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SEISMIC ANALYSIS OF THE IRREGULAR FIRE STATION BUILDING OF L'AQUILA

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ABSTRACT

Following the seismic sequence that struck the city of L'Aquila in April 2009, the Fire Station of the city, after the inspection of the technicians, was declared unfit for use. From subsequent investigations of the structure, it proved to be seismically inadequate and it was decided for its demolition and reconstruction with a significant planimetric redeployment. In the initial phase of the work, it was carried out a study of the layout plans and of the loads imposed on the floors. As a result of this investigation, it was decided to propose, as a structural solution for the fire headquarter complex, a framed steel structure. The structure has been analyzed using a finite element software with both linear and non-linear analysis. The possible structural solution is achieved in accordance with the Eurocodes and, only with respect to the base isolated building, according to the Italian standard called "Nuove Norme Tecniche delle Costruzioni". To meet the structural verifications required by design standards for the main building of the complex, it was necessary to adopt a base isolation system. Among the various solutions analyzed, the best was found to be that composed of elastomeric isolators and multidirectional support. It was considered appropriate to use a fixed base for the other two structures of the complex.

Keywords: critical building, metal structure, FEM analysis, base isolation, earthquake resistant buildings.

INTRODUCTION

Inside the seismic sequence that struck the city of L'Aquila in 2009, the main shock occurred on April 6 at 01:32:39 GMT, had a magnitude of Mw = 6.3 (Harvard CMT) and is found to be generated by a fault with NW-SE trend. The quake was recorded by 55 stations of the National Strong Motion Network, RAN. The East-West components of the time series acceleration 4 stations at a maximum distance of 6 km from the epicenter show peaks greater than 0.5 g (Ameri, 2009). The data recorded by the RAN network were available and it was evaluated the effect acceleration time histories on the maximum of different elastic oscillators answer period, thus obtaining the spectra response and highlighting so indirectly by the content in this frequency in the data registered (Ameri, 2009) and (Chioccarelli, 2009). The entire area was already the subject of seismic phenomena of similar or greater extent, still well above the damage threshold. Particular similarity is found, to the affected areas and the severity of the damage, with the event on February 2, 1703, as attested by historical sources (Antinori, 1703)

Structures were analyzed, using a finite element software, both with linear and non-linear analysis. Linear analyzes are: modal analysis and response spectrum analysis; the non-linear analysis performed are: Pushover analysis and nonlinear dynamic analyzes.

Finally, making necessary the introduction of an isolation system, were compared the results relating to the use of three different solutions: elastomeric isolators and multidirectional bearings, sliding bearings on the curved surface and a hybrid system made by laminating elastomeric isolators and sliding supports of curved surface.

DESCRIPTION OF THE FIRE STATION COMPLEX

The provincial command of the Fire Brigade of L'Aquila is located in the eastern part of the city and, specifically, in Via della Pescara. The complex consists of two components, the first, which dates back to the early 60s and the second has been built since 2001. The entire complex is made with the technology of reinforced concrete.

The complex object of studies, the most recently realization, is constituted by two buildings and a tower for practice, separated by seismic joints to prevent the collision and allowing to consider them as dynamically independent units, as shown in Figure 1.

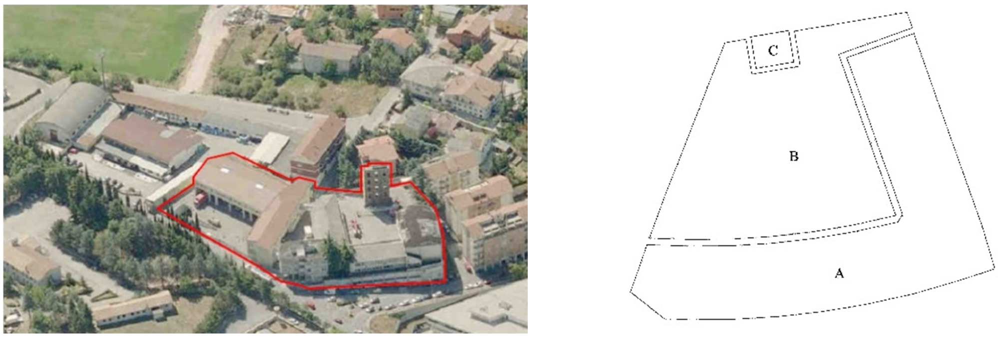


Fig. 1 - Aerial view and plan diagram of the complex object of the intervention (A-Building; B-Square; C-Tower) from (Provveditorato interregionale,2012)

What follows is a brief description of the factory buildings.

