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Evaluation of Progressive Collapse of Transmission Tower

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***Abstract*—**The transmission tower is one of the crucial lifeline structures in a modern society, and it needs to be protected against extreme loading conditions. However, the transmission tower is a very complex structure and, therefore, it is very difficult to simulate the actual damage and the collapse behavior of the tower structure. In this study, the actual collapse behavior of the transmission tower due to lateral loading conditions such as wind load is evaluated through the computational simulation. For that, a progressive collapse procedure is applied to the simulation. In this procedure, after running the simulation, if a member of the tower structure fails, the failed member is removed and the simulation run again. The 154kV transmission tower is selected for this study. The simulation is performed by nonlinear static analysis procedure, namely pushover analysis, using OpenSEES, an earthquake simulation platform. Three-dimensional finite element models of those towers are developed.

***Keywords*—**Transmission tower, OpenSEES, pushover analysis, progressive collapse.

I. Introduction

THE electric transmission tower is the important lifeline structure in the life of modern society. The damage of the electric transmission power causes the primary damage such as the damage and collapse of the structure and causes the secondary damage such as the blackout. In particular, the damage of the high-pressure electric transmission tower can bring on the large-scale blackout damage, which leads to the social confusion and economic loss. Therefore, electric transmission tower should be protected from the natural disaster such as the earthquake or strong wind.

'DS-1111 (KEPCO,2010)', a Korean steel tower design criteria for the overhead transmission, provides the only whether the allowed stress of the framework member by the wind load exceeds or not should be reviewed, and does not consider the earthquake load [1]. Due to the structural feature of the electric transmission tower that the mass is relatively smaller than the size and the strung wire is not in line with the steel tower, the cross section is decided by the lateral wind load rather than the earthquake load. The National Electrical Safety Code (2012) of US and The Building Standard Law (1994) of Japan also do not consider the earthquake load [2], [3]. However, there many cases the electric transmission tower designed by the wind load were damaged by the strong wind and gust. There is a case that 10 electric transmission towers were damaged and destroyed by the typhoon 'MAEMI' in 2003 in Korea [4]. Fig. 1 shows the figure of 154 kV electric transmission tower which was destroyed by the typhoon Maemi. Therefore, in order to prevent the damage and destruction of the electric transmission tower and maintain it more efficiently, the damage and destruction mechanism needs to be analyzed by apprehending the behavior characteristic of the electric transmission tower in the condition of the ultimate load. Therefore, this study developed the simulation of the three-dimensional finite-element model to analyze the destruction behavior characteristic of the electric transmission tower. The 154 kV electric transmission tower was selected as a target model of which usability was the biggest among the electric transmission towers operated in Korea. OpenSEES, the earthquake simulation platform, was used as the program of the simulation [5]. The model was constituted by means of the member of framework of 'non-linear beam column' to consider the geometric nonlinearity of the electric transmission tower, and the geometric transformation was applied to the 'corotational formulation'. The analysis was fulfilled by the pushover analysis which was the nonlinear static analysis. Also, the progressive collapse analysis of the electric transmission tower was conducted as a way to remove the destroyed member of framework.

Fig. 1 The collapse of transmission tower by the typhoon 'MAEMI'

II. The Failure Behavior of Transmission Tower

A. Linear Elastic Analysis

The linear elastic analysis for judging whether each framework member on the wind load of the electric transmission tower was damaged was carried out before this study. The general analysis program SAP2000 was used as the

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simulation program and the Korean 154kV electric transmission tower was selected as the simulation model. The model was constituted based on the 'power transmission design standard DS-1111' of Korea [1]. The uniform load on the wind-accepting area was calculated into the concentrated load to apply to each node. The analysis of simulation was carried out for total 4 load cases: high temperature normal time, high temperature abnormal time, low temperature normal time, and low temperature abnormal time by applying the design standard. The abnormal time means the severance of the strung wire of the electric transmission tower. If the stress of the framework member exceeded the allowable stress, it was defined as the damage of the framework member. Three allowable stresses on the seal, compression, and elastic buckling were calculated.

As a result of the simulation, the main post and arm post were not damaged in all load cases and the diagonal member and horizontal member were damaged in some load cases. However, although one braced member exceeds the design stress, it cannot represent the damage degree of the whole structure, and the allowable stress excess of the steel framework member does not mean the destruction of the framework member. Therefore, the behavior characteristics should be analyzed exactly to define and apprehend the damage degree of the electric transmission tower.

