A Study on Effect of Using Reinforcing Lateral Arch-Trusses on the Seismic Behavior of Barrel Vault Structures

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SUMMARY:

In this paper the effect of using lateral reinforcing Arch Trusses (AT) in the seismic behavior of a steel single-layer barrel vault structure of Lamella type with height-to-span ratio values of 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, and 1/8 has been studied. In each case the length of the barrel vault structure has been considered once equal to its span, and once as twice as it. The structures have been designed first under gravity loads, and then have been analyzed and checked subjected to seismic loads by using equivalent static, spectral and time history analysis methods. In all cases the structure has been considered with two end ATs in case of short structures, and two ATs plus one middle AT in case of long structures. Numerical results show that using the ATs significantly decrease the lateral deformation of the structure, and therefore, improves its seismic behavior to a great extent.

Keywords: Single-layer Lamella barrel vault, End arch trusses, Time history analysis

1. INTRODUCTION

Barrel vaults are among space structures which are known as very efficient systems around the world for covering large spans spaces, particularly gymnasiums, which may be used as the temporary shelters in disasters, and therefore, are considered of high importance. Several studies have been conducted so far on the seismic behavior of space structures, including the barrel vaults, among them the oldest one seems to goes back to mid 80s (Fujiwara 1984). Some studies have been specifically conducted on barrel vaults structures (Sadeghi 2006; 2009), however, most of them have considered double-layer barrel vault structures, and there are very few works done on the single-layer barrel vaults.

In this paper the effect of using lateral reinforcing Arch Trusses (AT) in various positions along a steel single-layer barrel vault structure of Lamella type have been studied. The height of the barrel vaults has been assumed to be 5 meters in all cases, and considering the height/span values of 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, and 1/8 various span length have been have been created. In each case the length of the barrel vault structure has been considered once equal to its span, and once as twice as it. The considered structures have been designed first under gravity loads, and then they have been analyzed and checked subjected to seismic loads by equivalent static as well as spectral methods, and finally some Time History Analyses (THA) have been conducted for each case. In all cases the structure has been considered with two end ATs in case of short structures, and two ATs plus one middle AT in case of long structures. The details of the study are presented in the following sections of the paper.

2. GENERAL FEATUERS AND PRELIMINARY DESIGN OF THE CONSIDERED BARREL VAULTS

A general view of the considered barrel vaults without the Arch Trusses (AT) is shown in Figure 1, and the used AT is shown in Figure 2.

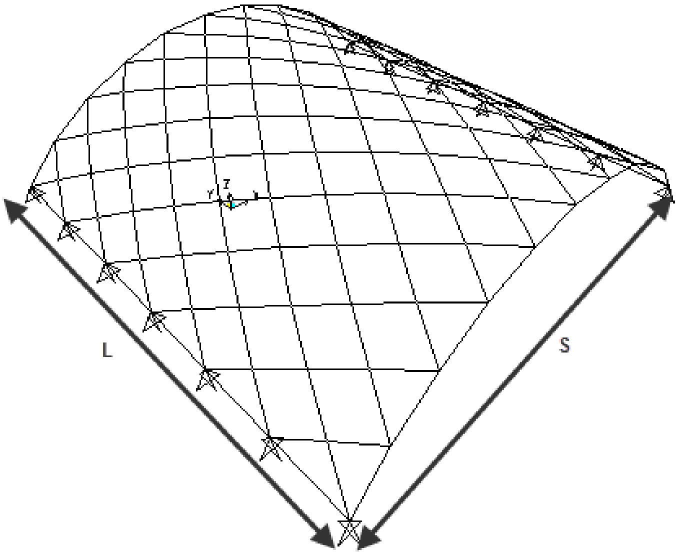

Figure 1. The general view of the considered barrel vaults without AT

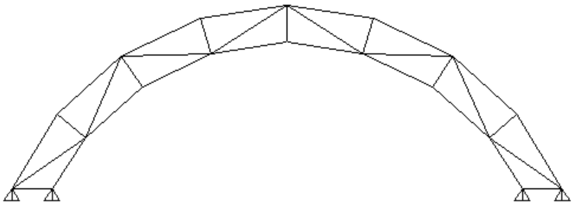

Figure 2. The considered Arch Truss (AT) for strengthening the barrel vaults

In all cases the length of the barrel vaults structural elements (pipes) has been considered to be in the range of 1.5 to 3.5 meters. The snow load and the cover load have been assumed to be, respectively, 150 and 15 kgf/m^2. Design has been based on the allowable stress method and the soil type of the site has been assumed to be of class C. It is worth mentioning that for a height of 5 m and spans of up to S=30 m the single-layer barrel vault can be deigned for gravity loads by using the common pipe profiles. However, for larger spans, say S=35 or 40 meters, common pipe profiles seem to be inadequate, and a double layer structure is needed. Instead of using double layer structure, it is proposed in this study to use two AT at both ends of the short structures (L=S) and also both ends as well as middle of the long structures (L=2S). Table 1 shows the weight of the designed barrel vaults for three cases of L=S (see Figure 1) without the ATs (see Figure 2), L=S with ATs, and L=2S with ATs.