The construction identified as "Building" consists of 4 floors, with varying heights and a cover on two distinct levels. The first level is partially buried. The plan of the building has an L-shape in which, the main left wing dimensions are approximately 14.5 m to 48 m for a total area of about 2700 m^2 and is equipped with a stairwell with a lift for vertical connection while those of the right side are approximately 14.5 m to 45 m for a total surface of approximately 2600 m^2 and is equipped with two compartments scale for the vertical connection, only one with elevator. The construction, in the basement, will be used as space for physical activities train and local intended for archives and stores, will host the thermal plant and a ramp for vehicle access to the part below the road level. The ground floor will house, in addition to the main entrance in the left wing, a throw of the media on both sides. The third level will house the offices open to the public in the left wing and laboratories in the right wing. The top floor will be used as offices for the left side, while the right side, in addition to accommodation of the commandant service, will be destined to the teaching premises. The building in addition to presenting an irregular distribution of masses in height, for different functions to which they are destined the floors, on the left side has a semi-circular planimetric dislocation configuration in seismic area presents critical issues. Plan, also the distribution of the masses is uneven, especially at the level of the ground floor, having the same plane different functions.

The body of the building identified as "Square" consists of a single level and is completely below the road level. The main dimensions are approximately 34 m to 36 m for a total area of approximately 1200 m^2 and it is not equipped with stairwells for vertical connection. The structure above the foundation plane will have the deposit feature and garage while the roof will be destined to the square for the movement of vehicles and training activities. The building has a regular distribution of the loads being destined to a single function but is not regular in plan in that, the difference between the area enclosed by the perimeter of the plan and that of a convex polygonal line that encloses the same plane is greater than the 5%.

The body of the building identified as "Tower" consists of five floors of equal height. The first level is underground. The main dimensions of the building are approximately 6 m to 7 m, for a total of about 210 m^2 and is equipped with an internal staircase. The building is fully used for training activities. The construction is regular both in height and in plan.

FINITE ELEMENT MODEL

The finite element analysis was carried out using the structural analysis program SAP2000 V.14.0.0 software. In modeling the component structures (A-B-C) by the models represented in Figure 2, it was possible to consider them as dynamically independent units.

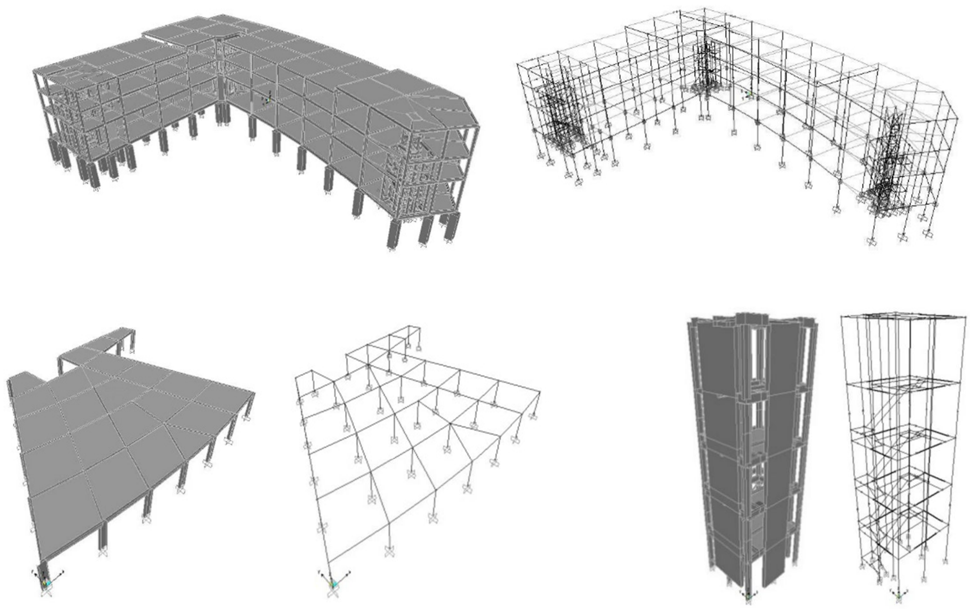


Fig. 2 - Physical and analytical model of Building (A), Square (B) and Tower (C), respectively

Each model has been developed with the blueprints available. The axes of the elements have been made coincide with the centers of gravity of the pillars to the massively of foundations, going to accomplish each of the model of the plant floor. This was left unchanged for each floor not being present the eccentricity caused by the change of section of the pillars in the passage from one level to another. From section, identified the interfloor heights as the height between the center of gravity of two consecutive slabs, is realized the three-dimensional model. Finally to match, as much as possible, the main directions of the building with the global coordinates X - Y of the software, they are rotated independent of the models angles from each other. Only for the building called "Square" is have made three different rotations to go to analyze the three main directions along which they are arranged the resistant elements and the corresponding orthogonal directions. For all three configurations it has been maintained the arrangement of the pillars described in (Scagnetti, 2015) that goes to optimize the dynamic behavior of the body of the building.

