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Experimental investigation of web-continuous diagrid nodes under cyclic load

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ABSTRACT

Applications of the diagrid structural system have recently increased, and substantial analytical studies have been conducted. However, the structural behavior under lateral loadings, such as wind and earthquake loads, cannot be fully understood through only analytical approaches, due to the complexity of diagrid nodes, and challenges of modeling the welding properties. Therefore, in this study, four web-continuous diagrid node specimens were tested under cyclic loads. Welding methods and design details were selected as testing parameters. The effects of the welding methods and design details on the initial stiffness and yielding stress were found to be not significant. However, the failure mode and energy dissipation of the nodes were significantly affected by the welding methods, and the design details.

1. Introduction

Developing structural technology makes it possible to build high-rise buildings, such as the Burj Khalifa, or Taipei 101. The technology of constructing high-rise building has concentrated on height, but recently, the aesthetic aspect of high-rise buildings is being considered as well. Researchers such as Beghini et al. [1] tried to combine aesthetics and functionality. The author gave several tall building examples to prove the possibilities of combination between design and engineering. Also, the main topic of the CTBUH World Conference held in 2006 was “Thinking outside: Tapered, Tiled, Twisted Towers”, which shows some of the current trends of high-rise buildings.

The diagrid structural system, which consists of triangular modules, is considered as one of the most appropriate structural systems for this trend. 30 St Mary Axe (London), Hearst Tower (New York), Capital Gate (Abu Dhabi), and Tornado Tower (Qatar) are well-known buildings that the diagrid structural system has been applied to.

The diagrid structural system resists vertical and horizontal forces with triangular modules of beams and braces, without columns. This structural system is very effective in resisting horizontal forces, such as wind or earthquake. Therefore, active research investigations to apply the diagrid structural system to high-rise buildings are in progress.

Moon [2] proved that the diagrid system has almost the same performance as the brace tube system, which is well-known for its high lateral strength. Moon et al. [3] also suggested optimal angles of the diagrid system, by measuring the lateral displacement of diagrid structures of various heights and angles. Leonard [4] investigated the shear lag of the diagrid system, and showed that the diagrid system performed better than a framed tube system. Kim and Lee [5] revealed progressive collapse characteristics of the diagrid system. Ko et al. [6] evaluated the seismic performance of irregular diagrid buildings by an analytical approach, and suggested a higher value of seismic performance factor than currently in use. Kim et al. [7] estimated response modification factors of various heights of the diagrid system. Bae et al. [8] conducted experimental study of the diagrid frame, and also suggested a higher factor than the current value.

Several researchers tried various kind of diagrid system. Chao et al. [9] tested diagrid nodes that are made of concrete filled steel tube and suggested bearing capacity equation based on the Chinese design codes for Concrete Filled Steel Tubular (CFST) columns. Kim et al. [10] developed beam-column connection of H-shape column and Ju et al. [11] assessed performance of Buckling Restrained Brace (BRB). Based on these two studies, Lee et al. [12] carried out experimental study of diagrid system that is composed of BRBs. As a results, the author showed that the BRB increased ductility of diagrid system.

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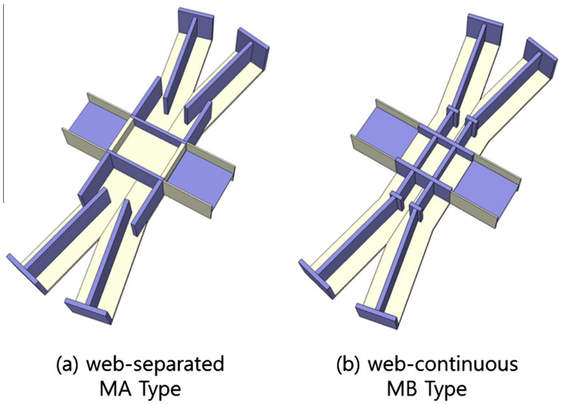

Fig. 1. Two types of diagrid.

However, structural behaviors or welding properties of real diagrid nodes under lateral forces cannot be completely evaluated by analytical studies only. Therefore, a series of studies were conducted by the authors. The authors [13,14] conducted experimental studies of a diagrid system subjected to lateral force. Seismic performances of web-separated H-section and Box-section nodes were investigated, in terms of design details and welding methods. The web-separated H-section diagrid node is a modified version of the web-continuous H-section diagrid node. Fig. 1 illustrates the two kinds of H-section diagrid nodes.

In this paper, seismic performance of the web-continuous H-section diagrid node is mainly discussed, with an emphasis on initial stiffness, strength, welding method and energy dissipation. Test results of the web-separated H-section diagrid node are introduced, to compare behaviors between web-continuous and web-separated diagrid nodes.

