Investigating Space Frames and the Effect of Earthquake on Them

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Abstract
Space frames show remarkably good performance in facing destructive earthquakes. Lightweight, a high indeterminate degree, special relations between parts, and existence of second line of defense are highly effective factors in seismic strength of such frames. Contrary to common frames whose dynamic behavior is mainly due to the mode of (first) horizontal pillar, in space frames, vertical modes and upper modes also cooperate effectively in dynamic responses.
In usual frames, under horizontal acceleration of earthquake, vertical movements are minute while in dome-shaped space frames, considerable vertical movements occur, space frames' power of Earthquake is also much more than common frames and can easily exceed the weight of structure. By creating strength and reducing resistance in substructures, seismic forces can be reduced to a certain extent. Yet, the movements would increase. Considering that current by-laws in regulations are based on the seismic behavior of normal frames, it is necessary to codify special laws for seismic loading of space frames. Such laws will undoubtedly lead to minor behavioral coefficient and greater base cutting coefficient for space frames that of course will be a subdominant of space structure features especially in condition of under structure. Creating great forces in space frames while quaking can lead to breaking connections near supports because with the attention to this fact that such connections are based on usual regulations the design power is much smaller and in destructive Earthquakes, the power of Earthquake and hence created power in connections would be much greater. Yield point in Space frames is not specified completely and structure's behavior is basically related to supports. If the support is connected to earth, it transfers more acceleration in compared to a condition in which the flexible base transfers acceleration to the structure.
Keywords: frame, space frame, earthquake

Introduction

Space frames are structures that consist of many parts with pivotal performance. These frames have different forms and, as a result, they are classified in different groups. These groups include: one-way grids, two-way and three-way, one-way and two-way barrels, one-way and two-way domes, space frame masts and so on. In recent years, using such frames have become very common and they are mainly used for covering huge openings such as gymnasiums, theater halls and similar spaces. Such frames, however, have never been used for building ordinary houses in Iran yet. Space frames are frames in which ceilings and lateral walls are grids. If we compare space frames with normal frames, we will see that the grids used in walls play the role of columns in a normal building and they transfer the vertical loads as well as lateral loads from wind and earthquake to the base. Two-way grids used in the ceiling of space frames have also the same performance as rigid ceiling in usual houses, and they divide the force from lateral loads of wind and earthquake to a hard proportion between backer walls.
Designing all parts and connections of space frames, because there are no especial regulation for such frames, are conducted according to authentic references and common regulations of

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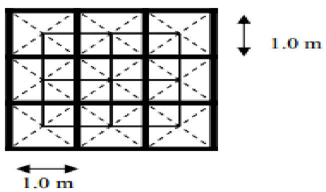
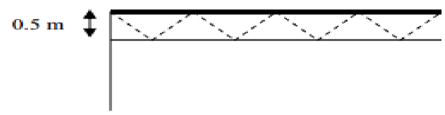
designing, AISC or Iranian Steel Regulation and Regulation 2800. In the following section, space frames are studies along with the effect of earthquake on them.

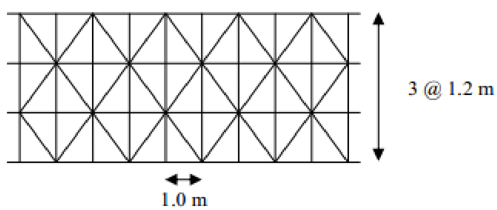
Construction system of space frames

Forms of Space frames that are applicable in ceiling's cover in multi-floor buildings are flat grids. One-way grids, because of having locking connections for relieving consistency conditions, involve stronger parts for burdening flexible anchors coming from forced loads. The created flexible anchor in them also makes a great leap in ceiling and extra lateral leap in vertical backer grids. Three-way grids, too, because of having a great height and being not economic for small openings are not applicable in such constructions. As a result, the most appropriate space frames to be uses as ceilings in such buildings are two-way grids.





Walls of such frames, in addition to burdening vertical loads, are used as resistance systems in facing lateral loads and are made of one-way grids with rigid connections. In addition, the diagonal parts in walls are applied for bearing lateral loads.



