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Seismic behavior of tensegrity barrel vaults

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Abstract

Tensegrity systems are spatial reticular systems in a state of self-stress. These systems are structures made up of an assembly of pin-jointed pre-stressed continuous tension members (cables) and discontinuous compressive members (struts), arranged in different complex shapes. Their stiffness is the result of a self stress that stabilizes infinitesimal mechanisms. Despite many studies on the seismic behavior of the space structures, so far a few investigations have been carried out to examine seismic behavior of these structures. Pioneers have suggested tensegrity systems as earthquake-resistant structures; nevertheless, this statement may be examined through extensive studies of the seismic behavior of tensegrity systems. In the present study, the seismic behavior of tensegrity barrel vaults has been investigated by carrying out linear and nonlinear analysis. All of the analyses have been undertaken using ANSYS package. Having verified the finite element modeling, eigenvalue and time history analysis have been undertaken in order to examine the seismic behavior of the tensegrity barrel vaults. Also, the effect of the rise to span ratio of these systems and influence of the self-stress level, have been investigated. Similar to reticular double layer barrel vaults, the dominant period of tensegrity barrel vaults increases with increase of rise to span ratio. As another result, it is shown that larger initial strains produce smaller natural periods. For selected models of tensegrity barrel vaults, horizontal accelerograms cause some cables yield or bars to buckle. However, vertical accelerograms are not so effective. Under horizontal component of earthquake, displacements grow with increase of rise to span ratio, while it is inverse under vertical accelerograms.

Keywords: space structures, tensegrity barrel vaults, self-stress, seismic behavior.

1. Introduction

Space structures are mostly interested for their lightness. One of the recent branches of space structures are called tensegrity structures. These structures are composed of compression bars and prestressed cables. Some researches realize that the first attempt to establish a tensegrity structure goes back to 1920 when Lark Longanson introduced a structure with 3 bars and 8 non-prestressed cables. However, this system in no longer called a tensegrity structure for the lack of prestress in cables. The real tensegrity structure was constructed in 1948 by Snelson. Afterwards, extensive efforts were made on form-finding, investigation on the stability and self-stress and prestress of tensegrity structures. Nevertheless, yet there are not sufficient works about dynamic characteristics and behavior of these structures. Motro 1986 and Furuya 1992 investigated linear dynamic behavior of tensegrity structures. Skelton and Sultan 1997 and Sultan 1999 carried out some research on nonlinear dynamic behavior of these structures. In 2000, Oppenheim and Williams studied dynamic characteristics and damping of tensegrity structures. Ben Kahla and Moussa 2000 studied the dynamic effects of rupture of a cable in an expanded tetrahedron. Ben Kahla 2001, carried out a numerical analysis study of seismic behavior of a tensegrity frame. In another attempt Ben Kahla 2003 studied behavior of tensegrity beam under harmonic loading.

Following these studies, in this research a set of tensegrity barrel vaults are considered and their seismic behavior is studied.

2. Tensegrity models

It is not easy to produce tensegrity barrel vaults with different rise to span ratios and variable initial strains. For this study, two set of barrel vaults with rise to span ratios of 1/4 and 1/6 are selected. For each set, four models with initial strains of 0.002, 0.004, 0.006 and 0.008 are established.

The models dynamic characteristics were derived by eigenvalue analysis. Then all eight models were analyzed nonlinearly under accellerograms of Kobe1995 and Tabas1982 earthquakes in horizontal and vertical directions.

For construction of the barrel vaults, we have used cylindrical simplexes. This simplex is composed of two planes of square cables that are connected by four web bars and 4 cables. The geometry is chosen to produce enough self strain. Also, to achieve curvature, location of points 6 and 8 are changed according to rise to span ratios, Figure 1.

