Proceedings of the 8th ***ICCAE-8*** *Conference, 25-27 May, 2010*

Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

8th International Conference
on Civil and Architecture
Engineering
ICCAE-8-2010

Investigation of the Benefits of Application of Earthquake Action on the Design of DLBVs

By

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Abstract:

Space structures are generally light and rich in redundancy. These two characteristics caused this assumption for a while that these structures are aseismic. However, some events like Kobe 1995 earthquake, Japan, showed that although the space structures are safer than ordinary structures, but are not aseismic. Sadeghi in 2004 have established some formula for assessing the equivalent static earthquake action on the double layer barrel vaults. In the current work, those formulae are considered in the design of six double layer barrel vaults with different rise to span ratios and support conditions. Then the seismic behavior of these double layer barrel vaults are compared with corresponding barrel vaults which are designed without considering the seismic actions. To do this, the finite element package of ANSYS is utilized. The results show that these formulae are practically useful and versatile and application of them on the barrel vaults improves the structures' seismic safety significantly.

Keywords:

Double layer barrel vaults, seismic behavior, dynamic nonlinear analysis

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1. Introduction:

Space structures are widely used for coverage of large areas like sport arenas, gymnasiums, transportation terminals and etc. These structures have been used as shelters aftermath of strong ground motions by home lost people, as well. Both the above reasons make it necessary that enough care should be taken in the design and construction of these structures to make them safe enough in earthquake prone areas. Unfortunately, there is not available code of practice for seismic loading and design of space structures like the barrel vaults or domes. However, there are some primitive efforts that may lead to satisfaction of this need. One of these efforts is a research carried out by Sadeghi 2002. He studied the seismic behavior of double layer barrel vaults and introduced some formulae for defining equivalent earthquake loadings acting on the double layer barrel vaults. In the current paper, these formulae are examined and their versatility is being addressed.

2. Models, Loads and Analysis methods:

For the assessing of the versatility of formulae introduced by Sadeghi, two groups of double layer barrel vaults are constructed. In each group, there are three double layer barrel vaults with rise to span ratios of 0.15, 0.3 and 0.45. The length, span and depth of these models are 42, 30 and 1.5 meters. The distinction of models of groups is their support conditions. In group *A*, simple supports are considered for only the edge nodes of the barrel vaults. In group *B*, the supports are assigned for all the surrounding nodes of the bottom layer.

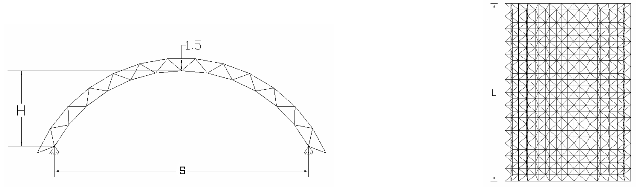

***Figure 1:** Layout of double layer barrel vaults*

At first, all the models are constructed by Formian which is a formex algebra based software developed by Professor Nooshin in the University of SURREY(1). Then for design and linear analysis, the models are input to SAP2000 through a medium package named Mechanical Desktop.

In the process of design, these 6 models are proportioned twice. Once, they are designed just under the action of dead and snow loading (symmetric and asymmetric) and then, the models are designed considering dead, snow and equivalent earthquake loadings introduced by Sadeghi.

In 2004, Sadeghi (2) developed some formulae for assessing the equivalent earthquake loading on the double layer barrel vaults as following:

$$V_b = CHo * Wt \qquad (1)$$

Where, V_b is the total base shear, CH_0 is the lateral earthquake coefficient and W_t is the total weight of the barrel vaults. In this formula, CH_0 is obtained by:

$$CHo = \alpha[SA(T_1)/g] \qquad (2)$$

Where, α is a constant, $SA(T_1)$ is the response acceleration of the site for first mode of the structure, T_1 is the period of the first horizontal mode and g is the gravity acceleration. The coefficient of α is 7.5 for barrel vaults with just supports along all the nodes of edge nodes (condition *A*) and 8.5 for barrel vaults supported on all surrounding nodes (condition *B*).
Then, the calculated V_b can be distributed vertically on the barrel vault by the following set of formulae:

$$0.3 \le \frac{h_i}{H} \le 0.96 \Rightarrow \frac{Fi}{V_b} = 0.135 \qquad (3)$$

$$\frac{h_i}{H} \le 0.3 \Rightarrow \frac{Fi}{V_b} = 0.27\left(\frac{h_i}{H} + 0.2\right) \qquad (4)$$

$$0.96 \le \frac{h_i}{H} \le 1.0 \Rightarrow \frac{Fi}{V_b} = 0.1.875\left(1.032 - \frac{h_i}{H}\right)$$

(5)

