The Examination of Shape and Type Effects of Supports on Performance Level of Space Structures by Capacity Spectrum for Vertical Load of Earthquake

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Abstract

Rapid growth of population in the societies has caused a great demand of having large spaces without intermediate columns. In this regard a number of professionals have been attracted by the unique potential of space structures to meet emerging needs of people. Acceptance and popularity of space structure among architectures and designers is because of some reasons such as: great orifice covering, magnificent architecture, extremely low weight, the ease of building process, speed in installation, quality of response to earthquake and …. Considering that usually large population live in space structured buildings, resistance and immunity of the structures against destructive factors such as earthquake is very important. In this paper we examine the effects of type and shape of support on performance level of single layer flat space structures and their performance at different risk stages are examined based on the regulations stated in Iranian Standard for Retrofitting of Existing Buildings. Since there are no acceptance criteria for space structures neither in Iranian code nor other International codes, first these criteria are suggested and then by sketching the capacity curves versus different performance levels, the performance point of the structures are obtained. Nonlinear static analyses (push-over) are carried out on the selected models using SAP and ANSYS software. The performance levels and capacity spectrums are obtained by FEMA and ATC40 bylaw.

Key words: Capacity Spectrum, Non-linear Static Analysis, Performance Level, Performance Point, Single Layer Plain Space Structures.

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1 Introduction to Space Structures

Space structures are structures that have three-dimensional behavior and cannot be analyzed in plane state. These structures are very regular in geometry and repeat by a specific pattern next to each other. The composing members of these structures have often the same or very close r in all directions. Thus the most suitable sections for these structures are circular sections, box sections and H-shape sections respectively. Steel is the most frequent material in space structures, but aluminum, wood and other materials can be used. Space structures have high redundancy degrees and their structure and connection types prevent the total failure should a member is removed. Thus, if some members in a grid lose their functioning due to the applied loads, other members can take part to tolerate the loads and can distribute the forces which were tolerated by the lost members. From the engineering point of view, light weight and high stiffness of space structures are the advantages of these structures. The different space structures are:

1- Plane grids (single-layer, double-layer, triple-layer and multi-layer): These structures usually have 2-side, 3-side or 4-side structure. The most usual single layer grid is a square grid in which the member are perpendicular to each other. Other usual gird is diagonal grid which makes an oblique angle with the walls. In the space structures where the number of layers is more than one, the layer patterns may be the same or different.
2- Barrel Value (single-layer and two-layer): If a grid is curved in one direction, the resultant structure is called Barrel Value. They are usually used to cover rectangle (square) surfaces. In some cases, Barrel Values have not columns and are placed on their sides which are placed on bearings.
3- Domes (single-layer and two-layer): If a grid is curved in two directions, the resultant structure is called dome. Domes are structures with very high rigidity and are used for very large spans until about 200 meters. The surface of a dome is usually a part of a sphere or a cone or is formed by connection of some surfaces.
4- Other space structures: air-field structures, folding structures, bridges and etc.

2 Introduction of Capacity and Reflection Spectrum

Before introducing the capacity spectrum method, some concepts such as demand, performance and capacity should be defined: demand shows the ground motions and capacity shows the ability of structure against seismic demand and performance is related to the case where capacity can respond demand.

Capacity: Total capacity of a structure depends on deformation capacity and the strength of every members of structure. To determine the after yield capacity of structure, nonlinear analysis such as pushover analysis are used. In this method, a series of consecutive elastic analysis is used to determine displacement-load curve. In every step, the mathematical model is revised in a manner that the strength less due to yielded members is considered in calculations. Vertical load distribution is repeated again until one of the predefined limitations is reached.

Demand: Ground motion during an earthquake generates a complicated pattern which varies by time. Consideration of these motions in each step to determine structural design demands is impossible. In usual linear analysis methods for determination of design conditions, a series of vertical loads are used, but in the case of nonlinear methods, it is easy and logical to use a series of displacement instead of vertical loads. The term “demand” which is usually mentioned as displacement demand, is the maximum expected response of a structure during a specific earthquake.

Performance: having determined the capacity curve and displacement demand of structure, performance control is done. Performance control is carried out to assure that no damage is occurred in structural and non-structural members under the forces and displacement generated by demand displacement until acceptable limitations of performance goal are reached.