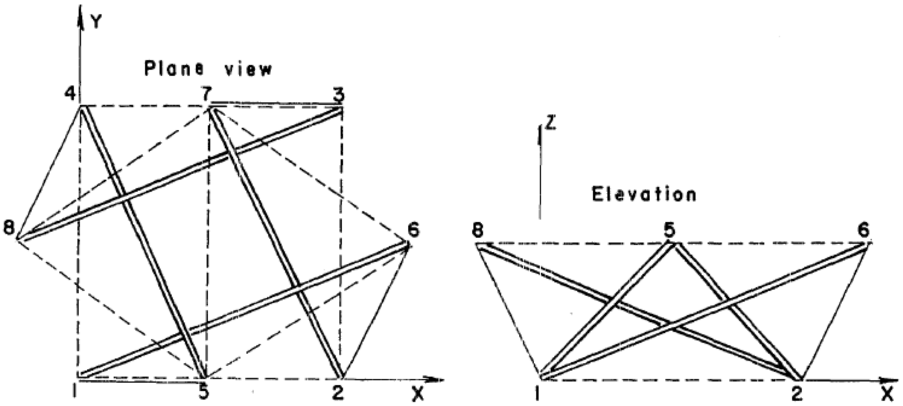

Figure 1: Simplex of tensegrity barrel vault models

At the bottom layer, the edge joints across z axis are restrained along x and y axes, and the edge joint across x axis are restrained along y and z axes. At the top layer, the edge joints across z axis are restrained along x axis and the edge joints across x axis are restrained across z axis (Figure 2).

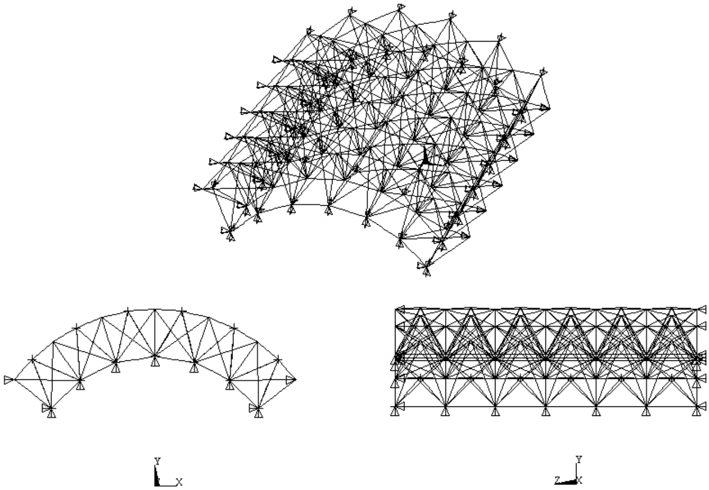

Figure 2: Layout and support conditions of tensegrity barrel vaults

Bar elements are from mild steel with F_y=240 MPa and E= 2E5 MPa. Their nonlinear behavior is taken to be bilinear as shown in Figure 3. The slenderness ratio of the bars is kept 100 for all, while their cross sectional area differ according to their axial forces. The mechanical behavior of cables is illustrated in Figure 4.

