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ANALYSIS OF THE DYNAMIC PERFORMANCE OF BUILDINGS BEFORE AND AFTER THEIR STRENGHTENING

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ABSTRACT

In this study, three buildings located in San Juan City, Argentina, are analyzed. These buildings were strenghtened after the Caucete Earthquake of 23 November, 1977, that showed their vulnerability when they were subjected to a destructive earthquake of IMM = VII. The buildings suffered different types and levels of damage during the earthquake. Two three-dimensional analytical models of each building were prepared and they were adjusted using the fundamental periods obtained from microvibration records. The dynamic analysis was done using the spectral and step-by-step methods in the elastic range. The results obtained showed better responses in the strenghtened buildings.

KEYWORDS

Strenghtening; Dynamic performance; Vulnerability; Microvibrations

OBJECT

The object of this study is to evaluate the effects of the strenghtening in the global seismic response of buildings and to compare their performance with the requirements of the current Seismic Code.

METHODOLOGY

The analyzed buildings suffered different types and levels of damage during the Caucete Earthquake of the 23 November 1977, San Juan, Argentina. The intensity of this earthquake was IMM=IX in Caucete City and IMM=VII in San Juan City, 30 km far from that, where the chosen buildings are located. These buildings are reinforced concrete infilled frames and they were designed in accordance with the seismic code in force during the period of their construction.

Considering the geometrical and mechanical characteristics of the buildings before and after their strenghtening, two three-dimensional analytical models of each building were prepared, Model I and Model II, respectively. These models were readjusted by correlating the calculated periods of the structures with the real values obtained from the analysis of environmental microvibration records. Two types of dynamic analysis were carried out in the main directions: free vibration and forced vibration. From the free-vibrational analysis the first six modes and their corresponding periods of each model were obtained and they were used to adjust the models. In the analysis of forced vibrations the step-by-step integration and modal superposition with response spectrum techniques were used. Considering three degrees of freedom per story, the dynamic analysis was carried out in the elastic range. Taking into account the first six modes, the total response was obtained using Pitagoric Superposition.

The buildings were subjected to the following excitations:
1- The acceleration record of the 23 November 1977 Caucete Earthquake registered in the Earthquake Research Institute (IDIA), San Juan National University, in San Juan City, at aproximately 80 km from the epicenter.
2- The same record with a modified maximum acceleration and frequency content corresponding to the maximum probable design earthquake for this region (in 1944 San Juan City experienced an earthquake of IMM = IX).
3- The design elastic spectrum and the reduced spectrum from the current Argentine Seismic Code INPRES-CIRSOC (I-C).

An elastic spectrum of pseudo accelerations was adopted, in accordance with the specifications of the seimic code, the location and the characteristics of the soil of foundation of the buildings. This spectrum corresponds to seismic zone 4, with a damping of 5 % and type of soil II (propagation velocity of shear waves between 100 and 400 m/seg and admissible tension between 1 and 3 kg/cm²). The spectrum was reduced using different reduction factors for each building. This reduction factor depends on the global ductility of the structure and on the considered period of vibration. The global ductility is a function of the relation between the Effective Resistant Capacity and the Required Resistant Capacity, and the nominal global ductility adopted as 3.5 for these buildings. The ductility factors were calculated for displacements, shears and overturning moments. Also the resistance capacity was calculated for particular structural elements. This capacity ratio is defined as the stress ratio between the stress produced by the seismic load and the ultimate stress.

ANALYSIS OF THE BUILDINGS

Building 1.

Description: This building belongs to the Earthquake Research Institute (IDIA) of the Engineering Faculty of the National University of San Juan (UNSJ), Argentina.
The building has three stories, its dimensions are 28 m by 10.10 m and its height is 11.65 m. The structure is a RC orthogonal frame system. The exterior walls are solid brick walls of 30 cm width and the interior ones are 15 cm and 20 cm width. In the E-W direction, the exterior walls have openings of 0.70 m width. The sections of the structural elements vary in the different levels, Fig. 1.