3 Structural Capacity Determination Method

The capacity of a structure is usually presented by capacity curve which is in the form of structure shear versus roof displacement. In this paper, the curve is composed of structure vertical force versus structure vertical displacement. Some nonlinear software, such as ANSYS, DRAIN, SAP2000 and ETABS2000 can directly conduct pushover analysis. This software can automatically increase load and correct stiffness and strength. It should be noted that capacity curve which is usually generate to indicate the structure response in the first mode is based on this assumption that the structure main vibration mode is the dominating mode of response. This assumption is valid for the structures whose main vibration mode is until 1 second, but for very soft structures whose main vibration period is more than 1 second, the effects of next vibration modes should also be considered.

4 Capacity Spectrum Method

In this method, performance point of structure is determined by crossing the capacity spectrum and suitable demand response spectrum which is decreased due to nonlinear effects. According to the recent studies carried out in Buffalo University in New York, displacements obtained by this method has less than 10% difference with the average of maximum displacements obtained by some time history analyses.

5 Determination of Performance Point by Capacity Spectrum Method

As it was mentioned before, performance point indicates a condition in which structure capacity and seismic demand are equal. Thus the position of performance point should be on the demand spectrum curve, in which nonlinear effects is considered and shows nonlinear demand in the same structural displacement.
On this basis, the best method for determination of performance point is to intersect capacity curve and the demand curve in which nonlinear effects are considered. The intersecting point of these two curves is the structure performance point. It should be noted that capacity curve is displayed by earthquake vertical load versus vertical displacement and demand curve is displayed by spectrum acceleration versus structure vibration period. Thus it is impossible to intersect these two curves in a same coordinates. So the demand and capacity curves are converted to acceleration response spectrum- displacement (ADRS) format. Then the curves are drawn in (S_a,S_d) coordinates to calculate the performance point. The calculation of performance point consists of the following steps:

5.1 Converting Capacity Curve to Capacity Spectrum

Capacity curve is drawn in vertical earthquake force versus vertical displacement coordinates. The capacity spectrum actually present structure capacity curve in the form of acceleration response spectrum-displacement (ADRS). For each point with coordination of ($\Delta_{Vertical}$,P) on capacity curve, the corresponding point on capacity curve in (S_a,S_d) is determined by following equations:

$$S_d = \frac{\Delta_{Vertical}}{PF_1 \times \phi_1} \quad (1)$$

$$S_a = \frac{P/W}{\alpha_1} \quad (2)$$

W: is the structure dead load plus a part of live load.

φ_1: is the structure shape number in the first mode (since the studied structure is plane single-layer, this value is equal to 1).
PE_1, α_1: are modal mass coefficient and modal participation coefficient for the structure first natural mode respectively.

$$PE_1 = \left[\frac{\sum_{i=1}^{N} (W_i \phi_{il})/g}{\sum_{i=1}^{N} (W_i \phi^2{}_{il})/g} \right] = 1 \tag{3}$$

$$\alpha_1 = \frac{\left[\sum_{i=1}^{N} (W_i \phi_{il})/g \right]^2}{\left[\sum_{i-1}^{N} W_i / g \right] \left[\sum_{i-1}^{N} (W_i \phi^2{}_{il})/g \right]} = 1 \tag{4}$$

In single layer plane space structures, both of the modal mass and modal participation coefficients are equal to unity.

5.2 Converting Demand Spectrum to ADRS Format

The standard response spectrum is drawn in spectrum acceleration (S_a) versus the period coordinate which should be converted to ADRS format. For every point with the coordination of (T,S_a) on the standard curve, displacement spectrum (S_d) is equal to:

$$S_d = \left[\frac{T}{2\pi} \right]^2 S_a \tag{5}$$

To convert the design earthquake acceleration response spectrum of 2800 code, following equations can be used:

$$\begin{aligned}
0 \le T \prec T_0 &\Rightarrow \begin{cases} S_a = AI(1+S(T/T_0)) \\ S_d = AIg(1+S(T/T_0)(T/2\pi)^2 \end{cases} \\
T_0 \le T \prec T_S &\Rightarrow \begin{cases} S_a = AI(1+S) \\ S_d = AIg(1+S)(T/2\pi)^2 \end{cases} \\
T_S \le T &\Rightarrow \begin{cases} S_a = AI(1+S)(T_S/T)^{2/3} \\ S_d = AIg(1+S)(T_S/T)^{2/3}(T/2\pi)^2 \end{cases}
\end{aligned} \tag{6}$$

