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The Time History Analysis of 300m Honeycomb Lattice Domes with Hexagonal Structure

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Abstract-The objective of this study is to investigate the dynamic response of 300m honeycomb lattice domes under seismic ground motion of El Centro and Mexico earthquake. For the investigation of dynamic response of 300m honeycomb lattice domes, the time history analysis is used for the estimation of the earthquake response. The lattice domes cause an asymmetric deformation and maximum stresses by the horizontal and vertical combined ground motion. The 300m honeycomb lattice dome is the effective structural system to resist the ground motion of Mexico earthquake, but the stresses of the dome cause over 400MPa at asymmetric mode for the El Centro earthquake. Compared with the horizontal ground motion of El Centro earthquake, the vertical displacement was increased 4.6%, and 12.4% for the vertical acceleration by 3-dimensional earthquake ground motion.
Keywords – 300m honeycomb lattice dome, Seismic ground motion, Time history analysis, Dynamic Response

I. INTRODUCTION

The hexagonal structure can be found in honeycomb shapes in snowflake, turtles, fly eyes, giraffe skin and diamond crystals. The hexagonal structure is one of the most economical structures to make the maximum space with the minimum material. It is also a stable structure that delivers the balanced force. The triangle structure requires a lot of material and the space for use is narrow. Square structure is easily distorted and deformed, and hexagons structure has shapes in which external forces are dispersed. The circle structure has the largest width when the perimeter is constant, but if you attach it, an empty space is created. The atom of gold is hexagonal crystal. DNA is twisted into a double helix of hexagons. Carbon nano-tubes are also hexagonal. The hexagonal structure of nature has evolved into the structure for the use of least energy. The snowflake's crystals show a combination of symmetry, the symmetric phase is the result of the hexagonal structure of ice, and the snow falling through the atmosphere changes a crystal shape by free motion. The crystals of the snowflake are composed of star-shaped plates, etc. and grow symmetrically. The physical mechanism that governs the growth of snowflakes by temperature, humidity, pressure, and density is one of the most optimized forms in nature. Many nature-inspired buildings diversify the city's landmark and beautiful city's images to provide a more optimal residential environment. Natural inspiration architecture is that takes into consideration the relationship between architecture and the natural environment as positively as possible, as a way to realize a human society that is intimate with nature and sustainable. Based on knowledge and understanding of the processes and mechanisms of natural ecosystems, it can be created ecologically urban environments and new ideas from many of the mysterious elements of nature.

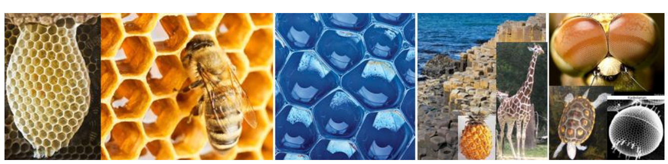
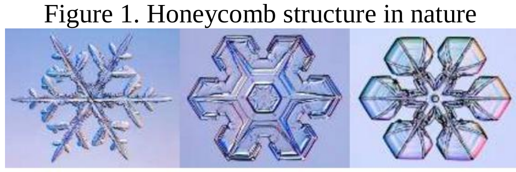


Figure 1. Honeycomb structure in nature



https://math.mit.edu/research/highschool/primes/materials/2014/Li-Jessica.pdf

Figure 2. Snowflake: (a) Stellar dendrite (b) Stellar plate (c) Sectored plate

The botanical garden of Eden Dome in the UK is the world's famous greenhouse and an eco-friendly educational architecture that interconnects humans and nature. A new model of community promotion and tourism revitalization through specialized plants of local area was arranged considering the relationship between human and nature in various climate zones of the earth. The main objective is to educate the importance of sustainable bio-environment through plant education for future generations. It is applied a number of innovative ideas to create a diverse array of biodiversity around the world for tropical plants, and humid wetland plants. The bio-dome design is inspired by the honeycomb structure and is mechanically very stable, so the large space dome does not need internal columns for a span of 240m. All of the unit frame structures that make up the hexagonal grid-type network were easily transported to the site as a unit assembly system. In terms of energy efficiency, hemispherical domes help maintain the heating required for humid tropical plants. This is because spherical domes have the largest volume compared to other forms. The ETFE film is a very light material and has very good sunlight transmittance, helping the plant to grow healthily. The structural system of hexagonal network provides a minimal energy principle with minimal material formed from natural crystals. The three-dimensional geometry of the Eden Dome allows for a large space system with a visually attractive dome due to the combination of bubble structures.