National regulation of space frames and appendices (Planning and Budget 400 Publication):

In a number of ASCE 2005 infrastructure, a number is specified to designing steel frames, and in Germany MERO company itself has some standards for designing different types of space frames that is passed by engineers' council in this country. In Iran, however, for the design of space frames, one of the international regulations has been used so far to; for instance, to calculate vertical force of earthquake, Chinese Regulation and to design MERO connections and for structure designing, AISC have been used, These show the necessity for a national regulation in Iran. With collaboration of Planning and Budget Organization, a publication according to Code 400 of Planning and Budget Organization as a regulation for space frames will soon be published and used by engineers. However, at the end of this publication, are two appendices and one glossary of space frames that have extraordinary application:

-Appendix of space frame regulation: this Appendix includes types of common geometries of space frames and types of formic codes related to each frames or, in other words patterns that will make easy designing job of usual type of frames especially common one and two-way flat grids, barrels and domes.

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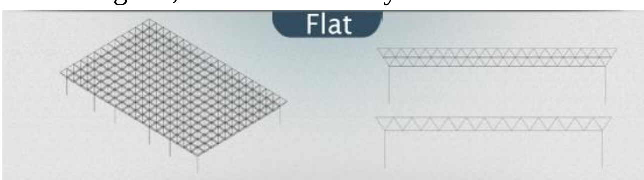
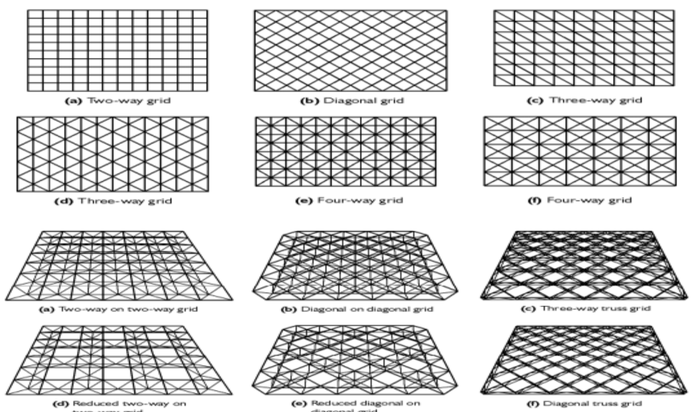
Of course, this regulation has now some other limitations such as the fact that presently only metal space frames are mentioned and the only discussion is concerned with designing them, while other related issues referring to controlling and installing ways are not included. In addition, one of great problems of current frames in Iran is that MERO regulation based on LRFD method suggests connections' details, while engineers design structure according ASD method, which leads to difference practices and concepts.

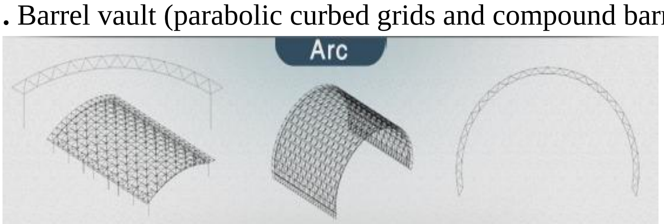
Types of geometrical models of Space frames

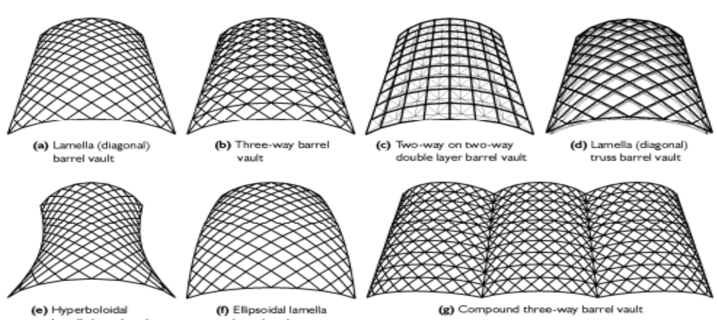
-One or two-way flat space frame: on one-way space frames, connection of connectors to each other are grids, while on two-way frames connections can be joints.





