A study on Dynamic behaviour of Braced Barrel Vault Space Structures

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Abstract.
To cover large areas without the use of intermediate columns or with the use of a small number of intermediate columns, space structures are commonly used. Light weight, elegant appearance, fast development, and ease of erection are all important characteristics of these structures. Barrel vaults are a type of latticed space structure that is arched in only one direction. The dynamic response of square-on-square offset steel barrel vault structures with various angles of curvature and depths is the focus of the analysis. The dynamic responses of the analytical model in the X, Y, and Z directions when exposed to a horizontal earthquake are investigated. Linear dynamic analysis (time history analysis) is carried out using SAP 2000 V22 program to examine the performance of the barrel vault during seismic loading. The barrel vault model with a 90° open angle generated the most efficient results for horizontal ground motions, according to the results.

Keywords: SAP2000 V22 program, Barrel Vault, Time-History Analysis, Open Angle
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1. Introduction

The term "space structure" mentions a structural system that includes three dimensions. This is the indifference with a "plane structure", such as a plane truss, which has only two dimensions. To explain, in the case of a plane structure, both the external loads and the internal forces are in a single plane [1]. Barrel vault is one of the families of space structure that involves three dimensions [2]. It is composed of member elements arranged on a cylindrical surface. A standard curve is a circular section; a parabola or an ellipse may also be used on occasion. Many different types of bracing have been used in the construction of single-layer braced barrel vaults, Orthogonal grid with single bracing of Warren truss (a), Orthogonal grid with single bracing of Pratt truss (b), Orthogonal grid with double bracing (c), Lamella (d), Three way (e). (Fig1) shows five principal types [3].

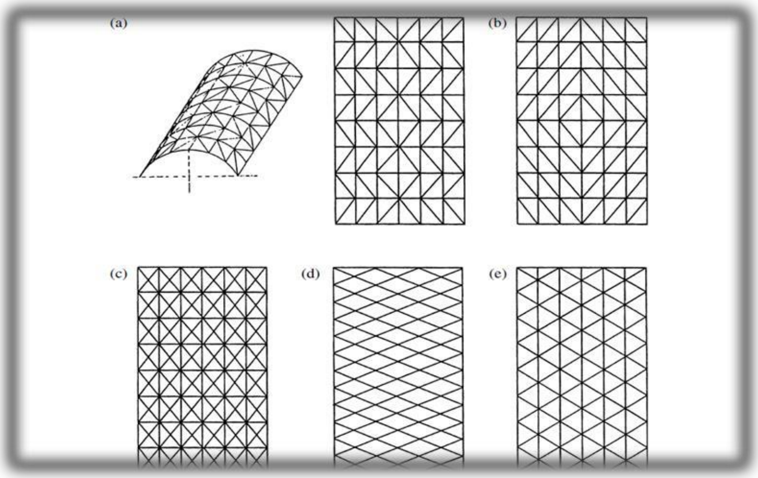


Figure (1): Types of bracing for braced barrel vaults [3].

A series of previous research about barrel vault that is considered as a type of space frame structures under dynamic and static loading, presented in chronological order, to show how the technology has developed. D Shougun et al (1993), Investigated the stability behavior of barrel vaults. The influence factors investigated include four configurations (vault A is a rectangular configuration without diagonal bracing, while B and C are with diagonal bracing and vault D is an isosceles triangle configuration), ratio of longitudinal span to transverse span and height to transverse-span ratio. The results showed that the vaults formed from isosceles triangles exhibit superior stability behavior compared with the other three types of configurations of vaults and its structural weight also is the lowest. Also, reducing the ratio of longitudinal span to transverse span and increasing the height-to-span ratio are effective ways to improve the stability of single layer barrel vaults. N Subramanian and P Mahadevappa (1988), the buckling behavior of braced barrel vaults was investigated in this paper. These experiments were also planned to examine the effects of a few main variables, such as edge trusses. Two types of single bay braced barrel vaults were designed and tested to failure, one with edge trusses and the other without. Another double-layer model with the same bracing pattern was made and checked to the point of buckling. A two-bay braced barrel vault model was also designed and tested up to failure. The behavior of these structures could be determined to within 10% accuracy using the computer programs produced, according to a comparison of theoretical results with experimental values. As a result, the authors' suggested nonlinear buckling analysis can be used to obtain the buckling loads with adequate precision. It's also been concluded that adding an edge truss to these structures enhances the performance. A Sadeghi (2004), The linear and nonlinear behavior of barrel vaults was studied during earthquakes with horizontal components. The offset pattern used was square-on-square. For the barrel vaults, three configurations with rise to span ratios of 0.15, 0.30, and 0.45 were chosen. Using eigen value analysis, the dynamic characteristics of the barrel vaults were found. LUSAS software was used in this work.

The study found that barrel vaults are vulnerable to earthquakes and exhibit brittle behavior, requiring careful design. R Surya (2014), Studied the buckling behaviour of braced barrel vault. STAAD Pro V8i was used to analyze the structure. From the instability analysis, the results showed that the maximum forces on the member are greater than the applied load hence the structure are safe against buckling. A Karim et al (2015), Nonlinear collapse analysis was used to examine the stability of a single-layer barrel vault with a lamella pattern, considering the effects of purlins. In all cases, the stability behavior of these structures with and without the purlins had been compared. The results of the study showed that the purlins can change the instability mode of structures. S Jadhav and PS Patil (2019), Introduced a computer analysis of double layer steel braced barrel vault. Four different vault configurations such that diagonal on square (DOS), square on square (SOS), square on diagonal (SOD) and diagonal on diagonal (DOD) were modeled and analyzed in Staad pro software. The results for maximum nodal deflection and axial forces in members for a particular group of elements were compared. The results showed that the square on square geometry and diagonal on square (DOS) has minimum deflection and axial forces. Hence they are optimum. In the current research, Finite Element (FE) models were employed using SAP2000 V22 software to investigate the impact of open angle and depth on the barrel vault's dynamic analysis

