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Strength Evaluation for Cap Plate on the Node Connection in Circular Steel Tube Diagrid System

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Abstract

Diagrid system has been in the spotlight for its superiority in terms of the resistance to lateral force when applied to skyscrapers. In diagrid system, most of columns can be eliminated because vertical loads (gravity loads) and horizontal loads (lateral loads) are delivered simultaneously thanks to the triangular shape of diagrid. However, lack of studies on connection shape and node connection details makes it hard to employ the system to the buildings. In this study, the structural safety of the node connections in circular steel tube diagrid system which has been considered in the Cyclone Tower in Korea (Seven stories below and fifty-one above the ground) was evaluated using the 4 full-scale specimens. The parameters are the extended length (20 mm, 40 mm & 60 mm), thickness (40 mm & 50 mm).

Keywords: Diagrid, Node, Connection, Stress concentration, Cap plate

1. Introduction

Skyscrapers today are irregular-shaped to be city landmarks and function as vertical cities to enable the efficient use of land. 3T (Twisted, Tilted & Tapered) designs are being suggested for irregular buildings and studies to develop new structural systems have been actively made to satisfy slender shape ratio. In this regard, new structural systems differentiated from traditional ones are being applied more often than before and diagrid system is the one most frequently applied.

Diagrid system has been in the spotlight for its superiority in terms of the resistance to lateral force when applied to skyscrapers. In diagrid system, most of columns can be eliminated because vertical loads (gravity loads) and horizontal loads (lateral loads) are delivered simultaneously thanks to the triangular shape of diagrid. The behaviors (tensile/compressive) of the diagrid in axial direction resist shear and thus minimize deformation. And, it is more applicable to the buildings of irregular shape than the traditional systems where the lateral behaviors of columns resist shear and enables excellent lateral resistance without additional reinforcement of core. Because of these advantages, diagrid system has been employed to the Swiss Re Building in London, the Hearst Tower and the New World Trade Center in New York, the Twin Tower in Guangzhou, the CCTV Building in Beijing and Mode Institute in Japan. In Korea, the diagrid system has been considered in projects for the Cyclone Tower in Asan, Lotte Super Tower in Seoul and Future-Ex in Daejeon. However, lack of studies on connection shape and node connection details makes it hard to employ the system to the buildings. Therefore, connection details should be suggested and developed in order to promote the application of the system and the generalization of the connections with secured safety should backup its application through structural performance evaluation and reliability verification for the connection details which have been suggested so far.

In this study, the structural safety of the node connections in circular steel tube diagrid system which has been considered in the Cyclone Tower in Korea (Seven stories below and fifty-one above the ground) was evaluated using the finite element analysis. And, 4 full-scale specimens were fabricated for tests with the variables of extended length (20 mm, 40 mm & 60 mm) and thickness (40 mm & 50 mm) of cap plate to suggest economically-efficient ways to mitigate stress concentration in columns.

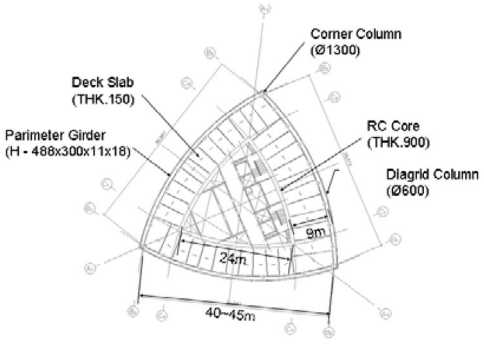
1.1. Shape of diagrid connections

Because of the simultaneous resistance to gravity loads and lateral loads which is inherent in diagrid system, strong stress is generated in node connections in the system. Securing reliability of connection details is significantly important because of highly complicated stress generation upon the application of lateral loads. Because

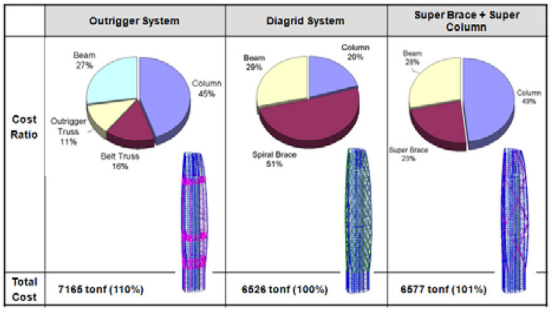
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(a) Air-view

