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# Sensitivity analysis for axis rotation diagrid structural systems according to brace angle changes

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**Abstract:** General regular shaped diagrid structures can express diverse shapes because braces are installed along the exterior faces of the structures and the structures have no columns. However, since irregular shaped structures have diverse variables, studies to assess behaviors resulting from various variables are continuously required to supplement the imperfections related to such variables. In the present study, materials elastic modulus and yield strength were selected as variables for strength that would be applied to diagrid structural systems in the form of Twisters among the irregular shaped buildings classified by Vollers and that affect the structural design of these structural systems. The purpose of this study is to conduct sensitivity analysis for axial rotation diagrid structural systems according to changes in brace angles in order to identify the design variables that have relatively larger effects and the tendencies of the sensitivity of the structures according to changes in brace angles and axial rotation angles.

**Keywords:** sensitivity analysis; axial rotation-diagrid structure; lateral behaviors

## 1 Introduction

Due to the urban concentration of the population, demand for high-rise buildings has continuously increased for economic and efficient use of land that is limited. Recently, in addition to the provision of work spaces and living spaces, high-rise buildings serve an important role as landmarks for a country or city. Therefore, many diverse shapes of irregular shaped buildings have been designed considering their representativeness of their regions and their symbolic nature, in addition to aesthetic elements and building designs. Vollers (2008) classify the shapes of irregular shaped structures into six types: Extruders, Rotors, Twisters, Tordos, Free-Shapers, and Transformers as shown in Fig. 1.

Diagrid structural systems equipped with structural or aesthetic shapes among Twisters out of the foregoing types are frequently applied as lateral load resisting systems of ultra high-rise buildings and studies of these structural systems have recently been actively conducted. Moon (2007) proposed the optimal diagrid angle by checking the maximum lateral displacement of the high-rise diagrid structural system through numerical analysis. Kim (2009) evaluated the seismic performance levels of diagrid structural systems at different brace angles and compared the results with those of tube structural systems. However, although many structural variables should be considered for diagrid structural systems because of the distinct characteristics of their irregular shapes, studies of these structural systems are relatively rare compared to other structural systems.

Sensitivity analysis is a method of improving the reliability of input variables when input variables of a model are uncertain by analyzing changes in the results of the model according to changes in the values of the input variables by substituting all possible values of the input variables into the model.

If loads such as wind and earthquakes are applied with fixed values based on structural design criteria, the modeled behaviors of the loads may be different from their actual behaviors and may vary with the material characteristics of members. Therefore, by conducting sensitivity analyses, the uncertainty levels of these input variables can be quantitatively dealt with to determine important variables that have the largest effects on resultant values when they change. By applying this analysis method, important structural influence factors can be found even in the case of structures with variable shapes, such as the irregular shaped structures shown in

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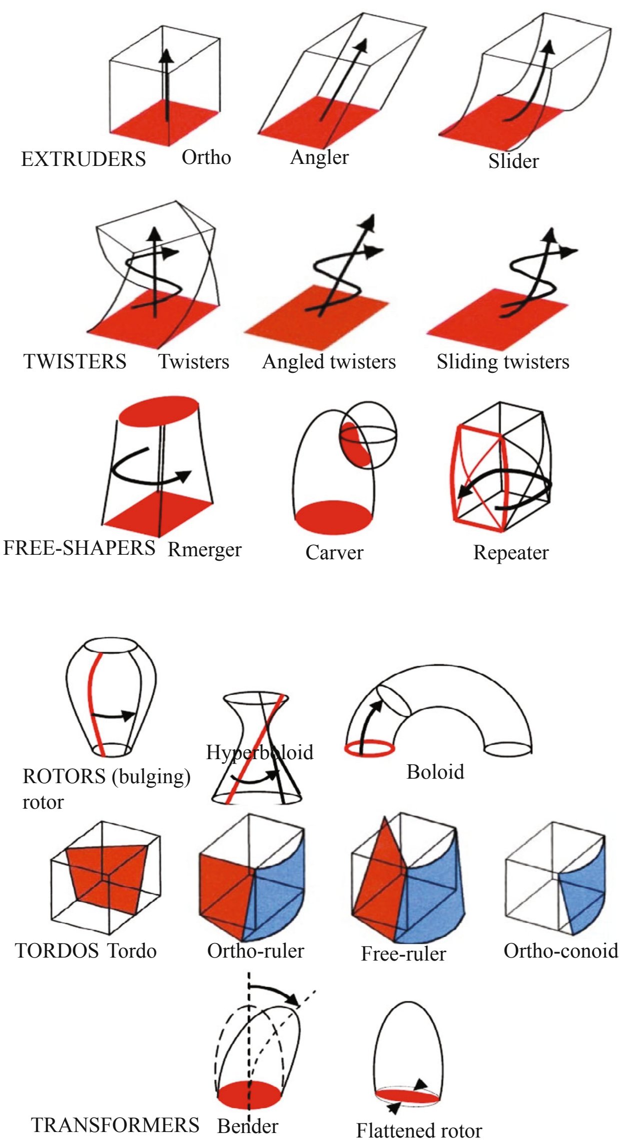


**Fig. 1 Classification of irregular shaped buildings (Vollers, 2008)**

Fig. 1, so that basic data that can provide diverse pieces of information when the design or structure is reinforced can be presented.

As for existing studies regarding sensitivity analysis, Porter *et al*. (2002) conducted sensitivity analysis for elements that affect the structures of reinforced concrete buildings affected by seismic loads and Lee and Mosalam (2009) conducted sensitivity analysis for ductile reinforced concrete frames to determine the importance levels of individual structural members. Ahn *et al*. (2015) conducted sensitivity analysis for limited types of regular shaped diagrid structures. However, since irregular shaped structures have diverse variables, sensitivity studies intended to evaluate behaviors resulting from various variables are continuously required to supplement various imperfections related to such variables.

