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Experimental and Analytical Investigation of Web-transferred Diagrid Node under Seismic Condition

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Abstract

The diagrid structural system is considered to be not only the best structural system for constructing free form structures, but also a very effective system in resisting lateral load. As a newly investigated structural system, its complicated node has not yet been completely investigated and minimal experimentation of manufacturing and constructing the system have been conducted. Therefore, the constructing cost of the diagrid structural system is still comparatively high. In this paper, the cyclic performance of a diagrid node with an H-section brace will be discussed. Design details that consider productivity were proposed and their structural performances were assessed through experimental and analytical investigation

Keywords: Diagrid, Node, Web-transferred, Test, Analysis

1. Introduction

The development of structural technology makes it possible to construct higher buildings. Attempts to defy gravity have been performed in many ways, such as developing high strength materials or new structural systems. However, aesthetic variety has been limited to only low-rise buildings or to the use of several methods such as set-backs or a change of exterior materials. Recently, however, aesthetic diversities in tall buildings have been attracting people's attention, and many attempts at aesthetic diversity are being made, resulting in the current trend of 3T (Twisted, Tilted and Tapered). Among these attempts, the diagrid structural system is gaining acceptance as the most appropriate structural system for free form tall buildings. The most distinctive characteristic of the diagrid system is that it has no vertical columns and consists of triangular modules, braces and beams, resisting external forces. This characteristic provides free form buildings with many possibilities. Also, these triangular modules act as trusses resisting external forces with their axial behavior and very high structural efficiency. The Heast Tower in New York saved 20% steel material using the diagrid system (Rahimian, 2006).

Despite these merits, study of the diagrid system is at an initial stage. Several theoretical studies such as seismic performance factors (Kim, 2009; Kim, 2009), optimal angles (Moon, 2007) and progressive collapse (Kim, 2008) are in progress. Construction cost is relatively high due to the lack of production and construction experience.

To overcome this lack of experience, a series of tests were conducted and supported by the Korea Institute of Construction and Transportation Technology Evaluation and Planning. With this support, a material test, monotonic tensile/compressive test, mock-up test, cyclic test, and frame test were conducted and are illustrated in Figure 1. Among these tests, the cyclic test will be discussed in this paper, including further research about the test. The seismic performance of diagrid nodes with H-section braces was assessed through experimental and analytical studies. The analysis was conducted using the same condition as that of the cyclic test and the results were well matched with the test results. Therefore, the generalized behavior of the diagrid node was derived by expanded parameter analysis.

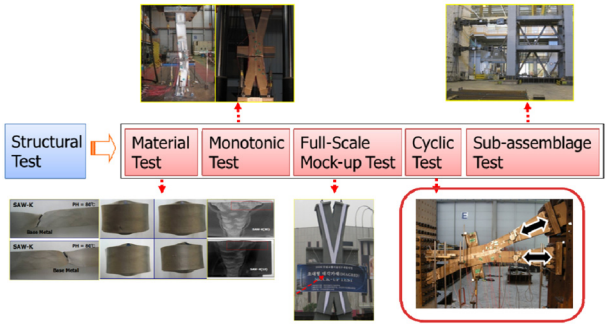


Figure 1. A series of Diagrid experiments.

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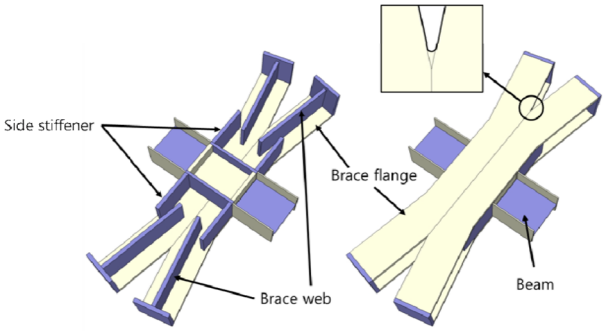


Figure 2. 3D image of specimen.

2. Experimental Study

2.1. Test specimen

Figure 2 illustrates the test specimen. The X-shape node at which the H-section braces are intersected has a continuous flange and transferred web. Through the transferring zone, the axial stress of the web flows to the side stiffener.

The parameters of the web-transferred node are the overlapped length between the side stiffener and web, and the welding method of the major parts. The stress transferring efficiency of the transferring zone depends on the overlapped length; therefore, the structural performances of the node according to the overlapped length were determined. For tall buildings, very thick plates, and consequently a considerable amount of welding, are used to manufacture the diagrid nodes. If partial penetration welding, which reduces the amount of welding required, can be applied in manufacturing the nodes, the total welding amount would be decreased significantly. Therefore, the partial penetrating welding method is introduced as a parameter.