https://www.edenproject.com/
Figure 3. Eden dome

Recently, there is growing the demand for the construction of super large spatial structures for stadiums, performance venues, exhibition halls, airport facilities, and bio-dome. In this study, the authors analyze the dynamic response of large spatial latticed domes to earthquakes. Horizontal ground motion during an earthquake causes a large asymmetric vertical reaction of the dome. The dynamic response analysis of earthquake motion is most efficient through time history analysis. Especially, due to the earthquake motion, large deformation and stress are generated at the upper part of the dome, which greatly affects the structural safety of the dome. In the dynamic response characteristic of the large spatial structure, the response in the vertical direction occurs large due to the horizontal and vertical ground motions. Therefore, in case of seismic design of large spatial structure, the response combining the horizontal and vertical seismic ground motion should be evaluated during the design of earthquake [1, 2, 3, 4, 5, 6].

II. THE BUCKLING ANALYSIS AND EIGENVALUE ANALYSIS OF 300M HONEYCOMB LATTICE DOMES

In this study, elastic analysis, buckling mode analysis, geometric and material nonlinear analysis for the 300 m spanned honeycomb lattice under vertical load were performed. Figure 4 is the results of elastic analysis for the dome under vertical loads. The maximum deflection is 159 mm, the maximum compressive force of the member is -4,278 kN, the maximum bending moment My is 1,226 kN-m, and the maximum stress is 74 MPa. Figure 5 shows the results of the buckling mode analysis and the maximum joint load of the primary and secondary buckling modes is 3,684 kN. Figure 6 is the result of the nonlinear analysis assuming that the ends of the members are elastic springs. As a result of the nonlinear analysis of the central loading condition, the yield joint load is 1,300 kN, and the maximum joint load when the vertical load acts on the whole of the dome is 1,400 kN.

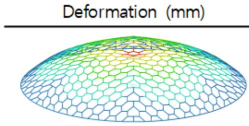
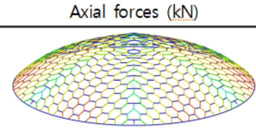
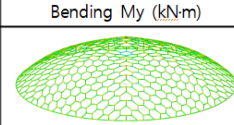
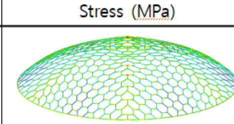
300m honeycomb lattice dome (P-1016x22, nodal load=100kN)			
Deformation (mm)	Axial forces (kN)	Bending My (kN·m)	Stress (MPa)
			
z=-159	-4,278~0	-1,226~689	-71~74

Figure 4. The static analysis for a 300m honeycomb lattice dome under vertical load

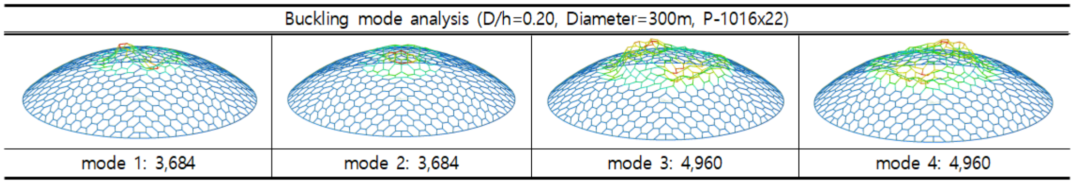


Figure 5. The buckling mode analysis for a 300m honeycomb lattice dome under vertical load