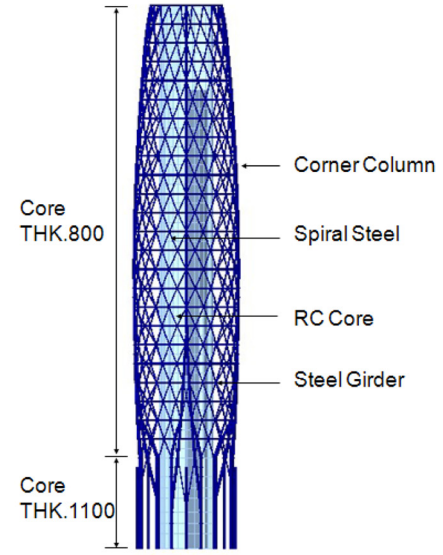


(b) Ground plan

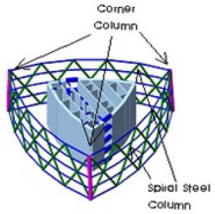


(c) economic efficiency

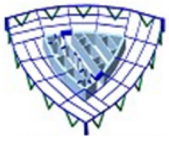
Figure 1. Cyclone Tower in Asan, Korea.



(a) Cyclone Tower Structure Type



Diagrid System 3D Modeling



Typical Floor 3D Modeling

· Diagrid
9 ~ 12F Ø600×45t
13 ~ 20F Ø600×40t
21 ~ 27F Ø600×30t
28 ~ RF Ø600×12t

· Corner column
Ø1300×40t

· Deck slab thk.150

· Perimeter girder
H - 488×300×11×18

(b) Diagrid Member Type

Figure 2. Cyclone Tower, using diagrid system.

diagrid members exist throughout the whole floors of a building, the constructional efficiency of the connections plays an importance role in shortening construction period. Consequently, the node connections of diagrid system should be decided in terms of construction efficiency and the workability and constructability of the connections should be considered from the planning stage in order to maximize constructional efficiency.

In the diagrid connections of the Cyclone Tower in Asan, Korea, node connections are formed at the intersection of columns as shown in Figure 2. A H-488 × 300 × 11 × 18 beam made of 600 MPa steel (Fu: 600 MPa) was set up horizontally at the center of the node connection. A cap plate was set up at the bottom of a steel tube and a stiffener plate was set up to support the cap plate.

2. Finite Element Analysis

Finite element analysis was conducted for the connections of the Cyclone Tower to evaluate their structural performance.

2.1. Finite element analysis of cap plate

Increasing cap plate thickness and extending its length have been suggested as the methods to mitigate stress concentration in connections. So, the finite element analysis was conducted for the two suggestions in this study.

2.2. Analysis model & method

Four objects with the variables of the extended length

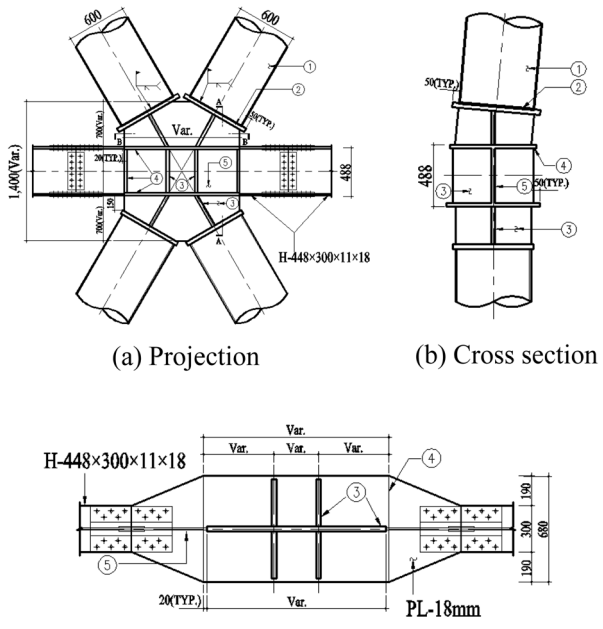


Figure 3. Diagrid connection.

