International Journal of Latest Trends in Engineering and Technology
Vol.(13)Issue(2), pp.042-048
DOI: http://dx.doi.org/10.21172/1.132.07
e-ISSN:2278-621X

DYNAMIC RESPONSE ANALYSIS OF 100M LATTICE DOMES WITH LRB SEISMIC ISOLATION DEVICE UNDER 3-DIMENSIONAL EARTHQUAKE GROUND MOTION

Sanghwa Shin[1], Kanggeun Park[2]

Abstract-The objective of this study is to investigate the dynamic response for the design of 100m single-layer lattice domes supported LRB seismic isolation device. In order to ensure the stability of single-layer lattice domes, it is investigated the load-displacement curve for the geometric and material nonlinear analysis of lattice domes considering the condition of elasto-plastic connection. One of the most effective methods to reduce the earthquake response of lattice domes is to install the lead rubber bearing isolation system at the support of a dome. The authors investigated the reducing effect for the seismic response of 100m spanned lattice domes with low rise/span ratio. The lattice dome with LRB isolation system can greatly reduce the dynamic response of domes by extending the period of structures and concentrating of seismic demand at isolation device.
Keywords – 100m spanned single-layer lattice dome, Earthquake response, Lead rubber bearing seismic isolation device, Geometrical and material nonlinear analysis, dynamic response

1. INTRODUCTION

The construction of large span lattice domes is increasingly in fields of spatial structures such as theaters, botanical gardens, exhibition halls, sports facilities, bio domes, etc. because it is aesthetically and mechanically attractive. In recent years, earthquakes have been occurring frequently, and therefore, the various studies of building design for an earthquake is required in the dynamic response of structures. It is necessary to evaluate the combined earthquake motion for the horizontal and vertical earthquake ground motion in seismic design. Especially, the asymmetrically vertical deformation of large spatial structure is highly affected by the horizontal earthquake ground motion, but it is very sensitive to the dynamic response of large span lattice domes for the vertical ground motion. Large deformation and stress are generated at the upper part of the dome, which greatly affects the safety of the dome.

In the dynamic response characteristics of the large spatial structure, the response in the vertical direction largely occurs due to the horizontal and vertical earthquake ground motions. In the case of seismic design of large spatial structure, the characteristics of seismic response should be estimated by the combined horizontal and vertical ground motion. For two directional earthquake motions, it is applied to the 100% in the main ground motion and 30% of the earthquake motion in the perpendicular direction at the same time. In case of actual earthquake, the up and down ground motion occurred in El Centro earthquake and Kobe earthquake. In the case of the dynamic response of large spatial structure, the influence of up and down ground motion should be evaluated. Since it is very difficult to consider all the effects of earthquakes in the design of buildings, there are many damages in which structures or members are broken or collapsed when an actual earthquake occurs. Therefore, it is necessary to evaluate dynamic response of structures for applying 3 dimensional earthquake ground motions according to the system and form of the structure for seismic design [1, 2, 3, 4].

The seismic isolation devices used in reducing the acceleration response by the extension of period of the structure, and absorbing the seismic energy due to the damping performance of the seismic isolator, and controlling the horizontal deformation of the structure to greatly reduce the response acceleration. The lead rubber seismic system has the high vertical support capacity and the high elastic deformation to extend the period of structures, and absorb the seismic energy in the isolation system, thereby it can greatly reduce the deformation of the upper structure [1, 2, 3, 4]. In this study, the dynamic response of 100m single layer lattice domes by the seismic ground motions of the horizontal and vertical directions was analyzed, and the effect of the LRB isolation device installed on the support of the domes were investigated. The analysis was performed using Midas Gen 2019 and NISA software, and it is assumed that there is no damping effect on the lattice dome.

2. THE GEOMETRIC AND MATERIAL NONLINEAR ANALYSIS

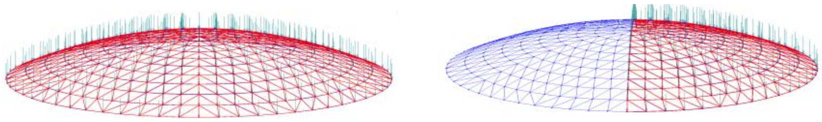
2.1 Geometric nonlinear analysis

This study is to analyze load-displacement curves by geometric and material nonlinear analysis for vertical loads of 100m lattice domes by the joint conditions and loading conditions. The loading conditions were the two cases where half and full

---

[1] Department of Urban Planning & Real Estate, International University of Korea, Jinju, South Korea
[2] Department of Large Spatial Structures, Technology Institute of I’ST Engineering Group, Seoul, South Korea

loading of the dome works. From the load-displacement curves, it is estimated the ultimate load and the snap-through behavior. In the case of the hinge joint, an upper vertex, which is geometrically weak, is assumed to be a rigid node.



