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Embedded steel column-to-foundation connection for a modular structural system

Keum-Sung Park [a], Jiho Moon [b,*], Sang-Sup Lee [a], Kyu-Woong Bae [a], Charles W. Roeder [c]

[a] Advanced Building Research Division, Korea Institute of Construction Technology, Goyang Si, Gyeonggi-do 411-712, South Korea
[b] New Transportation Research Center, Korea Railroad Research Institute (KRRI), Uiwang-Si, Gyeonggi-do 437-757, South Korea
[c] Department of Civil & Environmental Engineering, University of Washington, Seattle, WA 98195-2700, USA

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ABSTRACT

Pre-made modular units permit rapid and economical construction and are increasingly used where repetitive units are required. The assembled building must behave as a single structure to effectively transfer the forces and moments developed by gravity and lateral loads. For this, individual modular units must be properly connected to each other. Therefore, evaluation of the behavior of connections used in modular construction is crucial. This study proposes an embedded steel column-to-foundation connection for modular structural systems and evaluates the behavior of the proposed connection. Experiments were performed to investigate the effect of the column embedment depth, the shape of the column end plate, and shear studs in the embedded region of the column on the connection behavior. Further, three dimensional nonlinear finite element analyses were conducted for each test specimen to demonstrate the in-depth behavior of the connection. Finally, a design equation for the proposed connection was proposed.

1. Introduction

Fig. 1 shows a modular unit and an example of the assembly of these units into a complete building structure. Modular structural systems have been used increasingly for mid-rise schools, apartments, dormitories, hotels and other similar buildings where repetitive units are required [1]. Further, applications in high rise buildings can be found in the case study conducted by Lawson et al. [2]. Modular structural systems can lead to accelerated and economical construction with improved quality control and accuracy of construction [3]. Two different forms of modular unit construction have been employed [3]. The first form uses side walls of the modular units to transfer loads through the finished structural system. The other form consists of the corner-supported modules as shown in Fig. 1, and loads are transferred through the edge beams and the columns of this system. This study focuses on corner-supported modules.

For corner-supported modules, the modular structure must have proper lateral resistance to provide safety for lateral loads, such as an earthquake loading. The lateral resistance of the modular unit is often achieved by adding diagonal braces or shear walls, and some researchers have studied lateral resistance systems for the corner-supported module [4,5]. In addition, the individual modular units must be properly connected to each other to transfer the forces and moments developed by gravity and lateral loads, so that the final assembled structure behaves as a single structure. For this, it is crucial to thoroughly understand the behavior of connections used in modular construction. However, studies on the connections used for modular construction are limited.

There are two different types of connections in such structures. The first are connections between the individual modular units, and the other is connection to the foundation as shown in Fig. 1. An example of a connection between the modular units is shown in Fig. 2. For this connection, a cross shaped plate is installed at the interface between the columns and then bolted to the web of the edge beams as shown in Fig. 2. This connection permits easy connection between modular units, and there is a gap between the columns. The width of the gap is equal to the thickness of the cross shaped plate.

The column-to-foundation connection of modular system must be practical and economical. It must develop the full column strength, and provide good ductility to sustain inelastic deformation demands resulting from extreme lateral loading. For this, an embedded connection is proposed based on previous research into embedded connections for concrete-filled tube (CFT) members [6–8] in this study. Fig. 3 shows the proposed embedded column-to-foundation connection for interior columns of the

* Corresponding author. Tel.: +82 31 460 5898.
E-mail address: jmoon1979@gmail.com (J. Moon).

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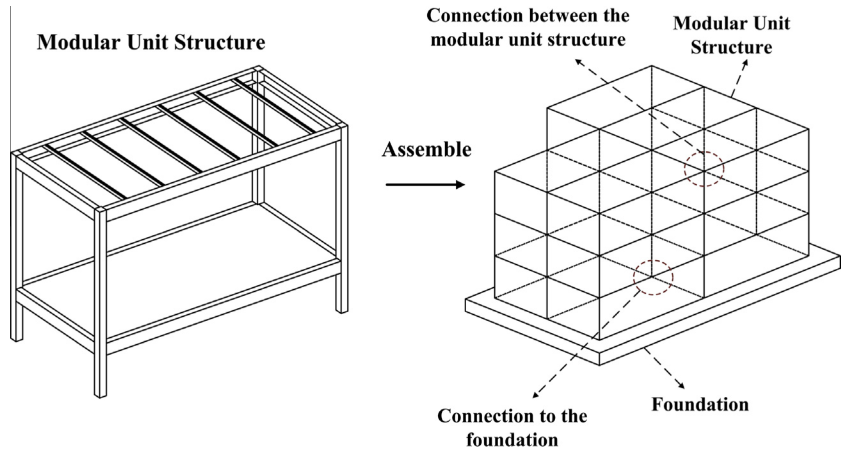

Fig. 1. Modular unit and an example of its assembly.

