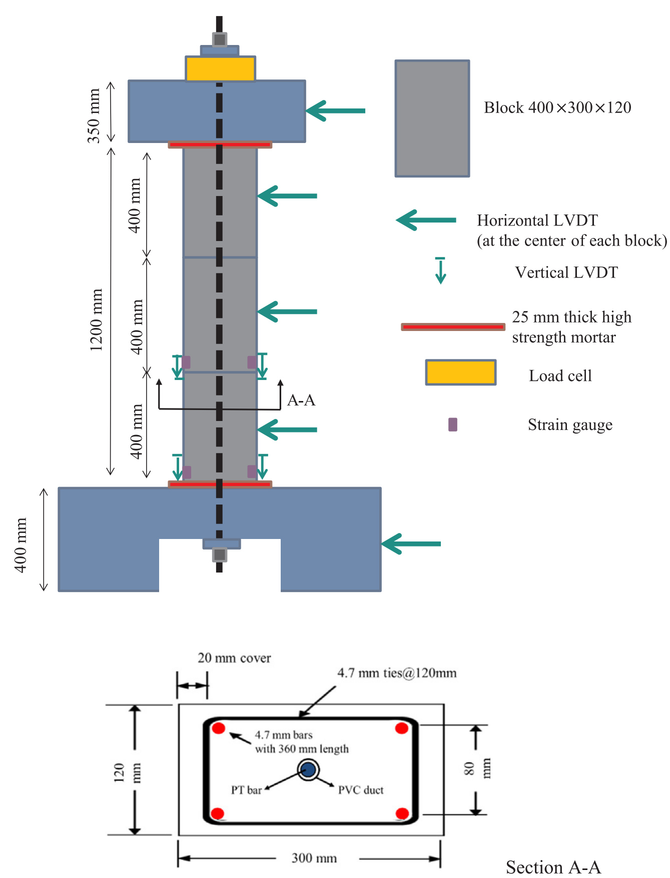

Fig. 1. Geometry of the tested column specimens.