Full loading condition (b) Half loading condition

Figure 1. Loading status for a dome (rise/span=15m/100m=0.15, P-500x12)

In Figure 2, the eigenvalue buckling load on the whole loading and half loading conditions are analyzed. The minimum eigenvalue buckling load of a full loading condition is 4,706kN for rigid connections and 869kN for pin connections. The minimum eigenvalue buckling load of a half loading condition is 7,282kN for rigid connections and 1,142kN for pin connections. In the buckling mode configuration, the upper part of the dome is vulnerable to vertical loads.

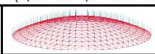
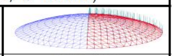
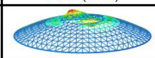
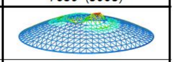
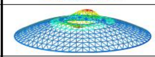
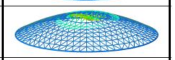
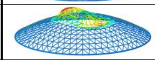
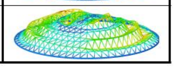
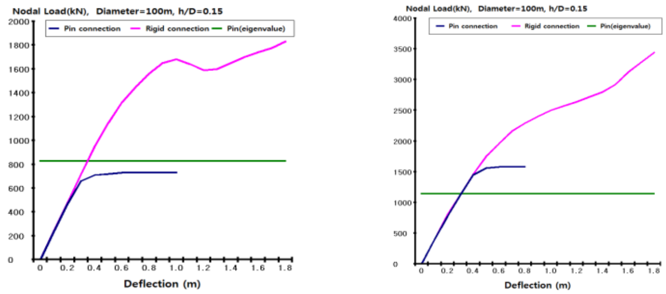
Eigenvalue Buckling Load (kN) (h/D=15m/100m=0.15, ∅ 500x12)		
Mode		
	Rigid (Pin)	Rigid (Pin)
1	4706 (869)	7282 (1142)
2	4706 (869)	7336 (1255)
3	5199 (2289)	7689 (3063)
Mode 1		
Mode 2		
Mode 3		

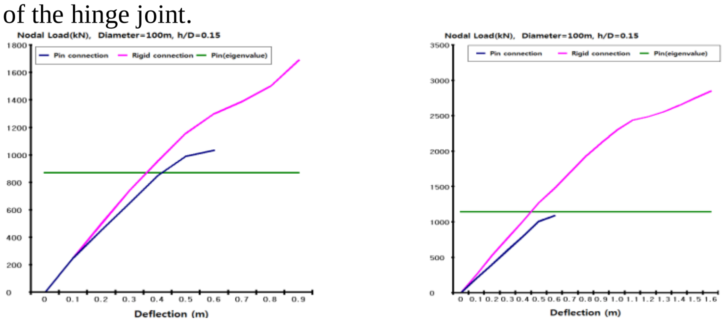
Figure 2. Eigenvalue buckling load



Full loading condition (b) Half loading condition

Figure 3. Geometrical nonlinear analysis for pin and rigid connections

The geometrical nonlinear analysis of the full loading is estimated the maximum nodal load 1,830kN and snap-through buckling load 1,680kN after 1.0m of deflection as shown in Figure 3(a). The maximum nodal load of the hinge jointed dome is 730 kN in Figure 3(a). In the geometric nonlinear analysis for the partial loading, the maximum nodal load for the rigid joint is 3,440kN and the maximum nodal load for the hinge joint is 1,580kN as shown in Figure 3(b). The maximum nodal load of the rigid jointed dome is 2.10~3.01 times of that of the hinge jointed dome. In material and geometric nonlinear analysis, the analysis is performed assuming that the end of the member is a tri-linear spring model. The maximum nodal load for the full loading condition is 1,690kN for the rigid joint and 1,034kN for the hinge joint. For the half loading, the maximum nodal load of the rigid joint is 2,850kN and the hinge joint is 1,090kN. The maximum nodal load of the rigid joint is 1.63 to 2.61 times the load of the hinge joint.



