*International Journal of Latest Trends in Engineering and Technology*
*Vol.(13)Issue(3), pp.044-049*
*DOI: http://dx.doi.org/10.21172/1.133.07*
*e-ISSN:2278-621X*

# THE TIME HISTORY ANALYSIS OF 200M HONEYCOMB LATTICE DOMES INSPIRED BY NATURE

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**Abstract-The objective of this study is to investigate the dynamic response of 200 m honeycomb lattice domes inspired by nature under seismic ground motion of El Centro and Mexico earthquake. For the investigation of dynamic response of 200m honey lattice domes, the time history analysis is used for the estimation of the earthquake response. The dynamic response of large span lattice domes by the horizontal and vertical combined ground motion cause an asymmetric deformation at the upper part of the dome, and the maximum stresses of the steel member occur when the vertical displacement is maximum. The honeycomb lattice domes are the effective structural system to resist the earthquake ground motion, and is a very convenient structures for installing the ETFE air cushion system.**
**Keywords – 200m honeycomb lattice dome, Dynamic response, Earthquake ground motion, Time history analysis**

## 1. INTRODUCTION

The hexagon structure of the honeycomb is also a stable system that distributes the equilibrium balance for external forces. The triangular structure requires a lot of material, and a square structure is easily prone to deform and collapse by an external impact. It has been argued that beehives are made up of elaborate hexagons, not because bees are excellent architects, but because they are the result of the equilibrium of physical forces of nature. The hexagon of the honeycomb is naturally made hexagonal to ensure optimum space. Bees first make a honeycomb of a circle, but after a certain amount of time they turn into hexagons by surface tension. Therefore, the hexagonal structure of the honeycomb has been applied not only to buildings but also to various industrial fields. For example, the corrugated board of a box has a hexagonal cross-section, which is light and stronger for external forces. In addition, the shock absorber called a honeycomb panel installed at in front of the high-speed train has a hexagonal structure like a honeycomb.

In this study, the authors propose a system of a large space dome composed of a hexagonal structure using steel members inspired by a honeycomb in nature, and analyze the stability of dynamic response by analyzing the time history of earthquake ground motion. The horizontal earthquake ground motion during an earthquake causes a large asymmetric vertical deformation of the lattice dome. The dynamic response of buildings for earthquake ground motion is most efficient through time history analysis. In the dynamic response characteristic of the large space structure, the response in the vertical direction is important to structural behaviors for the horizontal and vertical ground motions. Therefore, in case of seismic design of large space structure, the time history combining the horizontal seismic response and the vertical seismic response is evaluated during the seismic design. Therefore, it is necessary to evaluate the combined earthquake ground motion with 3-dimensional motion according to the system of the structure through time history analysis for seismic resistance design against earthquake. Time history analysis is to obtain the solution of the dynamic equilibrium equation when the dynamic load acts on structure, and can evaluate the structure behaviors (displacement response, velocity response, acceleration response, member forces, etc.). Using the mode superposition method and the direct integration method, the damping matrix consists of a combination of mass matrix and stiff matrix. In this study, displacement response, acceleration response, member forces, and stresses of a 200 m single layer lattice dome with a hexagonal structure are analyzed by applying the ground motion to an El Centro earthquake which has the characteristics of a hard soil and Mexico earthquake with the characteristics of soft soil.

The studies of large space lattice dome are follows. The buckling behavior of a single-lattice dome under vertical loads was studied by S. Oya, Y. Hangai and K. Kawaguchi (2000). The experimental study was performed and compared with the results of the nonlinear analysis. The buckling equation for a single-layered lattice dome was proposed and compared with the results of plastic hinge analysis. It was investigated the buckling load of the lattice dome for various rises/span ratio. The results of continuum theory, eigenvalue analysis, and geometric nonlinear analysis were compared. The results of geometric nonlinear analysis are lower than those of linear eigenvalue analysis. The proposed continuity theory proves that the buckling load of the single-layer lattice dome can be analyzed [1]. S. Kato, S. Nakazawa, M. Uchikoshi, and Y. Mukaiyama (2000) studied the effect of the 300m lattice dome with seismic isolation system under Kobe earthquake. The dynamic response analysis of the dome with a seismic isolation system was performed by analyzing the time history of the lattice dome

