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ARCHITECTURAL AND STRUCTURAL CONFIGURATIONS OF BUILDINGS WITH INNOVATIVE ASEISMIC SYSTEMS

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SUMMARY

A research is being currently carried out aimed at pointing out the most appropriate structural configurations, taking into account the innovative seismic protection systems, and to develop a methodology for building's seismic design based on the study of the main factors, both architectural and structural, which influence the seismic response of buildings. The research is structured in four phases: data collection, requirements definition, performance analysis, summary of results. The goal consists of an organic list of structural solutions allowing for the optimum articulation of architectural morphologies aiming at seismic protection; suitably outlined examples of typical architectural configurations including their most significant seismic performances; optimum classification of innovative seismic protection systems for the defined morphological classes. Considerations and results obtained from the first steps of the research development are commented and a sample design is presented.

INTRODUCTION

New globally oriented design methods and construction techniques have been devised in recent years to improve the seismic safety of buildings. In particular, it is now well acknowledged that seismic design must consider the system ability to dissipate energy and the effects of the lateral deformation on the response of the entire building.

Two fundamental principles regarding the characteristics buildings and their resistance to seismic events has been recognized and pointed out by Latina [1] for masonry buildings. The first is the morphological and constructive regularity, with homogeneous and uninterrupted passageways, which are capable of directing and opportunely involving the actions induced by the earthquake. The second consists of the correct use of materials, which can make the walls adequately resistant to the solicitations produced by the horizontal actions of the building. These design criteria, singularly present or synergistically coexisting, are the main reason that many ancient buildings are still standing and continue to be the two fundamental principles for the sound design and construction of buildings with bearing walls in seismic areas. Studies on the effects produced by numerous earthquakes have confirmed how much of the damage and subsequent building collapses can be attributed to a structure’s irregular configuration and morphology.

This can be considered as the result of the current design practice in which the architectural design comes before the structure: in fact, the architectural conception (intended as the definition of the formal,

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aesthetic and layout aspects), inexorably conditions the configuration of the seismic resistant structural system. In fact the structural dimensioning of an already defined morphological system results in it being a less trustworthy system, leading to a structure that is more vulnerable to seismic damage. The problem involves the existing relationship between architectural and structural design (Parducci [2]).
The concept of anti-seismic architectural morphology responds to the definition given by Arnold [3], meaning a morphology that includes not only the form and the dimensions of the building but also the nature, the "regularity", and most importantly the articulation of its structural and non-structural elements (characteristics such as quantity and layout). The term "regularity" does not mean symmetric and repetitive solutions bound by a strict regimen of rules, but the search for solutions suitable to a building's seismic behaviors that are in harmony with technological innovations.
The above listed considerations involve both the morphological and structural configurations of buildings, but so far they have not significantly influenced the fundamental concepts guiding the architectural design and in current practice one cannot substantiate the existence – and correct application – of clear guidelines of seismic architecture. This lack becomes even more pronounced when new conceptions of structural design and the related innovative techniques are adopted. The aspects regarding the morphological design and the definition of the structural configuration must be studied in depth, in order to establish a hierarchic definition of the most appropriate seismic configurations.
A research is currently carried out at the University of Perugia, involving both architects and structural engineers, devoted to analyze the relation between architectural morphology, structural configuration and seismic behavior of buildings equipped with innovative aseismic systems. The purpose is to outline the criteria that can lead the architectural conception and the selection of even complex forms, to achieve a suitable seismic behavior. The basic idea is that some essential characteristics, like volumetric irregularity, non-homogeneous materials, lack of symmetry, alignment, recurrent shape, usually considered non appropriate, on the contrary have to be suitably used to achieve damping effects and energy dissipation. Particularly, the application of innovative seismic protection systems, as base isolating and energy dissipating devices, is examined in order to outline new architectural morphologies.