The modeling is based on using one-dimensional finite element already present in the library of software. Both for the beams to the pillars and the walls, is are used elements "frame", finite element two-beam type of nodes where the deformability is also considered to cutting, having a section equal to that of the actual elements. In general, it tried to reduce the computational burden by not using "shells" elements while maintaining a good accuracy of the solution.

The floors, as it may be considered infinitely rigid in their plan, were modeled as crushproof plates in the horizontal plane. This assumption was made binding each plan node with a "diaphragm" type constraint. For the roof, being on two levels, these are made of four distinct constraints, one for each part, so that we then anchor the "master node" defined below. As for the cross-behavior, being slightly disruptive to the assessment of the effects of seismic actions, this has not been modeled.

The staircase, although with a not high contribution, helps to stiffen the structure and is chosen to take this into account. The modeling was carried out with two elements "frame", which connect the slabs to the landings, reflecting its geometry.

The slab loads, structural and permanent carried, were applied to the model by "shells" elements with zero thickness as distributed loads unidirectional, using the option "uniform to frame, one way", where the direction of application one coincides with the direction of the "shell", because it is seen that, for this type of use does not increase the computational burden. Even the accidental loads were applied with the same procedure. The wind and staircase load, with its more accidental structural and carried permanent, are applied as linear loads directly on the elements, distributing them through the method areas of influence of the respective beams.

In the modeling of the walls with "frames" elements, to respect the maintenance hypothesis the cross section plane, you have used the "end offset" option present in SAP2000 going to be an infinitely rigid section. This option has proved performant because, in addition to a lower computational burden which results in a shorter time of calculation, was closer to the behavior you want to model remaining straight. Additionally, the software having the ability to automatically vary the length of this portion based on the overlap between the elements corresponding to the wall and the beam, is shall not define, for each variation of the length of the wall, of the new nodes, to specify the length of the suddenly you want to keep is rigid, thus proving a very versatile procedure.

The mass of the elements "frame", once assigned the characteristics of the material and geometric properties of the elements, is calculated automatically by the software which, in addition, through the "from load" option, derive the mass of the floor directly by the loads that will they are applied.

In the analysis to consider it the accidental eccentricity as required by code has focused the entire seismic mass of each floor, constituted by permanent and accidental loads weighing on the floor and including that related to the upper and lower halves of the pillars, in a node master, a node located in the geometrical center of gravity of the plane and eliminating the mass of the elements. Subsequently, through the construction of four additional models if they have changed the position of the amount provided by the standard in order to be considered accidental eccentricity of the loads.

In the linear analysis of the isolation devices, both as concern the elastomeric isolators that the sliding bearings on the curved surface, were modeled as linear elements, resorting to the characteristics of stiffness and equivalent damping while in the vertical direction, have been impeded displacements, blocking the translation. The multidirectional supports were modeled as elements with horizontal equivalent stiffness and equivalent damping null and prevented vertical translation. In the analysis of non-linear, the hysteresis loop of elastomeric devices has been approximated by a bilinear curve with appropriate parameters, as shown in Figure 3.

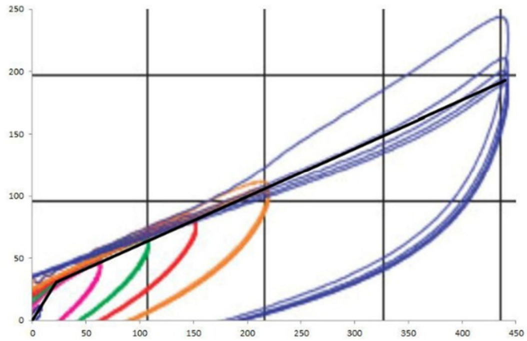
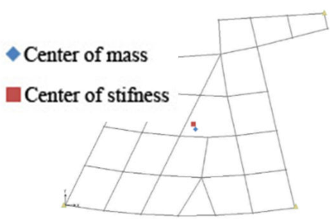