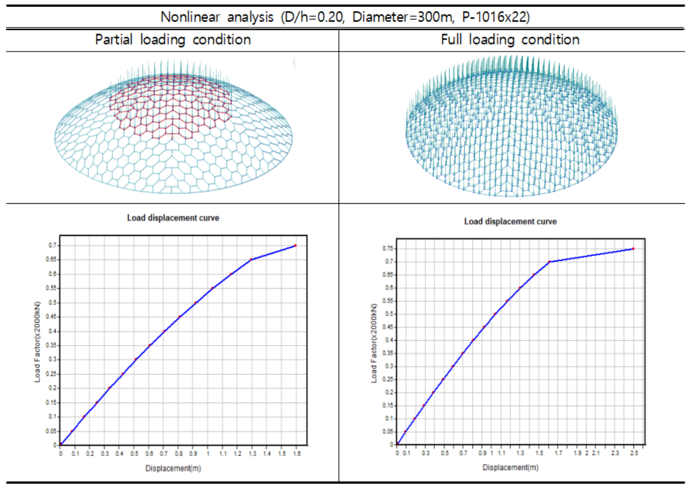


Figure 6. The nonlinear analysis for a 300m honeycomb lattice dome under vertical load

Figure 7 is the analysis results of the eigenvalue mode shape and period of the 300 m honeycomb lattice dome. The shape of the mode depends on the joining condition of the member, member size, boundary condition, assembling condition, etc. The first and second periods are 0.9859, and the third and fourth periods are 0.7000. The 1st, 2nd, 3rd and 4th period are S-shaped modes in which the top of the dome is asymmetrically deformed, and the 5th mode is a shape in which the top of the dome rises up. The sixth and seventh modes are modes in which the top of the dome oscillates up and down.

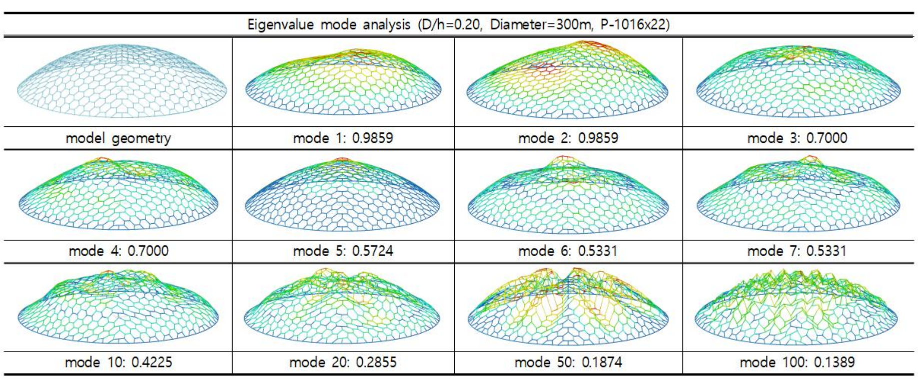


Figure 7. The results of eigenvalue analysis for 300m honeycomb lattice dome

III. TIME HISTORY ANALYSIS OF 300M HONEYCOMB LATTICE DOMES FOR EL CENTRO EARTHQUAKE

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

Applied the ground motion of El Centro 270 degree, the dynamic response of the 300 m spanned honeycomb lattice dome is analyzed by time history analysis. The peak ground acceleration at this time is 0.3569 gal. Figure 8 shows the results of 300 m honeycomb lattice dome for deformation, axial force, bending moment and stresses at 5.40 sec. The deformation in the vertical direction is the largest at 5.40 sec. The vertical displacement at this time is 353 mm, the compressive force is -9,810 kN, and the stress is 393 MPa. The vertical displacement (z=-353 mm) is larger than the maximum displacement in the horizontal direction (y=101 mm) for horizontal earthquakes. Figure 9 is the horizontal displacement response (-101~90 mm) and Figure 10 is the vertical displacement response (-353~348 mm). Figure 11 is the horizontal acceleration response (-787~676 gal) and Figure 12 is the vertical acceleration response (-3,045~3,152 gal), which is much higher than the horizontal acceleration. Similar to the characteristics of the El Centro earthquake ground motion, the dynamic response was greatly increased before 20 seconds and the dynamic response gradually decreased after 20 seconds.