BUILDING MORPHOLOGY AND SEISMIC PERFORMANCES

Dimensions

Since the beginning of the study of the building behavior under seismic attacks, the shape has been recognized as a fundamental parameter in controlling their response. At a first stage the attention was focused on the global dimensions of the buildings, so we find limitations on building dimensions in the first prescriptions regarding the constructions in earthquake prone zones. In Italy, on 1909 - about one century ago, after the destructive earthquake of Messina on 1908 - the first Italian seismic guideline [4] was drawn up. The guideline contained general qualitative, not quantitative, provisions, but focused the attention on three aspects that are still nowadays recognized as fundamental: the influence of the soil, the importance of the construction details, the dimensions of the buildings. Strong limitations were provided on building height (10 meters or two levels, just one for stone buildings): exceptions could be allowed but not for buildings having special occupancy involving higher risk (schools, barracks, hospitals, hotels). Limitations were fair if considering the seismic resistant construction systems used at the time, consisting of masonry walls. Afterwards, when new materials allowed greater and greater strength level, both in compression and in tension, it has been recognized that the height is not, in itself, a negative factor for the seismic response (Arnold [3]). In fact, a greater height can increase the natural period of the building, shifting it in the range where the response amplification is lower. On the contrary, the ratio height/wideness, that is a shape factor, has to be controlled because it influences the overturning of the building and the axial overloading of the external structural elements.

Shape

Building shape is important because it has a decisive influence on the dynamic behavior (inverse pendulum, soft story, torsion effects) and on the stress concentration (variations of vertical and horizontal shape). The geometric parameters qualifying the building shape, commonly referred as influence parameters of the seismic behavior, are the vertical and plan regularity, the symmetry and the compactness. All these aspects are acknowledged by the major codes that provide design criteria penalizing buildings not having regular and compact shape. Penalization can consist of more stringent and detailed evaluation of the response or of a reduction of the allowed ductility factor for taking into account the reduced dissipative capacity.

The global shape irregularity can be a negative factor in itself, but, most of all, because it affects the structural system. Irregularities in the seismic resistant system are determinant in reducing the good performance under seismic attack and are the factors especially controlled by seismic codes. For example, SEAOC [5] provides for both vertical and plan irregularities. Vertical irregularities do not only consist of irregular vertical geometry (30% variation of the horizontal dimension at any story), but also of irregularities of the structural system: stiffness discontinuity (soft story), weight irregularity, discontinuity of vertical lateral force resisting elements, strength discontinuity (weak story). Also plan irregularities consist of both geometric (reentrant corners, diaphragm discontinuity) and structural irregularities (torsional effects, vertical lateral load-resisting elements discontinuous or not parallel to or symmetric about the major axes). Also compactness is sometimes controlled, for example by Eurocode 8 [6] when providing to compare the inertia radius of the mass and stiffness.

Regularity

As a consequence of the above mentioned general criteria for earthquake resistant buildings, received by the advanced codes and guidelines, the suitable morphology has to be characterized by regularity. This essentially means that a symmetrical and compact shape should be the target when designing a seismic resistant building. The reasons for wishing regular buildings depend on the need of avoiding unpredictable stress concentration that can cause local collapses and modification of the dynamic behavior.

This is not generally true, in fact, if provisions are adopted for avoiding the dangerous local effects and if the distribution of the lateral force resisting elements fits the global shape and therefore the distribution of masses and inertia forces, the actual disturb given by the irregularity to the lateral response is limited. Analyses carried out by Faella [7, 8] on morphologically irregular structures, like structures having a L-shaped plan, that can be defined "irregular" according both to perceptive criteria and to irregularity rules provided by guidelines show that, if the diaphragms are rigid and the columns are distributed according to the shape, the irregularity is "apparent" and the disturb to the response induced by the irregularity consists of very slight torsional effects that can be accounted for at design stage. Moreover, regularity concepts have to be revised considering new aseismic systems, as it will be discussed in the following.

NEW ASEISMIC SYSTEMS AND THEIR INFLUENCE ON CONFIGURATION

Design philosophy

The current design philosophy of seismic resistant buildings provides for a resistance, to the forces induced by severe seismic attacks, relied to the capacity of the building to dissipate the energy furnished by the earthquake. This capacity is associated to plastic deformations that can develop in particular zones of the structural elements ("plastic hinges" in ductile frame systems) in a controlled way. The "capacity design" allows to design lateral load resisting systems controlling the sequence of the formation of the plastic hinges optimizing the energy dissipation and avoiding dangerous collapse mechanisms. In the last twenty years new philosophies - resumed in Skinner [9], Naeim [10], Constantinou [11], Soong [12] - based on the application of innovative systems, have been proposed for the seismic resistant structures. They allow for capacity levels larger than that resulting from conventional design methods up to grant to avoid any damages even in the case of the maximum credible earthquake (return period of 1000 or 2000 years) provided for the building. These systems can reduce the structural response thanks to different mechanisms: the reduction of the seismic input interesting the structure, the strong dissipation of the input energy, the active interaction with the motion of the building. Generally the systems are classified in passive, when they modify the dynamic parameter of the structure like mass, damping and stiffness, and active, when they supply energy to the structure.

