Finite Element Analysis of Structural Safety and Support Reinforcement Efficacy in a Large Old Zelkova Tree: A Case Study of a Natural Monument

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The structural safety of a natural monument tree was evaluated using the finite element method (FEM), assuming the tree's material properties to be isotropic. This research involved quantifying external forces, gravity, snow, and wind loads, and analyzing the resulting stress and displacement of the tree. The effectiveness of support structures in improving the tree's overall structural stability was also investigated. The results show that the greatest displacement and stress occur under snow load conditions. The highest stress was observed in branch D (13.63 MPa) under snow load without any support structure. When this stress was compared with the bending strength of the Zelkova tree's branches (69.7 MPa), it was found that the tree has a safety margin of 56.1 MPa. Furthermore, when the current support structure positions were considered, branch F, which is supported, exhibited a significant reduction in displacement (by 30% to 42%) and stress (by 84% to 92%) compared to conditions without support. Conversely, branch D, which lacks a support structure, showed no reduction in displacement or stress. These results show that FEM simulation can contribute to the review of reinforcement facility installation to ensure the stability of large old trees.

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INTRODUCTION

Large old trees exhibit the results of long-term growth, wherein they have adapted to the local natural environment to maintain balance and stability, giving rise to their current appearance (Mattheck and Breloer 1994). However, as these trees mature, their growth rate tends to slow down, they tend to lose vitality, and their ability to repair defects decreases (Bamber 1976; Kaufmann 1996; Martínez-Vilalta *et al.* 2007; Johnson and Abrams 2009). In addition, these trees often have large, thick branches and extensive rot and cracking. As a result, most natural monument trees are relatively vulnerable to damage and are structurally weak.

Natural monument trees in Korea are usually large old trees with significant cultural and historical value (Jung *et al.* 2023). As mentioned above, defects and cracks in these trees can weaken the structural stability of the tree and reduce its vitality and lifespan. Vitality may remain high despite structural weakening due to internal decay.

However, from a materials mechanics perspective, such defects reduce load-bearing capacity by decreasing the effective cross-section. In extreme cases, such damage can lead to significant destruction, ultimately reducing the conservation value of the tree. Therefore, these trees require long-term conservation strategies. Several researchers have attempted to assess the internal cavities and physiological decline of trees using non-destructive methods (Gilbert and Smiley 2004; Deflorio *et al.* 2008; Karlinasari *et al.* 2016; Son *et al.* 2021). These studies are mainly useful for diagnosing the internal condition of the tree, but they do not consider the influence of external forces such as wind, snow, and rain.

The structural safety of a tree can be assessed by comparing the internal stresses induced in the tree by external forces with the strength of the tree (Mattheck and Breloer 1994; Spatz and Bruechert 2000). The internal stresses within a tree can be simulated using the finite element method (FEM), which has been widely applied in various fields for structural analysis such as civil engineering (Ereiz *et al*. 2022), aerospace engineering (Rajanna *et al*. 2022), and mechanical engineering (Li *et al*. 2018; Shetty *et al*. 2017).

Several researchers have tried to use FEM to simulate the safety of the tree. Yang *et al.* (2014) simulated how tree roots react to wind forces to predict root damage more realistically. Ji *et al.* (2006) revealed that superficial lateral roots contribute more than 30% of the total anchorage strength in certain soil types. Dupuy *et al.* (2007) used 3D FEM to simulate tree root-soil interaction, revealing how root structures and soil properties influence overturning resistance and anchorage stability. Liu *et al.* (2023) analyzed the mechanical and physiological characteristics of the tree branch-stem junction using the FEM and explained how these features help minimize tree damage. These studies show that FEM can visualize the overall mechanism and analyze each part of the tree in detail.

The FEM analysis requires data on the geometry of the tree, applied external forces, and the mechanical properties. Although the geometry of the tree is non-uniform, a realistic approximation can be obtained using 3D scanning technology. Mattheck (1990, 1994, 2006) used FEM to calculate the relationship between tree shape and stress distribution within a tree, and Jackson *et al.* (2019) simulated the 3D geometrical shape of 21 trees to predict the degree of mechanical deformation applied to the tree trunk. Tsugawa *et al.* (2022) obtained 3D point clouds of *Zelkova serrata* and *Larix kaempferi* using a lidar scanner, extracted the column structure, and performed FEM simulations to evaluate the mechanical stress due to gravity and other mechanical properties.

External loads, such as wind, affect the formation of tree trunks and are essential information for structural analysis and stability review (Dean and Long 1986). The external forces, such as rain, wind, and snow, can be quantified using historical weather data. The load-carrying capacity of a tree depends on its size and shape and the material properties of its wood, such as elasticity and strength, can be estimated through experimental measurements and statistical analysis (Dahle *et al.* 2017).

The aim of this study was to evaluate the structural safety of a large old tree using the FEM analysis. This study includes quantifying the external forces acting on the tree, including gravity, wind, and snow loads, and analyzing the resulting stresses and displacement. Furthermore, the study evaluated the influence of the supporting structures on the tree to determine how effective such reinforcement is in improving the overall structural safety of the trees.

EXPERIMENTAL

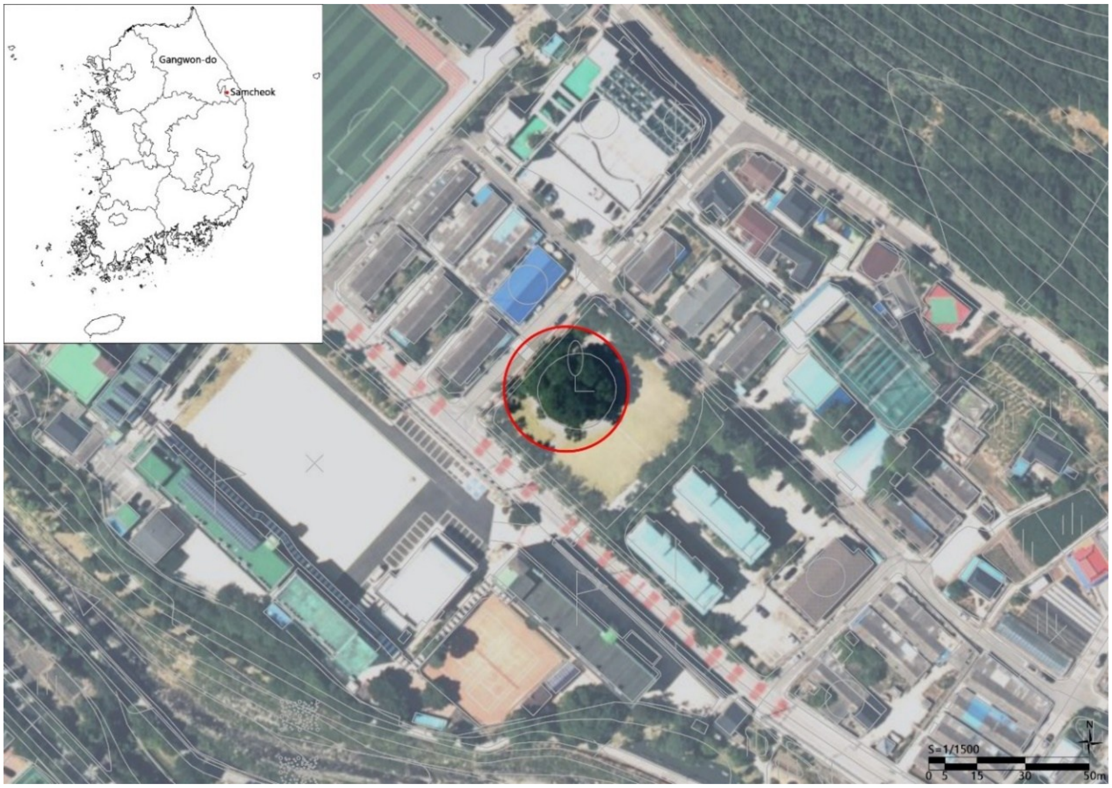
Case Study Tree

A Zelkova tree, *Zelkova serrata* (Thunb.) Makino, designated as a natural monument, was analyzed in this study. Figure 1 shows the shape of the tree, which was located in Dogye-ri, Dogye-eup, Samcheok-si, Gangwon-do, Republic of Korea.