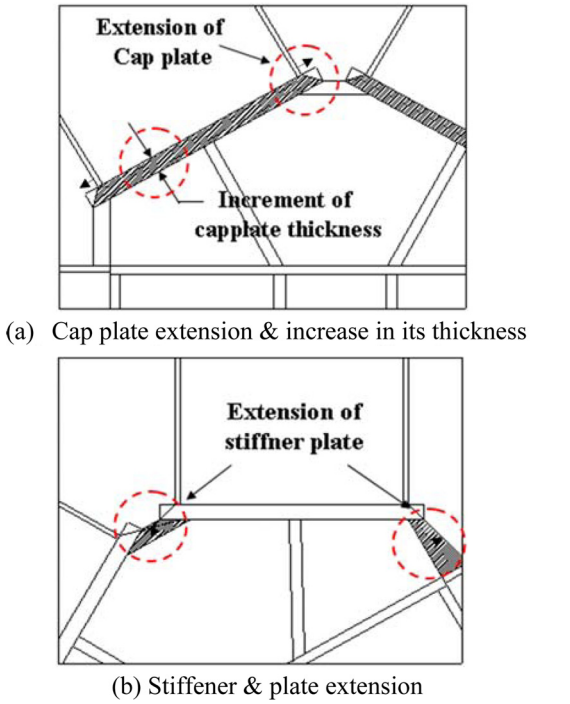


Figure 4. Suggestions for mitigating stress concentration in node connections.

of cap plate and extension of stiffener plate were analyzed as shown in Table 1. The Solid186 element having 20 nodes was used to make a 1/4 symmetrical model shown in Figure 5. Degrees of freedom in three directions (X, Y & Z) of side A were confined and simple compressive force equivalent to the yield point of steel tube was applied to side B.

Table 1. Analysis model with stiffener & plate extension

Object	Circular tube	Cap plate thickness	Length of cap plate extension	Stiffener & plate extension
C42X	600 × 12	40	20	X
C46X			60	X
C42O			20	O
C44O			40	O

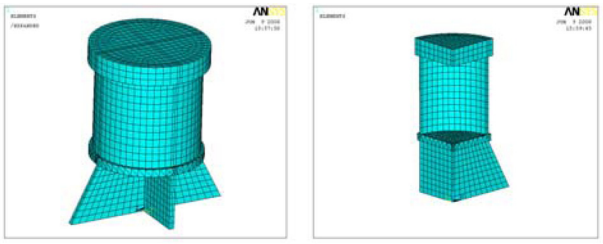


Figure 5. Analysis model for verifying the methods to mitigate stress concentration (1/4 symmetrical model).

2.3. Analysis result

C42X and C46X without stiffener plate extension presented stress concentration in the stiffener plate below cap plate, while mitigation of stress concentration was observed in C42O and C44O whose stiffener plates were extended.

3. Test

Structural test was conducted in order to analyze the structural behavior of diagrid connections.

3.1. Test plan

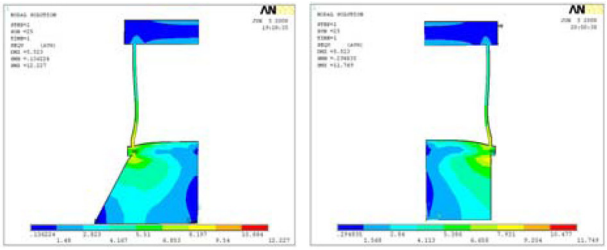
SS400 and 60012 circular tubes were used to fabricate four full-scale specimens with the variables of cap plate thickness (40 mm & 50 mm) and the length of cap plate extension (20 mm, 40 mm & 60 mm) as shown in Table 2. A 10,000 kN UTM was used for loading. (SS400: nominal yield strength: 235 Mpa, nominal tensile strength: 400 MPa).

3.2. Loading and measurement

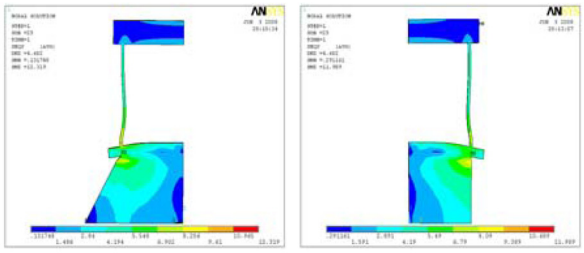
It has been found from structural design that the joint of a diagrid circular tube is the most vulnerable when the axial load in A-B direction which is less stronger than in C-D direction is approximately 30% of the tube's nominal yield load (Py). Accordingly, load of 1,563 kN which was 30% of the axial load in main loading direction (C-D) was applied in A-B direction as shown in Figure 7 and then in C-D direction using 10 Φ39 mm steel bars.

