MEASURED AND PREDICTED SEISMIC RESPONSE OF TWO SIMILAR BUILDINGS, ONE WITH RIGID FOUNDATION AND THE OTHER WITH A BASE CONTROL SYSTEM

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Abstract. Based on the study of two similar buildings equipped with seismic instrumentation, finite element models are developed and calibrated using seismic signals of input and response, recorded on the two buildings in August 2006. One building was constructed on a traditional rigid foundation and the other was isolated with a Base Control System (BCS). These numerical models are used to carry out an exhaustive comparison of the buildings' dynamic behavior and to evaluate the isolation system performance. The isolated building's behavior is weakly nonlinear, because the dynamic properties of isolators depend on displacements and frequencies. The stiffness and the damping coefficient of the isolators are considered as constants, these approximations allow the use of commercial finite element software to study the dynamic response due to the seismic excitation. The dynamic equations are numerically integrated in time domain, considering the non proportional damping caused by viscous dampers as a nonlinear load term. Acceleration at different buildings' levels, base displacements, axial forces and bending moments on different columns, base shear and dissipated energy are compared for the two considered cases, BCS and the fixed base building model. The results show an effective reduction of accelerations and seismic loads in the isolated building to less than one third of the values corresponding to the rigid base building. The strategy of including some vertical flexibility and vertical damping in the isolators and admitting some small rocking motion of the building is also validated; considering that in the present case the vertical movements contribute to dissipate 20 % of the seismic energy.

1 INTRODUCTION

The student's residence of the National Technological University at Mendoza, Argentina, is a set of buildings constructed in 2004 with the main purpose of providing housing facilities to students coming form distant places. Two of these buildings were identically projected and built with the only difference that in building #3 (**B3**) a base isolation system was installed while the other similar building #2 (**B2**) has a rigid traditional foundation (Stuardi, 2003). Both structures were instrumented in 2005 and since then, a data acquisition system has been obtaining information of the seismic responses.

The Base Control System (**BCS**) (Rakicevic et al., 2006) installed in B3 provides flexibility and damping in vertical and horizontal directions on the base of the building by using a combination of springs and viscous dampers (Nawrotzki, 2002). The system was provided by Gerb GmbH in Germany.

Both buildings have three floors and were constructed of concrete and reinforced masonry. The isolation system in B3 consists of four boxes containing helicoidal springs (Chouw, 2002) and four independent viscous dampers that support a peripheral beam designed to uphold the system.

The dynamic behavior of the two buildings was studied using the signals registered on August 5th 2006 of a 5.7 magnitude earthquake, whose epicenter was located 30 Km away from the city of Mendoza were the building are located. Finite element models of both buildings were made and then calibrated using the signals measured at foundation and at top level. The main purpose of this effort was to calibrate these models to carry out an exhaustive comparison of the buildings' dynamic behavior and to evaluate the isolation system performance.

The calibration of the structural model for the building with rigid foundation, B2, is not troublesome, despite the fact that it is a Multiple Input - Multiple Output (MIMO) System and that the registered signals available to work with are very scarce.

The first six modes of the isolated building are related to approximately rigid body motions of the building and high deformations on the isolators, because of the horizontal and vertical flexibility of the spring isolators. Therefore, these six modes are sufficiently uncoupled from the distortive modes of the building itself.

In order to obtain good adjustments, the model of the BCS isolators should take into account stiffness and damping dependency on displacement and velocity. In order to simplify the model and to make the calculations using standard commercial software, the stiffness and damping of the isolator were considered to be constant in the present work.

Due to the presence of dampers on the base of the structure B3, the damping model results non proportional. The system of equations was solved by means of integration on a reduced modal subspace in time domain and considering the damper forces as external forces.

In the present work, the isolation system effectiveness is demonstrated comparing the dynamic responses of both buildings. Acceleration amplitudes at base level and at the top are compared for this purpose. From the calibrated computational models it was also possible to calculate and compare reductions of axial and shear forces and of bending moments in columns of ground floor. Finally interstory drift and comparative magnitudes of dissipated energy are shown.

It is importance to point out that the values of the different forces used to draw conclusions about the performance of the isolated system, were not measured, they were calculated using reliable calibrated models.