B. Geometric Nonlinearity

Since the electric transmission tower analysis of the advanced research was the linear elastic analysis, it did not consider the geometric effect of the framework member. However, since the electric transmission tower is the slender structure of which height is bigger than the width, if the lateral external load is added, relatively many transformations happen. The framework member of the electric transmission tower is also the slender framework member of which length is longer than the width. Therefore, many transformations happen to the member of framework regarding the external load and the transformation of the framework member induces the stiffness change of the framework member. Since the electric transmission tower is a very complex structure comprised of these slender framework members, the interaction of the framework members following the stiffness change of the framework member should be considered. Therefore, the geometric nonlinearity should be considered in order to apprehend the exact behavior characteristic in analyzing the electric transmission tower.

This study applied the co-rotational geometric nonlinear analysis to consider the geometric nonlinearity of the electric transmission tower. Co-rotational geometric nonlinear analysis has a merit to reflect the deformation of the large rotation precisely [6]. The co-rotational geometric nonlinear analysis uses the natural deformation rather than the local displacement when calculating the framework strength unlike the geometric nonlinear analysis based on the Lagrangian approach. The natural deformation is a displacement that generates the member force and deformation rate in the framework member. It is divided into the rigid body motion that does not generate the framework member force and the natural deformation which generates the member force and deformation rate. Therefore, the extraction of the natural deformation that removed the rigid body motion in the entire motions of the member and the decision of the member coordinate system reflecting the rigid body motion precisely is the core of the Co-rotational geometric nonlinear analysis. In the simulation of this study, the geometric coordinate deformation was used as the 'geomTransf Corotational' to apply the Co-rotational geometric nonlinear analysis [5].

C. Progressive Collapse

The electric transmission tower is a very complex structure. Therefore, it is very difficult to exactly analyze the effect of the damage of each member on the whole structure. Also, since the electric transmission tower is the framed structure consisting of frame members, if a member collapses, the stress of the destroyed member transfers to other adjacent members so the members can collapse consecutively. Therefore, the analysis of the progressive collapse of the electric transmission tower is necessary.

There are various guidelines about the progressive collapse analysis. The American Society of Civil Engineers Standard 7-05 (ASCE, 2010) describes about the unity of the structure, and suggests the design method and load combination for the prevention of the progressive collapse [7]. The Unified Facilities Criteria Design of Buildings to Resist Progressive Collapse (UFC4-023-03,2009) suggests the design method for the prevention of the progressive collapse with respect to the existing and new buildings [8]. The U.S. General Services Administration Alternate Path Analysis & Design Guidelines For Progressive Collapse Resistance (GSA, 2013) suggests the guideline of the analysis and design on the progressive collapse based on Alternate Path Method (APM) [9], [10]. The progressive collapse analysis suggested in the guideline of GSA assumes the column destruction situation by the abnormal load such as the terror against the buildings and the collision of big and heavy objects by means of the column removal scenarios. It removes the column of buildings corresponding to the assumed scenario, conducts the analysis, and analyzes how much the stress on the structure exceeds compared with the design load.

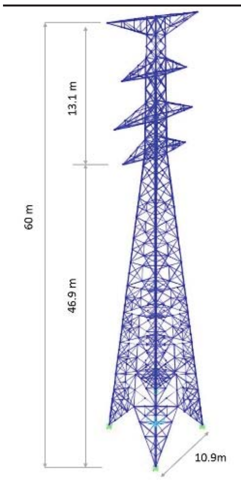
This study carried out the progressive collapse analysis of the electric transmission tower by removing and analyzing the members similarly to the progressive collapse analysis suggested by GSA. The difference of this study and GSA guideline is it conducted the pushover analysis of the electric transmission tower not the situation by the abnormal load, analyzed the response of each member, removed the member considered to be failed the first, and conducted the progressive collapse analysis of the electric transmission tower by conducting the pushover analysis again. The collapse prevention (C.P) points of moment-curvature curve of each member was defined as the criterion of the member failure.

III. Analysis Simulation Model

A. 3-Dimensional Finite Element Model

The electric transmission towers operated in Korea are distinguished according to the power transmission voltage such as 765 kV, 345 kV, 154 kV, and 66 kV, and the cross section of the composition member includes the types: angle, pipe, and double angle [1]. This study chose the power transmission tower of 154 kV type, one of the usually operated types in Korea, as an analysis model to develop the OpenSEES-using finite element model. The height of the developed power transmission tower was 60 m, width was 10.9 m. It was in form of lattice and consisted of total 1316 elements. The materials of the elements were SS540 and SS400 having the elastic coefficient of 200 GPa and the cross sectional image of all elements was composed as the angle type. As for the size of element cross section, 17 cross sections were used. The gusset plate, bolt, and other adjunctive structures were excluded from modeling. The spot condition of the analysis model was set as the fixed end. Table I shows the element properties and model shape of the 154 kV electric transmission tower which was used for this study. Fig. 2 shows the eigenvalue result of 154 kV transmission.