Fig. 3 - Approximation of the hysteresis loop of elastomeric isolators

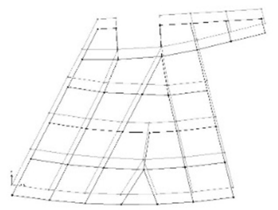
DESCRIPTION OF THE STRUCTURAL SOLUTION

Square Structure

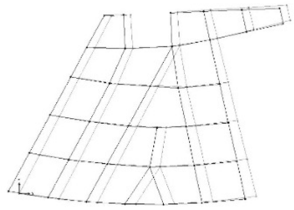
For this construction, the design process for reaching the final structural solution is started whereas a steel frame and orienting the axis of greatest inertia of the pillars before along X and along Y Failing to obtain a satisfactory dynamic behavior, for the ' eccentricity between the center of the masses and the center of stiffness, it proceeded to direct only a part of the pillars along X and the remaining long Y. In so doing, thanks to the containment of the eccentricity shown in Figure 4.a, there was obtained a good dynamic behavior, as shown in Figures 4(b) - 4(d).



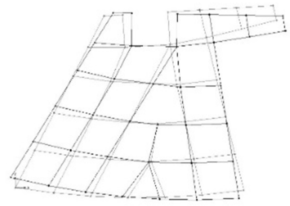
(a) Eccentricity of the Square



(b) Mode 1, T_1=0.191 s



(c) Mode 2, T_2=0.154 s



(d) Mode 3, T_3=0.134 s

Fig. 4 - Eccentricity of the Square structure and its mode shapes

In fact, the first mode of vibration is of a purely translational along the Y direction, the second way is also purely translational, but along X, while the third mode of vibration is of a purely rotational type, going to excite with only 3 modes, 100% of the mass, as shown in Table 1.

Table 1 - Participants masses of the Square of the first configuration analyzed

Mode	Period	UX	UY	UZ	SUX	SUY	SUZ
1	0,191225	0,00113	0,99853	5,749E-09	0,00113	0,99853	5,749E-09
2	0,153977	0,96487	0,00133	2,901E-10	0,96599	0,99985	6,039E-09
3	0,133531	0,034	0,00014	2,09E-10	1	1	6,248E-09

For the Square, since the results of the other two analyzed configurations are similar to those shown, the final solution is made up of a frame system, made with beams and pillars in steel and a mixed steel-concrete slab. This proposal can satisfy the checks and used sections are summarized in Table 4.

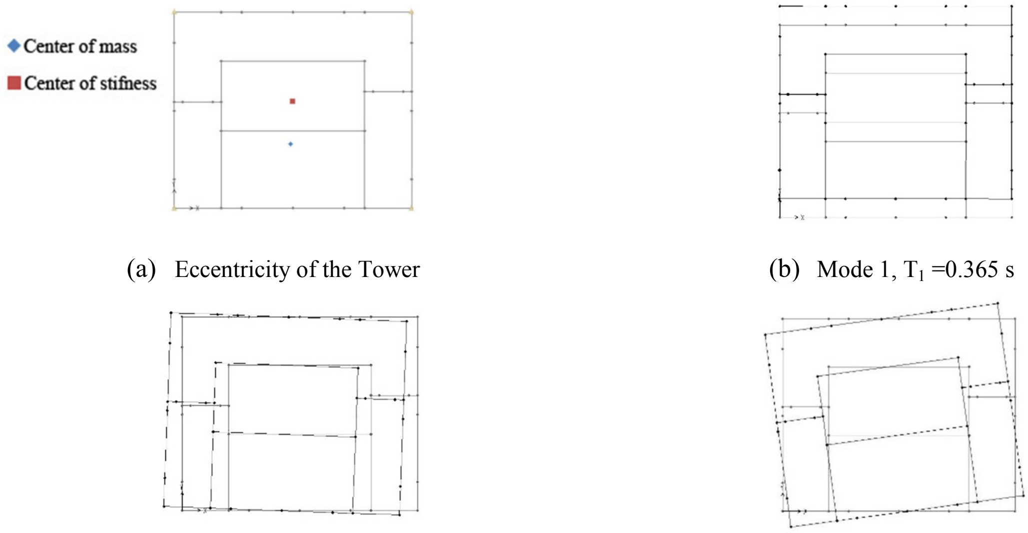
Tower Structure

The tower has the staircase and an opening in the floor places laterally that move the center of mass in the opposite direction, which is in the remaining part of the slab.

