J. Int. Environmental Application & Science, Vol. 11(3): 241-248 (2016)

Seismic Performance Assessment of Soft-Story RC Frame Buildings

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Received March 15, 2016; Accepted May 20, 2016

Abstract: Soft-story buildings are characterized by an inadequate stiffness or flexibility of the ground floor, which is less resistant to horizontal seismic forces than the upper storys. On the other hand, such inadequate stiffness causes disproportional displacement focused on that story. As a result, the ground floor becomes weak and susceptible to partial or complete damage to its structural elements, which in turn, results in collapse of the entire building. The results obtained from the performed linear and nonlinear push-over analyses show that the flexible story may result in a drastic change of the period of vibrations, which will further lead to a change of the seismic design force, the maximal relative story drifts and ductility of the considered structure. Within this paper, the effect of the flexible story on seismic performance of building has been explored through comparison between a structure with regular story heights and a structure with a flexible story. The effects of upgrading the critical story by appropriate structural interventions like enlargement of the base columns cross-section and/or insertion of RC walls are also investigated.

Keywords: *soft-story, seismic resistance, relative displacement, story stiffness, "pushover" analysis, strengthening, upgrading*

Introduction

Today, we are witnesses of the fast tempo of life imposing the need for construction of residential structures that will be both economically justified and safe. It is very difficult to bring together the socio-economic, the market economy, the architectonic functional and the rational performance concepts, the short time of construction and the first and foremost, the safety of the residents. It is exactly this reason that imposes the need for construction of RC buildings that deviate from the normal design dimensions, i.e., buildings of variable story heights, particularly with considerably greater first story height compared to the other stories, i.e., buildings with the so called soft-story (Guevara-Perez, 2012). To satisfy all the requirements of the investors and the architects, it is first of all, necessary to provide complete seismic stability of the structure that will guarantee safety of the people in the case of a large scale natural disaster, i.e., earthquake (Kanno *et al*., 2014).

Within the frame of the study, analytical investigations concerning seismic performance of soft-story RC frame building is carried out (Necevska-Cvetanovska *et al.,* 2011). The performed analytical investigations involved: investigation of characteristics of buildings with a soft-story, failure mechanism of these structures under seismic effects as well as possible modes of strengthening of soft-story RC buildings. Presented in the paper are selected results from the performed linear and nonlinear seismic analysis of an RC building with regular story heights and the same RC building with a soft-story. The RC building under consideration represents an actual five story RC frame building structure located in Skopje, Republic of Macedonia. The analyses have been performed for the purpose of comparison of the dynamic characteristics of the RC building with regular story heights and the same building with a soft-story in order to get an insight into the difference in the bearing and deformability capacity.

The seismic analysis has been performed in accordance with the regulations for construction of structures in seismic prone areas by using the SAP2000 programme package (Wilson & Habibullah, 2006). Comparative analyses of vibration periods have been performed by using multi-modal analysis. The maximum story displacements have been obtained by linear analysis. The bearing capacity of the structure and the nonlinear force-displacement relationship has been defined by nonlinear analysis providing thus important data on the strength and the ductility of the structure. The nonlinear analysis has been performed for two models as follows: the structure with regular story

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heights and the structure, with a soft-story, whereat the development of plastic hinges in both models is clearly seen.

Conclusions and recommendations regarding the performance of the RC frame system with a soft-story, its advantages and disadvantages are also given. These are meant to help design engineers in making their decisions and contribute to the applicability of RC structures with a soft-story in seismically active regions.

Main characteristics of soft-story buildings

The buildings with a flexible story also referred as buildings with SWOF – soft, weak, or open-front are potentially dangerous buildings in case of an earthquake. These are buildings with wide openings (windows, doors etc.) in the walls which often represent the primary seismic elements of the structure. Most frequently, such buildings are those constructed between 1920 and 1970-ties, housing shops or garages at the ground floor (Figure 1).