TABLE I
The Properties of Transmission Tower

	Section Standard	Material	The number of element
	HL90-7	SS540	164
	HL100-7	SS540	48
	HL120-8	SS540	52
	HL130-9	SS540	14
	HL150-12	SS540	12
	HL200-15	SS540	23
	HL200-20	SS540	36
	HL200-25	SS540	60
	HL250-25	SS540	20
	L45-4	SS400	158
	L50-4	SS400	88
	L60-4	SS400	110
	L65-6	SS400	190
	L70-6	SS400	88
	L75-6	SS400	104
	L80-6	SS400	88
	L90-6	SS400	72

B. Development Analysis Simulation

The pushover analysis simulation was developed by means of OpenSEES v.2.5.0 which was the earthquake simulation platform for the geometric nonlinear analysis of the electric transmission tower [5]. The 'nonlinearBeamColumn' was applied to the element of the electric transmission tower model, and the cross section was comprised of 'FiberSection'. Also, the co-rotational formulation was applied to the analysis simulation for the geometric nonlinear analysis considering the large deformation. The load application control of the pushover analysis was set up as the 'displacement control' and the observation point of the motion control was set up as No.453 node located in the center-top of the electric transmission tower.

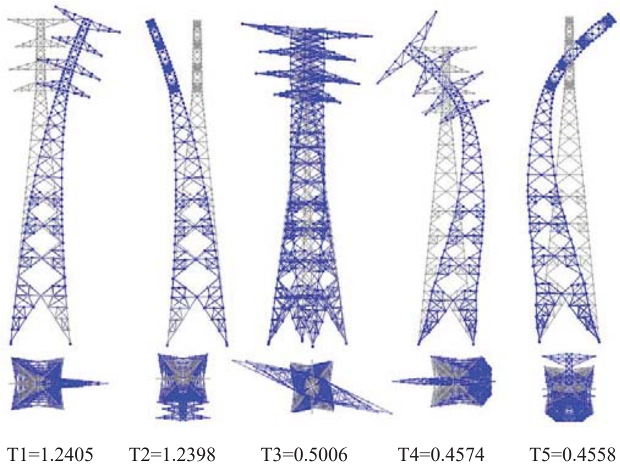


Fig. 2 Eigenvalue of 154kV transmission tower

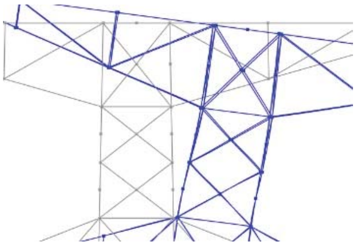
IV. Analysis and Results

A. Pushover Analysis

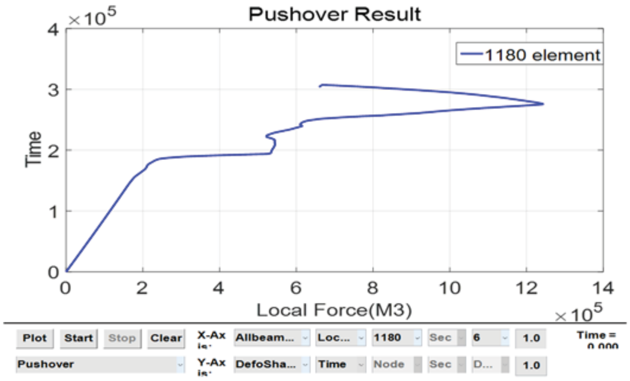
The pushover nodal load point was applied to the nodes of main post that the wind load worked based on the 'power transmission design standard DS-1111' for the nonlinear behavior by the wind load of the electric transmission tower. Thus, the analysis model was assumed that the same pressure of the wind load on the structure, not the behavior by the localized load. The load application control of analysis was set 'Displacement Control'. It performed by established that Global X-dir(U1), Y-dir(U2).

It is necessary to define the limit conditions of the respective members in order to analyze the results of analysis. As discussed in Section II *A Linear Elastic Analysis,* the design standard proposes damage of member to allowable stresses of the tensile, compression and buckling. However, in case of the main post of transmission tower, it functions as a flexural member. Therefore, the limit states of each member is considered the axial force and M2, M3 moment for characteristics of the member. The C.P point is selected to the limit state because of target to analysis of failure behavior of structure. And the buckling effect of the member is not considered.

The analysis results indicate that there is no significant difference of the behavior characteristic of 154kV transmission tower model since the structure and the element type is the same in the strung wire vertical direction and along the strung wire direction. Arm member may not be construed as a structural role in the behavior of the steel tower. Fig. 3 shows the pushover analysis result of transmission tower.