This tree is estimated to be approximately 1,000 years old and was officially designated as a natural monument on December 7, 1962. It stands 22.7 m tall with a breast height diameter of about 3.4 m. This makes the tree both exceptionally large and ancient, giving it significant biological preservation value. Additionally, it holds cultural importance as the local villagers regard it as sacred.

In 1987, a large southern branch broke off due to a typhoon, creating the current cavity on the trunk. The cavity was surgically filled in 1997, but the filling was removed in 2018. Consequently, a large cavity is now exposed on the southwest side of the trunk, as shown in Fig. 1(a). The tree is supported by structures installed on two long branches on the east side and one long branch on the west side. The selection of these support locations was based on the installer’s experience. However, differing opinions on the optimal placement of these supports prompted this study. This study will help to find more suitable locations for the supports to ensure the tree's long-term preservation and safety.

a) Ground photograph (south)



b) Location in South Korea

Fig. 1. Ground photograph and location of a natural monument tree analyzed in this study

Simulation of Structural Behavior of Tree

The displacement and stress caused to the tree by external force were simulated using FEM. The detailed procedure is as follows (Fig. 2).

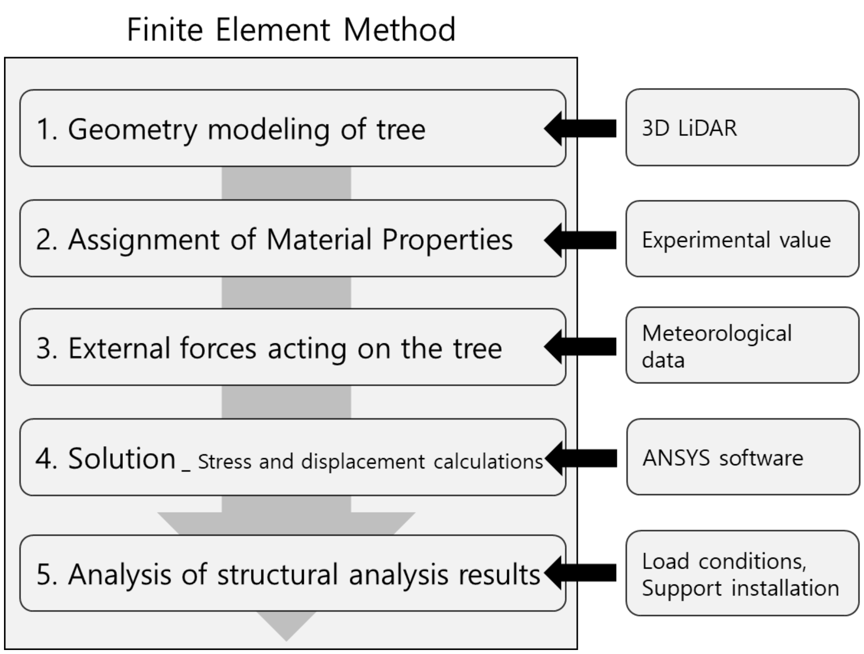


Fig. 2. Procedure to simulate the structural behavior of a tree using the finite element method

Geometric Modeling of Tree

The shape of the case study tree was modeled using 3D scanning technology. To acquire precise structural geometry, a 3D light detection and ranging (LiDAR) (RCT-360, Leica Geosystems AG; Heerbrugg, Switzerland) system was used to collect scanning data. The scanning was conducted between February and March of 2023, when the tree was leafless, to clearly capture its structure and shape. Six scanning positions were set within the tree's crown range, and eight additional positions were taken at a distance of 1.5 to 2 times the tree's crown diameter (Fig. 3). The scanned data (point cloud data) was used to generate the surface of the tree (surface generation) using Geomagic Control software (3D Systems, Rock Hill, SC, USA). The generated surface of the tree was imported into the ANSYS workbench software (2021 R2, ANSYS, Inc., Canonsburg, PA, USA) for analysis as shown in Fig. 4.

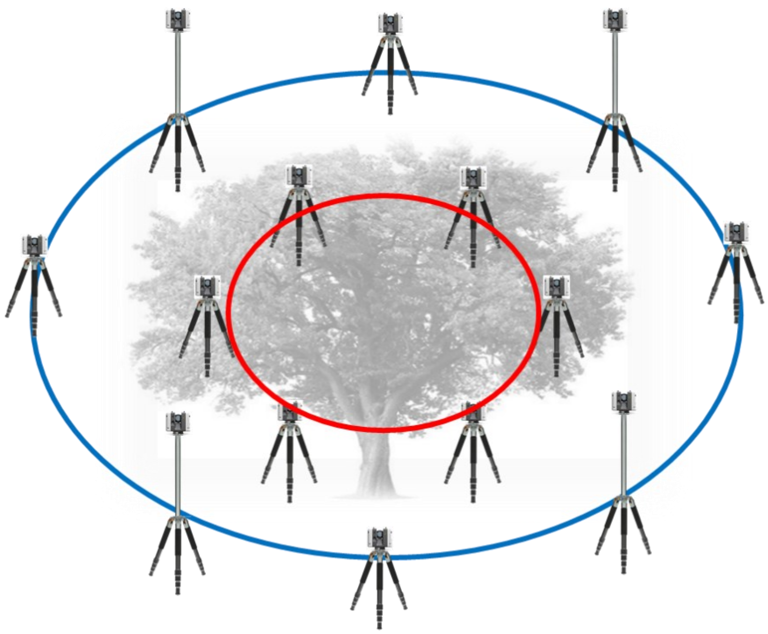


Fig. 3. Scanning position to obtain the geometry of the tree

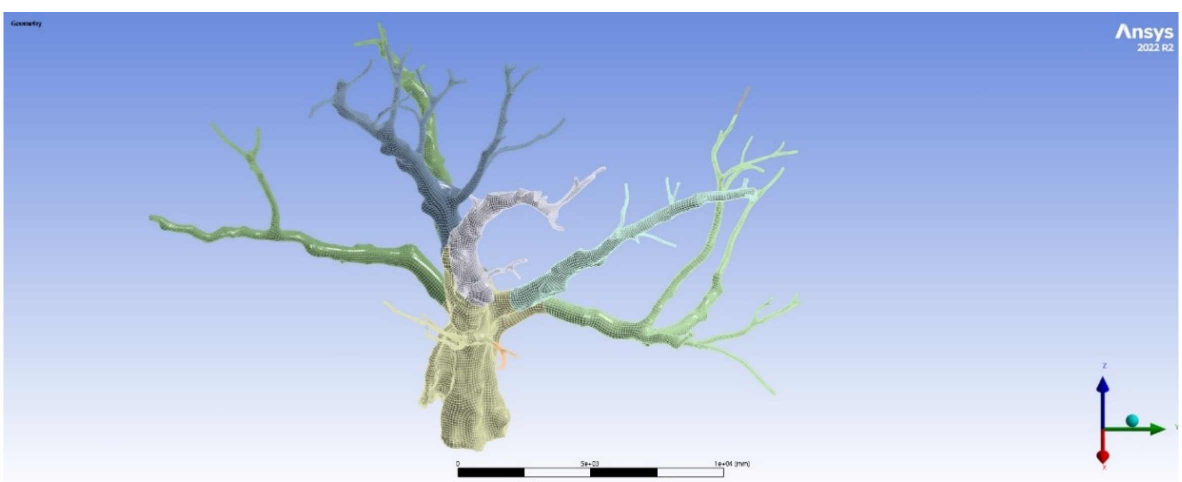


Fig. 4. Scanning position to obtain the geometry of the tree

Assignment of Material Properties

The material properties of the Zelkova tree were assigned separately for the branches and the trunk (Table 1). Although wood is an anisotropic material, several researchers have simplified the model by assuming isotropy to ease the analysis or meet specific experimental conditions. Mattheck and Breloer (1993) used FEM to analyze the shape and stress distribution of the tree, assuming the structure of the tree to be an isotropic material. Jackson *et al.* (2019) also assumed isotropic material properties, ignoring the anisotropic properties that vary along the direction of the wood, to facilitate modeling of wood. It is proposed that the most likely failure of a tree will be the results of tensile or compressive stress that is aligned with the grain direction (strongest direction) of the material. As a corollary, it is assumed that minimal error is introduced by assuming larger than realistic strength properties in the two other orthogonal directions within the material.