3.3. Test result

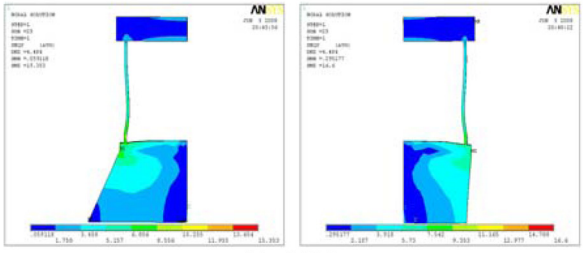
Table 3 shows the result of material sample test. Table



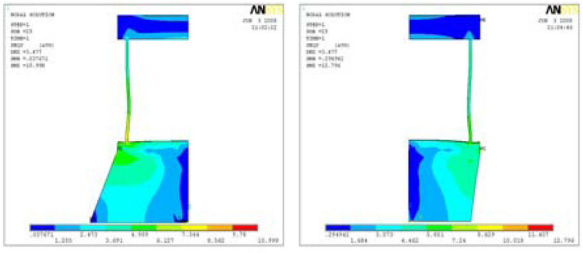
(a) C42X



(b) C46X



(c) C42O



(d) C44O

Figure 6. Mitigation of stress concentration in the connections between cap plate & stiffener and cap plate & plate.

4 shows initial stiffness, yield strength and maximum load capacity of the specimens and Figure 9 shows their load-displacement relations of C-D direction. As shown in Figure 10, local buckling at steel tubes caused the failure of the specimens.

4. Analysis and Implication

Mitigation of stress concentration associated with the extended length of cap plate and its increased thickness was analyzed based on the test result.

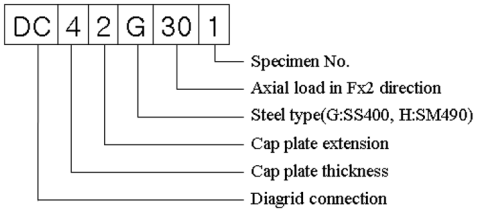
4.1. Evaluation of structural capacity associated with cap plate extension

Table 5 shows the structural capacity of DC42G301,

Table 2. Specimen overview

Specimen	D (mm)	t (mm)	Steel type	Cap plate		Axial load in Fx2 direction (%)
				t (mm)	Extension (mm)	
DC42G301	600	12	SS400	40	+20	Load in Fx1 direction 30%
DC44G302					+40	
DC46G303					+60	
DC56G304				50	+60	

Inner stiffner plate thickness: 30 mm, Outer stiffner plate thickness: 25 mm, Beam flange thickness: 25 mm.