2. Experimental program

2.1. Specimens

The prototype of testing specimens was selected to be the structural system used in the Lotte Super Tower in Seoul, which has been designed with a height of 555 m, using the diagrid system. A node in the lower level of this tall building was selected for this study.

Fig. 2 illustrates the details of a test specimen, which consists of two diagonal brace members (H-Section) with an angle of 24°. The test specimens are scaled down by a factor of five, due to the limitation of actuator capacity (3000 kN). At the intersection of the two braces, flanges are attached to each other, while webs are continuously connected through vertical stiffeners. The testing parameters are welding methods, and distances between vertical stiffeners. The details are shown in Fig. 3, and listed in Table 1.

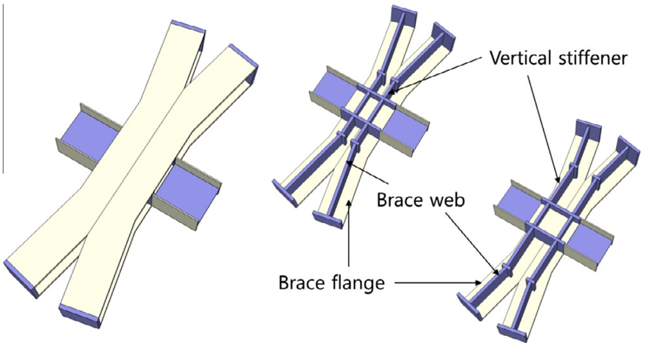

Fig. 2. 3D view of specimen.

For a conventional node, the full penetration (abbreviated as FP) welding method is commonly used. The proposed node has many welding areas, and the amount of the welding material will be great, in the case of tall diagrid buildings. If the stress distribution of the node is analyzed well, several parts of the FP welding areas will be substituted for by the partial penetration (abbreviated as PP) welding method. The amount of welding material can be reduced significantly, if the structural performance with the PP welding method is similar to that with the FP welding method.

The distances between vertical stiffeners are considered as design criteria. A close distance between vertical stiffeners would result in difficulty of manufacturing. Therefore, longer vertical stiffeners, which lead to a wider distance between vertical stiffeners, are introduced as a test parameter.

Fig. 4 depicts details of the four specimens. The MB-01 specimen is designed as a baseline specimen. The length of the vertical stiffener is 107 mm, and is denoted as L1. The FP welding method is used for the entire welding. The length of vertical stiffeners in the MB-02 specimen is identical to that of the vertical stiffener in the standard MB-01 specimen, while the PP welding method is used at flange–flange, and web–flange, welding areas. Since a high concentration of stress is expected at the center of the node, the PP welding method is not used there.

The MB-03 specimen is designed to make the fabrication easy. Because of wider distance (126 mm) between the vertical stiffeners, the intersection point of the web and the vertical stiffener is modified. This point is located beside the V-point, where the flanges of the braces meet each other. Consequently, the length of vertical stiffener become longer (238 mm), and is denoted as L2. The full penetration welding method is used for the entire welding. The MB-04 specimen has the same form as the MB-03 specimen having the L2 length of the vertical stiffener. The full penetration welding method is used, except at the web–flange welding area.

2.2. Loading protocol and measurement schedule

As shown in Fig. 5, two actuators were used for each brace member, to apply cyclic loads. One was installed horizontally, and the other was installed diagonally, with an angle of 24°. To represent the structural behavior of the diagrid structural system under lateral load, tensile force was applied to one brace, while compressive force was applied to the other. Tensile force to upper brace and compressive force to lower brace is the start of the loading protocol. As shown in Fig. 6, cyclic displacements of $\pm\delta/\delta_y$, $\pm 2\delta/\delta_y$, $\pm 4\delta/\delta_y$ and $\pm 6\delta/\delta_y$ were applied twice per cycle, where yield displacement, δ_y of the brace is about 2 mm, which is derived from the section area of the brace. The test was stopped when the load decreases below 80% of the maximum load, or the specimen fails

Fig. 7 shows the details of the measurement schedule. During the test, two dial gauges were used to measure axial deformation of the braces, and four LVDTs were used to measure horizontal and vertical displacements at the center of the node. Uni-axial and rosette strain gauges were used to measure stress flow and concentration.

3. Experimental results and observations

3.1. Material properties

The material properties of the specimens were tested by the Korean Standard Test Method. SM490 (Fy = 325 MPa) steels of three different thicknesses (6 mm, 12 mm, and 16 mm thick) were