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composed of triangular structures. LRB isolation devices can significantly reduce dynamic response due to earthquake ground motion [2]. T. Saka, Y. Taniguchi and T. Konishi, (2000) studied the buckling behavior of a double-layered lattice dome [3]. Recently, H. Kim and J. Kang (2016) conducted analytical studies on the seismic response of various lattice domes. The seismic response analysis of the lattice dome according to the earthquake has been carried out to investigate the effect of the damping device to control the dynamic behavior of the structure [4]. K. Park, M. Jung and W. Lee(2018) analyzed the time history of the seismic response of 300m single-layered lattices dome with LRB isolation system, and found that the reducing effect of seismic isolation system on dynamic behavior of the domes. It is analyzed the dynamic responses for the case with only the upper dome structure and the case with the lower structure. It is studied the case where the upper part of the dome is open and the case where a retractable cable structure is installed. LRB isolation system contributes significantly to reducing the dynamic response of the domes [5]. Richard Liew, J. Y. (2018) presented the structural system and design method for large space structures in Singapore. The spatial lattice domes have been conducted to investigate the dynamic response of the lattice dome to one-directional earthquake ground motion, and the horizontal and vertical earthquake ground motion. In this study, the dynamic response of the 200m honeycomb lattice domes under the El Centro and the Mexico earthquake will be analyzed through time history analysis for the combined seismic ground motion in the horizontal and vertical directions.

## 2. THE BUCKLING ANALYSIS AND EIGENVALUE ANALYSIS OF 200M HONEYCOMB LATTICE DOMES.

The study is performed elastic analysis, buckling mode analysis, and nonlinear analysis for vertical load. Figure 1 is the results of elastic analysis for vertical loads. The maximum deflection is 167 mm, the maximum compressive force of the member is -2,462 kN, the bending moment My is 384 kN-m, and the maximum stress is 140 MPa. Figure 2 is the result of the buckling mode analysis and the maximum joint load in the first and second buckling modes is 1,185 kN. Figure 3 shows the results of the nonlinear analysis assuming that the end of the steel member is a elasto-plastic spring. As a result of the nonlinear analysis of the dome under the central load, the maximum joint load is 850kN, and the maximum joint load when the full loading on the dome is applied is 900 kN. At the joint load of 800 kN, the displacement was reversed due to the geometry by the deformation of the dome.

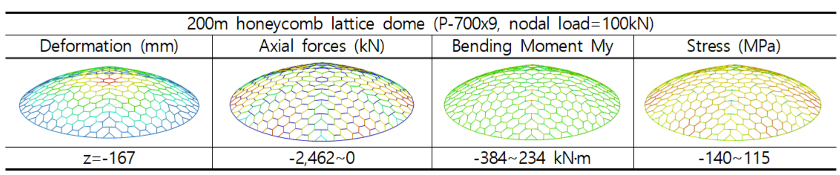



Figure 1. The static analysis for 200 m honeycomb lattice dome under vertical load

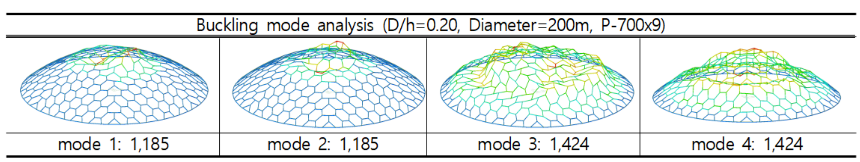



Figure 2. The buckling mode analysis for 200 m honeycomb lattice dome under vertical load