In this study, wood was also assumed to behave as an isotropic material. The property values used were tested based on the fiber direction properties of Zelkova wood specimens. Specimens were extracted from both the trunks and branches of Zelkova trees, following the Korean Industrial Standards (KS). The mechanical properties measured included moisture content (KS F2199), bending strength (KS F2208), tensile strength parallel to the grain (KS F2207), compressive strength parallel to the grain (KS F2206), hardness (KS F 2212), and shear strength (KS F2209). For each test, a total of 10 specimens were prepared. All experiments were performed at the Korea Forestry Promotion Institute, and the results are documented in test report numbers 802 and 896 (Korea Forestry Promotion Institute 2016).

Since simulating all real-world conditions is time-consuming and expensive, simulations are often simplified and idealized. Assuming isotropy in material properties allows simple analysis of specific factors under uniform conditions. The anisotropic and nonlinear characteristics of wood can enable more accurate simulations of real-world behavior. This study primarily aimed to evaluate the structural behavior of Zelkova trees following the installation of support systems. While the isotropic assumption simplifies the complex anisotropic nature of wood, it remains sufficient for assessing relative stress patterns and evaluating the comparative performance of various support arrangements.

Table 1. Material Properties of the Zelkova Tree for Simulation

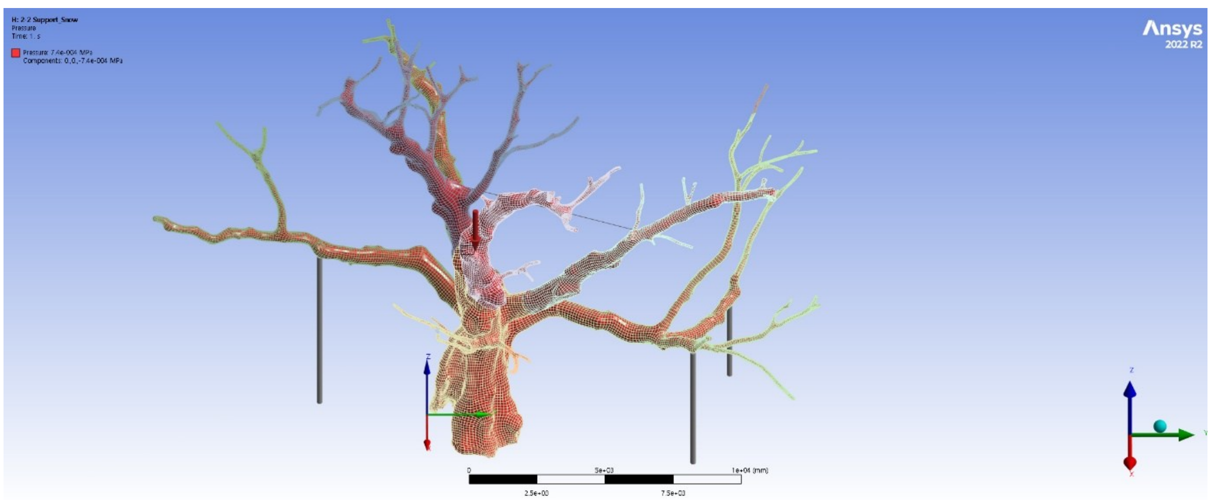
Categories		Trunk	Branches
Strength (MPa)	Tension	87.2	93.4
	Compression	25.4	26.5
	Bending	65.9	69.7
	Shear	8.2	9.3
Modulus of elasticity (MPa)		7554	7464
Hardness (MPa)		33.1	35.5
Moisture content (%)		44.9	49.1

External Forces Acting on the Tree

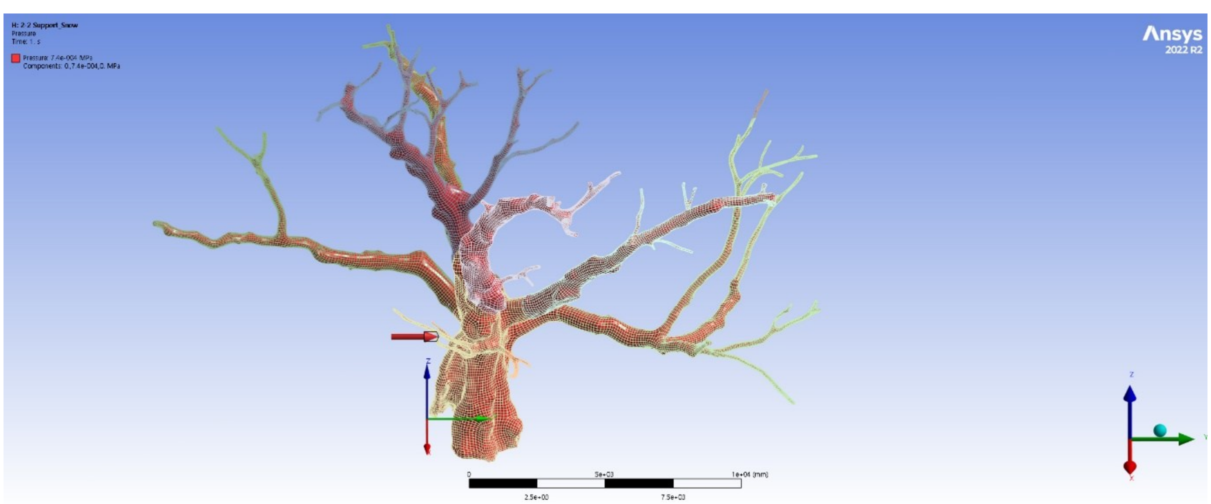
The external forces applied to the Zelkova tree, including gravity (self-weight), snow load, and wind load, were assigned as follows (Fig. 5). Gravity (self-weight) was applied based on the density of the tree's material properties. The snow load was determined based on the maximum snow depth (the deepest snow accumulation within a 24-h period) for the tree location region, as reported by the Korea Meteorological

Administration (KMA) (Table 2).

a) Gravity (self-weight)



b) Snow load



c) Wind load

Fig. 5. Application of external forces on the Zelkova tree

The maximum snow depth was converted to snow load by applying the weight of snow (160 kg/m³) and gravitational acceleration (Eq. 1),

$$Load_{snow} = W_{snow} \times D_{snow} \times g \tag{1}$$

where $Load_{snow}$ is the snow load (N/m^2), W_{snow} is the weight of snow (160 kg/m^3), D_{snow} is the maximum snow depth (m), and g is the acceleration of gravity (9.81 $\mathrm{m/s^2}$). The wind load was determined based on the maximum wind speed of the tree location region provided by the KMA. The wind load was converted to the wind load by applying the wind force coefficient and air density (Eq. 2),

$$Load_{wind} = \alpha \times \frac{1}{2}\,\rho\, V^2 \tag{2}$$

where $Load_{wind}$ is the wind load (N/m^2), α is the wind force coefficient (0.75 for circular sections), ρ is the air density (0.125 kgf·s^2/m^4), and V is the maximum wind speed (m/s)

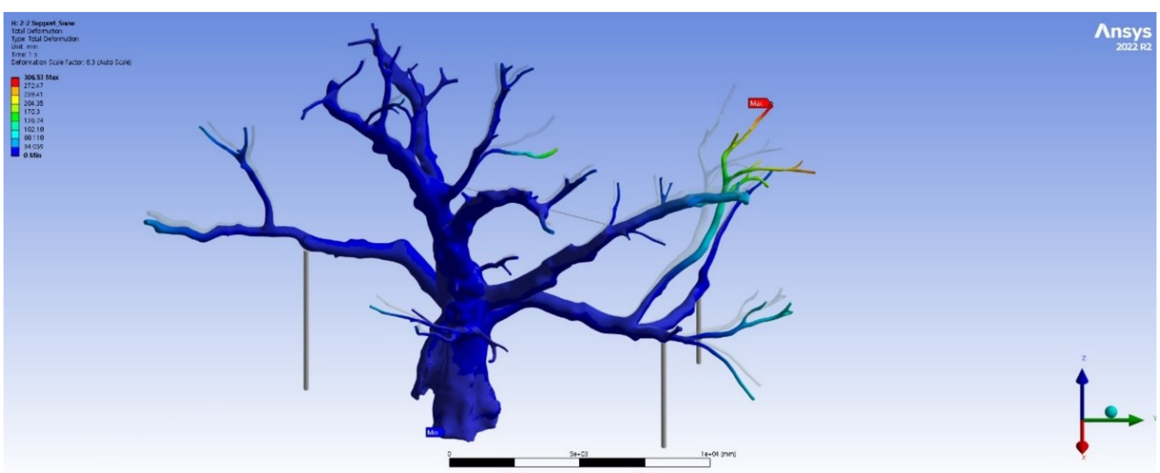
Table 2. Meteorological Observation Data and Observation Station Corresponding to the Tree's Location