Table 1. Weight of the designed barrel vaults (in tonf) for three cases of L=S without the ATs, L=S with ATs, and L=2S with ATs

S (m)	**Geometric Feature of the Barrel Vault**		
	L=S without AT	**L=S with AT**	**L=2S with AT**
10	2.386	1.574	2.712
15	5.836	4.992	7.366
20	15.375	13.464	18.190
25	13.132	13.497	21.900
30	50.745	43.399	62.228
35	-	54.135	101.825
40	-	124.55	178.662

Table 1 shows that using ATs generally leads to some decrease in the total weight of the barrel vault, particularly in case of short span barrel vaults, comparing to the single layer case, however, the main effect of using ATs is the change in the stiffness of the systems and therefore, change in its fundamental periods, as shown in Table 2. In these calculations a damping value of 2% has been assumed.

Table 2. The effect of using ATs on the natural periods of the single layer barrel vaults

S (m)	L=S, Without ATs			L=S, With ATs		
	No. of dominant mode	Period (sec)	Modal mass ratio	No. of dominant mode	Period (sec)	Modal mass ratio
10	1	0.393	0.647	36	0.098	0.262
15	1	0.522	0.685	9	0.16	0.567
20	1	0.535	0.498	3	0.209	0.358
25	1	0.916	0.375	9	0.286	0.315
30	1	0.707	0.294	36	0.066	0.281
35	1	-	-	55	0.058	0.168
40	1	-	-	36	0.067	0.23

It can be seen in Table 2 that for all span lengths in case of single layer barrel vault without using ATs the first mode (longest period) has been the dominant mode, while in case of the barrel vaults with ATs one of the higher modes is the mode with dominant lateral motion. The drastic shift of the dominant period of the system from long to short (from the original value to around 1/3 to 1/10 of that) due to adding the ATs is clear in Table 1 as well. It is also notable that in case of single layer systems, for S=35 and 40 meters a satisfactory design has not been achieved. In case of long structures (L=2S) similar results are obtained, which can not be given here because of lack of space, and can be found in the main report of the study (Izadi 2012).

3. TIME HISTORY ANALYSIS OF THE DESIGNED BARREL VAULTS

For Time History Analysis (THA) of the designed barrel vaults for evaluating their seismic behavior, seven set of three-component earthquake accelerograms have been chosen according to the soil type of class C, as shown in Table 3.

Table 3. Three-component earthquake accelerograms chosen according to the soil type of class C

Earthquakes	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
PGA UP	0.142	0.167	0.229	0.408	0.163	0.115	0.548
PGA 00	0.327	0.332	0.358	0.348	0.662	0.323	0.583
PGA 90	0.26	0.333	0.312	0.224	0.59	0.226	0.59

As shown in Table 3, among the selected earthquakes the vertical PGA value of the Morgan Hill earthquake is larger than its horizontal PGA values, and all three components of Northridge earthquake have almost the same PGA values, while in case of all other earthquakes the horizontal PGA values are larger than that of vertical component. As samples of acceleration time history and response spectra of the selected earthquakes those related to vertical component of Northridge earthquake are shown in Figures 3 and 4.