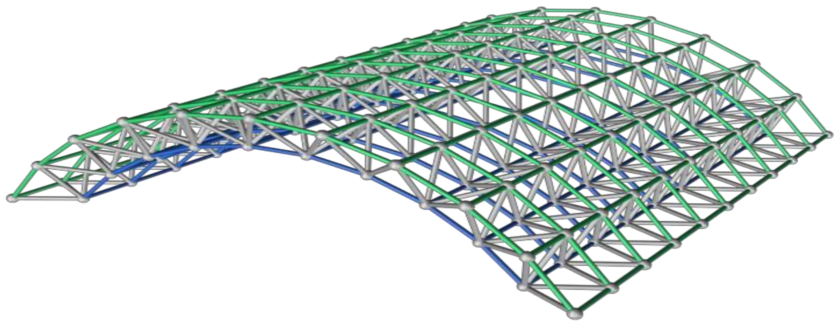
2. Finite Element Modeling

For the finite element analysis in this study, the computer software SAP2000 program is used. For structural formulation, the SAP2000 program has a variety of element forms [10]. A frame element is represented as a straight line that connects two points. In the graphical user interface, you can divide curved objects into several straight objects, subject to your specification. At each node, the element has six degrees of freedom: x, y, and z translations, as well as rotations around the x, y, and z axes. These elements were used to model and analyze the structure's top chords, bottom chords, and bracing members [10].

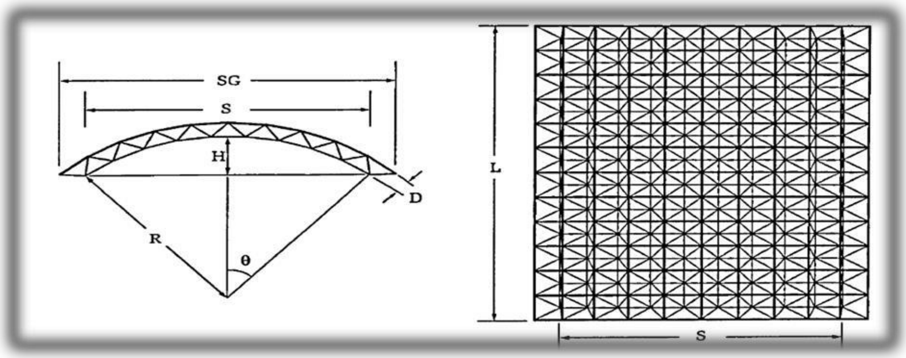
3. Results

3.1 Model Discription

This research is used of the square-on-square offset patternFig(2). For the barrel vaults the angle of curvature (represented by θ) was set from 90° to170° at 40° intervals are selected. The height of the top and bottom chords defines the depth of a double layer barrel vault (represented by D). In the current work, the depth of the double layer barrel vaults is varied between 1 and 1.5 m at 0.25 m intervals. The barrel vaults' length, span, and module angle are all kept constant at30 m, 30 m and 30° respectively. Pin-jointed connections are used to connect the elements of barrel vaults. The hinge supports are used for all barrel vault joints along the longitudinal edges. The model members are defined as steel frame under the specification of ASTM (American Society of Testing and Material) A36. A round pipe is used as the model's frame section. The geometry of barrel vault is presented in Fig(3).



Figure(2): Barrel vault with square-on-square offset.



Figure(3): Barrel vaults' geometric properties.

3.2 Forced vibration Analysis:

3.2.1 The effect of curvature angle on the dynamic response of a barrel vault (in the X,Y and Z-direction)

The linear dynamic analyses are carried out for the barrel vaults, using the earthquake's horizontal component. The results of these analyses are shown for the barrel vault with (θ) from 90° to 170° at 40° intervals in Table (1). In this table, the maximum displacement in the X-direction for each structure during the earthquakes is listed.

Table (1) Effect of angle of curvature on maximum displacements (mm) (in the X direction).

	ρ =30°		
D(m)	90°	130°	170°
1	0.069	0.109	0.157
redaction%	56.05%	30.57%	0
1.25	0.065	0.1	0.201
redaction%	67.66%	50.25%	0
1.5	0.062	0.19	0.28
redaction%	77.86%	32.14%	0

To find out the dynamic behavior of barrel vault structures with different angles of curvature, another set of figures and tables are provided. Figure (4) to (6) shows the relationship between the displacement and period of the earthquake at the joint of maximum displacement (in the X direction).

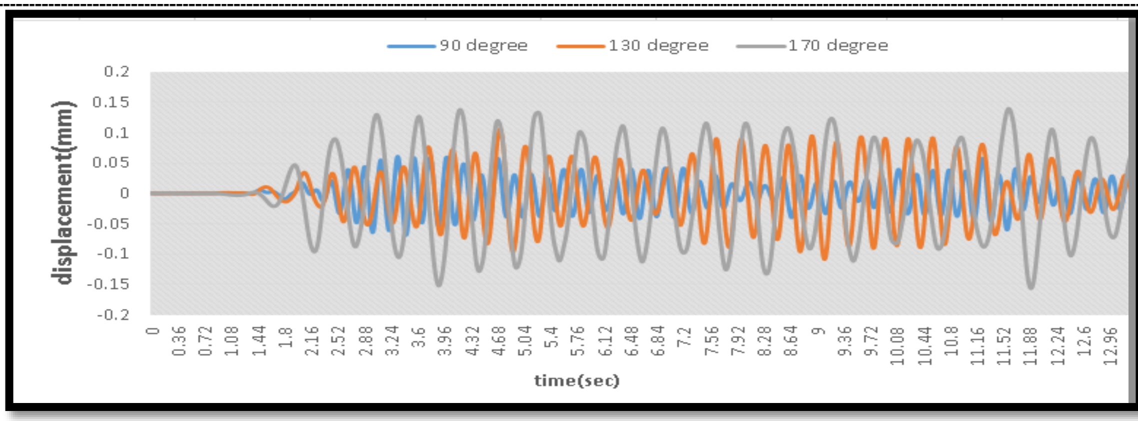


Figure (4): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1 m, ρ=30° (in the X direction).