A building is referred as a soft-story building when the ground floor level has lower stiffness than the level above it (according to some authors, the difference could be around 70%). These buildings are susceptible to collapse under a moderate to strong earthquake and that phenomenon is known as soft-story collapse. Due to the inadequate stiffness, i.e., flexibility of the ground floor, it is less resistant to seismic forces than the upper stories. Such disproportion causes large disproportional displacement focused at that story. This disproportional displacement and stress compared to the remaining stories make the ground floor weak and susceptible to damage (partial or complete), resulting in total collapse of the entire building.

a) 2003 Boumerdès, Algeria quake

b) 1985 Michoacan,Mexico quake

c) 2009 L'Aquila quake

Figure 1. Performance of soft-story RC buildings during past earthquakes

Seismic resistance of soft-story RC buildings

To define the effect of the soft-story to the seismic performance of RC frame structure, ample analytical investigations have been performed as follows:

(1) Linear seismic analysis of a prototype RC building. Analyses of four models have been performed as follows:

- Analysis of the principal structural system with regular story heights – referent model M1;
- Analysis of the same RC building with a soft-story – model M2;
- Analysis of soft-story RC building strengthened by increasing columns cross-sections at the ground floor – Model M3
- Analysis of soft-story RC building strengthened by insertion of RC walls at the ground floor – model M4

(2) Nonlinear seismic analysis of RC building prototype

- Nonlinear analysis of RC building with standard story heights – model M1.
- Nonlinear analysis of soft-story RC building– model M2.

The RC building prototype for which the above stated analyses have been performed represents a business building with five story heights (B + GF + 2 + R) and floor plan proportions of 3,8 x 20,4 m. The structural system is composed of 10 reinforced concrete frames in Y direction and 6 frames in X direction. The floor structures are monolith reinforced concrete slabs with dp = 14 cm and they are identical at all levels. The height of each story is H = 3,52 m, except for the last one due to the sloped roof structure. The columns have different cross section as follows: Level 0 – 60/60, 50/50; Level 1 – 50/60, 40/40; Level 100, 200 and 300 - 40/60, 30/30. The beams are proportioned: 30/50, 30/40 and 30/30. The floor plan and the cross-section of the structure are given in Figure 2.

Linear seismic analysis of RC building prototype

- *Analysis of Principal Structural System of Model M1 and Model M2*

The analysis of the building with a regular story height (model M1) and increased height of the first story (model M2) has been done by using the SAP 2000 programme package and using methodology for seismic design of RC buildings developed at IZIIS (Necevska-Cvetanovska & Apostolska, 2000). As results from the analysis the fundamental periods, the frequencies, the mode shapes as well as, shear forces, the maximum and relative displacements of the structure have been calculated. Presented below is part of the results obtained for both models as well as comparative results, (Figure 3 & Table 1).

From the below tables, it can be seen that for the model M2, the stiffness in x-direction at the first story is lower than the stiffness at the second story for 11%, whereas in y-direction, the stiffness at the first story is less than that of the second story for 6%. This is the result of the increase of the ground floor height for 42%.

Table 1. Displacement and stiffness at different story level for both models, (M1&M2)

Model M1, X-X direction					Model M2, X-X direction				
Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)	Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)
5	1970.763	1.89	0.23	8568.53	5	1971.547	2.25	0.23	8137.16
4	3525.609	1.66	0.40	8814.02	4	3376.751	2.02	0.38	8886.19
3	4681.251	1.26	0.51	9178.92	3	4530.966	1.64	0.50	9061.93
2	5445.523	0.75	0.47	11586.22	2	5341.209	1.14	0.51	10472.96
1	5872.498	0.28	0.28	20973.21	1	5872.498	0.63	0.63	9321.42

