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Research Paper

Designing of a new seismic base isolation system

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The design of a new base isolation system is proposed in this research with the objective that the system does not transmit any force to the structure under horizontal loading. The structure must remain operational and steady. Before investigating the dynamics problem of the base isolation system, the isolator components of the model can be solved analytically using different approaches. In order to calculate the deformation of any element of the isolator due to a compressive vertical load, the analysis focuses on the primary instability region to determine all deformations parameters which can lead to frictions coefficients. This region is located at the interaction contact point between the elements. The design is based on the contact point developed by different approaches. In the present study, the mathematical analysis methods by using formulations can calculate the different dimensions and deformations of the elements of the system and which are verified using ANSYS finite element analysis. After ensuring the adequate dimensions of the different parts of the isolator system from the analysis, the system can be applied on the structure. This technique can reduce significantly the displacements and accelerations at the underground level with a new seismic isolation system, which it is an uncoupled system between the structure and the underground.

1 Introduction

The energy concept is fundamental phenomenon to consider. The isolation base provides reliable results for a large number of applications even for historical building, strategic buildings and public buildings...etc. [1]. The target of structural stability in the future is to use isolators systems, which are the most effective technology to protect structural systems as well as their interior equipments on one hand, and to control the structure behavior under a seismic load [2, 3] on the other hand. A historic evaluation on seismic isolation systems is included in the literature [4 - 6].

The first seismic isolation system patent obtained in 1909 [7] and since the numerous researches on the topic were made [7-12].

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Several base isolation devices have designed, tested and installed on buildings and bridges all over the world. Among them, the most popular is elastomeric isolators. Other concepts have been developed such as the high damping rubber bearings device, lead rubber bearings device, high-damping rubber bearings device, the friction pendulum bearings device etc [13 - 17].The analytical detail of a base isolation system can be found in Alam et al [17]. The most popular isolation devices used are natural rubber bearing (NRB) or those with fiber reinforced composite plate [18]. These use, differents sorts of fibers such as carbon, glass, polyester and nylon by experimentally testing them in order to determine and to compare the differents mechanicals properties. Finally, the results can confirm that the mechanical properties of the carbon fiber reinforced elastomeric isolation system is the most performante because of its elastic modulus and high tensile strength compared to the others, including the reinforced steel elastomeric isolation system which is heavy and expensive [19-20]

The other isolation concept of a simplified three lumped-mass structural model for mid-story isolated is adopted to perform the equivalent linear analysis [21] and it can meet the building required functionality. The finite element method is used in this regard to study modeling, meshing and analyzing the NRB. The purpose of the behavior of this model is performed using ANSYS finite element software [22]. The new model introduced in this paper consists of a structure system where no lateral forces impact the structure by uncoupling the structure from the ground motion.

As far as the architecture is concerned, the model can satisfy any architectural design requirements. Regarding to real civil engineering design, the eccentricity in the building is unavoidable. However, by using this model, the structure above cannot be assumed to displace and the use of the shear walls all around the structure at the base isolators level and an additional material as supplemental dampers and can be considered as energy absorbers.

The isolators model can be installed at any given floor depending on the design but generally in the underground of the structure with possibly an additional damping system device installed along with the isolators that can add energy dissipating capacity to restrict the amplitude of the motion from the seismic force.

A high degree of performance must be expected from the structures subjected to earthquake motion. The feasibility of the isolators systems and the seismic performance of the structures assume that the structural elements must remain within the elastic limits during the earthquake ground shaking.

All the stories of the building must be assimilated as a single story because they are supposed to move as a rigid body, if the displacement occurs, this can explain why an isolated stories base can be designed as a single story.

In this study, the base isolators must be designed to take a large shear deformation and to act definitely as a block absorber, to provide satisfactory behavior in the nonlinear range under horizontal loading, to remain elastic respectively under basic design earthquake to keep the structure elastic as it is fixed. It is a joint and several liabilities between engineering innovations and accommodates architectural requirements design.

2 Design and description of the model

The model of isolator under investigation is (the same type of building with different number of stories) composed of two rigid squares steel plate separated by a spherical steel ball between them.

The purpose of the experiment is to make sure that whenever the model is excited in any horizontal direction the structure does not move. Another isolator system can be added to maintain stability and ensuring that no displacement occurs in the structure. The number and the diameter of the steel balls and the size of the steel plates depend on the vertical load of the structure.

The model shape is composed of four different parts of non-deformable body:

Top square steel plate: this first part is fixed under the last slab of the superstructure on the right of each column, which is a flat thick surface. This part allows the sliding and free rotation of the second part without any static deformation at the contact point area with the spherical ball and infinitesimal small compression on both sides.

Square bottom steel plate: is designed of many half spherical concaves shapes, which represent the contact point and the sliding surface as shown in figures 1 and 2 of the steel spherical ball. The steel plate on the base usually consists on bearing many spherical steel balls turning on themselves over a half concave shape. This part must be fixed above each socle on the underground level. The number of the spherical balls depends of the vertical load from each column with spherical balls in between we have assumed the same number for all isolators of the proposed model.

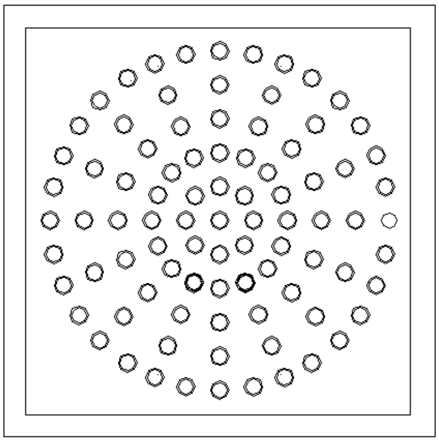

Fig. 1 - Bottom steel plate

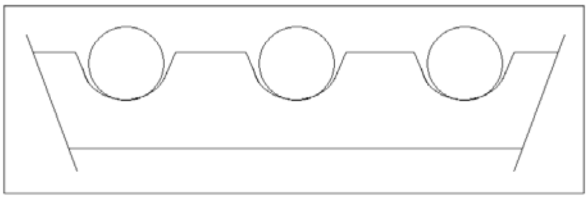

Fig. 2 - Cross section of one concave shape

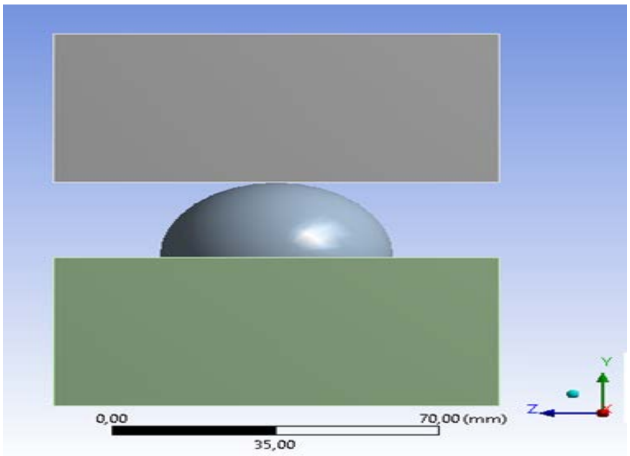

Fig. 3 - The differents parts of the isolator (just for only one ball)

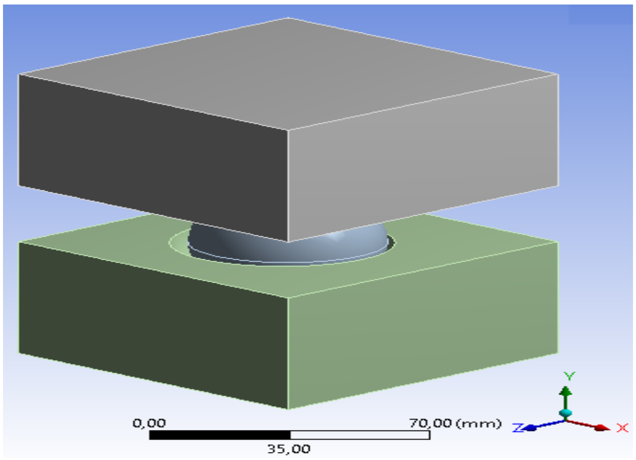

Fig. 4 - Position of differents parts of the isolator in perspective

The number and the dimensions of the spherical steel balls are designed according to the vertical weight as shown in figure 5 and as a function of the type of the building.