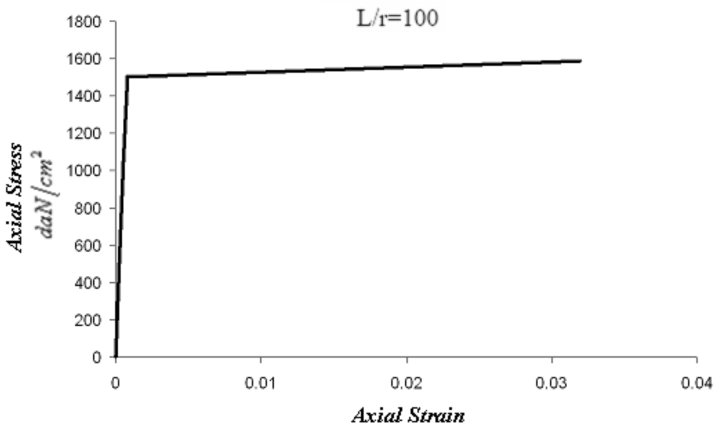

Figure 3: Stress – strain behavior of bars

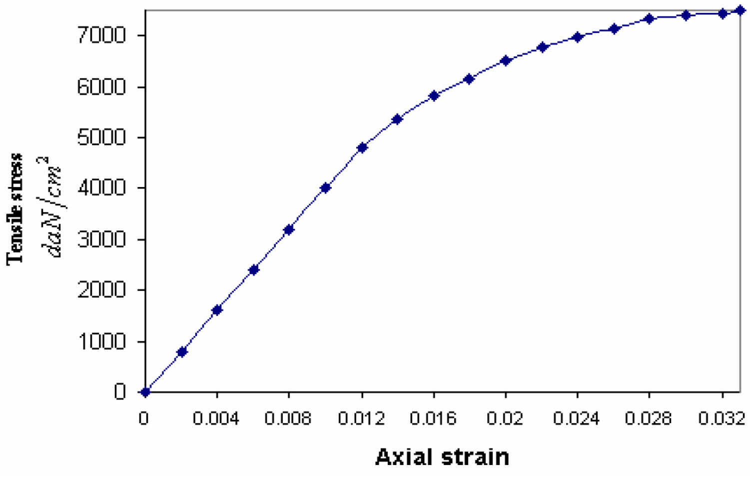

Figure 4: Stress – strain behavior of cables

Proportioning of elements is achieved by imposing a dead load and snow loading equal to 500 Pa and 1500 Pa, respectively.

The damping ratio for dynamic analyses is supposed to be 0.02.

3. Dynamic characteristics

To observe dynamic characteristics of the tensegrity barrel vaults, eignevaule analysis is carried out using ANSYS code. Some distinguished aspects of eigenvalue analysis of the tensegrity barrel vaults are presented in Figure 5.

Main Mode		H/S = 1/6				H/S = 1/4			
		is = 0.002	is = 0.004	is = 0.006	is = 0.008	is = 0.002	is = 0.004	is = 0.006	is = 0.008
x direction (Horizontal)	Mode No.	3	3	3	3	1	1	1	1
	Period (sec)	1.80	1.32	1.14	1.11	2.04	1.58	1.38	1.35
	Participation Factor	31.04	33.23	35.68	38.13	33.82	-35.73	-38.00	-40.36
y direction (Vertical)	No.	1	1	1	1	2	2	2	2
	Period (sec)	2.01	1.54	1.34	1.31	1.93	1.49	1.30	1.28
	Participation Factor	23.88	25.08	26.75	28.58	16.20	17.16	18.63	20.45

Figure 5: Dynamic characteristics of tensegrity barrel vaults

Figure 5 shows that an increase in initial strain, decreases main period. It also shows that increasing rise to span ratio makes the tensegrity barrel vaults softer in horizontal direction and stiffer in vertical direction. It is also seen that participation of the main modes in both horizontal and vertical directions increase with increase of initial strain of bars of the barrel vaults. The periods of main modes of the tensegrity barrel vaults are in the range of 1~2 seconds which are considerably larger than the main periods of double layer barrel vaults.

4. Timehistory analysis

In this research, acceleration records of two strong ground motions of Kobe1995, Japan and Tabas1978, Iran are used for time history analyses of tensegrity barrel vaults (Figure 6).

Earthquake	Kobe 1995/01/16	Tabas,Iran 1978/09/16
Record /Component	KOBE/TAZ-090	TABAS/TAB-TR
HP (Hz)	0.13	0.05
LP (Hz)	33	Null
PGA (g)	0.694	0.852
PGV (cm/s)	85.3	121.4
PGD (cm)	16.75	94.58
Record /Component	KOBE/TAZ-UP	TABAS/TAB-UP
HP (Hz)	Null	0.05
LP (Hz)	40	Null
PGA (g)	0.433	0.688
PGV (cm/s)	34.8	45.6
PGD (cm)	12.38	17.04

Figure 6: Characteristics of selected earthquakes

4.1. Earthquake horizontal effects

To assess seismic behavior of the tensegrity barrel vaults in both horizontal and vertical directions, two components of these earthquakes are applied separately. Implication of horizontal components of Tabas accelerograms resulted in rupture of cables for tensegrity barrel vaults with initial strain of 0.002 (Figure 7). But in barrel vaults with greater initial strains, imposing Tabas horizontal accelerograms caused some bars buckle (Figure 8).