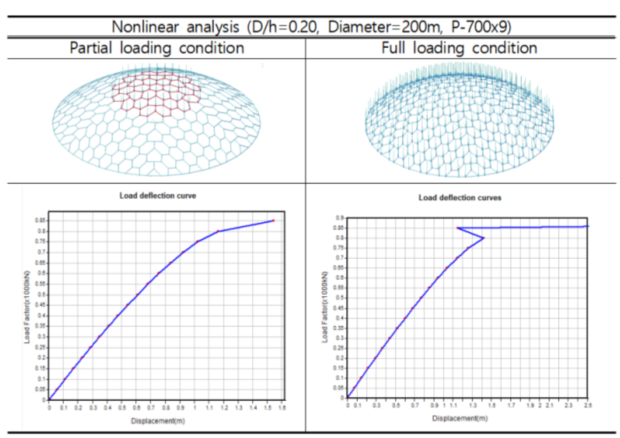



Figure 3. The nonlinear analysis for 200m honeycomb lattice dome under vertical load

Figure 4 is the analysis of the eigenvalue mode and period of the 200 m honeycomb lattice dome. The shape of the mode depends on the joining method of members and global geometry. The first and second period are 1.2041, the 3rd and 4th period are 0.8688, and the 5th and 6th period are 0.6717. The 1st to 4th period is an S-shaped mode in which the upper part of the dome is deformed in an asymmetric shape, and the 5th and 6th mode are a mode in which the upper part of the dome vibrates up and down. The seventh mode is a mode that deforms upward. The 10th, 20th, 50th, and 100th mode are oscillating up and down.

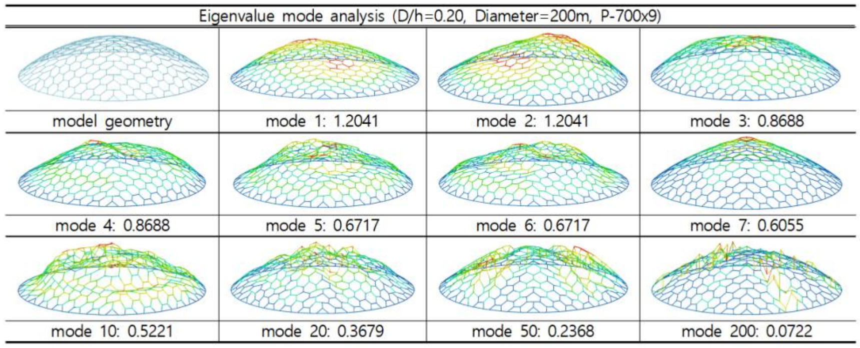



Figure 4. The eigenvalue analysis for 200 m honeycomb lattice dome

## 3. TIME HISTORY ANALYSIS OF 200M HONEYCOMB LATTICE DOMES

*3.1 The earthquake response analysis for the ground motion of El Centro 270 degree (PGA=0.3569 gal)*

The dynamic response of the proposed honeycomb lattice domes under ground motion of El Centro 270 degree is analyzed by applying the earthquake response history. The peak ground acceleration is 0.3569 gal. Figure 5 shows the deformation and stress status of the lattice dome by the dynamic analysis. Figure 6 is the results of the time history analysis of the 200 m honeycomb lattice dome and shows deformation, axial force, bending moment and stresses at 6.69sec. In the analysis, seismic ground motion of El Centro 270 degree is applied. The vertical deformation is the largest at 6.69 sec. The vertical displacement at this time is 257 mm, the compressive force is -1,931kN, and the stress is 343 MPa. The vertical displacement (z=-257 mm) is larger than the horizontal displacement (y=84mm). Figure 7 is the time history of the horizontal displacement response (-66~84 mm) of the honeycomb lattice dome, and Figure 8 is the vertical displacement response (-257~ 247 mm). Figure 9 is the horizontal acceleration response (-424~383 gal) and Figure 10 is the vertical acceleration response (-1,045~1,124 gal), which is much higher than the horizontal acceleration. Similar to the history characteristics of the El Centro earthquake ground motion, the dynamic response was greatly increased in the early part before 20 sec and after 20 seconds the dynamic response gradually decreased.