NeuroQuantology | November 2021 | Volume 19 | Issue 11 |Page 563-580| doi: 10.48047/nq.2021.19.11.NQ21261
Bhagirathi Tripathy et al/ A study on Dynamic behaviour of Braced Barrel Vault Space Structures

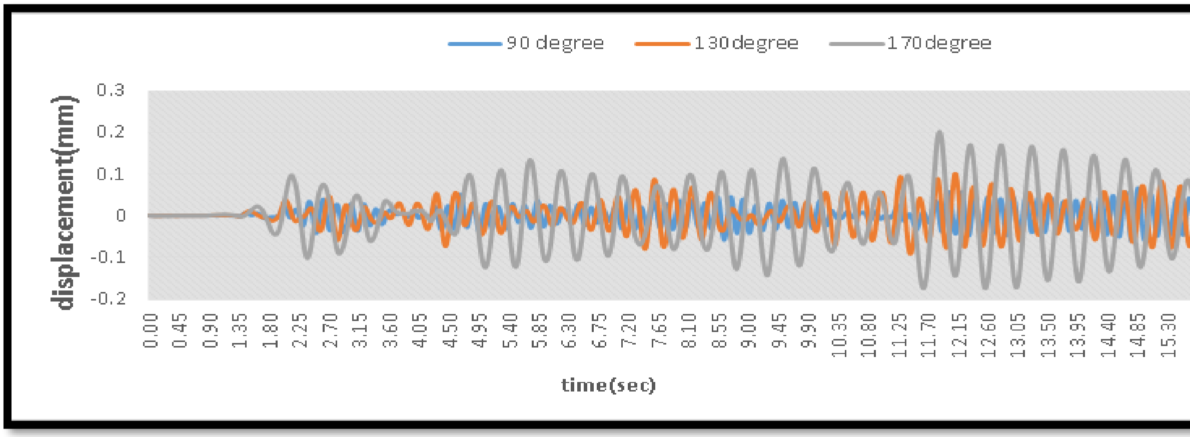


Figure (5): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.25m, ρ=30° (in the X direction).

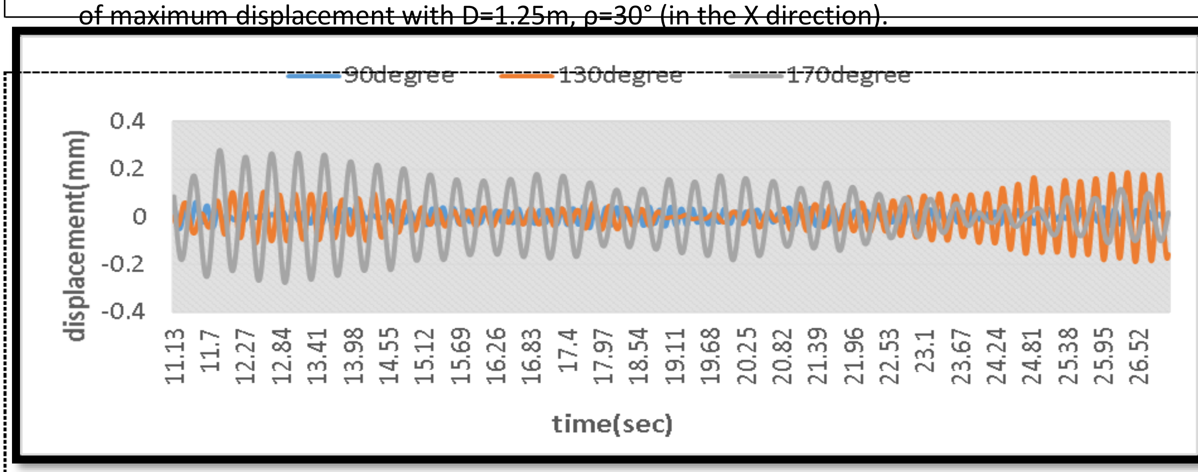


Figure (6): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.5m, ρ=30° (in the X direction).

Figure (4) shows that the vault with an open-angle of 170°, D=1m and ρ = 30°, gives the highest displacement values in all three models. When compared with cases with open angles of 130° and 90°, the maximum displacement is reduced by 30.57 % and 56.05 % respectively.

For the barrel vault with θ=130° and 90°, the values of the maximum displacement are less by percentages 50.25% and 67.66% respectively compared with the reference model with θ=170° D=1.25 m and ρ = 30° (Figure 5).

By taking the barrel vaults with θ=170°, D=1.5m and ρ =30° as a basis of comparison, the maximum displacement is reduced by 32.14% and 77.86% for the models with open angles of 130° and 90° respectively Figure (6). It is evident that in the case of small values of angles, the lowest values of displacements were obtained. This is may be attributed to the double-layer barrel vaults with a lower rise-to-span ratio that is nearly flat, the vertical mode is more effective.

The maximum displacement in the Y-direction for each model is presented in Table (2). Figures (7) to (9) show the relationship between the displacement and period of the earthquake at the joint of maximum displacement (in the Y direction).

Table (2) Effect of angle of curvature on max displacements (mm) (in the Y direction).

	ρ =30°		
D(m)	90°	130°	170°
1	7.20	20.44	52.59
redaction%	86.31%	61.13%	0
1.25	5.20	13.74	49.84
redaction%	89.57%	72.43%	0
1.5	4.03	20.46	53.04
redaction%	92.40%	61.43%	0