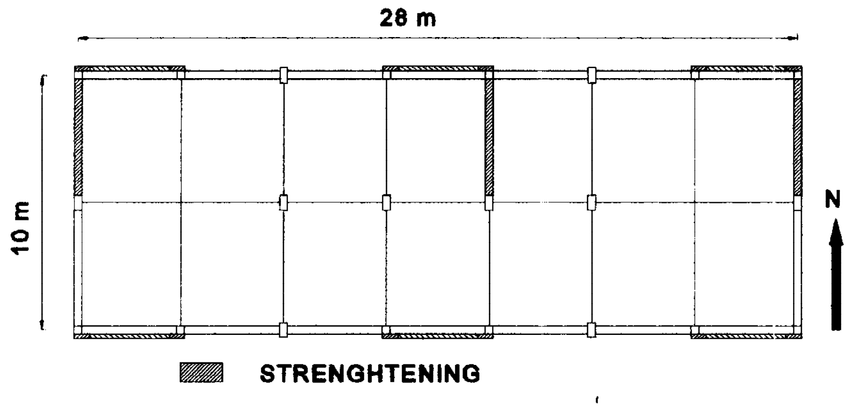
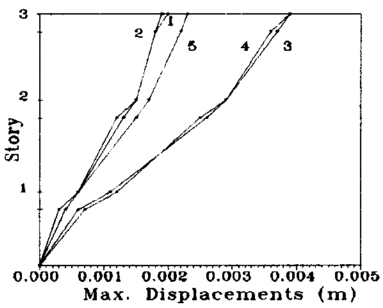


Fig. 1 - Building 1. Plan view.

Damages: This building was not heavily damaged. In the west part of the first level, the windows located in the upper part of the walls led to the effect of "short column". In those columns appeared small cracks because of the shear stress produced by the variation of rigidity.
The same phenomena could be observed in the columns of the north side of the building in the underground level. In the partition walls of the first level (solid brick with 15 cm width) diagonal cracks of considerable width were observed. Also, these diagonal cracks appeared in the exterior wall located in the west side of the building.

Strenghtening: In the N-S direction, the masonry walls of 30 cm and 20 cm of width were replaced by RC walls of 20 cm of width, in the extreme and central frames.
In the E-W direction, in the external frames, the sections of beams and columns were increased in three of the seven vains.

Dynamic Analysis: When comparing the vibration modes it can be observed the effect that the strenghtening has in the building. The graphics show the maximum displacement of each level, in both Models and in the two principal directions, Fig. 2.



1 Model I - Caucete Earthquake (0.18 g)
2 Model II - Caucete Earthquake (0.18 g)
3 Model II - Caucete Earthquake (0.36 g)
4 Model II - Elastic Spectrum (I-C)
5 Model II - Reduced Spectrum (I-C)

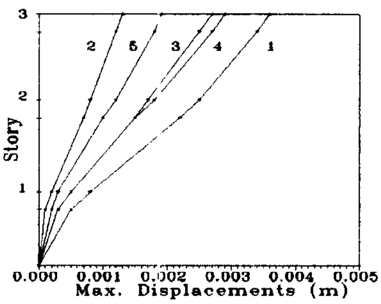


Fig. 2-a - Maximum displacements direction E-W.

Fig. 2-b - Maximum displacements direction N-S.

In the curves corresponding to the E-W direction, Fig. 2-a, for Model I, it can be observed the variation of slope between levels because of the rigidity variation in the zones where the short column effect appeared. The variation of slope in Model II is not so pronounced because the short column effect decreased as a consequence of the relative rigidity increase in the RC columns with respect to the masonry walls. The displacements in both Models for the same excitation are aproximately the same. Comparing the ductility values of both the reduced spectrum and the maximum probable earthquake adopted, for displacements, shears and overturning moments, it is found that they are lower than the limit values given by the Seismic Code (I-C).

In the curves corresponding to the N-S direction, Fig. 2-b, for Model I, there are not discontinuities. In Model II, the displacements, compared to those of Model I for the same excitation, decrease considerably and the requirements of ductility are lower than in the other direction, Fig. 3. This is because the strenghtening was more effective in this direction than in the other, where the masonry walls were replaced by RC walls. These walls produce more increase of the structure rigidity than the one produced with the increase of the sections of beams and columns. Because of this, the most significant changes in the total response are observed in N-S direction being the structure more rigid in this direction than in the other.
With reference to shears and overturning moments, the demand of ductility is not greater than the demand of displacement ductility.

The capacity ratios for a column line are shown in Fig. 4. Here it can be seen that all demands are less than the nominal capacities, however, it is of interest to note that the maximum demands occur at the levels with "short column" effect.