. Barrel vault (parabolic curbed grids and compound barrel)





. Other forms (towers and lattice grids)

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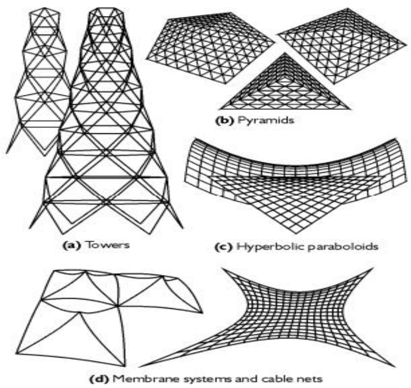
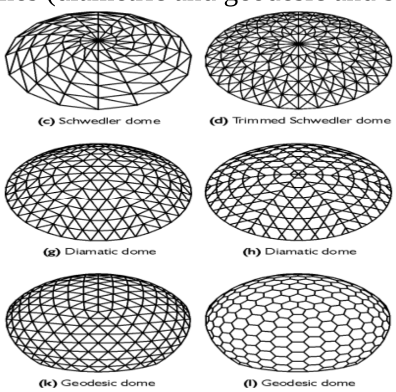


. Domes (diametric and geodesic and schwedler domes)



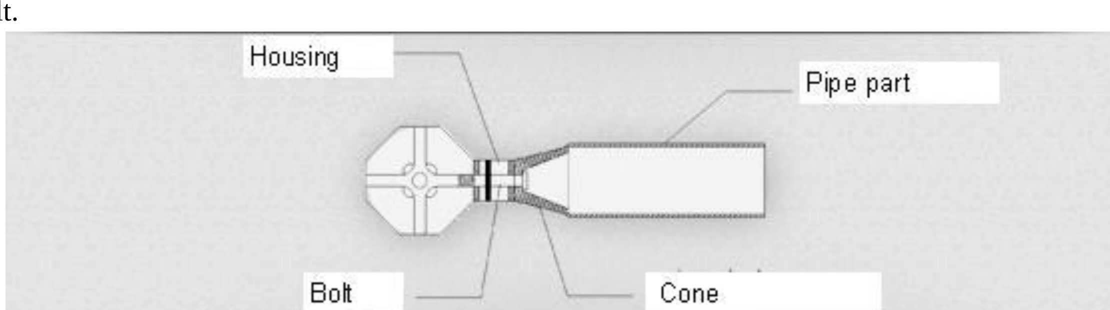
Types of connections of space frame

. MERO
. CATRUS
. UNIBAT

1- MERO, KK-Ball group

This system which is a subset of Nodular systems, was first designed by MERO Company of Germany in 1942 and delivered commercially. This system includes steel spheres made of CK45 used in space frames to connect parts and transfer between connecting parts to the connector (sphere).

In this system (and most of spherical systems), parts are pipe-shaped and their central pivots pass from center of the connector, and these parts and connectors are produced apart in the factory and then in the project site, through connections of parts and connectors, the grid of space frame is built.



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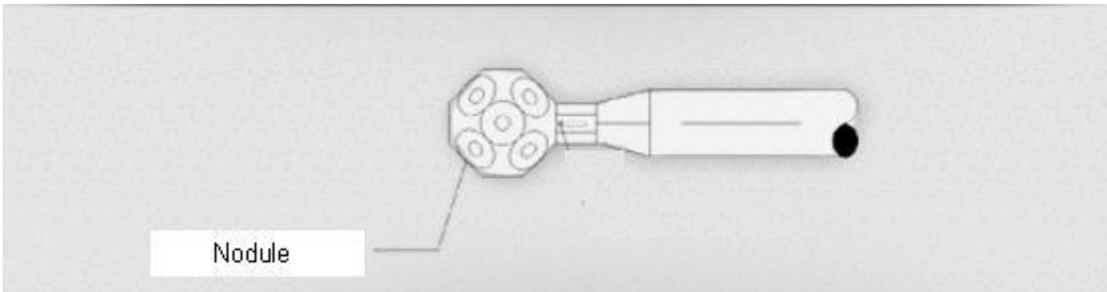
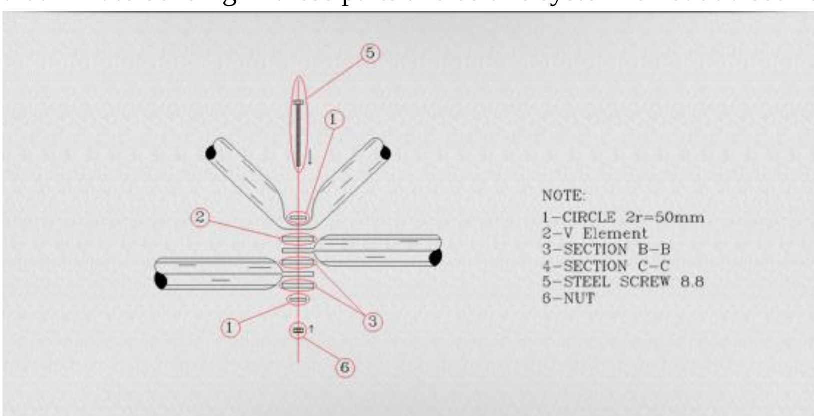