The iterative process to arrive at the final solution is started from the study of a steel frame, where, in order to contain the displacements, of braces have been inserted in the inner sides of the staircase body. The internal positioning instead of in front view, although not optimal, was dictated by the interference that was emerging with windows. The second phase saw halve the length of the braces in order to increase the critical load for buckling. Failing to obtain a good dynamic behavior of the structure and to satisfy the tests, the concrete walls are in place, the outer sides of the building. In doing so the eccentricity between the center of mass and center of rigidity was contained, obtaining a certain degree of symmetry and ensuring the satisfaction of the checks is to limit states that exercise over that a good dynamic behavior as shown in Figures 5(a) - 5(d). The first mode of vibration is, in fact, purely translational along Y, the second way is translational along X, with a negligible rotational component due to the low value of the participant and a third rotational mass way. For the asymmetry due to the disposition planimetric, to achieve the participating mass value provided by the standard, equal to 90%, 8 modes must be considered, however modest value compared to a same building made entirely of steel, as shown in Table 2.

Table 2 - Participants masses of the Tower

Mode	Period	UX	UY	UZ	SUX	SUY	SUZ
1	0,365281	0,00007432	0,70605	0,0000199	0,00007432	0,70605	0,0000199
2	0,342196	0,68813	0,00009113	2,283E-09	0,6882	0,70614	0,0000199
3	0,22566	0,05699	0,00000849	1,092E-07	0,74519	0,70615	0,00002001
4	0,097788	0,14264	0,00018	4,816E-09	0,88783	0,70633	0,00002002
5	0,092878	0,00017	0,18079	0,00012	0,888	0,88712	0,00014
6	0,065583	0,00934	0,00003645	0,000007775	0,89733	0,88716	0,00014
7	0,048729	0,04959	1,413E-07	0,000002425	0,94693	0,88716	0,00015
8	0,042801	2,623E-07	0,06094	0,00514	0,94693	0,94809	0,00528



(a) Eccentricity of the Tower
(b) Mode 1, T_1 =0.365 s
(c) Mode 2, T_2=0.342 s
(d) Mode 3, T_3=0.226 s

Fig. 5 - Eccentricity of the Tower structure and its mode shapes

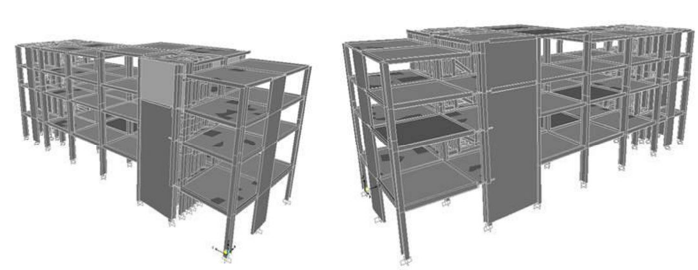
For the tower, the final solution is constituted by a large walls weakly armed in the X direction and a dual structure in Y direction system, made with reinforced concrete walls, steel beams and pillars and a mixed steel-concrete slab. This proposal can satisfy the checks and used sections are summarized in Table 5.

BUILDING

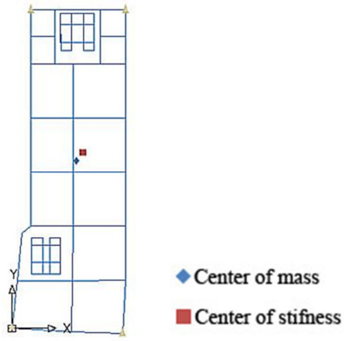
Reaching the final configuration for the building has passed through many phases. Initially this building has been thought to fixed base and with the two sides of the "L" separated by a seismic joint, so as to avoid the concentration of stresses in the inner part of the angle.

The first structure of the building, the right wing of the "L" which we call here "Building 2", has a regular plan, but the two staircases are not aligned, going to generate an eccentricity between the center of stiffness and the center of the masses which makes the torsion sensible building. To limit this effect, as well as to contain the displacements, of the braces in the staircase bodies they have been inserted. For the presence of openings for the passage of the vehicle, the braces cannot be established along the sides, a solution that would maximize its effectiveness. However, the resulting sections of the latter are too large going to interfere with the side elements of the ladder. It is appeal then, in the reinforced concrete walls, arranged in a suitable position as shown in Fig. 6(a), thus managing to reduce the aforesaid eccentricity, as shown in Figure 6(b), but failing to satisfy the verification at the ultimate limit state with no commercial profile.