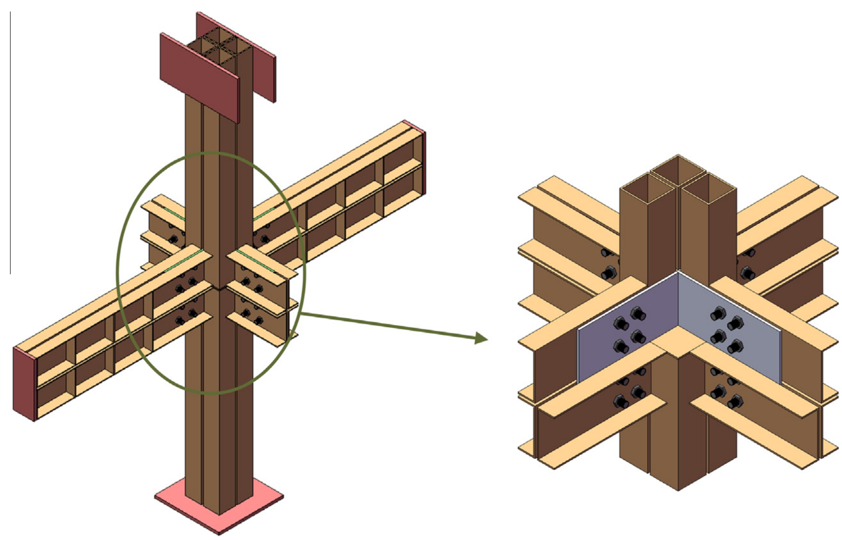

Fig. 2. Example of the connection between the modular units.

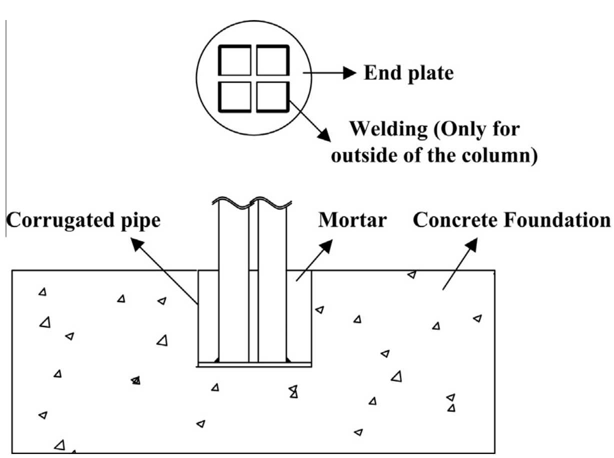

Fig. 3. Proposed column-to-foundation embedment connection for interior column of modular unit structure.

modular structural system. For interior columns, four individual columns meet at the joint, and these columns are welded to an end plate, which efficiently transfers forces and moments to the foundation. The columns and the welded end plate are then placed at the recess of the foundation and connected with mortar. It should be noted that only the outside perimeter of the column can be welded to the end plate as shown in Fig. 3. As a result, the columns are not connected to each other and there is a gap. Thus, the plastic moment capacity of the section is obtained by summing the plastic moment capacity of the individual unit columns.

This study focuses on the behavior of the proposed column-to-foundation connection for the modular system as shown in Fig. 3. Experiments were performed to investigate the effect of the embedment depth, the shape of the end plate, and the use of shear studs in the embedded region of the columns on the connection behavior. Further, three dimensional nonlinear finite element analyses were performed to demonstrate the failure modes of the proposed connection in depth. Finally, a simple design equation to determine the minimum embedment depth of the column was proposed.

2. Experimental study

2.1. Description of test specimens and test setup

The key parameters for the experimental study of the proposed connection are: (a) the embedment depth of the column; (b) the