(a)



(b)

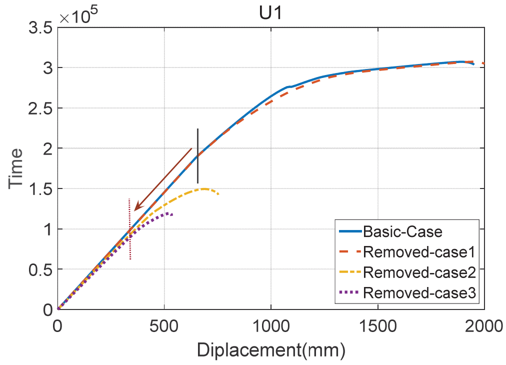
Fig. 3 The pushover analysis result of transmission tower

B. Progressive Collapse Analysis

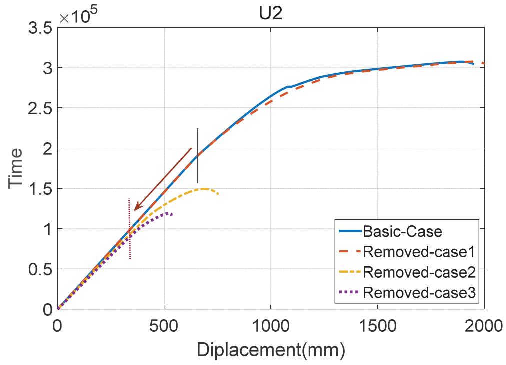
It conducted the pushover analysis of the transmission tower, analyzed the response of each member, removed the member considered to be failed the first, and conducted the progressive collapse analysis of the transmission tower by conducting the pushover analysis again. The C.P point of moment-curvature curve of each member was defined as the criterion of the member failure.

In first analysis case, both direction of U1 and U2, the failure due to bending moment at braced member which located same elevation has occurred, and removed the failed member, run again pushover analysis. The analysis results indicate that when one braced member is fail, sequential failure of adjacent member at the same elevation has occurred. Each case of analysis, it examined the Displacement – Time plot to using pushover analysis results. And it was confirmed that failure occurs of the main post in analysis case which the linear response region of the structure is rapidly change. Therefore, the failure of main post was defined as the collapse of structure.

Fig. 4 shows the Displacement – Time analysis results of each cases by U1 direction and U2 direction.



(a)



(b)

Fig. 4 The Displacement – Time analysis results

V. Conclusion

This study was a basic study for analyzing the destruction behavior characteristic of the electric transmission tower, 154kV electric transmission tower was selected which was most frequently used among the electric transmission towers operated in Korea and it developed the simulation of the OpenSEES-using three-dimensional finite element model and conducted the pushover analysis of the electric transmission tower considering the geometric nonlinearity, and carried out the progressive collapse analysis of the electric transmission tower in the manner of removing the destroyed elements based on the analysis result.

The conclusion of this study is as follows:

1) The electric transmission tower should be composed by the complex elements of beam and truss, and the buckling of each element must be considered.
2) In order to apprehend the more exact behavior characteristic of the structure while conducting the progressive collapse analysis, the mechanism that the effect of element destruction can transfer to other elements should be applied.
3) As a result of progressive collapse analysis of the electric transmission tower, while the electric transmission tower is a very complicated structure that is expanded into the element-story bay-structure, as a result of analysis, it is expanded to the element-story bay-structure and the

destruction happens.

4) If the destruction happens in a certain story bay, the successive destruction happens in the same story bay, which results in the destruction of the main post.

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REFERENCES

[1] KEPCO, *Design Standard of Transmission Tower(DS-1111)*, Korea Electric Power Corporation, 2010.
[2] IEEE-SA, *The National Electrical Safety Code*, IEEE Standard Association, 2012.
[3] MIAC, *The Building Standard Law,* Ministry of Internal Affairs and Communications, Japan, 1994.
[4] National Institute for Disaster Prevention, “The Field Survey Report of Damages Caused by Typhoon MAEMI in 2003”, The Ministry of Government Administration and Home Affairs, Report, Korea, 2003.
[5] S. Mazzoni, F. McKenna, M.H. Scott, G.L. Fenves, “OpenSees Command Language Manual”, Pacific Earthquake Engineering Research (PEER) Center, 2005.
[6] K.C. Lee, “Corotational Formulation for The Geometrical Nonlinear Analysis of Space Frames with Finite Rotations”, Seoul Univ., Thesis, 2007.
[7] ASCE 7-05, *Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, 2005.
[8] Unified Facilities Criteria (UFC), *Design of Buildings to Resist Progressive Collapse*, Department of Defense, United States of America, 2009.
[9] U.S. GSA, *Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects*, General Service Administration, United States of America, 2003.
[10] U.S. GSA, *Alternate Path Analysis & Design Guidelines for Progressive Collapse Resistance*, General Service Administration, United States of America, 2013.