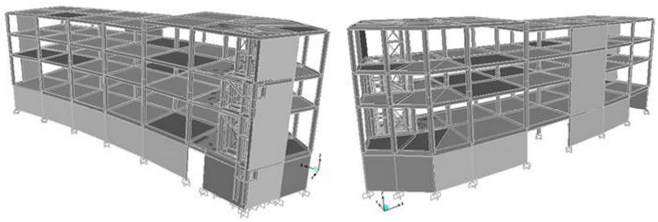
The second part, the left wing, which we will call "Building 1," has a semicircular planimetric dislocation, which even if of very large radius do not make it particularly effective to withstand seismic actions. In addition, this building has only one stairway which is located laterally, resulting in a significant eccentricities. In this case, besides the presence of the openings at the level of the ground floor, there are also the balconies on the upper floors which constitute a further restriction. The reduction in this value was first sought by inserting the steel braces and then are inserted perimeter of the septa in reinforced concrete to the level below the road surface, together with the walls, always in reinforced concrete, in a suitable position as shown in Figure 6(c). The resulting effect is shown in Figure 6(d), but even in this case it is not found a commercial profile that meets the verifications at the limit state considered.



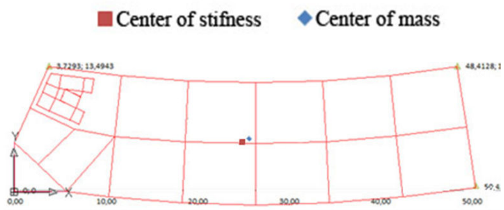
(a) Disposition of the walls in Building 2



(b) Eccentricity of Building 2



(c) Disposition of the walls in Building 1



(d) Eccentricity of Building 1

Fig. 6 - Disposition of the Walls I Building and its eccentricities

As just said, it was decided to isolate both buildings, still keeping them separate, and placing the insulation level below the ground floor slab. We have chosen this position, not to create differences in height between the Square and the floor of the buildings and be able to allow the exit of the vehicles while you is not isolated to the above, that is, at the base of the first level of the pillars, as it goes left free space around each pillar to enable its swing unhindered. This solution, in addition to not optimize the use of the internal space, would expose the isolators to chemicals such as gasoline or other, compatible with the function of the garage, which may deteriorate their properties.

For the development of this solution, the main limitations were the ones to avoid the collision between the various parts of the building, having the buildings at a distance so that you can use a commercial joint cover and meet the ultimate limit state checks, by reducing stress guaranteed by the insulation system.

The first devices used were elastomeric the isolators HDRB. With these devices could not satisfy all the above conditions simultaneously, so it turned to elastomeric devices with lead core LRB (FIP S03, 2013) in which, relying on a greater dissipation of energy, we have tried to meet various restrictions. Even in this case he could satisfy only one condition at a time, for which, the fixed distance of the buildings according to the joint cover, or the insulation system had a stiffness such that they avoided or the collision but were not met the checks envisaged from the norm or vice versa. This has led to think the two buildings as a single building block, maintaining the same position of the insulation system of separate buildings.

The decoupling of the dynamic behavior of the substructure and overstructure of Building was analyzed by three different isolation strategies. In the first has been considered a system composed of elastomeric isolators for high damping HDRB and sliding supports multidirectional, in the second state is evaluated a system solely composed of curved surface in sliding isolators with a low friction coefficient, also said "Friction Pendulum" and in the third a hybrid system consisting of elastomeric isolators and "Friction Pendulum".

In the first seismic protection strategy, the insulation system consists of 33 elastomeric isolators FIP of SI 1000/140 N-type (FIP S02, 2012) and 17 FIP supports multi-VM 1300/100/50 type (FIP B01, 2013). To contain the eccentricity in plan between the center of masses of the superstructure and the center of rigidity of the insulation system, the elastomeric isolators are arranged in the plant as shown in Figure 7 while, in correspondence of the remaining pillars, have positioned the multidirectional bearings. This configuration is reached initially by placing insulators perimeter position, for centrifuging the more the rigidity and then varying it possible to obtain the optimum arrangement. In this way it is obtained a distance between the two centers of 0.10 m along the X axis and 0.09 m along the Y axis from the values given are contained torsional effects, as required by the standard and get Eigen modes translational, as shown in the modal analysis results in Figures 8(a)-8(c), and reaching almost the totality of the participating mass with only 3 mode, as shown in Table 3.