Base isolation

Base isolation [9, 10] provides for setting up of special devices between the foundation and the elevation structure allowing for the relative displacements between the superstructure and the substructure. This controlled degree of freedom involves the uncoupling of the movement of the elevation that rigidly moves above the isolators. Several device types can be used: normal or high damping rubber devices, lead core rubber devices, friction devices, plastic devices. If using elastic devices, their stiffness can be suitably set for having a very high natural period of oscillation, in the frequency range of the lowest seismic energy. The friction and plastic devices limit the transmitted force, that is the base shear, to the value of the threshold defined by their sliding or plastic force.

Energy dissipation

Dissipative devices [11] are usually introduced in special bracing systems allowing the dissipation of energy associated to the displacements between two level of the buildings. Applications have been also proposed providing for dissipative devices located between two adjacent buildings or two sections of the same buildings and utilizing the relative displacement between the two bodies. Different devices have been developed, the most diffused are based on the flexural plasticization of ductile metal elements, sliding of friction surfaces, shear deformation of viscous-elastic rubber elements, axial displacement of fluid viscous dampers. Moreover, a number of particular devices have been implemented in both experimental and practical applications. The energy dissipation is related to the displacement, therefore these systems can perform at their best if the lateral deformations of the structure is relevant, as it happens in flexible structures, but compatible with their service performance.

Active and hybrid control of the dynamic response

Instead of passive systems, like base isolation and energy dissipation, which are not sensitive and cannot be regulated according to the instant response to the actual input, active or semi-active systems [12] can be used for reducing the structural response to dynamic inputs. Their principle consists of the application of one or more forces to the structure, having strategic location and suitable value, with the effect of counterbalancing the displacement induced by the excitation. Usually, not active, but hybrid systems are used in practice, because they are characterized by high efficiency of the control, low sensitivity to the site conditions, efficiency against different dynamic actions, and selectivity of the control target. They represent a middle path between active and passive systems, with the aim of optimizing advantages and disadvantages: like passive systems, they modify one or more of the structure parameters (mass, stiffness, damping) and, like active systems, they supply energy to the structure but requiring lower power.

Influence on configurations

Figure 1 shows three buildings in which the three methods for reducing the lateral response have been applied. Two main aspects have to be considered when the application of innovative seismic protection systems is hypothesized. The first consists of the optimization of both the device location and the structural and architectural configurations to attain the optimum performances of the building in terms of its seismic response. The second consists of the influence that the characteristics of the innovative protection systems determine on the architectural design from the stage of the conceptual design level to that of the detailing design. These aspects will be discussed in the following paragraphs.

PASSIVE PROTECTION AT CONCEPTUAL DESIGN STAGE

While the keywords of the conventional aseismic design are strength, stiffness, regularity, redundancy, new concepts are introduced by the application of the new systems for the seismic protection of the constructions. These concepts are resumed by the keywords discontinuity, motion, flexibility.

Figure 1. Buildings with innovative systems: Union House, Auckland (base isolated); Cal Fed Building, Sherman Oaks (friction damper braced); John Hancock Tower, Boston (hybrid control equipped)

Discontinuity

The insertion of devices within the construction requires the disconnection among two or more portions of the building that move, one with respect to another, when undergo a seismic attack. Typical samples are reported in figure 2. Base isolated buildings are characterized by a gap between the elevation and the foundation. A gap, equipped with devices, can separate two sections of the same buildings. The third model represents a proposal of Mezzi [13] for seismic isolated buildings where the suspended floors' pack is isolated from the central core. The last scheme of the same figure regards a solution of an architectural theme recognized as typical within a study carried out with the aims of identifying recurrent solutions adopted in current architectural design. It is characterized by horizontal and vertical paths irregularly distributed within a free space. The structural solution adopted consists of the suspension of the irregular structures that are laterally connected to the main structure by means of dissipative devices limiting the lateral force induced in the lateral force resistant system.