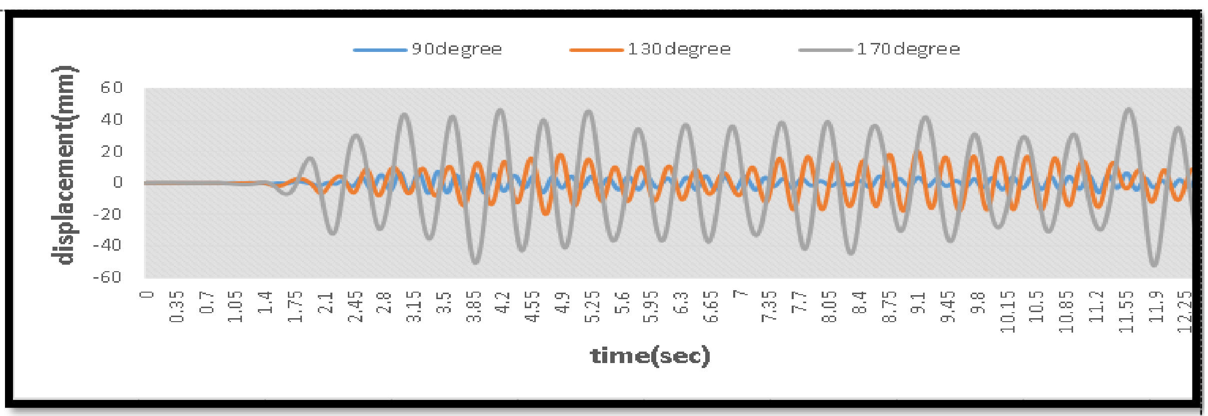


Figure (7): Relationship between the displacement and period of the earthquake at the joint of max. displacement with D=1 m, ρ=30° (in the Y direction).

NeuroQuantology | November 2021 | Volume 19 | Issue 11 |Page 563-580| doi: 10.48047/nq.2021.19.11.NQ21261

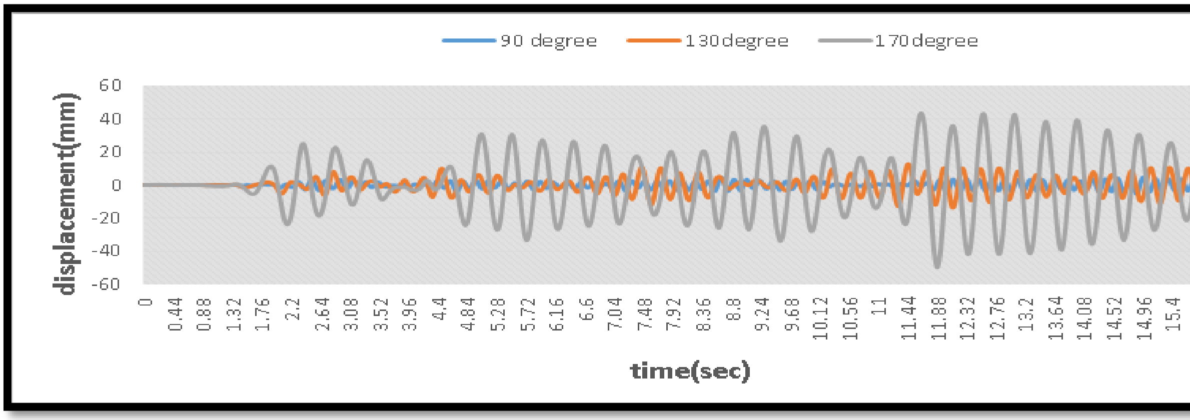


Figure (8): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.25m, ρ=30° (in the Y direction).

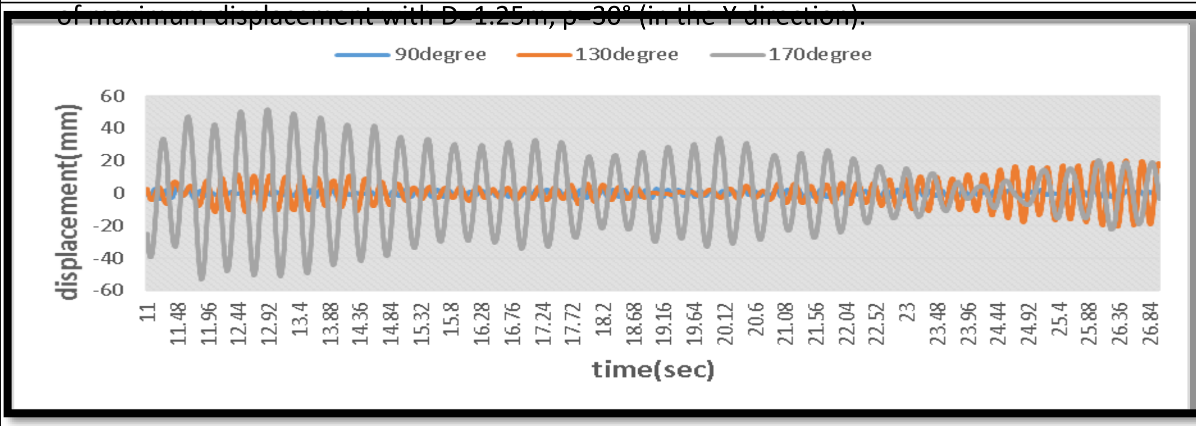


Figure (9): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.5m, ρ=30° (in the Y direction).

Comparing the three different models with open angles 90°, 130° and 180° in Figs(7), (8) and(9), the barrel vaults of 90° gives small-displacement (i.e. by taking the barrel vaults with θ=170°, D=1.5m and ρ =30° as a basis of comparison, the maximum displacement is reduced by 61.43% and 92.4% for the models with open angles of 130° and 90° respectively).

The maximum displacement in the Z-direction for each model is presented in Table (3). Figures (10) to (12) show the relationship between the displacement and period of the earthquake at the joint of maximum displacement (in the Z direction).

Table (3) Effect of angle of curvature on maximum displacements (mm) (in the Z direction).