2- CATRUS

CATRUS systems, made from single knot bolts and nuts, were first invented in Scotland. In CATRUS systems, all parts are made of pipes of profiles and are usually used for openings between 5 to 12 meters. In this system, the need for connecting parts is less than MERO system so that in the same situations it is more cost-effective compared to other systems.

In this system, inhibitory parts of in, are sections of pipe which at each end are punched and bended and main parts in appropriate lengths are produced with dimensions of space frame's grid and are connected in proper points. In this system, some parts (especially middle layer parts) in center of parts' section do not straightly pass from center of knot and then lead to that minute bending in these parts and so this system is not advised for big openings.



3- UNIBAT from group of prismatic connections (pyramided-single unit)

This system, which was invented for the first time in England, is made of pyramided units in a way that these reverse pyramids with rigid frames of standard modules create this system in upper and middle layers and in angles they are connected by using steel bolts with high resistance tension. These pyramids, including grids, are produced in the factory apart for certainty of their accurate dimensions and melding quality, and they are built by connecting them to each other in project site where space frames are used. Each unit is made of four upper parts (square frame in form of pyramid) four inner parts (inhibitory) and five parts of connectors in four angles of pyramid, and its head that in them stronger sections are used for accordance with greater cutting forces appearing around columns of space frame. After assembly job by UNIBAT system a diamond grid is created on square.

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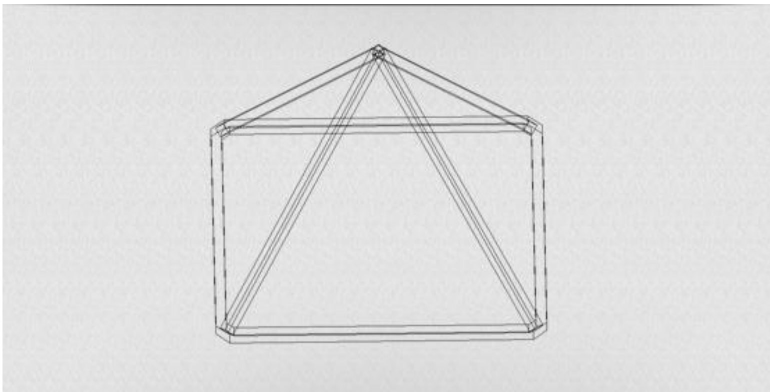

Effect of Earthquake on space frames

Analyzing time history

Effect of earthquake is recorded accelerograms. These accelerations are used for analyzing structure's quaking. Although this method is less used in designing problems, but analyzing time history can give us a better view of performance of a frame in time length of earthquake. Vertical movements of earth can create inertia forces in different parts. In different regulations, there are numerous confrontations. Some of these regulations necessitate research on vertical effects of earthquake for frames having arch performance.

Non-linear statistical method

In methods of non-linear statistical analysis, performance of a frame is just evaluated in conditions of maximum frame's response to earthquake. For reaching this condition, first the base shear is determined against the movement of a point of frame that is usually the roof. This relation appears as a curve that is called *capacity curve* of increasing load curve. After calculating the point's curve, we specify the highest place change. This point as movement is our goal. Even numerous researches of several decades have shown that out of this analysis for frames that have their first mode of frequency dominant, can come good and proper estimations of frame's behavior. So that the responses of increasing load analyzing method can be known acceptable. One of limitations of the increasing load method is that the base of loading is statistical. Because of this reason, it cannot be representative of dynamic behavior and the phenomenon exactly.

