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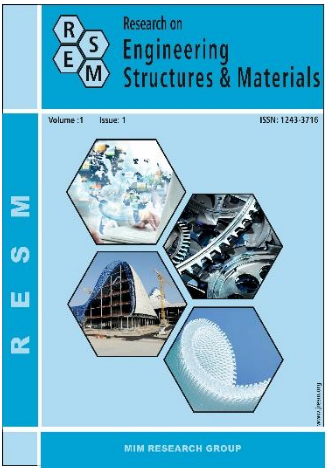

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Research Article

The required ductility reduction of soft storey buildings through application of base isolation

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Abstract

The Response Spectrum Analysis of the structures is based on the allowable ductility considered for that structure. In the case of multi-degree-of-freedom buildings, the required ductility cannot be the same with the allowable ductility; furthermore, the required ductility values are different for different storey. In the case of first soft/weak storey building, the required ductility of this storey is much higher compared to allowable ductility and impossible to achieve. Nowadays there are many cases of existing reinforced concrete structures with the possibility of soft/weak storey. Even new structures are required to have open space at ground floor level as the owners want them for shops or garages usage. This paper analysis the influence of base isolation to the required storey ductility of weak storey buildings. A five storey shear frame type structure is considered as the model. The elastic and elasto-plastic modeling of the structural elements and bilinear modeling of rubber isolators are used. Linear Response Spectrum analysis and Nonlinear Time History analysis are performed in order to determine the required storey ductility for the existing and new soft/weak storey buildings using the SAP2000 computer program. The analysis results show the reduction of the required storey ductility due to the application of base isolation not only in new structures, but in existing structures too. This means that the base isolation technique is a good alternative to be applied in buildings with first soft/weak storey structure.

1. Introduction

The seismic response of the structure can be obtained using response spectrum analysis, RSA or time history analyses, THA [1]. Response spectrum analysis is based on the seismic response spectrum which is considered for different values of the allowable ductility of the structure. For the single-degree-of-freedom systems the required ductility is the same as the allowable one, whereas for multi-degree-of-freedom systems these values are different (larger or smaller).

Ductility depends on several factors. For building structures with storeys it is important to know the relation of the required ductility and the yield strength and stiffness of the storeys. To analyse this relationship we have used the concept of “weak” storey, which has a smaller yield strength compared to the required one, and also the concept of “soft” storey, which has a smaller stiffness compared to the required one.

Base isolation technique was developed as an attempt to reduce the effects on buildings and their structural elements during seismic events, and is becoming one of the most effective

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methods for a wide range of problems of structures under the seismic action. [2] [3]. In recent decades, based isolation has become one of the most accepted techniques for seismic protection of buildings [4].

In order to study the influence of seismic isolation to the required ductility of a soft storey building, we have considered a five storey building with the first soft/weak storey to be isolated. These buildings can be existing or new structures, thus we have analyzed the application of base isolation in both cases. The elastomeric isolation system is used. Mostly they are characterized by high vertical stiffness and low horizontal stiffness [5] [6]. The analysis performed in linear and nonlinear using elastic and elasto-plastic modelling of the structural elements allow us to determine the required ductility and make the comparison with the allowable ductility for different situations of structure. Linear Response Spectrum analysis and Nonlinear Time History analysis are performed in order to determine the required storey ductility using the SAP2000 computer program [7].

The required ductility of soft first storey of the existing structures can be very high and impossible to achieve. Applying base isolation on these buildings can reduce the required ductility to the desired value [8]. Based on the code, in case of base isolation of new buildings, the structure is designed to behave almost within the elastic range with the allowable ductility μa=1. If this new structure tends to be soft/weak first storey, the base isolation is shown to be a good alternative to solve the problem of these structures.

2. Allowable and Required Ductility

Based on the response spectrum analysis, the design yield strength is determined, as a function of the allowable ductility by the following expression (Eq. 1):

$$f_y = A_y \cdot m \tag{1}$$

where m is the mass of system and Ay is the pseudo-acceleration obtained from response spectrum of the considered allowable ductility.