	ρ =30°		
D(m)	90°	130°	170°
1	7.62	13.08	18.33
redaction%	58.43%	28.64%	0
1.25	5.15	8.37	16.96
redaction%	69.63%	50.65%	0
1.5	3.75	11.82	17.24
redaction%	78.25%	31.44%	0

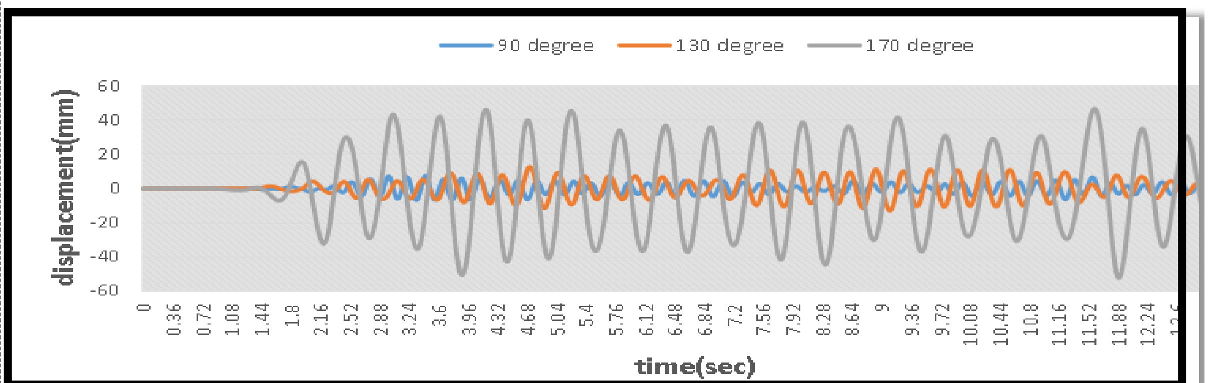


Figure (10): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1 m, ρ=30° (in the Z direction).

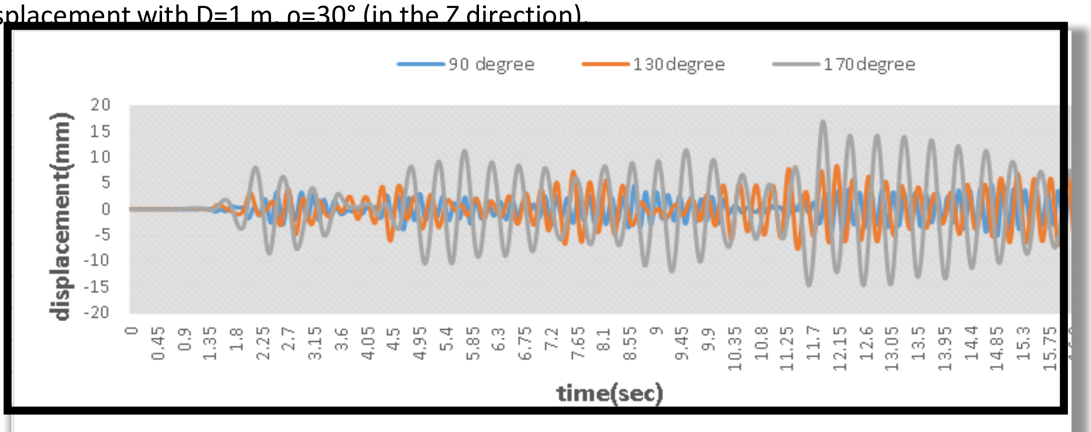
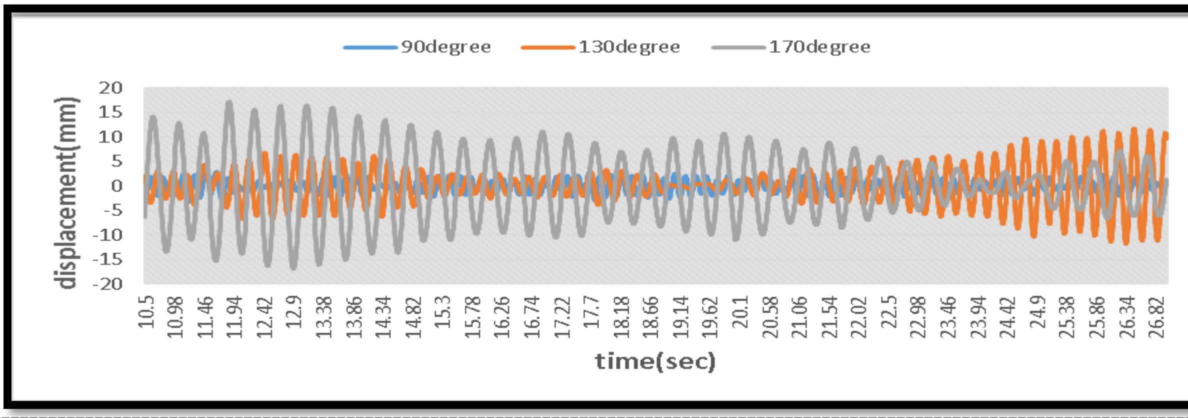


Figure (11): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.25m, ρ=30° (in the Z direction).

Figure (12): Relationship between the displacement and period of the earthquake at the joint of maximum displacement with D=1.5m, ρ=30° (in the Z direction).



By taking the barrel vaults with θ=170°as a basis of comparison, the maximum displacement is reduced by 28.64% and 58.43% for the models with open angles of 130° and 90° respectively Fig (10). Fig (11) explains that the results of maximum displacement for cases of open angles of 130° and 90° are reduced by 50.65% and 69.63% respectively. The biggest value reduction of maximum displacement had occurred in the vault with an open angle of 90° Fig (12).

3.2.2 Effect of depth on the dynamic response of barrel vault (in the X, Y and Z-direction)

To consider the dynamic responses of barrel vault structures exposed to a horizontal component of the earthquake, models with depths vary from 1m to 1.5m at 0.25m intervals are considered in this study. Table (4) is listed the maximum displacement in the X-direction for each structure.

Table (4) Effect of depth on maximum displacements (mm) (in the X direction).

Open angles		ρ =30°	
	D=1m	D=1.25m	D=1.5m
9	0.069	0.065	0.062
redaction%	0	5.80%	10.14%
130°	0.109	0	0.190
redaction%	42.63%	47.37%	0
170°	0.157	0.201	0.2
redaction%	43.93%	28.21%	0

Figures from (13) to (15) show the relationship between the displacement and period of the earthquake at the joint of maximum displacement(in the X direction).

