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Reinforced concrete beam–column joint strengthened with carbon fiber reinforced polymer

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ABSTRACT

An effective rehabilitation strategy is proposed to enhance the strength and stiffness of the beam–column joint in this study. An analytical model is proposed to predict the column shear of the joints strengthened with carbon fiber reinforced polymer (CFRP). Three full scale interior beam–column joints, including two specimens strengthened with CFRP and one prototype specimen, are tested in this study. The specimens are designed to represent the pre-seismic code design construction in which there is no transverse reinforcement. A new optical non-contact technique, digital image correlation (DIC), which can measure the full strain field of specimen, is used to measure and observe the full strain field of the joint. The experimental results show that the beam–column joints strengthened with CFRP can increase their structural stiffness, strength, and energy dissipation capacity. The rehabilitation strategy is effective to increase the ductility of the joint and transform the failure mode to beam or delay the shear failure mode. By observing the measured results, it is found that the mechanical anchorages can prevent the debonding of CFRP. Comparing the analytical and experimental results, the proposed model can accurately predict the column shear and shear strength of the joints strengthened with CFRP.

1. Introduction

The shear failure of an RC beam–column joint may cause the immediate collapse of a building, and strengthening such joints can have a significant influence upon the earthquake resistance of structures. However, many buildings were designed and built without considering this issue, and thus it is necessary to develop an effective rehabilitation strategy to strengthen such joints in order to avoid or delay their shear failure. The common rehabilitation techniques are RC or steel jackets, and these have been investigated by many researchers, such as Alcocer and Jirsa [1], Ghobarah et al. [2], Tsonos [3], and Hakuto et al. [4]. In recent years, a new method of using FRP has been widely applied. Compared with the traditional rehabilitation techniques, FRP has the advantages of being lightweight, easy to construct and having a high specific strength. Gergely et al. [5] experimentally demonstrated the exterior joints strengthening with CFRP could improve the shear capacity of the joints, while Granata and Parvin [6] experimentally proved that it could also enhance the moment capacity of the exterior beam–column joints. In addition, Li et al. [7] showed that the stiffness and load carrying capacity could be improved by FRP reinforcement, while Ghobarah and Said [8,9], El-Amoury and Ghobarah [10], and Ghobarah and El-Amoury [11] used FRP to enhance the shear resistance of the exterior joints. Antonopoulos and Triantafillou [12] investigated the behavior of beam–column joints strengthened with FRP through 2/3-scale testing of 18 exterior joints. Their results showed that the mechanical anchorages played an important role in limiting the premature debonding of FRP. Mukherjee and Joshi [13] demonstrated the effect of FRP to improve the shear strength of the beam–column joints. Al-Salloum and Almusallam [14] and Almusallam and Al-Salloum [15] predicted the diagonal tensile stresses in the joint through small scale tests and analysis [16] and their results demonstrated that an analytical model [16] can be used to accurately predict the shear capacity of interior joints. Parvin and Wu [17] presented a numerical model to analyze the effect of ply angle of the beam–column exterior joints strengthened with CFRP wraps, with their results indicating that layers of wrapping placed successively at ±45° ply angles are the most suitable way to improve the shear capacity and the ductility of the joints. Although some researchers have experimentally studied the beam–column joints strengthened with CFRP, few have measured and observed their full strain field.

Digital image correlation (DIC) is an optical non-destructive and non-contact technique. DIC can obtain the displacement fields on a

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specimen's surface by comparing local correlation of two images before and after deformation. Compared with conventional measurement approaches, DIC has the advantages of low-cost, high precision, and a relatively simple experimental procedure, and has thus been widely applied to analyze a variety of problems. Wan et al. [18] used it in an experimental study of FRP that is bonded to concrete, while Stephen et al. [19] used it to observe the interfacial shear stress of RC beams strengthened with FRP. Some researchers have also used this method in the experimental investigation of composite structures [20,21].

Three full scale interior beam–column joints are tested in this study, including two specimens strengthened with CFRP and one prototype specimen, and two rehabilitation schemes are used. One of the strengthened specimens uses mechanical anchorages to prevent the debonding of CFRP, while the other does not. The DIC method is then used to measure the full strain field strain of the joints strengthened with CFRP, and the test is conducted under the displacement-controlled test method, while the cyclic lateral loading and the constant axial loading are applied to the top column of the beam–column joint. An analytical model is proposed to predict the column shear of the joint strengthened with CFRP. The analytical results are shown to agree well with the experimental results.