Basics of behavior quotient

Designing regulators of facing earthquake don't know the remaining elasticity of frame in facing powerful earthquake necessary but it is allowed that frame enters plastic and the energy coming from earthquake get vanished in it. Because of this reason in determining forces equal to earthquake for linear analyzing and designing in method of allowed tension the earthquake's force is divided into a quotient called quotient of dividing behavior. This quotient shows performance of earthquake and ability of energy absorption. In following the method of calculating behavior quotient and its shaping in two different modes of loading is presented.

Quotient of behavior under increasing static load

For calculating Quotient of behavior under increasing static load, frame is analyzed in push over method and curve of basic shear –movement related to this analysis is drawn. A point of curve which in that diagram moves from being linear to becoming nonlinear shows movement and force in moment of flowing $(\Delta s, Vs)$.

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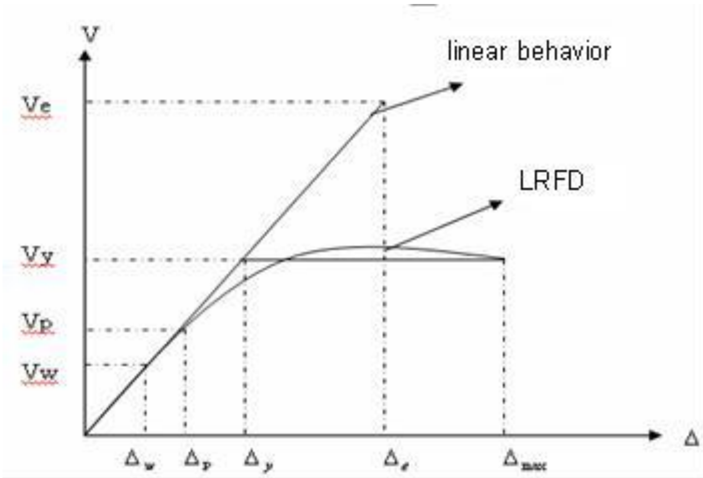
For determining utmost load in mode of elastic we act as following method. First we enter load step by step and with small amount to the frame and after each step we search to see if plastic joint is created or not. After appearing plastic joint, we calculate the amount of force and movement and specify this point on a nonlinear diagram. We connect beginning to this point and continue till the last movement. The corresponding force to this place changing is the utmost force of elastic limit. (V_e) Then by using given methods the behavior quotient is calculated.



A: behavior quotient based on corresponding surface of last load

$$R = R\mu * R\rho = \frac{Ve}{Vy} * \frac{Vy}{V\rho} = \frac{Ve}{V\rho} \qquad (1)$$

B: behavior quotient based on corresponding surface of allowed tension

$$R = R\mu * R\rho * Y = \frac{Ve}{Vy} * \frac{Vy}{V\rho} * Y \qquad (2)$$

Formation quotient

Formation quotient is equal to relation of utmost changing shape into give-in changing shape; formation quotient is calculated under increasing load based on giving in on the beginning or first plastic joint. In this manner:

Place changing increasing quotient

$$C_d = \frac{\Delta_e}{\Delta_p}$$

Adding resistance quotient

$$Rs = \frac{Vy}{Vp}$$

Formation quotient

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$$\mu = \frac{C_d}{R_s}$$

Δ_e Is movement of frame in extreme mode and V_y is basic shear of give-in limit.

Calculation of necessary behavior quotient for special earthquakes

The basis of operation is moment of calculating behavior and formation quotient based on energy uptake that was discussed in previous section. The model is dynamically in non-linear way analyzed with different quotient (B) which multiplies in expected earthquake accelerations and maximum basic shear and movement points of each step is recorded. Then, the cover diagram calculated from points of maximum movement and basic shear is drawn and is calculated by using previous methods of behavior quotient.

This quotient which shows earthquake performance of frame and ability of energy absorption is an important and determiner factor in designing frames. It is natural that with pointing a greater quotient than quotient of real behavior of frame in confrontation with earthquake, system's need for formation, becomes more than capacity of designing frame and takes it to destruction. In reverse with pointing smaller quotient than real behavior quotient, non-economical frames will be designed. Because there has no special regulation been suggested for such frames, most of designers use behavior quotient one. But by analyzing two flat models of increasing static loading and earthquake the behavior quotient 2.5 can be suggested for such frames.