Categories	Observed Data	Observation Station
Maximum instantaneous wind speed1) (m/s)	25.82) (2016)3)	Taebaek (1985 to 2022)
Maximum snow depth4) (m)	0.945 (1998)	Taebaek (1985 to 2008)

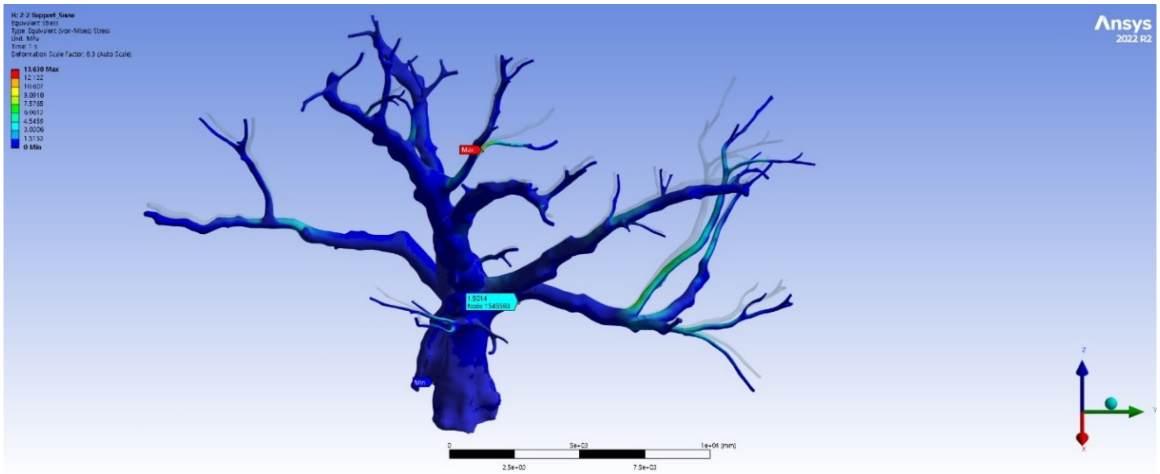
1) Wind speed during the strongest instantaneous gust within a 24-h period (00:00 to 24:00).
2) The wind direction of the measured wind speed was 188° (with 0° representing north and measured clockwise).
3) Parentheses indicate the year the observation data was recorded.
4) The maximum thickness (depth) of snow accumulation.

Analysis of Simulation Results

The FEM solution provides displacement and stress distribution of the tree, as shown in Fig. 6. In this study, the FEM simulation was conducted to analyze the displacement and stress distribution of the Zelkova tree under various load conditions (gravity, snow load, and wind load) to identify the key factors influencing the tree's behavior. Additionally, the effect of support structures was evaluated by simulating the tree with and without the installation of supports.



a) Displacement distribution



b) Stress (von-Mises) distribution

Fig. 6. FEM simulation results of the Zelkova tree

RESULTS AND DISCUSSION

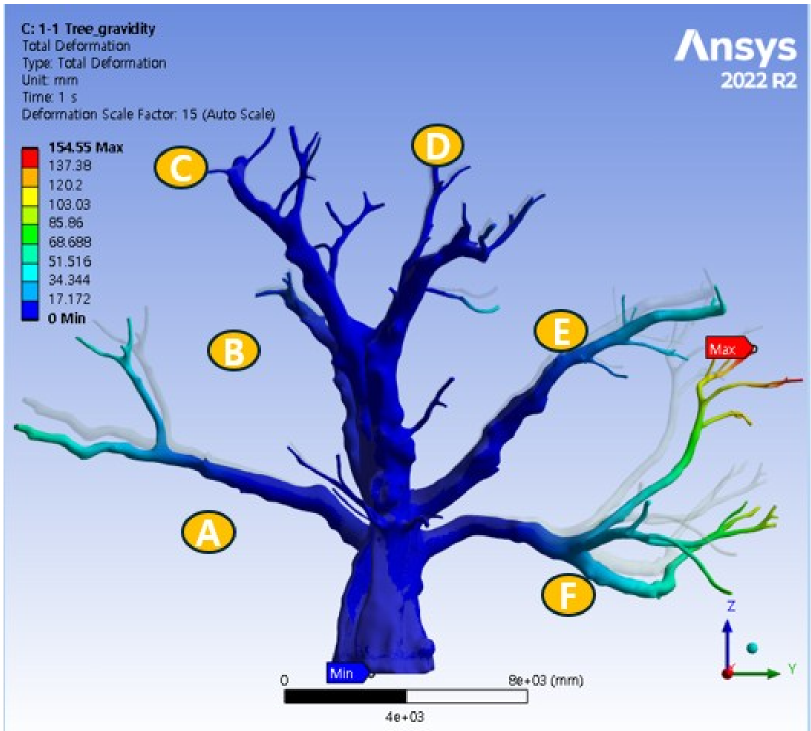
Effect of Gravity Load

Table 3 presents the maximum displacement and stress occurring in the tree under different loading conditions. Figure 7 illustrates the displacement of the tree due to gravity load. For clarity, the six main branches have been labeled from A to F. In the absence of support structures, displacement primarily occurred near the tips of branches A, E, and F, with the maximum displacement (155 mm) observed at the end of a branch extending upward from the secondary junction of branch F. When the current positions of the support structures were taken into account, the maximum displacement of the tree's branches was reduced approximately 42.87%, resulting in a maximum displacement of 88.3 mm.

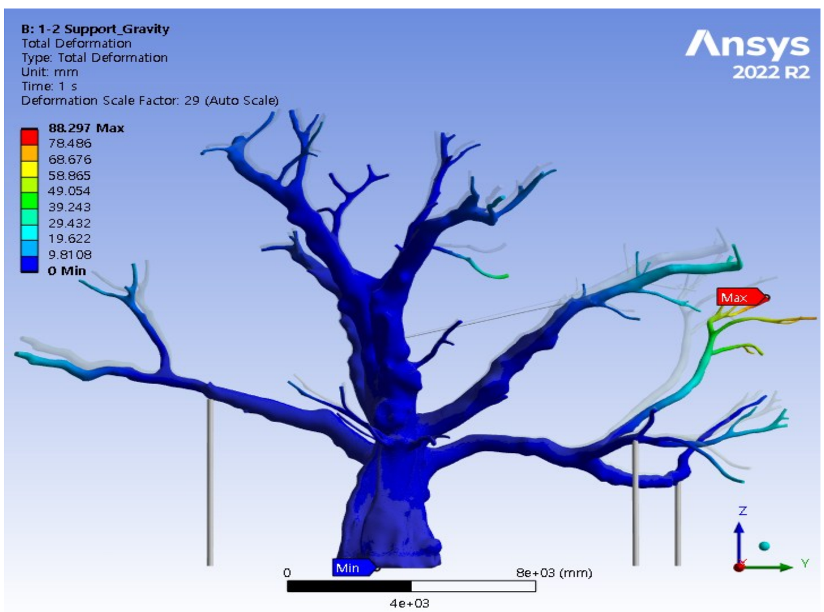
Table 3. Meteorological Observation Data and Observation Station Corresponding to the Tree's Location