In this study, materials elastic modulus and yield strength were selected as variables for strength that would be applied to diagrid structural systems in the form of 'Twisters' among the irregular shaped buildings classified by Vollers (2008) and would affect the lateral behavior of such structural systems. The purpose of the present study is to conduct sensitivity analysis for axial rotation diagrid structural systems according to changes in brace angles in order to identify those design variables that have relatively larger effects and the tendencies of the sensitivity of the structures according to changes in brace angles and axial rotation angles.

## 2 Sensitivity analysis

### 2.1 Concept of sensitivity analysis

Sensitivity analysis is used in diverse areas such as economics and earth science. In the area of building structures, the sensitivity analysis method has been mainly used to identify major design variables when seismic loads act on buildings. Sensitivity analysis is used when parameters are uncertain in one model. All possible values that this parameter can take are assigned and the results of the Engineering Demand Parameter (hereinafter, EDP) are analyzed according to the parameter change.

There are various variables that affect the interpretation of the result. Among them, the values of the remaining variables except for one variable are fixed and the changes of EDP according to specific variables are investigated.

This process is repeated for all variables. As a result, the influence of the variable can be analyzed and the sensitivity to all variables can be shown. The larger the sensitivity value, the higher the relative importance of the variable.

In this study, in authors refer to statistical data of input variables investigated by previous researchers, and the Tornado diagram analysis method was used.

### 2.2 Tornado diagram analysis

In tornado diagram analysis (TDA), when the upper bound, lower bound, and average values of input variables have been determined, structural analysis is conducted to obtain resultant values for individual input variables. After conducting structural analysis for upper and lower bound values, the swings of the resultant values are obtained to analyze the sensitivity. The swings vary in size according to changes in input variables and form the shape of a tornado when arranged in order of size and this shape is called a tornado diagram. Although TDA is simple because the resultant values are derived based on only the values at both ends and the value in the middle, it has a drawback that the shape of the probability distribution of the resultant values cannot be identified. Figures 2 and 3 show the processes through which the upper and lower bound values of a design variable are entered to produce the EDP and the resultant

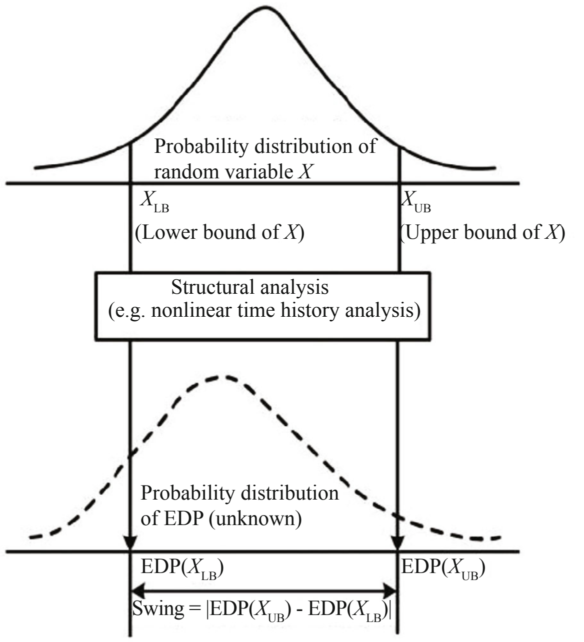


**Fig. 2 Procedure of developing a swing in tornado diagram (Lee, 2005)**

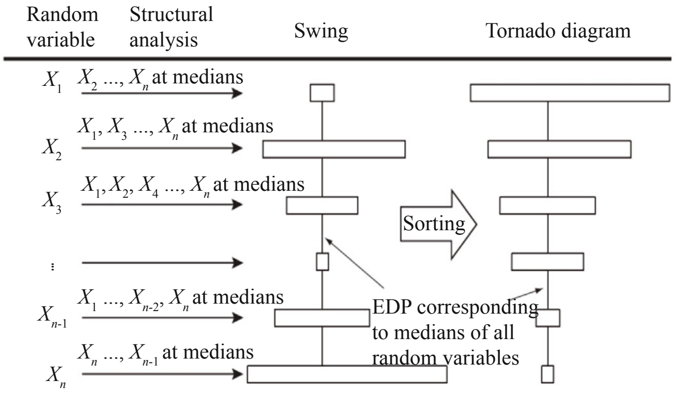


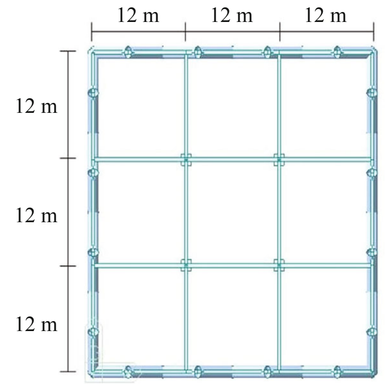
**Fig. 3 Procedure of developing a tornado diagram (Lee, 2005)**

values derived accordingly are arranged in descending order to complete the tornado diagram.