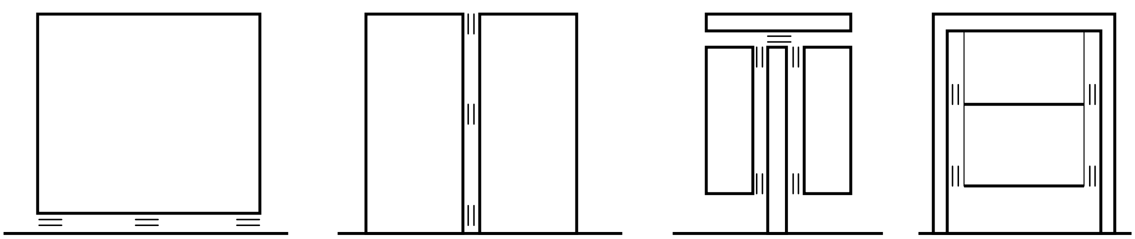

Figure 2. Discontinuity between building sections.

Motion

The strategies for reducing the seismic response using new protection systems are substantially based on the fundamental period shift or the energy dissipation (Mezzi [14]). In the first case, the shift of the period to values greater than 2 seconds involves large displacements. In the second case, for having a significant energy dissipation but limited forces, relevant displacement have to be provided. Therefore, while traditionally the constructions were conceived as very stiff bodies, practically rigid, the use of new devices suggests the idea of the motion, since portions of the structure have to move with respect to the ground or to other portions of the same structure, as represented in figure 3.

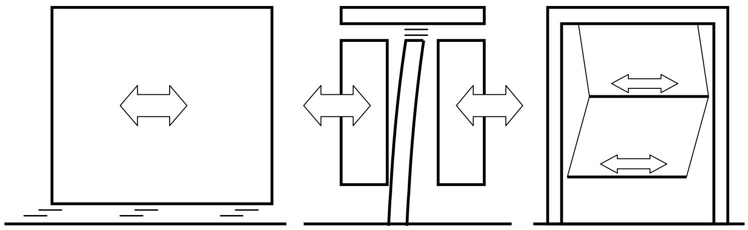

Figure 3. Movement of sections of the building.

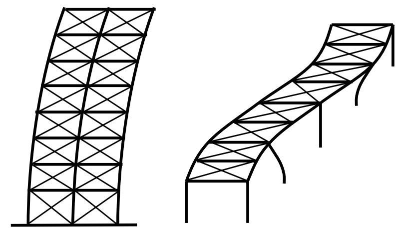

Figure 4. Flexibility of the building.

Flexibility

Alternatively to have practically rigid portions of the structure separated and movable, one with respect to another, the displacement required for the optimum performance of the protective systems can be found within the structure. Therefore a marked flexibility has to be pursued for structures internally equipped with dissipative devices (Figure 4). The device location can, and must, be suitably defined for avoiding the effects determined by morphological irregularities. The internal flexibility of the main structural system obviously involves also important technological aspects regarding the materials that can be used for structural and non structural elements and, most of all, the connection systems that have to grant the deformation compatibility.

OPTIMIZATION OF THE SEISMIC PERFORMANCE OF ISOLATED BUILDINGS

Some optimization analyses of the structural system of base isolated buildings have been carried out and some results, widely illustrated by Mezzi [15], are resumed in the following paragraphs.

Plan distribution of mass and stiffness

With the aim of identifying criteria for the optimum distribution of the elevation mass and isolator stiffness minimizing the torsional deformations, parametric analyses have been carried out on simplified schemes having circular and square plan shape. Models were characterized by the translational and rotational component of both the elevation mass and the isolation stiffness. Sensitivity analyses have been carried out varying the mass eccentricity ratio, e_r, from 0.01 to 0.20, and the ratio between torsional and translational period, ω_r, from 0.75 to 1.25, assuming alternatively the uniform distribution of masses or stiffness as a constant.

An increment of the isolator displacement, from 15%, when e_r tends to 0, to over 30%, when e_r tends to 0.20 is computed, when ω_r =1. Any not uniform mass distribution causes an amplification of the maximum displacement at low eccentricities. Models with concentrated mass (ω_r < 1) show rapid increments at low e_r values followed by flat thresholds with values between 40% and 45%. The models with centrifuged mass (ω_r > 1) show maximum increments of about 30% for eccentricity included between 0.02 and 0.10 followed by decreasing values. Therefore larger ω_r values can be useful if obtained by centrifuging the mass. If the mass is uniform, models with centrifuged stiffness (ω_r < 1) show slow increments of the torsion effect increasing the eccentricity for the lowest ω_r values (a 12% displacement increment at e_r =0.05 is computed when ω_r = 0.75) and the torsional effects are always lower than in the reference model if ω_r < 0.85. The maximum increment increases if concentrating the stiffness, except at the highest eccentricity values: in the range of $e_r \cong 0.07$ the models $\omega_r \cong 1$ are the best performing ones.

