EVALUATION OF EARTHQUAKE RESPONSE ANALYSIS METHODS FOR LOW-RISE BASE ISOLATED BUILDINGS

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ABSTRACT :

The seismic isolation approach is extremely rational approach especially for low-rise and medium-rise buildings with natural periods close to fundamental periods, i.e., buildings that are under the risk of the resonance. This paper deals with available analysis methods determined on a comparative basis for most suitable and realistic approaches, especially for cases where the isolators are provided for the foundations of low-rise and medium-rise buildings. To this end, a brief introduction is followed by the investigations performed for different analysis methods, namely the static equivalent earthquake force analysis, linear response spectrum analysis, linear time history analysis and nonlinear time history analysis. For each analysis method, the comparisons are performed and conclusions are discussed for the total base shear forces, story shear forces at columns and absolute and relative story drifts. It can be concluded, upon assessments on the results of the analyses especially for first three analyses, that they are reasonable and extremely practical. The results obtained from the nonlinear analysis tend to deviate from each other as compared with other methods, mainly because of the facts that its is extremely sensitive to numerous parameters and that such nonlinear parameters used in the calculations are derived from simple static methods. On the other hand, even static equivalent earthquake force analysis yields more correct results especially in designing the isolation systems for the low-rise building. Accordingly, it is more reasonable, in the course of the design, to perform first static and then linear response spectrum analysis prior linear time history analysis.

KEYWORDS: Seismic Isolation, Earthquake Response Analysis Methods, Low-Rise Building, Medium-Rise Building,

1. GİRİŞ

Seismic isolation is a new trend in the earthquake resistant structural design, embodying a great potential for the future. Conventional approach in earthquake resistant structural design focuses on the prevention of total collapse of the structure under the impact of severe earthquake. As the performance shown by the structure, in this approach, depends on the damage suffered by the structural members, it began to loose its acceptability gradually nowadays. Briefly, this perception, while being adequate in building structures not collapsing under the earthquake; falls short when the structures not being damaged in the earthquake are required. If the previously acceptable damage levels now becoming unacceptable for various reasons, this means that a need is born for the development of a new methodology in the design of earthquake resistant structures.

Seismic isolation emerges as an extremely rational approach especially for the low-rise and medium-rise structures, having their natural periods close to earthquake's fundamental periods i.e., having resonance risk. Also, usage of seismic isolation is becoming widespread very rapidly in structures for which the operations are expected to continue during and after the earthquake. Its usage is made mandatory in the regulations of some countries. Seismic isolation is now commonly used especially in the repair and strengthening projects of the historical structures for the purpose of protecting the original architectural characteristics of the structure and its sensitive and valuable content, and in some cases it appears as the only alternative in front of us.

Setting off by thinking seismic isolation being appropriate for all kinds of structures is wrong. A preparatory work appropriate for the design requirements of the structure must be carried out first, and the decision must be given afterwards. Furthermore, as different design requirements rationalize different seismic isolation systems, preparatory work must also be evaluated with these alternatives.

2. CONVENTIONAL DESIGN PERCEPTION

In the regions with high seismic activity, it is almost impossible to built, with conventional design concept, medium or high-rise structures with acceptable costs, capable of resisting to the severe earthquakes without damage. For this reason, many regulations contain principles on prevention of loss of lives and total collapse. According to this conception, the damage, which is the result of behaviours beyond elastic range in the structure, is an important solution for dissipating the energy of the earthquake and for minimizing the probability of collapse. Occurrence of damage acts as a kind of circuit breaker. Even though this design approach saved many lives in many countries, it failed to prevent the very heavy burden brought upon the economy and social life of the country by thousands of seriously damaged and unusable structures.

Designing a structure capable of resisting even the most severe earthquakes is neither easy nor cheap. For this reason, engineers use the “ductility” allowed to them by the regulations. Ductility is an expression for the capacity to meet the deformations beyond the elastic behaviour of the structure. When the elastic limit is exceeded, even the smallest increase in the force shall create extensive deformations. The elastic limit is the threshold value which returns back to its initial value in a manner not to leave any permanent deformation behind after the earthquake. Transition to the ductility region means damage on the structural members. This in turn means a decrease in the strength capacity of the structure against the loads.