Five specimens are illustrated in Figure 3, and the parameters are tabulated in Table 1. The MA-00, MA-01 and MA-02 specimens have the same form, with an overlapped length of 70 mm, while their welding methods differ. The MA-03 and MA-04 specimens have an overlapped length of 105 mm and 42 mm, respectively.

Table 1. List of specimens

Specimens	MA-00	MA-01	MA-02	MA-03	MA-04
Web-Flange welding	FP[(a)]	PP[(b)]	PP	PP	PP
Flange-Flange welding	FP	FP	PP	PP	FP
Side stiffener welding	FP	FP	FP	PP	FP
Overlapped length	L[(c)]	L	L	1.5L	0.6L

(a) FP: Full Penetration welding, (b) PP: Partial Penetration welding, (c) L = 70 mm.

2.2. Test setup

To describe a structure that is applied by lateral forces, tensile force is applied to one brace and compressive force is applied to the other brace. The angle between the two braces is 24 degrees, and is scaled to 1/5. Yield strength and displacement are calculated with the area of brace section in Eq. (1) and Eq. (2).

$$P_u = F_y \times A_g = 357MPa \times 6{,}720mm^2 \approx 2{,}400kN \quad (1)$$

$$\delta_y = P_y L/EA = \frac{2{,}400kN \times 10^3 \times 1{,}200mm}{210{,}000MPa \times 6{,}720mm^2} \approx 2mm \quad (2)$$

Forces are applied twice at one cycle and the magnitude is increased as axial deformation of the brace reaches 2 mm, 4 mm, 8 mm and 12 mm, which is one, two, four and six times of yield displacement, respectively (Figure 4). The tests are completed when the specimens are fractured or the applied load is decreased to 80% of maximum strength.

Figure 5 shows the test setup. Two actuators were installed at each brace to apply tensile and compressive loads to each brace simultaneously. For the convenience of the test setup, the lower actuator was installed horizon-

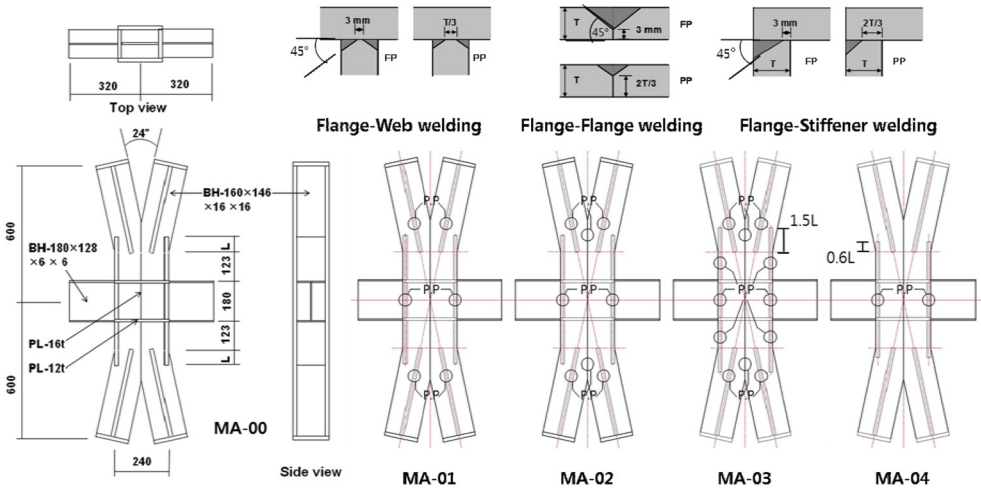


Figure 3. Details of parameters.

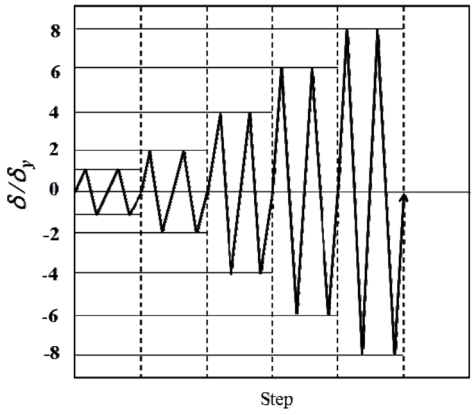


Figure 4. Loading protocol.