2. Experimental procedures

2.1. Test specimens

Three beam–column joints, named JI0, JI1, and JI2, are tested in this study. JI0 represents the prototype, while JI1 and JI2 represent the strengthened specimens. The cross sections of the beam and column are 300 mm × 600 mm and 400 mm × 400 mm, respectively. The longitudinal reinforcements for the beam and column are eight 25.4 mm diameter bars, and their yield and ultimate strength are 456 MPa and 633 MPa, respectively. The stirrups in the beam and column are 10 mm diameter, their spacing is 150 mm, and their yield and ultimate strength are 331 MPa and 476 MPa, respectively. The compressive strength of the concrete used in the specimen is 27 MPa. The cross sections and details of all of the specimens are shown in Fig. 1. All of the test specimens are designed with no transverse reinforcement in the joint. The properties of the CFRP and resin used in the test are as provided by the manufacture. The tensile strength and elastic modulus of CFRP are 4382 MPa and 258 GPa, respectively, and the thickness and fracture strain of CFRP are 0.11 mm and 0.0181, respectively. The tensile and compressive strength of the resin are 20 MPa and 25 MPa, respectively.

In order to make the concrete surface smooth, an electric stone wheel grinder is used to smoothen out the uneven surface of specimen JI1. After the surface of the specimen is smooth, the epoxy resin is used to bond the CFRP. The excess epoxy and air bubbles are pressed out to ensure a tight and smooth bond between the concrete and CFRP. Four vertical unidirectional CFRP layers are first applied to the corners of the joint zone for a distance of 50 mm. Two horizontal unidirectional CFRP layers are then wrapped around the column. The exploded rehabilitation scheme of the strengthened specimen JI1 is shown in Fig. 2, and this specimen is only strengthened with CFRP, and does not use anchoring.

The rehabilitation scheme of the strengthened specimen JI2 is shown in Fig. 3. First, four horizontal unidirectional CFRP layers

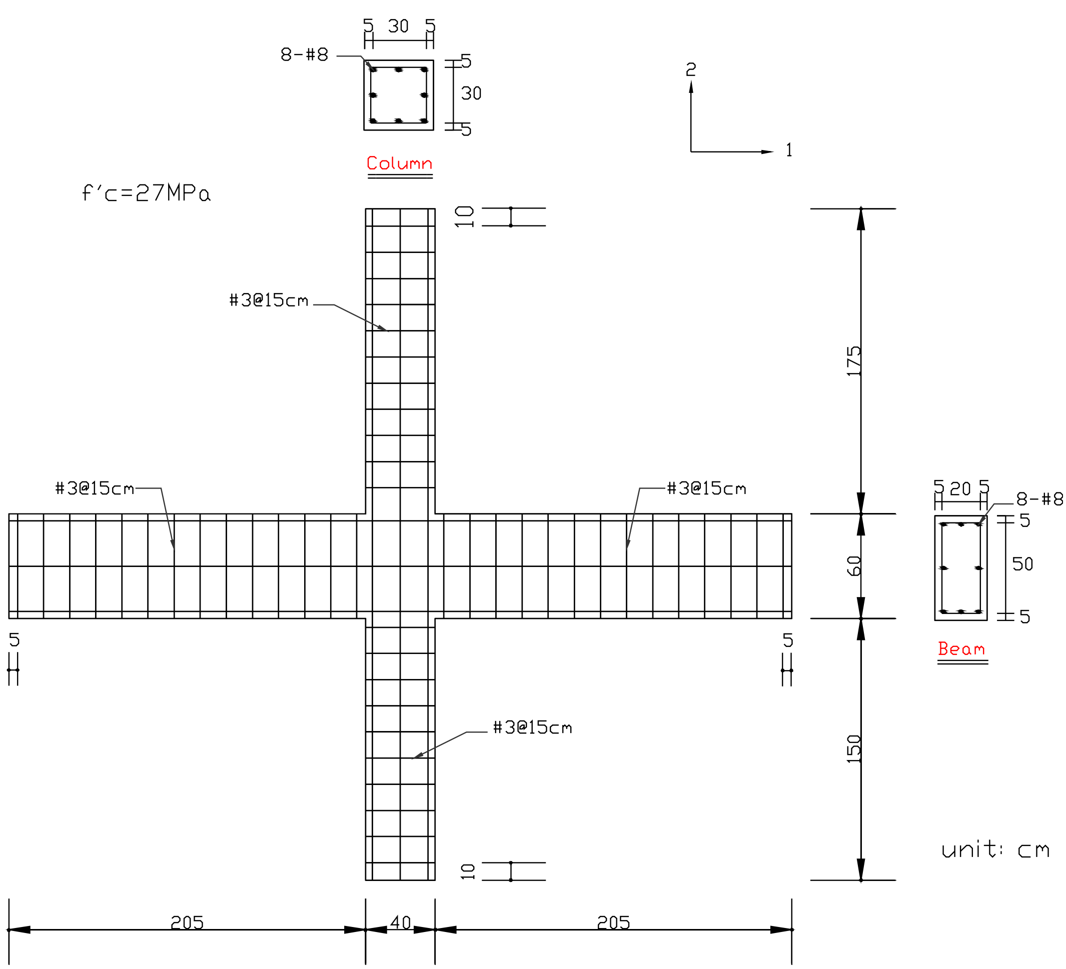

Fig. 1. Schematic configuration of specimen design.