Full loading condition (b) Half loading condition

Figure 4. Material nonlinear analysis for pin and rigid connections

3. LEAD RUBBER BEARING SIEIMIC ISOLATION DEVICE

The LRB (Lead Rubber Bearing) seismic isolation device concentrates the energy generated by the earthquake, and minimizes deformations of the upper structure to protect the building from earthquakes. When an earthquake occurs, the LRB system extends the vibration period of the structure and effectively reduces the acceleration of structure. The LRB seismic isolator consists of rubber layers, steel sheet layers and a lead core forming a bearing with very high vertical stiffness and low horizontal stiffness. For the control of deformation of the structure due to earthquakes, the lead core disperses the energy of the earthquake. The rubber acts as a flexible spring system and is flexible in the horizontal direction but has high bearing capacity in the vertical direction. The large vertical stiffness is achieved by laminated rubber layers reinforced by steel plate layers. The lead core provides damping by plastic deformation when the structure moves horizontally during the shaking of an earthquake.

The LRB isolation system disperses the inertial forces of the building, extends the period of the building and reduces the acceleration, so the structure remains in its original shape and serves to prevent damages of the structural members. High-performance damping rubber bearings are made of a special rubber with excellent damping characteristics, and are characterized by the absence of a lead plug. The LRB absorbs large earthquake energy and achieves high flexibility, friction and viscous damping. To protect the building from deformation and damage, the high-performance damping rubber bearings are very flexible in the horizontal direction, which can effectively reduce the earthquake energy by changing its own shape. The LRB device can return to its original shape after an earthquake, in analysis the bearing is assumed as high elasto-plastic properties with bi-linear behavior. Excessive flexibility of high-performance damping rubber can cause an amplification effect on the seismic response of the upper structure for the vertical ground motion of the soft soil [1, 2, 3, 4]. The flexible hysteresis of high performance damping rubber bearings is reliable in the design of structural performance. In the LRB system, the lead core controls the horizontal displacement of the upper building and absorbs the part of the earthquake energy. The hysteresis of the elastomeric properties can be adjusted by changing the lead plug diameter. The elastic friction bearings consist of a rubber bearing combined with a PTFE material and stainless steel pads. During the earthquake, the displacement of the structure is absorbed by the rubber and the bearing slips between the plates.

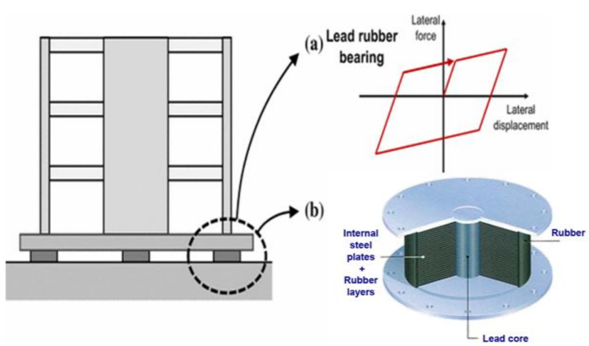


Figure 5. Lead rubber bearing

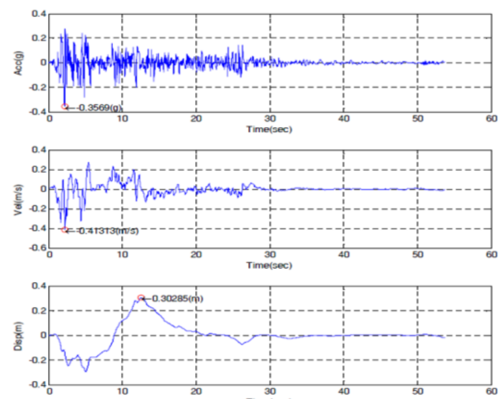
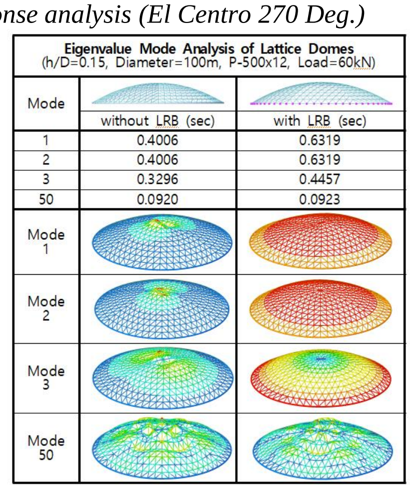


Figure 6. El Centro earthquake (270 Deg.)