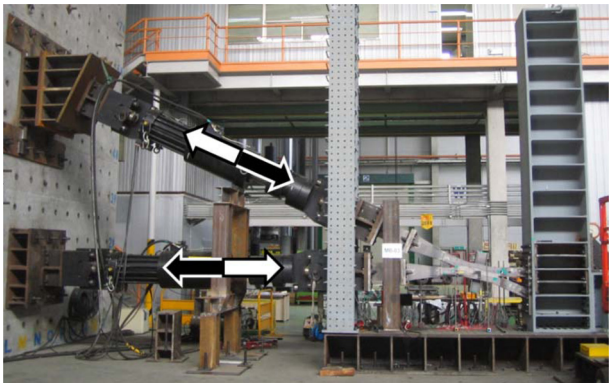


Figure 5. Test setup.

tally and the upper actuator was installed at 24 degrees obliquely.

Figure 6 describes the measuring plan. The applied loads refer to the axial displacement of the brace, and the dial gauges were installed to measure the axial displacement. Horizontal and vertical displacements of the node center were measured by two LVDTs at the node center. LVDTs are installed at each beam for measuring lateral buckling and torsion.

Rosette gauges were used to check the shear strains at the point at which the large stress was expected to concentrate, such as at the V-point or center of node. Other strain gauges were stitched to measure the flow of stress.

Table 2. Coupon test result

Specimen	Yield stress [MPa]	Tensile stress [MPa]	Yield ratio [%]	Elongation [%]
Plate-6	421	518	81	23
Plate-12	378	542	70	26
Plate-16	357	528	68	29

3. Test Results

3.1. Failure mode

Steel grade SM490 was selected for the specimens. The mechanical properties of steel materials used are summarized in Table 2. According to tensile tests, all specimens showed a higher yield strength than the standard strength (= 325 MPa), and showed yield ratios ranging from 68 to 81% and an elongationranging from 23 to 29%.

Figure 7 shows the measured cyclic response of all test specimens in the axial direction of diagonal braces. In Figure 7, the graphs listed on the left hand side indicate the load-displacement relationship of the upper diagonal brace, and the graphs listed on the right hand side indicate the load-displacement relationship of the lower diagonal brace. When the upper diagonal brace became loaded with a tensile force, the lower diagonal brace became loaded with a compressive force.

The major failure mode is as follows: the combination of tensile and compressive forces, which have an angle of 24 degrees, causes vertical displacement of the node center (Figure 8) and this displacement leads to extra moment which is the main reason for the crack of flange. The tensile force of the upper brace and the compressive force of the lower brace force the node center to move upward. This displacement and compressive force act similarly to the P-Δ effect, resulting in extra moment at the outside of the flange. At the tensile loaded brace, the moment strain combined with the tensile strain causes a

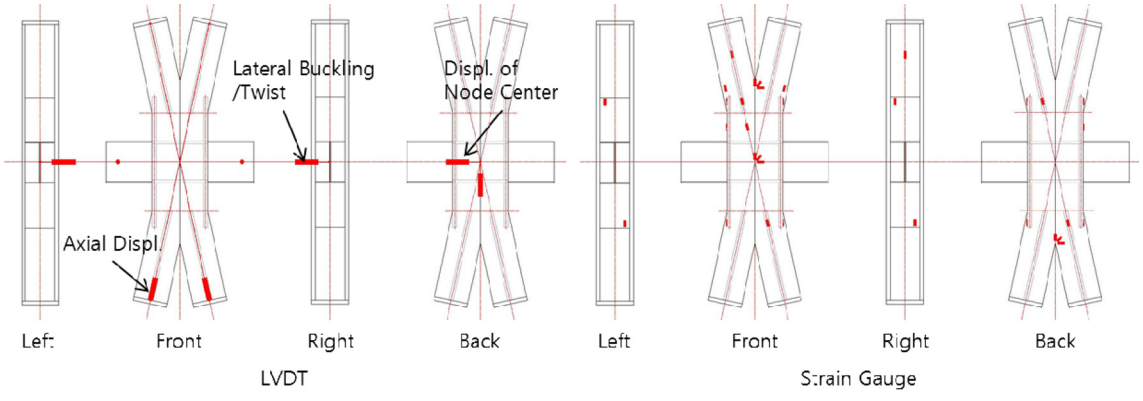
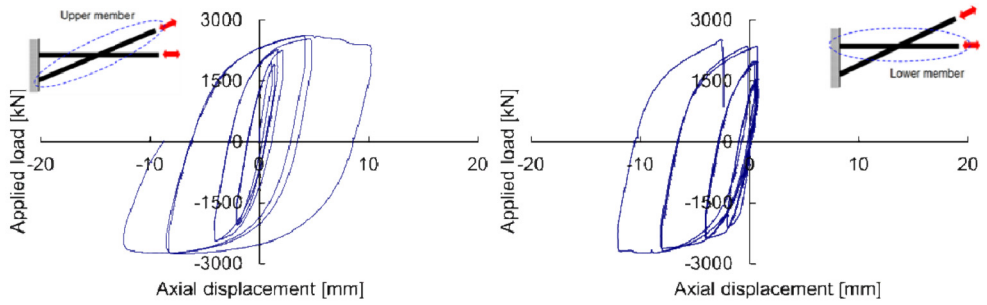
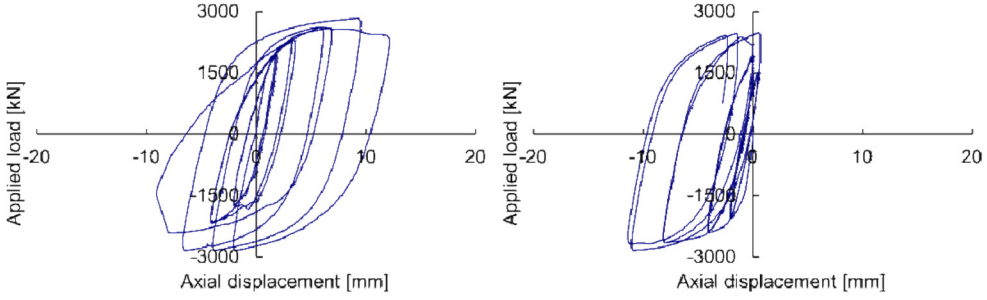