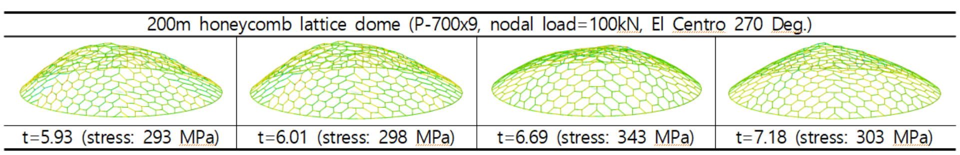



Figure 5. The results of time history analysis for 200 m honeycomb lattice dome

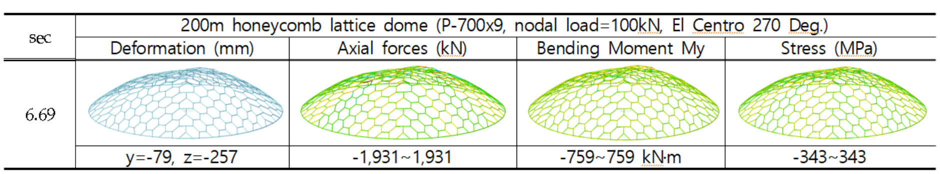



Figure 6. The results of time history analysis for 200 m honeycomb lattice dome at 6.69 sec

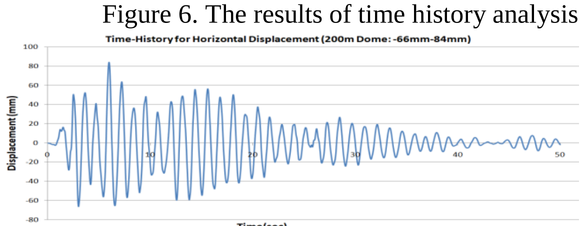



Figure 7. Horizontal displacement response

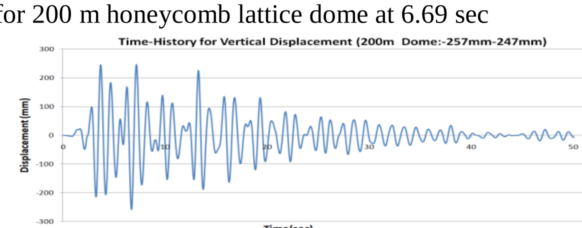



Figure 8. Vertical displacement response

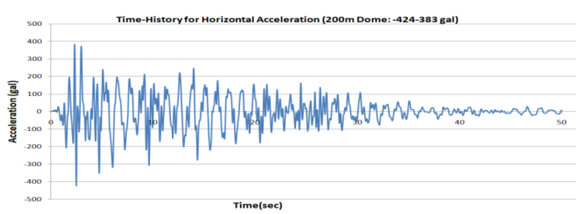



Figure 9. Horizontal acceleration response

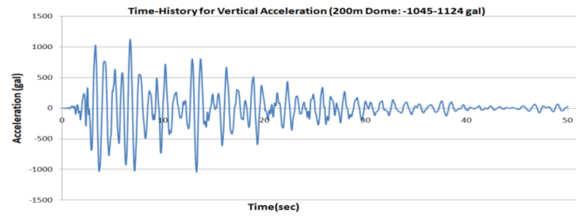



Figure 10. Vertical acceleration response

*3.2 The earthquake response analysis for the up and down ground motion of El Centro earthquake*

Figure 11 is the status of the deformation and stresses of the lattice dome by up and down seismic ground motion. Figure 12 is the results of time history analysis of the 200 m honeycomb lattice dome and shows deformation, axial force, bending moment and stresses of members. The vertical deformation was the largest at 3.87 sec. The maximum vertical displacement at this time is 48.3 mm, the compressive force is 763 kN, and the maximum stress is 56 MPa. Figure 13 shows the time history of the vertical displacement response(-48~40 mm), and Figure 14 is the vertical acceleration response (-554~670 gal).