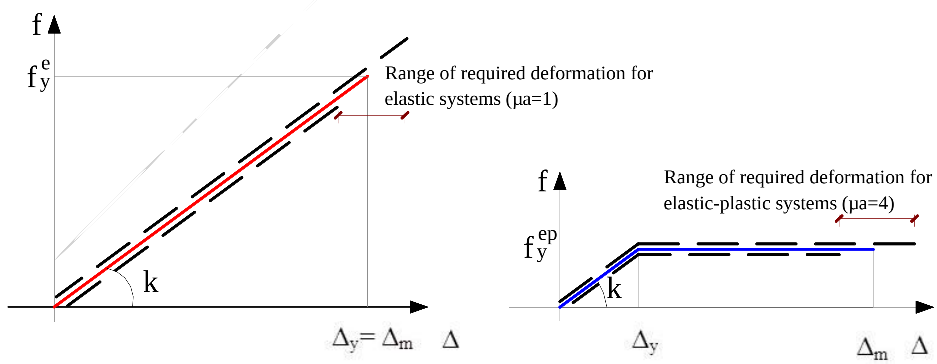


Fig. 1 Maximum allowable and required deformation for two systems, μ_a=1 and μ_a=4

From the response spectrum analysis, the yield strength (fy) and yield deformation (Δy) are determined using the response spectrum for the corresponding values of the ductility μa.From the time history analysis, based on the elasto-plastic behaviour diagram, and parameters resulting from the response spectrum analysis (k, fy, Δy), we have determined the maximum deformation Δm of the structure. The required ductility is determined by the ratio between the maximum deformation and the yield deformation (Eq. 2):

$$\mu_r = \frac{\Delta_m}{\Delta_y} \tag{2}$$

Question: Does the required ductility (μ_r) has the same value with the allowable ductility (μ_a)? The response of elasto-plastic elements requires a certain level of the deformations. The required deformation can be bigger or smaller than the structure's deformation capacity [9]. This is schematically shown in Fig. 1, for two different cases of the structure; the first with allowable ductility μa = 1 and the second with μa = 4.

3. Seismic Response of Multi-Storey Building and Storey Ductility

Different models were developed to study the seismic response of fixed base or base isolated multi-storey buildings with different storey yield strength and storey stiffness distribution, or with different values of allowable ductility. The TYPE 1 represents the normal structure with uniform storey stiffness. The TYPE 2 represents the soft/weak first storey structure, which is obtained by structure TYPE 1, multiplying the stiffness of storey two to five by 4. TYPE 2a BI and TYPE 2b BI represent the application of base isolation to the structure TYPE 2 in case of new and existing buildings. These models are schematically shown in Table 1.

Table 1: The analyzed models of a 5 – storey structure

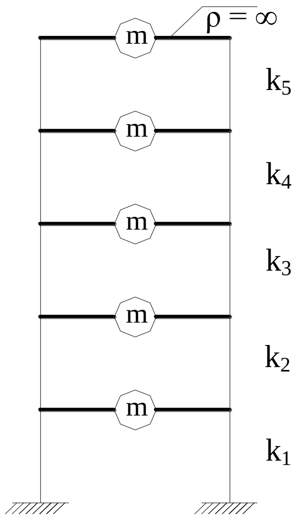
Base situation	Types of structure considered	Analysed cases for each Type
Fixed base structures	TYPE 1 (normal structure) k_1 x 1 and $k_{2\text{-}5}$ x 1	μ_a = 1
Fixed base structures	TYPE 2 (soft/weak first storey) k_1 x 1 and $k_{2\text{-}5}$ x 4	μ_a= 1 and μ_a= 4
Base isolation of new buildings	TYPE 2a BI k_1 x 1 and $k_{2\text{-}5}$ x 4	μ_a = 1
Base isolation of existing buildings	TYPE 2b BI k_1 x 1 and $k_{2\text{-}5}$ x 4	μ_a = 4

The shear frame 5 storey structure considered on analyses is shown in Fig 2:

The seismic response of the structure can be obtained usingtime history analyses, THAor response spectrum analysis, RSA.

For time history analysis, the El Centro earthquake acceleration is used as the input excitation, considering the structure with η = 5% damping. The input acceleration time history of El Centrowith ground acceleration PGA = 0.349g is shown in Fig. 3.

The Response spectrum analysis is based on the same earthquake El Centro seismic response spectrum with η = 5% damping, as shown in Fig. 4 for two allowable ductility values; μa=1 (elastic structure) and μa=4 (elasto-plastic structure).