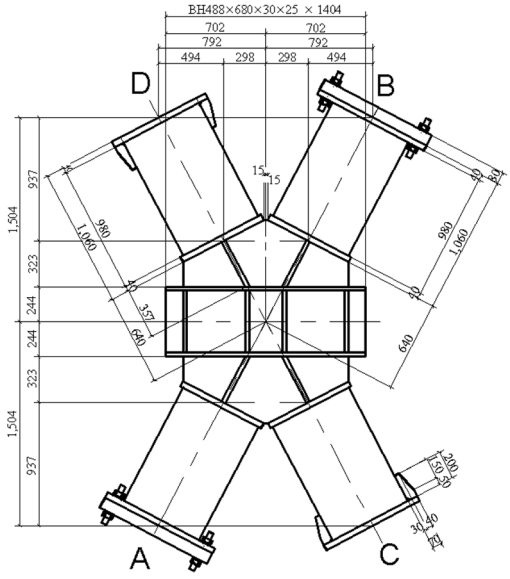
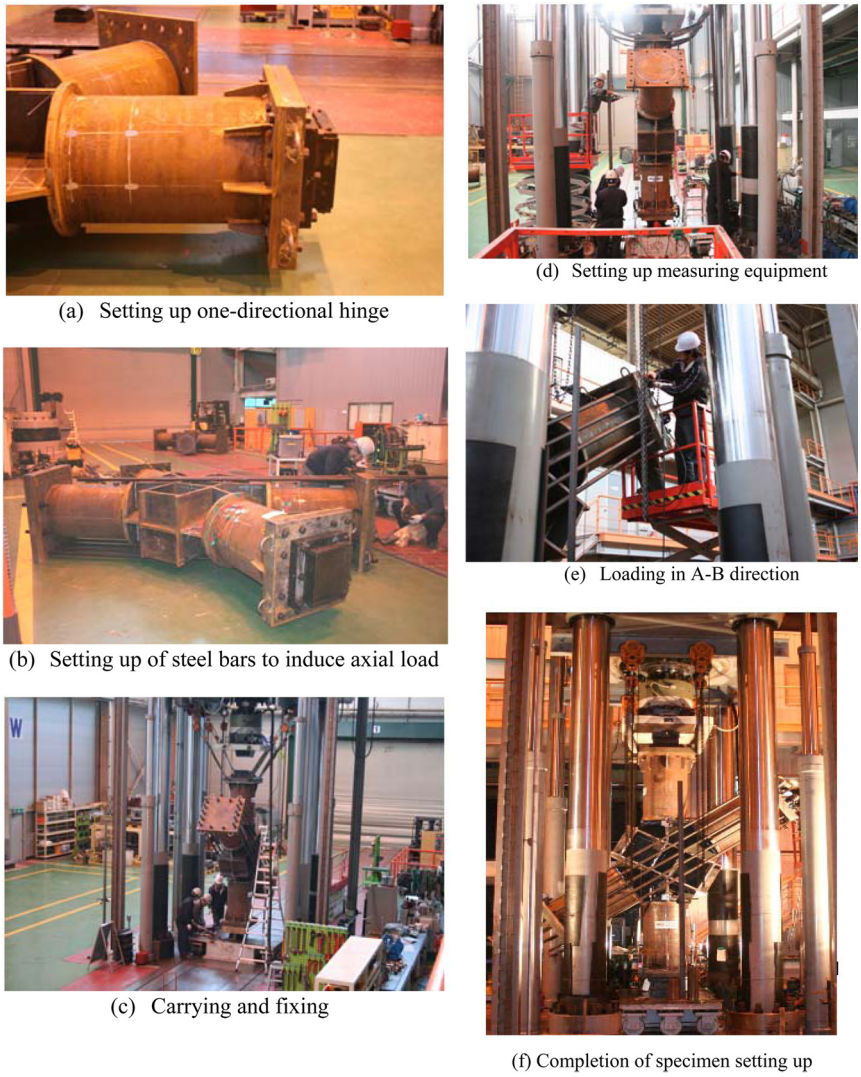


Figure 7. Loading directions of specimen.

DC44G302 and DC46G303 whose cap plates were extended by 20 mm, 40 mm, and 60 mm, respectively. The maximum load capacity of DC44G302 was stronger than DC 46G303 by 17% possibly because the tensile strength of the former is higher than that of the latter by approximately 31%. Figure 11 shows the structural capacity comparison among the specimens with their load capacity non-dimensionalized by tensile strength. Structural capacity of DC 44G302 and DC 46G303 improved by 1% and 14%, respectively when compared with DC 46G301.

4.2. Mitigation of stress concentration associated with cap plate extension

Strain gauges were set up at the 1/3 points of steel tubes and the connections between the tube and cap plate in order to analyze the change in stress concentration in DC



(a) Setting up one-directional hinge

(b) Setting up of steel bars to induce axial load

(c) Carrying and fixing

(d) Setting up measuring equipment

(e) Loading in A-B direction

(f) Completion of specimen setting up

Figure 8. Specimen setup process.

42G301, DC44G302 and DC46G303 specimens in various load steps associated with cap plate extension. As shown in Figure 13, stress concentration in DC46G303 was significantly mitigated when compared with DC42G 301 and DC44G302 and the structural performance of its connections also improved. However, strain concentration in the connection between circular tube and cap plate under maximum load implied that the problem of stress concentration was not solved completely.