Referring to the base shear and torsional moment it can be observed that for small eccentricity (e_r = 0.01) shear tends to reduce of 30% while the moment tends to a threshold value. The trend is more and more smoothed as ω_r increases or decreases.

A sample building

The main building (Figure 5) of the Emergency Management Center of Central Italy in Foligno described by Mezzi [16], that is currently being built, represents a sample of optimum global configuration applied

to an actual isolated building. The criteria for optimum distribution of masses and stiffness have been applied. The building has a dome shape standing on 10 perimeter HDRB isolators ∅800 mm. R/c shells support the external ring of the first floor, having a diameter of 30 m. Ten radial r/c semi-arches start from the ring and sustain, at their top, a suspended prestressed cylindrical r/c core containing lift and stairs.
Floor slabs, joining the arches and the core, form a strong boxed structure. The building has the first two translation periods equal 2.1 s and the torsional period equal 1.6 s. It has been designed for the performance level of "integral protection" (all the structural elements remain below the ultimate limit strength without ductility request) with respect to the maximum quake expected at the site, having a return period of 950 years and PGA equal 0.35 g.

Figure 5. The isolated "dome building" of the Emergency Management Centre in Foligno (Italy)

Overturning effects

A fundamental issue of the structural configuration of isolated buildings is the definition of the shape ratio and minimum distribution of the stiff lateral-resistant systems within the global structural system. These two parameters allow to control the overturning moment provoking tensile vertical force in the isolating devices which generally are not allowed or strongly limited. Some sample structural systems, including different types of lateral force resistant systems, have been modeled for defining criteria of optimum configuration. The building are designed assuming the use of HDRB isolators with a percent damping equal 10%. All the models have been designed with a fundamental isolated period of 2 seconds. Response spectrum analyses have been carried out taking into account both horizontal and vertical components and the usual combination rules are assumed. The structural systems consists of lateral flexible frames (FF) alternated by lateral force resisting schemes (LFRS) consisting of plain r/c walls (W), dual systems (DS), complex framed system (CF), as schematically represented in figure 6.

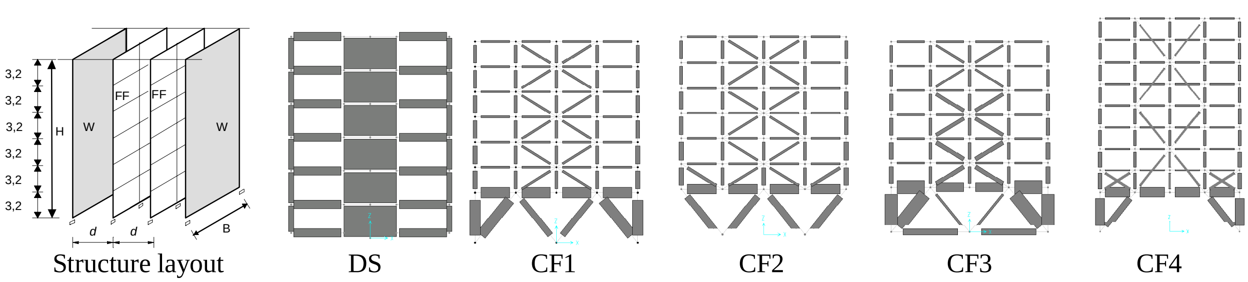

Figure 6. Structural layout and LFRS

Walls

The examined structural configurations differ in the number of FF, varying from 0 (no frames) to 3, included between two walls. Analyses have been carried out varying both the configuration and input characteristics: ratio between frame and wall lateral stiffness (0.05, 0.10, 0.15), number of floor (3-6), elastic response spectrum shape (A or B of Eurocode 8 [6]), PGA (0.35 g, 0.25 g). Some results are summarized in the diagrams of Figure 7. The minimum width/height ratios of the walls, allowing to avoid tension in the isolating devices located at the external side, have been computed. The characteristics of seismic input result to be the influence parameters: a width/height ratio 0.5 with one FF for each wall is allowed for PGA=0.35 g (high seismic zones) on medium soil B, but for a soil type A, two frames can be used for each wall and even three if the ratio becomes 0.6. Diagrams on the right allow to compute the maximum lateral to vertical load ratio when the wall shape ratio is assigned and then the distance between the walls, giving the corresponding value of masses as a function of the input intensity.