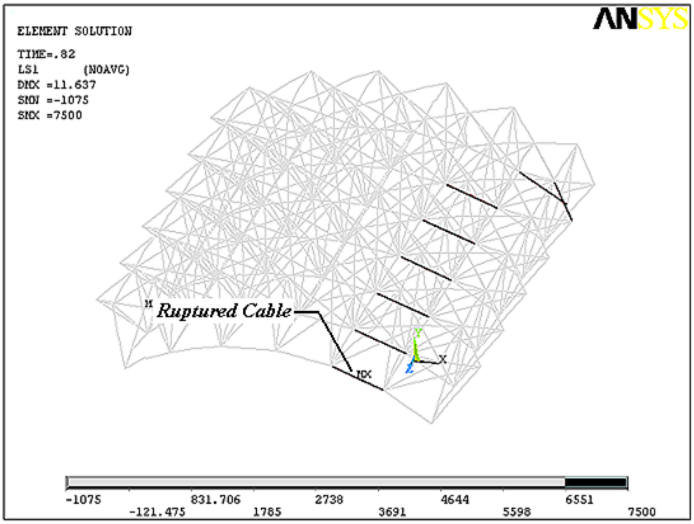

Figure 7: Layout of ruptured cables

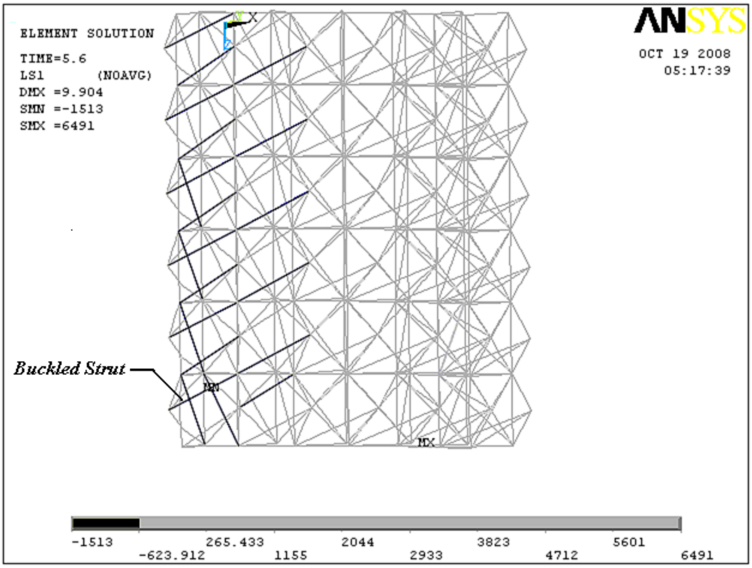

Figure 8: Layout of buckled bars

Figure 9 illustrates behavior of a ruptured cable in a tensegrity barrel vault of rise to span ratio of 1/6 and initial strain of 0.002. The illustration shows that the cable loses its strain from point B to C and it gets strained again and the increase of stress makes the cable to rupture at point D. These points are specified in Figure 10 which shows displacement of a node adjacent to ruptured cable in x –direction at corresponding times.