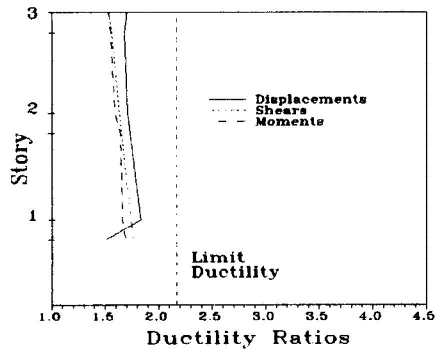


Fig. 3 - Ductility Ratios.

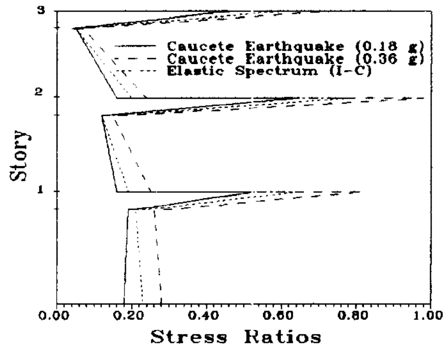


Fig.4 - Capacity Ratios.

Building 2.

Description: This building belongs to the Hydraulics Department and the Hydraulic Research Institute of the Engineering Faculty of UNSJ. The building has three stories, its dimensions are 30 m by 12 m and its height is 10 m. The structure is a RC orthogonal frame system. The exterior walls are solid brick walls of 30 cm width and the interior ones are 10 cm and 15 cm width. The exterior walls have openings of 90 cm width in the first and second levels in the E-W direction, and in the second and third levels in the N-S direction, Fig. 5.

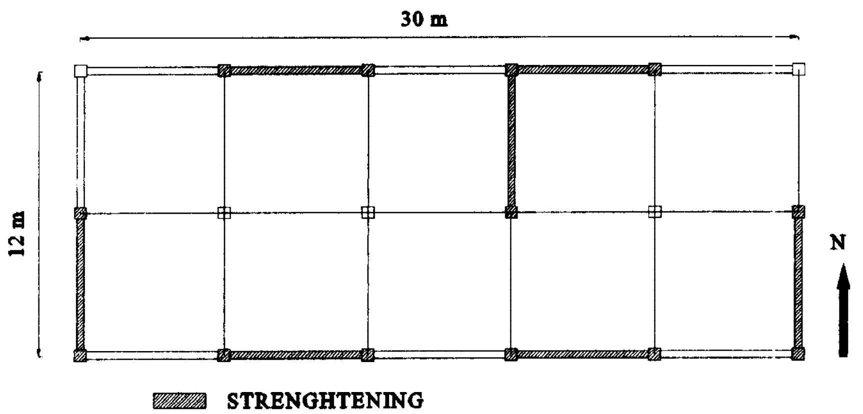


Fig. 5 - Building 2. Plan view.

Damages: There is no information about the damages produced in this building during the 23 November 1977 Earthquake.

Strenghtening: The strenghtening of this building consisted in adding RC walls of 20 cm and 30 cm width in both principal directions, from the foundation level to the upper level.

Dynamic Analysis: Comparing the two Models, the effect of the reinforcement produced with the addition of RC walls in both directions can be observed, Fig. 6.

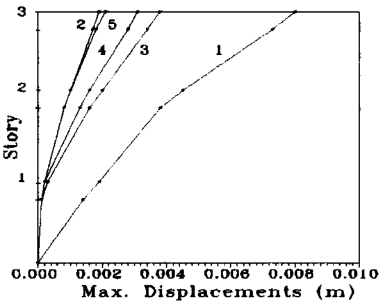


Fig. 6-a - Maximum displacements direction E-W.

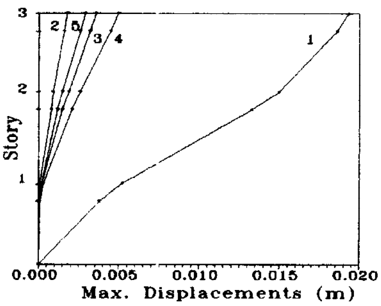


Fig. 6-b - Maximum displacements direction N-S.