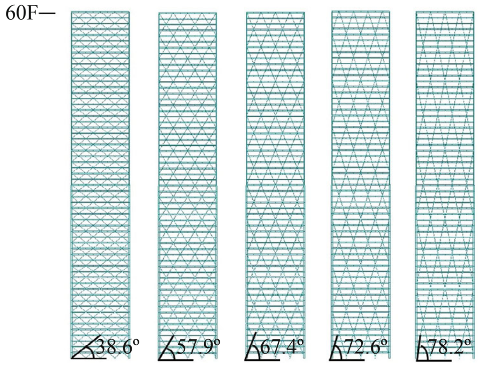
## 3 Analysis model

### 3.1 Numerical modeling

The analysis model used in the present study is a 60 story diagrid structural system consisting of plans that are mainly used in ultra high-rise buildings as shown in Fig. 4 and modules and structures rotated around the vertical axis of the building as shown in Fig. 5. The modeling was conducted using the Midas Gen program. According to the results of an existing study (Moon *et al*., 2007), in the case of 60 story diagrid buildings, brace members installed with brace angles in a range of 65º–75º are the most effective in controlling lateral behavior. However, in the present study, to identify the tendency of sensitivity while changing brace angles diversely, brace members were modeled with five angles; 38.6º, 57.9º, 67.4º, 72.6º, and 78.2º. The braces were installed at intervals of 9m, thereby installing four braces per side. The interior beam members were designed so that they play the role

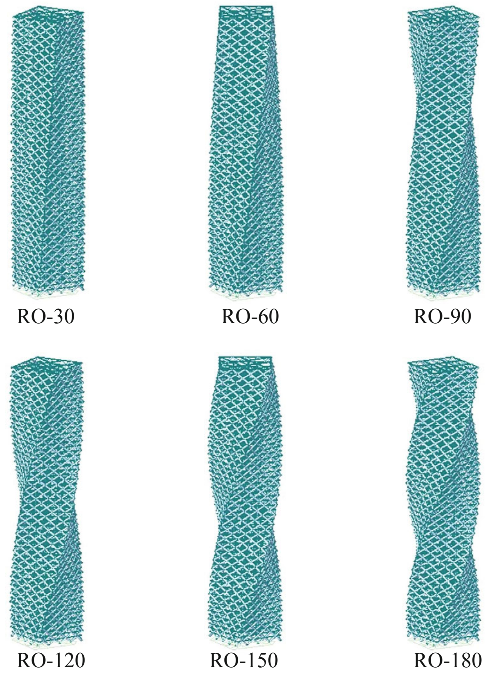


(a) Plan



(b0 Elevations by module angle

**Fig. 4 Diagrid analysis model**


RO-30 RO-60 RO-90

RO-120 RO-150 RO-180

**Fig. 5 Analysis model by rotation angle**

of delivering vertical loads to the external braces and the brace and horizontal rotation angles become major variables of the model. The slabs on individual floors were assumed to be rigid diaphragms. The story height was 3.6 m for all floors and the building height was 216 m (60 story).

As for the design loads, a fixed load of 4.5 kN/ and a live load of 2.5 kN/ were applied pursuant to the Korean Building structural design criteria KBC2009. As for the wind load, the site was assumed to be the Pusan region with roughness B and as for the seismic load, the soil was assumed to be soil corresponding to earthquake zone 1. Importance factor 1.1 and response modification factor 3 were applied. SM490 was used as a material of columns and brace members and SS400 was used as a material of beams. The general properties of SM490 and SS400 are shown in Table 1. The sizes and beams and column members were identical in all the models and the sizes of the braces were adjusted by the model so that the resisting force of the members would not exceed working design roads. Table 2 shows the rotation angles per floor of the plans of the structural systems.

Individual analysis model names were made with the module angles of diagrid braces (hereinafter referred to as module angle) and the horizontal rotation angles (hereinafter referred to as the rotation angle) of the structural systems.

**Table 1 Nominal Strength of Steel**

| Steel type | Thickness | Yield strength | Tensile strength |
|---|---|---|---|
| SM490<br>(rolled steel for welding structural purpose) | $40 < t \leq 100$ | 295 MPa | 490 MPa |
| SS400<br>(rolled steel for general structure) | | 215 MPa | 400 MPa |

**Table 2 Rotation angles per floor**

| Model name | Rotation angles per floor | Top floor rotation angle |
|---|---|---|
| RO-0 | 0° | 0° |
| RO-30 | 0.5° | 30° |
| RO-60 | 1.0° | 60° |
| RO-90 | 1.5° | 90° |
| RO-120 | 2.0° | 120° |
| RO-150 | 2.5° | 150° |
| RO-180 | 3.0° | 180° |

**Table 3 Quantity ratio of the analysis model**

| | 38.6° | 57.9° | 67.4° | 72.6° | 78.2° |
|---|---|---|---|---|---|
| 0° | 1 | 1 | 1 | 1 | 1 |
| 30° | 1.000 | 1.001 | 1.001 | 1.001 | 1.001 |
| 60° | 1.001 | 1.003 | 1.004 | 1.004 | 1.005 |
| 90° | 1.001 | 1.006 | 1.009 | 1.010 | 1.010 |
| 120° | 1.004 | 1.011 | 1.015 | 1.017 | 1.018 |
| 150° | 1.007 | 1.018 | 1.024 | 1.027 | 1.027 |
| 180° | 1.009 | 1.026 | 1.034 | 1.039 | 1.042 |

Table 3 shows the quantity ratios according to the structure horizontal rotation angles in models with the same brace module angles. When the rotation angle is assumed to be 0° and the quantity of the models is assumed to be 1, the models were adjusted so that the quantities would not vary much among the models according to rotation angles.

Figure 6 shows the quantity ratios by brace module angle when the structures' rotation angle was 0°. The quantity ratios are relative quantity ratios by brace module angle based on the quantity of a building with a brace module angle of 38.6°.

### 3.2 Statistical characteristics of the variables

In the present study, statistical data on input variables are essential to conduct sensitivity analysis. Although collecting data through experiments is the best, since there were difficulties in conducting numerous experiments due to conditions, input variables were selected based on the data presented by existing researchers (Kim *et al*., 2000a; Kim *et al*., 2000b) and the statistical properties of the probability variables are as shown in Table 4. Differences in the yield strength of steel materials were applied with differences in elastic modulus at the same strain as shown in Fig. 7. In the present study, only up to the elastic behaviors of members were considered.