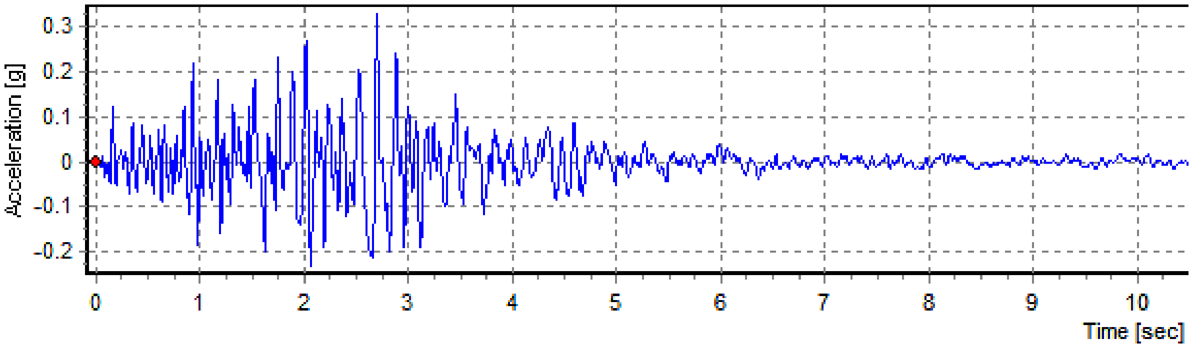

Figure 3. The acceleration time history of vertical component of Northridge earthquake

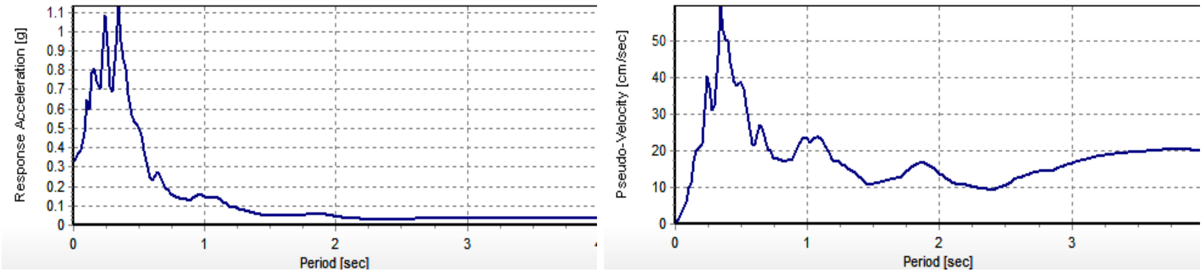

Figure 4. The pseudo acceleration and pseudo velocity spectra of the vertical component of Northridge earthquake

All the designed systems have been analyzed once by spectral method and once by THA using the seven selected earthquakes, scaled to 0.35g. Out of the result of these analyses the maximum stress ratios in the system elements, which have been divided into four groups of a) elements of the upper part of the barrel vault, b) elements of the upper chord of the ATs, c) elements of the lower chord of the ATs, and d) the diagonal element of the ATs (see Figure 4), have been considered for investigation, as shown in Tables 4 to 7 for the systems with L=S, and in Tables 8 to 11 for the systems with L=2S. In all cases of THA a damping value of 2% has been assumed for all types of domes.

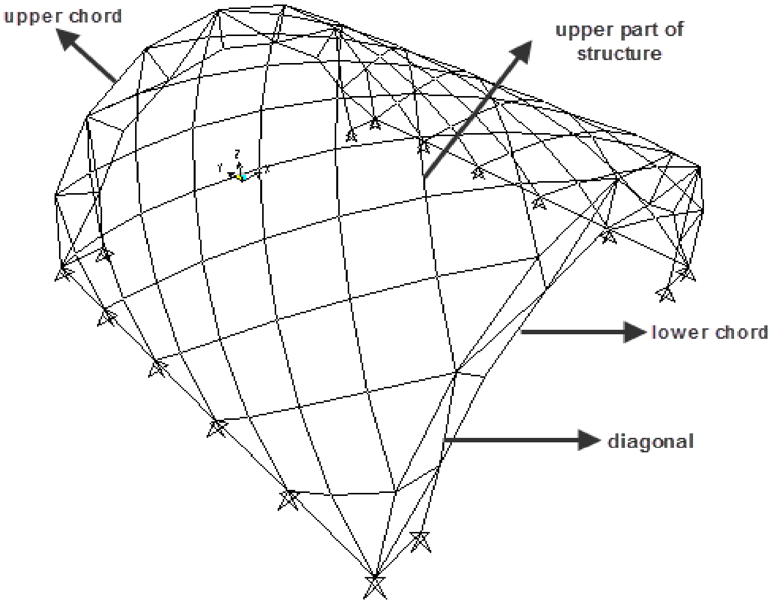

Figure 4. The general view of the considered barrel vaults with ATs in which the four groups of elements have been indicated as well

Table 4. Maximum stress ratios in the group (a) of the barrel vaults elements in case of L=S with ATs