Earthquake has a demand, and only the structures meeting and exceeding this demand may remain standing. As the demand of the earthquake can not be changed, in the conventional design approach the structures are designed to have a bigger capacity than the demand. The elastic strength is increased to increase the capacity. This is an option both difficult and expensive, and also causes great storey drifts in the buildings. Another way is the limitation of the elastic strength, and detailing of the structure for ductility. This option means the acceptance of occurrence of irreparable damage in the structural components.

The natural periods of the low and medium-rise buildings and the fundamental periods of earthquakes being in the same range creates resonance problem. The effect of the resonance occurred causes serious increases in the impact of the ground motion on the structure, and great structural damages. This may be explained as follows; the natural period of an ideal rigid structure is zero. This means structure responds to the ground motion as one to one, and a relative translation between the structure and ground is not created. In this case, the structure shall move with acceleration equal to that of the earthquake. When an exactly the opposite situation is considered, the natural period of an ideal flexible structure is infinitive. In this case, even if the earth moves the structure shall remain still. There shall be a relative drifts between the structure and the ground equal to the displacement of the ground. In other words, the acceleration shall be zero, and the displacement shall be at its maximum value.

In actual life, the structures are neither totally rigid nor totally flexible. The response shown to the ground motion shall be somewhere between these two marginal values. The rigid structures with low periods are exposed to high acceleration values, often exceeding the acceleration of the ground motion with the amplification effect created by the resonance. As the period increases, great storey drifts come to the scene. It is highly difficult to meet this undesirable situation with the conventional structure design perspective.

3. NEED FOR A NEW DESIGN APPROACH – SEISMIC ISOLATION

If the negativities, some of which are mentioned above, are wished to be eliminated or minimized by using the conventional design perception, the building costs shall increase significantly or it shall be necessary to make to much concession from the architectural aesthetics and usability values. Yet, it is not reasonable and possible to build a structure not suffering any damage under the impact of severe earthquake, within the framework of this conception.

Seismic isolation is an earthquake resistant structural design approach based on the principle of decreasing the demand of the earthquake from the structure, instead of increasing the earthquake resistance capacity of the structure. The most important characteristics of the structural system, in terms of determining its response against the earthquake, is its natural period. The natural period depends on the mass, horizontal rigidity and damping of the structure. One of the important things the seismic isolation actualizes on the structure is the prevention of coincidence with the fundamental period of the earthquake by increasing the natural period of the structure, in other words; preventing the acceleration amplifications created by the resonance effect. It is mentioned earlier that earthquake demands acceleration from the rigid structures and large displacements from the flexible ones. When the seismic isolation is used, in the structure approaching towards the elastic behaviour, a great displacement demand shall occur as the period increases. The work done by the seismic isolation is to meet this demand in itself by creating large deformations without transmitting to the structure.

Another important duty of the seismic isolators is damping the energy of the earthquake by acting as an energy damping device. There are two types of damping for the isolation systems in general; hysteric damping-displacement dependent damping and viscous damping-velocity dependent damping. While the increase in the natural period of the structure causes decrease in acceleration and increase in displacement, whereas the increase in damping causes decrease both in acceleration and displacement. While the seismic isolation system do all these, it must also have the rigidity to ensure the stability of the structure under the applied loads such as gravity, wind, temperature effects, shrinkage and creep effects.

There are four fundamental duties of an ideal seismic isolation system. These are low horizontal rigidity, high vertical rigidity, damping and flexibility. Even though, factors such as durability, cost, ease of installation, project specific needs also constitute importance in the selection of isolators, all the isolators must have the above indicated self-qualities.

4. EVALUATION OF THE EARTHQUAKE ANALYSIS METHODS – A CASE STUDY

In the application example considered in this study; numerical analysis of a two-storey structure isolated by rubber isolators, which is a widely used ones, is performed by using various analysis methods and the results obtained from different methods is compared.