Load Conditions	Maximum Displacement (mm)			Maximum Stress (MPa)		
	Without Support	With Supports	Difference[1] (%)	Without Support	With Supports	Difference (%)
Gravity load	154.6 (F)[2]	88.3 (F)	- 42.9	4.92 (F)	0.36 (F)	- 92.7
				3.31 (D)	3.31 (D)	0
Gravity load + Snow load	450.4 (F)	313.5 (F)	- 30.4	13.63 (D)	13.63 (D)	0
				10.28 (F)	1.50 (F)	- 85.4
Gravity load + Wind load	193.7 (F)	132.5 (F)	- 31.5	5.16 (F)	0.82 (F)	- 84.1
				3.86 (F-1)	3.86 (F-1)	0

1) (Without support−With supports) / Without support × 100
2) Parentheses indicate the label of the corresponding branch



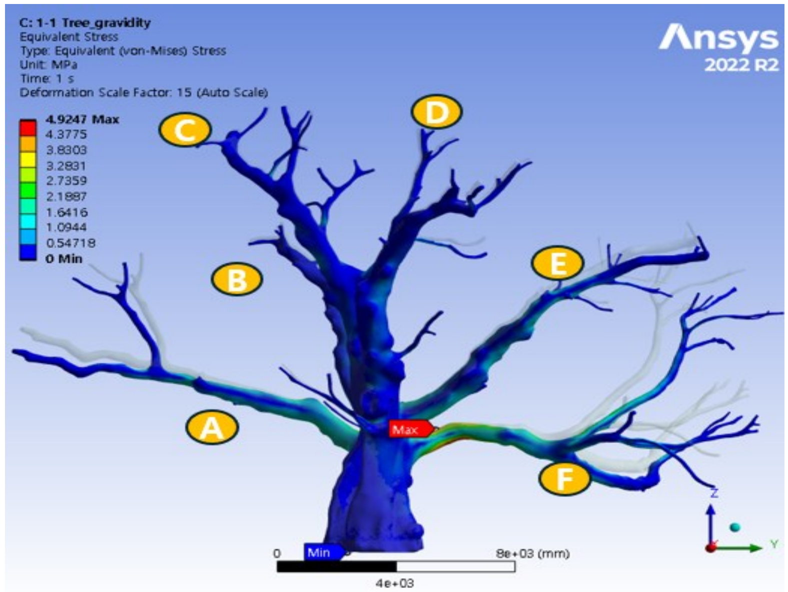
a) Without support



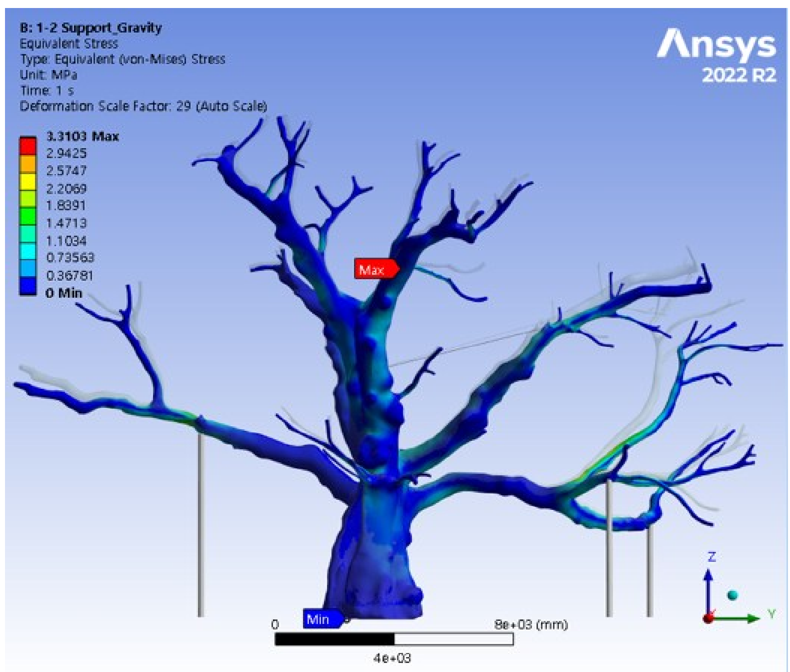
b) With supports

Fig. 7. Displacement of Zelkova tree by the gravity load

Figure 8 shows the stress distribution within the tree under gravity load. Without the support structures, stress was primarily concentrated near the junctions close to the trunk for branches A and F, as well as near the secondary junction of branch F. The maximum stress (4.92 MPa) was observed at the junction of branch F.



a) Without support



b) With supports

Fig. 8. Stress distribution of Zelkova tree by the gravity load

When the current positions of the support structures were considered, the maximum stress in branch F was significantly reduced approximately 92.7%, resulting in a maximum stress of 0.36 MPa (indicated by the blue color). The stress observed in branch D, which lacked support structures, was the highest at 3.31 MPa. In other words, the stress in the branches with support structures was significantly reduced, while the stress in the branches without support structures remained unchanged. This shows that the stress distribution in the tree with an uneven cross-section can be intuitively assessed, which can help determine the optimal location for installing supports.

Effect of Gravity Load with Snow Load

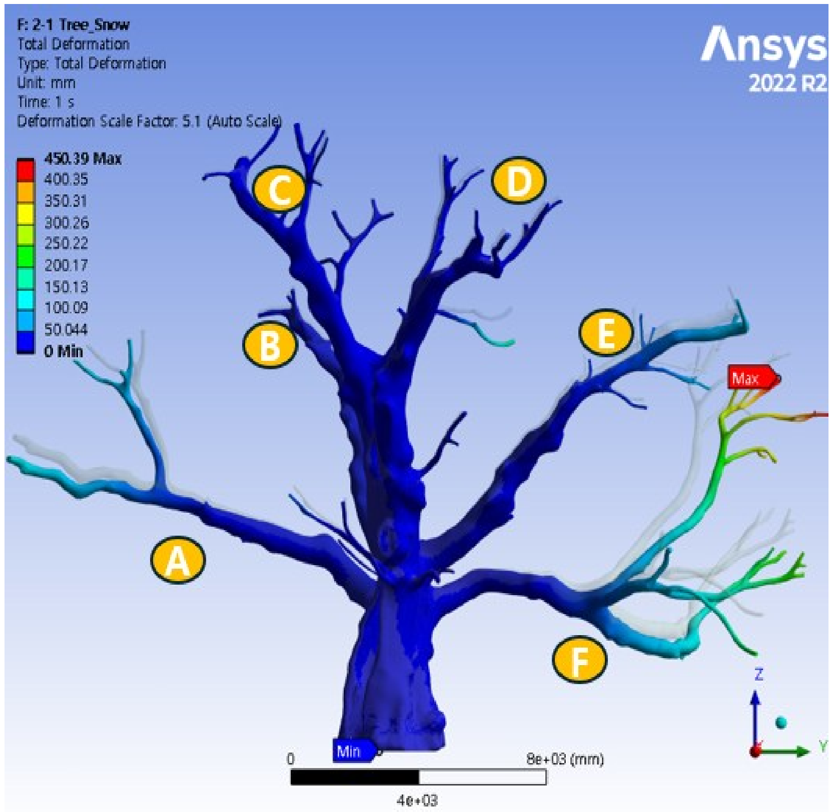
Figure 9 illustrates the displacement of the tree when snow load is added to the gravity load. In the absence of support structures, displacement primarily occurred near the tips of branches A, E, and F. This is similar to the case where only gravity load is applied. The maximum displacement (450 mm) was observed at the end of the branch extending upward from the secondary junction of branch F. This displacement was 2.91 times greater than that under gravity load alone, due to the additional load from snow accumulation.

When the current positions of the support structures were taken into account, the maximum displacement (313.19 mm) occurred in the same position. However, the supports reduced the displacement approximately 30% (137 mm) compared to the situation without support, demonstrating the effectiveness of the support structures.