Model M1, Y-Y direction					Model M2, Y-Y direction				
Story	kN)	dmax (cm)	δ (cm)	K (kN/cm)	Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)
5	1970.763	1.90	0.26	7579.86	5	1971.547	2.16	0.25	7486.19
4	3525.609	1.64	0.45	7834.69	4	3376.751	1.91	0.44	7674.43
3	4681.251	1.19	0.57	8212.72	3	4530.966	1.47	0.56	8091.01
2	5445.523	0.62	0.41	13281.76	2	5341.209	0.91	0.42	12717.16
1	5872.498	0.21	0.21	27964.27	1	5872.498	0.49	0.49	11984.69

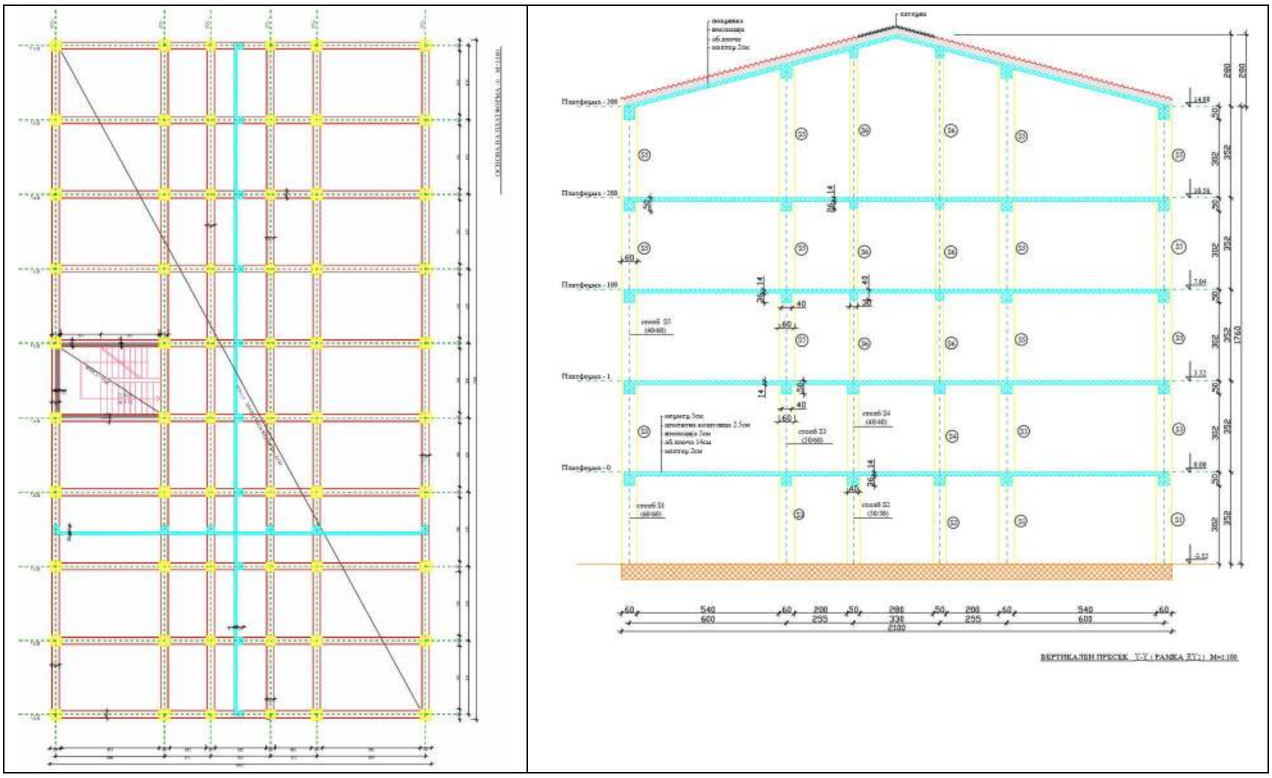

Figure 2. Floor-plan and cross-section of the structure

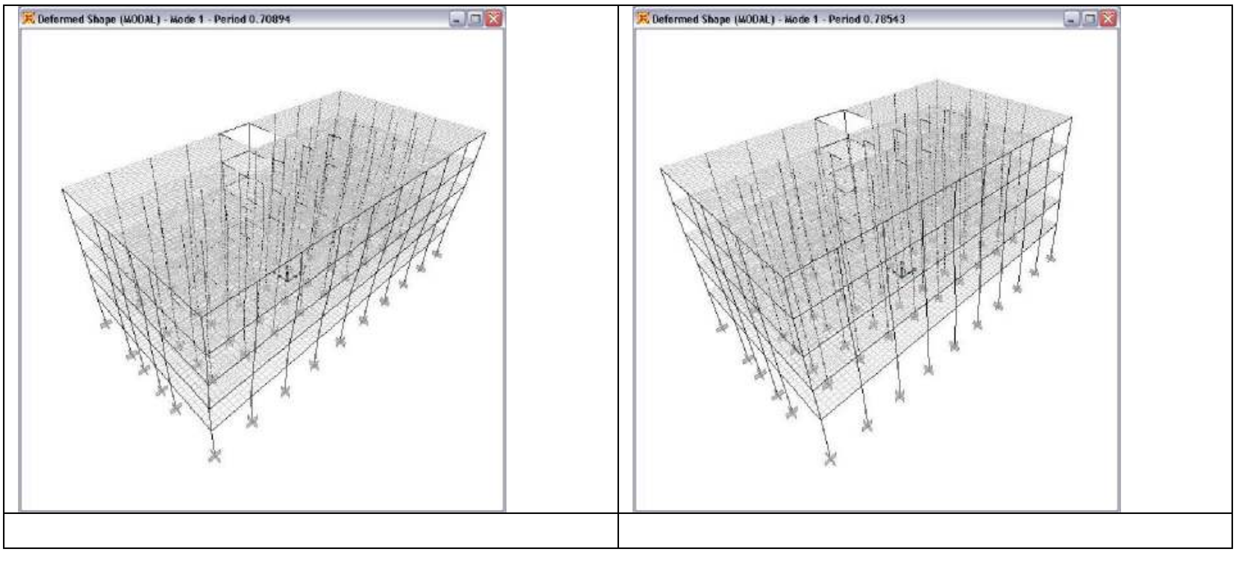

Figure 3. First fundamental period of models M1 and M2

To get a better insight into the difference between the model with regular story heights M1 and the model with a soft-story – M2, comparative diagrams of maximal and relative displacement in x and y direction as comparative diagrams of story stiffness are given in the paragraphs below.

As to the maximum displacement of the models in both directions (Figure 4), it can be concluded that the greatest difference in displacements is obtained regarding the displacements at the first story where the difference amounts to 125%, which means that from 0,28 cm in model M1, it is increased to 0,63 cm in Model M2 in x-direction, whereas in y direction, the difference amounts to 133%, which means that it is increased from 0,21 cm to 0,49 cm in model M2. However, the displacement at the top of the structure amounting to 1,89 cm in Model M1 is increased to 2,25 in model M2, meaning a difference of 20%. It is important to note that in both models, the maximum displacement at the top of the structure does not exceed the allowable one according to the national regulations for seismic design.