4. EARTHQUAKE RESPONSE ANALYSIS OF 100M SINGLE LAYER LATTICE DOMES

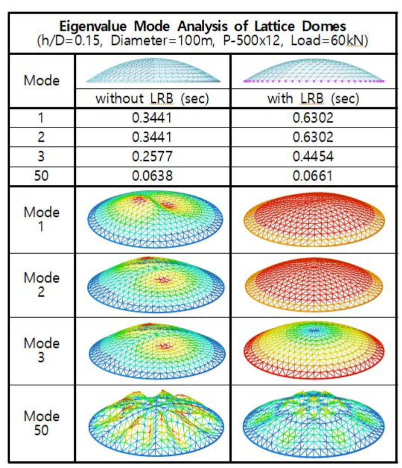
4.1 Earthquake response analysis (El Centro 270 Deg.)



Eigenvalue Mode Analysis of Lattice Domes (h/D=0.15, Diameter=100m, P-500x12, Load=60kN)

Mode	without LRB (sec)	with LRB (sec)
1	0.4006	0.6319
2	0.4006	0.6319
3	0.3296	0.4457
50	0.0920	0.0923

(a) Hinge connection



Eigenvalue Mode Analysis of Lattice Domes (h/D=0.15, Diameter=100m, P-500x12, Load=60kN)

Mode	without LRB (sec)	with LRB (sec)
1	0.3441	0.6302
2	0.3441	0.6302
3	0.2577	0.4454
50	0.0638	0.0661

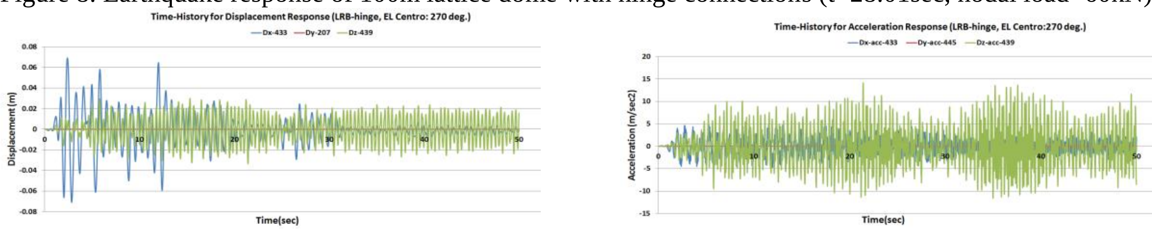
(b) Rigid connection

Figure 7. Eigenvalue mode analysis

Figure 7 is the result of eigenvalue analysis of a 100m single layer lattice dome with and without the LRB isolation system. The LRB seismic isolator has the following characteristics: vertical stiffness Kv=5,572,000 kN/m, primary stiffness K1=5,840 kN/m, secondary stiffness K2=1,310 kN/m, effective strength Keff=2,120 kN/m, yield force Fy =150kN. The period of the 100m span single-layer lattice domes with LRB is extended from 0.4006 sec to 0.6319 sec and the rigid jointed dome is extended from 0.3411 sec to 0.6302 sec. The dome with LRB in the 1st and 2nd mode shows the vibration with little deformation of the lattice dome.

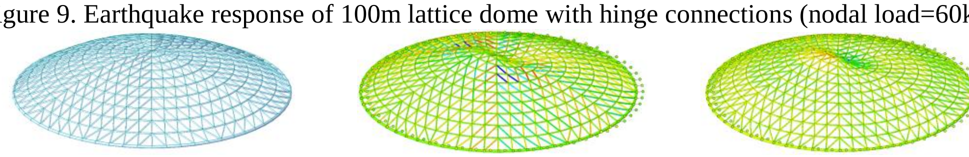
(a) Deformation status (x=-16mm, z=-33mm) (b) Axial forces (-950~841kN)

Figure 8. Earthquake response of 100m lattice dome with hinge connections (t=28.01sec, nodal load=60kN)



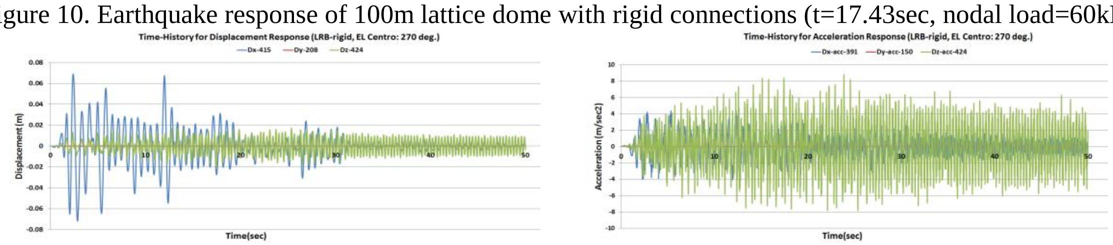
(a) Displacement response (b) Acceleration response