The steel spherical ball can move in any horizontal direction and sits in a half cup shape on the bottom steel plate. This articulation point allows the spherical ball to turn on itself as represented in figures 3 and 4. The rotation by sliding of the spherical ball might cause a very low or slight friction interface, which is the purpose and the way to avoid any transfer of the shear force to the isolated structure.

The lubricant: as the fourth part of the system is used to eliminate all rigid stiffness provided by the friction of the sliding and the rotation of the spherical steel balls on one hand. On the other hand, making the concave shape very smooth. Figures 5 and 6 showed the lubricant inside the concave shape and the spherical balls. Selective long life lubricant with corresponding viscosity can insure a very negligible friction.

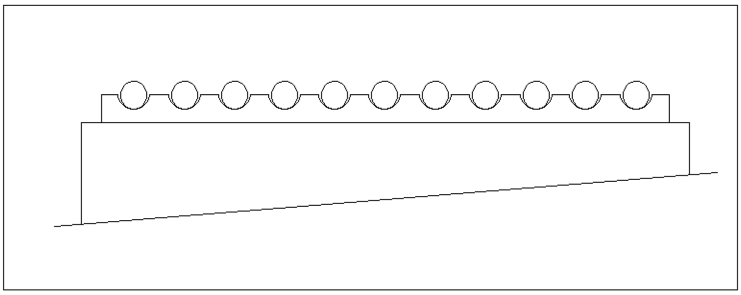

Fig. 5- The spherical ball inside of concave shapes

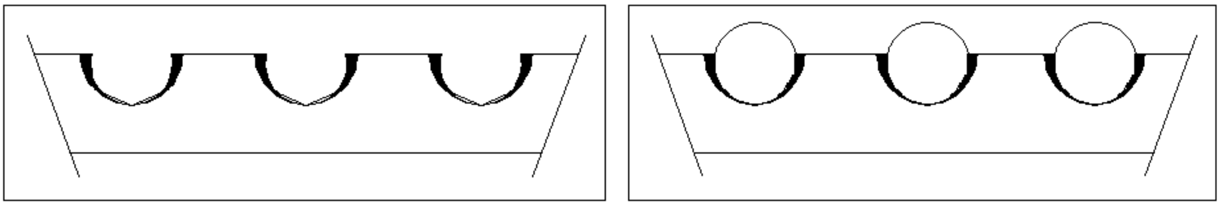

Fig. 6- The lubricant inside of concave shape and steel spherical-ball in the concave shape lubricated

3 Analysis methods of the model

The system has three degrees of freedom, namely two horizontal directions Ux, Uy and a rotation. In zero area contact at all around the spherical ball and the plate (as represented in figure 7), the contact points must be composed of hard atoms on each element. The deformation of each can influence the geometry. The sphere cannot lie directly above the center of the contact point (shown in figure 8) and disturb the rotation of the ball. The type of bearing and the contact area is circular, resulting in a semi elliptic pressure distribution determined analytically. A flat and curve isolation system is represented in different figures (7, 8 and 9). The movement of the spherical ball (turning on itself and sliding inside the curve shape) is governed by the earthquake load and repeated earthquake cycles.

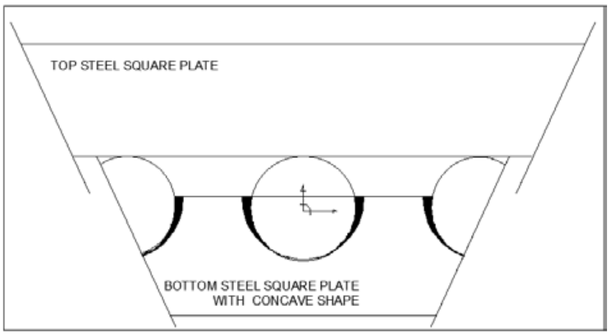

Fig. 7 - Different parts of isolator

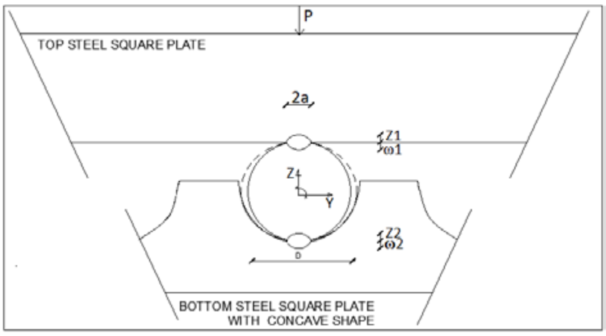

Fig. 8 - Illustration of distribution of the pressure and deformation at contact area

3.1 Analytical analysis

A punctual or surface contact created under the effect of vertical load, which is the tangent plan common to the different sides of the system contact point. This punctual contact is called Hertzian.

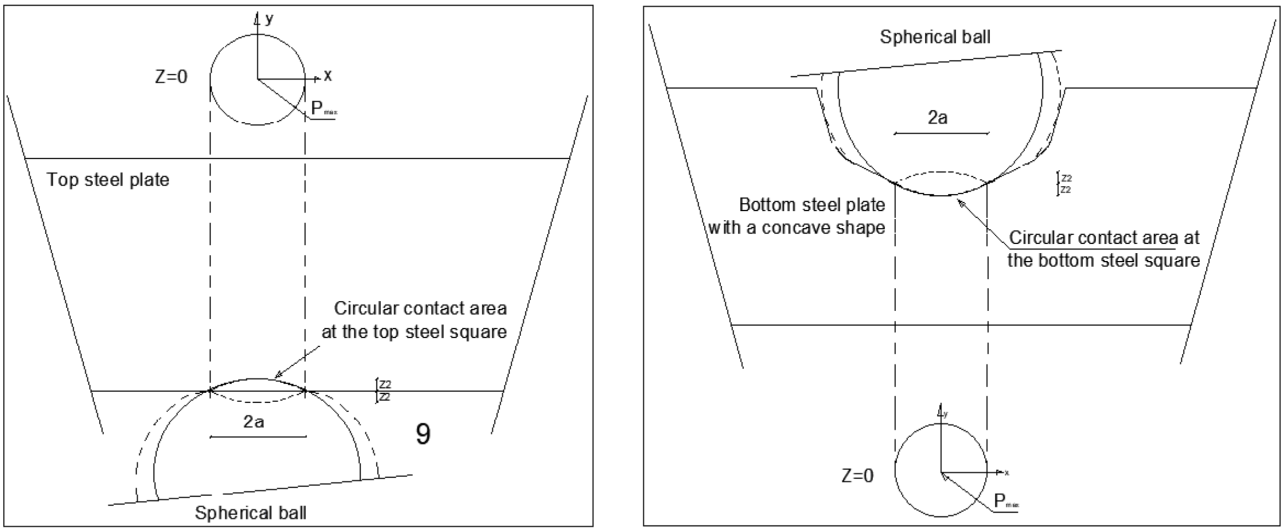

Fig. 9- The mximum contact pressure at the center of each side

Contact, which illustrates the prediction of the deformation and the dimensions of the surface contact pressure. The equation for area contact pressure distribution and compression when two entities press each side together, with displacement will occurring in both sides as shown in figures 8 and 9.

$$dT1 = Z1 + \omega 1 \tag{1}$$

$$dT2 = Z2 + \omega 2 \tag{2}$$

Where, dT1 and dT2 are respectively, the deformation of the top plate and the bottom plate under the pressure. ω1, ω2 are the deformations of the spherical ball on each point contact.

$$Z = Z1 + Z2 \tag{3}$$

Z is the total deformation of the top and bottom plates.

$$dT = dT1 + dT2 \tag{4}$$

$$dT = Z + \omega \tag{5}$$

dT is the total deformation of different parts of the system

The second part is a circular area (2a) of the deformation, since the different entities touch each other, causing a semi elliptic pressure distribution (sphere on a spherical groove and plane on a flat plate). This allows us to calculate the time of the eventual change or control the different parts of the isolators.

$$\mathrm{a}^3 = 3.\mathrm{P.R.}(1 - \upsilon^2)/4E \tag{6}$$

υ: Poisson’s ration

$$\mathrm{P_{max}} = 3\mathrm{P}/2\pi\mathrm{i.a}^2 \tag{7}$$

P is the maximum contact pressure at the center of the circular contact area; the center of displacement is highly a nonlinear function of the load and consists on determining the pressed area.