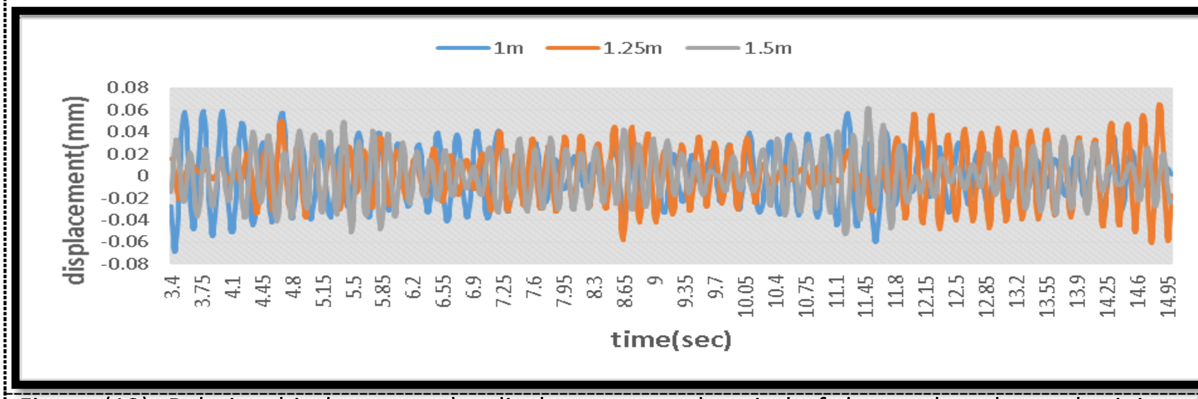


Figure (13): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =90°, ρ =30° (in the X direction).

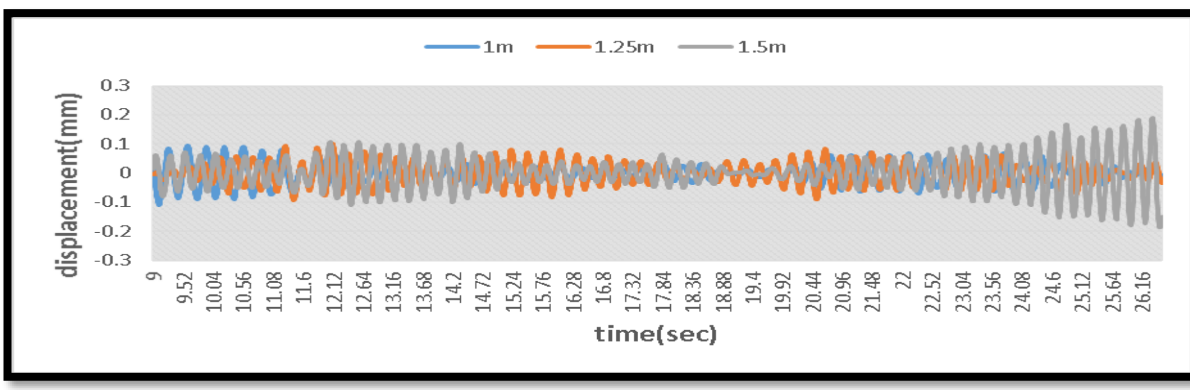


Figure (14): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =130°, ρ =30° (in the X direction).

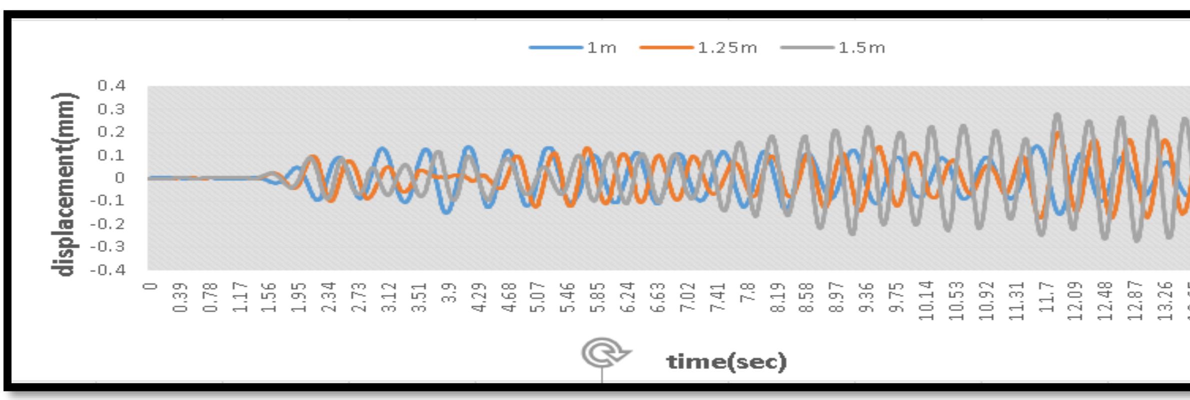


Figure (15): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =170°, ρ =30° (in the X direction).

Figure (13) shows that the vault of the depth of 1m, θ =90° and ρ =30°, gives the highest displacement values in all three models. When compared with cases of depths of 1.25m and 1.5m, the maximum displacement is reduced by 5.80% and 10.14% respectively.

It is clear from Figure (14) that, the maximum displacement for the vault of depth 1.5m is greater than the vaults of depths of 1m and 1.25m by 42.63% and 47.37% respectively.

By taking the barrel vaults with a depth of 1.5m as a basis of comparison, the maximum displacement is reduced by 43.93% and 28.21% for the models with depths of 1m and 1.25m respectively Fig (15).

The maximum displacement in the Y-direction for each model is presented in Table (5). Figures (16) to (18) show the relationship between the displacement and period of the earthquake at the joint of maximum displacement (in the Y direction).

Table (5) Effect of depth on maximum displacements (mm) (in the Y direction).