## 4 Results of analysis conducted

### 4.1 Preliminary analysis

The model analysis in this study is a linear static analysis. Figure 8 is a graph that shows the lateral displacements of

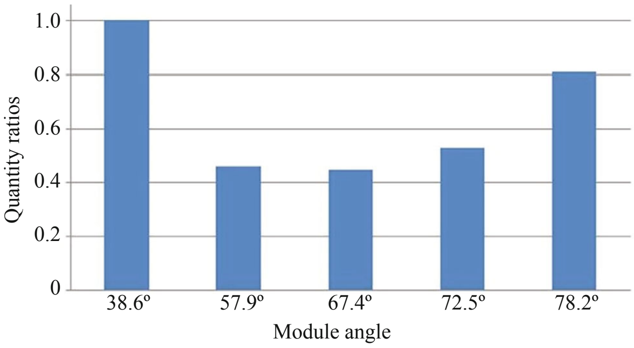


**Fig. 6 Quantity ratios by module angle**

**Table 4 Statistical property of variables**

| Variable | $\mu$ | $\sigma$ | COV |
|---|---|---|---|
| Brace strength (MPa) | 340.06 | 35.28 | 0.104 |
| Column strength (MPa) | 340.06 | 35.28 | 0.104 |
| Exterior, Interior beam Strength (MPa) | 270.48 | 25.48 | 0.094 |
| Modulus (MPa) | 204800 | 3665.9 | 0.0179 |

$\mu$ : mean , $\phi$ : standard deviation
COV : coefficient of variation ( $\phi$ / $\mu$ )

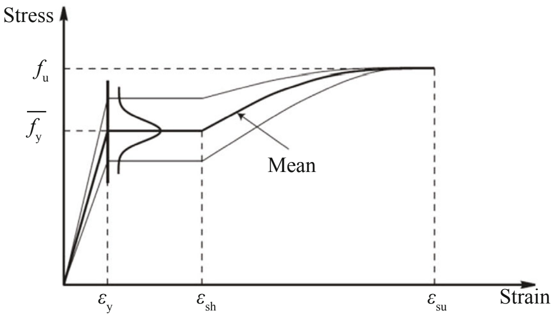


**Fig. 7 Probabilistic constitutive model of Steel (Lee, 2005)**

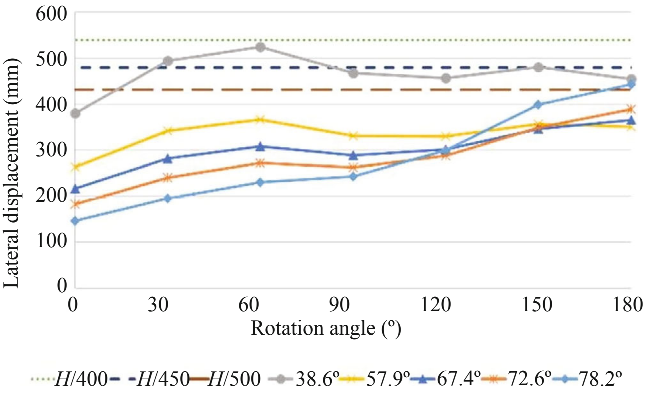


**Fig. 8 Lateral displacements of models applied with average values of input variables**

the models when all of the material properties were entered as average values. All models satisfied the condition not to exceed to the limit value *H*/400 (*H*: building height) of the horizontal displacement of the top floor. When the limit value was set to be *H*/450, among those models that had a brace installation angle of 38.6º, those with a rotation angle of 30º, 60º, or 150º exceeded the lateral displacement limit value while other models did not exceed the limit value.

Figure 9 shows the lateral displacement values of the models derived by applying the lower limit values to the braces. When the lateral displacement limit value was set to be *H*/450, in the case of the RO-38.6-90 model, although the lateral displacement did not exceed the limit value when the input values were average values, it exceeded the limit value when the input values were lower limit values. The lateral displacement of the models may or may not exceed the limit value depending on the probability distribution of input values of variables. Since this is directly related to the safety of the structure, the uncertainty of the material due to the probability distribution cannot be ignored and it is an important parameter in design.

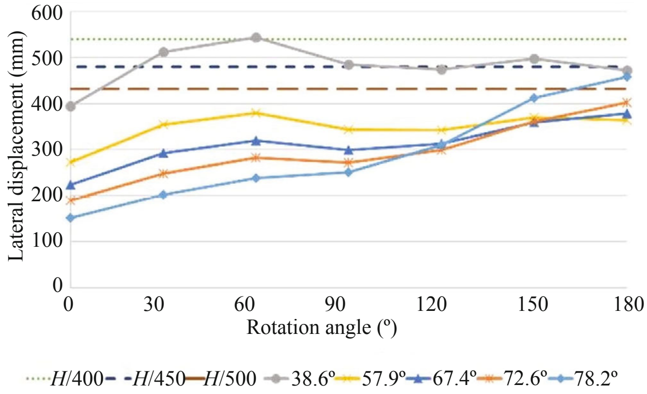
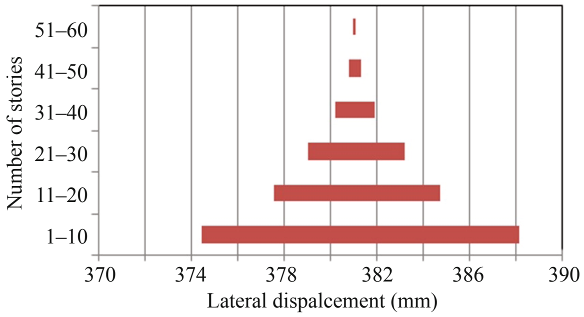