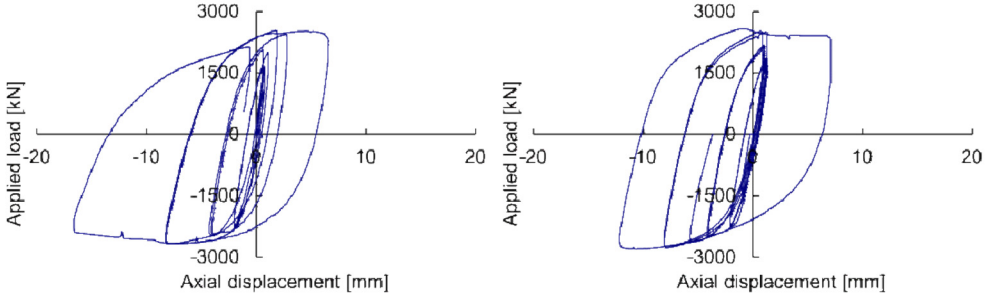
Figure 6. Measuring plan.



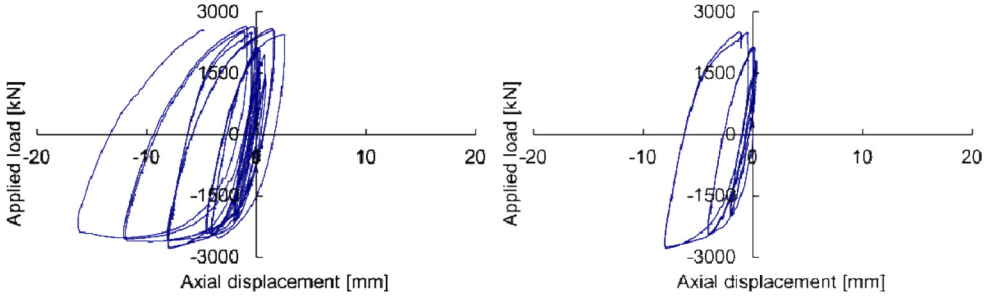
(a) MA-00



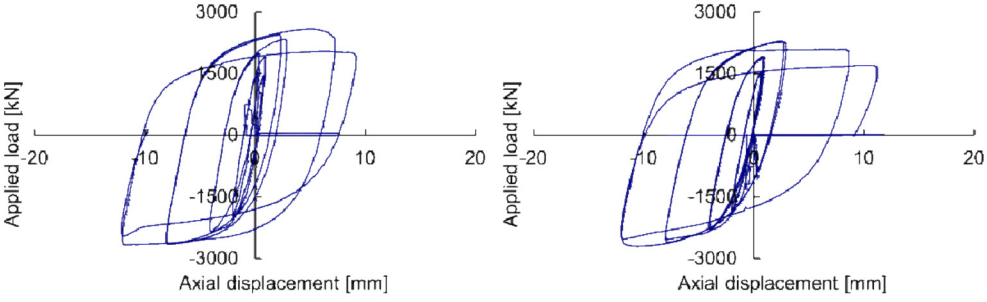
(b) MA-01



(c) MA-02



(d) MA-03



(e) MA-04

Figure 7. Load-displacement curve.