2   BUILDINGS CHARACTERISTICS AND DATA ACQUISITION SYSTEM

The buildings under study have been constructed of reinforced concrete and reinforced masonry. Their dimensions are 8.2 by 8.7 m in plant, 8.6 m height and they have a total weight of 320 kN. The building #3 structure is identical to the building #2 with the exception of an existing peripheral beam located at the base of B3 whose purpose is to suitably transmit loads to the 4 sets of base isolators located under each corner of the building foundation. Each set of isolators consist in an helical spring and a viscous damper. The plant view and section of the isolated building together with a set of isolators are shown Figure 1.
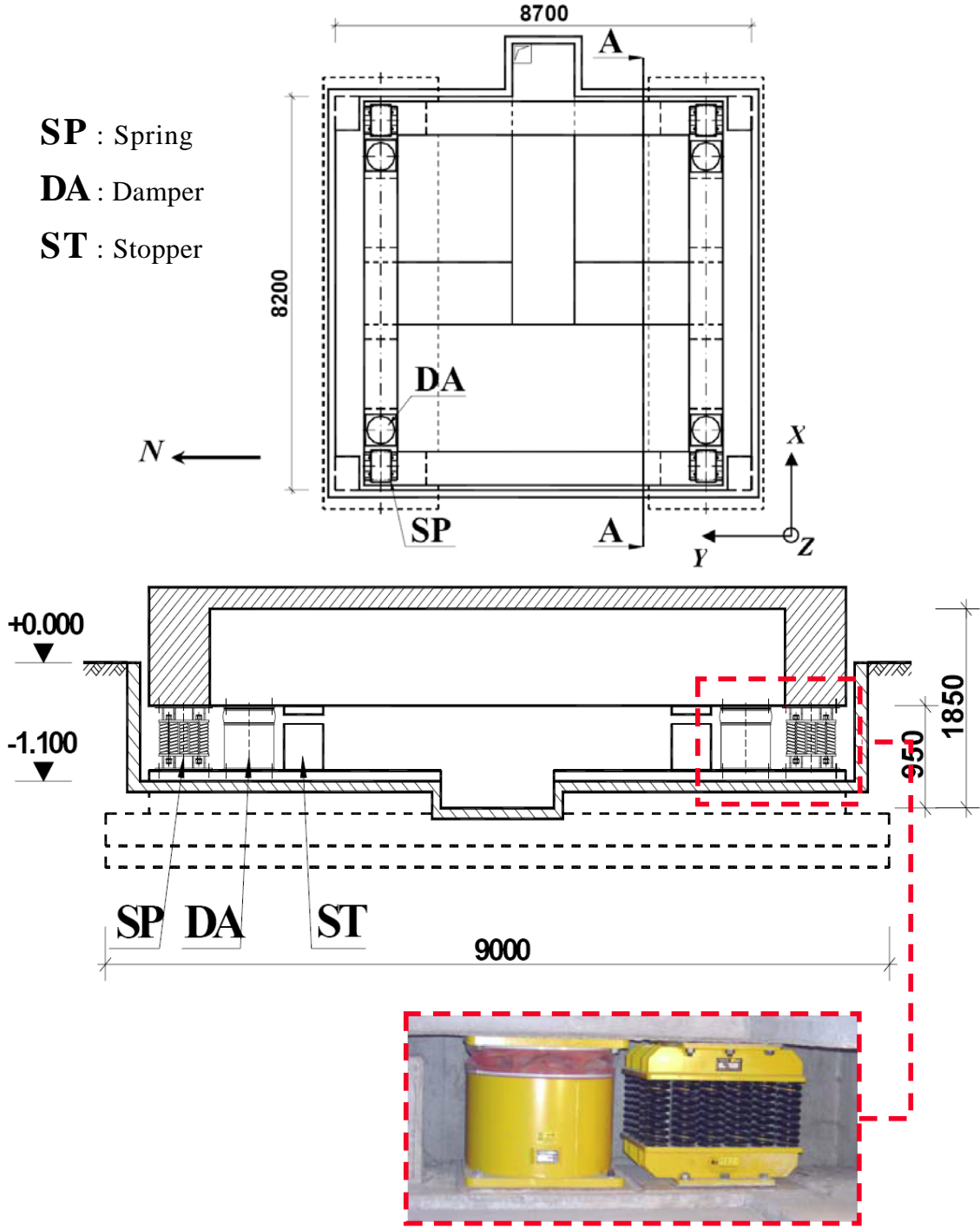

Figure 1: Plant view and section of building base of building #3

While in the YZ plane the building can be considered to be approximately symmetrical, in the XZ plane there is a slight shape asymmetry. Isolators with different stiffness were installed in order to obtain equal vertical static displacement on the isolators to level the building. Average nominal values of the installed sets of isolators, placed in the corners of the building as shown in Figure 1, are given in Table 1. The average resulting vertical displacement due to self weigh is 23.4 mm.

Direction	Stiffness [kN/mm]	Damping coefficient
Horizontal	4.57	360
Vertical	34.22	180

Table 1: Stiffness and damping coefficients in different directions of the isolated building