Figure 9. Earthquake response of 100m lattice dome with hinge connections (nodal load=60kN)



(a) Deformation status (x=-25mm, z=-19mm) (b) Axial forces (-532~530kN) (c) Bending moment (-92~89kN-m)

Figure 10. Earthquake response of 100m lattice dome with rigid connections (t=17.43sec, nodal load=60kN)



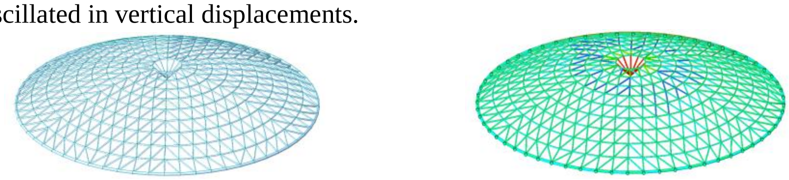
(a) Displacement response (b) Acceleration response

Figure 11. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

For 270 degree ground motion of El Centro earthquake of 100m lattice dome with hinge connections in Figure 8 and 9, the maximum displacement in the horizontal direction is 72 mm, the maximum displacement in the z direction is 33 mm, and the maximum compressive force of the member is 950 kN. In the early of the earthquake, the horizontal displacement vibrates large, and the vertical vibration is repeated continuously without reducing. The nodal acceleration shows large response in the z direction, the axial force of members has large forces in the upper part of the dome. The vertical displacement decreased from 33 mm to 19 mm due to the rigid joint condition as shown in Figure 10 and 11. It can be seen that, in the case of the rigid joint, the torsion Mx, the bending moments My and Mz affect significantly the stress of members.

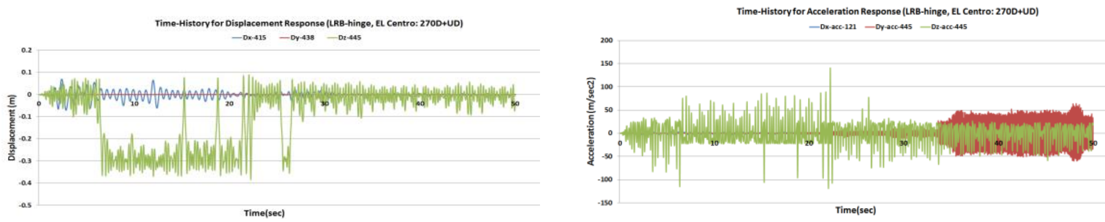
4.2 Earthquake response analysis (El Centro 270 Deg.+UD)

Time history analysis of EL Centro seismic ground motion (270 Deg.+UD) was performed as shown in Figure 12 to 15. Figures 12 and 14 show the deformation shape, axial force and bending moment according to the joining conditions when the vertical displacement is maximum. The down vertical displacement is large as shown in Figure 13(a). Figures 15 shows the displacement response and acceleration response for horizontal and vertical direction for a dome with rigid connections., the upper part of a dome is oscillated in vertical displacements.



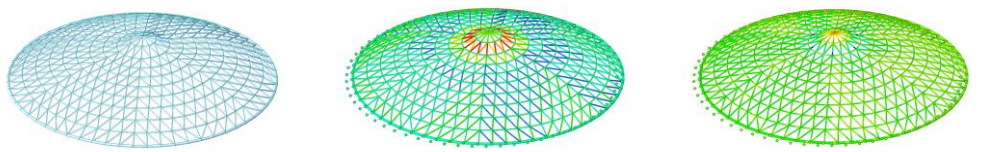
(a) Deformation status (x=-5mm, z=-384mm) (b) Axial forces (-498~2,708kN)

Figure 12. Earthquake response of 100m lattice dome with hinge connections (t=22.24sec, nodal load=60kN)



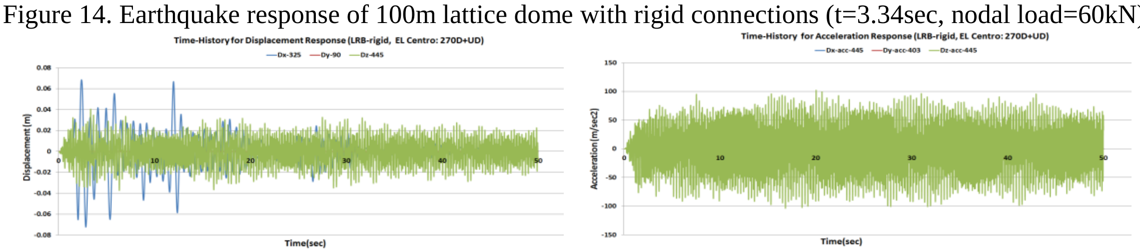
(a) Displacement response (b) Acceleration response