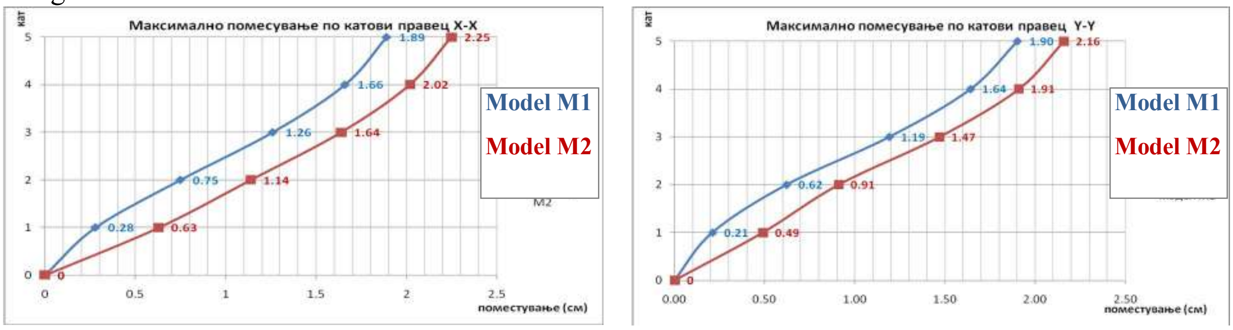

Figure 4. Maximum displacements of model M1 and model M2 in both orthogonal directions

From the below diagrams (Figure 5), it is noticed that relative displacement deviates only at the first story, whereas at the upper stories, it is almost identical. The difference is clear because of the increase of the story height at the ground floor i.e. the effect of soft-story.

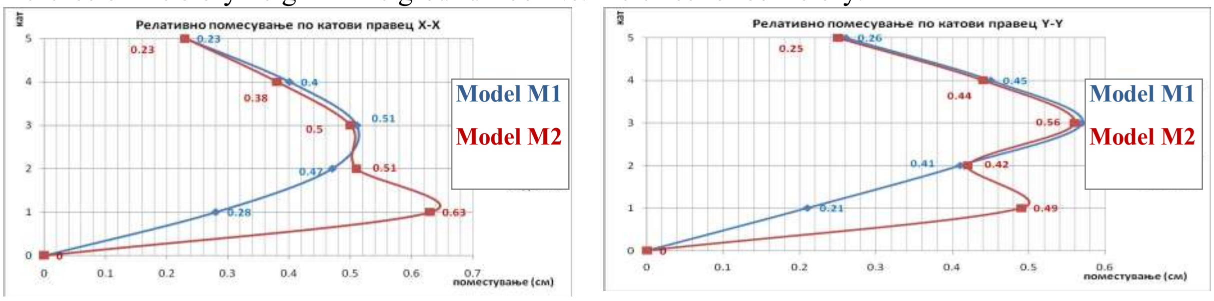

Figure 5. Relative displacements of model M1 and model M2 in both orthogonal directions

It is also observed (Figure 6) that there is difference in stiffness only at the ground floor, whereas at the upper stories, it is almost identical. In x direction, the difference is 125%, while in y direction, the difference is 133% which means the same as in the case of the displacements.

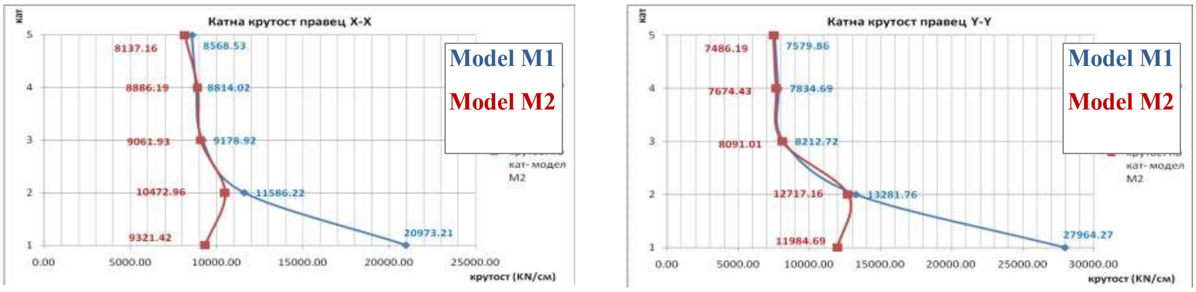

Figure 6. Stiffness distribution per story for model M1 and model M2 in both orthogonal directions

- *Analysis of structural system with soft-story upgraded by increasing columns cross-section dimensions at the ground floor – model M3 and inserting of RC walls – model M4*

In model M3, the cross-section of all the RC columns at the ground floor is enlarged as follows: columns proportioned 60/60 cm into columns proportioned 80/80 cm, while columns proportioned 50/50 cm into columns proportioned 60/60 cm. In model M4, RC walls were inserted at the ground floor. Presented further are some of the results, (Figure 7 and Table 2).