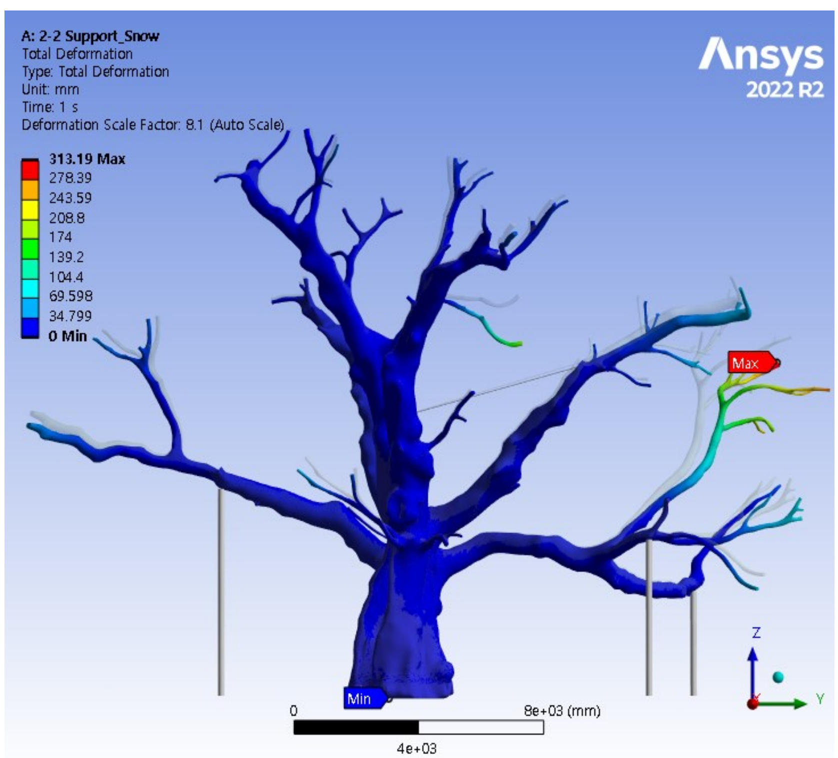
Figure 10 shows the stress distribution within the tree when snow load was added to the gravity load. Without support structures, the stress distribution was similar to that observed under gravity load alone, with stress primarily concentrated near the junctions close to the trunk for branches A and F, as well as at the lower part of the branch extending upward from the secondary junction of branch F. The maximum stress (13.6 MPa) occurred at the upper point of branch D. Notably, the stress near the junction of branch F was 10.3 MPa, which is approximately twice the stress observed under gravity load alone (4.92 MPa), due to the added snow load.

For the branches with support structures, most of the stress levels were indicated by the blue color. This shows that very little stress was generated. Especially, the stress near the junction of branch F decreased from 10.3 MPa to 1.5 MPa after the installation of the support structure, representing a reduction of approximately 85.4%. Thus, the support structures have a significant effect in reducing the overall stress on the tree, even under snow load conditions.

However, in branch A, there was no significant change in the stress generated above the point where the support was installed. The upper part of the point where the support is installed is curved and thinner than the part where the support is attached. That is, the support has the effect of fixing the up-and-down movement of the branch, but because there is no change in the load applied to the upper part of the support, there does not seem to be a significant difference in the change in stress. Similarly, the upper part of the branch extending upward from the secondary joint of branch F also showed little stress change, meaning that this part was not greatly affected by the support structure. Therefore, while support structures are effective in reducing movement and stress distribution at the installation point, they are limited in reducing the load distribution and stresses in branches beyond the installation point. To optimize load distribution and improve overall structural stability, detailed analysis of stress distribution across various parts of the tree is essential. The stress distribution in each part of the tree should be carefully analyzed and the placement of support structures should be planned rationally.