S (m)	H/S	Elements of the upper part of the barrel vault (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.858	**1.022**	**1.005**	**1.002**	**1.02**	0.974	**1.031**	**1.0073**
S=15	1⁄3	0.991	**1.02**	**1.018**	**1.046**	**1.062**	**1.077**	**1.032**	**1.078**
S=20	1⁄4	0.886	**1.002**	0.925	**1.015**	0.968	0.925	0.924	**1.019**
S=25	1⁄5	0.929	0.963	0.954	0.968	0.951	0.96	0.976	**1.041**
S=30	1⁄6	0.999	**1.101**	**1.108**	**1.136**	**1.148**	**1.202**	**1.119**	**1.173**
S=35	1⁄7	0.995	**1.017**	**1.098**	**1.046**	**1.055**	**1.026**	**1.03**	**1.137**
S=40	1⁄8	0.991	**1.018**	**1.016**	**1.051**	**1.045**	**1.143**	**1.027**	**1.145**

Table 5. Maximum stress ratios in the group (b) of the barrel vaults elements in case of L=S with ATs

S (m)	H/S	Elements of the upper chord of the ATs (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.809	0.961	0.926	0.901	0.918	0.915	0.928	0.951
S=15	1⁄3	0.947	**1.067**	**1.053**	**1.043**	**1.104**	**1.124**	**1.057**	**1.092**
S=20	1⁄4	0.86	**1.249**	**1.018**	**1.14**	**1.032**	**1.011**	**1.034**	**1.139**
S=25	1⁄5	0.852	**1.05**	0.97	**1.102**	**1.113**	0.981	**1.033**	**1.634**
S=30	1⁄6	0.911	**1.046**	**1.071**	**1.176**	**1.085**	1.349	1.076	**1.133**
S=35	1⁄7	0.79	0.856	0.928	0.88	0.864	0.858	0.869	0.937
S=40	1⁄8	0.813	0.89	0.876	0.924	0.866	0.954	0.989	0.979

Table 6. Maximum stress ratios in the group (c) of the barrel vaults elements in case of L=S with ATs

S (m)	H/S	Elements of the lower chord of the ATs (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.613	0.913	0.86	0.801	0.779	0.904	0.788	0.987
S=15	1⁄3	0.529	0.702	0.743	0.647	0.644	1.176	0.707	0.825
S=20	1⁄4	0.987	**1.186**	**1.048**	**1.183**	**1.086**	**1.023**	**1.012**	**1.121**
S=25	1⁄5	0.954	**1.693**	**1.236**	**1.821**	**1.648**	**1.523**	**1.413**	**N/C**
S=30	1⁄6	0.898	**1.09**	**1.109**	**1.191**	**1.112**	**1.789**	**1.107**	**1.181**
S=35	1⁄7	0.876	0.968	**1.077**	**1.001**	0.97	0.965	0.985	1.067
S=40	1⁄8	0.759	0.811	0.801	0.883	0.809	0.87	0.832	0.897

Table 7. Maximum stress ratios in the group (d) of the barrel vaults elements in case of L=S with ATs

S (m)	H/S	The diagonal element of the ATS (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.735	1.116	0.92	0.824	0.893	0.855	0.858	0.932
S=15	1⁄3	0.807	**1.194**	**1.128**	0.875	0.965	**N/C**	**1.159**	**1.165**
S=20	1⁄4	0.807	**1.186**	0.926	**1.109**	0.941	0.894	0.909	**1.001**
S=25	1⁄5	0.795	**1.136**	0.83	**1.177**	**1.117**	0.833	0.911	N/C
S=30	1⁄6	0.813	0.921	0.939	**1.03**	0.95	**1.169**	0.947	0.98
S=35	1⁄7	0.907	**1.012**	**1.196**	**1.075**	**1.011**	**1.008**	**1.036**	**1.095**
S=40	1⁄8	0.923	0.989	0.974	**1.013**	0.971	**1.07**	0.997	**1.079**

Table 8. Maximum stress ratios in the group (a) of the barrel vaults elements in case of L=2S with ATs

S (m)	H/S	Elements of the upper part of the barrel vault (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.979	0.980	0.780	0.979	0.980	0.984	0.984	0.980
S=15	1⁄3	0.845	0.928	0.845	0.845	0.845	0.840	0.845	0.845
S=20	1⁄4	0.854	0.854	0.854	0.854	0.854	0.854	0.854	0.854
S=25	1⁄5	0.993	**1.142**	**1.142**	**1.142**	**1.142**	**1.142**	**1.142**	**1.177**
S=30	1⁄6	0.961	0.925	0.960	**1.033**	0.925	0.925	0.925	**1.154**
S=35	1⁄7	0.987	0.988	0.987	0.988	**0.988**	0.988	0.987	**1.004**
S=40	1⁄8	0.933	**1.012**	**1.012**	**1.012**	**1.09**	**1.012**	**1.011**	**1.012**