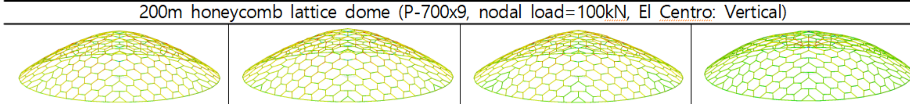
| 200m honeycomb lattice dome (P-700x9, nodal load=100kN, El Centro: Vertical) | | | |
|---|---|---|---|
|  | | | |
| t=3.52 (stress: 31 MPa) | t=3.54 (stress: 34 MPa) | t=3.56 (stress: 3.56 MPa) | t=3.87 (stress: 56 MPa) |

Figure 11. The results of time history analysis for 200 m honeycomb lattice dome

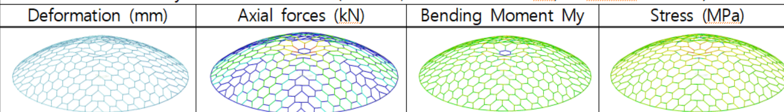
| sec | 200m honeycomb lattice dome (P-700x9, nodal load=100kN, El Centro: Vertical) | | | |
|---|---|---|---|---|
| | Deformation (mm) | Axial forces (kN) | Bending Moment My | Stress (MPa) |
| 3.87 |  | | | |
| | z=-48.3 | -763~0 | -109~73 kN·m | -56~33 |

Figure 12. The results of time history analysis for 200 m honeycomb lattice dome at 3.87 sec

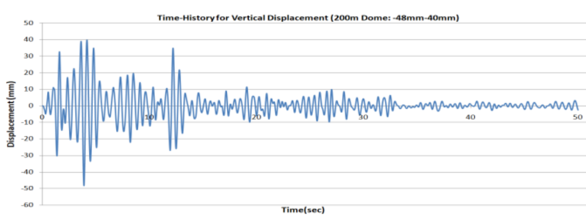



Figure 13. Vertical displacement response

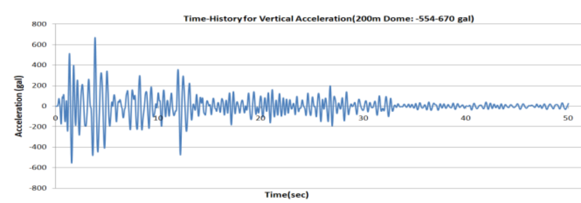



Figure 14. Vertical acceleration response

*3.3 The earthquake response analysis for the 3-dimensional ground motion of El Centro earthquake*

Figures 15 and 16 are the global deformation, the axial force, the bending moment and the stresses of the members as a result of the time history analysis of the El Centro earthquake ground motion (270D+0.3x180D+UD). And the vertical displacement was 264 mm at 6.69 sec, the axial force is -1,896~1,985 kN, the bending moment is -775~781 kN.m, and the maximum stress is 349 MPa. Figures 17 and 18 are displacement responses (horizontal: -82~80 mm, vertical: -242~264 mm), and Figures 19 and 20 are acceleration responses (horizontal: -500~476 gal, vertical: -1,201~1,049 gal). When the vertical displacement is the largest, the stress of the member is the largest, and the mode at this time is an asymmetric S-shaped deformation