Open angles	ρ =30		
	D=1m	D=1.25m	D=1.5m
90°	7.20	5.20	4.03
redaction%	0	27.78%	44.03%
130°	20.44	13.74	20.46
redaction%	0.09%	32.84%	0
170°	52.59	49.84	53.04
redaction%	0.85%	6.03%	0

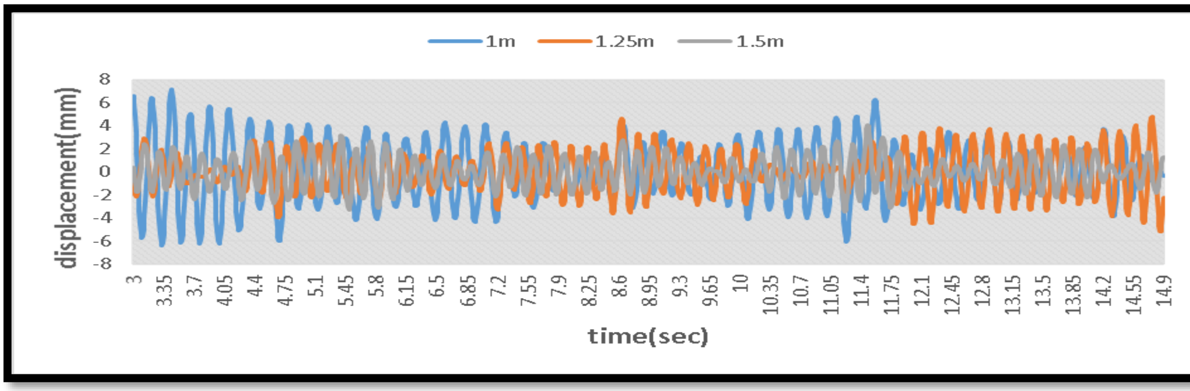
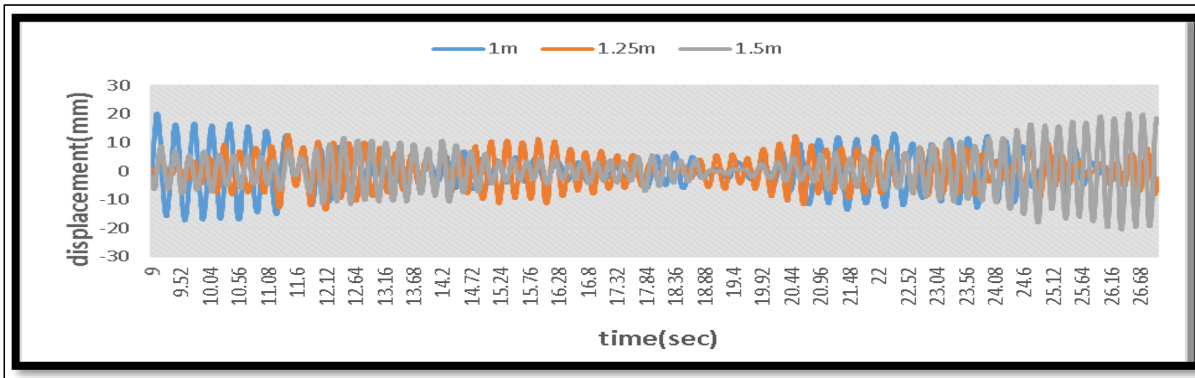


Figure (16): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =90°, ρ =30° (in the Y direction).

Figure (17): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =130°, ρ =30° (in the Y direction).



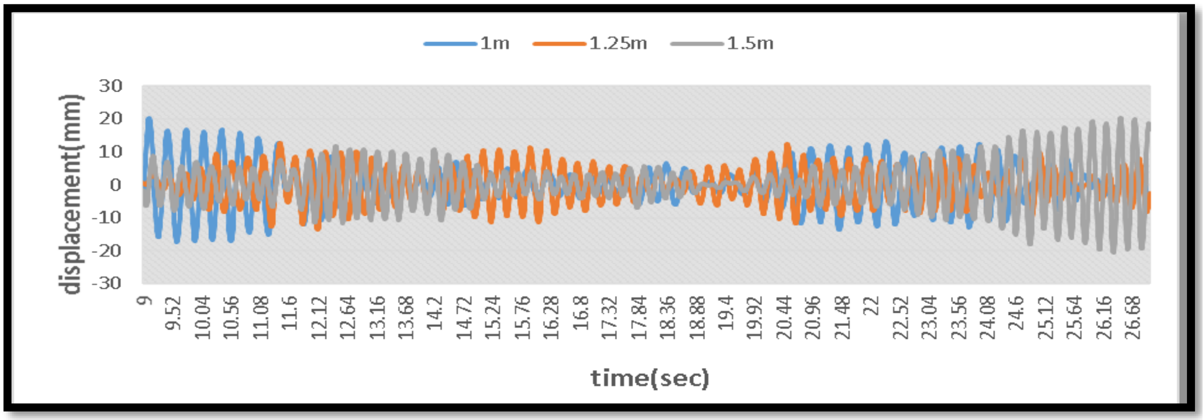


Figure (18): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =170°, ρ =30° (in the Y direction).

It appears Figure (16) that, the reduction in maximum displacement for the model with a depth of 1.5m higher than the reduction percentage of the model with depths of 1.25m and 1.5m (i.e. by taking the barrel vaults with a depth of 1m, θ =90° and ρ =30°as a basis of comparison, the maximum displacement is reduced by 27.78% and 44.03% for the models with depths of 1.25m and 1.5m respectively).

By taking the barrel vaults with a depth of 1.5m as a basis of comparison, the maximum displacement reduced by 0.09% and 32.84% for the models with depths 1m and 1.25m respectively Figure (17).

Comparing the three different models with depths of 1,1.25 and 1.5m in Figure(18), the barrel vaults of 1.25m gives the biggest value of the reduction in maximum displacement.

The maximum displacement in the Z-direction for each model is presented in Table (6). Figures (19) to (21) show the relationship between the displacement and period of the earthquake at the joint of maximum displacement(in the Z direction).

Table (6) Effect of depth on maximum displacements (mm) (in the Z direction).