Figure 13. Earthquake response of 100m lattice dome with hinge connections (nodal load=60kN)



(a) Deformation status (x=31mm, z=40mm) (b) Axial forces (-216~1,346kN) (c) Bending moment (-250~138kN-m)

Figure 14. Earthquake response of 100m lattice dome with rigid connections (t=3.34sec, nodal load=60kN)



(a) Displacement response (b) Acceleration response

Figure 15. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

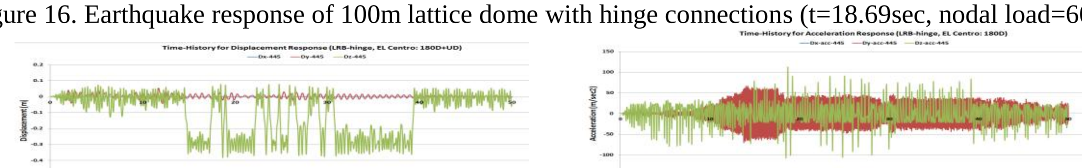
The rigid jointed lattice dome in comparison with the hinged jointed lattice dome was reduced from 384 mm to 40 mm in the z direction and the axial force from 2,708 kN to 1,346 kN as shown in Figures 12 and 14. The displacement in the up and down direction is large at the beginning of the earthquake as shown in Figure 15(a), but is reduced after the middle of the earthquake, and the vertical displacement response oscillate continuously. The vertical deformation at the upper part of the dome occurred largely in up and down direction.

4.3. Earthquake response analysis (El Centro 180 Deg.+UD)

Time history analysis for El Centro horizontal and vertical ground motion (180 Deg.+UD) was performed in Figures 16 to 19. Figure 16 and 18 compares a deformation shape, axial forces and bending moments with respect to the hinge joints and the rigid joints. In Figure 16, the maximum displacement in the z direction was reduced from 384 mm to 41 mm and the vertical displacement in the vertical direction was large in the middle of the shaking of the earthquake for hinge connection. In the case of the hinge jointed dome, the vertical displacement is large to compare the rigid jointed dome. Both the hinge and the rigid joints showed large accelerations in the vertical direction. The base shear force by applied nodal load was similar forces in the case of the seismic isolation system. In the lattice dome without the seismic isolation device, the larger the applied load was, the larger the base shear force was.

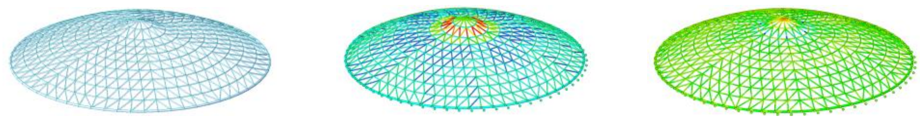
(a) Deformation status (y=-23mm, z=-384mm) (b) Axial forces (-981~2,532kN)

Figure 16. Earthquake response of 100m lattice dome with hinge connections (t=18.69sec, nodal load=60kN)



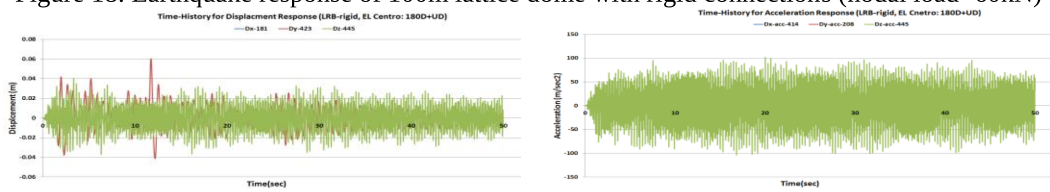
(a) Displacement response (b) Acceleration response

Figure 17. Earthquake response of 100m lattice dome with hinge connections (nodal load=60kN)



(a) Deformation(x=23mm, z=41mm) (b) Axial forces (-1,237~1,474kN) (c) Bending moment (-251~143kNm)