It has been shown that due to the strengthening of the soft-story structure, its dynamic characteristics, displacements and stiffness approach referent structure (model M1). However, it is important to point out that these structural interventions should be done in a mode to preserve symmetry and regularity of the structural system (Necevska-Cvetanovska & Apostolska, 2012). From the comparative diagrams, on all the four models (Figure 8), it can be concluded that behavior of the models M3 and M4 is very similar to the reference model M1 and even better.

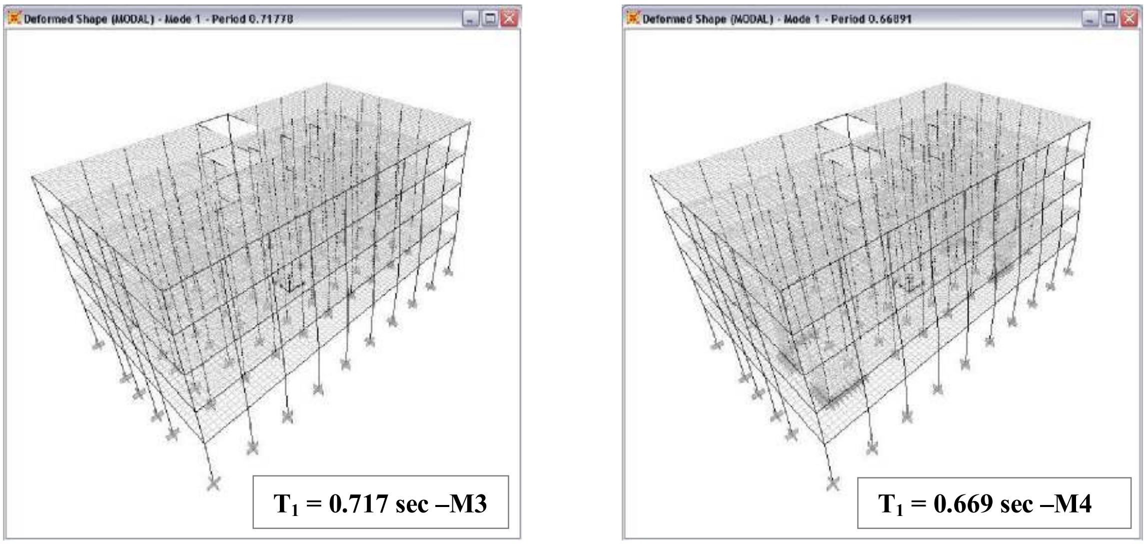

Figure 7. First fundamental period of models M3 and M4

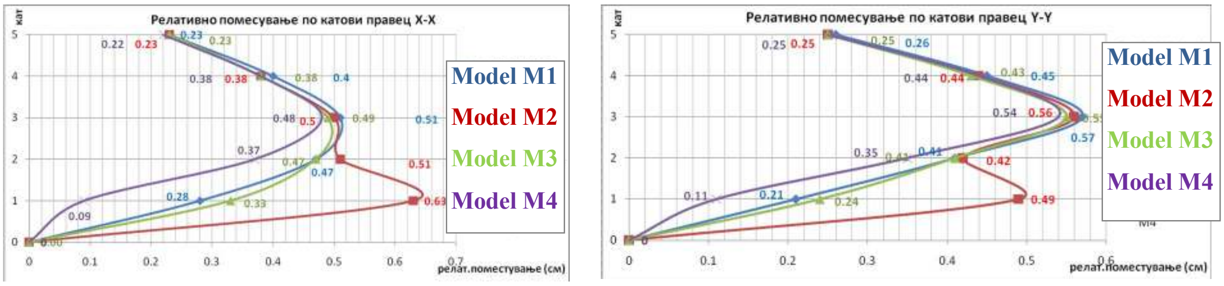

Figure 8. Relative displacements of all four models in both orthogonal directions