The general equation to obtain the contact stress or compression effect from each side of the spherical ball, subjected by the applied load from the top and reaction from the bottom. Considering it as mutual approach under axial load, the two bodies must be isotropic, linearly elastic and the areas in contact are perfectly smooth. This allows considering the second-degree relationship consisting of three orthogonal components axis as general equation for the following theory.

$$ax^2 + by^2 + cz^2 + 2fyz + 2gzx + 2hxy + 2ux + 2vy + 2wz + d = 0 \tag{8}$$

As the planes *x-x’* and *y-y’* are in common tangent plane to the normal axis plan *z-z’* which is parallel to axials load.

According to these considerations, which permit to assume that the tangent plane (dz/d*x* and dz/d*y*=0) and at the origin,*x*=0, *y*=0, *z*=0, therefore *d*=0 and differentiating with respect to *x*.

Again at the origin *u*=0 and with respect to *y*, so *v*=0.

After calculation and assuming from formula (8) the sphere in contact with the planes, the formula dTfor deformation or compression will be adequate for the topic of research becomes as follow:

$$dT = (3\pi/2)^{2/3}.P^{2/3}.V^{2/3}.(1/D)^{2/3} \quad (9)$$

$$V = (1-\upsilon^2)/2\pi E \quad (10)$$

$$dT = (3/2E)^{2/3}.P^{2/3}.(1/D)^{1/3} \quad (11)$$

Spheres and both planes are all in steel and Young Modulus adopted is 210 GPa. As the compression is in both sides, the formula (9) will be:

$$dT = 0.000040.P^{2/3}.D^{-1/3} \quad (12)$$

The drawing of various diameters is plotted in figure 10 from the formula 12 [22]. The compression of the sphere depends of the dimension of the diameter and the vertical load. This drawing can allow the selection of the most appropriate elastic material.

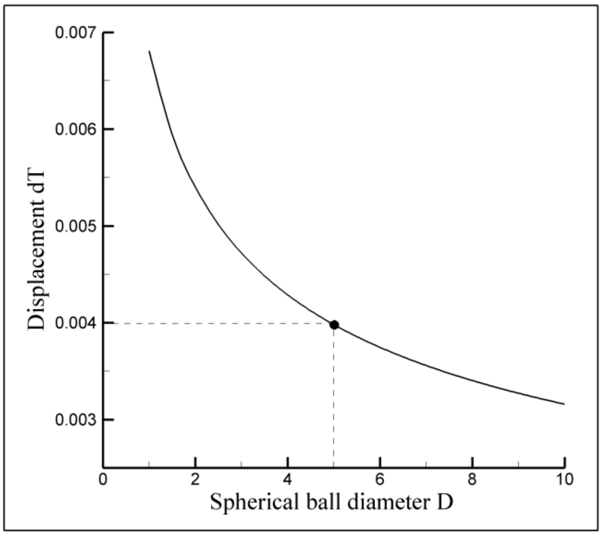

Fig. 10 - Variation of diameter function applied load of displacment dT = f(D)

3.2 Elastic analysis

The spherical-ball and planes are all made of steel; the applied axial load required at the point of contact must ensure purely the elastic range of strain (building of ten stories in this study). The vertical load generated in the superstructure is directly proportional to the deformation across the isolation system.

The total compression vertical load supported by each one the isolator parts, can confirm the same result from the curve plotted by using the formula [20] with the others approaches. The following properties can be used to design any part of the isolator in the figure 11.

$$\sigma_{el} = W_{max}/s \quad (13)$$

$$E = tg\alpha = \sigma_{el}/\varepsilon \quad (14)$$

Where E is The Young modulus and $P = w_{max}$: maximum applied vertical load

The different parts of the system depend on the axial compression load (top and bottom point contact), the Young modulus can be determined by loading and unloading gradually the spherical-ball until reaching the elastic limit strength of each part, without any permanent deformation and yield of each contact point between the different element as shown in figure 11. As far as the Poisson's ration is concerned, it is assumed to have a constant value across the different components of the system.

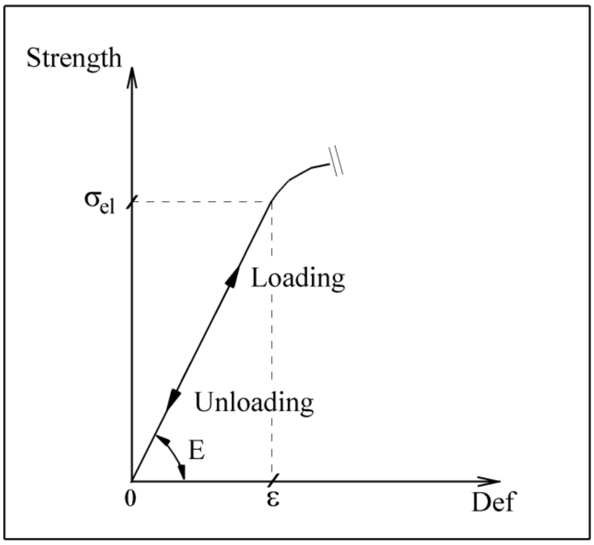

Fig. 11- Strength deformation curve

3.3 Finite element approach

A finite element analysis performed because structure and load have two orthogonal symmetry planes and in order to increase analysis precision [23] using the Ansys program R12.0, to compare and to confirm the principle of convergence a numerical approaches by adopting the same mechanical characteristics, same dimensions of the different parts of the system and adopting the same applied loading. The figures 12 and 13 indicate the complete the meshing nodes of the different parts of the isolator given by the output of the Ansys program.

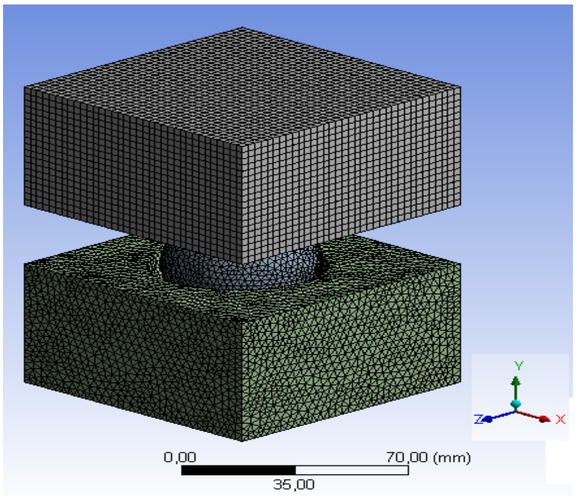

Fig. 12 - perspective view of the different mesh

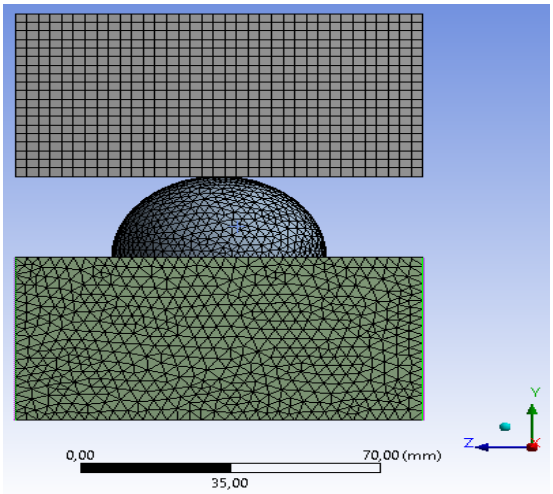

Fig. 13 - the total meshing of the different parts of isolator

There are: 254438 meshing nodes in total for the different parts of the isolator for one spherical ball. 100944 meshing nodes in the top steel plate. 36899 meshing nodes in the spherical ball. 116595 meshing nodes from the bottom steel concave plate.

We adopt the steel of different parts of the isolator the 100Cr6 with 210GPa as Young modulus (European designation ISO 683-17Standard Norm).

Figures 12-16 indicates the strength, the displacement and the deformation with the total meshing nodes of the different parts of the isolator by using the Ansys program. The obtained results are according to the material 100Cr6 with 210MPa as Young modulus and the same data base.