In this context, the model of a two-storey building shown in Figure 1 is considered. Static equivalent earthquake force analysis, linear response spectrum analysis, linear time history analysis and nonlinear time history analysis methods are used in the analysis of the model building. Total base shear forces, storey shear forces in the middle column and absolute and relative storey drifts are taken into account as comparison criteria in each analysis method.

The structure is lays on a 24 x16 m2 area with 6m space in the x direction and 4m in y direction. The height of the storeys is 3m, the thickness of the floor is 15cm on all storeys The cross-section of the columns used in the structure is determined as 30x30cm, and the cross-section of the beams as 25x50cm. Live load of 3kN/m^2 is defined for the floors on all storeys. Total weight of the structure (dead load + 0,3 x live load) is 18.500 kN. C25 is selected as concrete material and the elasticity module is taken as 30.250.000 kN/m^2. The isolator type used in the analysis is basically LRB type circular rubber isolators.

Static equivalent earthquake force analysis, linear response spectrum analysis, linear time history analysis and nonlinear time history analysis methods are used in the study, and the total base shear forces and storey shear forces in the middle column and the absolute and relative storey drifts are taken as the comparison criteria.

4.1 Static Equivalent Earthquake Force Analysis

While this method is used, the static equivalent earthquake force affecting the storeys in the structure is calculated in accordance with the principals of the UBC-97 Regulation. The following parameters are taken into consideration in the analysis.

Seismic zone factor : Z=0,40 (Zone 4)
Soil profile type : S_D
Seismic source type : A
Near source factors : Δ>10 km N_a=1 N_v=1
MCE behaviour factor : ZN_v= 0,40.1=0,40 M_M=1,25 (from table)
Seismic factors: (from table) C_V=0,64 → C_{VD}=0,64 and C_A=0,44 → C_{AD}=0,44
$\alpha = M_M Z N_a$ = 1,25 0,40. 1 = 0,50 → $C_{AM} = 1{,}1\alpha$ = 1,1 . 0,50 = 0,55 (from table)
$\alpha' = M_M Z N_v$ = 1,25 0,40. 1 = 0,50 → $C_{VM} = 1{,}6\alpha$ = 1,6 . 0,50 = 0,80 (from table)
Damping ratio of seismic isolators : β=0,15 (Lead core rubber bearing)
Damping reduction factor : B=1,35 (by interpolation through the table)
Fundamental natural period (fixed based) : T=0,39 sec. (by modal analysis)
Building importance factor : I=1
Structural behaviour factor : R_i = 2
Total weight of building : (DL + 0,3 LL) = W = 4900 kN (weight of storey : W_1= W_2= 2450 kN)

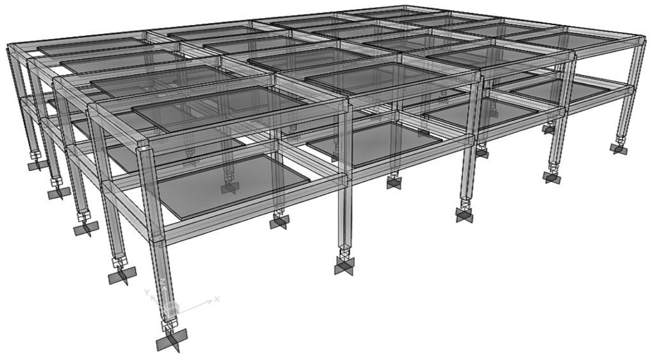

Figure 1 An aerial perspective of the structure

Targeted Isolator Period and the Material Characteristics:

A value between 2-3 sec. is selected for the period values of the isolation system.
T_D = 2,3 sec. target design level (DBE) period
T_M = 2,7 sec. target maximum possible level (MCE) period

It is seen that while the maximum vertical load on the 16 columns in the external axis is 168,77 kN, the maximum vertical load pertaining to the other 9 columns remaining inside is 287,85 kN. Two types of LRB isolator, called A and B, having different characteristics shall be used in the structure by taking these two values (170 kN and 290 kN may be accepted) into account.

