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Dynamic Response of 100 m, 200 m, 300 m Lattice Domes with LRB Seismic Isolator

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Abstract: The objective of this study is to analyze the seismic response characteristics of 100 m, 200 m, 300 m spanned lattice domes under both horizontal and up-down ground motion of El Centro earthquake. For the analysis of earthquake response of lattice domes, the time history analysis is used for the estimation of the dynamic response. Horizontal and up-down earthquake ground motions cause a large asymmetric vertical deformation in the large spatial domes. This study is to investigate the seismic characteristics of lattice domes for eigenvalue modes, displacement and acceleration response. The earthquake response of lattice domes with LRB (lead rubber bearing) isolation device by the horizontal and up-down combined ground motion is significantly reduced for the asymmetric vertical deformation and accelerations of domes.

Key words: 300 m dome, seismic isolation, response reducing effect, time history analysis, seismic ground motion.

1. Introduction

The LRB (lead rubber bearing) seismic isolation system can very effectively reduce the earthquake response of large space structures. The seismic isolation system is a very important device that protects buildings from earthquakes by concentrating the seismic energy in seismic isolation devices and minimizing the deformation of the whole structures, thereby extending the vibration period of the structures and reducing the acceleration. By reducing the acceleration response due to the long period of the structure and absorbing the earthquake energy due to the damping performance of the seismic isolator, the deformation of the structure is controlled to reduce the dynamic response. LRB isolation device consists of a rubber layer and a steel sheet layer, and a lead core forming a bearing with high vertical stiffness and low horizontal stiffness. Lead cores disperse seismic energy and provide attenuation by plastic deformation for horizontal deformation against earthquake. Rubber acting as a spring system is flexible in the horizontal direction, but has a high resistance in the vertical direction. The lead rubber bearings extend the period and reduce the acceleration, prevent structural damages, and provide a more economical and safer design for earthquakes. Since the seismic isolation device absorbs most of the earthquake energy and reduces the deformation of upper structure, and the vibration is slowly oscillated, so that the inner structure can be prevented from being overturning and damages.

In this study, time history analysis of 100 m, 200 m, and 300 m single-layer lattice domes equipped with LRB seismic isolator is performed to analyze the dynamic response of El Centro earthquake ground motion. The rise/span ratio of the lattice dome is 0.2, the 100 m lattice dome has a rise of 20 m, the 200 m dome has a rise of 40 m and the 300 m dome has a rise of 60 m. For earthquake ground motion, it is required to apply 100% of the acceleration in the main

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direction of the horizontal ground and 30% in the direction perpendicular thereto. Since the large deformation of the large span structure occurs largely in the vertical displacement for the horizontal and vertical combined ground motion, it is necessary to perform seismic response analysis for three dimensional earthquakes [1, 2].

Kato et al. [1] investigated the response reducing effect of a seismic studies system installed between a large dome and a lower structure under both horizontal and vertical seismic ground motions. The isolation system is effective to greatly reduce the asymmetric vertical acceleration due to horizontal seismic ground motion. The vertical response accelerations caused by the vertical ground motions may not be reduced. Saka et al. [2] investigated the elastic buckling loads and buckling modes of double-layer domes with various lattice patterns for all loading condition and half loading condition. Park et al. [3] investigated the earthquake response of 300 m spanned single-layer lattice domes with and without lead rubber bearing seismic isolation device. Richard Liew [4] presented the design challenges recent innovations and the issues related to the design and construction of complex spatial structures for Garden by the Bay and Changi Jewel in Singapore. Recent trends show that steel structure is the preferred choice and increasingly being employed to produce innovative and spectacular architectural design with complex geometrical profiles. Lee, Sung, Kim and Kang [5] analyzed the response control for the performance evaluation of a retractable roof with TMD (turned mass damper) mass for spatial structures. The spatial structures were analyzed with the turned mass damper to control the dynamic response for the earthquake.

Since the large spatial lattice dome is very sensitive to the up-down earthquake motions, it is necessary to analyze the dynamic characteristics of the 3-dimensional ground motion.

In this study, to evaluate the dynamic characteristics of 100 m, 200 m and 300 m single-layer lattice dome, the time history analysis of 3-dimensional earthquake ground motion is performed to analyze displacement response, acceleration response, and member stresses to investigate the reducing effect of dynamic response.

2. 100 m Single-Layer Lattice Dome

2.1 Eigenvalue Analysis

The seismic response of 100 m single-layer lattice dome is compared with the model without installed LRB isolation device and the installed model. The structural model has a diameter of 100 m and a height of 20 m. Sixty (60) seismic isolation devices were installed at the support, and the device is assumed to be a bi-linear spring model. The seismic isolation system applies the data for the linear hysteresis. The vertical stiffness Kv is 1,087 kN/mm, the effective stiffness Keff is 1.11 kN/mm, the yield displacement is 16 mm, the maximum displacement is 400 mm, the yield force Fy is 172 kN, maximum horizontal force is 368 kN.

Table 1 shows the period and mode shapes of the dome installed with the isolation device as a result of eigenvalue analysis from the primary mode to the 100th mode. The period of the primary mode was increased from 0.3888 to 1.1070 by the isolation device. In the analysis results of the primary mode, the 1st and 2nd modes are the shape of the S-shaped asymmetrical mode, and the 100th mode is the shape in which the top part of the dome vibrates up and down, it is a vibrating shape. When an LRB isolation device is installed, the primary mode has a mode shape with small deformation of the dome. In the 10th mode, the central part of the dome is in the shape of an S-shaped anti-symmetric vibration mode. The 100th mode is a mode shape in which the entire dome oscillates up and down. The LRB seismic isolator caused a shape with small deformation of the dome in the primary and secondary modes.

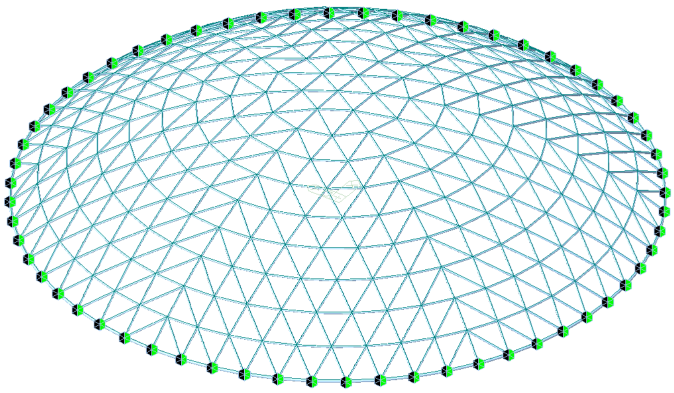
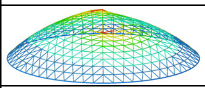
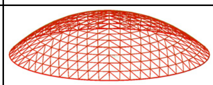
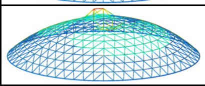
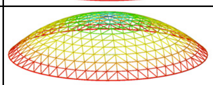
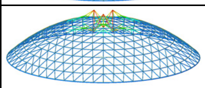
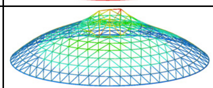
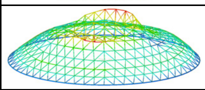
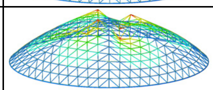
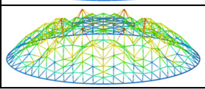
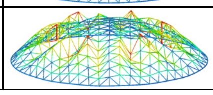


Fig. 1 Structural model.

Table 1 Eigenvalue mode analysis.