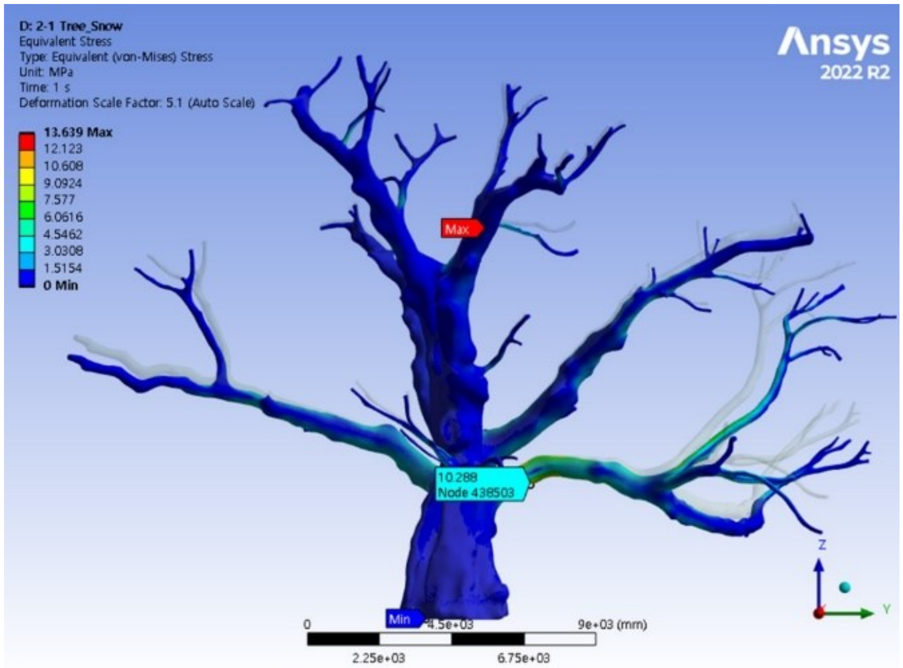


a) Without support

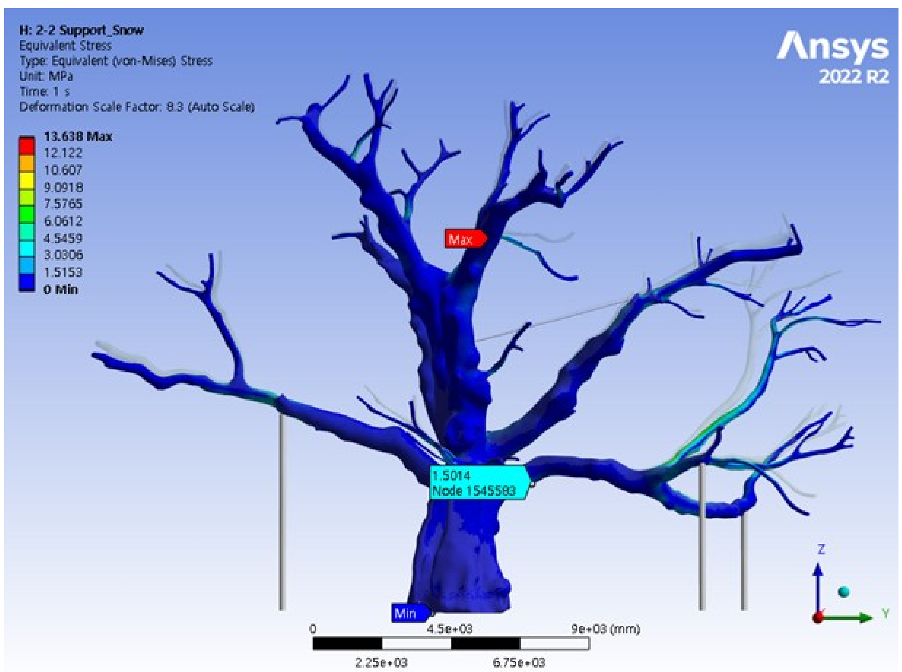


b) With supports

Fig. 9. Displacement of Zelkova tree by the gravity load with snow load



a) Without support



b) With supports

Fig. 10. Stress distribution of Zelkova tree by the gravity load with snow load

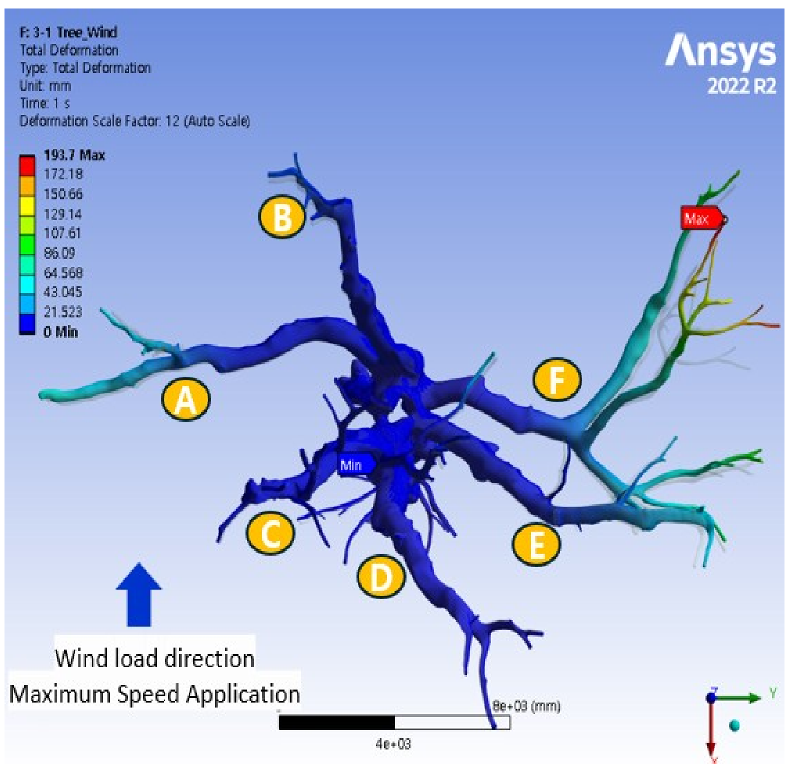
Effect of Gravity Load with Wind Load

Figure 11 illustrates the displacement of the tree when wind load is added to the gravity load. In the absence of support structures, displacement primarily occurred near the tips of branches A, E, and F, with the maximum displacement (194 mm) observed at the end of the branch extending upward from the secondary junction of branch F. This pattern is similar to the displacement observed under combined gravity and snow loads.

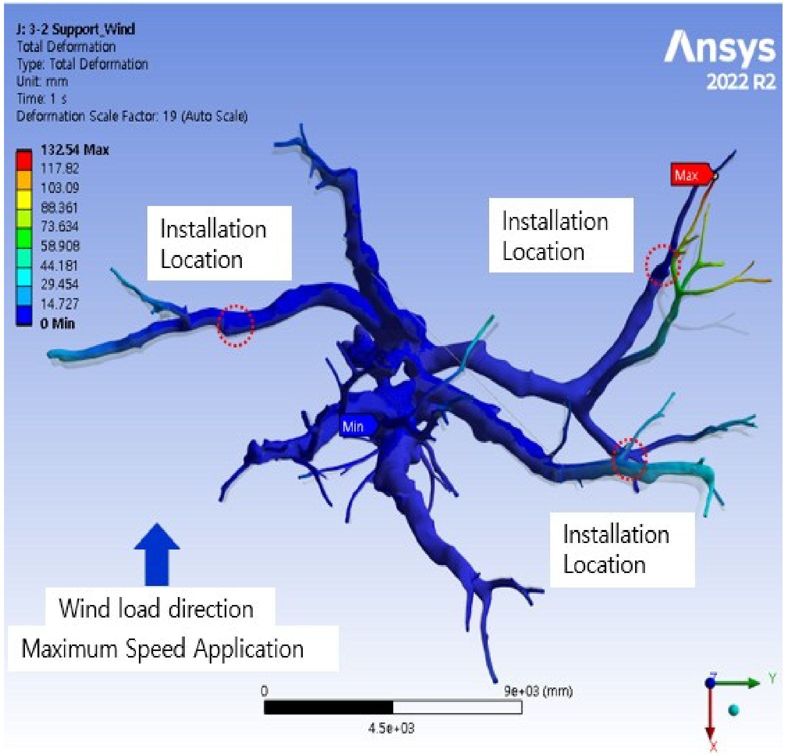
When the current support structure locations were considered, the overall displacement in branches A and F was reduced. Notably, the maximum displacement at the end of the branch extending upward from the secondary junction of branch F decreased approximately 31.6% (61.2 mm), resulting in a displacement of 133 mm.

Figure 12 shows the stress distribution within the tree when wind load was added to the gravity load. Without support structures, stress was primarily concentrated from the junctions near the trunk on branches A and F to the points where the secondary branches begin. The maximum stress (5.16 MPa) was observed near the junction of branch F. When the current support structure locations were applied, the maximum stress near the junction of branch F was significantly reduced to 0.82 MPa (Fig. 12 b), representing an 84.1% reduction. Overall, there was a substantial decrease in stress, particularly around the junctions of branches A and F. The stress in the upward-extending secondary branch (F-1) from F was the highest, reaching 3.86 MPa.

Jeong and Lee (2024) conducted a FEM of four old trees under wind loading conditions (70 m/s) applied in various directions. They reported that the maximum stress ranged from 1.15 to 11.4 MPa, depending on tree geometry and wind direction. This range is comparable to the maximum stress observed in this study, supporting the validity of the present modeling assumptions and stress predictions.

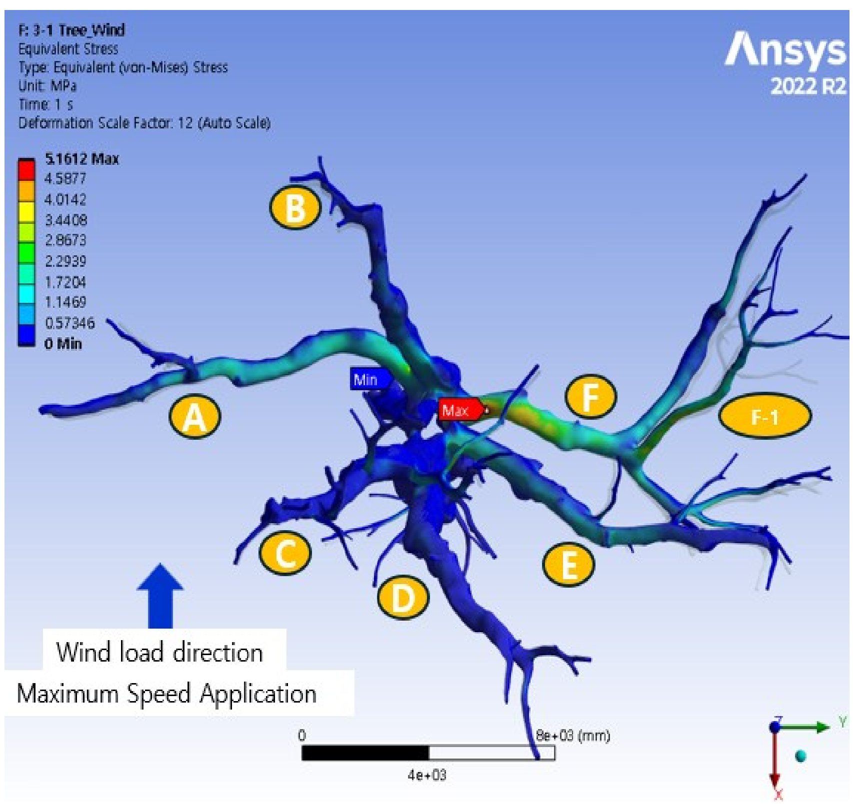


a) Without support

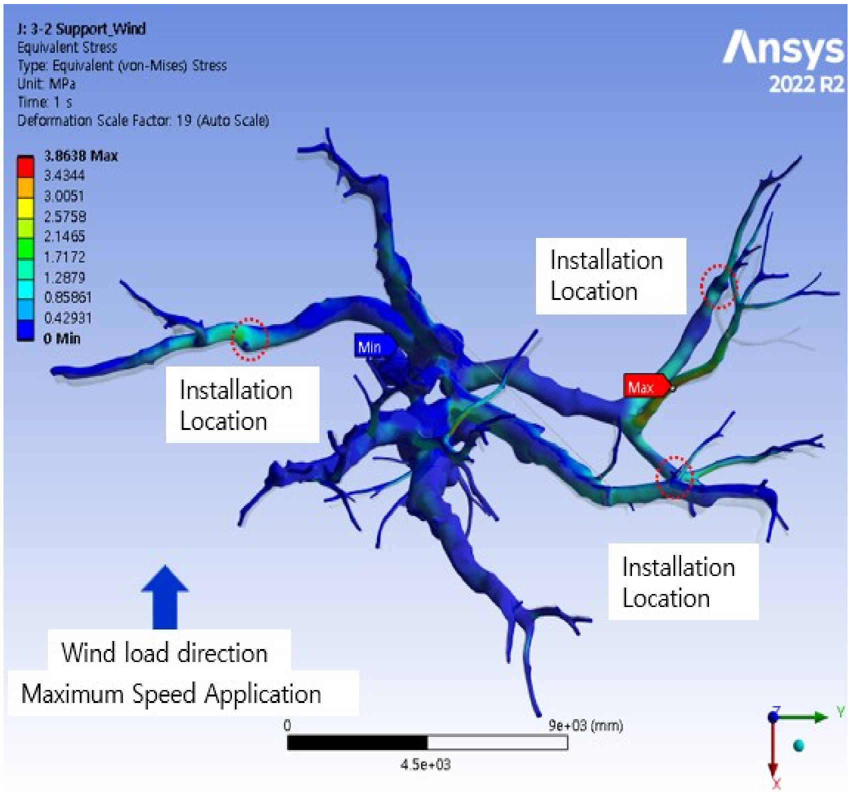


b) With supports

Fig. 11. Displacement of Zelkova tree by the gravity load with wind load



a) Without support



b) With supports

Fig. 12. Stress distribution of Zelkova tree by the gravity load with wind load

Optimization of Reinforcement Facilities and Management Considering Tree Condition