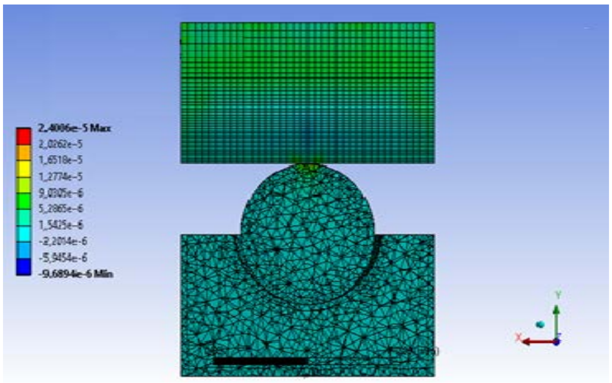

Fig. 14 - Normal principal strenght (MPa)

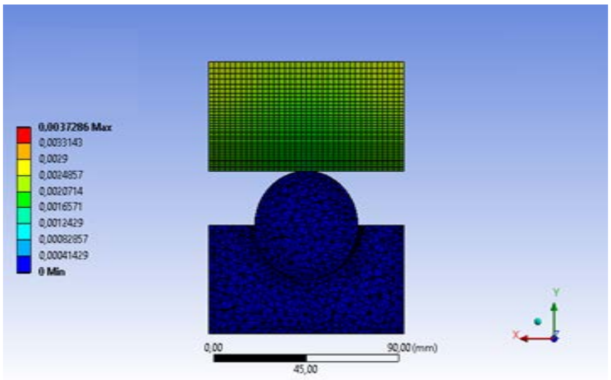

Fig. 15 - Total displacement (mm)

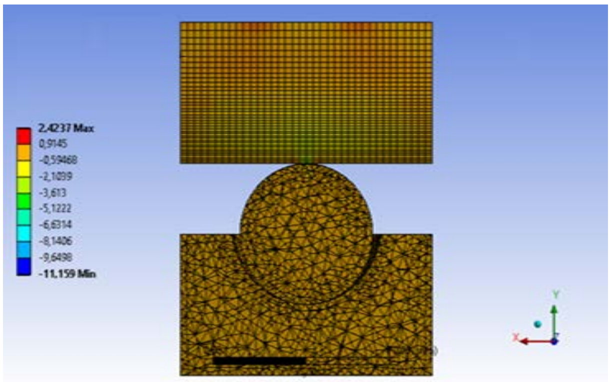

Fig. 16 - Elastic deformation (mm/mm)

Chemical analysis can be seen of the 100Cr6 with 210MPa as Young modulus in accordance with ISO 683-17 Norm.

The elastic properties of materials are related to interatomic links. This is why molecular static make it possible to calculate the constants of elasticity of materials, it can also range it upon the final properties and it is capable of enhancing wear surface for an eventual safety margin.

The mechanical properties of thickness all around the sphere and the plates become very strong, keep dimensional stability according to the arrangement of solid atoms in some definite crystallographic pattern allowing it to easily support the vertical load than the previous by the previous approaches.

4 Results and discussion

The physical model is designed to have a total uncoupled system between the structure and the base, in other terms, a true nonlinear behavior in term of strength or force deformation relationship restricted in isolation system only and rigid in vertical direction, supporting the maximum gravity service load along the life span of the structure. The design of this model has faced a very large concept of displacement for the isolation. To reduce this displacement the suggestion of supplemental shear wall at the basement level can increase the resistance capacity of the foundation by reducing the movement of the base from the ground into the isolators. The shear wall and the isolation system should remain continuous in order to respond to ground motion.

4.1 Analytical results

By using the formula dT (12) and the corresponding sketch in the figure 10, it is possible to obtain the compression effect by direct use of the applied load between the two contact points. The required result is obtained in the plot of figure 11, the higher the diameter of the spherical-ball, is the lesser deformation (displacement and compression), is considered negligible or ignored.

4.2 Elastic analyses results

Only mechanical characteristic properties of the different parts of the system are concerned by the axial compression load and can be determined provided that the elastic limit is not exceeded as shown in figure 11. We can notice that there is slight negligible deformation in the elastic range of strain; all this is dependent of the diameter of the sphere. The elasticity theory has expressed the relation of the displacement at different contact point or sub-layer of the spheres with a plane due to axial load pressure to another point as input of the system.

4.3 Finite element results

The performance of the numerical simulations results as shown in the figures such as 14, 15 and 16, assuming the same values of different dimensions of the system and the same Young modulus. The results of the finite element approach can be confirmed the others by normal principal values of strength, total values of the displacement of each point of the elements and elastic deformation of the system.

The contact area is infinitesimal small, but not technically null, in a pur mathematical sens the limit of the contact point area approaches zero.

The contact point defined as being infinitely small can create a considerable deformation if the spherical ball, the top and bottom plate are not infinitely hard, isotropic, homogeneous and the elastic limit of the material must not be exceeded in order to prevent the spherical ball to slide and to turn on itself.

5 Mechanical characteristic and chemical composition

The value of the displacement in table 1 must be the maximum according to the weight of the structure (vertical load), so the principle of this research cannot tolerate any small deformation, which might influence or disturb the rotation of the spherical ball.

Table 1 - results of mecanical caracteristic of the spherical-ball by using Ansys 12.0

Weight (KN)	Displ max (mm)	Deformation	Strenght (MPa)	Young Modulus (Gpa)	Volumic Mass (Kg/m)	Compressibility Modulud (Pa)	Poisson Coef	Shear Modulus (Pa)	Specific Heat (J/KgC)
26.5	0.0012996	0.0000488	9.7637	200	7850	$1.6667*10^{10}$	0.3	$7.7923*10^{10}$	434

This is one of the main aim, which is the condition that leads to increase the Young modulus to *E*=210GPa value, which allows and maintains intact coaxiability with no deformation. The steel ball slide in a solid state and turn on itself taking the same spherical shape from earthquake to earthquake without any permanent deformation or yield point. This explains the molecules attraction of the steel generates very weak or negligible frictional heat, through energy dissipation.

We can see the chemical analysis of the 100Cr6 with 210MPa as Young modulus is in accordance with ISO 683-17 Standard as indicated in table 2.

Table 2 - Chemical composition of the differents parts of the isolator (100Cr6 as a material adopted)

%	C	SI	Mn	P	S	Cr	Mo
Min	0.93	0.15	0.25	/	/	1.35	/
Max	1.05	0.35	0.45	0.025	0.015	1.60	0.10

5.1 Design criteria for isolation model

The different parts of the model must ensure a lifelong performance under vertical service load of the structure. The material of all parts of the system is made of steel (100Cr6) available from different manufacturers. The number, dimensions, sizes and location must be in accordance with the design criteria. The control of the performance of the system under all possible loads condition vertical or horizontal must be ensured.

6 Application of the model

6.1 Structure solution

The architects must take into consideration the underground or sub-basement as necessary along with the sufficiency condition for designing a practical area to allow for the inspection of the isolation system. The location of the seismic isolation must be accessible for an eventual need, for maintenance, repair or checking the state of all components of the system after each seismic event.

6.2 Configuration of fixed base

We consider four buildings with different heights as required in the geometry plan. Respecting the same foundations scheme as shown in figures 17 and 18 and adopting the same materials for the structural elements and the same usage for a conventional design. The principle of the seismic isolators is to install them at the underground level in the horizontal plane, which is the base of the structures. Meanwhile the damping device element must be installed at the same level to restrict the displacement of the motion caused by the seismic forces.