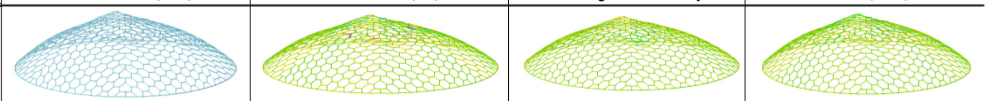
sec	300m honeycomb lattice dome (P-1016x22, nodal load=100kN, El Centro 270 Deg.)			
	Deformation (mm)	Axial forces (kN)	Bending Moment My	Stress (MPa)
5.40				
	y=90, z=-353	-9,810~9,810	-4,074~4,074 kN·m	-393~393

Figure 8. The results of time history analysis for 300m honeycomb lattice dome at 5.40sec

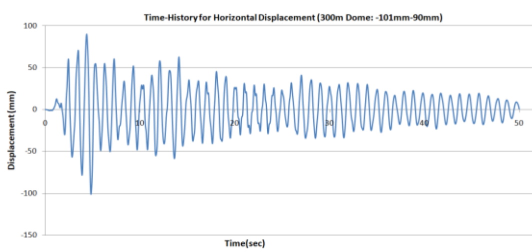


Figure 9. Horizontal displacement response

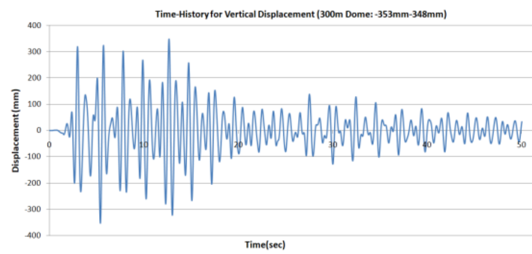


Figure 10. Vertical displacement response

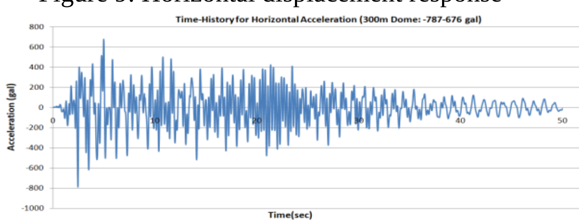


Figure 11. Horizontal acceleration response

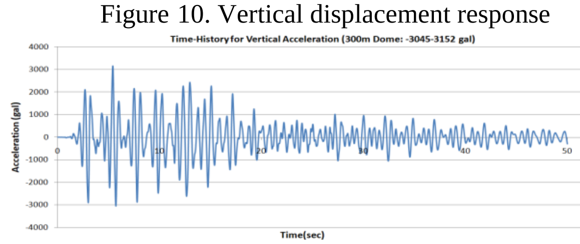


Figure 12. Vertical acceleration response

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

Figure 13 is the results of time history analysis of the 300 m honeycomb lattice dome under up-down ground motion, and shows deformation, axial force, bending moment and stress situation. The deformation in the vertical direction is the largest at 5.22 sec. The vertical displacement at this time is 63.31 mm, the maximum axial force is 2,083 kN, and the maximum stress is 56 MPa. Figure 14 is the vertical displacement response curve (-55~63.31 mm), and Figure 15 is the vertical acceleration response curve (-1,306~1,164 gal).

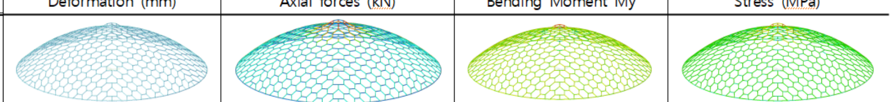
sec	300m honeycomb lattice dome (P-1016x22, nodal load=100kN)			
	Deformation (mm)	Axial forces (kN)	Bending Moment My	Stress (MPa)
5.22				
	z=63.31	-1,468~2,083	-419~331 kN·m	-19~56

Figure 13. The results of time history analysis for a 300m honeycomb lattice dome at 5.22sec