In the E-W direction, Fig. 6-a, the type of deformation of the structure did not change after the strenghtening. The displacements produced by the maximum probable design earthquake are greater than the ones produced by the reduced design spectrum of the Code. This fact could produce inelastic deformations with a requirement of displacement ductility of approximately 2, compatible with the ductility values given by the current seismic code for this type of structure. The shear and overturning moment ductilities are lower than the ones specified in the Code.

In the N-S direction, Fig. 6-b, the RC walls produced a change in the global response of the building. Before the strenghtening, the building had a frame type deformation and now, after the strenghtening, it has a shear wall type deformation. A great difference between the displacement in level 1 and the other levels can be observed. The displacement in level 1 is approximately 0, and the building behaves like fixed in that level. In this direction the required ductilities are small, and the structure may develop them without problem because of its characteristics, Fig. 7.

The distribution of maximum capacity ratio over the height is presented in Fig. 8.

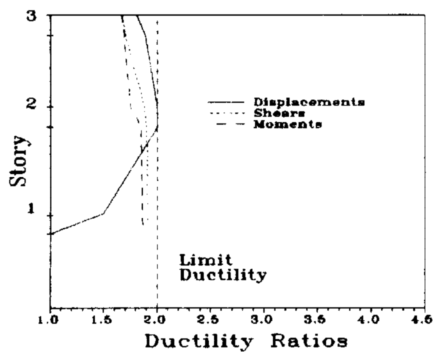


Fig. 7 - Ductility Ratios.

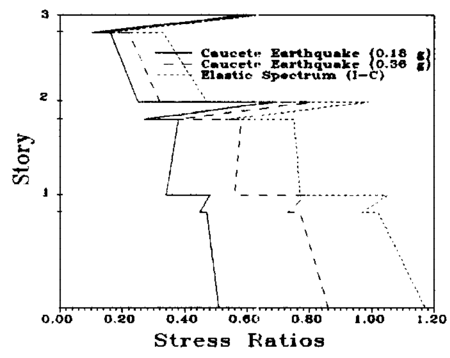


Fig. 8 - Capacity Ratios.

Building 3.

***Description*:** This building belongs to a Technical Secondary School of San Juan. The building is a RC type with four levels and it is divided in three blocks. The east block consists of classrooms, the central block of stairs and the west block of administrative offices (this block has only two levels). The first level of the east block of the building was originally "soft story". The dimensions of this block are 32.4 m by 17.4 m. The height of the first level is 4.5 m and the other levels are 3.8 m high. The original structure is a RC frame system in two orthogonal directions. The slab in the central hall connects the frames in both sides of the building, in the N-S direction, and it has no beams. The classrooms in the different levels are separated with solid brick panels of 10 cm width, while the exterior panels are 20 cm width, Fig. 9.

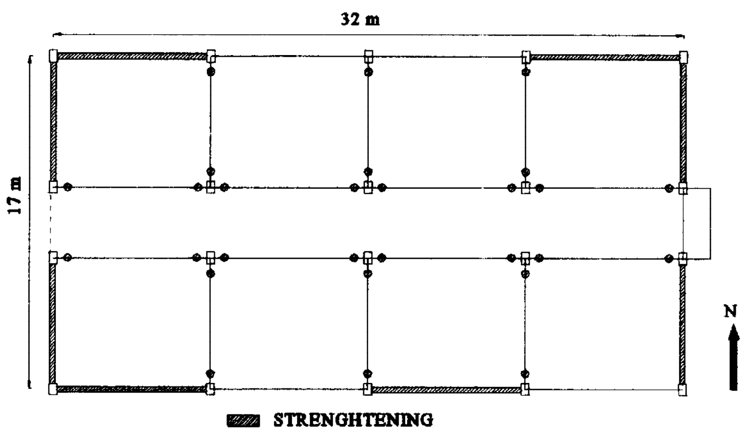
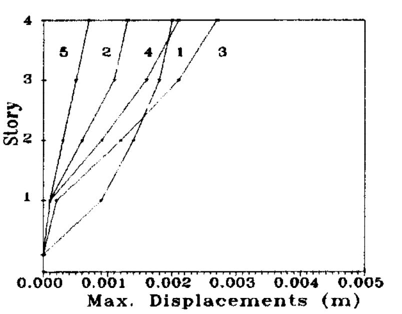


Fig. 9 - Building 3. Plan view.