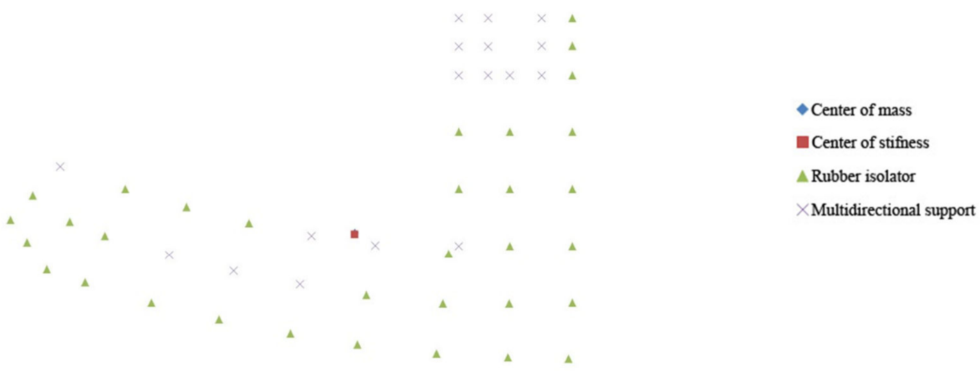
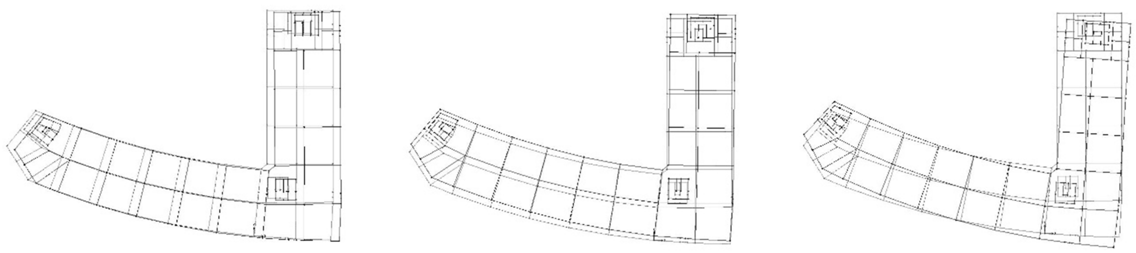


Fig. 7 - Position of elastomeric isolators and multidirectional bearings

Table 3 - Participants masses of the Building

Mode	Period	UX	UY	RZ	SUX	SUY	SRZ
1	1,196254	0,90983	0,0732	0,15108	0,90983	0,0732	0,15108
2	1,18765	0,07855	0,83128	0,4433	0,98838	0,90448	0,59438
3	1,045283	0,00012	0,08663	0,39491	0,9885	0,99111	0,98929

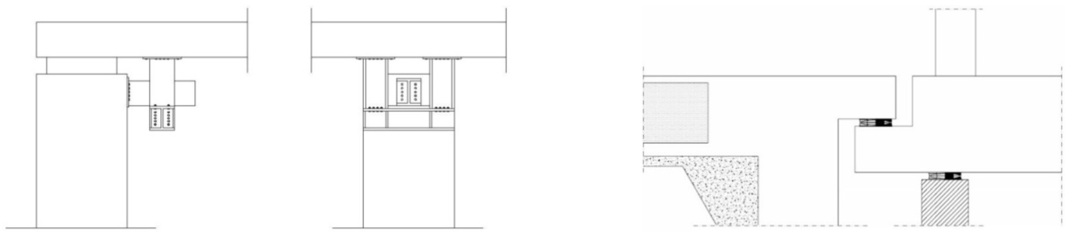


(a) Mode 1, T_1=1.19 s (b) Mode 2, T_2=1.18 s (c) Mode 3, T_3=1.04 s

Fig. 8 - Eccentricity of the Building structure and its mode shapes

In use of the friction pendulum, for the own characteristics of the devices do not have the above-mentioned eccentricity, so these were disposed in correspondence of all the pillars, then going to employ devices 50 of the type FIP_D L 1650/500 (3100) (FIP S04, 2013), where the letter "D" indicates that the devices are double curvature.

In both systems, the devices are subject to traction but, only for the system composed of elastomeric isolators this can be absorbed by the anti-lifting devices connected to the columns and the concrete slab. Between the two parts of the device it is allowed the relative sliding in the horizontal direction while, in the vertical direction, absorb the traction and, therefore, acts as a constraint, as shown in Figure 9(a). For the insulation system consists of the sliding devices on curved surface these devices are not feasible given the presence of the vertical displacements. An alternative solution consists of systems, integral with the ground, to put to contrast and which are interposed between more devices, as shown in Figure 9(b). The solution, from a theoretical point of view, it is advantageous in that it allows to insert additional friction isolators that would allow an increase of the energy dissipation in the input, but, in this case, it is not adoptable as the side where there is the Square, to realize the contrast system would be to close the access of the vehicles below the Square, making it incompatible with the intended function garage.



