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Punching shear behavior of flat slabs composed of normal concrete and ECC under the unbalanced moment

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ABSTRACT: Load capacity and ductility are the two main characteristics of flat slab-column connections in highly seismic areas. To date, different methods have been employed to strengthen the connection against shear punching, including column capital, drop panel, high strength concrete, and shear reinforcement. In the current experimental study, the effect of using Engineered Cementitious Composite (ECC) on upgrading the punching shear strength of flat slabs under an unbalanced moment was investigated. ECC can provide the composite with features such as the ability to spread multiple cracks under load, strain hardening, shear force, scabbing strength, and high deformation. To this end, seven reinforced concrete flat slab specimens with the dimensions of 1000mm*1000mm*100 mm under the load with the eccentricity of 150mm were examined. The slabs were made from two layers of normal concrete and ECC in their thicknesses. The variable parameters included the unbalanced moment effect, improved interaction of the two materials, and ECC thickness. It was observed that improving the contact surface of normal concrete and ECC increased the shear capacity. In addition, the replacement of slab concrete with ECC increases the punching capacity and post-punching strength of the slab without a large and sudden drop in load. The change in failure mechanism was observed from a sudden and abrupt failure to a formable failure with high-energy absorption when using more ECC layer thicknesses.

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1. INTRODUCTION

Due to the presence of unbalanced moment in the slab-column connection, it is necessary to increase the strength and ductility at the connection. Although the use of column capital and drop panel increase the shear capacity of the slab-column connection, the ductility at the joint does not change. The application of high-strength concrete at the connection enhances the shear strength and flexural capacity of the joint; however, it demonstrates a strong brittle failure in severe earthquakes [1, 2]. Adding shear reinforcement around the column in the slab-column connection would improve the connection behavior; yet, the presence of severe cracks in the flat slab under cyclic loading is unavoidable [3]. Despite the fact that there are various methods of strengthening the slab-column connection, a method that can simultaneously meet the strength and ductility of the connection by considering the implementation and economic aspects is of interest to researchers.

Using engineered cementitious composites (ECC) with features such as the ability to spread multiple cracks under load, strain hardening, shear force and scabbing strength, and high deformation which was previously used for reinforcing the beams [4], columns [5], beam-column connection [6] and masonry wall [7], the present study sought to investigate the effect of such composites on enhancing punching shear resistance of flat slabs under an unbalanced moment. To do so, first, a suitable design for ECC mixing was prepared based on the previous studies, and then, the effect of using ECC on upgrading the punching shear strength of flat slabs under an unbalanced moment was examined.

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2. EXPERIMENTAL PROGRAM

In order to enhance the efficacy of using ECC on the punching shear behavior of the flat slabs under the unbalanced moment, the ECC was initially formed with mechanical and flexural properties indicated in Table 1 and Figure 1, respectively. Then, a total of seven half-scaled reinforced concrete flat slab specimens with dimensions of 1000 mm × 1000mm ×100 mm were designed and made according to ACI-318-14 code. Slabs were made of two layers of normal concrete (NC) and ECC in their thicknesses. The slabs were examined under load with an eccentricity of 150 mm and according to the configuration presented in Figure 2. The variable features included the unbalanced moment effect, improved interaction of the two materials, and ECC thickness.

Table 1. The mechanical properties of composite material (ECC)

density (kg/m^3)	Flexural Strength (MPa)	Compression strength (MPa)
1748	8	31

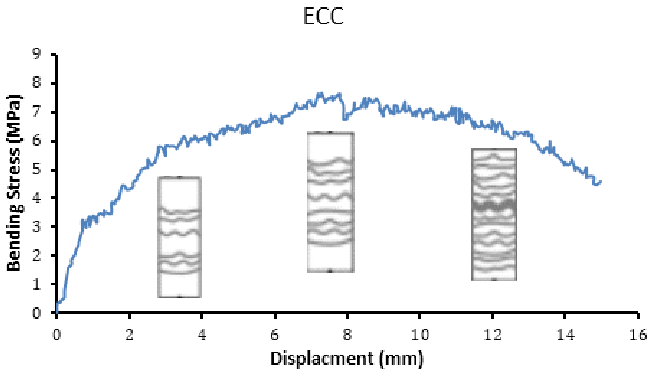

Fig. 1. Bending stress – Mid-span displacement curve for the four-point bending test