<u>A Type Isolators:</u>
for large deformations G=0,5 Mpa and γ_{max}=1,5
for small deformations G=0,7 Mpa and γ=0,2
<u>B Type Isolators:</u>
for large deformations G=1 Mpa and γ_{max}=1,5
for small deformations G=1,4 Mpa and γ=0,2

Modulus of Elasticity : E_c=2000 Mpa

Equivalent Earthquake Force

Base shear force found for the superstructure may be distributed to the storeys. Thus:

As $V_{D,S}$ = 732 kN, the equivalent static earthquake force on the each storey is,

$$F_i = \frac{W_i.h_i}{\sum W_i.h_i}.V_{D,S}$$ F_1=244kN and F_2=488kN.

Just one direction shall be adequate to make the comparison in this application. Storey forces affect the storeys in the longer (x) direction of the structure in a manner as shown in Figure 2.

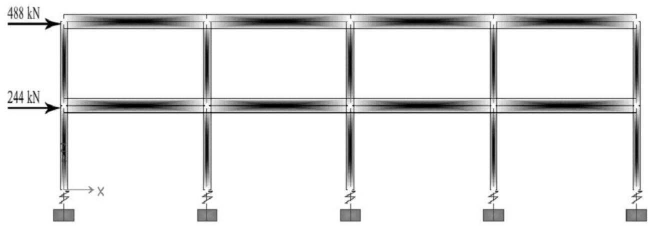

Figure 2 Static equivalent story shear forces for UBC-97

4.2. Linear Response Spectrum Analysis

The first thing should be done for the linear response spectrum analysis is to form the UBC-97 Regulation acceleration spectrum curve as seen in Figure 3.
The parameters selected to define the utilized isolators in the SAP2000 program (kN-m):

<u>A Type Isolators</u>

Nonlinear Link Type	:	Rubber
U1 Linear Effective Stiffness	:	40000 kN/m
U2 and U3 Linear Effective Stiffness	:	122,5 kN/m
Effective Damping	:	0,15

<u>B Type Isolators</u>

Nonlinear Link Type	:	Rubber
U1 Linear Effective Stiffness	:	80000 kN/m
U2 and U3 Linear Effective Stiffness	:	245 kN/m
Effective Damping	:	0,15

4.3. Linear Time History Analysis

The acceleration values, in this alternative, shall not be taken from a general spectrum curve representing all the earthquakes like in the response spectrum, but from the actual recorded earthquake acceleration data; and the response given to these accelerations by the structure and the seismic isolation system shall be calculated step by step. The North-South component of 17 August 1999 Kocaeli Earthquake- Petkim acceleration recording is defined as the earthquake acceleration.

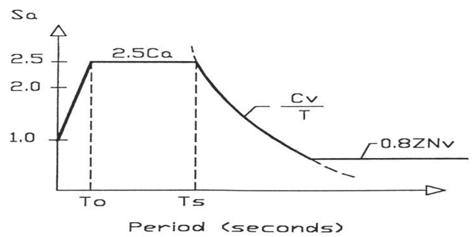

Figure 3 Acceleration spectrum inUBC-97

4.4. Nonlinear Time History Analysis

The utilized LRB type bearings are modelled bi-linearly to determine the parameters pertaining to the isolators to be used during the nonlinear calculation.

It may be assumed that $k_1 = 10.k_2$. The value shown as *post yield stiffness ration* parameter in SAP2000 shall be entered as 0,1.