2.1 Data acquisition system

A 12 channel data acquisition system was installed at the basement of building #3. A triaxial accelerometer was located at the top of building #2. Two triaxial accelerometers and three uniaxial ones were installed on building #3. The location of this equipment is shown in Figure 2. The system was set to a maximum sampling frequency of 100 Hz. The accelerometers have a sensibility of 1.25 V/g and the digital recorder has a 0-80 Hz useful frequency range.
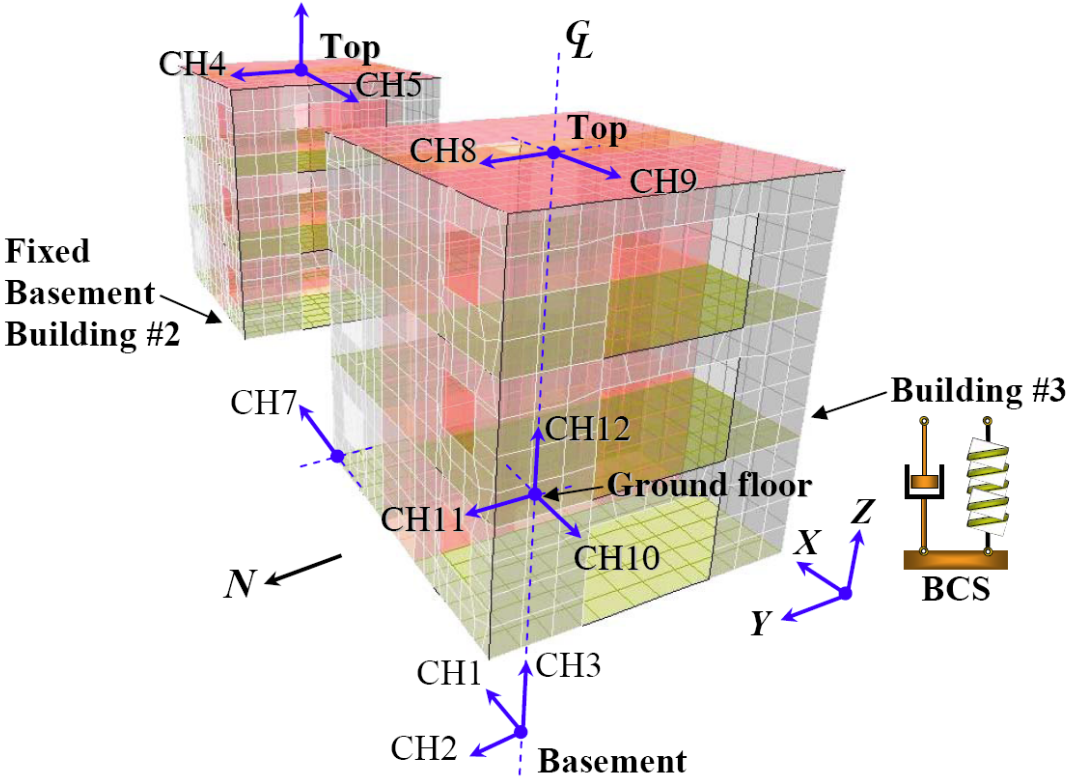
CH #	Location	Dir.	CH #	Location	Dir.	CH #	Location	Dir.
CH1	Basement	E-W	CH5	Top of B 2	E-W	CH9	Top of B 3	E-W
CH2	Basement	N-S	CH6	Top of B 2	UP	CH10	Ground floor B 3	E-W
CH3	Basement	UP	CH7	Ground floor B 3	E-W	CH11	Ground floor B 3	N-S
CH4	Top of B 2	N-S	CH8	Top B 3	N-S	CH12	Ground floor B 3	UP

Figure 2: Location of accelerometers in the studied buildings

3 PERFORMED CALCULATIONS

3.1 Model Calibration

Eigenfrequencies of the rigid base building were first adjusted, using the measured signals, modifying shear stiffness of walls and mass distribution in height and in plant. Then the properties of the isolation system were adjusted, i.e. horizontal and vertical stiffness and damping coefficient. All of these properties were considered to be constant for the calculations. A first approximation of the eigenfrequencies was obtained using estimators coming from frequency response functions. The latter were calculated from the registered signals using standard modal analysis procedures (Ewins, 2000) to achieve the best possible adjustment. Notice, that only approximations are possible because of the constant stiffness and constant damping considered in the model. Table 2 shows the frequencies of the calibrated model.

As a result of the calibration the model presents the following eigenmodes and eigenfrequencies:

Mode	Rigid base building	Hz
1	YZ plane	4.44
2	XZ plane	5.78
	Structural damping	3 %

Mode	BCS building	Hz
1	XZ plane lower pole	1.38
2	YZ plane lower pole	1.43
3	Torsional	2.23
4	Vertical	3.61
5	XZ plane upper pole	3.82
6	YZ plane upper pole	4.13
7	Combined BCS-building mode	10.75

Table 2: Modes and natural frequencies:

3.2 Measured seismic signal

The seismic input signals measured at the basement of the building in time domain along with their corresponding response spectrum for the three coordinate axes are shown in Figure 3. The accelerometers are located on the basement at center line of the building. These signals are used as the input for the system and no further soil-structure interaction is therefore considered in the present model.

4 RESULTS

4.1 Calibration

Figure 4 shows the adjustment achieved by calibrating the rigid foundation model of the building in directions X and Y and comparing accelerations measured at the top of the building with the corresponding accelerations calculated using the calibrated model for B2. Only the significant part of each signal -16 seconds- is shown (left side of Figure 4) together with the FFT of this part of the signal (at the right side). The shear stiffness of the walls was modified in order to approximate the bending mode frequencies of the building. The achieved correlations between measured and calculated signals are 87 % and 93 % for X and Y directions respectively.