Frame properties:

Reinforced concrete E = 3.15×10^{7} kN/m^2
Columns a x b = 63.5 x 63.5 cm
Beams EI = ∞ (shear frame)
Storey stiffness: k1 to k5
Storey height H = 3 m
Mass m = 300 t
The El Centro earthquake acceleration a_g=0.349g

Fig. 2 Five-story shear frame of linear elastic model

First we conduct the response spectrum analysis using SAP2000 computer software, in elastic range (μ = 1) with η = 5% damping. From this analysis we obtain the results given in Table 2 below. Since these results represent the yield phase, we note them with the index "y" (yield).

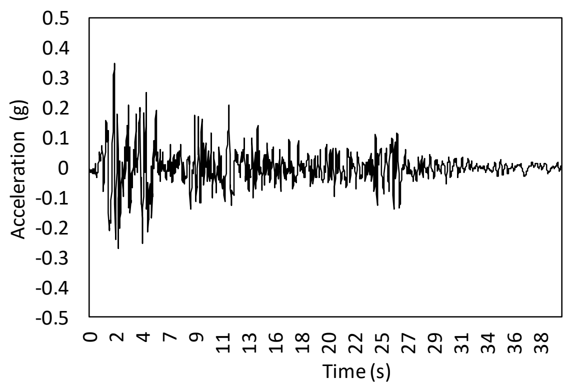


Fig. 3 El Centro accelerogram scaled for ground acceleration PGA = 0.349 g

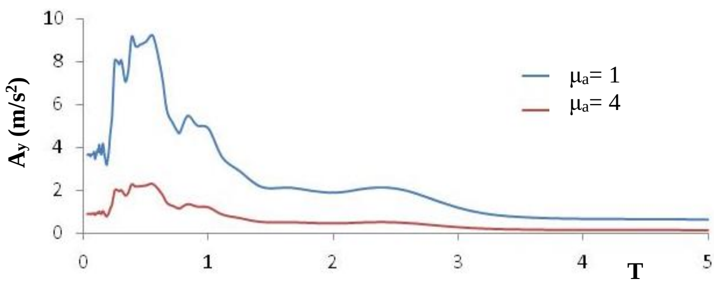


Fig. 4Pseudo acceleration response spectrum of El Centro earthquake (5% damping)

From the dynamic analysis, the first three vibration periods are: T1 = 0.79s, T2 = 0.3s, T3 = 0.2s.

Table 2: Results of linear elastic response of a 5 – storey structure

Storey	Displacement U_{yj}(cm)	Deformation Δ_{yj}(cm)	Shear force $f^e_{y,j}$ (kN)	Storey stiffness k_j (kN/m)
5	11.07	1.82	1149	63132
4	9.25	2.24	1953	57185
3	7.01	2.43	2504	103045
2	4.58	2.42	2937	121364
1	2.16	2.16	3221	149120

where Uyj is the yield displacement of storey "j"; Δyj = Uyj - Uy(j-1) is the yield deformation of storey "j"; $f^e_{y,j}$ is the shear force of storey "j", which in case of elasto-plastic systems, represents the yield strength; and kj is the stiffness of storey "j", $k_j = f^e_{yj}/\Delta_{yj}$. For the time history analysis we have considered a new model of the shear frame in order to perform the analysis in the elasto-plastic range (μ > 1) besides the elastic one (μ = 1). Fig. 5 shows this model, where the columns are replaced with elements with infinite stiffness EI = ∞ while the elastic parameters are represented by the nonlinear elements NLINj, the characteristics of which are the same of the columns they replace. Nonlinear elements NLINj (beam column joint) are modelled with stiffness kj and yield strength f^{ep}_{yj}. Fig.6 shows the elasto-plastic diagram of the nonlinear elements NLINj. It is obvious that in case of elastic systems $f^{ep}_{yj} = f^e_{yj}$ (because μ = 1), while in case of elasto-plastic systems f^{ep}_{yj} is a function of the allowable ductility.

Two analysis are conducted: the response spectrum analysis (RSA) and time history analysis (THA). These analysis are performed for two different allowable ductility levels: allowable ductility μ_a= 1 (elastic system) and allowable ductility μ_a= 4 (elasto-plastic system).

First, the response spectrum analysis is performed using El Centro earthquake response spectrum with 5% damping for the allowable value of ductility.