<u>A Type Isolators:</u>

$$k_2 = k_D - \left((1 - \frac{k_2}{k_1}) \frac{Q_y}{d_D} \right) = 122{,}7 - \left((0{,}9) \cdot \frac{7{,}5}{0{,}26} \right) = 96{,}7 \text{ kN/m}$$

$k_1 = 10.\ (96{,}7) = 967$ kN/m

$$d_y = \frac{Q_y}{k_1 - k_2} = \frac{7{,}5}{967 - 96{,}7} = 0{,}0086 \text{ m}$$

$F_y = Q_y + k_2.d_y = 7{,}5 + 96{,}7.\ (0{,}0086) = 8{,}33$ kN

<u>B Type Isolators:</u>

$$k_2 = k_D - \left((1 - \frac{k_2}{k_1}) \cdot \frac{Q_y}{d_D} \right) = 245 - \left((0{,}9) \cdot \frac{15}{0{,}26} \right) = 193{,}1 \text{ kN/m}$$

$k_1 = 10.\ (193{,}1) = 1931$ kN/m

$$d_y = \frac{Q_y}{k_1 - k_2} = \frac{15}{1931 - 193{,}1} = 0{,}0086 \text{ m}$$

$F_y = Q_y + k_2.d_y = 15 + 193{,}1.\ (0{,}0086) = 16{,}66$ kN

4.5. Comparison Criteria

Total base shear forces, storey shear forces in middle column and the absolute and relative storey drifts of the model building are taken as comparison criteria in each analysis method; the obtained results are given in Figures 4, 5, 6 and 7.