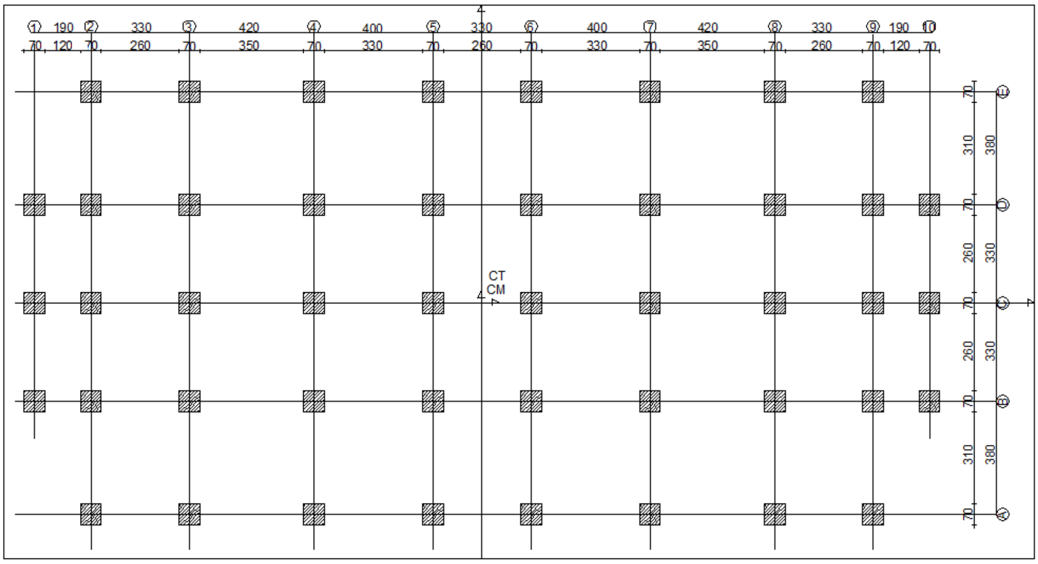

Fig. 17 - Level storey of the structure

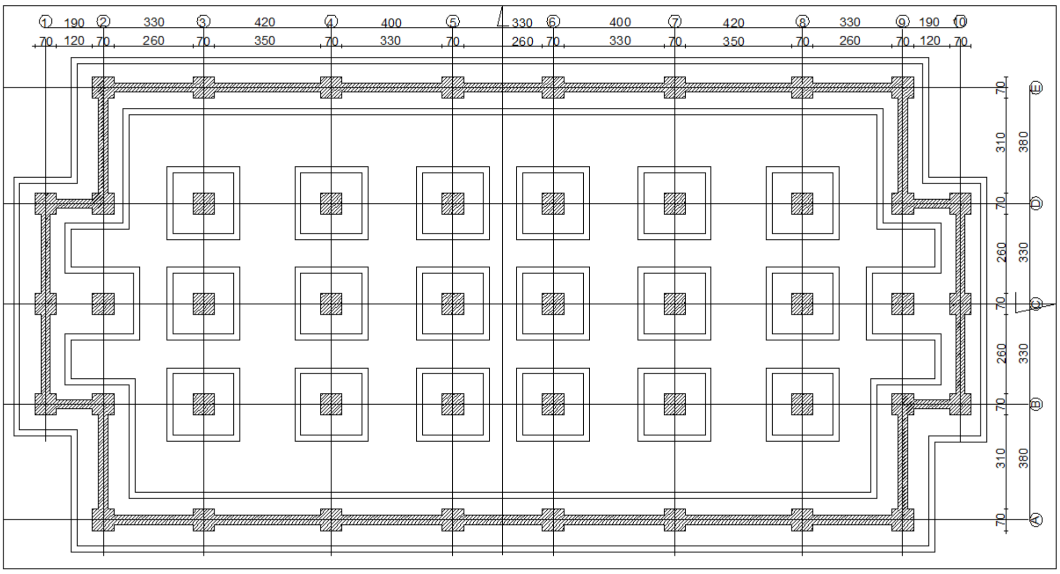

Fig. 18 - foundation of structure without isolation

In this study we have focused on the significant benefit of the different horizontal displacements shown in figure 19 and the fundamental periods of each type of structures with displacements without base isolations as a fixed base with different seismic zones table 3.

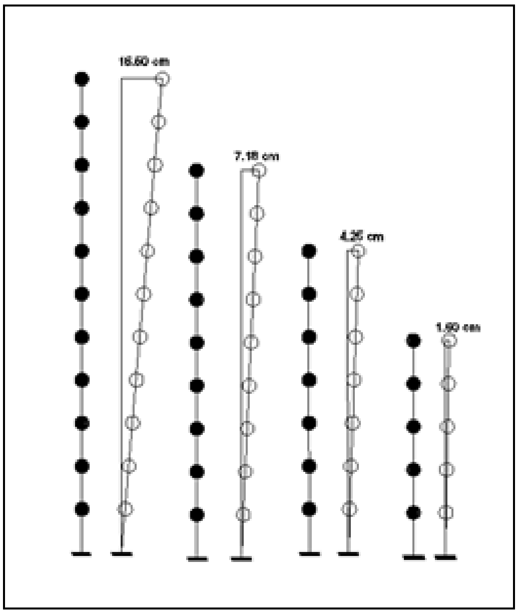

Fig. 19 - Modellisation of differents heighstructure fixed base mode shape(linear first mode and displacment)

Table 3-Weights and displacements of different structures according of seismic zone

Algerian Seismic Zones					
		Zone II A		**Zone II B**	
Structure	Ultime effort (KN)	Depl X-X (cm)	Depl Y-Y (cm)	Depl X-X (cm)	Depl Y-Y (cm)
RDC+10 stories	2220	8.52	11.63	14.92	16.50
RDC+08 stories	1695	3.82	5.60	6.78	7.18
RDC+06 stories	1315	1.35	1.98	3.17	4.25
RDC+04 stories	907	0.7	0.6	1.21	1.60

The tallest structure reaches the long period and the largest amplitude shown in figure 19 for the seismic loading and this provide a corresponding flexibility in the horizontal direction with an eventual transfer of the vertical load to the structure. For each column we assumed more than 80 bearings (spherical balls of five cm in diameter) divided by 2220 KN to determine 26.5KN as a vertical load for one ball Table 3

According to different periods of each structure, as a result of the design of fixed structure. The same materials is adopted, the design and the dimension of the isolator system is related to the fundamental mode of linear analysis of the system and should serve our purpose.

The main idea and the ultimate objective is to mount a convenient flexible base or isolator system, which is able to absorb or to filter out all the frequencies. The isolators are rigid in the vertical direction and the transmissibility must be less than the unity automatically the non-linear behavior is restricted in the isolation system level. Among the four different buildings, the building of 10 stories as presented in figure 20 was selected in this study.

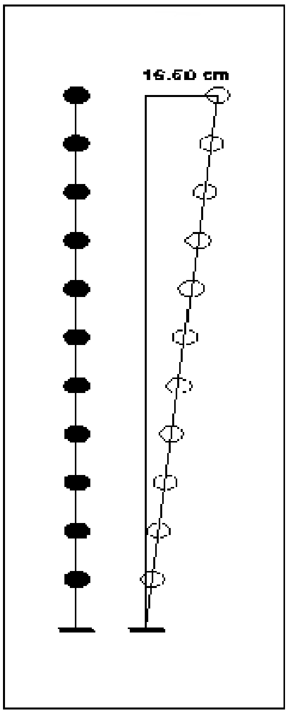

Fig. 20 - Modellisation of structure (fixed base) mode shape (linear first mode and displacment)

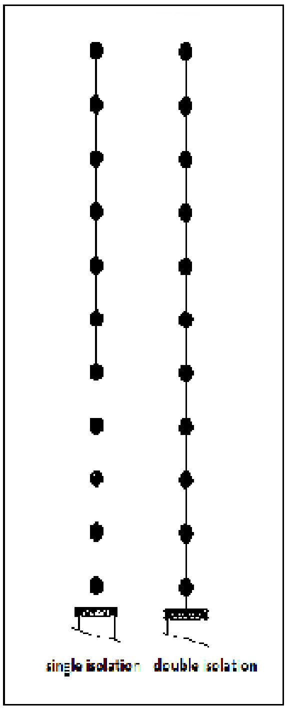

Fig. 21- Modellisation of structure (isolated base)

6.3 Configuration and practical application of isolated base

We consider the underground with two meters high, where the isolators have been placed at the top of each pillar as shown figure 21. The structure is sustained by concrete shear walls all around the foundation see figure 22 and even inside between some pillars, this technique gives a useful source as first of natural damping at the base level. It is clear the pillars have the location at the underground level and the superstructure must remain elastic all times.

The structure designed in accordance with the plan for fixed base, modeled in figure 22 and isolated base, modeled in figure 23.