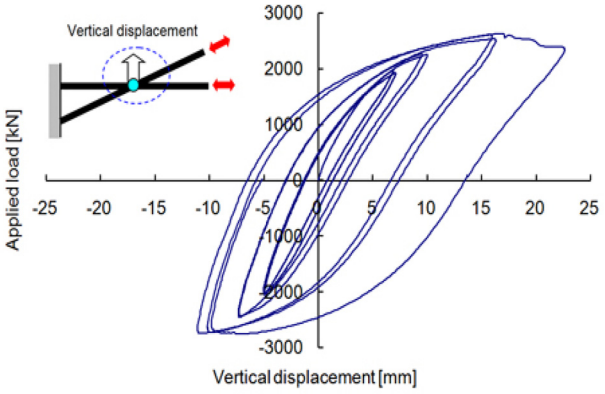


Figure 8. Displacement of node center.

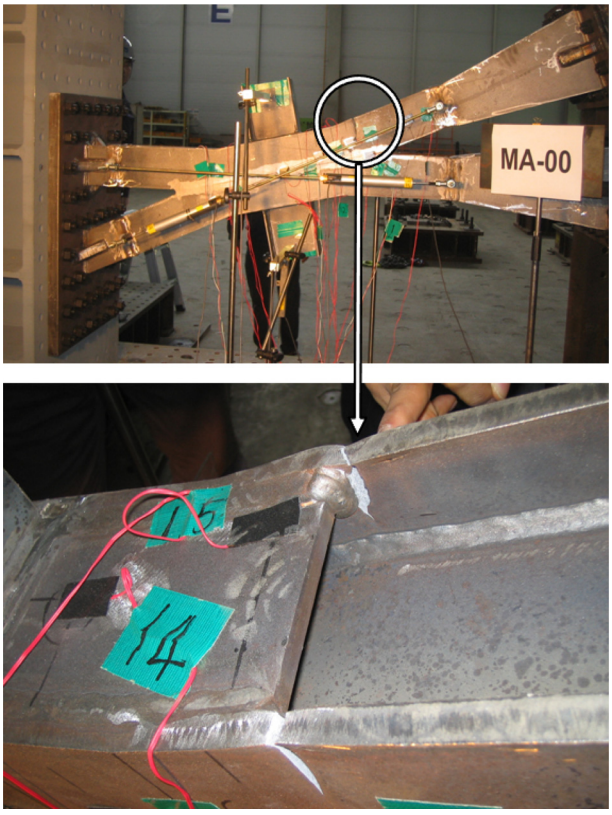


Figure 9. Crack of outside of flange.

in Figure 9. The extra moment can be verified by a strain graph, as shown in Figure 10. The strain of the outside of the flange is larger than that of the center and reaches yield strain early. Local buckling was found at the compressive loaded brace as shown in Figure 11, but it has little effect on the strength of the specimen. Figure 12 shows the V-point of the specimen where massive deformation was expected, but no significant deformation was observed.

3.2. Initial stiffness, Yield strength and Energy absorption

The test results are summarized in Figure 13 and Table

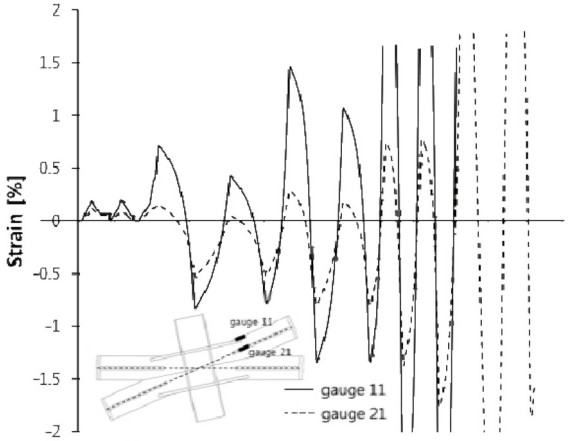


Figure 10. Strain of center and outside of flange.



Figure 11. Local buckling.