With the response spectrum analysis results, the nonlinear elements $NLIN_j$ are modelled in order to continue with the time history analysis, using the same earthquake acceleration with 5% damping. With the nonlinear analysis results we determine the maximum storey displacements U_{mj}, which then are used to calculate the maximum storey deformations (by the difference of maximum storey displacements):

$$\Delta_{mj} = U_{mj} - U_{m(j-1)}$$

Knowing the elastic deformations of the storeys Δ_{yj} and their maximum required deformations, it is possible to calculate their required ductility

$$\mu_{rj} = \frac{\Delta_{mj}}{\Delta_{yj}}$$

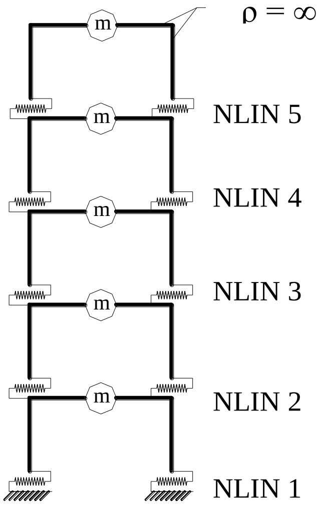


Fig. 5Shear frame of elasto-plastic (nonlinear) model

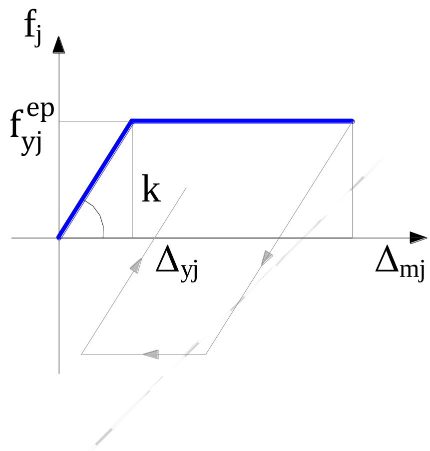


Fig. 6Elasto-plastic diagram between shear force and storey deformation

4. Multi-Storey Buildings with Soft and Weak Storey

There are reasons the engineers are facing to the situation of soft/weak storey buildings. Mostly, it happens because of architectural requirements to have an open space at ground floor level. To illustrate this relation, let us consider a different structure, called TYPE 2, with soft/weak first storey. Practically, weak storey buildings are also soft storey buildings because this storey will be more flexible than the others. This happens because the strength and the stiffness are inter-related.

In order to stimulate the soft first storey case, the parameters of structure TYPE 2, are performed from structure TYPE 1, multiplying the stiffness of second to fifth storeys by 4, keeping the same value of the first storey stiffness. By this, the TYPE 2 structure becomes with soft first storey[1]. Using the elasto-plastic model, two types of analyses are conducted: response spectrum analysis and time history analysis, with two different levels of the allowable ductility $\mu a = 1$ and $\mu a = 4$.

First the response spectrum analysis is conducted, which gives us the results of the yield strength of the second to fifth storeys.

Then we perform the time history analysis, taking results of the maximum required displacement of the storeys, Umj, to calculate the maximum required deformations, Δmj, and the required storey ductility μrj.

From the dynamic analysis, the first three vibration periods are: T1 = 0.54 s, T2 = 0.18 s, T3 = 0.11 s.

The analysis results of the parameters of interest are given in the Tables 3 and 4.

Table 3: Analysis results of structure TYPE 2, with μa = 1

Analysis type		**Response spectrum analysis (L)**			**Time – history analysis (NL)**		
Storey	kj(kN/m)	U_{yj}(cm)	Δ_{yj}(cm)	f_{yj}^{ep}(kN)	U_{mj}(cm)	Δ_{mj}(cm)	μ_{rj}
5	252528	8.24	0.66	1665	5.71	0.35	0.53
4	348740	7.58	0.92	3196	5.36	0.47	0.51
3	412180	6.66	1.10	4542	4.89	0.53	0.48
2	485456	5.56	1.16	5664	4.36	0.53	0.46
1	149120	2.1	2.1	3126	3.83	3.83	1.82