Figure 5 shows the adjustment achieved of the calculated vs. the measured signals at the top point of the isolated building in X direction, in Y direction and on the ground floor point in Z direction. In this case the adjustment was achieved by modifying the dynamic properties of the isolation system. The correlation between measured and calculated signals is 0.942, 0.943 and 0.895 for X, Y and Z directions respectively.
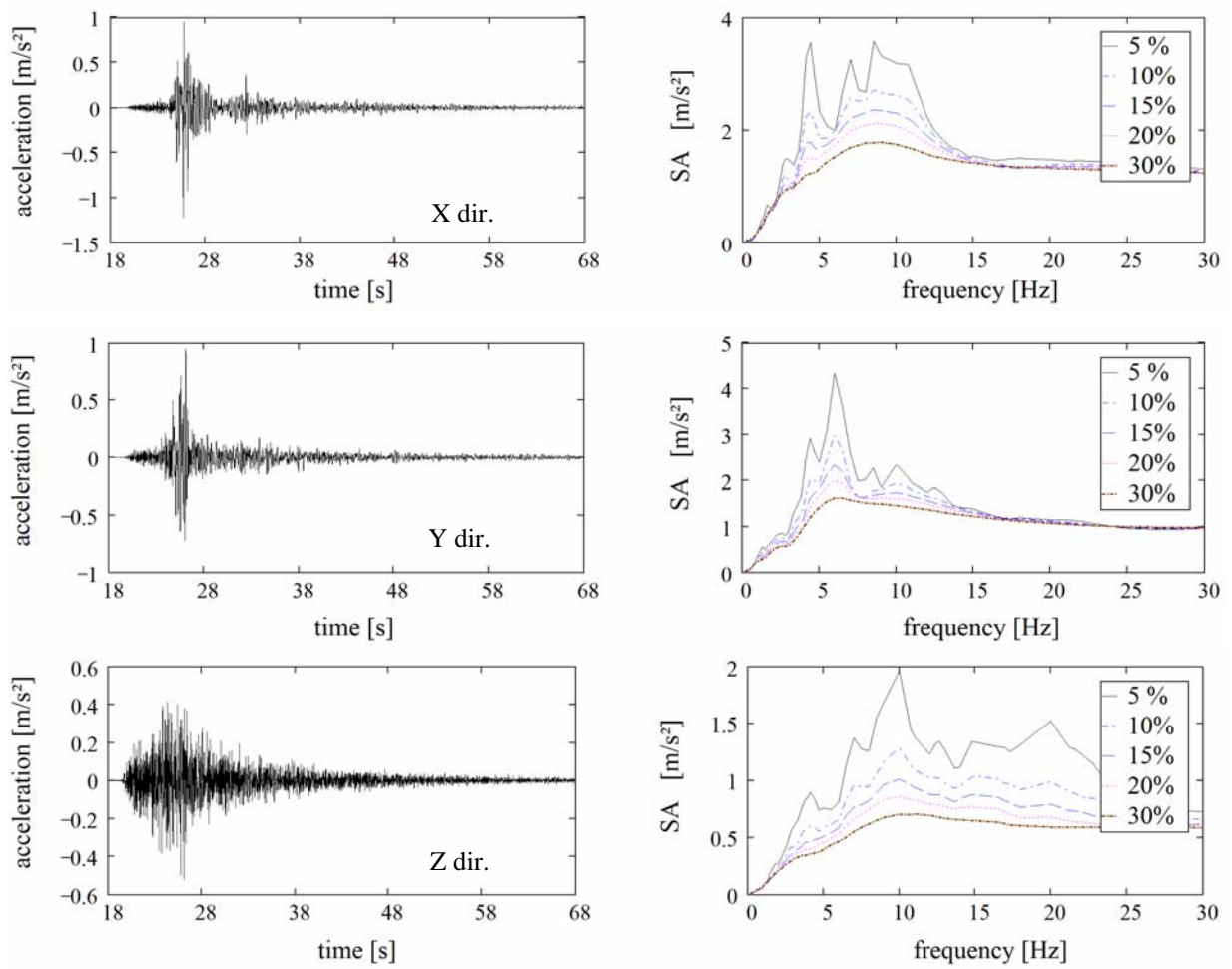
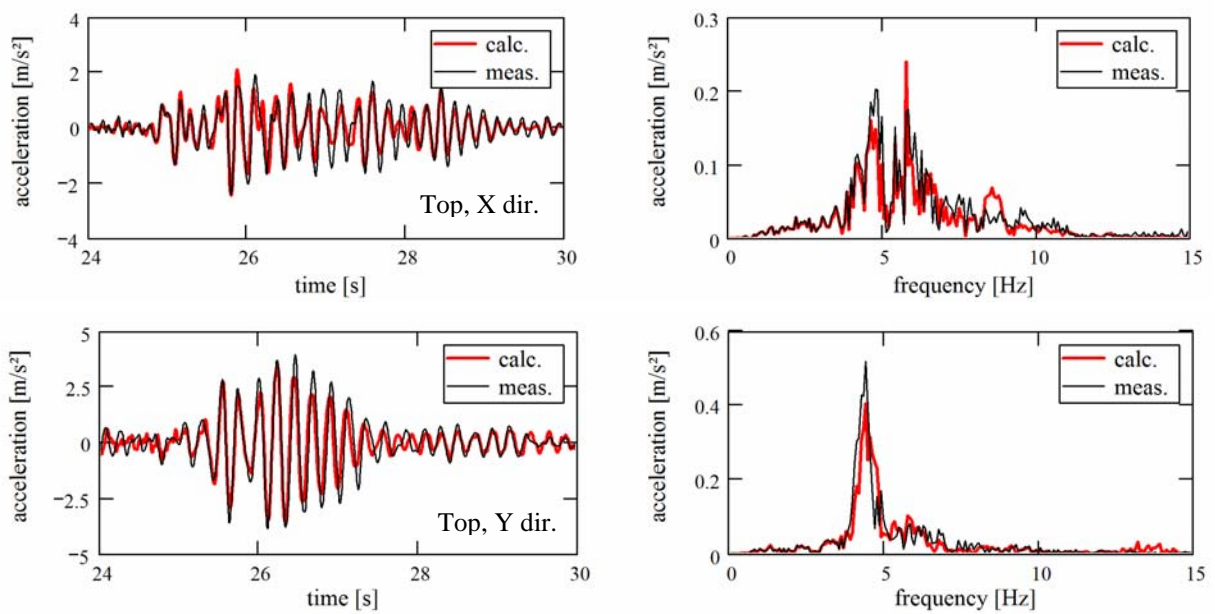Figure 3: Signal registered on the basement of the building