5.3 Making a Bilinear form for Capacity Spectrum

To estimate the effective damping and consequently determination of suitable reduced demand spectrum, a bilinear form for capacity spectrum should be drawn. To make a bilinear model, a point with (d_{pi},a_{pi}) coordinates should be determined. This point is a trying performance point which is estimated engineers to obtain the reduced demand response spectrum. If a reduced demand response spectrum is achieved who intersects the capacity spectrum at (d_{pi},a_{pi}), this point will be the real performance point of the structure. To generate a bilinear form of capacity spectrum, a straight line is firstly drawn whose steep is equal to the elastic stiffness of structure and intersects the origin. The second line is drawn from (d_{pi},a_{pi}) point in a way that when this line intersects the first line at the point (d_{pi},a_{pi}), the area of the two generated regions between these two lines and the capacity spectrum be approximately the same.

5.4 Approximating the Equal Damping and Viscous

When a structure enters the nonlinear region during an earthquake, its damping can be defined by combination of natural viscous damping and hysteresis damping. Hysteresis damping is proportional to the under area of force-displacement curve of structure during an earthquake.

$$(\beta_{eq}) = \beta_0 \pm 0.05 \tag{7}$$

β_0: Hysteresis damping presented in the term of viscous damping equal to 5% of structure natural viscous damping. It is constant until the end of analysis.

$$\beta_0 = \frac{63.7(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} \tag{8}$$

$$\beta_{eq} = \beta_0 + 5 = \frac{63.7(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} + 5 \tag{9}$$

Then for correction of model, effective viscous damping concept is used by damping correction factor k, and effective viscous damping β_{eff} is determined as following:

$$\beta_{eff} = k\beta_0 + 5 = k\frac{63.7(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} + 5 \tag{10}$$

K: Correction factor by which equal viscous damping obtained by ideal hysteresis curve is converted to the equal viscous damping corresponding to real hysteresis curve of structure. K factor depends on real performance of structure which is in return depends on the quality of lateral-resistant system of structure and duration of earthquake excitation. According to ATC40 code, three different classed of structural performance are considered:
A: Indicate stable hysteresis loops. In this class, the performance of hysteresis loops is stable in all cycles and is very close to the ideal shape (parallelogram).
B: shows rather incomplete hysteresis loops. This performance is accompanied by average decrease of hysteresis loop areas.
C: Indicates incomplete hysteresis. Significant decrease of hysteresis loops occur during consecutive cycles.
Space structures are classified in B class.

K	β_0	Structure performance class
1.0 1.13 – 0.008 β_0	≤ 16.25 % > 16.25 %	A
0.67 0.845 – 0.007 β_0	≤ 25 % > 25 %	B
0.33	Other	C

Table 1: Value of correction factor of structure performance

5.5 Reduction of Demand Spectrum of 5% Damping

If β_{eff}, the effective viscous damping be equal to the energy absorption due to 5% natural viscous damping of structure and permanent plastic deformations (hysteretic deformations) until performance point the design elastic spectrum of 5% damping is reduced to the demand spectrum corresponding to β_{eff} damping. According to ATC40, these portions are specified by SR_A and SR_V factors respectively which are called spectrum reduction factors:

$$SR_A = \frac{3.21 - 0.68Ln(\beta_{eff})}{2.12} \geq (SR_A)_{min} \tag{11}$$

$$SR_V = \frac{2.31 - 0.41Ln(\beta_{eff})}{1.65} \geq (SR_V)_{min} \tag{12}$$

$(SR_A)_{min}$ and $(SR_V)_{min}$ which are the minimum permissible values of spectrum reduction factor are:

$(SR_V)_{min}$	$(SR_A)_{min}$	Structure performance kind
0.5	0.33	A
0.56	0.44	B
0.67	0.56	C