Table 4: Analysis results of structure TYPE 2, with μa = 4

Analysis type		**Response spectrum analysis (L)**			**Time – history analysis (NL)**		
Storey	kj(kN/m)	U_{yj}(cm)	Δ_{yj}(cm)	f_{yj}^{ep}(kN)	U_{mj}(cm)	Δ_{mj}(cm)	μ_{rj}
5	252528	2.06	0.16	416	8.05	0.04	0.25
4	348740	1.90	0.23	799	8.01	0.06	0.26
3	412180	1.67	0.28	1135	7.95	0.10	0.36
2	485456	1.39	0.29	1416	7.85	0.11	0.38
1	149120	1.10	1.10	781	7.74	7.74	14.6

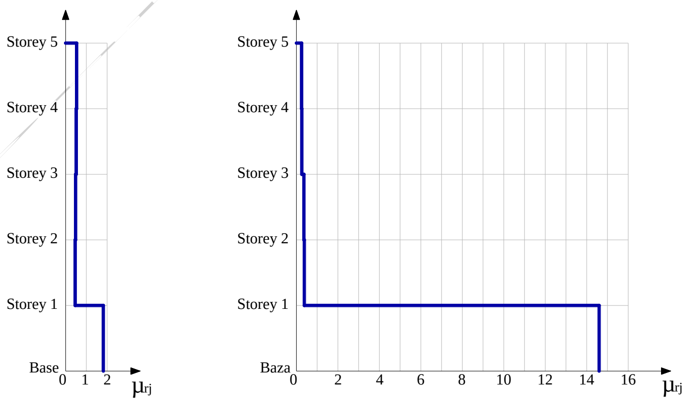


Fig. 7 . Required story ductility of TYPE 2 structure: a) for μa=1, b) for μa=4

From the results of Tables 3 and 4 it is obvious that TYPE 2 model, represent the structure with soft and weak first storey. The required storey ductility is shown in shown graphically in Fig.7, for the two analyses cases with allowable ductility μ_a= 1 and μ_a=4:

So, the required ductility of the first storey μ_{r1} = 14.6 is much larger than the allowable one μ_a=4 and practically impossible to be possessed by conventional structures. Thus, this structure cannot resist the design seismic action.

5.The Influence of Seismic Isolation to the Required Ductility

In order to study the influence of seismic isolation to the required ductility of a soft storey building, we will consider the previous structure (TYPE 2), but with a base isolation.

Isolators are considered bilinear [10]and their characteristics are calculated for the given quantities W= 350 kN, T=2.3s, D=0.15m, β= 5% and r =0.1, the isolators characteristics are:

Keff = 5591 kN/m; K1 = 42256 kN/m; Qy = 228 kN; $u_y = Q_y/K_1 = 0.539$ cm.

First the response spectrum analysis is performed using SAP2000 computer software, for the elastic phase (μ = 1) with η = 15% damping.

For the time history analysis, in order to perform the elasto-plastic nonlinear analysis besides the elastic one, we will use the model with nonlinear elements. Schematically this model is shown in Fig.8.

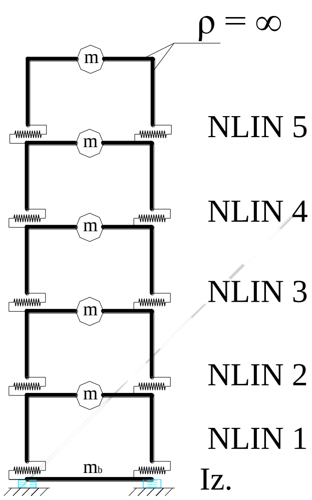


Fig.8 Elasto-plastic (nonlinear) model of base isolated frame

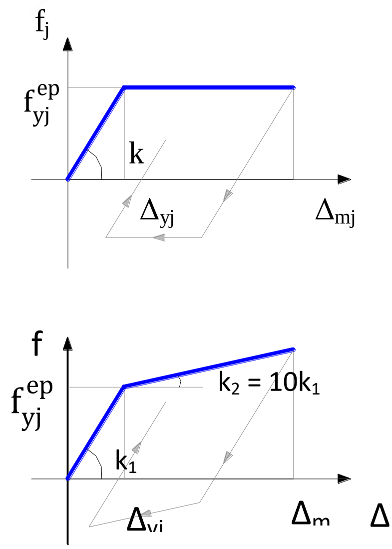


Fig. 9 Nonlinear diagram of elements:

a) Elasto-plastic diagram between shear force and storey deformation,

b) Isolators bilinear diagram

. This model represents the replacement of the columns with elements with infinite stiffness EI = ∞ and with elastic characteristics of nonlinear elements, NLINj, which are the same as the characteristics of the column replaced. Practically, the nonlinear elements NLINj are modelled with with stiffness kj and yield strength f_{yj}^{ep}. The elasto-plastic diagram of the nonlinear elements, NLINj, is shown in Fig.9a while the bilinear diagram of the isolators is shown in Fig.9b.