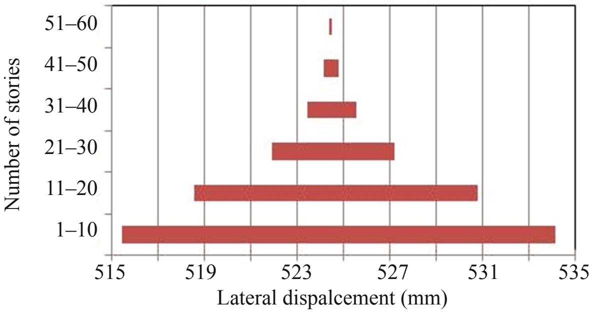
**Fig. 9 Lateral displacements of models applied with the lower limit values of brace input variables**

### 4.2 Analysis of sensitivity by section

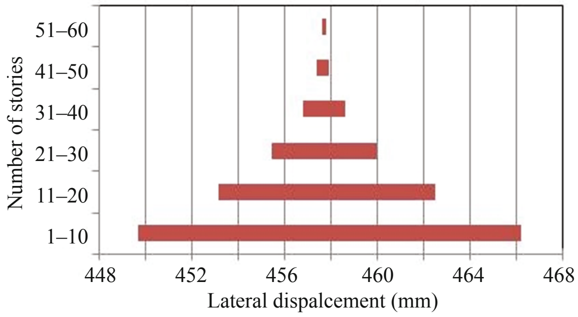
Figure 10 shows the results of sensitivity analysis by section of a representative model with a module angle of



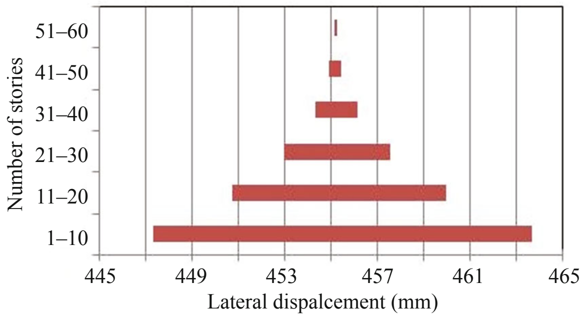
(a) TDA of RO-38.6-0 model by section



(b) TDA of RO-38.6-60 model by section



(c) TDA of RO-38.6-120 model by section



(d) TDA of RO-38.6-180 model by section

**Fig. 10 TDA by section**

38.6º as tornado diagrams. When a 60 story structure was axial rotated, the lower floors showed high highest sensitivity. Among them, the swing of the 1–10th floor section of the RO-38.6-60 model showed the largest value and was 37% larger than that of the RO-38.6-0 model.

The uncertain lateral displacements of the buildings may be reduced by using members with small differences from each other in the 1–10 floor section.

### 4.3 Analysis of sensitivity of members by rotation angle according to brace module angles

Figure 11 shows the results of sensitivity analysis of representative models with a module angle of 38.6º as tornado diagrams. As with regular shaped diagrid structures, it can be seen that most of the effects on the lateral behavior of axial rotation diagrid structures is attributable to the braces followed by the interior beams. Among them, the RO-38.6-60 model showed a brace swing level that was 37.7% higher than that of the RO-38.6-0 model and the RO-38.6-60 model showed the highest level of brace swing. It can be seen that brace sensitivity varies with structures' rotation angles.

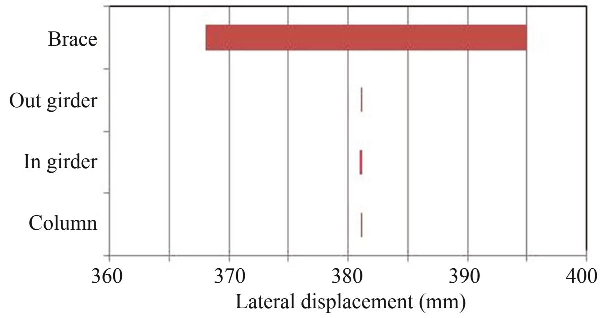
Figure 12 shows the results of sensitivity analysis of axial rotation diagrid models as swings. It can be seen that the model with a brace module angle of 38.6º had larger maximum displacements than the other models and had a distribution of swings in a range of 430 mm–550 mm. When the lateral displacement limit value was set to $H/450 = 480$ mm, the swings of the models with a rotation angle of 30º, 60º, 90º, 150º exceeded the limit value.

Models with a brace module angle of 38.6º or 57.9º showed the maximum lateral displacement when the rotation angle was 60º and models with other brace module angles showed the maximum lateral displacement when the rotation angle was 180º.

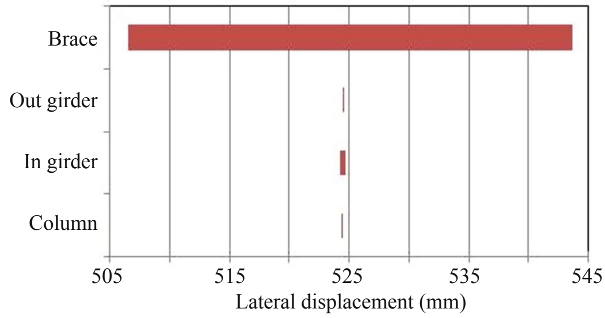
On reviewing Figure 12-(b), it can be seen that the swings of the models according to rotation angles are in the range of 300–400 mm, indicating that the swings are closer to each other compared to other models. It is judged that in the case of axial rotation diagrid structures that satisfy the lateral displacement limit value, the lateral displacements following increases in rotation angles can be reduced by designing the brace module angle as 57.9º.

Since sensitivity cannot be easily compared among structure rotation angles or brace module angles, the swings of the displacements were divided by the average displacement of the relevant model to express the value as ratios (hereinafter referred to as sensitivity=swing/average displacement) to compare the sensitivity of members among individual models. Here, the average displacement refers to the displacement of models applied with average values of member input variables.