Studying effect of earthquake time steps on space domes

For studying effect of different time steps, dynamic analysis with different times on a special space dome is done. With the attention to performed studies following conclusions are gained:

1- With increasing time step the amount of moment bending is decreased.
2- Amounts of moment bending in time steps equal to 0.2 and 0.4 and 0.8 and…
3- Maximum amounts of moment bending in different time steps are placed exactly on an element.

In dome shaped space frames with numerous elements this conclusion is very important and efficient and saves time in calculations because with operating one analysis the elements having maximum amounts are known and in latter analysis's we go right to those elements.

Studying effect of earthquake's death quotient on space domes

This should be considered that choosing low death quotient (about 0.02) is because in space frames, energy wasting is mainly done by steel material itself and role of construction materials such as bricks and concrete is minute.

So that contrary to usual frames which in high ranges of vibration (when tensions get close to give-in tensions) death quotient can be equal to 0.05, in space frames this number even in give-in time hardly gets to 0.05.

With attention to observations, following conclusions are gained:

1- With increasing death quotient the amount of moment bending is reduced
2- Maximum amounts of moment bending in death quotient are exactly happened on one element and death quotient has no effect in movement of maximum amounts from an element to the other element.

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P-Delta effect on space frames

Because of light weight, special relation of parts, high indeterminable degree and existence of second line of defense the effect of P-Delta in frame is low and is to some limits special.

1- Leap from dynamic loads in compare with P-Delta place changing is less important, because with increase in hardship place changing decreases, but this happening does not have important effect on decreasing accelerations.
2- In compare with functions of P-Delta effect on dome no important change in percentage of errors is gained, amount of this tolerance is less than one percent in compare with dome in normal situation.

At all continuously with performing this effect of comparing between tolerance percentage of error in all cases is analyzed and presented.

This research shows that the effect of P-Delta does not have less importance in percentage of error coming from comparing dome.

With the attention to both analyses we get to following conclusions:

1- Percentage of error in two analyses of dynamic and geometric non-linear dynamic is less than one percent.
2- Amounts of forces and moments coming from geometry non-linear dynamic analysis is more than amount of dynamic analysis.
3- Maximum amounts gained in two analyses are exactly placed on one element and analyses have no effect on movement of maximum elements.

Conclusion

At all relative functioning of one-way space frames is good in facing earthquake. Light weight, high indeterminable degree, special relation of parts and existence of second line of defense are of great effective reasons in Earthquake perseverance of frames. Based on studying researches that are mainly done in recent decade in field of quake behavior of space frames following conclusions can be briefly expressed:

1- Space frames have shown very good performance in facing destructive earthquakes. Such frames can be used as a good shelter after earthquakes.
2- Contrary to normal buildings which their dynamic behavior is mainly due to mode of horizontal basic (first) space frames of vertical modes and upper also share in dynamic answer.
3- In ordinary buildings under acceleration of horizontal earthquake, vertical movements are minute, while in dome shaped space frames considerable vertical movements are created.
4- Type of leftover parts has effect on frame's quake answer. Analyses show that rate of reduced resistance is because of buckling is important controller agent in leftover behavior and the more the reduction the more the quake behavior.
5- Force of earthquake for space frames is much greater than usual structures and can easily exceed from weight of frame.
6- With creating rigidity and reducing resistance under frame to a limit the power of earthquake can be reduced but in reverse the movements increase.

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7- Considering that the current laws of regulations are based on the earthquake behavior of normal structures, it is necessary to codify special laws for earthquake loading of space frames. Such laws will undoubtedly lead to lower behavior quotient and greater basic shear quotient for space frames that of course is subset of features of space frames especially in conditions of under structure.

8- Creating enormous forces in space frames during earthquakes can cause breaking of connections adjacent to supports, because the design of these connections is based on ordinary laws of regulations, and the force of design is much smaller; in destructive earthquakes, seismic force and hence force exerted on connections will be much greater.

9- Give-in point in space frames is not exactly known and frame's behavior is basically related to supports. If support is connected to earth it will transfer more acceleration in compare with when a flexible base transfers acceleration to frame. For example, we study behavior and effect of modes in space domes and we can conclude:

1- Percentage of modes' errors (alternating time) in two types of analyses are less than 0.1%.

2- Alternating time in geometric non-linear dynamic analysis is greater than that dynamic analysis.

3- In space frames, upper modes are also involved in dynamic response.

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