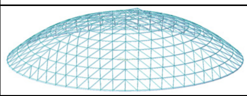
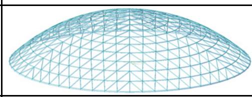
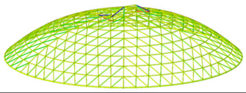
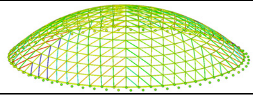
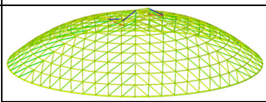
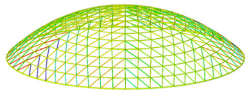
Eigenvalue mode analysis of 100 m lattice domes (h/D = 0.2, P-318.5 × 6, nodal load = 50 kN)		
Mode	Without isolation (sec)	With isolation (sec)
1	0.3888	1.1070
3	0.3205	0.8346
10	0.2128	0.2372
20	0.1495	0.1748
100	0.0585	0.0599
Mode 1		
Mode 3		
Mode 10		
Mode 20		
Mode 100		

2.2 Time History Analysis

In this study, the dynamic response of a 100 m lattice dome is analyzed through time history analysis of 3-dimensional ground motion (270 Deg. + 0.3 × 180 Deg. + UD) of El Centro earthquake. Since the lattice dome with an isolation device is in the elastic range, the upper structure can be assumed an elastic model. Since the upper lattice dome is less deformed, the damping constant should not be overestimated. The effective damping constant of the steel lattice dome applied in this study was 2%, and the damping constant of the lattice dome equipped with the isolation device was 1%. A damper of the laminated lead rubber device can be assumed as A bi-linear model.

Table 2 shows the deformation, axial forces and stresses when maximum vertical displacement occurred as a result of time history analysis applying El Centro ground motion. Figs. 2-5 are the displacement and the acceleration in the horizontal direction and the vertical direction. Figs. 6-9 are the responses to displacement and acceleration for horizontal and vertical directions of a dome installed with an isolation device. The maximum horizontal displacement increased from

Table 2 Time history analysis.

Earthquake response of 100 m lattice domes (h/D = 0.2, P-318.5 × 6, nodal load = 50 kN)		
	Without isolation	With isolation
Time	5.04 sec	4.55 sec
Deform (mm)		
	y = -16, z = -104.7	y = 136, z = 13
Axial force (kN)		
	-1,264~954	-299~229
Stress (MPa)		
	-214~161	-51~51

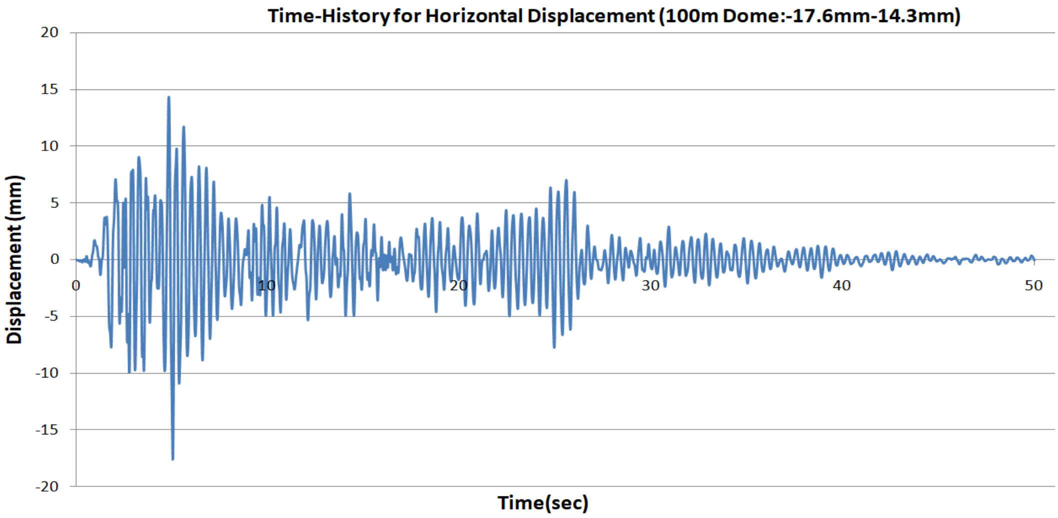


Fig. 2 Horizontal displacement response.

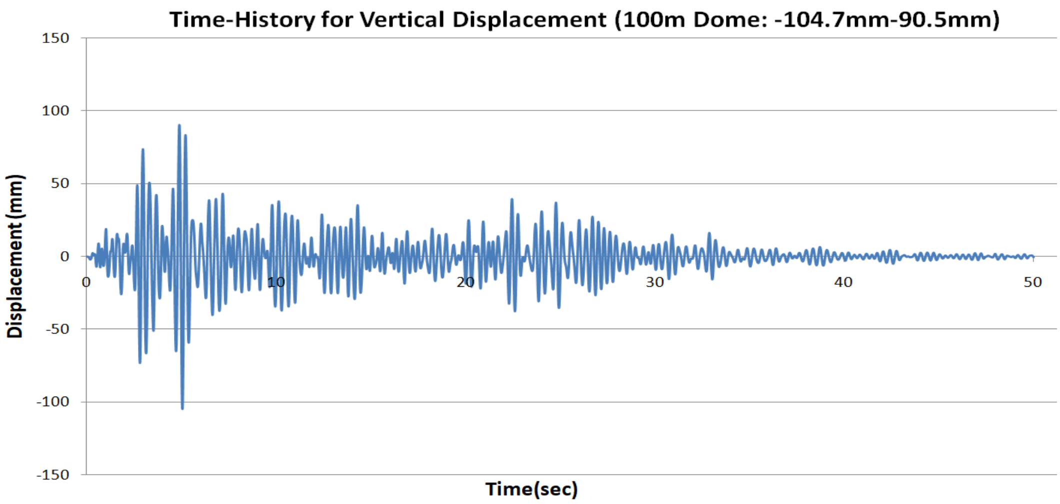


Fig. 3 Vertical displacement response.