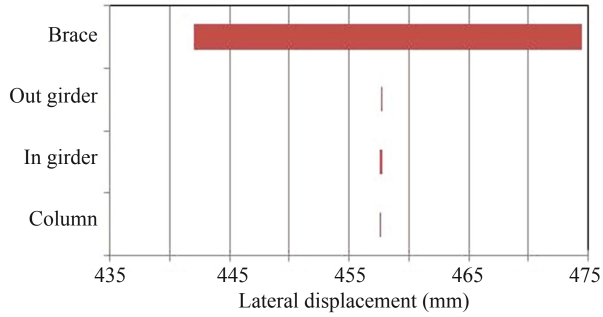
Figure 13 shows the brace sensitivity of the analysis models. The models with a brace module angle of 38.6º or 57.9º did not show not much difference in brace sensitivity even when the structure rotation angles increased. The models with a brace module angle of 67.4º or a larger brace module angle showed decreases in sensitivity little by little as the structure rotation angles increased. When the brace module angle was 72.6º, the sensitivity showed a tendency to gradually decrease from a rotation angle of 90º. In cases where each brace module was 78.2, it showed a tendency to sharply decrease from the rotation angle 30.



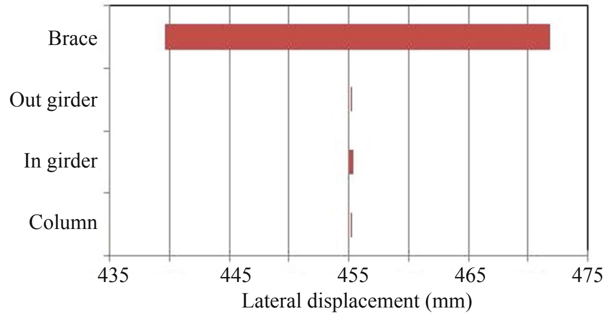
(a) RO-38.6-0 model member TDA



(b) RO-38.6-60 model member TDA



(c) RO-38.6-120 model member TDA

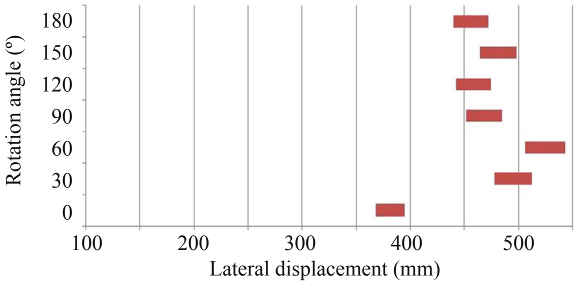


(d) RO-38.6-180 model member TDA

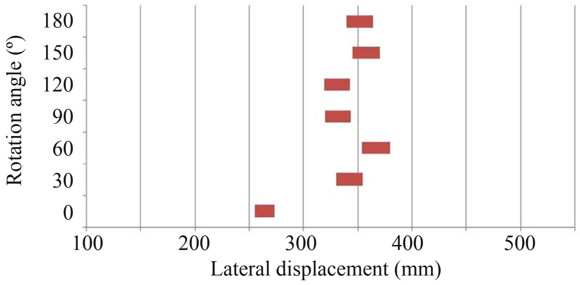
**Fig. 11 Model member TDA**

Figure 14 through Figure 16 are graphs that compare changes in the analysis models' columns, exterior beams, and interior beams.

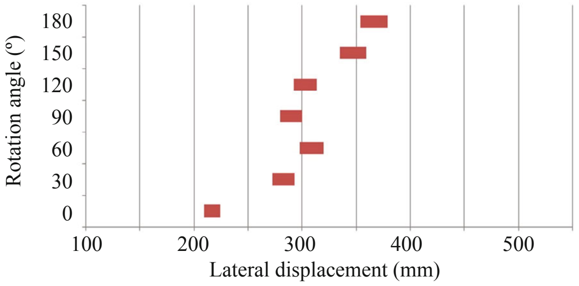
When the brace module angle was 38.6º or 57.9º, changes