Table 2: Permissible values of spectrum reduction factors

5.6 Standard Design Spectrum of New 2800 Standard Reduced in ADRS Format

According to the spectrum reduction factors $(SR_A)_{min}$ and $(SR_V)_{min}$, the reduced design spectrum of 2800 standard are equal to:

$$S_a = S_a \times \begin{cases} SR_A \Rightarrow T \prec T_S \\ SR_V \Rightarrow T \geq T_S \end{cases} \tag{13}$$

5.7 Determination of Performance Point

For determination of performance point on the capacity curve, two unknowns exist:

1) Position of performance point.
2) Effective viscous damping corresponding to performance point.

Both of these unknowns depend on each other and consequently, if one of them be known, the other can be determined. So try-and-error method should be used to determine them.

6 Different Levels of Structure Performance

To define the performance of a specific structure, it is necessary to specify the acceptable damage level due to the corresponding earthquake level. Some performance levels are defined in FEMA and ATC40 provisions and for each of these levels a specific damage level is specified:

Immediate occupancy performance level (continuous use) (IO): in this performance level, the earthquake damages are very slight and vertical and lateral load resisting systems maintain unchanged. Thus the probability of losses due to structural and non-structural damages is negligible. In this level, the structure is usable immediately after the earthquake and where there is need for repairs, no disturbance occurs in structure service.

Life safety performance level (LS): In this performance level, noticeable damages occur in structure, but the structural and non-structural members do not fall and the structure is rather far from structural collapse. Thus no losses occur in or out of structure. Major repairs are needed before the structure services which can disturb the serviceability of structure.

Structural stability performance level (SS) or collapse prevention (CP): In this performance level, structural damages are so heavy that the structure is close to complete collapse, but it is still has vertical stability. In this performance level, it is possible that

losses occur in or out of structure and the probability of collapse due to next vibration exists. Major repairs are needed before next operation.
In frame structures, previous studied have determined the formulations for these performance levels and their performance point can be compared to determine that the structure is placed in which performance level. But for space structures, no formulation I proposed and the different boundaries of performance levels are not defined. The purpose of this paper is to determine the behavior point of structure.

7 Studying the selected models

The analyzed models are single layer flat structure that plane elements shape of which are square (Shape A & B) or square-diagonal (Shape C & D). The length of every square members are assumed 1 meter. All connections are supposed rigid to maintain the stability structures.
In order to transmit the roof forces into foundation of structure, 2 kinds of supports are used which are actually the connection of column and roof.
Considering two 1 meter consul at each side, the total length of structure is supposed between 10 to 15 meters.

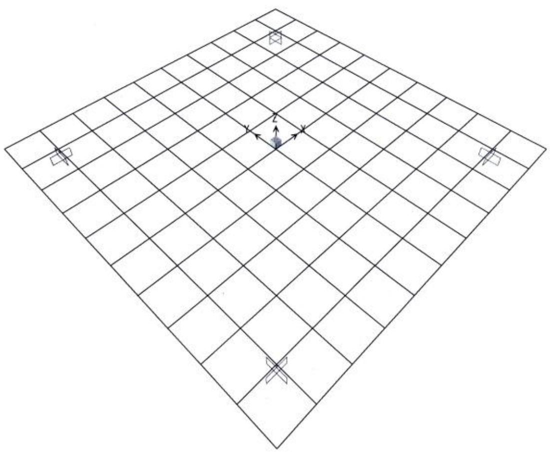

Fig 1: Shape (A)

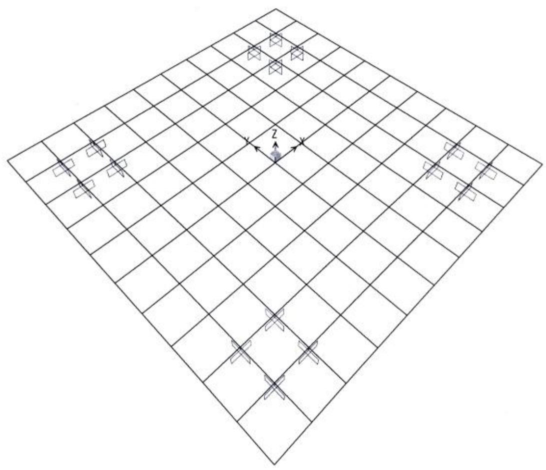

Fig 2: Shape (B)