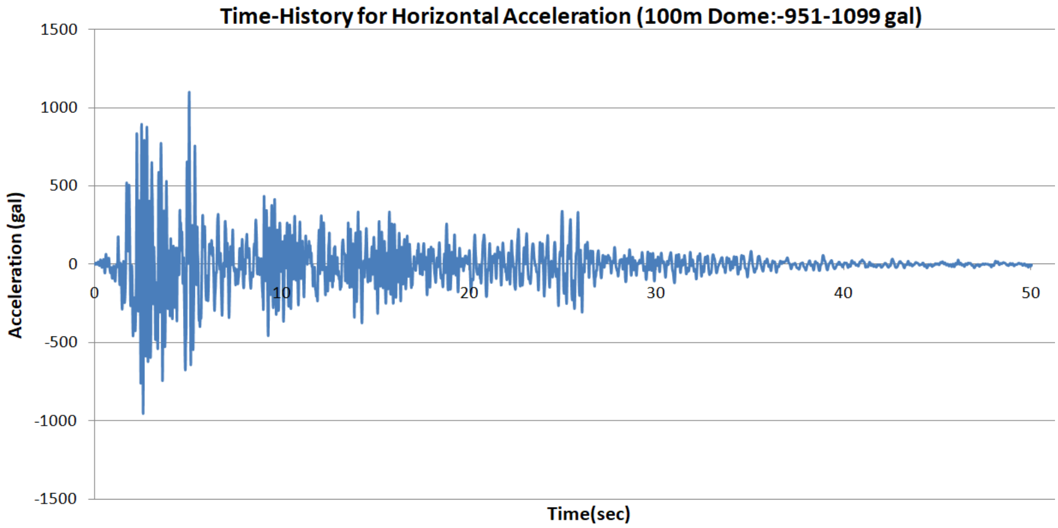


Fig. 4 **Horizontal acceleration response.**

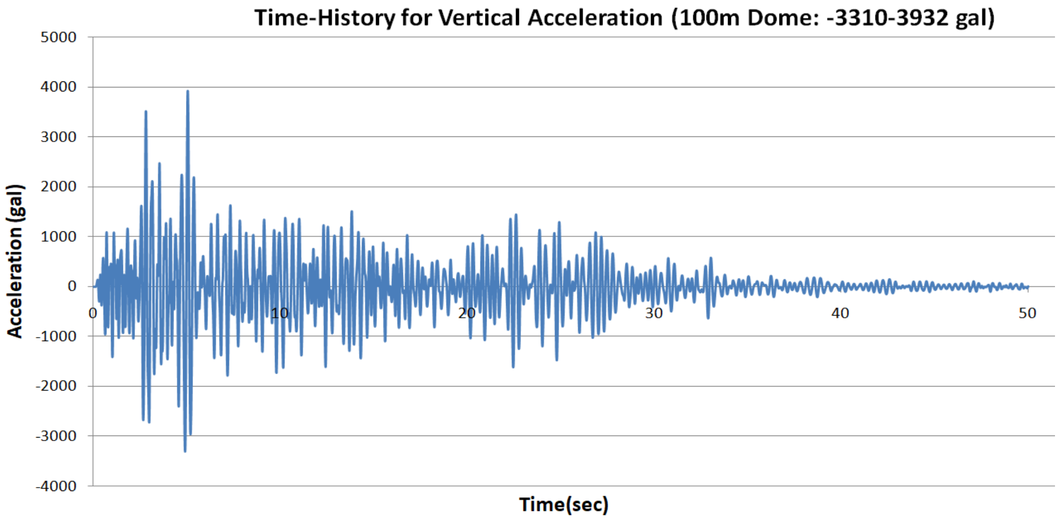


Fig. 5 **Vertical acceleration response.**

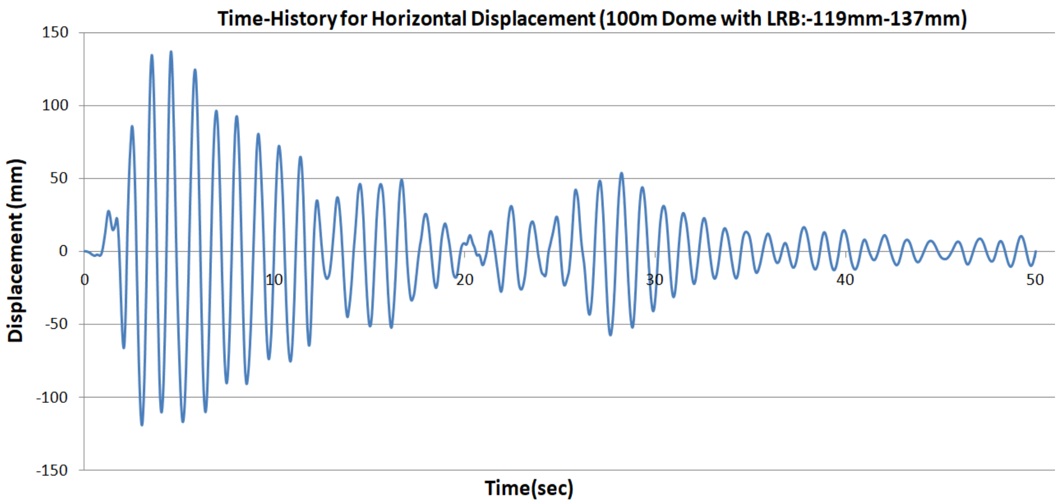


Fig. 6 **Horizontal displacement response (LRB).**

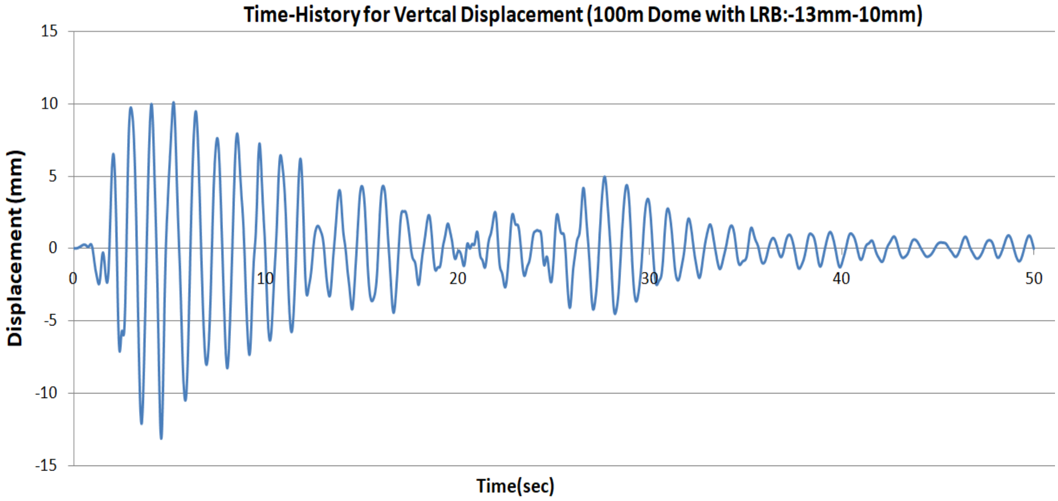


Fig. 7 Vertical displacement response (LRB).

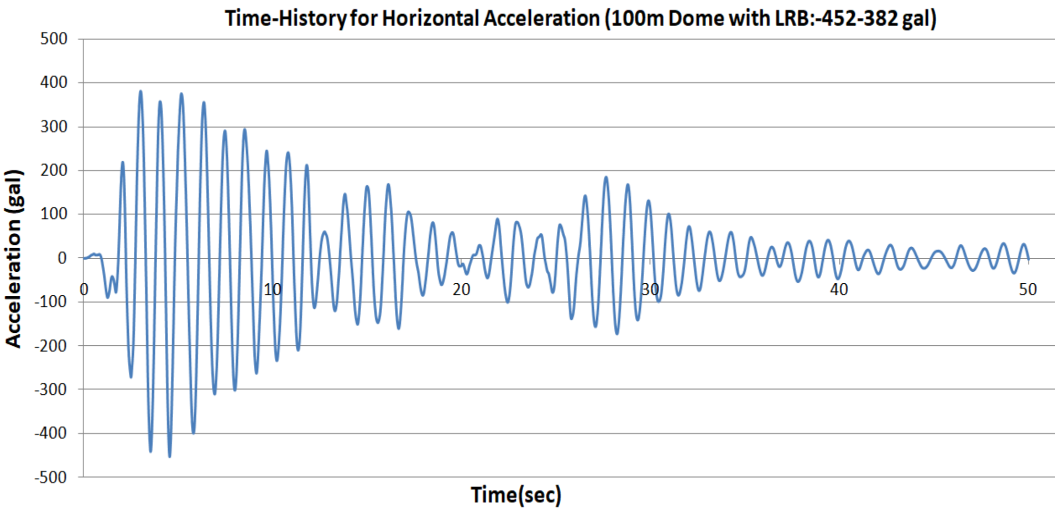


Fig. 8 Horizontal acceleration response (LRB).