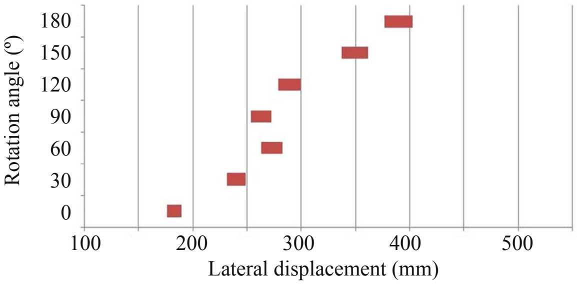
(a) Module angle 38.6º



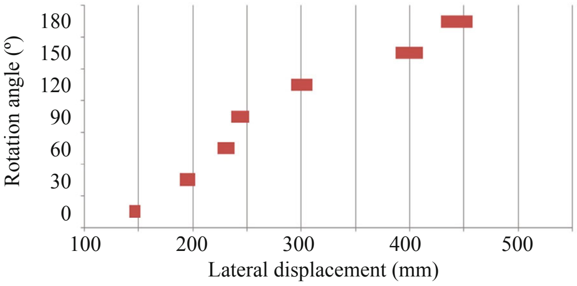
(b) Module angle 57.9º



(c) Module angle 67.4º



(d) Module angle 72.6º



(e) Module angle 78.2º

**Fig. 12 TDA of braces according to structure rotation angles**

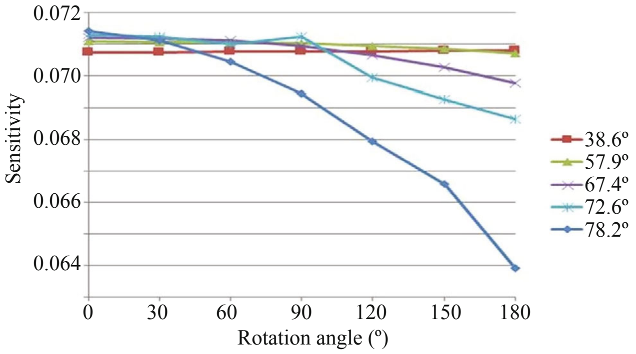


**Fig. 13 Brace sensitivity by module angle**

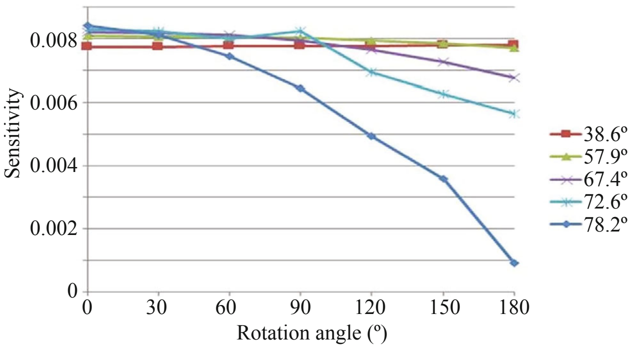


**Fig. 14 Column sensitivity by modul angle**

in the sensitivity of columns, interior beams, or exterior beams were not large even when the rotation angle increased to 180º. As can be seen in Fig. 14, the models with a brace module angle of 67.4º or 72.6º showed an increase in column sensitivity by approximately 10 times and 20 times between when the rotation angle was 0º and when the rotation angle was 180º. In the case of the model with a brace module angle of 78.2º, the column sensitivity increased more rapidly than other models to the extent that the column sensitivity when the rotation angle was 180º was approximately 120 times higher than when the rotation angle was 0º.

On reviewing Fig. 15, it can be seen that when the rotation angle was 0º or 30º, the interior beam sensitivity showed larger values when the brace module angle was smaller. Although the model with a brace module angle of 78.2º showed the lowest interior beam sensitivity compared to the other brace models, it showed rapid increases in the sensitivity as the rotation angle increased to show the highest sensitivity when the rotation angle was 150º or 180º. It can be seen that as the rotation angles of the structures increase, the effects of interior beams on lateral displacements increased.

On reviewing Fig. 16, it can be seen that in the case of the model with a brace module angle of 78.2º, the exterior beam sensitivity showed a sharp increase from 30 degrees. The sensitivity of 180 degrees is about 6 times higher than that of 72.6 degrees.

### 4.4 Analysis of sensitivity according to brace module angles at the same rotation angle

Through sensitivity analysis, changes in sensitivity were examined while changing structures' brace module angles at the same rotation angle.

On reviewing Fig. 17, it can be seen that models with a rotation angle of 0º or 30º did not show large changes