Dual systems

Analyses have been carried out assuming the same above mentioned values of parameters. Two structural solutions have been assumed for the dual system: the first provides for the stiffening of the beams at all the floors and the second for the strong stiffening of the only beams at the ground floor. The latter structural solution appears as the more efficient, in fact it allows a larger number of FF for each stiff dual system (i.e. 8 and 3 frames for PGA of 0.25 or 0.35 g, respectively, for a building of 4 stories). It has to be noted that the ground floor beams have to be very stiff, corresponding to a solid or strongly braced first level.

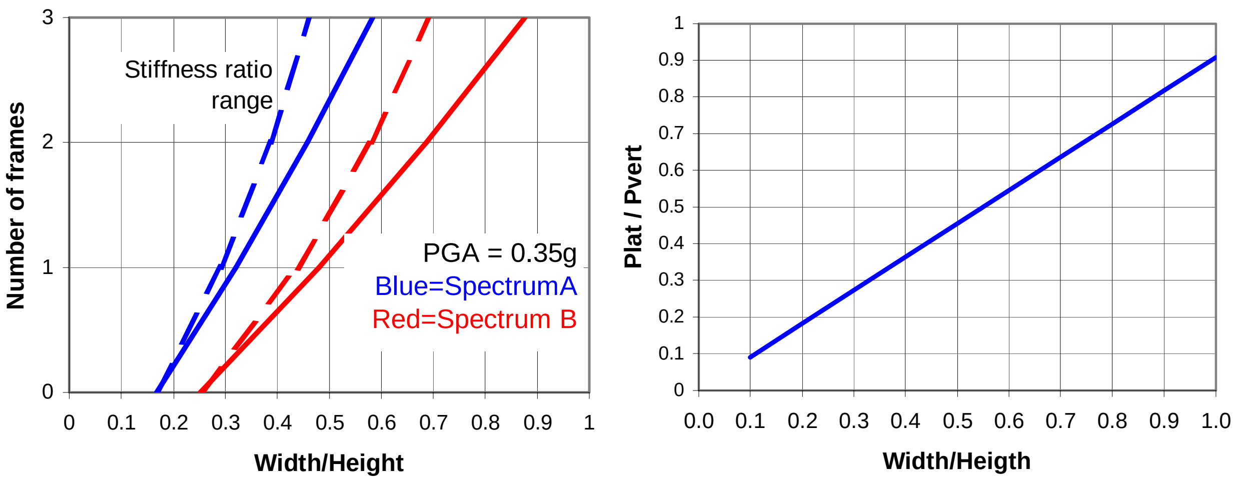

Figure 7. Number of frames (left) and lateral/vertical load ratio (right)

Complex framed systems

The third hypothesis of lateral load resisting systems consists of CF systems which configurations have the following aims: decreasing the number of isolating devices and increasing their compression force, positioning the isolators at the boundary of the building for reducing the axial force variation due to horizontal overturning forces, arranging the columns of the first floor to direct the compression forces from the vertical loads in those devices having the maximum overturning forces.

Configuration CF1, without ground floor beams, has to be used without any alternated FF and very stiff elements have to be used at the first level to limit the lateral deformations at the device level. Also configuration CF2 has to be used without FF. It reduces the number of bearings, but also their distance, therefore the favorable increase of the static vertical reaction is compensated by the reduction of their arm. Configuration CF3, with ground floor beams, is more efficient allowing two FF for each lateral-resistant system. Configuration CF4 allows one frame for each framed system. It offers large free spaces at the ground floor but requires very stiff vertical and horizontal elements at the first level to limit the lateral deformation of the supports. 3D Extension of the last solution is illustrated in Mezzi [15].

A SAMPLE DESIGN USING INNOVATIVE DEVICES

The urban renewal project illustrated is focused on the area outside the historical center of Massa Marittima, a town of Tuscany in Central Italy, that is a zone of low to moderate seismicity. The area, shown in figure 8, is currently not in use and in an increasingly dilapidated state. It is right below the cathedral of San Cerbone, which is a beautiful monumental complex dating back to the 12th century.