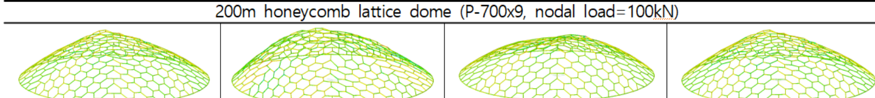
| 200m honeycomb lattice dome (P-700x9, nodal load=100kN) | | | |
|---|---|---|---|
|  | | | |
| t=3.64 (stress: 323 MPa) | t=5.99 (stress: 298 MPa) | t=6.69 (stress: 349 MPa) | t=7.21 (stress: 315 MPa) |

Figure 15. The results of time history analysis for 200 m honeycomb lattice dome

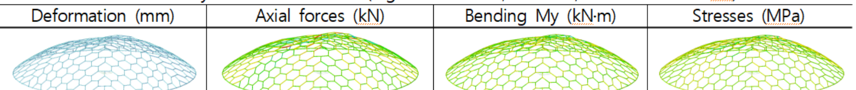
| sec | 200m honeycomb lattice dome (Rigid connection, P-700x9, nodal load=100kN) | | | |
|---|---|---|---|---|
| | Deformation (mm) | Axial forces (kN) | Bending My (kN·m) | Stresses (MPa) |
| 6.69 |  | | | |
| | y=-78, z=264 | -1,896~1,985 | -775~781 | -349~348 |

Figure 16. The results of time history analysis for 200 m honeycomb lattice dome at 6.69 sec

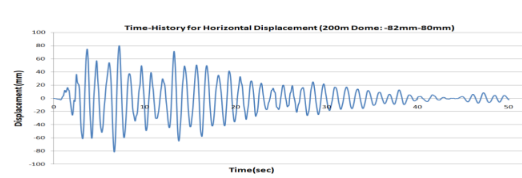



Figure 17. Horizontal displacement response

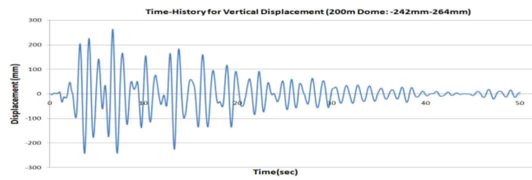



Figure 18. Vertical displacement response

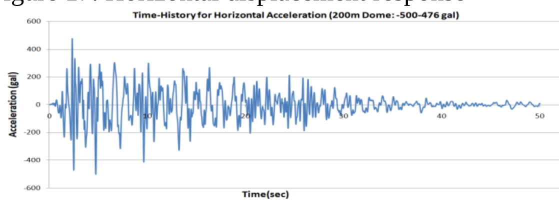



Figure 19. Horizontal acceleration response

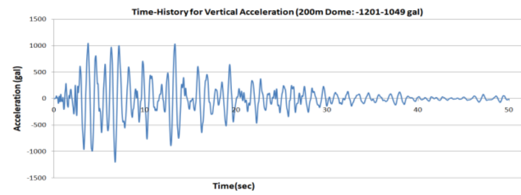



Figure 20. Vertical acceleration response

*3.4 The earthquake response analysis for the ground motion of Mexico earthquake (180 Degree)*

Figure 21 shows the deformation and stress status at the arbitrary time of the earthquake. Figure 22 is the deformation of the whole dome, the axial force, the bending moment and the stresses of the member by the time history analysis of the 200m honeycomb lattice dome for the Mexico earthquake. At 58.99 sec, the vertical displacement was the largest. The axial force at this time is -1,440 to 1,440 kN, the bending moment is -403 to 403 kN-m, and the maximum stress is 175 MPa. Figures 23 and 24 are displacement responses (horizontal: -58 ~ 47 mm, vertical: -74~92 mm), and Figures 25 and 26 are acceleration responses (horizontal: -206~257 gal, vertical: -198 ~ 217 gal). When the vertical displacement is large, the stress is the largest, and the mode at this time is an asymmetric S-shaped deformation.