Table 9. Maximum stress ratios in the group (b) of the barrel vaults elements in case of L=2S with ATs

S (m)	H/S	Elements of the upper chord of the ATs (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.948	0.939	**1.824**	0.940	0.939	**2.475**	**1.059**	0.939
S=15	1⁄3	0.82	0.836	0.836	0.836	0.836	0.836	0.836	0.836
S=20	1⁄4	0.901	0.901	0.901	0.901	0.901	0.901	0.901	0.901
S=25	1⁄5	0.951	0.947	0.947	0.947	0.947	0.947	0.947	0.947
S=30	1⁄6	0.958	0.819	0.799	0.924	0.799	0.799	0.755	0.885
S=35	1⁄7	0.882	0.903	0.903	0.903	0.903	0.903	0.903	0.987
S=40	1⁄8	0.770	0.770	0.770	0.770	0.770	0.770	0.773	0.770

Table 10. Maximum stress ratios in the group (c) of the barrel vaults elements in case of L=2S with ATs

S (m)	H/S	Elements of the lower chord of the ATs (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.814	0.789	0.795	0.789	0.789	**1.091**	0.789	0.802
S=15	1⁄3	0.596	0.536	0.617	0.561	0.582	0.599	0.539	0.757
S=20	1⁄4	0.932	0.932	0.932	0.932	0.932	0.932	0.932	**1.021**
S=25	1⁄5	0.99	0.878	0.826	**1.095**	0.823	0.866	0.798	**1.599**
S=30	1⁄6	0.923	0.897	0.895	0.937	0.895	**1.003**	0.921	**1.112**
S=35	1⁄7	0.959	0.944	0.945	0.945	0.955	0.945	0.945	**1.001**
S=40	1⁄8	0.866	**1.044**	**1.047**	**1.039**	**1.038**	**1.047**	**1.047**	**1.224**

Table 11. Maximum stress ratios in the group (d) of the barrel vaults elements in case of L=2S with ATs

S (m)	H/S	The diagonal element of the ATs (see Figure 4)							
		Spectral	Imperial Valley	Whittier Narrows	Kocaeli	Morgan Hill	Cape Mendocino	Loma Prieta	Northridge
S=10	1⁄2	0.814	0.773	0.782	0.773	0.773	N/C	0.725	0.773
S=15	1⁄3	0.596	0.751	0.875	0.758	0.823	0.843	0.775	**1.01**
S=20	1⁄4	0.932	0.965	0.965	0.965	0.965	0.965	0.965	**1.050**
S=25	1⁄5	0.99	0.665	0.646	0.824	0.630	0.699	0.688	**1.031**
S=30	1⁄6	0.923	0.799	0.799	0.878	0.799	0.799	0.788	0.832
S=35	1⁄7	0.959	0.901	0.922	0.9	0.9	0.9	0.9	0.9
S=40	1⁄8	0.866	0.866	0.866	0.889	0.888	0.866	0.866	0.866

It can be seen in Tables 4 to 11 that in several cases, shown in the tables by **bold** figures, the stress ratio exceeds 1.0. As another set of the seismic analyses results, the maximum stress ratios obtained by linear THA by using the three-component accelerograms of the selected earthquakes are given in Tables 4 to 11, and cases in which the stress level in a member has the buckling level are shown as Not Calculated (N/C). This means that the designed barrel vaults are somehow vulnerable. Furthermore, it can be seen in Tables 4 to 11 that the effect of earthquake in barrel vault for L=S is more than L=2S.

4. CONCLUSIONS

Based on this study the following conclusions can be stated:

- Adding the lateral trusses, obviously, increase the stiffness of the system, and decrease its natural period, which can reach little values by using a relatively stiff truss in case of the studied structures.
- This period reduction, by using the reinforcing trusses, is more drastic in case of barrel vaults with larger height/span ratios.
- Furthermore, as expected, using lower height/span ratios results in lower period values of the system, and therefore, this ratio can be used as a control tool for obtaining the appropriate natural period.
- The appropriate value for the fundamental period of the system can be found in each case by a series of THA by using the accelerograms compatible to the site soil.
- The effect of earthquake in barrel vault for L=S is more than L=2S.
- Finally it can be said that the use of lateral arch trusses and choosing an appropriate height/span ratio are two useful tools for control of the natural period of the barrel vault system.

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