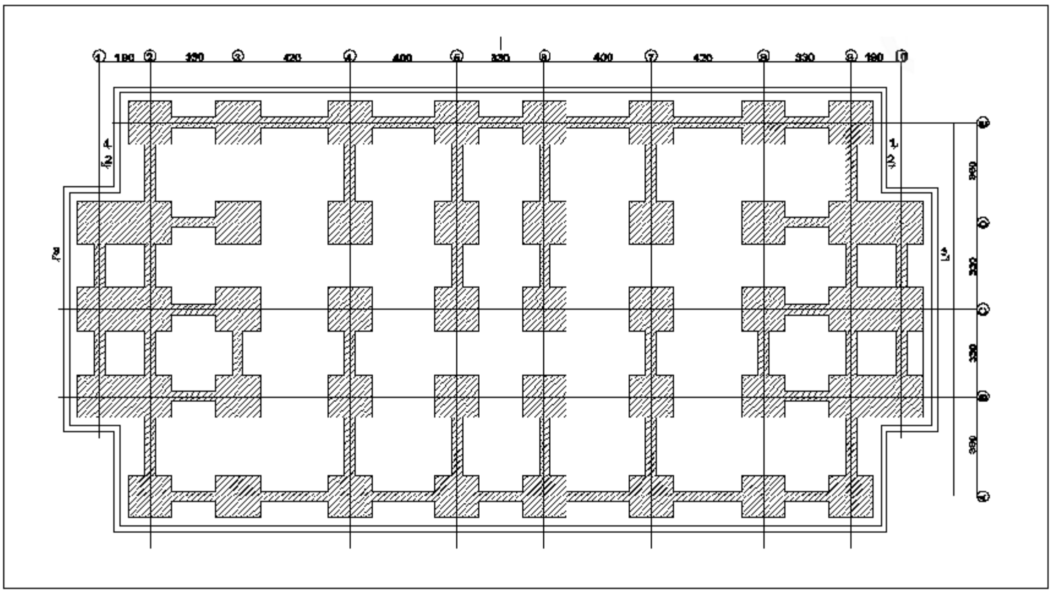

Fig. 22 - Fondation of the structure for the base isolated

The location of the isolators system should allow future access to inspect, control and replace if necessary any parts of the isolators, depending of the types of the configuration as indicated in figures 23 and 24 from the cross section of longitudinal foundation.

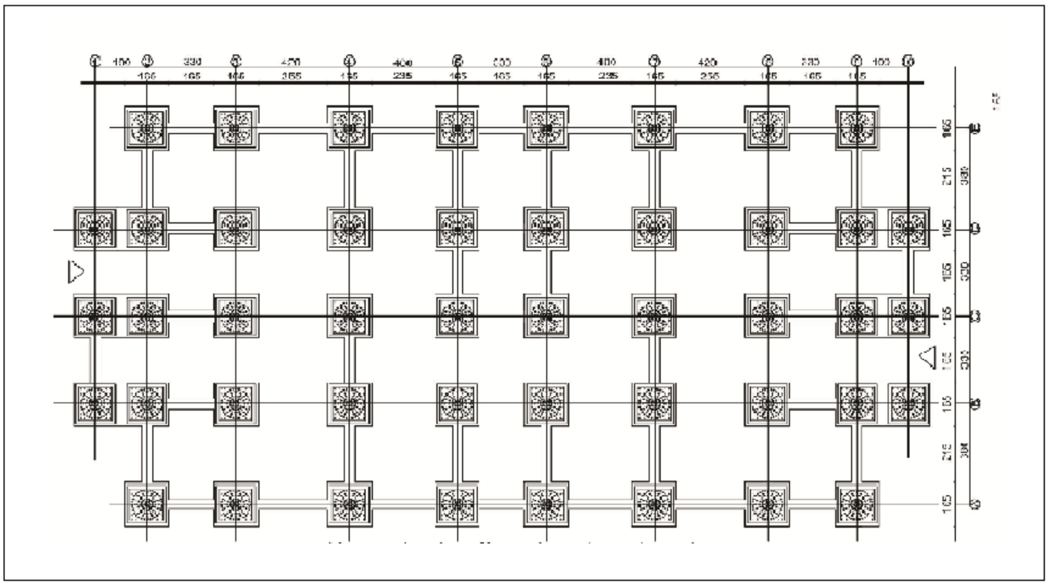

Fig. 23 - Design of the possition of sismic isolation

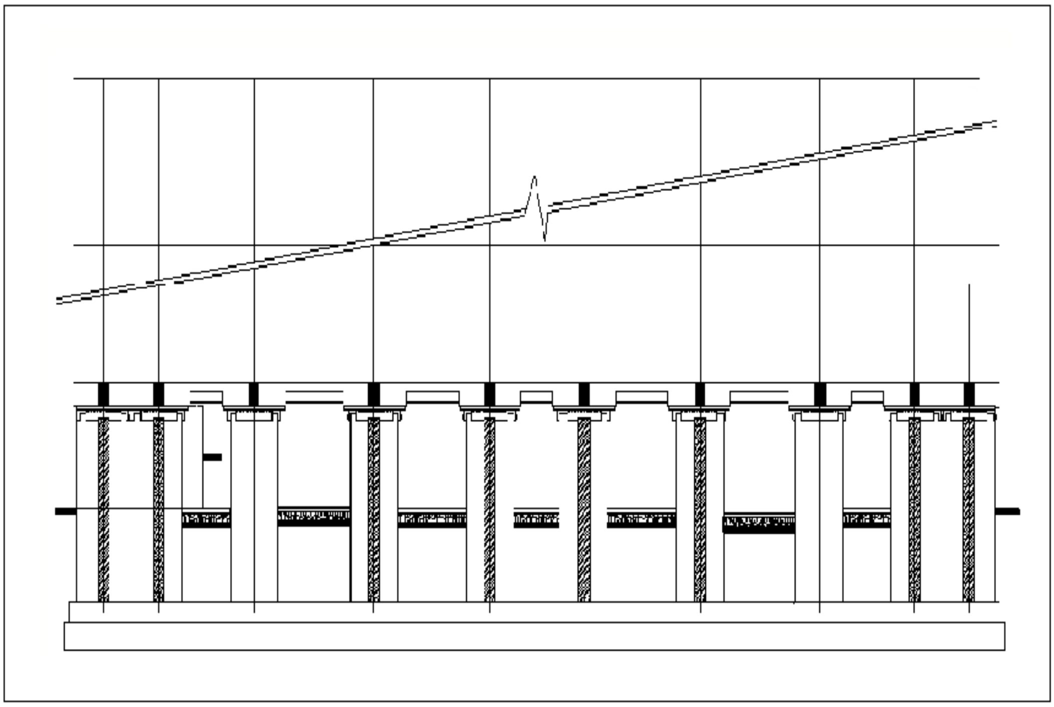

Fig. 24 - Isolator bearing under each pillar (socle)

Interposed between the base of the structure and the foundation, these spherical-balls are strong and stiff under the vertical load and can rotate on themselves under the lateral forces inside the concave shape.

Some of shear wall fixed at the pillars in the underground level as a natural damper and the dampers as a supplementary device fixed between the pillars and the above assumed rigid diaphragm, both of them can act as energy absorber to reduce the ground excitations at the base as shown in figures 25 and 26.

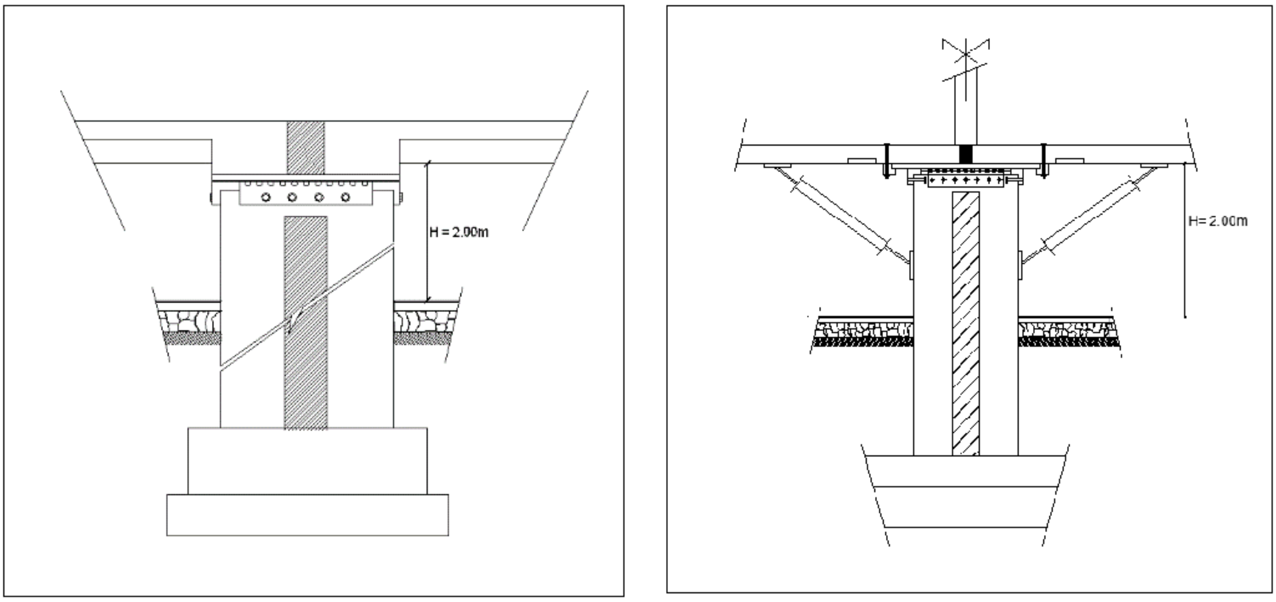

Fig. 25 - Bearing located in sub-basement with sher wall (h=2m)