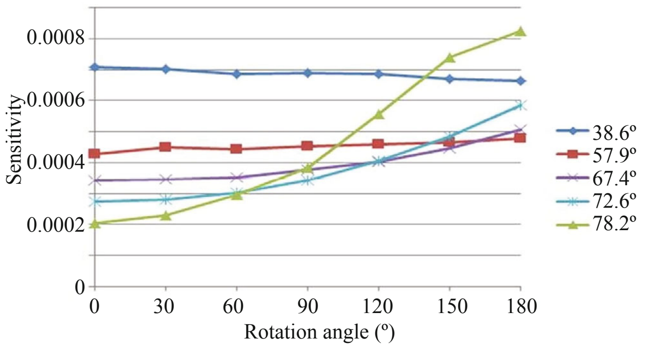


**Fig. 15 Interior beam sensitivity by module angle**

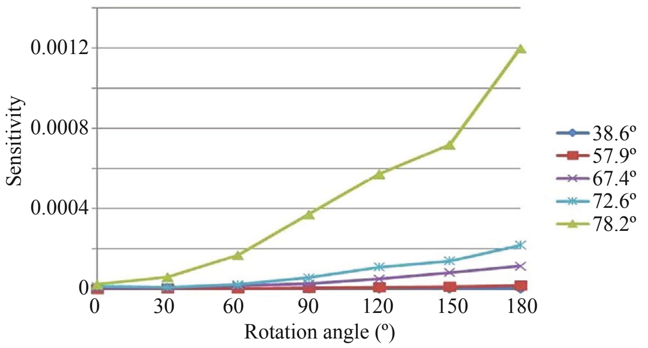


**Fig. 16 Exterior beam sensitivity by module angle**

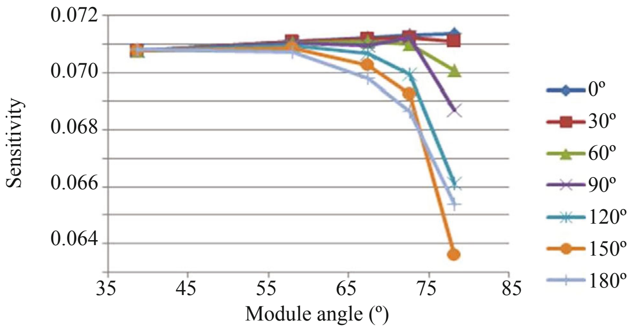


**Fig. 17 Brace sensitivity by rotation angle**

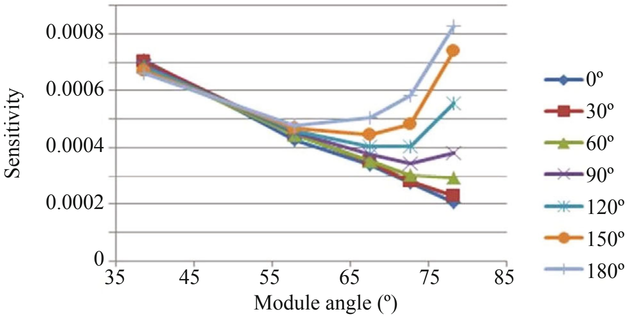


**Fig. 18 Interior beam sensitivity by rotation angle**

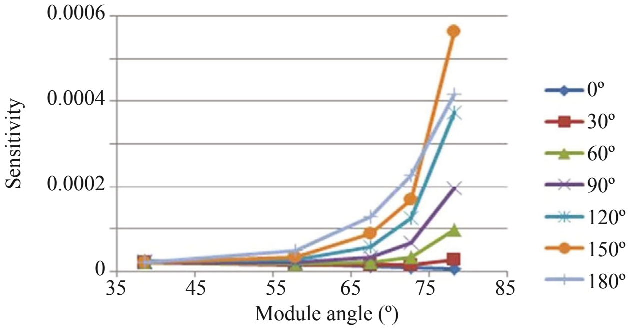


**Fig. 19 Column sensitivity by rotation angle**

in sensitivity even when brace module angles changed. In the case of models with a rotation angle of 150° or 180°, the brace sensitivity showed a tendency to rapidly decrease from when the brace module angle reached 67.4°.

In Fig. 18, models with a rotation angle of 0°, 30°, or 60° show a tendency to have lower interior beam sensitivity as the brace module angle increases. In the case of models with a rotation angle of 90° or 120°, the interior beam sensitivity showed a tendency to decrease until the brace module angle reached 72.6° and increase thereafter and in the case of models with a rotation angle of 150° or 180°, the interior beam sensitivity showed a tendency to decrease until the brace module angle reached 67.4° and increase thereafter.

In Fig. 19, in the case of models with a rotation angle of 0° or 30°, the sensitivity did not change very much even when the brace module angle increased and in the case with models with other rotation angles, the sensitivity showed a tendency to increase from when the brace module angle reached 57.9°. The model with a rotation angle of 150° showed higher sensitivity than the model with a rotation angle of 180° from when the brace module angle reached 72.6°.

## 5 Conclusion

In the present study, using the tornado diagram analysis method, sensitivity analyses for lateral behaviors were conducted by changing brace member installation angles and increasing the horizontal axial rotation angles. The conclusions drawn herein are as follows.

(1) In the present study, relatively important variables of irregular shaped structures were examined through sensitivity analysis although a limited numbers of models were used and the tendencies of sensitivity of structures according to changes in brace angles and axial rotation angles were identified to present new directions for future irregular shaped structure designs.

(2) According to the results of the application of the present method, in cases where only fixed values of material properties such as nominal strength and elastic modulus were used, the behavior of the entire structure became unstable due to differences in materials. In the case of the sample structure used in the present study, the fixed values presented in the standard (KBC2009) were used as loads and the probability variables presented in existing studies were used for material properties. According to the results of the analysis, even those structures designed not to exceed the lateral displacement limit value using fixed values of material exceeded the limit values at times when the statistical characteristics

of the materials were considered. Therefore, when designing structures, deviations in material properties should be considered.

(3) As with regular shaped diagrid structures, brace members were identified as the most resisting factor against lateral loads in the case of axial rotation diagrid structures and the effects of brace members on the behaviors were also large. However, unlike regular shaped structures, in the case of irregular shaped structures, the effects varied with changes in the axial rotation angle. Structures with a brace module angle of at least 67.4º showed a tendency to have lower brace sensitivity as the rotation angle increased.

(4) In the case of axial rotation diagrid structures, models with a brace module angle of at least 67.4º showed a tendency to have lower interior beam sensitivity as the rotation angle increased. In the case of regular shaped diagrid structures with a rotation angle of 0º, models with a brace module angle of 78.2º showed the lowest sensitivity but the sensitivity increased as the rotation angle increased to show the largest value when the rotation angle was 180º.

(5) A previous study (Moon *et al*., 2007) presented optimum brace angles for a 60 story regular shaped diagrid structures as 65º–75º. However, in the case of the irregular shaped structure used in the present study, changes in lateral displacements due to increases in rotation angles were shown to be the smallest in the case of models with a brace module angle of 57.9º. Therefore, since the optimum brace angle varies with changes in the rotation angle in the case of axial rotation diagrid structures, the optimum angle should be reviewed again for irregular shaped diagrid structures.

## References

Ahn KW, Yang JK and Park SS (2015), "Sensitivity Analysis on the Lateral Behavior of Diagrid Structure," *Journal of The Korea Institute for Structural Maintenance and Inspection*, **19**(3).

KBC2009 (2009), *Architectural Institute of Korea*, Korean Building Code, South Korea.

Kim JK, Lee YH (2009), "Seismic Performance Evaluation of Diagrid System Buildings," *Journal of the Architectural Institute of Korea Structure & Construction*, **25**(6).

Kim JR, Kim SB, Park YH and Jung WG (2000), "A Statistical Study on the Mechanical Properties and Chemical Components of Rolled Steels for General Structure, SS400," *Proceeding of Architectural Institute of Korea*, **20**(1): 229–232.

Kim JR, Kim SB, Park YH and Jung WG (2000), "A Statistical Study on the Mechanical Properties and Chemical Components of Rolled Steels for Welded Structure, SM490." *Journal of Architectural Institute of Korea*, **16**(11): 3–10.

Lee TH and Mosalam KM (2009), "Identifying Significant Components of Structures for Seismic Performance Using FOSM Method," *Earthquake Engineering Society of Korea*, **13**(4).

Moon KS (2007), "Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design." *The Structural Design of Tall and Special Buildings*, **16**: 205–230.

Porter KA, Beck JL, and Shaikhutdinov RV (2002), "Sensitivity of building loss estimates to major uncertain variables," *Earthquake Spectra*, **18**(4): 719–743.

Vollers K (2008), "Morphological scheme of second-generation non-orthogonal high-rises," *CTBUH*.