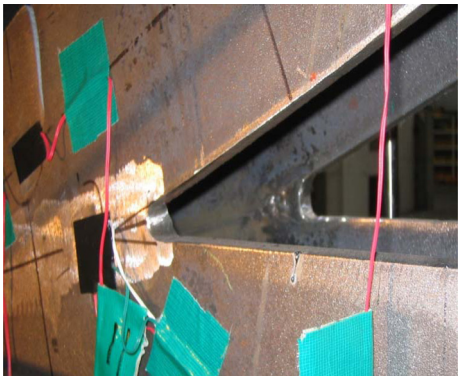


Figure 12. V-point.

3. According to the results, the welding method has no effect on initial stiffness. The MA-00 specimen, which has full penetration welding, has slightly higher initial stiffness than the MA-01 and MA-02 specimens, in which the partial penetration welding method is used, but this is negligible. The MA-03 specimen has higher stiffness than the MA-04 specimen. This indicates that the initial stiffness increases as the overlapped length increases. The yield strength is also affected by the overlapped length.

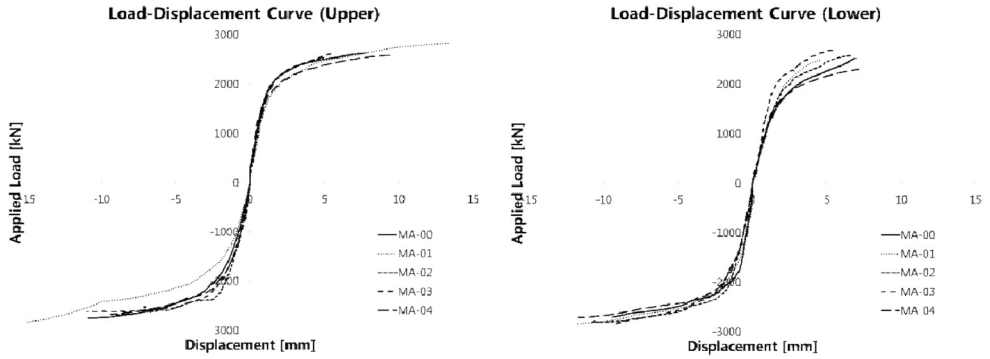


Figure 13. Skeleton curve.

Table 3. Test result

Specimen	Initial stiffness [kN/mm]	Yield strength [kN]	Ductility	Energy dissipation [kN.m]
MA-00	1914 (100%)	2017 (100%)	6.73 (100%)	304 (100%)
MA-01	1812 (95%)	2143 (106%)	7.95 (118%)	353 (116%)
MA-02	1646 (86%)	2112 (105%)	5.70 (85%)	340 (112%)
MA-03	1975 (103%)	2318 (115%)	6.66 (99%)	289 (95%)
MA-04	1428 (75%)	1828 (90%)	9.71 (144%)	410 (135%)

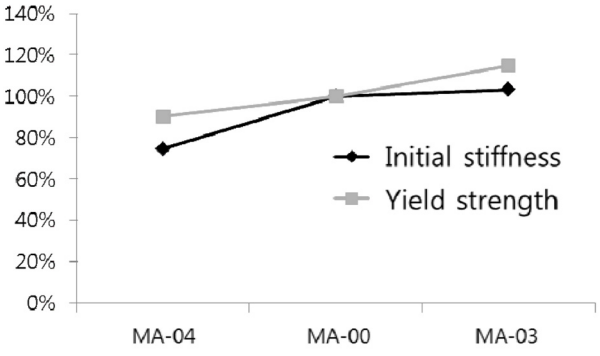


Figure 14. Test result.

The MA-03 specimen has higher yield strength than MA-04. No significant differences are found between MA-00, MA-01 and MA-02.

4. Analytical Study

4.1. Modeling

The test results are rearranged according to the overlapped length and are graphically illustrated in Figure 14. The trend for stiffness and strength to increase as the overlapped length increases can be clearly seen. However, the general behavior can be obtained by more accurate and wider investigation. Therefore, an analytical study of the expanded parameter was conducted.

The same conditions as those of the test were used for the analysis and the ABAQUS/CAE 6.7 program was used. All elements were designed using solid elements and the material properties of the coupon test were used. All instances were assembled with tie interaction.