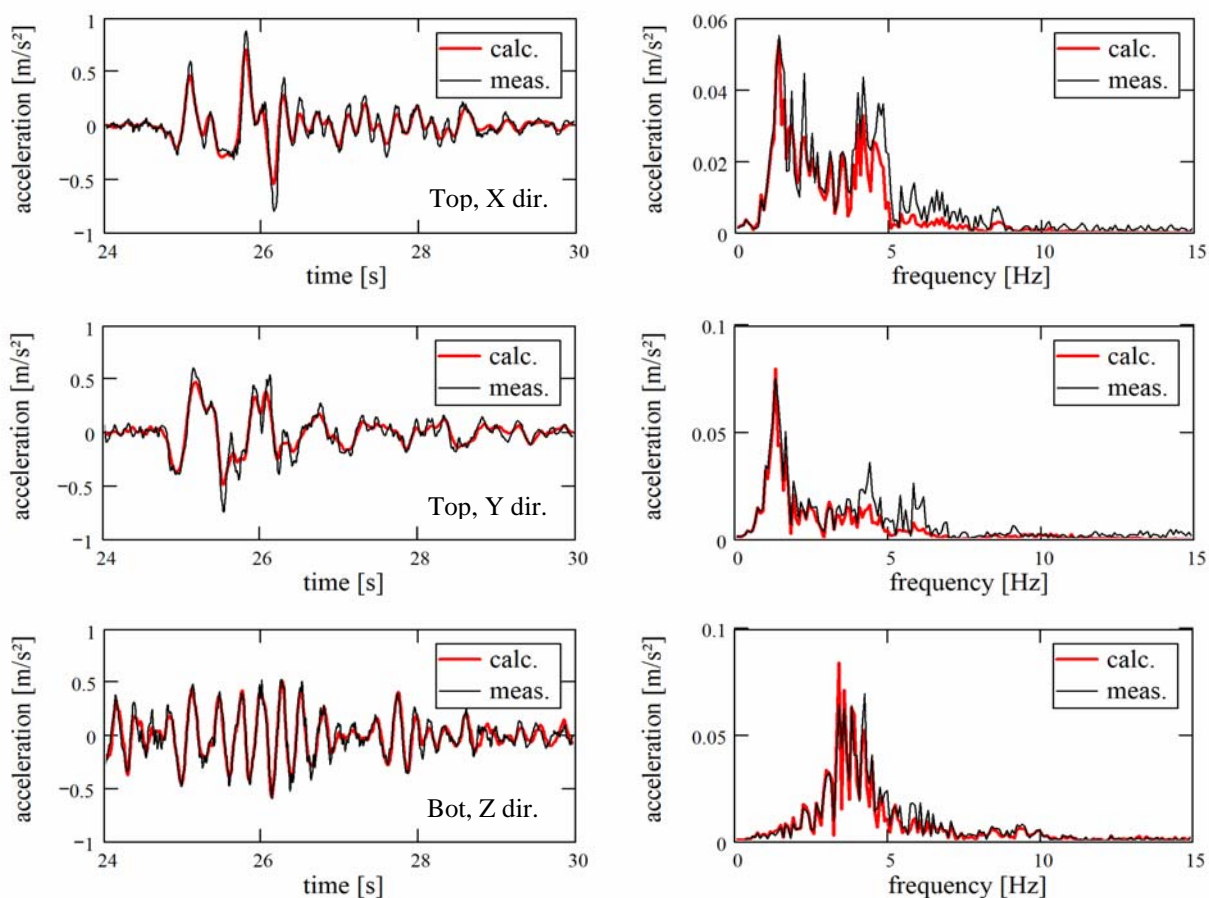Figure 4: Calibration of rigid basement building model

Figure 5: Calibration of BCS building model

4.2 Accelerations

Figure 6 shows the calculated accelerations at the center top point of the buildings for X, Y and Z directions. Calculated values obtained using the rigid base building model and the BCS building model are compared.
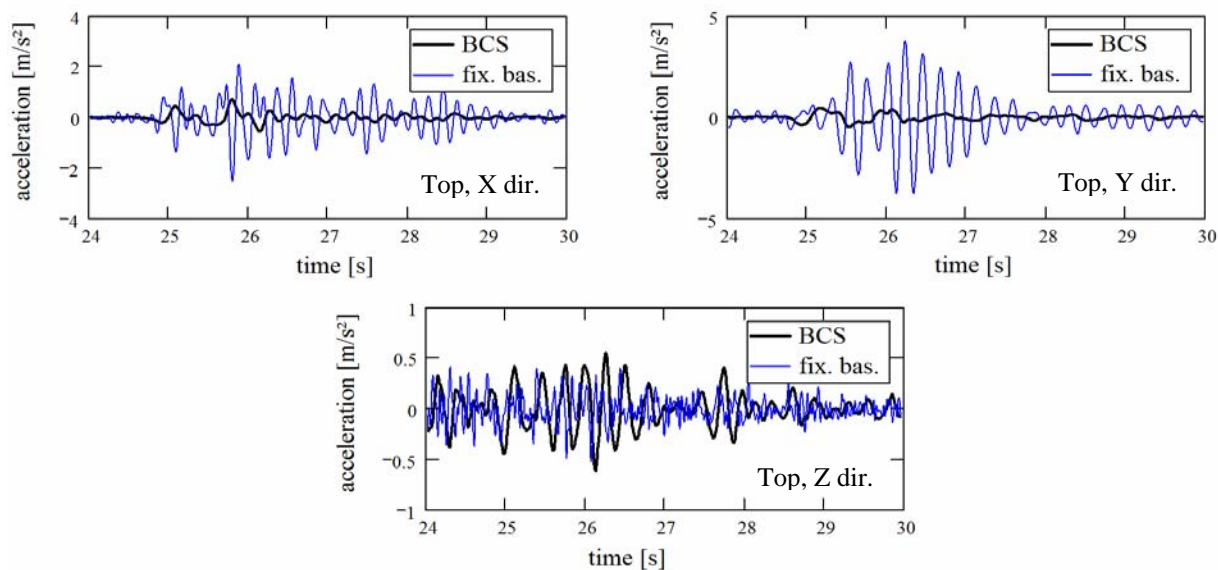