Table 3. Material test result

Specimen	Sampling location	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio (%)	Elongation (%)
DC42G301	Circular tube	322	450	72	23
	Cap plate	215	445	48	26
DC44G302	Circular tube	406	565	72	20
	Cap plate	210	443	47	28
DC46G303	Circular tube	315	430	72	23
	Cap plate	202	446	45	32
DC56G304	Circular tube	312	451	69	23
	Cap plate	388	605	64	46

4.3. Evaluation of structural capacity associated with the increase in cap plate thickness

Table 6 shows the structural capacity of DC46G303 and DC56G304 specimens whose cap plate thickness was 40 mm and 50 mm, respectively. Figure 14 shows the comparison of their capacity non-dimensionalized by ten-

Table 4. Initial stiffness & maximum load capacity

Specimen	Initial stiffness (kN/mm)	Yield strength (kN)	Maximum load capacity (kN)	Failure mode
DC42G301	1,349	3,890	5,894	Buckling at steel tube
DC44G302	1,376	5,327	7,503	
DC46G303	1,585	4,422	6,410	
DC56G304	1,830	5,330	7,507	

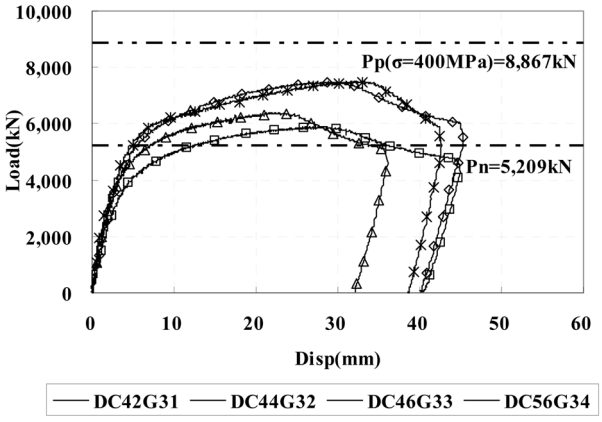


Figure 9. Load-Displacement curves.

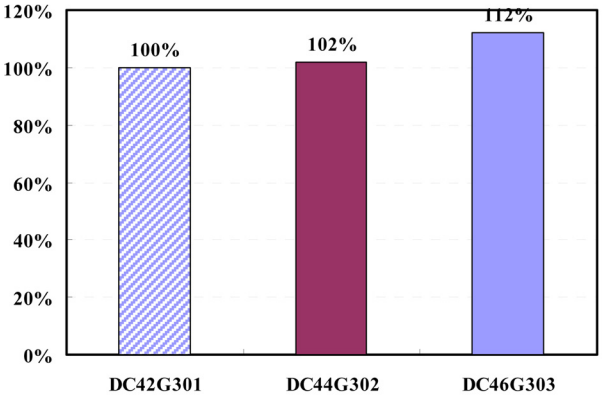
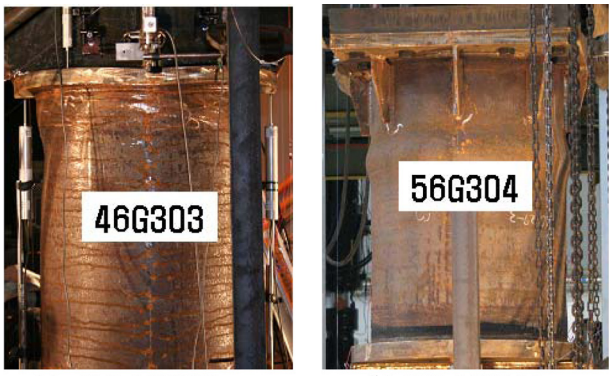


Figure 11. Non-dimensionalized comparison of maximum load capacity associated with cap plate extension.



(a) DC 46G303 (b) DC 56G304

Figure 10. Failure mode.

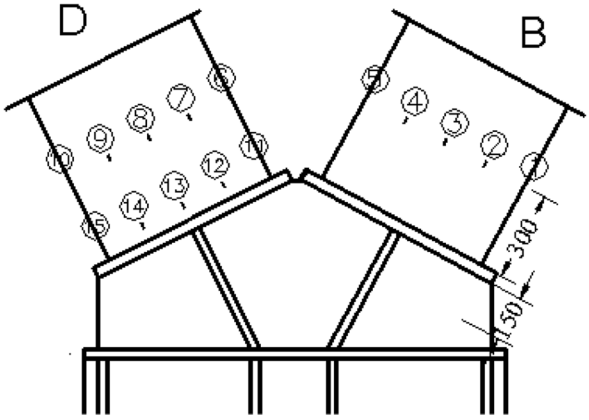


Figure 12. Locations of strain gauges.

sile strength. The result shows that maximum load capacity of DC56G304 improved by 12% when compared with DC46G303.