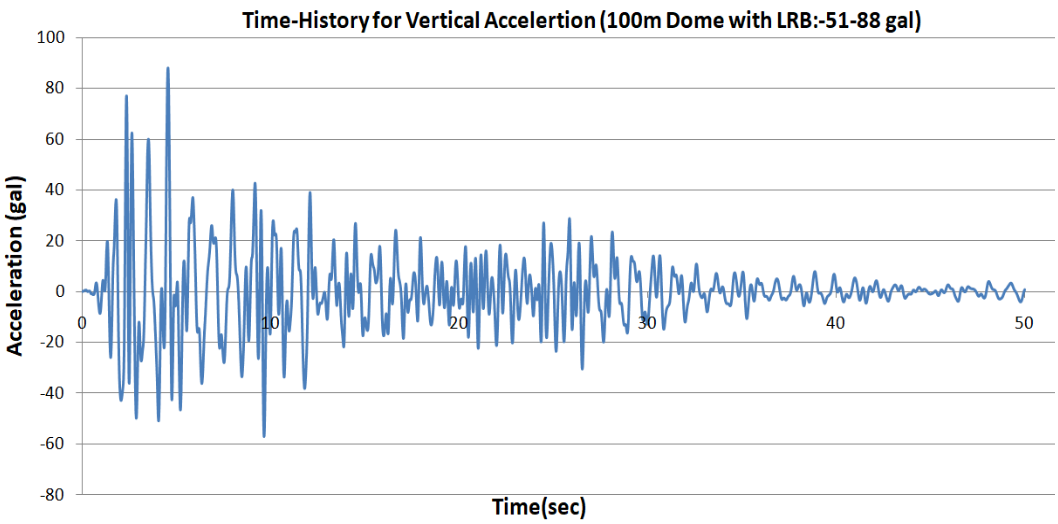


Fig. 9 Vertical acceleration response (LRB).

17.6 mm to 137 mm, and the peak vertical displacement decreased from 104.7 mm to 13 mm. The maximum axial force decreased from 1,264 kN to 299 kN, and the maximum stress decreased from 214 MPa to 51 MPa. The peak displacement decreased by 86.6%, the maximum axial force decreased by 76.3%, and the maximum stress decreased by 76.2%. The horizontal acceleration decreased from 1,099 gal to 452 gal and the vertical acceleration decreased from 3,932 gal to 88 gal.

3. 200 m Single-Layer Lattice Dome

3.1 Eigenvalue Mode Analysis

The seismic response of the 200 m single-layer lattice dome is compared with the model without installed LRB isolation device and the installed model. The diameter of the structural model is 200 m and the height is 40 m. The properties of the LRB system are as follows. The vertical stiffness Kv is 1,176 kN/mm, effective stiffness Kv is 1.28 kN/mm, the maximum displacement is 400 mm, yield force Fy is 197 kN, maximum horizontal force is 427 kN, and breaking force is 512 kN.

Table 3 shows the eigenvalue mode of the lattice dome. The primary mode is an inversely symmetrical S-shaped mode, and the 20th mode is a mode in which the top of the dome vibrates up and down. The period of the dome extended 0.6798 sec as 1.7913 sec by the seismic isolation device. The primary and secondary modes of the dome equipped with an isolation device have almost no deformation, and the 3rd mode is a mode shape in which the vertex of the dome vibrates up. The higher mode is a mode in which the entire dome oscillates up and down.

3.2 Time History Analysis

In Table 4, the vertical displacement is reduced from 174 mm to 93 mm and the axial force is reduced from 2,261 kN to 765 kN. The stress is reduced from 201 MPa to 75 MPa. The vertical displacement was reduced by 46.6%, the axial force by 66.2%, and the stress by 62.7%. The lateral acceleration (-548-901 gal) was reduced 73.6% by the isolation device (LRB: -216-237 gal), and the vertical acceleration (-2,341-1,992 gal) was decreased by 49.6% (LRB: -1,175-1,095 gal).

4. 300 m Single-Layer Lattice Dome

4.1 Eigenvalue Mode Analysis

The seismic response of the 300 m single-layer lattice dome is compared with that of the model without installed LRB isolation device. The diameter of the structural model is 300 m and the height is 60 m. The upper part of the lattice dome with the hinged connection is weak, and the deformation becomes large and the stresses are concentrated. The connection of all members is hinged joints and the size of the steel member is P-700 × 9. The vertical stiffness Kv of the seismic isolation system is 3,560 kN/mm, the effective stiffness Keff is 3.53 kN/mm, the yield displacement is 22 mm, the maximum horizontal displacement is 400 mm, the shear yield force Fy is 434 kN, maximum shear force is 1,177 kN, and fracture shear forces is 1,412 kN.

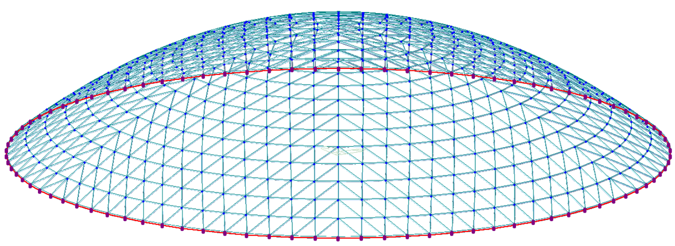


Fig. 10 Structural model (diameter: 200 m).

Table 3 Eigenvalue mode analysis.

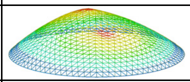
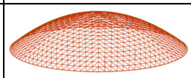
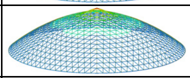
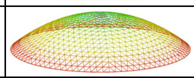
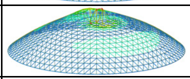
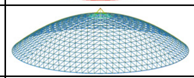
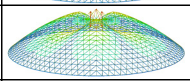
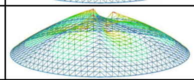
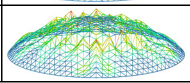
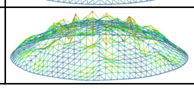
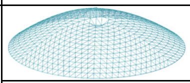
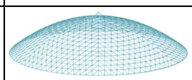
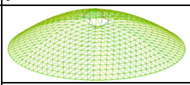
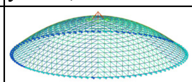
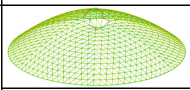
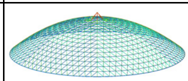
Eigenvalue mode analysis of 200 m lattice domes (h/D = 0.2, P-406.4 × 9, nodal load: 100 kN)		
Mode	Without isolation (sec)	With isolation (sec)
1	0.6798	1.7913
3	0.5965	1.3223
6	0.4777	0.5967
20	0.2748	0.3066
200	0.0717	0.0729
Mode 1		
Mode 3		
Mode 6		
Mode 20		
Mode 200		

Table 4 Time history analysis.

Earthquake response of 200 m lattice domes (h/D = 0.2, P-406.4 × 9, nodal load: 100 kN)		
	Without isolation	With isolation
Time	3.01 sec	4.17 sec
Deform (mm)		
	y = 27, z = 174	y = 37, z = 93
Axial force (kN)		
	-2,261~2,261	-85~765
Stress (MPa)		
	-201~201	-75~68

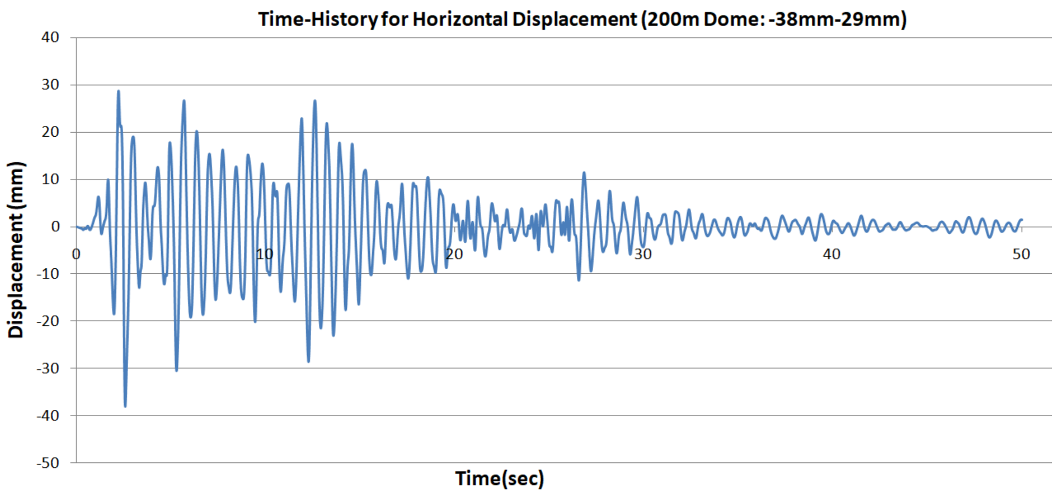


Fig. 11 Horizontal displacement response.