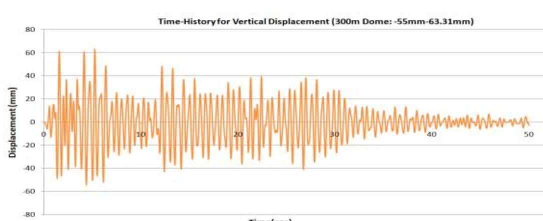


Figure 14. Vertical displacement response

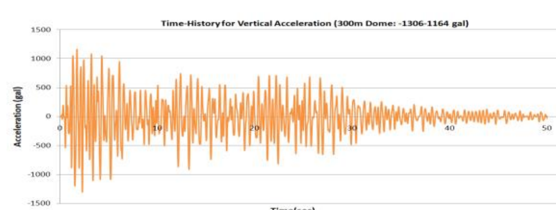


Figure 15. Vertical acceleration response

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

Figure 16 is the deformation of the dome, axial force, bending moment and stress of the member as a result of the time history analysis of the 3-dimensional El Centro earthquake motion (270 Deg.+0.3x180 Deg.+UD), and the peak displacement in the vertical direction was the largest at 369 mm. The axial force is -9,559~10,364 kN, the bending moment is -3,958~3,848 kN-m, and the member stress is -405~410 MPa. Figures 17 and 18 are the displacement response (horizontal: from -101 to 90 mm, vertical: from -362 to 364 mm) and Figures 19 and 20 are the acceleration response (horizontal: from -788 to 675 gal and vertical: from -3,206 to 3,421 gal). When the vertical displacement is maximum, the stress is the largest, and the mode at this time is an asymmetric S-shaped deformation.

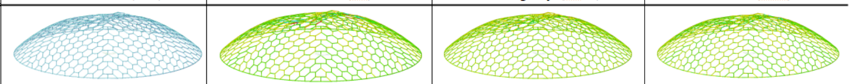
sec	300m honeycomb lattice dome (P-1016x22, nodal load=100kN)			
	Deformation (mm)	Axial forces (kN)	Bending My (kN-m)	Stresses (MPa)
12.67				
	y=-75, z=-369	-9,559~10,364	-3,958~3,848	-405~410

Figure 16. The results of time history analysis for 300m honeycomb lattice dome at 12.67sec

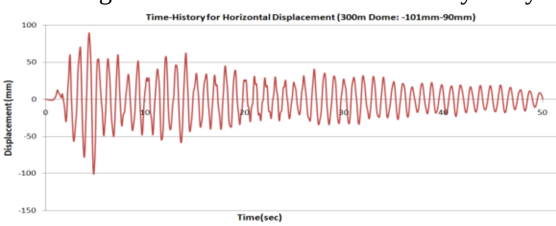


Figure 17. Horizontal displacement response

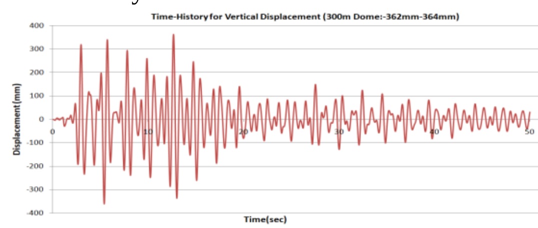


Figure 18. Vertical displacement response

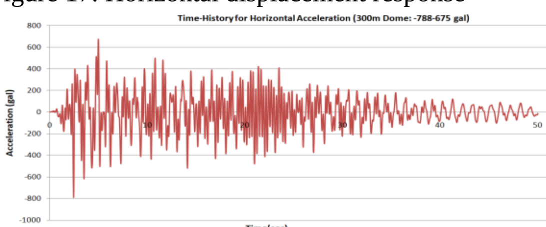


Figure 19. Horizontal acceleration response

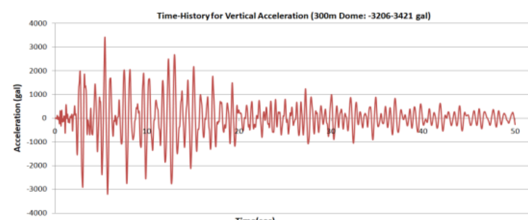


Figure 20. Vertical acceleration response

IV. TIME HISTORY ANALYSIS OF 300M HONEYCOMB LATTICE DOMES FOR MEXICO EARTHQUAKE

The response analysis for the ground motion of Mexico Earthquake 180 Degree (PGA=0.1714 gal)