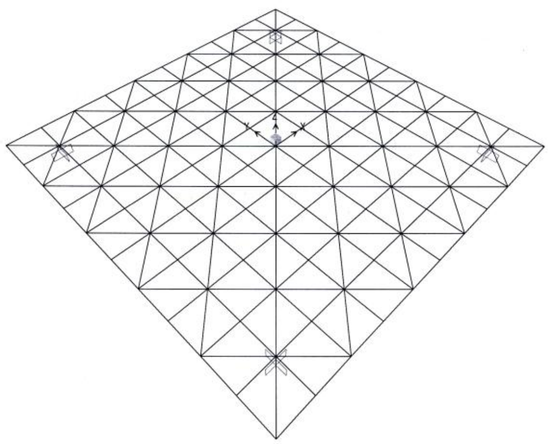

Fig 3: Shape (C)

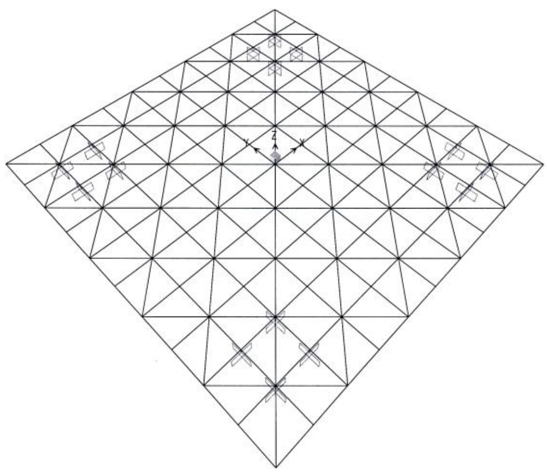

Fig 4: Shape (D)

To obtain the performance point of structure, the structure is initially modeled and linearly analyzed by SAP2000 software and after optimization of design for elements and structure

weight and then the models are categorized in some similar tips. In the next step, the optimized structure is modeled by ANSYS10 and nonlinear analysis is conducted. Beam189 element which has three nodes is used for modeling the structures by ANSYS. The reason for choosing this element is the ability of this element to simulate the rigidity of connections. Having conducted the nonlinear analysis steps, pushover curve is drawn for each structure using the available output. The capacity spectrum and demand spectrum are determined in ADRS format and using the available equations, the reduced demand curve can be drawn. Finally, the performance point of structure which is the intersection point of reduced demand curve and the capacity curve of structures is determined.
In this section, the diagrams and calculation steps for determining the performance point of a single-layer structure of size 10*10 meters is presented for instance. Since the parameters such as A (design base acceleration), I (structure importance factor), S (depends on the soil and condition of the region) are very important in determination of S_a, these parameters are assumed to be constant in all of the models. In this manner, the response of structure analysis is only depends on the structure itself. In below diagrams, the process of determining the performance point is presented. It is assumed that A=0.3, I=1.2 and region type=2)