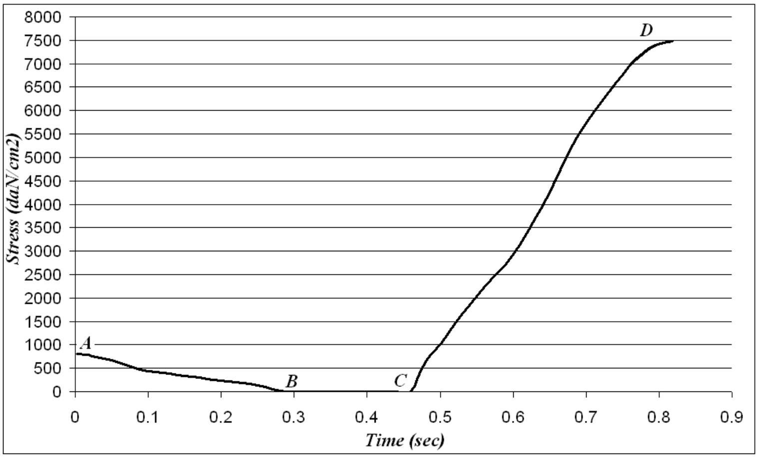

Figure 9: Behavior of ruptured cable

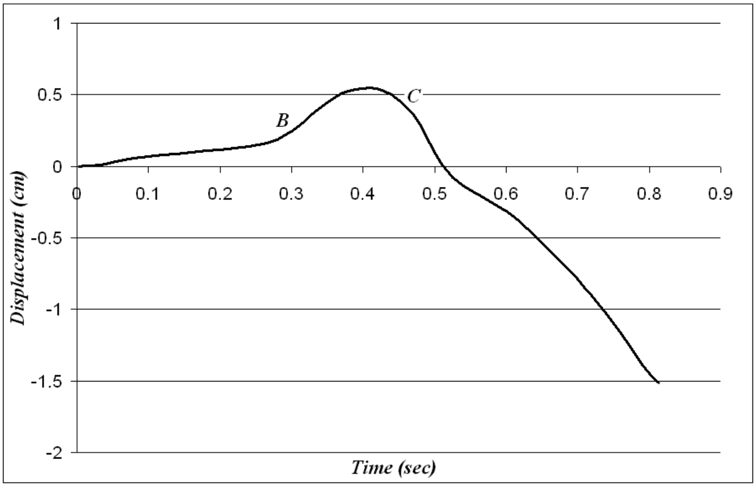

Figure 10: Displacement time history of critical node

The result of imposing horizontal accelerograms of Tabas on tensegrity barrel vaults with higher initial strains is quite different. In these circumstances, the first failure occurs in bars as buckling, Figure 8. Stress time history of a bar is shown in Figure 11 which experiences buckling at point C corresponding to a maximum deflection of the barrel vault in x direction, Figure 12. After this point the structure becomes unstable and fails at point D.

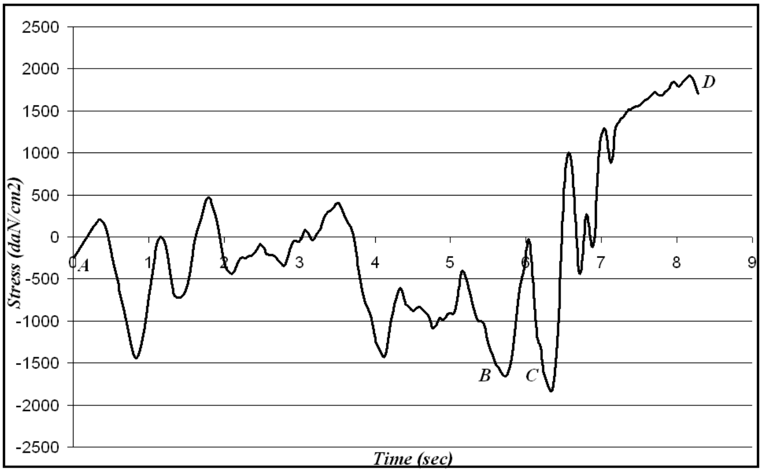

Figure 11: Stress time history of a buckled bar

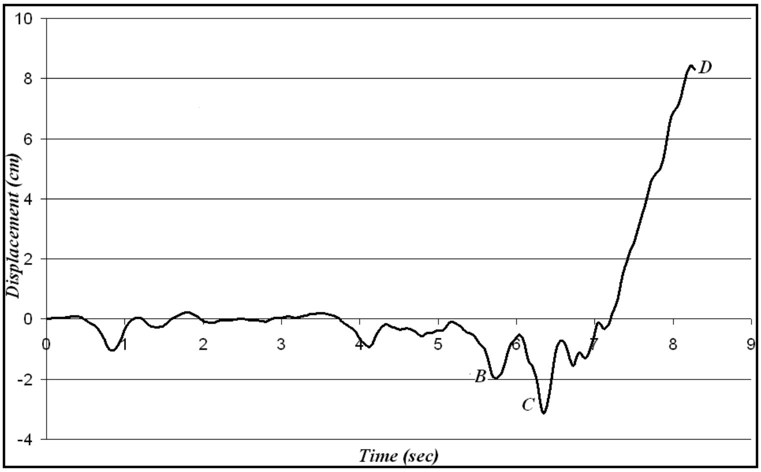

Figure 12: Deflection of a node adjacent to a buckled bar

The overall results of these analyses are summarized qualitatively in Figure 13. The Table reads that in low initial strain, that is 0.002, the failure starts by cables rupture and in high initial strain, failure is triggered by buckling of bars. Also, it is observed that higher initial strains cause the barrel vaults resist failure longer and higher rise to span ratios results in the failure occurs earlier.

		is = 0.002	is = 0.004	is = 0.006	is = 0.008
H/S = 1/6	Failure mode	Cable rupture	Bar buckling	Bar buckling	Bar buckling
	Time of failure (sec)	0.82	5.6	5.64	6.26
H/S = 1/4	Failure mode	Cable rupture	Bar buckling	Bar buckling	Bar buckling
	Time of failure (sec)	0.80	5.54	5.54	5.58