Figure 18. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

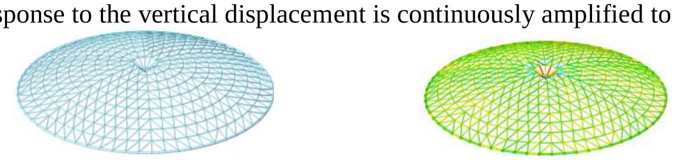


(a) Displacement response (b) Acceleration response

Figure 19. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

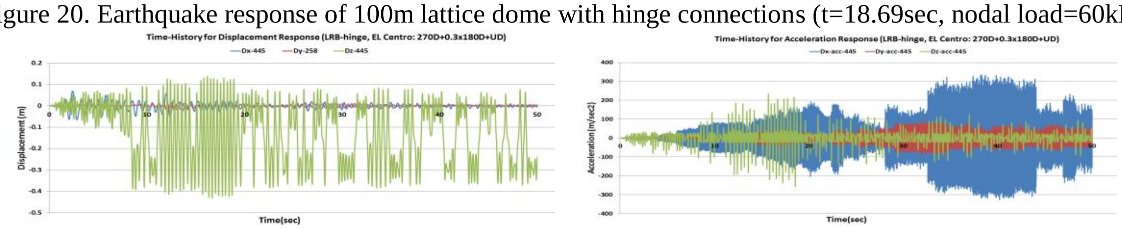
4.4. Earthquake response analysis (El Centro 270D+0.3x180 Deg.+UD)

In this study, the time history analysis of a dome by the El Centro earthquake ground motion (270D+0.3x180D+UD) was performed as shown in Figure 20 to 23. The maximum vertical displacement is 432mm at 16.68sec for the hinge joints and 41mm at 3.34sec for the rigid joints. The axial force of the hinge joints was 4,200kN and that of the rigid joints was 1,474kN, which was 2.9 times lower. In the rigid joints, the dynamic deformation is greatly reduced, but the bending stresses due to the moments My and Mz were further added. The vertical displacement in Figure 21 is oscillated continuously, horizontal and vertical accelerations were continuously amplified. Figure 22 shows the results of analysis of displacement, acceleration, axial force and bending moment for rigid jointed lattice dome. In Figure 23, the horizontal displacement is large at the beginning, and the dynamic response to the vertical displacement is continuously amplified to the end of earthquake.



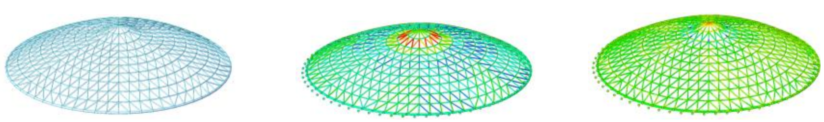
(a) Deformation status (y=-11mm, z=-432mm) (b) Axial forces (-2,993~4,200kN)

Figure 20. Earthquake response of 100m lattice dome with hinge connections (t=18.69sec, nodal load=60kN)



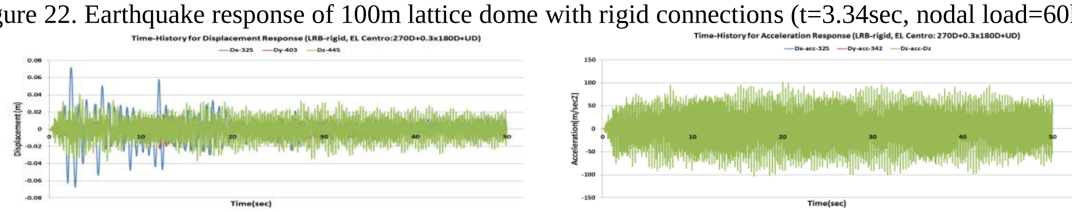
(a) Displacement response (b) Acceleration response

Figure 21. Earthquake response of 100m lattice dome with hinge connections (nodal load=60kN)



(a) Deformation(x=27mm, z=41mm) (b) Axial forces (-1,237~1,474kN) (c) Bending moment (-172~172kNm)

Figure 22. Earthquake response of 100m lattice dome with rigid connections (t=3.34sec, nodal load=60kN)



(a) Displacement response (b) Acceleration response

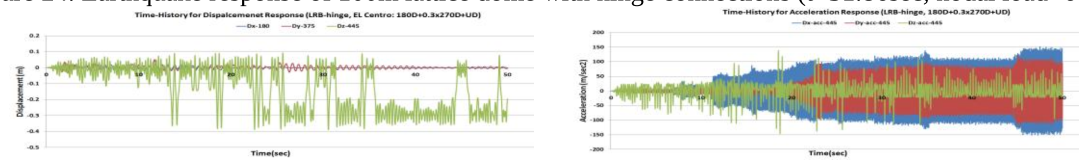
Figure 23. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