Where *H* is the maximum rise of the double layer barrel vault from the ground supports level, h_i is the length of the i^{th} node and F_i is the equivalent earthquake loading of the i^{th} node. In the process of assessing these formulae, it was found that a minor modification should be applied to these relations. Therefore, the modification is explained in the following. The modification is carried out by multiplying all the nodal forces, F_i, by a correction factor of δ extracted from following:

$$\delta = \frac{V}{\sum F_i} \qquad (6)$$

Therefore, at first the nodal forces, F_i, should be calculated from the relation 6 to 9 and then ΣF_i should be calculated and when δ is in hand, the nodal forces should be corrected by multiplying it to nodal forces:

$$F_i^{'} = \delta \times F_i \tag{7}$$

Where $F_i^{'}$ is the modified nodal forces and F_i is primary nodal forces obtained from equations 6 to 9.

The applied load combinations for the models are shown in Table 1. The models which in their design, earthquake is not considered are named as *D* models and the models which in their design, earthquake loading is considered are named as *E* models. The models identification is done by two characters and two digits. The first character, that is *B*, stands for the double layer barrel vault and the second character stands for supports conditions, say *A* or *B*. The digits are the rise to span ratio of the barrel vault in percentage, for example *15* stands for a rise to span ratio of 0.15.

The weight of the designed double layer barrel vaults of *D* and *E* models and weight increase in *E* models are given in Table 2.

***Table 1**: Load combination for models*

Without earthquake	With earthquake
DL DL + SL	DL DL + SL 0.75(DL + SL +EX) 0.75(DL + SL – EX) 0.75(DL + EX) 0.75(DL – EX)

***Table 2**: Weight of the models in kg*

Model ID	Total Steel Wight in D models, in kg	Total Steel Wight in E models, in kg	Weight Increase of E models to D models in %
BA15	15083	15052	0
BA30	13871	17420	25.6
BA45	19077	29250	53.3
BB15	12534	12517	0
BB30	11469	13463	17.4
BB45	14822	16889	13.9

Table 2 shows that consideration of equivalent earthquake loading in design of the double layer barrel vaults, results in an increase in the total weight of these structures. However, this increase is dependant on the rise to span ratio of the barrel vaults and varies from 0 to 53 percent. Also, the table shows that the weight increase for models with support conditions *A* is more than for models with support conditions *B*.

3. Dynamic analysis results:

To investigate the versatility of earthquake action formulae in the design of the barrel vaults, all the models are analyzed dynamically nonlinear. The damping ratio for all the models is taken as 0.02. In these analyses, both the geometric and material nonlinearities are considered. The material nonlinearity is selected from the work of Ishikawa et al (3) where for the models of this research the slenderness ratio is kept as 100.

The analyses are carried out using ANSYS general purpose finite element package. For modeling of the elements of the barrel vaults, COMBIN39 is used. Also, MASS21 is utilized to assign mass to the nodes of the barrel vaults.

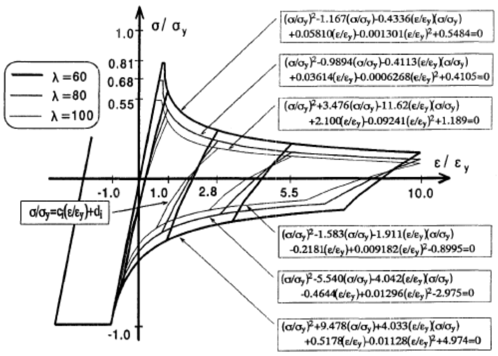

Figure 2: *Ishikawa post-buckling model for bars(3)*

For the purpose of dynamic analysis, the horizontal records of three strong earthquakes are selected. These earthquakes are Tabas1978 of Iran, Kobe1995 of Japan and Chi-Chi2002 of Taiwan.

4. Analyses results:

The nonlinear dynamic analyses of the models show that in general, the application of equivalent earthquake loading in the design of the double layer barrel vaults, significantly improves their behavior. The improvement consists of diminishing the deflections of the structure and decreasing of the number of buckled elements. For example, the results of these analyses for the double layer barrel vaults with support conditions A and B under Tabas accelerogram are presented briefly in Tables 3 and 4, correspondingly.

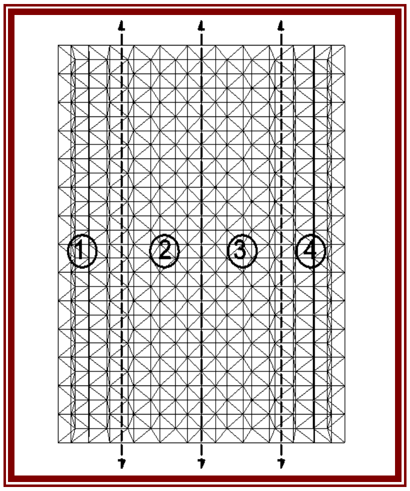

***Figure 3**: Regions of the barrel vault*

As Tables 3 and 4 show, the application of equivalent earthquake action introduced by Sadeghi in design of the double layer barrel vaults, is very effective in support condition A. so that, the number of the buckled elements falls down from 52 to 6 for the barrel vaults with rise to span ratio of 0.3 and to zero from 58 in the double layer barrel vaults with rise to span ratio of 0.45.