(a) Anti-lifting device

(b) Example of contrast structure for Friction pendulum subject to traction

Fig. 9 - Eccentricity of the Building structure and its mode shapes

Finally, as isolation strategy, it is also evaluated the possibility of using a hybrid system composed by elastomeric isolators and "friction pendulum", which would replace the multidirectional supports. The coupling portion advantage is due to the fact that, thanks to the "Friction Pendulum", it has a greater dissipation of energy which consequently gives rise both to minor displacements, so that those absolute interfloor those, which at a lower level of stresses, both at the level of the superstructure that of the substructure. Another advantage is given by the fact that, the "Friction Pendulum", do not change the position of the center of stiffness of the isolation system. The system, although in theory it is very advantageous, for this specific case, it is not possible to use, as such, not being able to vary the position of elastomeric isolators for maintaining the good dynamic behavior, you have the possibility to only take five isolators sliding on the curved surface, resulting in the other subject to traction. In addition these devices, as mentioned previously, are incompatible with the anti-lifting devices designed to absorb the traction agent of elastomeric isolators.

For the building, the final solution is constituted by an isolated structure with a superstructure consisting of a frame system, composed by steel beams and pillars and a substructure made up of reinforced concrete pillars. The attic floor above the insulation is realized by means of a concrete slab while the remaining are provided mixed steel-concrete floors. This proposal can satisfy all the checks required and used sections are summarized in Table 4.

CONCLUSIONS

The Aquila's Fire Station complex presents an excellent dynamic behavior of the various units.

All used devices are available in the FIP Industriale commercial catalog. The devices were chosen for only one manufacturer as they are able to meet all the necessary requirements to avoid having to create ad hoc devices and, in a possible realization, it should perform a smaller number of acceptance tests, as required by standard, going, in both cases, to contain costs.

In the choice of the stiffness of the isolators it has been sought a solution by balancing the containment of the stresses in the superstructure obtained by increasing the oscillation period and the maintenance of the displacements within limits which exclude the collision with the square.

The Pushover analyzes were made only for fixed-base buildings to get confirmation that, for the design seismic action, do not develop plastic hinges in no element as well as the nonlinear dynamic analyzes. The latter, also carried out for the building based isolated with elastomeric isolators and sliding bearings, allow a more refined modeling of elastomeric isolators going to approximate the hysteresis loop of elastomeric devices with a bilinear curve of which are suitably selected parameters.

The adopted sections are summarized in Table 4.

Table 4 - Summary of used sections

Building	Floor	Element	Material	Section	Class
Square	Only one	Frame	Steel S275	IPE O 550	1
	Only one	Pillar	Steel S275	HL 920 x 784	1
Tower	All	Frame	Steel S275	IPE 600	1
	All	Pillar	Steel S275	HE 600 M	1
	All	Wall dir. X	Concrete C32/40	4,0 x 0,35 m	/
	All	Wall dir. Y	Concrete C32/40	3,0 x 0,35 m	/
Main Building	Basement	Pillar	Concrete C32/40	1,3 x 1,3 m	/
	Ground floor	Frame	Steel S275	IPE 500	1
	Ground floor	Pillar	Steel S275	HD 400 x 347	1
	First floor	Frame	Steel S275	IPE 450	1
	First floor	Pillar	Steel S275	HD 400 x 347	1
	Second floor	Frame	Steel S275	IPE 400	1
	Second floor	Pillar	Steel S275	HD 400 x 347	1

At the end of the design process, all the elements that make up the complex structures remain in the elastic as required by code and all the checks carried out have been satisfied. Therefore, as a structural solution, consistent with the classification recommended by the standard, the following structural types may be deemed appropriate:

- for the Tower, a mixed structure, consisting of reinforced concrete walls and steel frames;
- for the Square, a steel frame structure, it consists of beams and pillars in steel;

- for the building, an isolated structure, with an insulation system consisting of elastomeric isolators and sliding bearings located at the top of the pillars in reinforced concrete of the substructure and a superstructure consists of a steel frame;

The section of the pillars of reinforced concrete substructure is generous and highly reinforced. This is due both to the need of the elements to remain in the elastic range, and to the fact that, to limit the displacements of the superstructure and have no collision with the Square, the stiffness of the devices is relatively high, being only sufficient to reduce the forces in the superstructure but not to completely decouple the superstructure from the substructure.

For the other elements of the complex it was not considered necessary for the introduction of an isolation system and the checks have been satisfied with commercial profiles. In addition to the Piazzale they would have two additional disadvantages: an increase in costs linked to the insulators, as it would be to isolate only a slab, being constituted by a single plane and would have problems of availability of the joint covers, making necessary an enlargement of the seismic coupling between the Building and the Square.

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