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Seismic performance of predamaged RC columns strengthened with HPFL and BSP under combined loadings

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ABSTRACT

This paper presents an experimental investigation of the seismic behavior of coupling predamaged reinforced concrete (RC) columns strengthened with high-performance ferrocement laminate (HPFL) and bond steel plate (BSP) that are subjected to combined loadings. A total of four specimens were fabricated. After they were predamaged with corrosion and an earthquake environment, they were strengthened with HPFL and BSP, and then tested under four different combined loadings, separately, which are unidirectional compression, bending, and shear (CBS); bidirectional CBS; unidirectional compression, bending, shear, and torsion (CBST); and bidirectional CBST. Their seismic behavior, including failure mode, bearing capacity, ductility, energy dissipation, stiffness degradation, damage index and residual displacement, was analyzed. The results revealed that the coupling predamaged RC columns still had retrofit value and that the retrofitting method utilized in this paper was effective. After repairing with HPFL and BSP, the bearing capacity can be significantly improved especially for torsional specimens, which increased by more than 100%. Other seismic behavior like ductility coefficient, stiffness, and single cyclic energy dissipation can be recovered well. In addition, the horizontal eccentricity had a negative effect on the seismic behavior of specimens, while the negative effect was reduced after strengthening.

1. Introduction

Many reinforced concrete (RC) members are exposed to humid, acidity and heat environments, resulting in corrosion damage. After an earthquake, the damage of corrosion to columns is much more serious, but a large number of columns with corrosion and earthquake damage can still be repaired and used again. This represents an important way to achieve sustainable use of resources. RC columns, during seismic events, are considered vital for the overall stability of the superstructure. Meanwhile, some columns are often subjected to several load combinations during an earthquake (i.e., compression, bending, shear and/or torsion) [1]. When columns fail during an earthquake, huge casualties and economic losses can be caused. Hence, it is necessary to investigate the seismic behavior of coupling damaged strengthened columns subjected to combined loading cases.

So far, many previous studies have investigated the behavior of RC columns under cyclic biaxial bending loading. Rodrigues et al. [2] conducted an experimental study on the effect of variable axial loads on the hysteretic behavior of RC building columns under biaxial horizontal loading. They found that the maximum columns' strength and ultimate ductility were reduced under biaxial load path combined with axial load variation. Zopoo et al. [3,4] experimentally investigated the effects of biaxial bending on inelastic behavior of existing RC columns and proposed a practice-oriented formulation for the ultimate rotation domain. In practical engineering, side beams and upper-side columns are often outward deviations that align with the outside of the bottom-side columns to meet the esthetic appearance and increase the indoor space of RC structures. Therefore, there are not only concentric loadings but also vertical and horizontal eccentric loadings, leading to multiloading cases on columns in an earthquake, which is disadvantageous. At present, there has been a limited amount of research on the effect of combined compression, bending, shear and torsion on RC columns [5–7]. According to the available combined loading tests, Song et al. [8] experimentally investigated the effect of vertical eccentricity on the mechanical behavior of FRP-strengthened columns. They found that the maximum compression load decreased with the increase of the vertical

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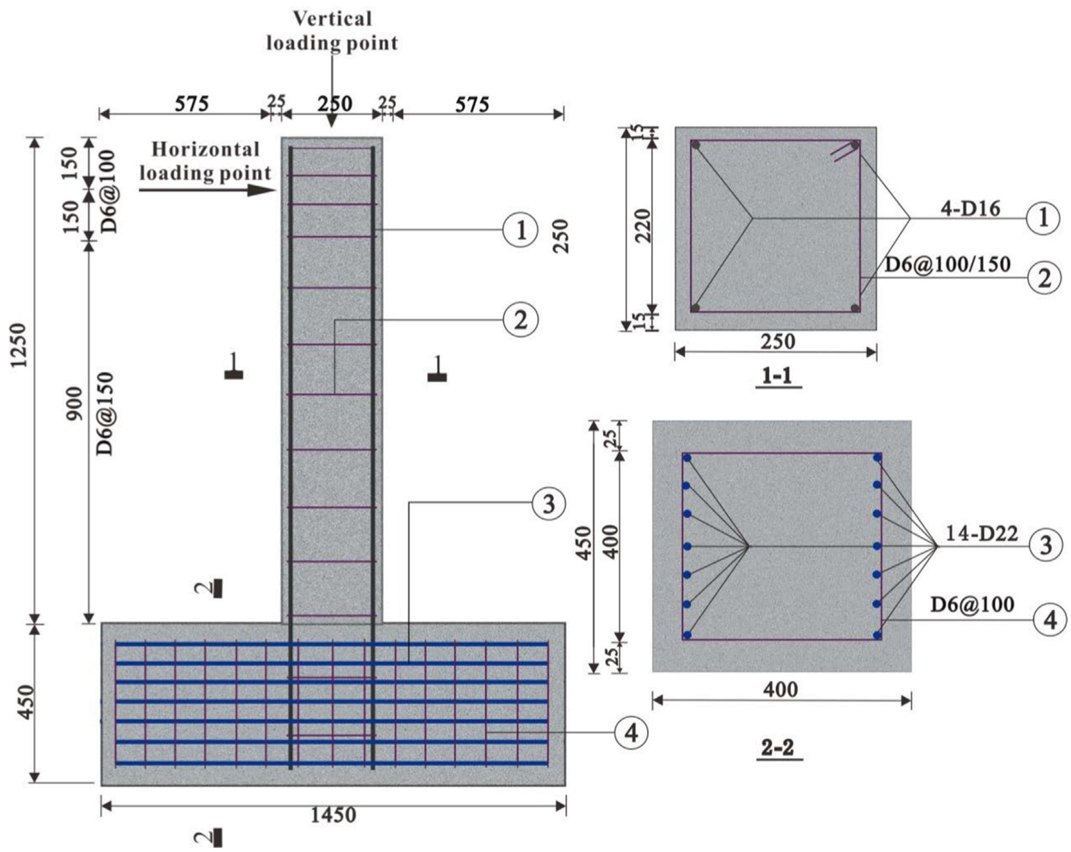