Table 2. Displacement and stiffness at story level for both models, (M3&M4)

Model M3, X-X direction					**Model M4, X-X direction**				
Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)	Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)
5	1871.55	1.90	0.23	8137.16	5	1871.55	1.54	0.22	8507.03
4	3376.75	1.67	0.38	8886.19	4	3376.75	1.32	0.38	8886.19
3	4530.97	1.29	0.49	9246.87	3	4530.97	0.94	0.48	9439.51
2	5341.21	0.80	0.47	11364.27	2	5341.21	0.46	0.37	14435.70
1	5872.50	0.33	0.33	17795.45	1	5872.50	0.09	0.09	65249.97

Model M3, Y-Y direction					**Model M4, Y-Y direction**				
Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)	Story	Q (kN)	dmax (cm)	δ (cm)	K (kN/cm)
5	1871.55	1.88	0.25	7486.19	5	1871.55	1.69	0.25	7486.19
4	3376.75	1.63	0.43	7852.91	4	3376.75	1.44	0.44	7674.43
3	4530.97	1.20	0.55	8238.12	3	4530.97	1.00	0.54	8390.68
2	5341.21	0.65	0.41	13027.34	2	5341.21	0.46	0.35	15260.60
1	5872.50	0.24	0.24	24468.74	1	5872.50	0.11	0.11	53386.34

Nonlinear static (Push-over) analysis of model M1 and model M2

To perform nonlinear static analysis, pushover analysis module from SAP2000 programme package has been used. Pushover analysis is one of the methods available for evaluating buildings against earthquake loads. As the name suggests, a structure is induced incrementally with a lateral loading pattern until a target displacement is reached or until the structure reaches a limit state. The structure is subjected to the load until some structural members yield. The model is then modified to account for the reduced stiffness of the building and is once again applied with a lateral load until additional members yield. A base shear vs. displacement capacity curve and a plastic hinging model is produced as the end product of the analysis which gives a general idea of the behavior of the building (Chopra & Goel, 2001; Dya & Oretaa, 2015).

As a result from the performed analysis, the distribution of plastic hinges in the structural elements has been obtained. The different color of the formed plastic hinges shows the nonlinearity range in correlation with the so called “acceptance criteria”. Whereat:
B – point of transition from elastic into post-elastic state;
IO (immediate occupancy) – initial nonlinearity – repairable damage;
LS (life safe) – deeper nonlinearity, whereat the damages to the structure don’t cause human loss;
CP (collapse prevention) – extensive damage but without failure of the structure.
Presented further is distribution of plastic hinges for both characteristic frames of both models M1 and M2, (Figure 9).

It can be concluded that the distribution of the plastic hinges in the characteristic frames of both models is different. In model M2, the formation of plastic hinges appears in the base columns much earlier compared to the formation of plastic hinges in model M1 due to the different height of the columns at the first story. So, at step 4, the first plastic hinge is formed in frame RX2 of model M2, whereas in the same frame in model M1, the first plastic hinge is formed at step 6. In frame RY2 of model M2, at the time when the plastic hinges in the columns at the lower story reach zone IO, i.e., initial nonlinearity, there are still no plastic hinges in the same frame of model M1, or there is only one hinge in zone B - transition from elastic into post-elastic range.