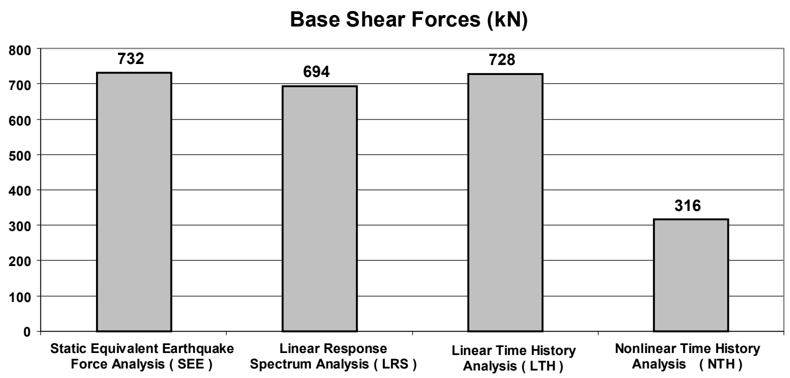

Figure 4 Base shear forces

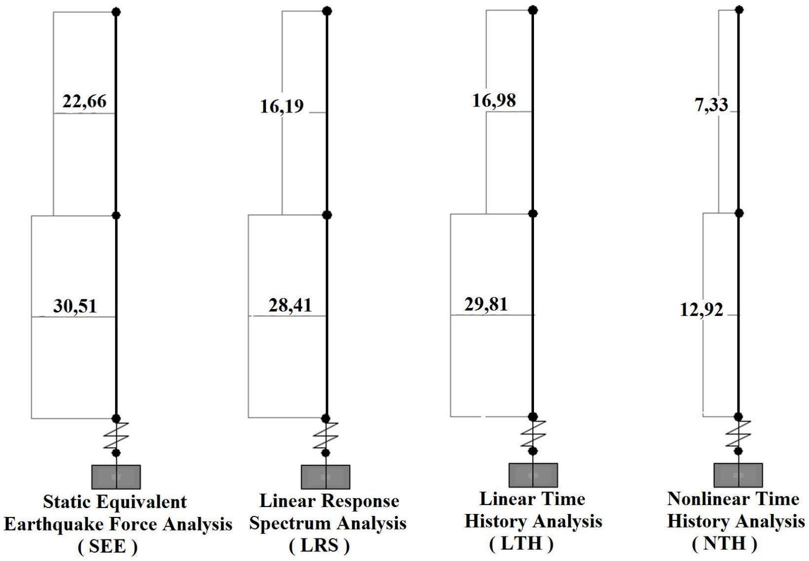

Figure 5 Shear forces in the mid column

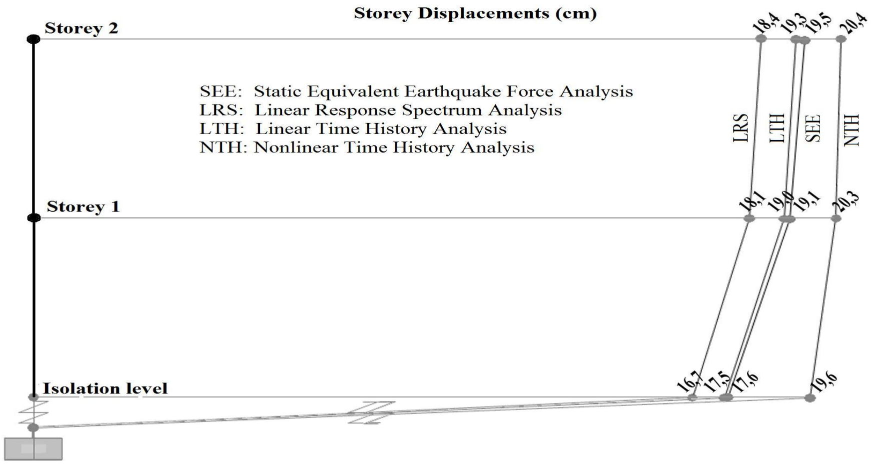

Figure 6 Absolute story drifts

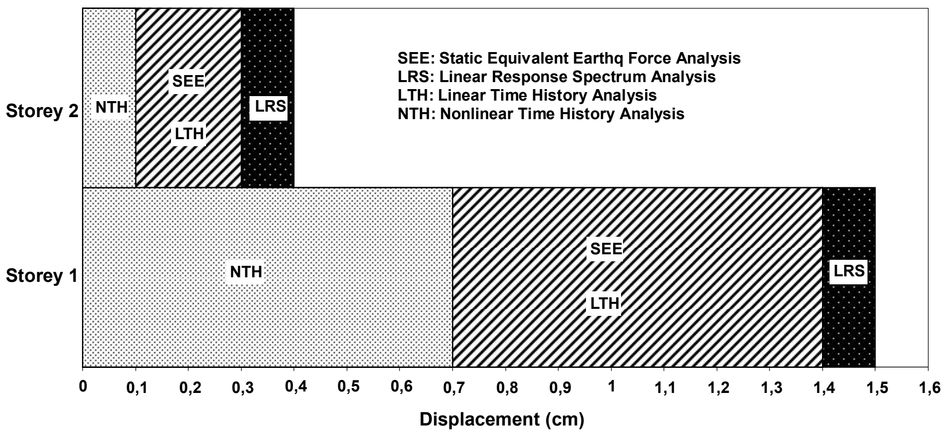

Figure 7 Relative story drifts

4.6 Evaluation and Conclusion

In this section, the results obtained from the analysis are examined within the framework of comparison criteria mentioned previously. The important results obtained may be summarized as follows:
In the Ritz analysis carried out to obtain the vibration modes to be used in the dynamic analysis, the natural period of the structure is calculated as 2,275 sec. It is seen that this value is rather close to the T_D=2,17 sec. value, which was calculated at the end of static calculation.

When the base shear forces, the storey drifts and the shear forces in the middle columns are examined; it is seen that reasonable and extremely close results are obtained especially for the first three alternatives of analysis (SEE, LRS and LTH).

Results of nonlinear analysis (NTH) constitute much bigger variation when compared with the other alternatives. The reason for this is that this analysis method is extremely sensitive to many parameters, and the non-linear parameters used in the calculation are obtained through simple static methods. If non-linear analysis is performed; it will be more appropriate to select from the manufacturing company's catalogue the ones most appropriate to these values, and to read the non-linear parameters from the laboratory test results of that isolator.

It is seen that even the static equivalent earthquake force method has given almost real results, while designing seismic isolation systems for low-rise structures. In this context, it will be rational to carry out first the static and afterwards the response spectrum and finally the time history analysis while designing. Thus, while benefiting from the incentive shown to the complex calculation method by the regulations, the accuracy of the results are also checked.

Although not taking place in the alternatives, the structure is analysed on fixed base for control purposes, and the base shear force is calculated to be around 2500 – 2900 kN. Accordingly, it is seen that the use of seismic isolation provides approximately 75% decrease in the base shear forces on the structure.

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