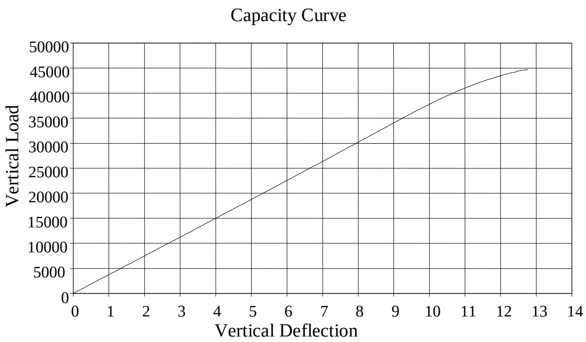

Fig 5: Capacity Curve–Vertical Load

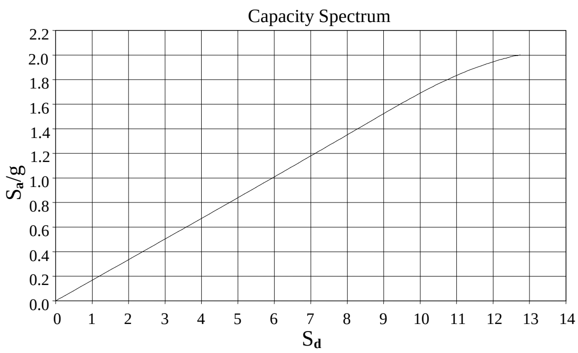

Fig 6: S_d–S_a/g for Capacity Spectrum

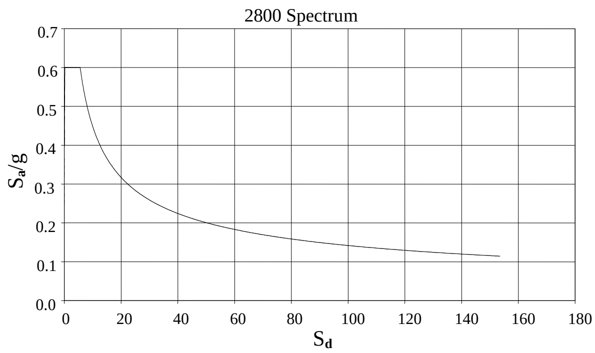

Fig 7: S_d–S_a/g for 2800 Spectrum

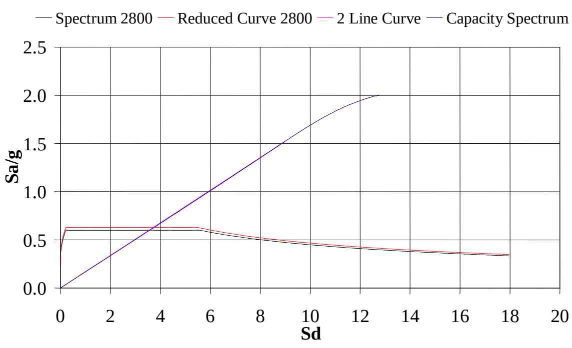

Fig 8: S_d–S_a/g for ADRS format

This process is carried out for the structures with size of 10*10 and 15*15 meters and after drawing the related diagrams, the performance point is determined for all of them.

8 Conclusion

Using the curves and the results of single layer plane space structure analyses, it can be concluded that the performance point in spans of about 15 meters are placed in life safety level and in small spans are placed in immediate occupancy level. In these structures, S_d is increased slightly by increasing the span length.

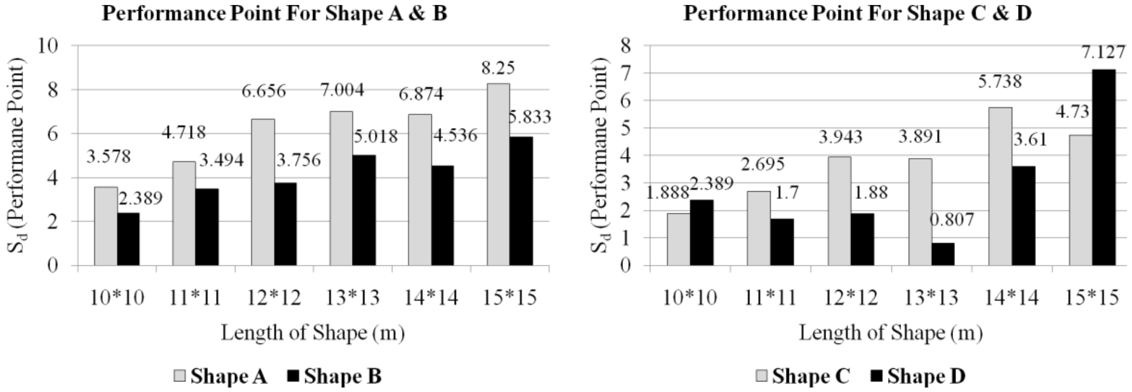

Table 3 & 4: Performance point for shape (A, B, C, D)

Single supports in structure with square elements can perform better and stronger than in quadrate supports shape.
In structure with square-diagonal elements, excluding 10 and 15 meters spans, structure with single supports can perform better and stronger than structure with quadrate supports.
It seems that the performance can be better with fewer and smaller supports in single layer plane structure applying this type of connection and short length of spans.

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