Figure 8. General view of the area where inserting the new construction

The design hypothesis is characterized by the following three main principles:

1) the improvement of public areas in Massa Martittima's historic center (through the creation of town squares and landscaped areas),
2) a strong integration between the building and the outdoor areas (both public and private);
3) the use of traditional materials and eco-conscious building techniques.

Some preliminary remarks are required in order to better understand the role the seismic isolation has had in the structural and architectural conception of the building. Undoubtedly, one of the fundamental criteria that the project had to respond to, was to be a "connector" with the existing in order to appear to be a great work of landscaping, similar to various outdoor areas in the historic center of Massa Marittima, as, for example, the Candeliere Tower. This approach determined the configuration of the building (figure 9) that is particularly sensitive to the graduations of the ground and, above all, to accommodate a series of pedestrian passageways in its interior (both horizontal and vertical) that, in going up, take on the shape of real retaining walls. This reasoning led to forms that are strongly organic in relation to the nature of the surroundings, thereby contributing to the maximum formal integration between the building and the articulation of the exterior spaces (figure 10).

Figure 9. Plan (left) and 3D aerial view (right) of the area

Figure 10. 3D views of the building, from the lowest (left) and highest level (right)

From a constructive point of view the building will be built and mounted using a dry building technique. The steel support structure, developed as a sort of balloon frame (with the beams placed at about 2 meters from each other) should allow for the creation of large spaces that are flexible and easily adaptable, both for the bank and the restaurant. Stone has been considered for the exterior finishes, similar both in cut and arrangement to the retaining wall of the gardens of the San Cerbone Cathedral. The stone finishes will be clamped to the support structure with an underlying structure that will allow for natural ventilation.
From a functional point of view, as can be seen by the sections in figure 11 and 12, the project provides for two parking levels, a building for public services (bank and restaurant) and a series of vertical and horizontal connections in order to distribute the pedestrian and automotive traffic in the historic center.
Considering the unique morphological configuration of the site and the need to have two different and independent structures (the parking "below" with its regular grid in pillars and reinforced concrete, and the building "above" with its completely independent structure, to be made with "dry" construction techniques), the designers immediately thought of using a system of seismic protection systems in order to "detach" the "below" from the "above".
Moreover, as it is shown by the transversal sections of figure 12 and the plan of figure 13, the building will be built adjacent to an anchored r.c. retaining wall that is already existing. With the aim of not influencing the stability of the wall, the new building has not to transfer relevant horizontal forces to it, then sliding supports will be installed as connections between the decks and the wall allowing the isolation of the new building and the control of the transmitted lateral forces.