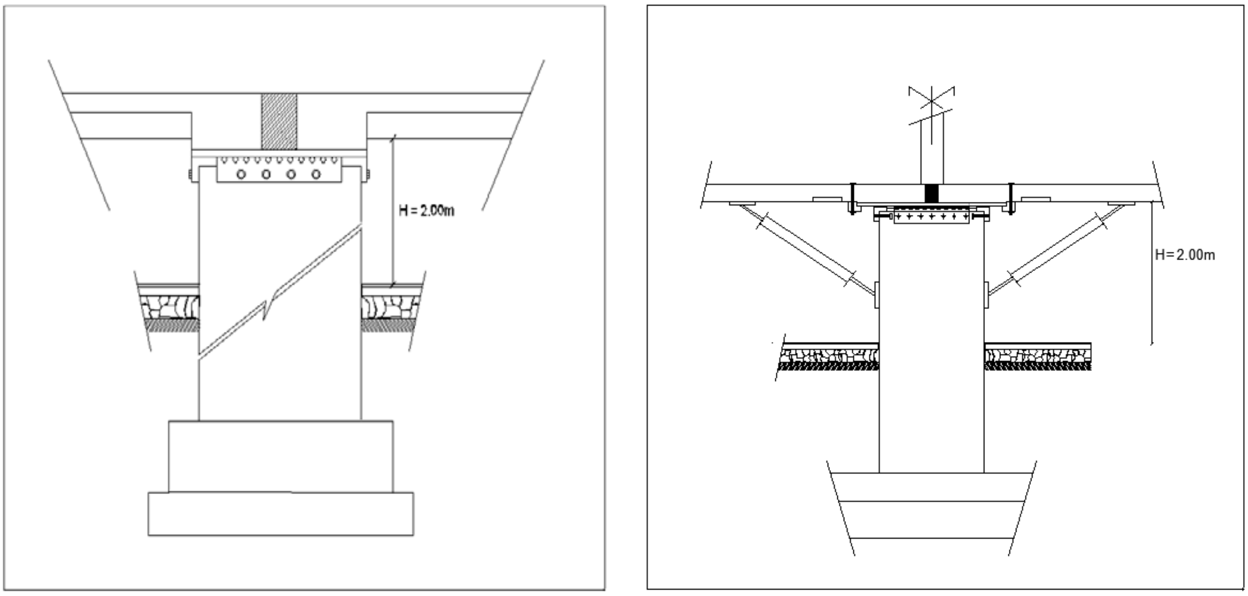

Fig. 26 - Bearing located in sub-basement (h=2m)

6.4 Details of the isolation base concept

In the current figures, configurations as presented in figure 30 the fixation of the top steel to the last slab of the superstructure, is designed to show the locations of the others different parts of the isolator at the pillar as shown in figures 27, 28, 29, 30 and 31. The top steel plate will be the space of the sliding of the isolation system meanwhile the lateral displacement area of the foundations.

All these types of isolations depend on the behavior of the structure in figure 27, they must not transmit any residual displacement from the horizontal loading to the superstructure, in order not to incorporate another bottom steel with a spherical ball as a double isolation as indicated in figure 21