Open angles		ρ =30°	
	D=1m	D=1.25m	D=1.5m
90°	7.62	5.15	3.75
Redaction %	0	32.41%	50.79%
130°	13.08	8.37	11.82
Redaction %	0	36%	9.63%
170°	18.33	16.97	17.24
Redaction %	0	7.42%	5.95%

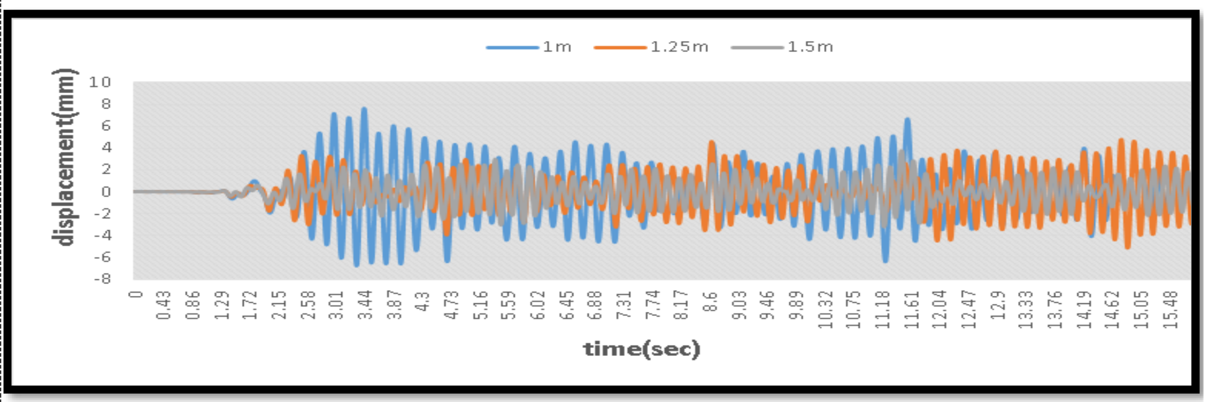


Figure (19): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =90°, ρ =30° (in the Z direction).

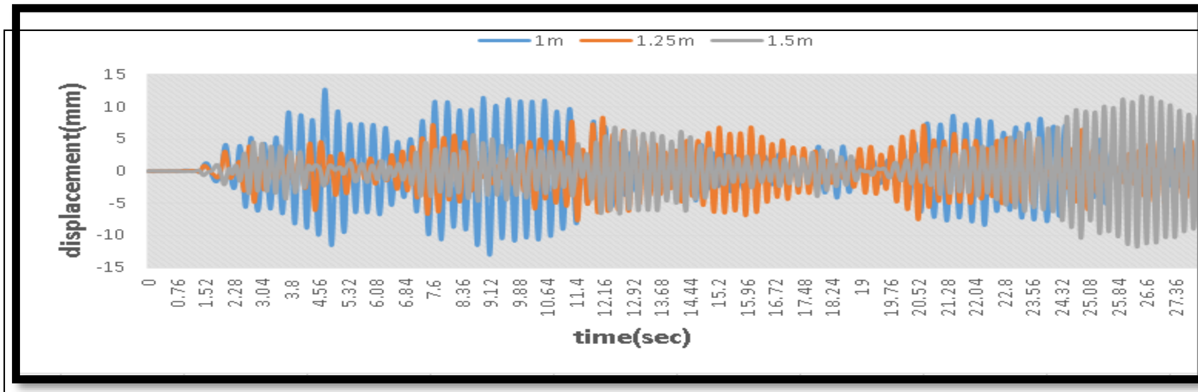


Figure (20): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =130°, ρ =30° (in the Z direction).

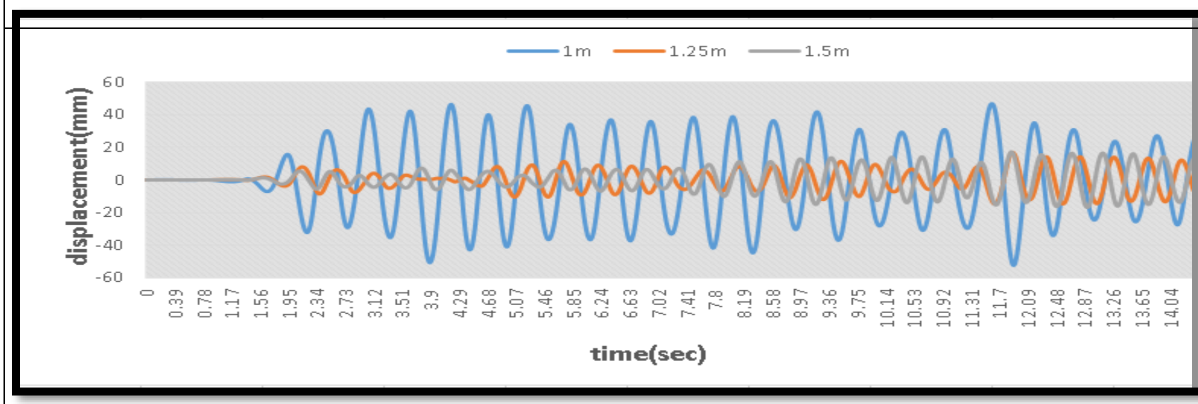


Figure (21): Relationship between the displacement and period of the earthquake at the joint of maximum displacement θ =170°, ρ =30° (in the Z direction).

Comparing the three different models with depth of 1.1.25 and 1.5m in Figure(19), the barrel vaults of 1.5m gives small-displacement(i.e. by taking the barrel vaults with a depth of 1m, ρ=30° and θ =90° as a basis of comparison, the maximum displacement is reduced by 32.41% and 50.79% for the models with depths of 1.25m and 1.5m respectively).

It appears from Figure (20) that, the reduction in maximum displacement for the model with a depth of 1.25m higher than the reduction percentage of the model with depths of 1m and 1.5m.

By taking the barrel vaults with a depth of 1m as a basis of comparison, the maximum displacement is reduced by 7.42% and 5.95% for the models with depths of 1.25m and 1.5m respectively Figure (21).

4. Conclusion

The following can be concluded from the current work:

As horizontal excitation is applied to the barrel vault models, there is a noticeable vertical displacement, while in ordinary buildings; there is no noticeable vertical displacement. For horizontal ground motions, a barrel vault model with θ =90° provides the most effective performance. The horizontal earthquake has a small effect on the X and Z directions since the primary earthquake loading occurred in the Y direction. Based on the study's results and a comparison of the responses of horizontal ground motions for all analytical models, with respect to the X, Y, and Z directions. D=1.5m is evaluated as the minimum response.

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