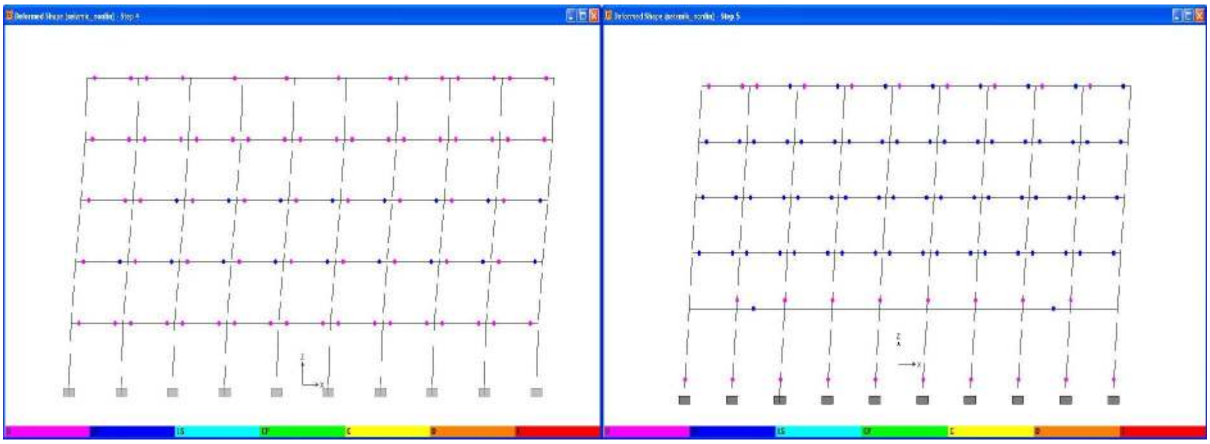

Figure 9. Distribution of plastic hinges in characteristics frame of model M1 and M2

The same tendency is reflected in the defined capacity curves, (Fig.10). It can be concluded that, in model M1, the higher base shear force induced lower displacement in comparison with model M2, where lower base shear force induced bigger displacements. That means that the capacity of the structure with regular story heights is greater than the capacity of soft-story the structure.

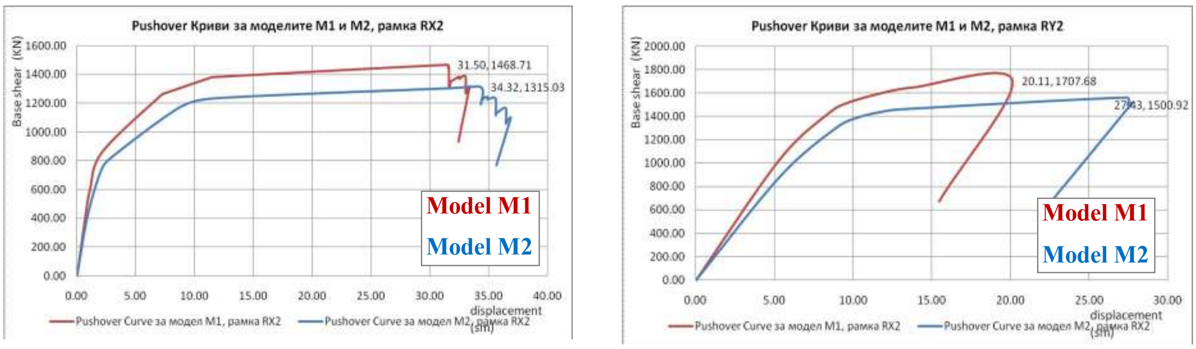

Figure 10. Capacity curves of both models M1 & M2

Conclusion

As a result of the performed linear and nonlinear analytical investigations of the RC frame building structure with regular story heights and with a soft-story, the following general conclusion is drawn:

In the soft-story structure, there is a considerable reduction in stiffness and increase of displacement at that story comparing with the building with regular heights. This means that, in seismically active regions, the soft-story essentially reduces the seismic resistance of the structure. Therefore, in order to prevent collapse of the structure due to reduced stiffness at the ground floor, it should be strengthened by appropriate structural interventions like enlargement of the base columns cross-section, insertion of RC walls, insertion of braces and alike.

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