4.4. Mitigation of stress concentration associated with the increase in cap plate thickness

Strain gauges were set up at the 1/3 points of steel tubes and the connections between the tube and cap plate in order to analyze the change in stress concentration in DC46G303 and DC56G304 specimens in various load steps associated with the increase in cap plate thickness. Strain distribution in DC56G304 upon each loading shown in Figure 15 was compared with that in DC46G303 shown in Figure 13(c). It was observed that the increase in cap plate thickness mitigated stress concentration in the connections between circular tube and cap plate significantly.

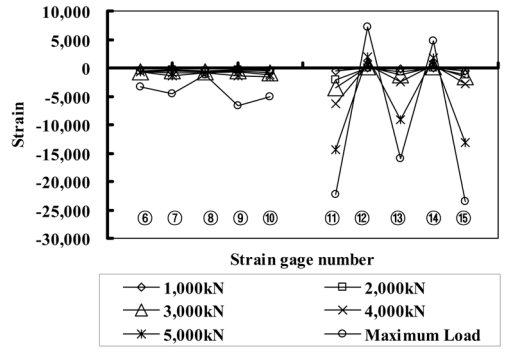
4.5. Evaluation of the methods to mitigate stress concentration in terms of economical efficiency

Table 7 and Figure 16 show steel amount and structural capacity of DC42G301, DC46G303 and DC56G304 specimens in order to analyze economical efficiency associated with cap plate extension and width suggested for mitigating stress concentration.

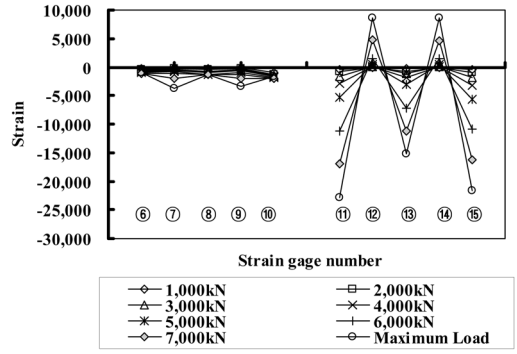
From the above comparison of the two methods suggested for mitigating stress concentration in the connections between circular tube and cap plate, it was found that increasing cap plate thickness is more effective than

Table 5. Structural capacity comparison associated with cap plate extension

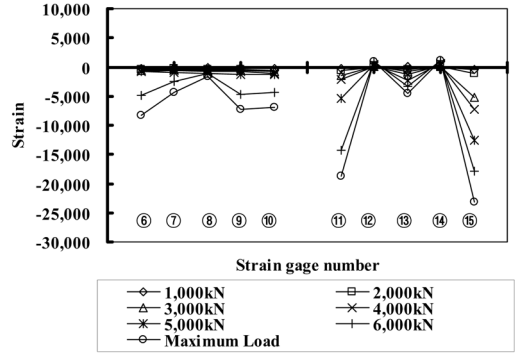
Specimen	Yield strength [A]	Yield resistance		Ultimate resistance [B]		Non-dimensionalized ultimate resistance [B/A]	
DC 42G301	325MPa	2,975kN	100%	5,894kN	100%	18.14	100%
DC 44G302	406Mpa	4,185kN	141%	7,503kN	127%	18.48	102%
DC 46G303	315Mpa	3,440kN	116%	6,410kN	109%	20.35	112%



(a)Strain distribution in DC42G301 at each loading stage



(b)Strain distribution in DC44G302 at each loading stage



(c)Strain distribution in DC46G303 at each loading stage

Figure 13. Strain distribution at each loading stage associated with cap plate extension.