Fig. 1. Specimen configuration (Unit: mm).

eccentricity ratio. Otsuka et al. [9] used nine rectangular columns to study the effect of axial force and spacing of tie reinforcement on the mechanics of columns under cyclic torsion. It was found that the axial force increased the torsional strength of the column and that the reduction of tie spacing could improve the secondary torsional stiffness. Tirasit and Kawashima [10] experimentally investigated the performance of RC columns under combined cyclic bending and torsional loading. It was revealed that the damaged area of torsional columns occurs upward outside the flexural plastic hinge region. Hsu et al. [11,12] studied the effect of combined cyclic bending and constant torsion on the performance of composite columns. They found that the ductility and flexural capacity of composite columns decreased under the participation of torque, similar to the findings of Prakash [13]. According to the damage record in past earthquakes, the effect of seismic torsion is significant and cannot be neglected [14,15]. Therefore, it is necessary to take into account combined loadings in the seismic design of columns when they are subjected to several combined loadings of compression, bending, shear, and torsion. Thus far, little research has focused on combined loading interaction.

Moreover, considering energy conservation and environment protection, the repair of damaged structures has gradually become the interest of many researchers. Fiber-reinforced polymer (FRP) is a widely used strengthening material due to its high strength-to-weight ratio, high corrosion resistance and convenient retrofitting process [16–19]. Saadatmanesh et al. [20] found that the flexural strength and ductility of damaged RC columns retrofitted with glass FRP were improved compared with those of unretrofitted columns. Ozcan et al. [21] experimentally investigated the seismic behavior of undamaged and moderately damaged RC columns retrofitted with carbon FRP. They found that the ductility, dissipated energy and secant-stiffness degradation of columns strengthened with CFRP were improved. Ma et al. [22] conducted an experiment about the earthquake-damaged RC frame structure strengthened with basalt FRP. The results show that for an earthquake-damaged low-rise structure, its seismic capacity can be restored and significantly improved through epoxy injection and FRP retrofitting. Li et al. [23] tested 18 columns to study the effects of reinforcement corrosion level, initial earthquake damage degree, retrofit with CFRP and loading pattern on the cyclic behavior. It is reported that for the column models with initial earthquake damage levels of less than 30%, strength and fatigue life after the retrofit was fully restored to the levels prior to earthquake damage. But when the retrofitted corroded columns with a reinforcement corrosion level of about 10% exhibited lower loading capacity than the un-corroded intact columns. In addition, some researchers [24–26] experimentally revealed that the ultimate load capacity was not fully restored for severely damaged columns strengthened with FRP. Li et al. [27] proposed to adopt combined carbon fiber-reinforced polymer and steel jacket to repair corrosion-damaged RC columns. But the steel jacket is easy to rust. Therefore, in this paper, a new reinforcement technology, High-Performance Ferrocement Laminate (HPFL) and Bond Steel Plate (BSP), was adopted to strengthen the coupling damaged columns. This technique adopts the advantages of HPFL reinforcement and bonded reinforcement technology. It can significantly improve axial compression performance, shear, bending behavior and ductility [28–31].

In this paper, to investigate the seismic performance of coupling damaged RC columns reinforced with HPFL and BSP, four RC columns were fabricated and exposed to a NaCl solution for corrosion damage. Lateral cyclic loads were applied to them to cause earthquake damage before they were strengthened with HPFL and BSP. Finally, they were tested under different combined loadings. The seismic behavior of the retrofitted RC columns was investigated, including analysis of failure mode, skeleton curves, bearing capacity, ductility, hysteretic curves, energy dissipation, damage indexes, stiffness degradation and residual deformation.