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Disadvatages of RC building structures with a soft storey

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Abstract

The buildings with a soft storey represent a great danger for the safety of the tenants in seismically active areas. Because of the improper distribution of stiffness in height of the building, the seismic effect results in a failure in the most unfavourable way, that is, an unannounced collapse through a soft storey, whereby plastic joints are formed first in the columns, without dissipation of energy through plastic joints in the beams. The purpose of this research is to compare the behaviour of a regular RC building and a RC building with a soft storey, which will show the negative effects that the soft storey has on the overall behaviour of the building. Additionally, a linear and nonlinear static analysis of RC buildings with a soft storey is made according to the applicable Macedonian regulations and according to the Eurocode. The comparison made justifies the applicability of the recommendations and criteria for the design and construction of these systems. Linear static analysis of regular RC building and RC building with a soft storey according to Macedonian regulations and according to Eurocode was performed and a comparison of the obtained results is given. More detailed insight in the influence of the soft storey to the buildings is given through the non-linear static analysis (Pushover) made on the same RC building designed according to different rulebooks, one according to Eurocode and another according to the Macedonian regulations, and another comparison of the obtained results with a more detailed non-linear analysis was made where the development of the plastic hinges along the height of the building is shown.

Key words: Soft storey, Non-linear static analysis – Pushover

1 Characteristics of the models

To show the differences of regular RC buildings and RC buildings with a soft story designed according to different regulations, 4 models were analysed:

- Model M1: regular RC building designed according to national regulations;
- Model M2: RC building with a soft story designed according to national regulations with coefficient for ductility and damping Kp=1;
- Model M3: RC building with a soft story designed according to national regulations with Kp=2;
- Model M4: RC building with a soft story designed according to Eurocode.

The soil is II category, class B, IX zone of seismicity. The dimensions of the building are 20 x1 4,7 m with story height of 3m. It consists of 4 three-span frames of columns and beams only, with dimensions:

Table 1. Characteristics of the models

Model	M1	M2	M3	M4
Beams	30 x 50 cm	30 x 50 cm	40 x 60 cm	30 x 50 cm
Columns (Ground and I floor)	50 x 50 cm	50 x 50 cm	60 x 60 cm	60 x 60 cm
Columns (II-IV floor)	40 x 40 cm	40 x 40 cm	50 x 50 cm	50 x 50 cm

2 Comparison of the linear analysis results

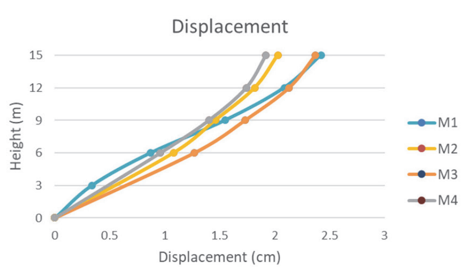

Figure 1. Displacements diagram of model M1, M2, M3 and M4

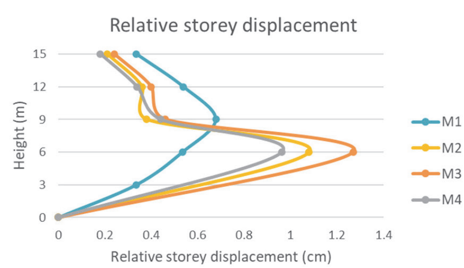

Figure 2. Relative storey displacements diagram of model M1, M2, M3 and M4

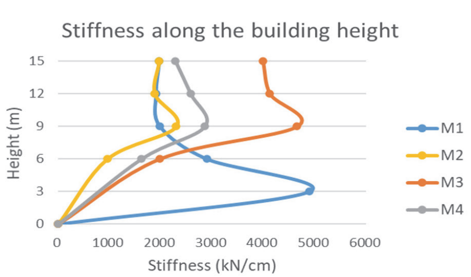

Figure 3. Diagram of stiffness along the building height for model M1, M2, M3 and M4