Table 6. Structural capacity comparison associated with cap plate thickness

Specimen	Yield strength [A]	Yield resistance		Ultimate resistance [B]		Non-dimensionalized ultimate resistance [B/A]	
DC 46G303	315 Mpa	3,440 kN	100%	6,410 kN	100%	20.35	100%
DC 56G304	312 Mpa	3,720 kN	108%	7,507 kN	117%	18.48	118%

extending cap plate in terms of steel amount and structural capacity of the connections.

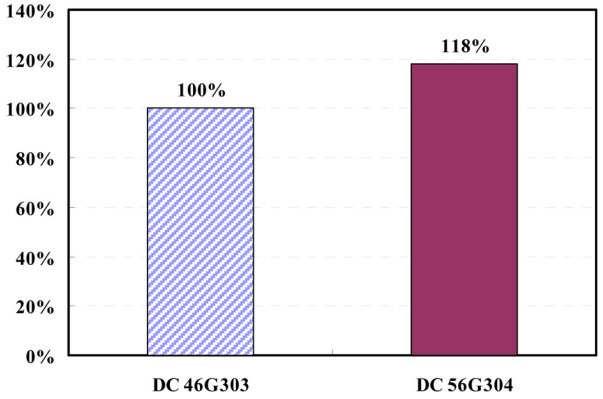


Figure 14. Non-dimensionalized comparison of maximum load capacity associated with the increase in cap plate thickness.

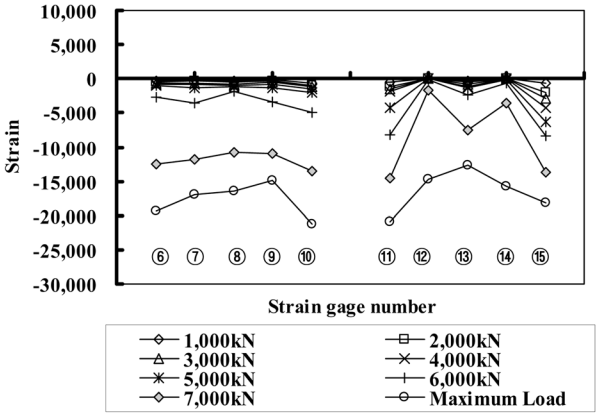


Figure 15. Strain distribution in DC56G304 upon each loading.

Table 7. Steel amount - structural capacity comparison

Specimen	Steel amount (kg)	Structural capacity (kN)
42G301	101	5,894
46G303	128	6.410
56G304	160	7.507

5. Conclusion

The conclusion of the structural analysis and test conducted in this study in order to analyze the influence of cap plate extension and increase in cap plate thickness is as follows.

1) Non-dimensionalized analysis of structural capacity of the connections associated with cap plate extension showed that structural capacity of DC44G302 and DC46G303 improved by 1% and 14%, respectively when compared with that of DC42G301. However, strain concentration in the connection between circular tube and cap plate under maximum load observed in DC46G303 specimen implied that the problem of stress concentration was not solved

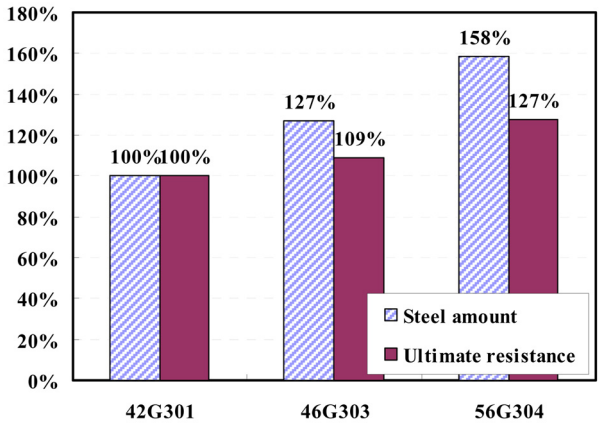


Figure 16. Steel amount - structural capacity comparison.

completely.

2) Non-dimensionalized comparison of structural capacity among the specimens associated with the increase in cap plate thickness showed that structural capacity of DC56G304 improved by 12% when compared with that of DC46G303. In addition, it was observed from the comparison of strain distribution in each loading stage that the increase of cap plate thickness mitigated stress concentration significantly.
3) Between the two methods suggested for mitigating stress concentration in the connections between circular tube and cap plate, the increase in cap plate thickness was found more effective than cap plate extension in terms of steel amount and structural capacity of the connections.

Acknowledgements

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