The trunk of the Zelkova tree has a large cavity that is more than 1/3 of the total diameter, which was created when the large southern branch fell off during a climatic event. Such damage is commonly observed in large, old trees. Internal defects, such as heartwood rot within the trunk, significantly weaken the connections between branches and the trunk. Branches may also fall due to shedding collars or incomplete fiber integration caused by irregular growth patterns at branch junctions (Mattheck and Breloer 1994). These junctions serve as critical load transfer zones, and defects in these areas reduce the effective cross-sectional area, making them more prone to failure compared to the branch tips.

The FEM structural analysis results revealed that the largest stress occurred under snow load conditions. Notable bending stress occurred in the lower parts of branches A and F, close to the trunk (Fig. 10 a). Notable bending stress also occurred in the lower parts of branches extending upward from the secondary junction of branch F. Branches C and D, which correspond to cavity dominance, showed almost no bending stress.

To optimize the support location, the structural stability according to the adjustment of the support location was analyzed. When the support was installed in the middle of the A branch, bending stress occurred from the support installation point to the end of the branch, but when the support location was changed to 2/3 of the branch length, the bending stress in the branch decreased overall (Fig. 13). In the case of branch F, there was no effect of reducing stress or deflection due to the installation of the support and cabling between branches B and E in Fig. 10, and there was no effect of reducing stress by adjusting the position of the support. The branch extending upward from branch F has a stable branching angle and branching shape, and no reinforcement facility was applied previously. Therefore, it seems appropriate to observe additional defects and reduce the load through branch pruning rather than installing reinforcement facilities.

Additionally, the natural retrenchment process is currently underway, in which the upper branches of the crown are dying off, allowing the formation of the lower crown. Recently, a significant number of buds have emerged around the upper part of the trunk (above the cavity). This appears to be due to the dieback of the upper branches, which has caused changes in the tree's overall hormonal balance and hydraulic capacity, promoting the growth of these buds in the lower part of the tree. In the future, these buds, which are directly emerging from the trunk, may form the lower crown and potentially replace the upper crown in the long term. Therefore, it is necessary to manage them in a way that preserves these buds rather than removing them.

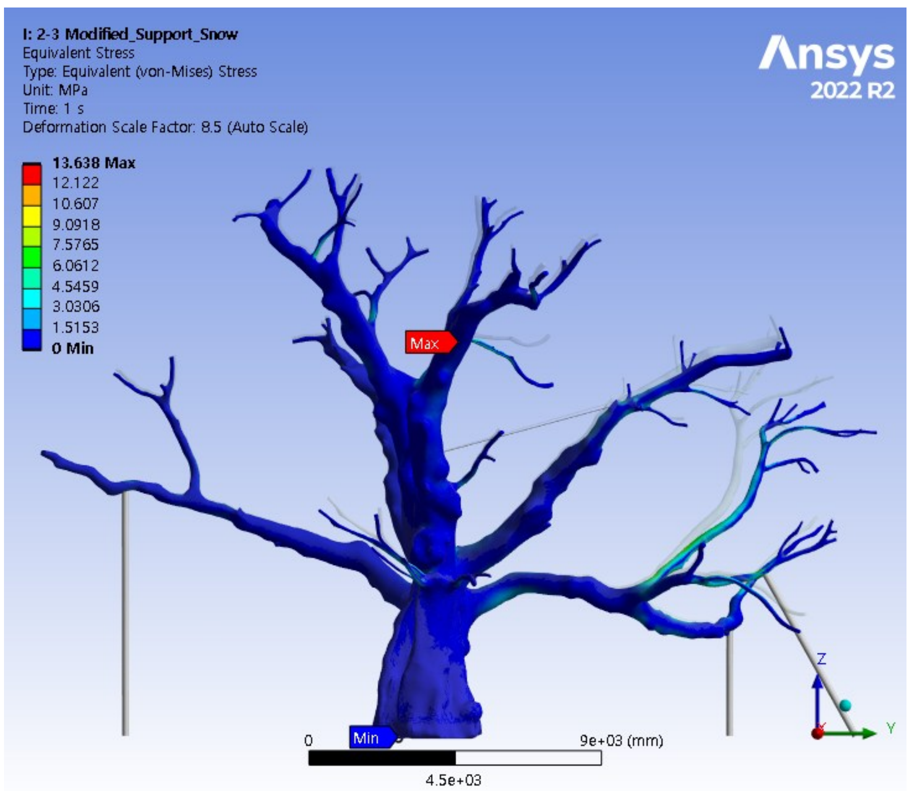


Fig. 13. Stress distribution according to change in support position

The limitations and future work of this study are as follows. First, while the relative stress distribution based on the support structure was analyzed, the internal state of the tree was not accurately reflected. Structural defects, such as heartwood rot, were not considered, which may have resulted in lower stress values than the actual conditions. Therefore, future research should incorporate results from non-destructive testing to better account for internal defects. Second, the contact conditions between the support structure and the branches may differ from the actual conditions, requiring further investigation to accurately represent these interactions. Lastly, to improve the precision of failure predictions for old trees, it is essential to reflect the strength characteristics related to anisotropy and moisture content. Old trees have unique characteristics, such as denser heartwood and reduced moisture content, which influence their mechanical behavior differently from green wood (Frederick *et al*. 1982). As a result, developing a comprehensive database of mechanical properties for old trees is necessary to support these efforts.

CONCLUSIONS

In this study, the structural stability of a Zelkova tree was evaluated using the finite element method (FEM). Based on the FEM results and the current condition of the tree, a management plan and optimization of reinforcement facilities were proposed. The key findings are as follows:

1. The analysis of displacement and stress under gravity load, snow load, and wind load conditions revealed that the largest displacement and stress occurred under the snow load condition. This indicates that the tree is most vulnerable to snow load.
2. The highest stress was observed in branch D (13.6 MPa) under the snow load condition without any support structure. Comparing this maximum stress with the wood strength of the Zelkova tree (bending strength of the branches: 69.7 MPa, as shown in Table 1), it is estimated that the tree has a safety margin of 56.1 MPa.
3. When considering the current support structure positions, branch F, which is supported, showed a reduction in displacement by 30% to 42% and a reduction in stress by 84% to 92% compared to the condition without support. In contrast, branch D, where no support was installed underneath, showed no reduction in deflection or stress.

These results demonstrate that the proper placement of support structures plays a crucial role in enhancing the structural stability of large old trees. However, this study has certain limitations, including the assumption of isotropic wood properties and the exclusion of internal defects such as heartwood rot, which may have led to an underestimation of stress. To address these limitations and improve the accuracy and applicability of future studies, it is recommended to incorporate internal defects through non-destructive testing, consider wood anisotropy and moisture content, and refine the modeling of support-tree interactions. Furthermore, developing practical field guidelines based on these refined models will strengthen long-term conservation strategies for heritage trees.

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Competing Interests

The authors declare they have no competing interest.

Authors' Contributions

Sung-Jun Pang conducted and analyzed the simulation and drafted the manuscript. Ji Sun Jung revised the manuscript, including figures and tables. Gwang Gyu Lee and Jin Ho Shin designed and analyzed the collection of 3D imagery and meteorological data. Ji Won Son managed the research project and approved the final manuscript.

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