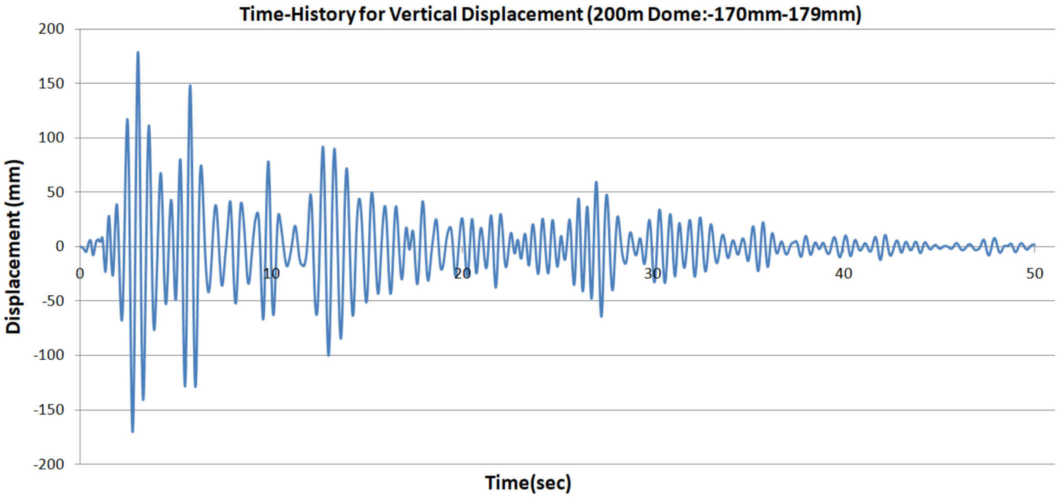


Fig. 12 Vertical displacement response.

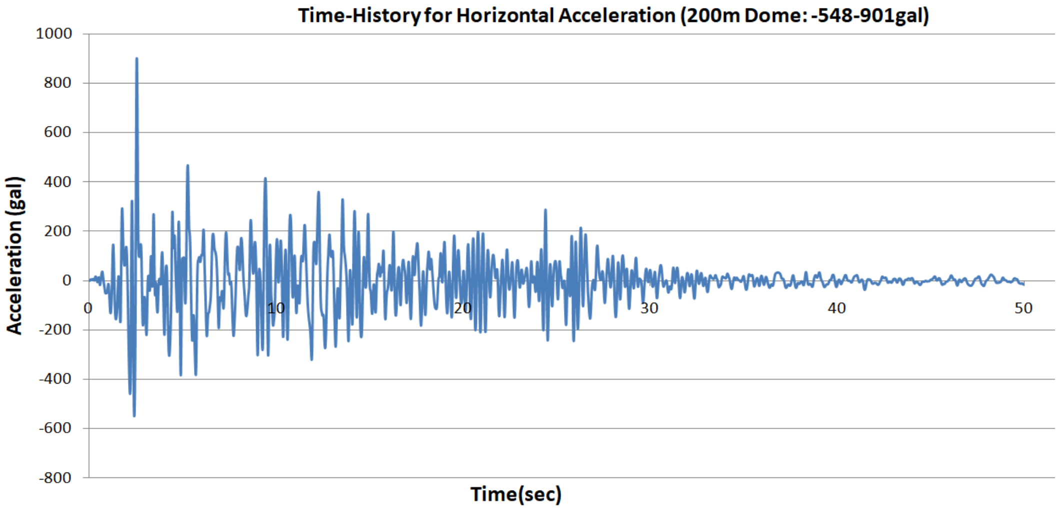


Fig. 13 Horizontal acceleration response.

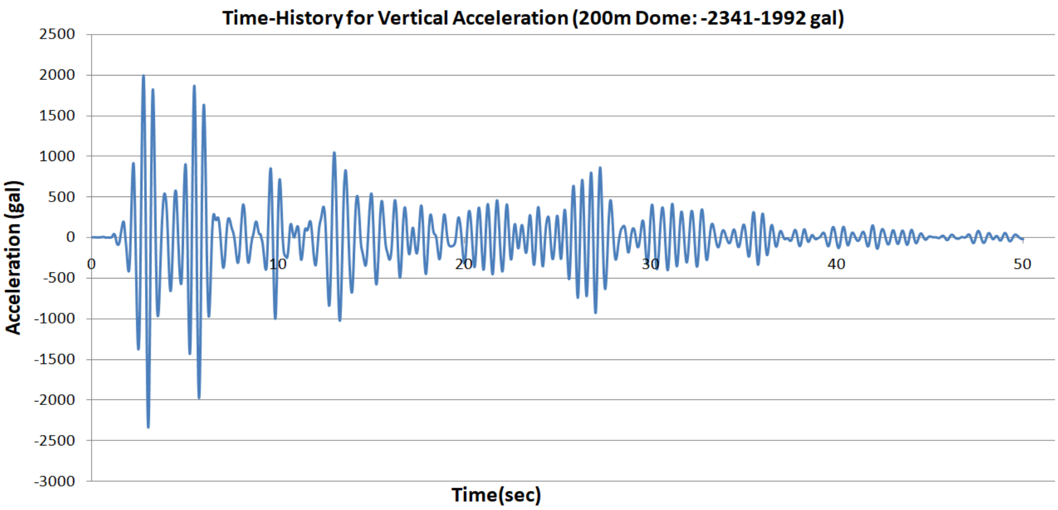


Fig. 14 Vertical acceleration response.

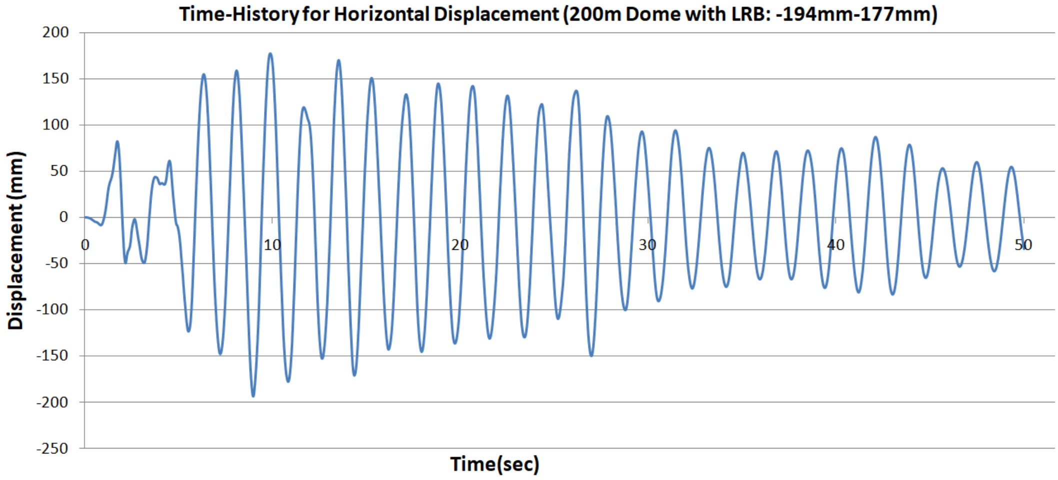


Fig. 15 Horizontal displacement response (LRB).