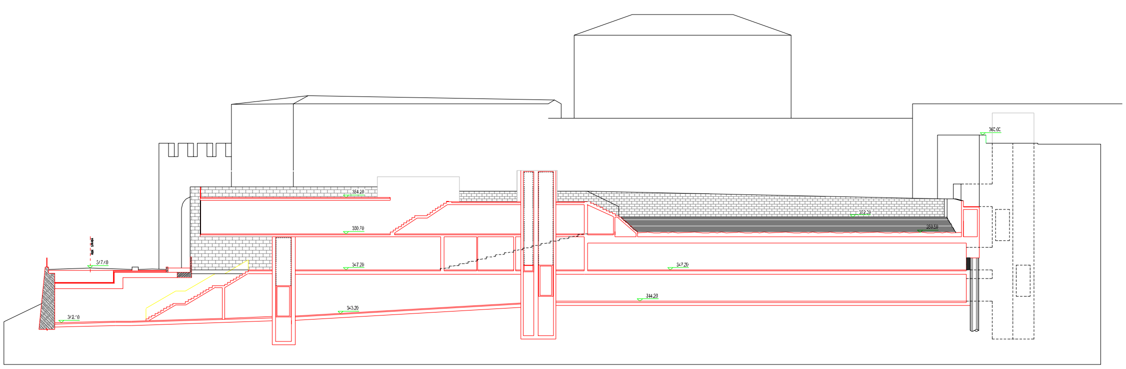

Figure 11. Longitudinal section of the building

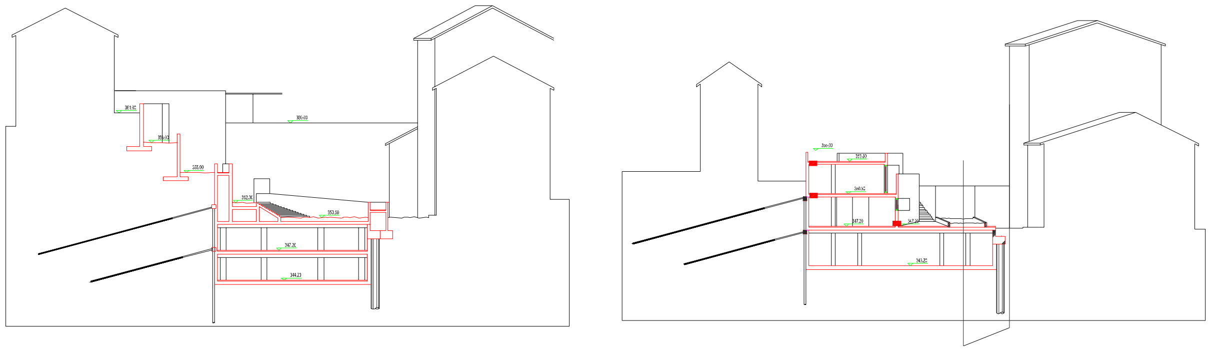

Figure 12. Transversal sections

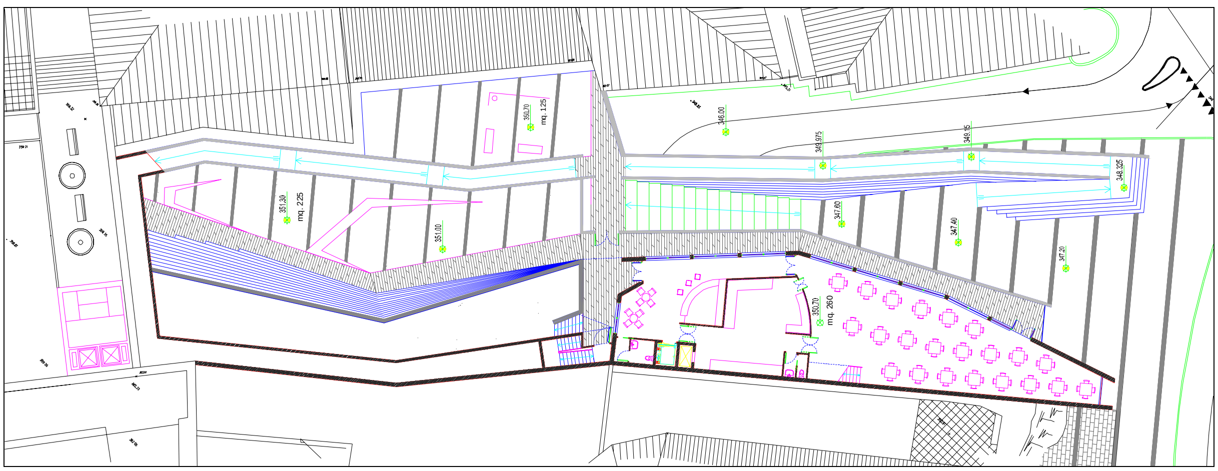

Figure 13. Plan of the upper level

In conclusion, the design hypothesis, even if still in the process of being studied from a technological point of view, is proof that a correct structural design must always be the result of the simultaneous contribution of both architectural and engineering components; or rather the architectural concept must, from the very start, respect the seismic design criteria regarding the morphological configuration in relation to its reaction under seismic conditions.

CONCLUDING REMARKS

Making reference to the research carried out by both structural engineer and architects with the goal of define the most appropriate structural configurations of buildings equipped with innovative seismic protection systems, the architectural and structural aspects influencing the seismic response of buildings are discussed.

New tools to be applied at conceptual design level for building including new protection systems have been pointed out deriving them by the special behavior of these constructions that have to be characterized by the capacity to move. They have been defined as discontinuity, motion and flexibility.

Some optimization evaluations regarding the global distribution of mass and stiffness in isolated building are presented together with a significant application to a special building. Also some first indications on optimized structural schemes for base isolated buildings are resumed.

A sample design of a building for a urban renewal project is presented in which the morphological configuration has been conceived taking into account the seismic protection, the urban constraints and the architectural expression. All the requirements have been respected thanks to the use of innovative protection systems.

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