Two types of analysis are conducted with the elasto-plastic model: the response spectrum analysis (RSA) and time history analysis (THA). First, the response spectrum analysis is performed using the El Centro earthquake response spectrum with η = 15% damping (to consider the damping level of the isolators). With the results of this analysis, the characteristics of the nonlinear elements NLINj are modelled, further to be used for the time history analysis. Since isolated structures response is within the elastic range, the damping level of the structures is low, thus the nonlinear elements NLINj are considered with η = 2% elastic damping. To study the seismic isolation effect on different structures we will analyze the base isolation of new buildings and the base isolation of existing ones

5.1. Base isolation of new buildings

Since base isolated structures are designed to behave almost within the elastic range, then the allowable ductility, for the analysis of this case, is considered level 1 (μa = 1).

The third model, called structure TYPE 2a BI, represents the seismic isolation of structure TYPE 2 with allowable ductility μa = 1. Since the yield strength of this type of structure is accepted to be different from the results of response spectrum analysis, the storeys yield deformation will be calculated by the expression $\Delta_{yj} = f_{yj}/k_j$ for all storeys (as shown in Table 5). For this case, only time history analysis is performed in order to estimate the required deformations and the required ductility of each storey (Δ_{mj} and μ_{rj}). The analyses results of structure TYPE 2a BI, are given in Tables 5.

The first three vibration periods of structure TYPE 2a are: T1 = 2.34 s, T2 = 0.22 s, T3 = 0.12 s.

From the comparisons of results of storey required ductilityμ_{rj} between structure TYPE 2 (Table 3) and structure TYPE 2a BI (Table 5)we can point out the reduction of first storey required ductility from $\mu_{rj} = 1.82$ for fixed base structure to $\mu_{rj} = 0.73$ for base isolated structure. This means that base isolation of the structure with soft (and weak) first storey is very effective to the reduction of storey required ductility.

Table 5: Analysis results of structure TYPE 2a BI, with μa = 1

Analysis type		Response spectrum analysis (L)			Time – history analysis (NL)		
Storey	kj(kN/m)	U_{yj}(cm)	Δ_{yj}(cm)	f_{yj}^{ep}(kN)	U_{mj}(cm)	Δ_{mj}(cm)	μ_{rj}
5	252528	20.78	0.11	223	14.89	0.1	0.91
4	348740	20.67	0.14	445	14.79	0.11	0.79
3	412180	20.53	0.16	655	14.68	0.13	0.81
2	485456	20.37	0.18	874	14.55	0.15	0.83
1	149120	20.19	0.66	1079	14.40	0.48	0.73

5.2. Base isolation of existing buildings

Analysing the application of the seismic isolation to the problematic case ofan existing building, designed and built as fixed base with soft and weak first storey structure shows that the required storey ductility is obviously reduced.

To illustrate the effect of base isolation we consider the five-storey shear frame analyzed before, structure TYPE 2. Supposing that the existing buildings are designed with allowable ductility μa = 4. The Isolated structure is called TYPE 2b BI. The characteristics of isolators are the same as those used for structure TYPE 2a BI. The results of the time history analysis are given in Table 6:

The first three vibration periods of structure TYPE 2a are: T1 = 2.34 s, T2 = 0.22 s, T3 = 0.12 s.