Figure 6: Calculated accelerations at the top of buildings

4.3 Base Shear

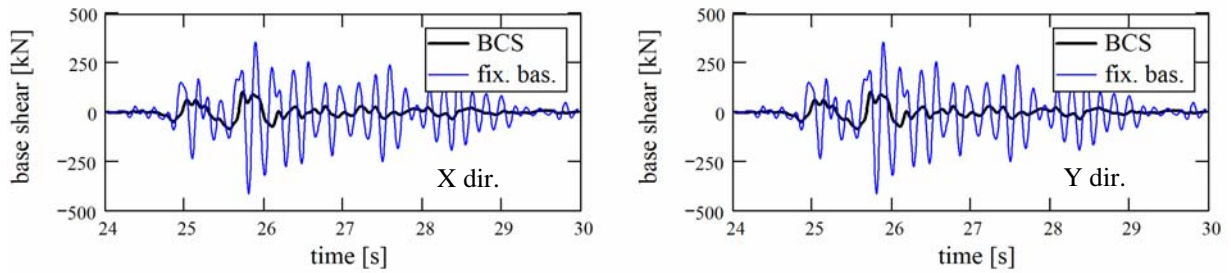Base shear for directions X and Y are shown in Figure 7.

Figure 7: Base shear

4.4 Frame Forces

Figure 8 shows axial forces, shear forces in X and Y direction and bending moments in X direction for one column located at the bottom on the southwest corner (left) and at the center point of the north lateral side of the building (right).
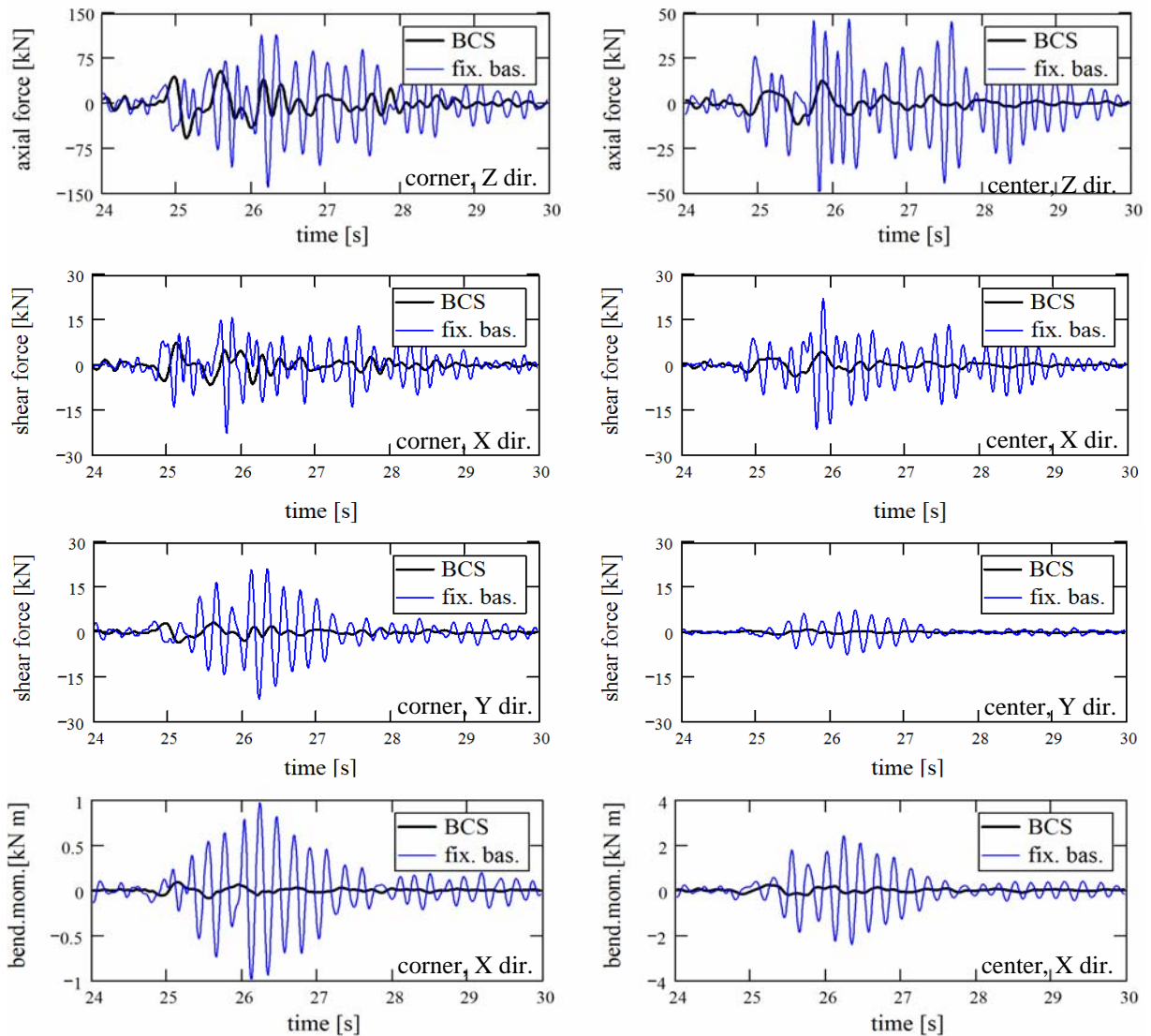