Figure 21 is the deformation of the dome, axial force, bending moment and stress of the member as a result of the time history analysis of the 300m honeycomb lattice dome under Mexico earthquake ground motion. The vertical displacement was the largest at 65.75 sec. The axial force at this time is from -3,935 to 3,935 kN, the bending moment My is from -1,581 to 1,581 kN-m, and the maximum stress is from -162 to 162 MPa. Figures 22 and 23 are the displacement response (horizontal: from -45 to 37 mm, vertical: from -137 to 129 mm) and Figures 24 and 25 are the acceleration response (horizontal: from -258 to 304 gal and vertical: from -1,143 to 1,193 gal). When the vertical displacement is large, the stress is the largest, and the mode at this time is an asymmetric S-shaped deformation.

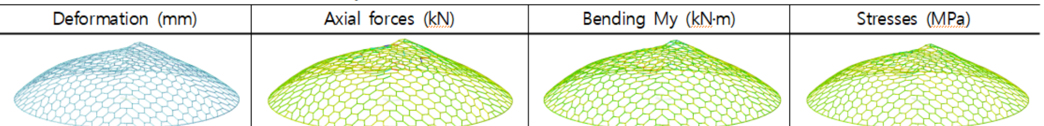
sec	300m honeycomb lattice dome (P-1016x22, nodal load=100kN)			
	Deformation (mm)	Axial forces (kN)	Bending My (kN-m)	Stresses (MPa)
65.75				
	x=23, z=-137	-3,935~3,935	-1,581~1,581	-162~162

Figure 21. The results of time history analysis for 300m honeycomb lattice dome at 65.75sec

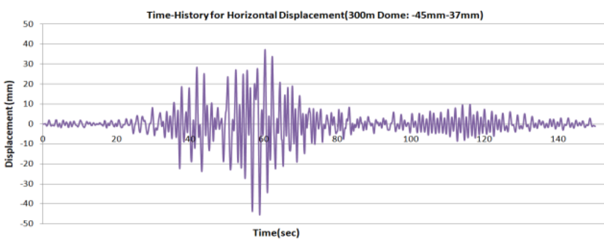


Figure 22. Horizontal displacement response

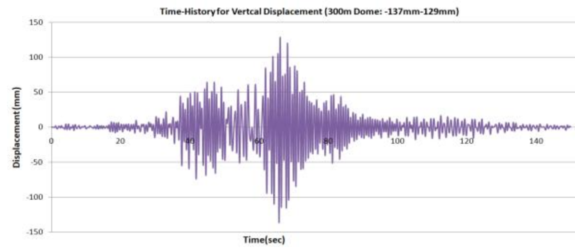


Figure 23. Vertical displacement response

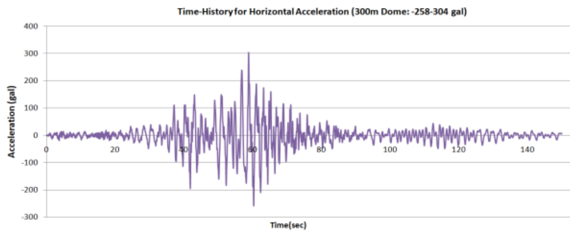


Figure 24. Horizontal acceleration response

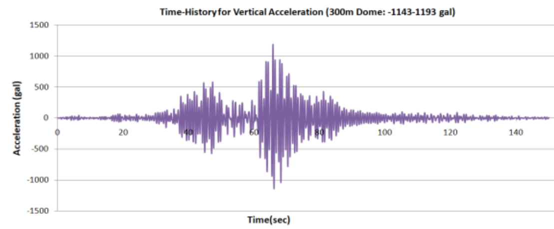


Figure 25. Vertical acceleration response

The response analysis for the ground motion of Mexico Earthquake (PGA=0.1714 gal)

Figure 26 shows the deformation of the dome, axial force, bending moment and stress of the member as a result of time history analysis for the two-way combined earthquake ground motion (180 Deg.+0.3x270 Deg.). The vertical displacement was the largest at 65.75 sec. The axial force at this time is from -3,943 to 3,943 kN, the bending moment My is from -1,582 to 1,582 kN-m, and the maximum stress is from -163 to 163 MPa. Figures 27 and 28 show the displacement response (horizontal: from -45 to 37 mm, vertical: from -137 to 128 mm), while Figures 29 and 30 show the acceleration response (horizontal: from -258 to 304 gal, vertical: from -1,139 to 1,196 gal). When the vertical displacement is maximum displacement, the stress is the largest, and the mode at this time is an asymmetric S-shaped deformation.