Figure 13: Failure modes of tensegrity barrel vaults under horizontal accelerograms of Tabas earthquake

More or less, similar results were achieved for Kobe horizontal accelerogram. The results summary is presented in Figure 14.

		is = 0.002	is = 0.004	is = 0.006	is = 0.008
H/S = 1/6	Failure mode	Cable rupture	Cable rupture	Bar buckling	Bar buckling
	Time of failure (sec)	2.03	2.53	2.58	2.61
H/S = 1/4	Failure mode	Cable rupture	Bar buckling	Bar buckling	Bar buckling
	Time of failure (sec)	1.99	2.06	2.13	2.16

Figure 14: Failure modes of tensegrity barrel vaults under horizontal accelerograms of Kobe earthquake

4.2. Earthquake Vertical effects

Applying vertical components of accelerograms of Tabas and Kobe earthquakes to 8 tensegrity barrel vaults showed that none of them fails and, in effect, neither buckling of bars nor rupture of cables happens. This may be interpreted as a result of relatively short spans of the models or to somewhat related to the pattern of restrained nodes of the barrel vaults, that makes them vertically stiffer.

Nevertheless, there are some points that can be considered worth of reminding. The first point is that tensegrity barrel vaults with high rise to span ratios have lower vertical deflections. Also, the results of analyses confirm that tensegrity barrel vaults with higher initial strain undergo lower deflections, Figure 15.

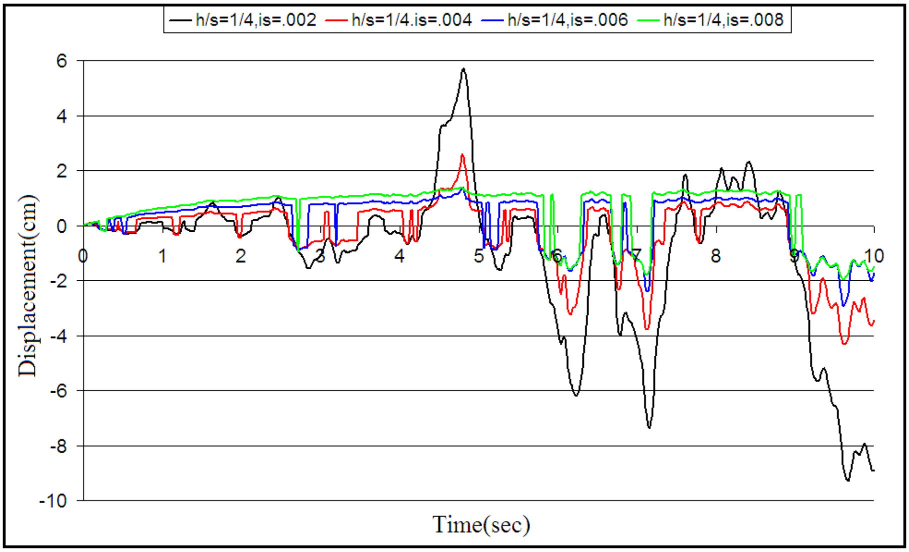

Figure 15: Comparison of displacements of barrel vaults with rise to span ratio of 1/4

5. Conclusions

1- Principal periods of the tensegrity barrel vaults increase with increase of rise to span ratios of the tensegrity barrel vaults.
2- On the contrary, the principal periods of the tensegrity barrel vaults decrease with increase of initial strain of the cables.
3- When the tensegrity barrel vaults tend towards the tensegrity flat grids, their vertical modes of dynamic response become more effective, however, with higher rise to span ratios, the horizontal modes take part more in the dynamic response.
4- When the tensegrity barrel vaults undergo horizontal accellerograms, a failure of kind of tension rupture or compression buckling occurs in the members. But under vertical accellerograms none of the rupture or buckling of the members were observed.
5- Under horizontal earthquake actions, for low initial strains, the governing failure mode is rupture of tensile elements, but for intermediate and large initial strain, that is for 0.004, 0.006 and 0.008, the failure mode is buckling of bars.
6- Tensegrity barrel vaults with higher rise to span ratios, experience relatively greater deflections under horizontal earthquakes and bear lesser deflections under vertical earthquakes.
7- Increase of the rise to span ratio makes the onset of the failure of the structure to happen earlier, while on the contrary, the increase of initial strain prolongs the failure time.