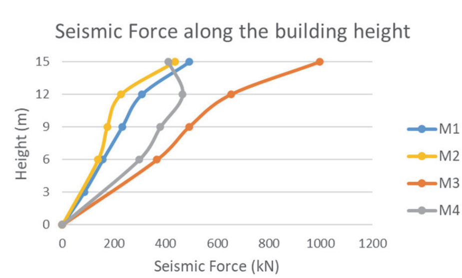

Figure 4. Diagram of seismic force intensity along the building height for model M1, M2, M3 and M4

The diagrams shown show that large relative storey displacements occur in RC buildings with a soft storey that adversely affect the behaviour of the structure as a whole, despite the increase in the dimensions of the columns. The increase in the dimensions of the columns is a result of the larger moments in the columns due to the presence of a soft storey, as well as due to the restriction that the total displacement is less than allowed by the regulations.

Despite the increase in the dimensions of the columns in the model M3, the stiffness of the ground floor is almost 50 % less than the stiffness of the model M1 which is a result of the increased height of the ground floor and from the diagrams it can be seen that there are large changes of the stiffness along the building height. While the stiffness of the ground floor in model M2 is 50 % of the stiffness of the ground floor in model M3 which leads to an even more flexible construction in model M2 and it would not have the capacity to withstand the design seismic forces that would be applied if the regulations are followed, ie if Kp = 2. In this model, too, there are large changes in stiffness along the building height, ie it is irregular in height. The M4 model designed according to Eurocode is more flexible, but due to the lower applied seismic force, it satisfies the allowed displacements. At M3 and M4 the ground floor has a much lower stiffness compared to the other storeys, with this difference being much smaller in the model designed according to Eurocode (Figure 3).

Despite the observed differences in the behaviour of the models, from the linear analysis it cannot be concluded which RC building would work better in the event of an earthquake, ie whether they possess the necessary ductility and what failure mechanisms will develop. Therefore, a nonlinear static analysis (Pushover) is performed in order to show the behaviours of the two RC buildings in the nonlinear area.

3 Comparison of the results concluded from nonlinear analysis of RC buildings with soft storey designed according to Macedonian regulations and Eurocode

Although there was a soft storey failure in both models, according to the shown schemes of formation of plastic joints, it can be concluded that the model designed according to Eurocode has a certain announcement of failure, with the formation of plastic joints in most beams before the columns on the ground floor reach their maximum load capacity. In the model designed according to Macedonian regulations, a very small number of plastic joints are formed in the beams before the plastic joints in the ground floor columns reach their maximum load capacity. The occurrence of a soft storey failure occurred due to the large height of the ground floor, which is twice the height of the other floors, and thus the stiffness is much lower compared to the other floors. Further research came to the conclusion that in order to prevent a soft storey failure, the dimensions of the columns on the ground floor should be more than 100 / 100 cm, which calls into question the economy of this design, so at such floor heights it is best to combine columns with RC walls.

From the nonlinear analysis it can be concluded that the M3 model analysed according to the Macedonian regulations [1-3] can receive 45 % higher force before the plasticization of the elements starts, compared to the M4 model analysed according to the Eurocode [4-7], which means that the Macedonian regulations are on the safe side when designing RC buildings of this type. The M2 model is the most flexible and with the highest ductility, but it does not have the capacity to withstand the predicted seismic forces while consistently following the regulations. The M4 model is more flexible than the M3 model, with larger displacements when reaching the LS point from the M-F diagram. The M3 model designed according to the Macedonian regulations has the greatest stiffness, reaching the LS point at the highest horizontal force.