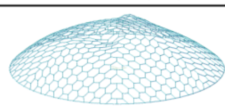
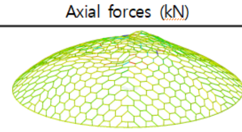
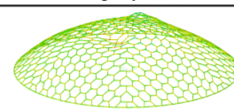
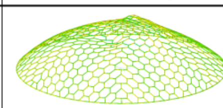
sec	300m honeycomb lattice dome (P-1016x22, nodal load=100kN)			
	Deformation (mm)	Axial forces (kN)	Bending My (kN·m)	Stresses (MPa)
65.75				
	x=23, z=137	-3,943~3,943	-1,582~1,582	-163~163

Figure 26. The results of time history analysis for 300m honeycomb lattice dome at 67.75sec

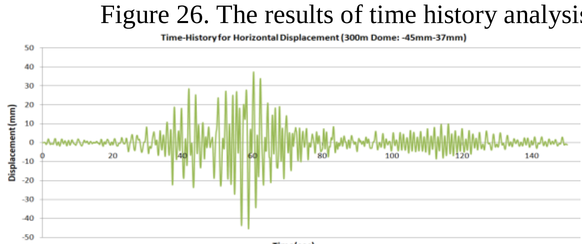


Figure 27. Horizontal displacement response

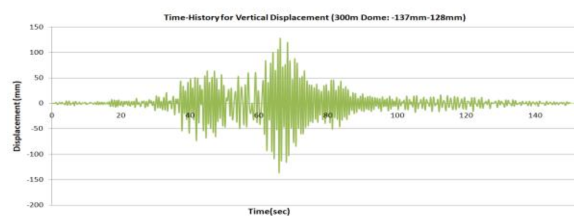


Figure 28. Vertical displacement response

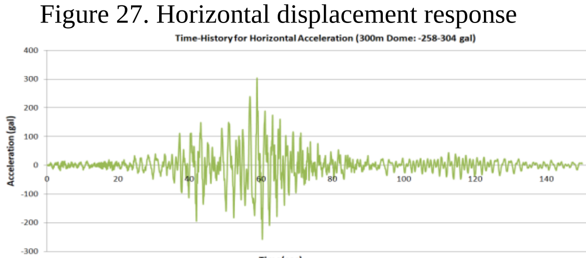


Figure 29. Horizontal acceleration response

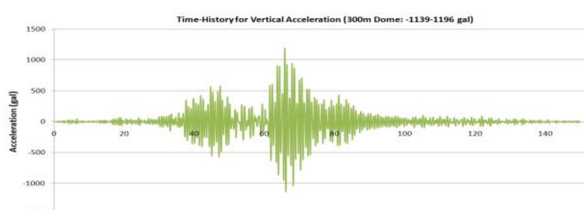


Figure 30. Vertical acceleration response

V. CONCLUSION

In this study, dynamic response characteristics (displacement response, acceleration response, member strength, stress, etc.) were analyzed by the time history analysis for the honeycomb lattice dome with diameter of a 300m.

(1) Large spatial honeycomb lattice dome caused S-shaped asymmetry in vertical direction due to horizontal earthquake ground motion, and maximum stress of members occurred when vertical displacement was maximum value.

(2) In the comparison of dynamic response for one direction and three dimensional ground motion of El Centro earthquake, the vertical displacement increased by 4.6% and the vertical acceleration increased by 12.4% due to 3-dimensional ground motion.

(3) For Mexico earthquake, almost similar dynamic responses were observed in the comparison of one-direction and two-direction earthquake ground motion.

VI. ACKNOWLEDGEMENTS

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