Figure 8: Axial forces, shear forces and bending moments

Figure 9 allows comparing the performance of the BCS isolation system for accelerations, shear and normal forces and bending moments.
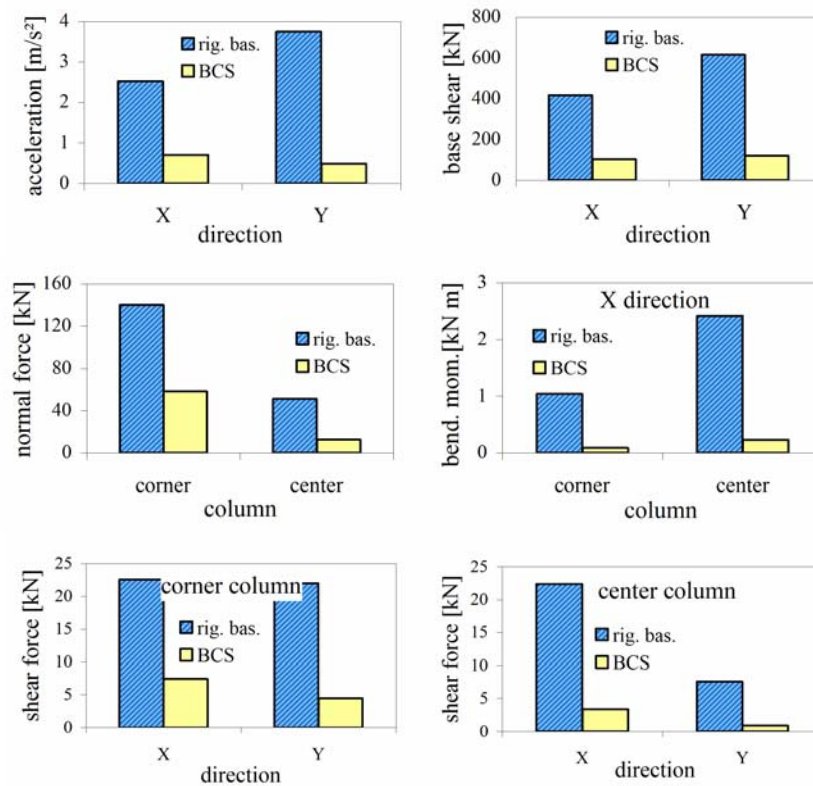

Figure 9: Summary of accelerations and forces reduction

Maximum and minimum accelerations are presented in Figure 10a for the southwest corner point at each level of the rigid base building and the one with the BCS.

Figure 10b shows the displacements related to ground floor in Y direction (calculated on the center line point) for the analyzed cases. The rigid body motion curve represents the relative displacements caused by the isolator's deformation, that is the horizontal displacement at the top of the isolators at 0 level. The contributions of horizontal displacements caused by pendular movements of the base are also seen for levels 1, 2 and 3. The real relative displacement is represented by the BCS curve, so the drift that generates deformations on the structure is represented by the difference between the BCS and the rigid body motion curve. This difference can be then compared with the rigid base curve.
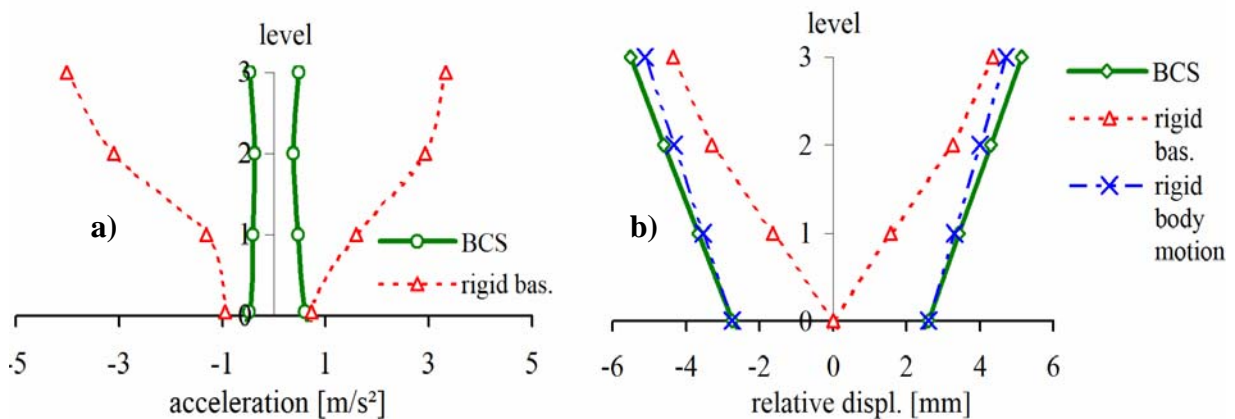

Figure 10: a) Horizontal accelerations at different building levels, b) Relative displacements