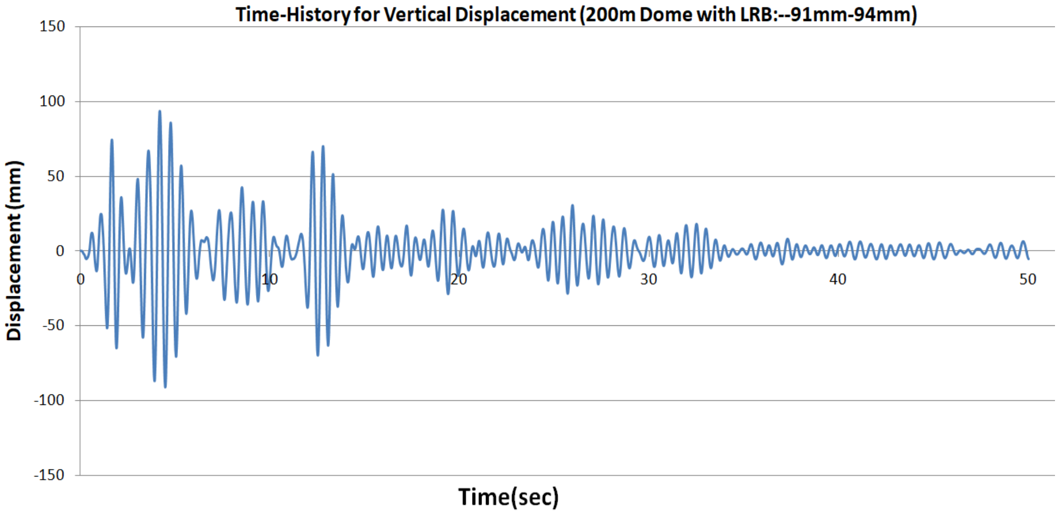


Fig. 16 Vertical displacement response (LRB).

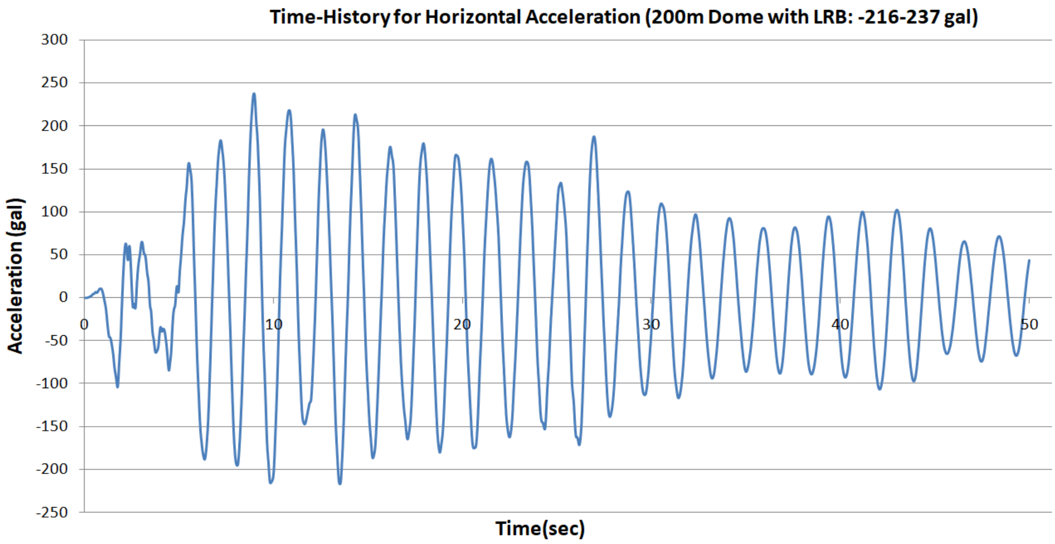


Fig. 17 Horizontal acceleration response (LRB).

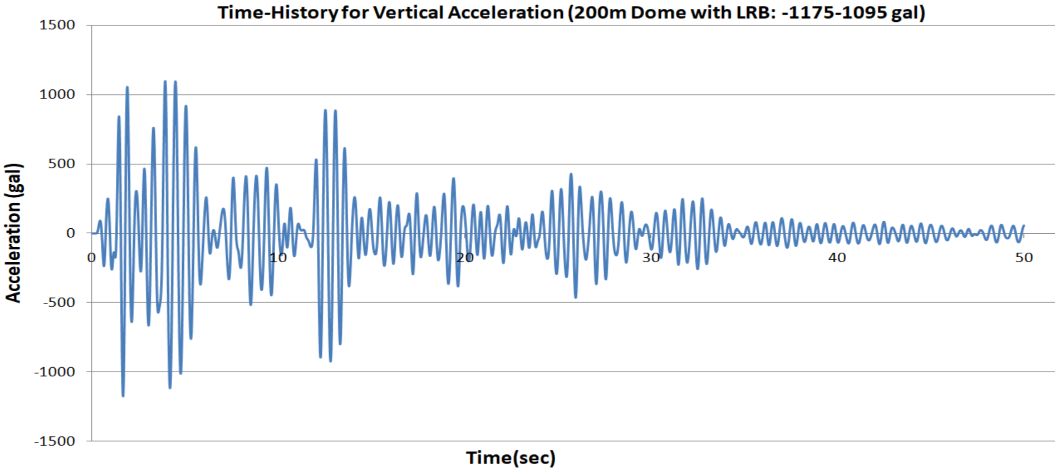


Fig. 18 Vertical acceleration response (LRB).

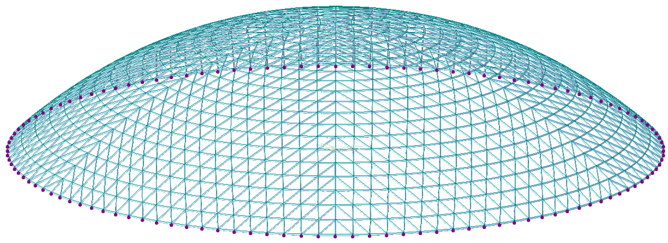


Fig. 19 Structural model (diameter: 300 m).

Table 5 Eigenvalue mode analysis.

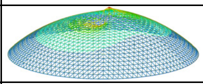
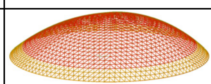
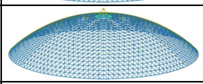
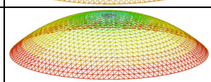
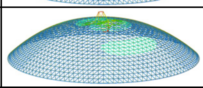
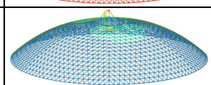
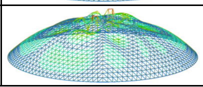
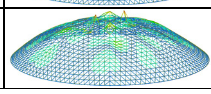
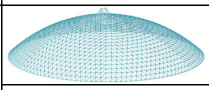
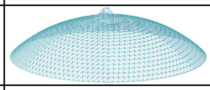
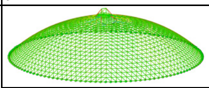
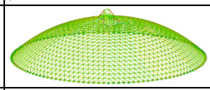
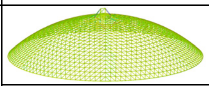
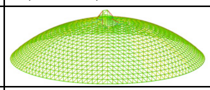
Eigenvalue mode analysis of 300 m lattice domes (h/D = 0.2, P-700 × 9, nodal load: 200 kN)		
Mode	Without isolation (sec)	With isolation (sec)
1	1.0797	1.8182
3	1.0291	1.3096
6	0.8017	1.0291
100	0.1868	0.1879
Mode 1		
Mode 3		
Mode 8		
Mode 100		

Table 6 Time history analysis.