4.5. Earthquake response analysis (El Centro 180D+0.3x270 Deg.+UD)

Figure 24 shows the result of the time history analysis for the combination (180D+0.3x270D+UD) of three dimensional earthquake ground motions. In the case of the hinge joint as shown in Figure 24, a large displacement of 361 mm in the vertical direction occurred at the vertex of the dome. In Figure 25(a), the displacement in the up and down direction is amplified continuously, and in Figure 25(b) the accelerations in the horizontal and vertical directions are continuously amplified. Figures 26 and 27 show the earthquake response of a lattice dome with rigid joint.

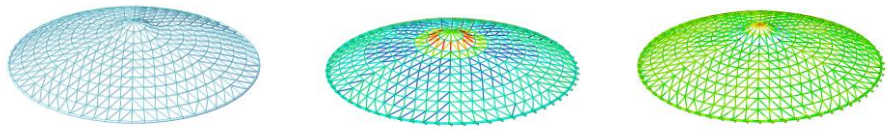
(a) Deformation status (y=15mm, z=-361mm) (b) Axial forces (-3,941~3,523kN)

Figure 24. Earthquake response of 100m lattice dome with hinge connections (t=31.86sec, nodal load=60kN)



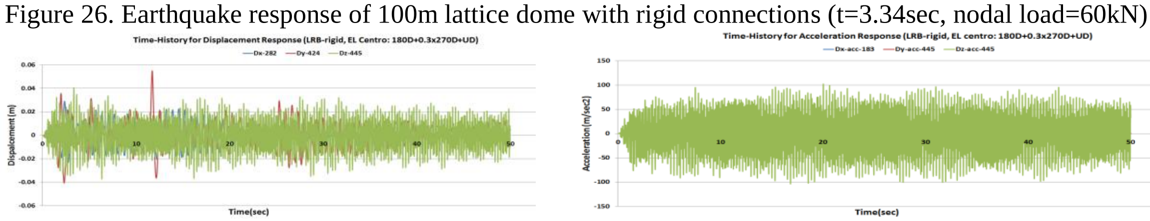
(a) Displacement response (b) Acceleration response

Figure 25. Earthquake response of 100m lattice dome with hinge connections (nodal load=60kN)



(a) Deformation(x=9mm, z=41mm) (b) Axial forces (-208~1,335kN) (c) Bending moment (-165~181kNm)

Figure 26. Earthquake response of 100m lattice dome with rigid connections (t=3.34sec, nodal load=60kN)



(a) Displacement response (b) Acceleration response

Figure 27. Earthquake response of 100m lattice dome with rigid connections (nodal load=60kN)

5. CONCLUSION

As a result of the seismic response analysis for 100m lattice domes, it can be confirmed that the installation of the seismic isolation device in the lower part of the lattice dome has a great reduction effect for the asymmetric vertical deformation and accelerations against the earthquake. The base shear force of lattice domes appears to be proportional to the applied load when there is no seismic isolation device, but it is relatively similar base shear forces regardless of the magnitude of the load when the seismic isolation device is installed. The lattice dome with a rigid joint was greatly reduced in deformation in the up and down direction than a single layer lattice dome with hinge joints. The rigid jointed lattice dome showed generally stable responses for the dynamic shaking of earthquake. The dynamic response at the upper part of the single layer lattice domes was very large in up and down direction.

6. 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.

7. REFERENCE

[1] S. Kato, S. Nakazawa, M. Uchikosh & Y. Mukaiyama. "Response Reducing Effect of Seismic Isolation System Installed between Large Dome and Lower Structures," Sixth Asian Pacific Conference on Shell and Spatial Structures, pp.323~330, 2000

[2] H. Kim, S. Kim & J. Kang, "Seismic Response Evaluation of Mid-Story Isolation System According to the Change of Characteristics of the Seismic Isolation Device," Journal of Korean Association for Spatial Structures, Vol.18, No1, pp.109-116, 2018

[3] K. Park, M. Jung & D. Lee, D, "Earthquake Response Analysis for Seismic Isolation System of Single Layer Lattice with 300m Span," Journal of Korean Association for Spatial Structures, Vol.18, No.3, pp.105-116, 2018

[4] J. Y. Richard Liew, "Design and Construction of Complex Large Roof Structures," 12th Asian Pacific Conference on Shell and Spatial Structures, pp.56~70, 2018