***Table 3**: Some information for models with support conditions A under Tabas accelerogram*

Model ID	BA15		BA30		BA45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	1.70	1.70	6.04	5.40	25.10	5.79
Deflection in Y dir, cm	1.16	1.16	5.00	1.70	11.80	2.64
Time of first buckling	-	-	4.20	5.88	4.82	No buckling
Location of first buckling	-	-	Region 4 Upper layer	Region 4 Upper layer	Region 4 Upper layer	-
No of buckled elements	-	-	52	6	58	-

This effect is not similar for the barrel vaults with support conditions B. where, the number of buckled members remains considerable after decreasing. Nevertheless, the buckling time increases for all models.

Table 4*: Some information for models with support conditions B under Tabas accelerogram*

Model ID	BB15		BB30		BB45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	1.21	1.23	6.23	4.50	1.91	2.52
Deflection in Y dir, cm	0.44	1.98	5.14	1.90	5.56	3.47
Time of first buckling	4.44	-	3.68	4.60	4.16	4.60
Location of first buckling	Region 1 Lower layer	-	Region 4 Upper layer	Region 2&3 web layer	Region 2&3 Web layer	Region 2&3 Web layer
No of buckled elements	2	--	82	68	72	40

The results of analyses of the structures under the horizontal accelerogram of Kobe are presented in Tables 5 and 6.

Table 5*: Some information for models with support conditions A under Kobe accelerogram*

Model ID	BA15		BA30		BA45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	0.46	0.45	30.37	3.32	93.12	11.79
Deflection in Y dir, cm	0.83	0.81	21.51	2.29	47.83	2.16
Time of first buckling	-	-	2.18	-	2.3	3.02
Location of first buckling	-	-	Region 1 Upper layer	-	Region 1 Upper layer	Region 1 web layer
No of buckled elements	-	-	103	-	96	26

***Table 6**: Some information for models with support conditions B under Kobe accelerogram*

Model ID	BB15		BB30		BB45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	4.46	0.5	6.77	1.50	2.96	1.80
Deflection in Y dir, cm	0.85	0.92	5.57	5.46	7.58	0.45
Time of first buckling	-	-	3.06	-	2.12	-
Location of first buckling	-	-	Region 4 Upper layer	-	Region 1 Web layer	-
No of buckled elements	-	-	64	-	84	-

In this case, the formulae are completely versatile for support conditions B and very effective for the models with support conditions A.

Tables 7 and 8 show that the application of the earthquake action during the design of the double layer barrel vaults, improves the behavior of these structures, effectively.

***Table** 7: Some information for models with support conditions A under Chi-Chi accelerogram*

Model ID	BA15		BA30		BA45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	0.61	0.61	15.74	2.70	39.17	11.79
Deflection in Y dir, cm	1.08	0.96	11.05	0.90	18.18	2.16
Time of first buckling	-	-	3.18	-	3.26	-
Location of first buckling	-	-	Region 1 Upper layer	-	Region 1 Upper layer	-
No of buckled elements	-	-	86	-	70	-

***Table 8**: Some information for models with support conditions B under Chi-Chi accelerogram*

Model ID	BB15		BB30		BB45	
	D models	E models	D models	E models	D models	E models
Deflection in X dir, cm	4.66	0.46	6.12	2.20	3.07	2.75
Deflection in Y dir, cm	0.84	0.83	1.77	0.99	3.25	0.63
Time of first buckling	-	-	9.22	-	9.21	-
Location of first buckling	-	-	Region 4 Upper layer	-	Region 3 Web layer	-
No of buckled elements	-	-	35	-	52	-

5. Conclusions:

1- Deflections of the barrel vaults for the models designed without consideration of the earthquake effects (*D* models) is larger than for the models designed considering equivalent earthquake actions (*E* models).
2- Buckling time threshold of members in *D* models is less than the *E* models, that is *D* models experience the buckling earlier.
3- The number of buckled elements in *D* models is considerably more than the *E* models and in fact, in most cases no buckling takes place for *E* models.
4- In the double layer barrel vaults with low rise to span ratios, like 0.15, consideration of the horizontal earthquake action is not useful and they can be designed without taking account the horizontal earthquake effects.

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