4 Conclusion

In order to define the behaviour of RC buildings with a soft storey during seismic actions, several analyses of RC buildings designed according to the current regulations in Macedonia [1-3] and Eurocodes [4-7] were performed. General conclusions will be made about the dimensioning and behaviour of the structures, as well as specific conclusions made when comparing the behaviour of the structures dimensioned according to different regulations, and the appropriate models (M1, M2, M3, M4):

- The obtained period of oscillation of the building with a soft storey (model M3) of 0.56 sec. is 16 % less than the period obtained in the building without a soft storey (model M1) which is 0.65 sec. This is due to the larger dimensions of the columns which are increased from 50/50 cm to 60/60 cm on the first two storeys where the soft storey is located and from 40/40 cm to 50/50 cm on the other floors, as a result of accepting the moments due to the existence of a soft storey.
- The seismic force in the model M3 is 143 % higher than the seismic force in the model M2, due to the condition of the regulation that the coefficient Kp for ductility and damping is 2.0, as well as due to the shorter period of oscillation, which has a great impact on further dimensioning of the building.
- Despite the increase in the dimensions of the columns in the model M3, the stiffness of the ground floor is almost 50 % lower than the stiffness of the model M1 which is due to the large height of the ground floor, and also large changes in stiffness were observed along the building height. Whereas, the stiffness of the ground floor in model M2 is 50 % of the stiffness of the ground floor in model M3 which leads to a more flexible construction in model M2 and it would not have the capacity to withstand the design seismic forces that would be applied if the regulations are followed, ie if Kp = 2. In this model there are also large changes in the stiffness of the storeys in height, ie it is irregular in height.
- A building with a ground floor height of 4.5 m and a coefficient of ductility and damping Kp = 1 was analysed, something that can often be found in the projects where the designers simply ignore this coefficient. The calculated stiffness of the gro-

und floor is 1853 kN/cm, while the stiffness of the first floor is 2689 kN/cm, ie the stiffness of the ground floor is 69 % of the stiffness of the first floor, which means that it can and should be classified as a soft storey, and treated accordingly. .

- During the analysis of the models, different seismic forces were obtained depending on the geometry of the elements and the design regulations used. Thus, in the model M1 the total seismic force is 10 % of G, in the model M2 is 9.1 % of G, in the model M3 is 20 % of G, in the model M4 is 14.6 % of G, while in the model with ground floor height of 4.5 m is 10 % of G. The model B3 has the highest seismic force, due to the coefficient Kp = 2, and the lowest force is the model B2, due to the lower stiffness and because Kp = 1.
- With a period of oscillation of 0.62 sec. we can conclude that the RC building designed according to Eurocode (model M4) is more flexible than the one designed according to MK regulations (model M3) where the period is 0.56 sec. However, as far as the displacements are concerned, in the building designed according to Eurocode, they are smaller, but the seismic force acting on the building is lower as well, due to the smaller mass and the way of determining the seismic force. That is, according to Eurocode, the seismic force is lower, but there are many verifications in the design to ensure the occurrence of joints in the columns, as well as to prevent failure from shear forces that would occur during an earthquake. In both models the ground floor has a much lower stiffness compared to the other floors, with this difference being smaller in the model designed according to Eurocode.
- The relative storey displacement in the model M3 is 1.27 cm, which is 32 % higher than the relative storey displacement in the model M4 where it is 0.96 cm, while the total displacement in the model M3 is 2.36 cm, which is 23 % higher than the total displacement in the M4 model which is 1.92cm, where the biggest difference in displacement appears on the first floor. The difference of the displacements is due to the different seismic force which in model M3 is 2505.5 kN, and in model M4 is 1785.4 kN. The obtained displacements satisfy the maximum displacements according to both regulations, which means that both constructions are well designed in accordance with the regulations.

With the extensive analysis made in this paper, a conclusion can be made that in the design of vertically irregular RC buildings in seismic prone areas, the verifications against soft-story failure given in the regulations must not be neglected. With extreme differences in the stiffness and the height of the different floors, a non-linear analysis is recommended because for certain stiffness differences the verifications given in the regulations are not sufficient, as it was with the case presented. While with smaller stiffness differences along the height of the building, a satisfactory behavior can be accomplished with enlargement of the dimensions of the columns, when higher stiffness differences are present, additional bearing elements should be foreseen such as RC walls.

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