Earthquake response of 300 m lattice domes (h/D = 0.2, P-700 × 9, nodal load: 200 kN)		
	Without isolation	With isolation
Time	5.65 sec	5.02 sec
Deform (mm)		
	y = -81, z = -985	y = -26, z = -237
Axial force (kN)		
	-13,723~13,723	-1,824~2,965
Stress (MPa)		
	-702-702	-93~151

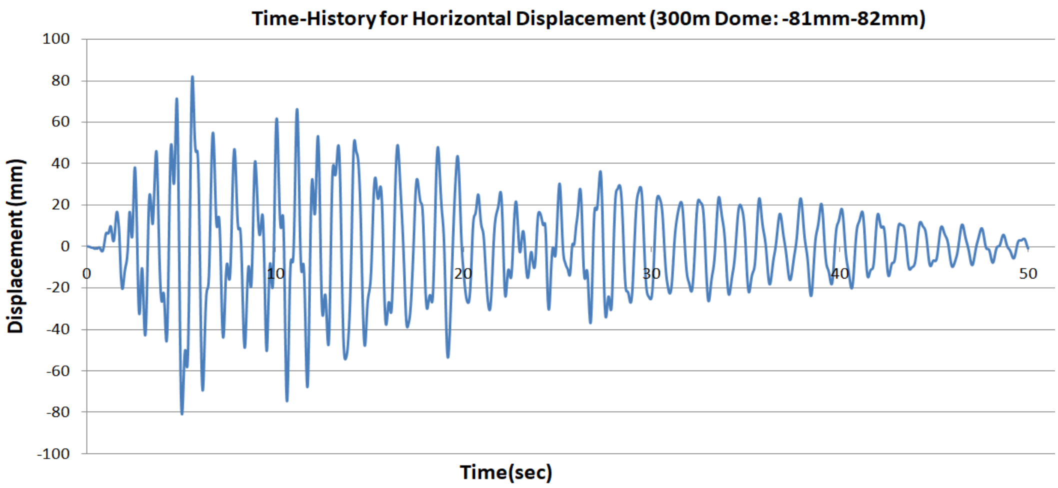


Fig. 20 Horizontal displacement response.

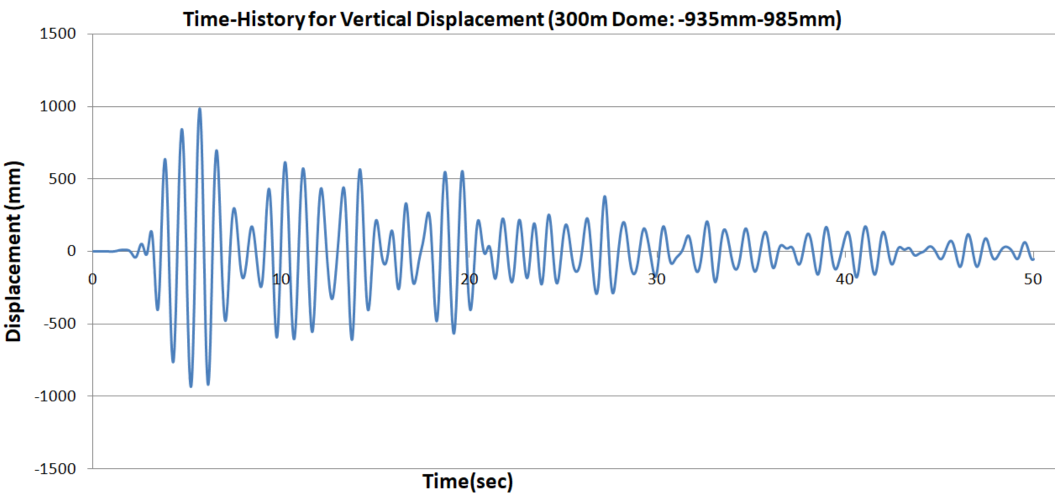


Fig. 21 Vertical displacement response.

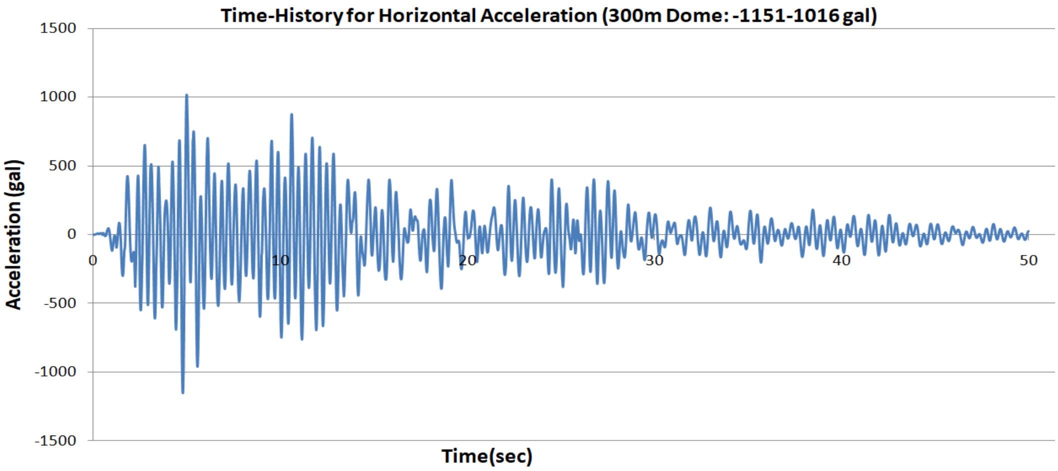


Fig. 22 Horizontal acceleration response.

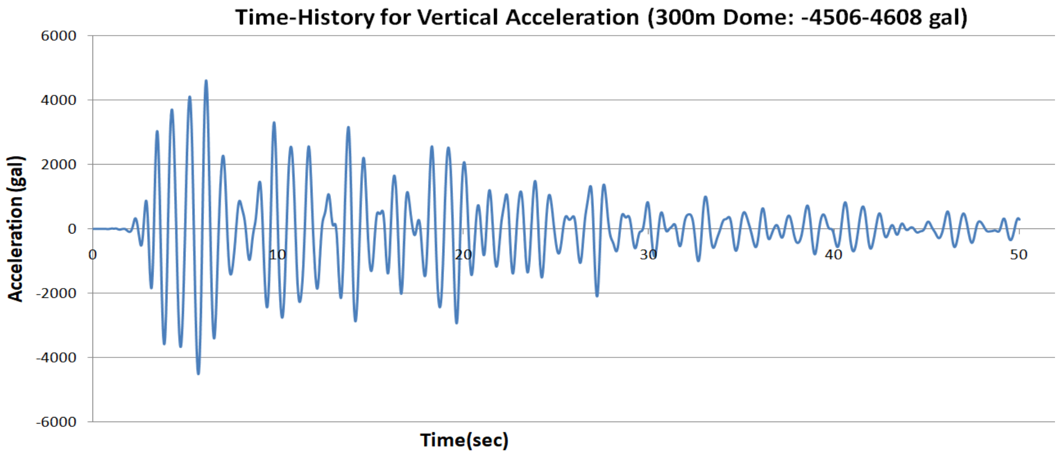


Fig. 23 Vertical acceleration response.