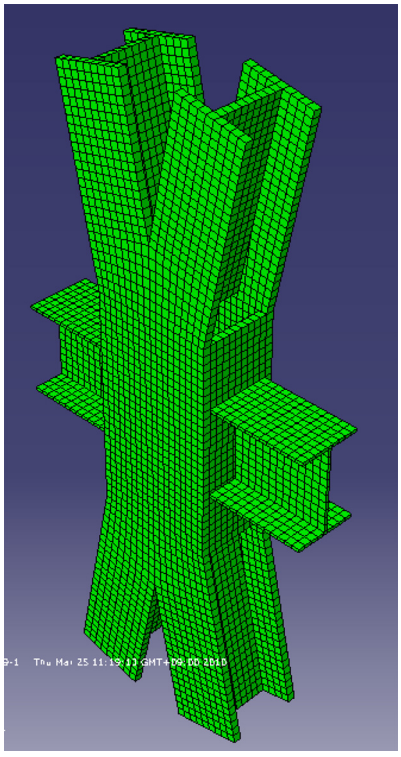


Figure 15. Analysis model.

4.2. Comparison with experimental results

The brace axial-directional load-displacement relationships of the test and the analysis are compared in Figure 16. This shows a good agreement between the test and the analysis despite the imperfection of the tests. Therefore, the validity of the analysis is assumed to be secured and further analysis has proceeded.

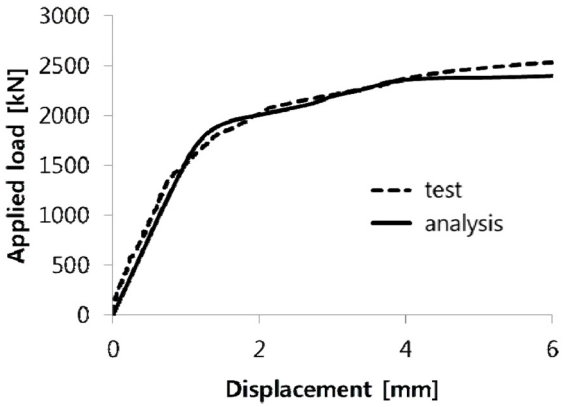


Figure 16. Comparison of test and analysis.

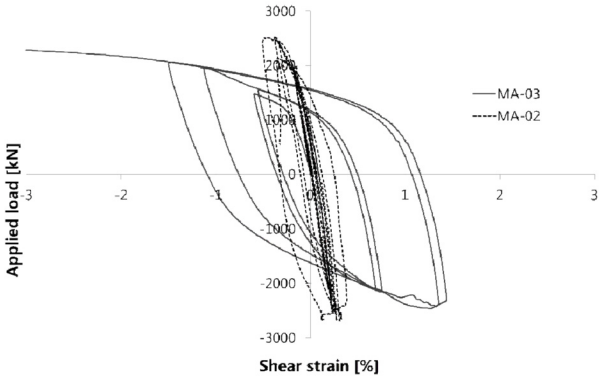


Figure 19. Shear strain of V-point.

4.3. Parameter

The analysis parameter is the overlapped length as described in Figure 17. The basis of the overlapped length is the distance between the web and the side stiffener, which is 70 mm. The notation OL means "Overlapped Length ratio" and 15 means 1.5 times of standard length, which is 70 mm. All of the 29 models from OL-00 to OL-40 were analyzed.

4.4. Analysis results

The analysis results are summarized in Figure 18. As the graph shows, initial stiffness increases as overlapped length increases and this phenomenon is also found in results of the test. The tield strength is stabilized as overlapped length ratio becomes longer than 1.0. The average value of the short-OL models is 1852 kN and the long-OL models have the 27% higher value of 2354 kN. In short-OL models, stress was concentrated at transferring zone but long-OL models have significantly lower stress concentration. But very long-OL models such as OL-34, OL-36, OL-38 and OL-40 have stress concentration at V-point and show relatively lower strength. This stress concentration also can be found in test results. Figure 19 shows shear strain of the specimen MA-02 and MA-03. The MA-03 has longer OL than MA-02 and relatively

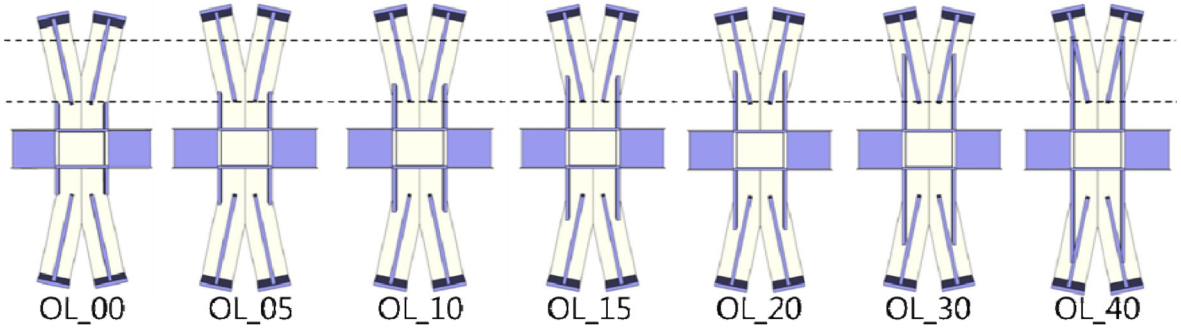


Figure 17. Analysis parameter.