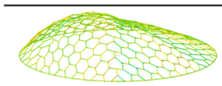
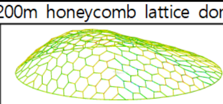
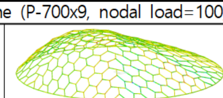
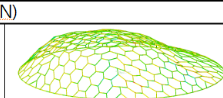
| 200m honeycomb lattice dome (P-700x9, nodal load=100kN) | | | |
|---|---|---|---|
|  |  |  |  |
| t=51 (stress: 97 MPa) | t=58.98 (stress: 175 MPa) | t=58.99 (stress: 175 MPa) | t=61.63 (stress: 65 MPa) |

Figure 21. The results of time history analysis for 200 m honeycomb lattice dome

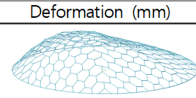
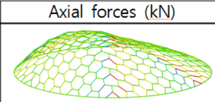
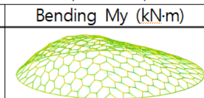
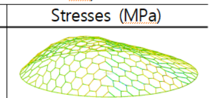
| sec | 200m honeycomb lattice dome (Rigid connection, P-700x9, nodal load=100kN) | | | |
|---|---|---|---|---|
| | Deformation (mm) | Axial forces (kN) | Bending My (kN·m) | Stresses (MPa) |
| 58.99 |  |  |  |  |
| | x=-58, z=92 | -1,440~1,440 | -403~403 | -175~175 |

Figure 22. The results of time history analysis for 200 m honeycomb lattice dome at 58.99 sec

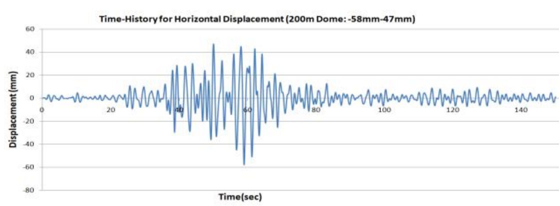



Figure 23. Horizontal displacement response

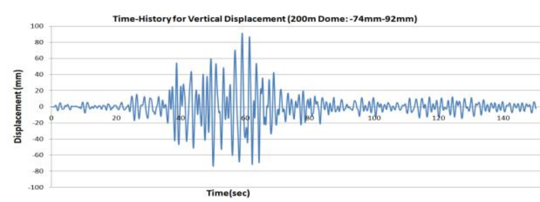



Figure 24. Vertical displacement response

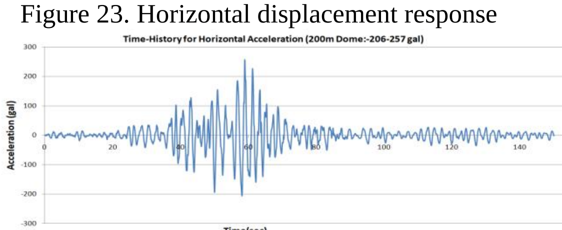



Figure 25. Horizontal acceleration response

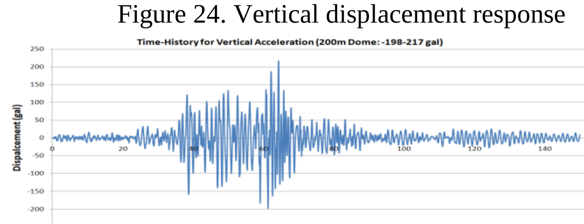



Figure 26. Vertical acceleration response

*3.5 The earthquake response analysis for the combined ground motion of Mexico earthquake (180 D+0.3x270D)*

Figure 27 is the deformation and stress status at the arbitrary time during the combined ground motion of Mexico earthquake. Figure 28 is the global deformation, axial force, bending moment and stresses of the member as a result of the time history analysis of the 200 m honeycomb lattice dome. The vertical displacement was the largest at 58.99 sec. The axial force at this time is -1,461~1,461 kN, the bending moment is -404~404 kN-m, and the maximum stress is 177 MPa. Figures 29 and 30 show the displacement response (horizontal: -58~47 mm, vertical: -92~75 mm), and Figures 31 and 32 show the acceleration response (horizontal: -207~257 gal and vertical: -216~199 gal).