Figure 11 presents the vertical and horizontal displacement demand on isolators during the earthquake. Horizontal values are less than 3 mm and maximum vertical values do not exceed 2 mm.
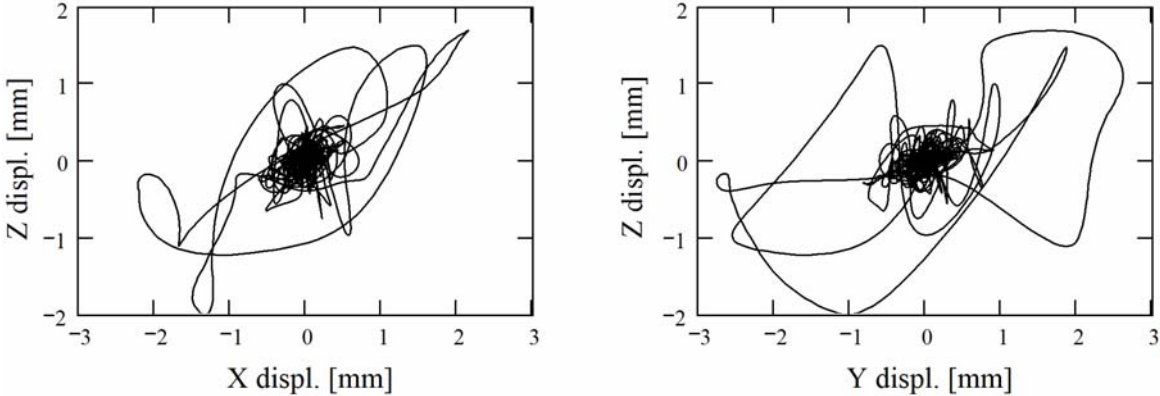

Figure 11: Vertical and horizontal displacement demand on BCS

Finally, Figure 12 shows the total energy of the seismic signal entering the building. In the case of the rigid base, this energy is entirely dissipated by the building damping. However, for the building with BCS, the viscous dampers dissipate 80 % of the total energy, with contributions of 58 % from horizontal movements and 22 % from vertical movements.
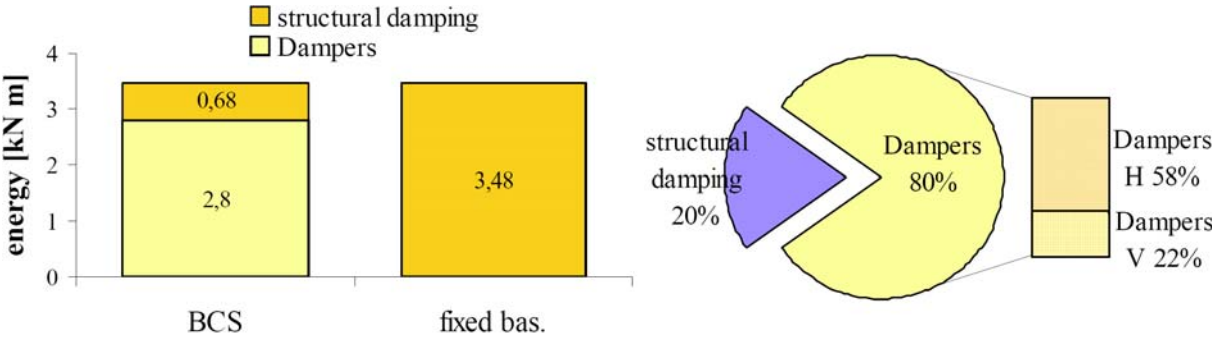

Figure 12: Dissipated energy

5 CONCLUSIONS

The use of seismic signals recently recorded on two similar buildings, one with rigid foundation and other equipped with BCS isolation, allowed to calibrate a simplified model of the nonlinear behavior of the BCS-Building system. Although the stiffness and damping of the isolators were considered as constant for different displacements and operational frequencies, the results have enough accuracy to draw conclusions about the performance of the isolated system. This is because forces, although not measured, were calculated using a reliable calibrated model.

In order to calibrate the computational finite element models of the rigid base building and the isolated system, signals registered in three orthogonal directions were used as input. Correlations of more than 95 % were obtained between measured and calculated signals in all cases. This fact allows a realistic comparison between the dynamic response of the isolated building and the expected response of a traditional foundation building using magnitudes that were not measured, such as forces.

The results show that the isolation system is very effective in reducing forces when they are compared with the values corresponding to the rigid base building. Horizontal accelerations at different building levels are effectively reduced by the isolation system, more than 70 % at the top of the building. Axial forces are reduced more than 60 %, shear forces are reduced more than 75 %, while bending moments on different columns are reduced 90 %.

Interstory drift has to be specially considered when BCS isolation is present. Considering displacements caused by distortions instead of by rigid body movements, drift is reduced more than 80 % from its original value. It is important to remember, that the building experiences small pendulum movements on BCS isolators because of the vertical flexibility of helical springs.

On the other hand, the dissipated energy on the building's structure is only 20 % compared with the energy wasted on the building with rigid base. The vertical movements of the buildings allow the dampers to contribute with a dissipation of 22 % of the seismic energy.

The earthquake considered in this work has been the greatest in magnitude since the buildings were finished in July 2004 and, although it is relatively small -having maximum accelerations value of 10 % g- is used to show the effective performance of the isolation system. Taking into account that both isolator stiffness and damping diminishes with greater demands, smaller transmissibility ratios are still expected for earthquakes of greater magnitude. Considering that the horizontal displacement demand at the isolators level has been less than 3 mm (5 mm at the top), it can be concluded that the Base Control System represents an effective seismic protection tool, which provides proper acceleration and dynamic forces reduction specially with a low level of building displacements.

The scope of future investigations in this area relays on the possibility of registering more signals to allow better calibrations of the complete system over extended displacements and frequency ranges, which would enable a better understanding of the dynamic behavior of the system.

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