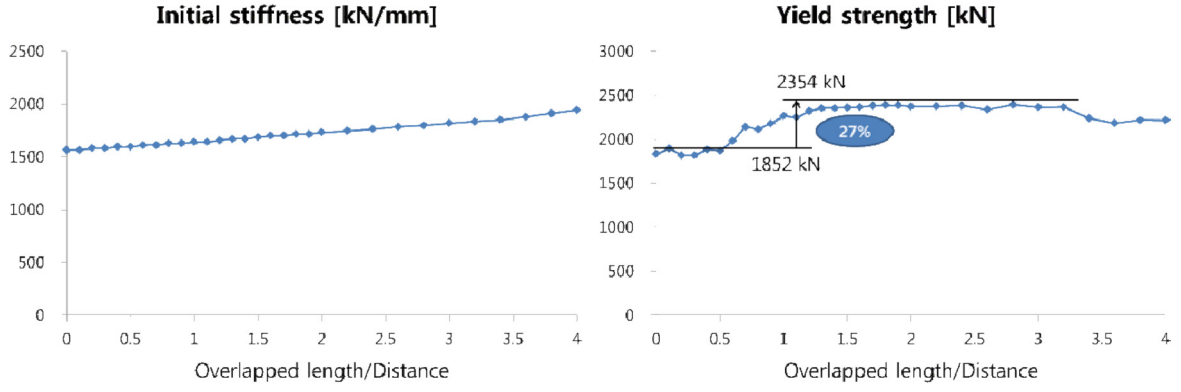


Figure 18. Analysis result.

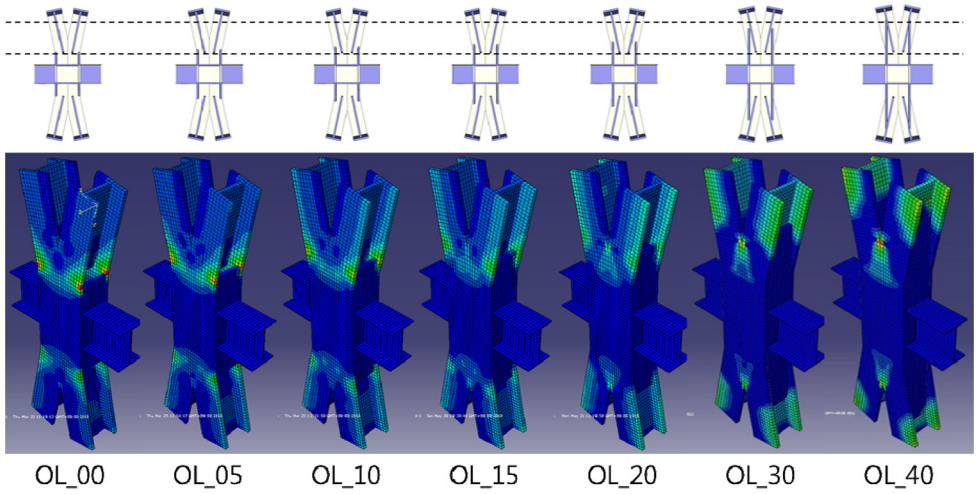


Figure 20. Distribution of PEEQ value.

large shear strain was measured. Figure 20 illustrates distribution of PEEQ values from the analysis. Changes of stress concentration also can be checked in this figure.

5. Conclusion

1) All specimens were fractured by a crack of the flange where extra moment and tensile force are combined. This type of bending failure should be considered in designing a diagrid node
2) It is found that welding method has no significant effect on structural performance. Therefore, careful use of the partial penetration welding method can be approved to save welding material.
3) Yield strength and initial stiffness are affected by the overlapped length. At least the same length as the distance between the web and the side stiffener is necessary for the transferring zone.
4) The results of the analysis agreed well with the test results. According to the expanded parameter analysis, an overlapped length longer than a 1.0 overlapped length ratio assures stable structural behavior.

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