Damages: The building had important damages in the east block with a lateral permanent displacement of the first level columns of 4 cm in the E-W direction. This permanent displacement reached the 6 cm because of the aftershakes. The structure damages in the first level consisted in the failure of the covered concrete in the top of the columns and the buckling of the longitudinal bars of these columns. The walls in the stairs block had cracks in the first level. In the first level there were not walls and this story is higher than the others with perimetral walls of 20 cm width and interior walls of 10 cm width. That is why the rigidity of the building changes considerably in those levels, giving as a consequence a discontinuity of the stiffness. These observed damages show that the structure behaved as a "soft story" structure during the earthquake.

Strenghtening: Four metallic columns were built temprorily with lifting jacks, in order to recover the most damaged columns, and RC columns so as to recover all the others. Also RC walls of 25 cm width were built, four in each direction. These walls are supported directly over the floor and connected to the upper beams and lateral columns.

Dynamic Analysis: When analyzing the predominant modes of both models it can be noticed that before the strenghtening the first mode was in the E-W direction while in model II it was in N-S direction, Fig. 10.



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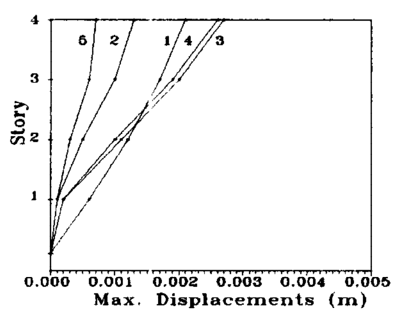

Fig. 10-a - Maximum displacements direction E-W.

Fig. 10-b - Maximum displacements direction N-S.

Also it should be noticed that in E-W direction the behaviour of the building during the earthquake corresponds to the "soft story" building. Because of this, the first level was reinforced with the construction of RC walls which resulted in an over-rigidity with respect to the other levels. This fact can probably be no real, because of the rotation of the shear walls that are supported directly over the floor, Fig. 10. Figure 11 shows that for the upper levels, the ductility required for displacements is irregular, being greater than the ductility given by the Code for such structures. Also the required shear and overturning moment ductilities are greater than the ductility the structure can develop in accordance with the Code.

The difference of ridigity among the first level and the other levels of this building can be readily seen from the distribution of maximum capacity ratio over the height, which is shown in Fig. 12.

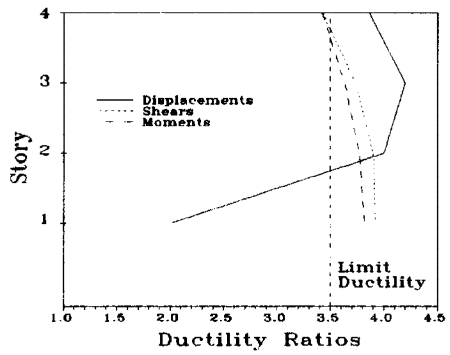

Fig. 11 - Ductility Ratios.

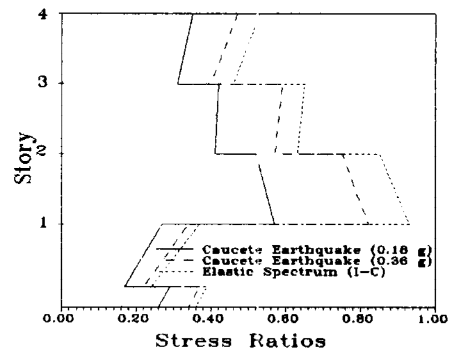

Fig. 12 - Capacity Ratios.

CONCLUSIONS

As a consequence of the strenghtening, the modal shapes changed in all the analyzed buildings. The fundamental period appears in a certain direction in Models I, and in the opposite direction in Models II.
From the required ductility point of view, the result was satisfactory in buildings 1 and 2, because the results obtained, comparing the response to the maximum probable design earthquake adopted with the response to the reduced spectrum given by the Code, are lower than the allowed ones. In building 1 the "short column" effects were reduced. In building 2 the response in both principal directions is now homogeneous.
These better responses observed in these two buildings can not be observed in the case of the third building in which appeared an over-rigidity of the first level in respect to the others. Also, the demand of ductility and the resistance capacity are higher than those that this type of structure can develop. These results show that these buildings could suffered more damages if they were subjected to the maximum probable earthquake of the region. It results in the necessity of making this type of analysis to those buildings designed and constructed using a seismic code which, at present, is not in force.

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