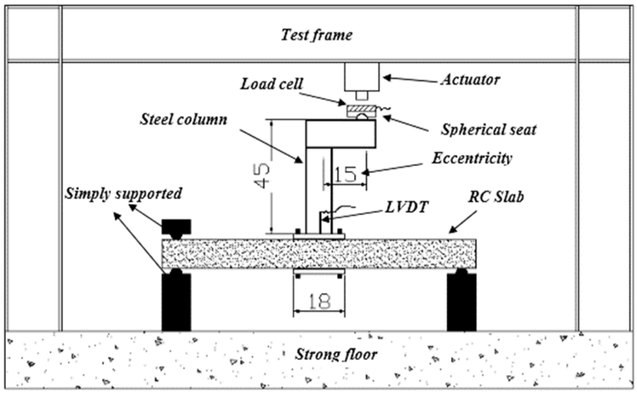

Fig. 2. Test setup

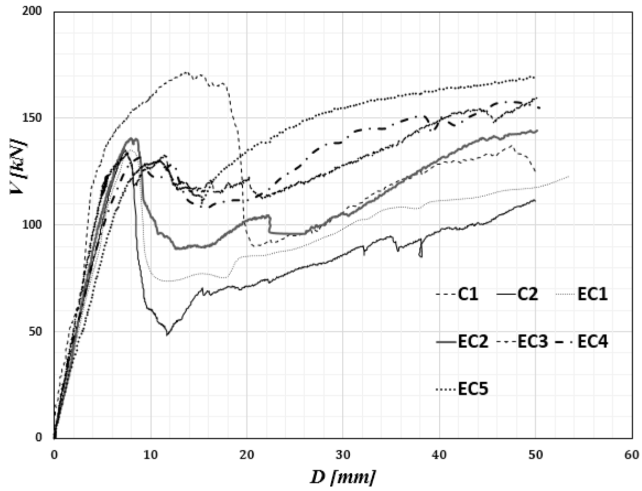

Fig. 3. Load - displacement relationship for connections with different h_e/H

3. RESULT AND DISCUSSION

According to Figure 3, the final load capacity of the specimen with unbalanced moment (C2) was reduced by 21 percent compared to the specimen with net shear (C1). The application of U-shaped rebars in the connection of the NC and the ECC (EC3 compared to EC2 specimen) improved the interaction of the two materials; hence, it increased the shear capacity and changed the brittle failure mechanism to soft failure in the composite slab.

Also, the ECC replacement height (he) to slab thickness (H) ratio was investigated at the ratios of zero (C2), 0.15 (EC1), 0.3 (EC3), 0.5 (EC4) and 1 (EC5). According to Figure 3, as the force and unbalanced moment increased, the fine cracks were gradually formed and the stiffness decreased. Put differently, the increase in ECC layer thickness leads to a noticeable decrease in stiffness. Despite the fact that the rise in the amount of ECC replacement in EC3, EC4, and EC5 specimens expanded the multiple micro-cracks and the tensile hardening of ECC, leading to noticeable deformation of the slab-column connection, the sheer capacity drop is, however, much less and it is about 11, 15, and 15%, respectively.

Due to the presence of integral reinforcement in the compression aspect (compression reinforcement that passes through the connection), the slab after punching failure is still able to withstand the load to prevent the progressive damage (post-punching behavior). The results showed that the replacement of conventional slab concrete (C2 specimen) with ECC has increased the post-punching capacity of EC3, EC4, and EC5 specimens by 44, 45, and 54 percent, respectively. Energy absorption of EC1, EC3, EC4, and EC5 specimens were 14, 50, 52, and 63 percent, respectively, which is higher than the amount of energy absorbed in the C2 specimen, which was completely made of normal concrete. The presence of ECC in the tensile zone of the slab, not only increases the shearing capacity of the slab, but also prevents failure with crushing and separation of crushed pieces from the surface of the slab. Therefore, the features of a flat slab change from a brittle shear failure to ductile bending fracture with hardening property.

4. CONCLUSIONS

In the current study, first, a suitable design for ECC mixing was suggested based on previous studies. Then, the effect of using ECC on the punching shear behavior of flat slabs under an unbalanced moment was investigated. Besides, the effect of the unbalanced moment, concrete and ECC contact surface improvement, and the replacement of slab concrete with ECC were investigated in the specimens. Based on the experiments, the following results are obtained:

1- The use of ECC at the slab-column connection maintains the shear capacity, yet the behavior after the failure of the connection is significantly improved. The whole replacement of slab concrete with ECC results in an increase in the energy absorption capacity by 63 percent.

2- By increasing the replacement of slab concrete with ECC, the behavior of the flat slab is shifted from a sudden brittle failure with crushing and separation of concrete pieces to a ductile failure without crushing and separation of the concrete cover on the rebars.

3- As the replacement of slab concrete with ECC increases, the post-punching behavior, which is effective in preventing progressive failure, increases significantly. Complete replacement of slab concrete with ECC increases the post-punching strength by 53 percent.

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