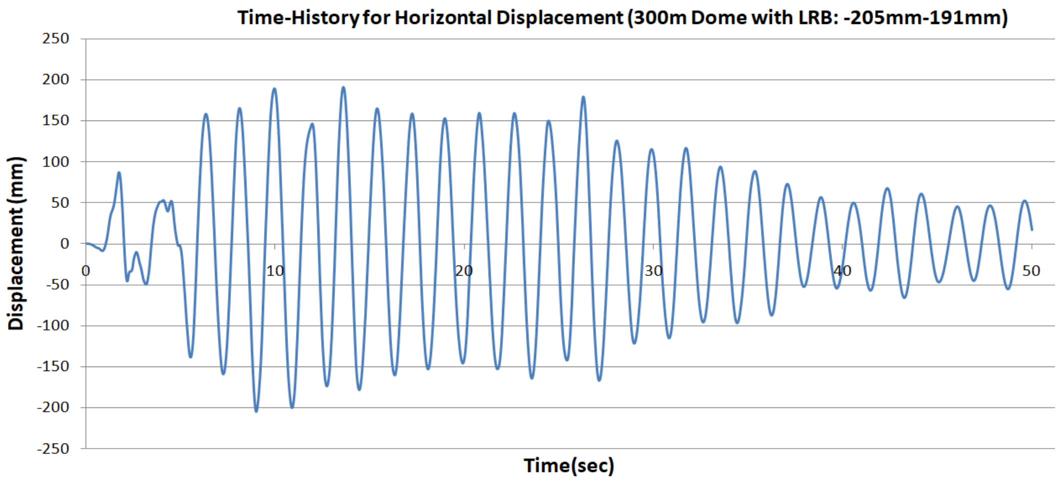


Fig. 24 Horizontal displacement response (LRB).

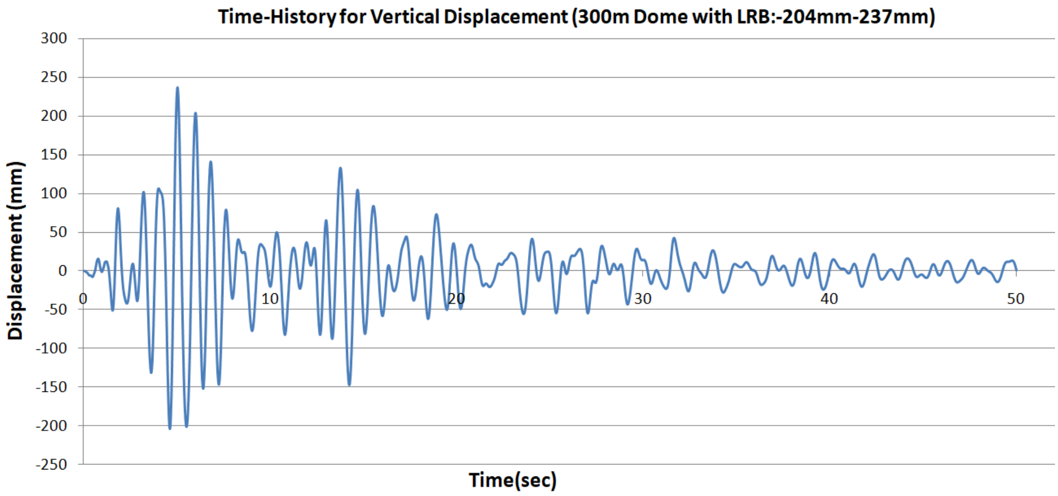


Fig. 25 Vertical displacement response (LRB).

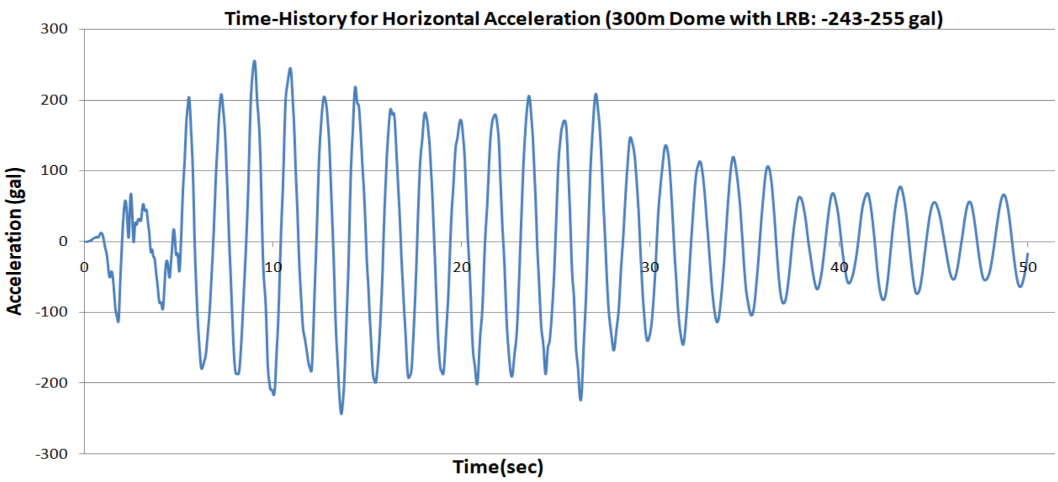


Fig. 26 Horizontal acceleration response (LRB).

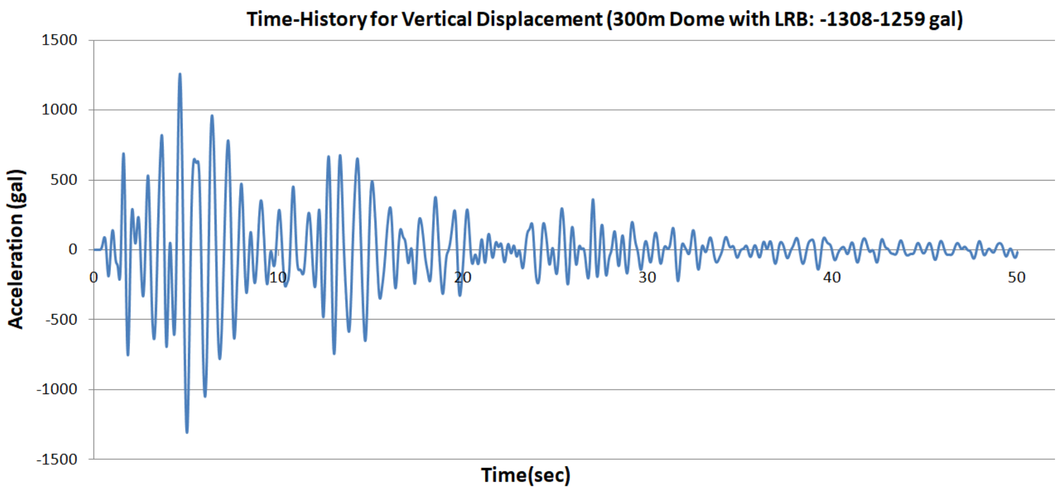


Fig. 27 Vertical acceleration response (LRB).

In the eigenvalue analysis of the 300 m single-layer lattice dome, the first mode is an S-shaped mode, the 3rd mode is an upward mode, and the 8th and 100th mode are vertically oscillating modes. In the case of the dome with the isolation device, the first mode is an S-shaped mode, the 3rd mode is a vertex shape, and the eighth mode is an S-shaped mode.

4.2 Time History Analysis

The vertical displacement decreased from 985 mm to 237 mm and the horizontal displacement increased from 82 mm to 205 mm. The axial force decreased from 13,723 kN to 2,965 kN and the stress decreased from 702 MPa to 151 MPa. The axial force and stress were reduced by about 78.5%. The peak displacement reduced by 75.9%. The peak acceleration reduced by 71.6%. The 300 m single-layer lattice dome shows that the response to the up and down ground movements is greatly affected at the center of the dome.

5. Conclusion

In this study, the LRB isolation system was analyzed the effect of the mechanical characteristics of single-layer lattice domes with large span. The seismic isolator greatly reduced the vertical displacement and acceleration of the lattice dome. The isolator absorbs the seismic energy by increasing the horizontal displacement and greatly reduces the vertical displacement, thereby greatly reducing the axial forces and stresses of the members.

Acknowledgements

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