Table 6: Analysis results of structure TYPE 2b BI, with μa = 4

Analysis type		**Response spectrum analysis (L)**			**Time – history analysis (NL)**		
Storey	kj(kN/m)	U_{yj}(cm)	Δ_{yj}(cm)	f_{yj}^{ep}(kN)	U_{mj}(cm)	Δ_{mj}(cm)	μ_{rj}
5	252528	2.06	0.16	416	14.91	0.09	0.56
4	348740	1.90	0.23	799	14.82	0.13	0.57
3	412180	1.67	0.28	1135	14.69	0.14	0.50
2	485456	1.39	0.29	1416	14.55	0.15	0.52
1	149120	1.1	1.10	781	14.40	0.52	0.98

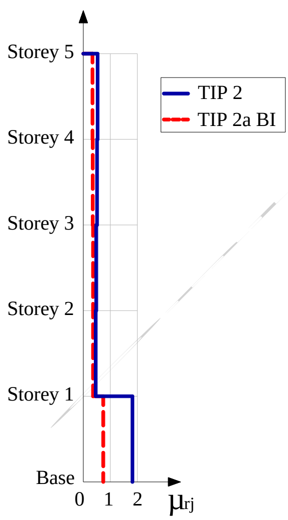


Fig. 10a The required ductility for each storey of fixed base (TYPE 2) and base isolated (TYPE 2a BI) of new structures designed with allowable ductility μa = 1.

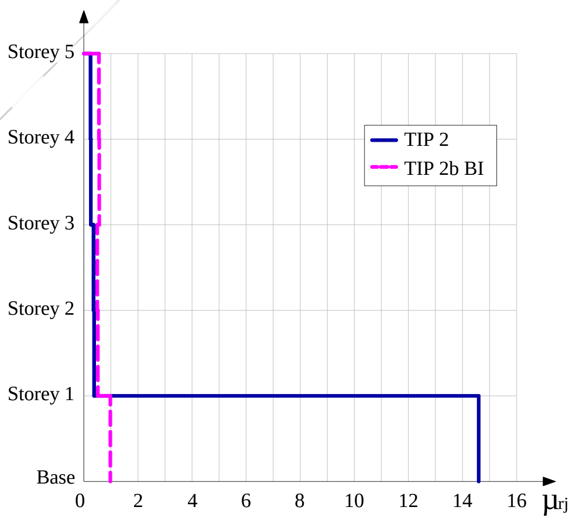


Fig. 10b The required ductility for each storey of fixed base (TYPE 2) and base isolated (TYPE 2b BI) of existing buildings) designed with allowable ductility μa = 4

To better understand the change of the required ductility values, Fig.10 shows the required ductility of isolated and non isolated structures, for both cases, base isolation of new structures and base isolation of existing structures.

Seismic isolation of existing buildings with soft first storey (and weak storey) reduces the required ductility of the first storey from $\mu_{r1} = 14.6$ as in the case of structure TYPE 2, to $\mu_{r1} = 0.98$ in the structure TYPE 2b BI. So, with seismic isolation of existing soft storey structures, it is provided that the structure behaves in the elastic range (even the soft storey).

The nonlinear analysis of isolated structures, TYPE 2a BI and TYPE 2b BI, are conducted using the yield strength of the existing storeys. The fact that the required ductility of isolated structures is less than 1, shows that the structure has sufficient strength (because its elastic strength capacity can be higher than needed).

6. Conclusion

In this paper, two types of structures are analyzed, fixed base and base isolated buildings in order to study the influence of seismic isolation to the required ductility of a soft storey building. Considering a five storey building with the first soft/weak storey asexisting or new structures, and applying the base isolation on them, from the analysis results the following conclusions can be drawn:

- The deformation demand is higher for the nonisolated structures, while for isolated structures, structural elements almost do not have deformations, because these deformations are mostly developed on the isolation system.
- In structures that represent the soft storey phenomenon, the seismic isolation manages to improve the structure response and is able to eliminate the defect.
- For new base isolated structures, it is possible to design them to behave close to elastic range. So the isolation of buildings calculated in linear phase (μa = 1) improves the first storey to develop no plastic deformations.
- The benefit of seismic isolation in the reduction of yield strength (shear force) is well known. This study shows another benefit, the reduction of storey ductility of building structures.
- If we apply the seismic isolation on existing structures (designed and built in a previous period of time) with soft and weak first storey, it will state that storeys ductility demand will be significantly improved.
- Through seismic isolation of existing buildings with soft storey (and weak storey) with high required ductility it is possible to reduce considerably the value of this ductility. By using the seismic isolation, even the soft storey response is within the elastic range.
- Seismic isolation is used very effectively to improve the ductility of the structure if it is designed with higher value ductility demand which in practice is impossible to achieve.

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