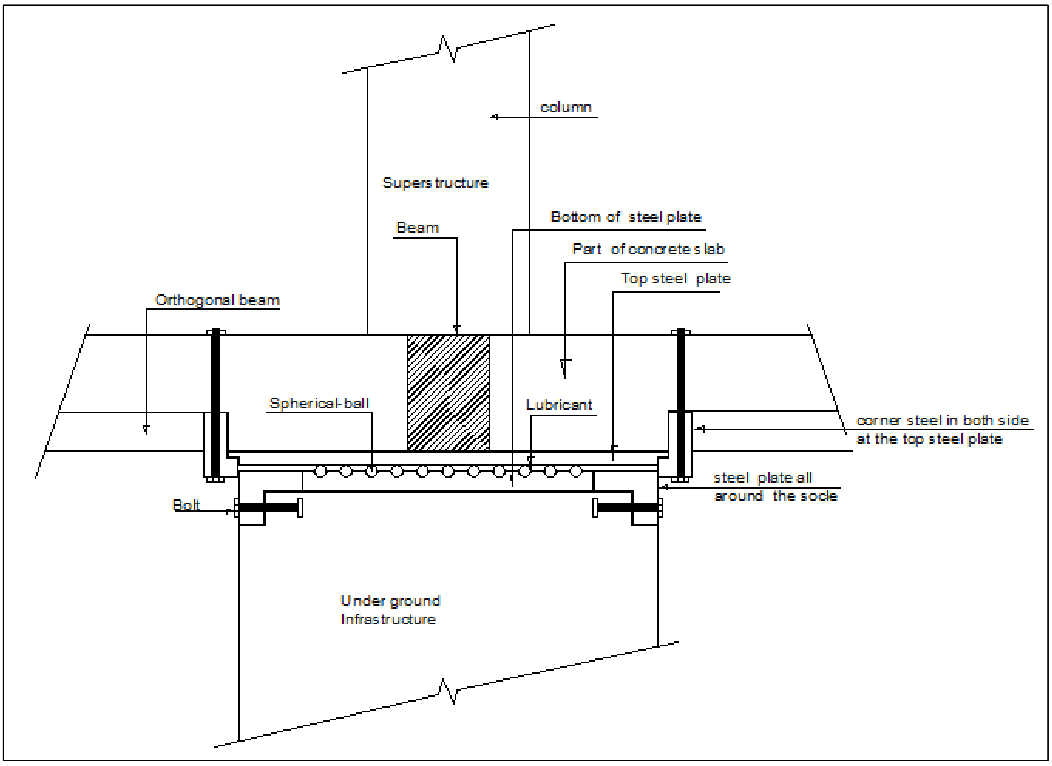

Fig. 27 - Configuration detailled of isolator system

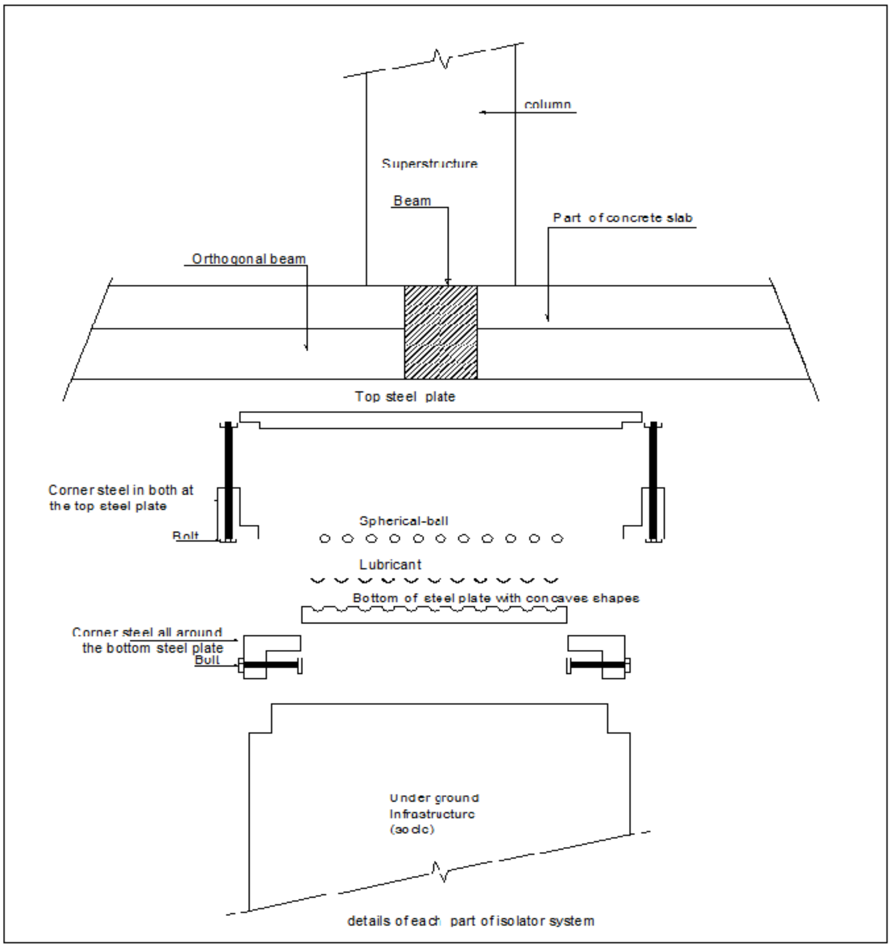

Fig. 28 - Details of the configuration of the system

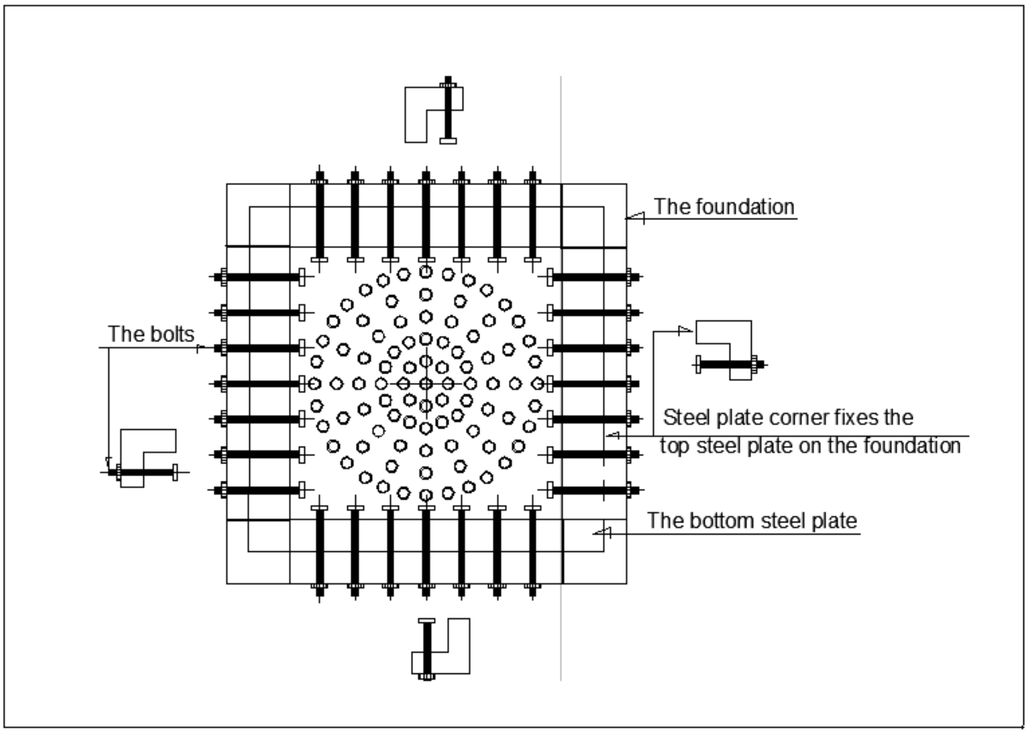

Fig. 29 - Bottom steel plate with differents bolts and dowels

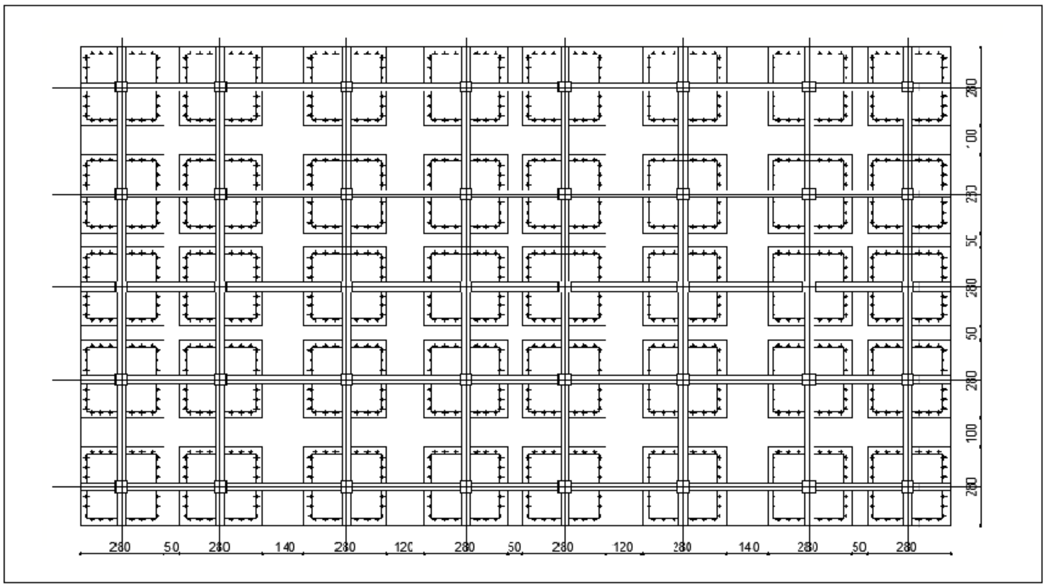

Fig. 30 - large square of parts of slab above and the on the right of each isolators system.

7 Conclusion

A methodology describing the use of two or more analytical approaches for the design of isolation system to any structure is very important because of the accuracy, the convergence of the right result values that we looked for from the different approaches, especially the mechanical properties of the materials used, deformation, durability and vulnerability due to different applied loads.

The different parts of the isolation system must represent the stiffness of the material in its resilience phase; all sorts of deformations of the different parts of the isolator must be fully covered after horizontal unloading by some mechanical properties such as high elastic modulus and Poisson's ratio.

No, or slight friction allows to achieve really the true longue natural period as well as to moderate large amplitude of the underground. This lead the study to confirm the high performance of seismic isolation helping architects to innovate the design without any limitation of civil engineering code such as:

- Design geometry;
- Functionality of the design (center of mass and center of rigidity;
- The height of the buildings.

One of the primary conditions of the isolated system is to ensure that the contact area is perfectly smooth and the three parts of the material of the system are isotropic and homogeneous.

The number of spherical balls, the thickness of the bottom steel and the top steel plates depends on the type of the structures. Furthermore, the more spherical ball is used, the better stability is achieved, ensuring security, linearity of the system from seism to seism loading and after the seism. When the friction is slight, it should not be taken into consideration, because the spherical balls help to overcome the problem of high friction coefficient at each area contact point.

The isolator can be subjected to various excitations forces until the ensuring nonlinear behavior, the performance increases according to the energy dissipation capacity, ductility phase and fatigue properties.

The isolation system became an attractive alternative for all types of buildings; it must remain in the same initial form after consecutives repeated ground shaking.

All this is in order to understand, the optimal axial load, seismic behavior, the type of soil condition where the structure is fixed, how to analyses the design of the seismic isolation type and the most performant and efficient system to enhance seismic protection.

This paper presents an innovative new design argued by different approaches since it achieves the principle of convergence of the results to increase people safety.

This design strategy provides an economical and practical model for new design of different building structures and seismic rehabilitation of existing strategic building and to allow for better architecture design with sound seismic performance.

The feasibility of the isolation system and the applicability of the different analysis approaches requires shaking table test in order to achieve the same results, for the safe design of adequate model. This model helps to avoid displacement of the superstructure as greatly the likelihood small displacement accepted from the bottom of the structure to the top by the use of all sort of different elastomering bearings isolation systems, which can be a source of the linearity of the structure. This does not mean that the system is fully isolated, however an advantage or issue of transmitting the force to the structure.

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