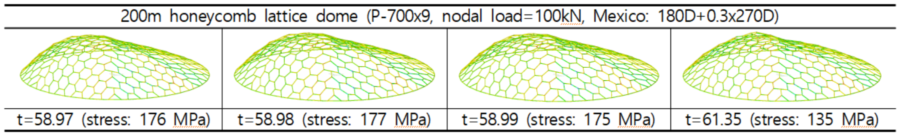



Figure 27. The results of time history analysis for 200 m honeycomb lattice dome

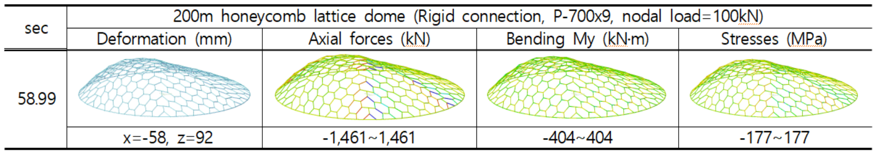



Figure 28. The results of time history analysis for 200 m honeycomb lattice dome at 58.99 sec

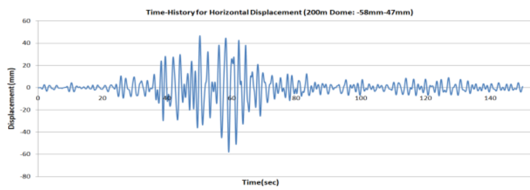



Figure 29. Horizontal displacement response

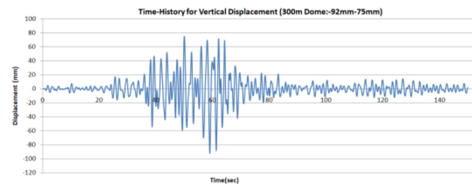



Figure 30. Vertical displacement response

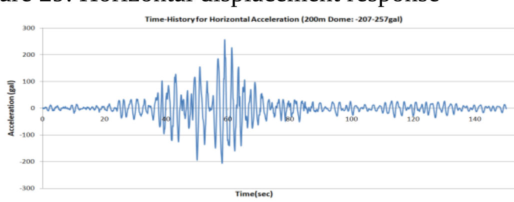



Figure 31. Horizontal acceleration response

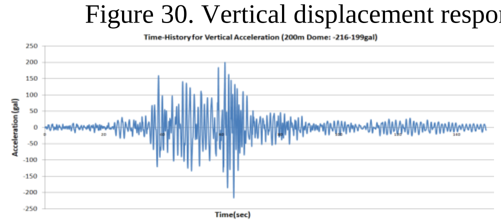



Figure 32. Vertical acceleration response

## 4. CONCLUSION

In this study, the dynamic response characteristics (displacement response, acceleration response, member strength, stress, etc.) were analyzed by performing time history analysis on a 200m honeycomb lattice dome inspired by nature.

(1) The honeycomb lattice dome showed a large S-shaped asymmetric deformation in vertical direction due to earthquake ground motion, and maximum stress occurred when vertical displacement was maximum. A lattice dome composed of a hexagonal structure is a very effective structural system for resisting earthquake ground motions, and the hexagonal lattice dome is an efficient structure for installing the ETFE air cushion system.

(2) Vertical displacement increased by 2.7% and vertical acceleration decreased by 6.5% in the comparison of earthquakes in one direction ground motion (270 Deg.) and the combined ground motion with three directions (270D+0.3x180D+UD) of El Centro earthquake.

(3) For Mexico earthquakes, almost similar dynamic responses were observed in the comparison of one-direction earthquake (180 Deg.) and two-direction earthquakes (180D+0.3x270 D).

## 5. ACKNOWLEDGEMENTS

This research was supported by a grant (19AUDP-B100343-05) from Architecture & Urban Development Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

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