Recent earthquakes in Italy (L’Aquila, 2009 and particularly Emilia, 2012) have evidenced the high seismic vulnerability of many existing industrial buildings, being designed with rc prefabricated elements, and conforming to isostatic schemes. The lack of connections, often characterizing the structural nodes, and the presence of simply supported members, reduce the lateral resistance system to the one set up by the single column fixed at the base, which acts independently as a SDOF system (for one-level buildings) with no possible redistribution of inertial forces. Retrofit and rebuilding strategies allowing to reduce the intrinsic seismic fragility of this kind of structures need to be found.

This article shows how isolation is applied for seismic protection in a new large industrial facility situated in L’Aquila (Italy). The proposed construction system combines the application of lead-rubber isolation devices and multi-directional bearings for base isolation, and the use of a prefabricated system with wet joints for the superstructure, which allows to restore the structural continuity at the internal nodes of the rc frame. The isolation devices filter the seismic action transmitted to the superstructure, which, in itself, has an additional ductility capacity due to the iperstatic frame system obtained. The result is a seismically protected building, exhibiting an enhanced seismic performance both as regards the structure and the content, the typical shortcomings of rc prefabricated industrial constructions being removed.

1 INTRODUCTION

Recent seismic events that have dramatically affected the Italian territories (L’Aquila in April 2009 and in May 2012 the Emilia Romagna) have highlighted the serious common deficiencies and the high seismic vulnerability of prefabricated industrial structures. This vulnerability is closely related to the following aspects:

- the seismic hazard has been only recently recognized by the national structural codes, e.g. in Italy by the O.P.C.M. n.3274 of 2003 (President of the Council of Ministers 2003), so that in many cases industrial facilities have been designed and constructed with insufficient or completely absent seismic design specifications;
- the static scheme is of isostatic type, such as the simple support scheme (main and secondary beams of the diaphragm) and the cantilever scheme (for the pillar, considered fixed at the bottom in correspondence of the plinth); regarding the horizontal forces, the transmission function is generally entrusted to the friction between the elements or to weak metal connections, while the absorption function is entrusted to the pillars without the possibility of force redistribution among the other elements of the frame.

Because of this static scheme, the following inherent weaknesses can be individuated:

- there are no strength reserve when the elastic resistance limit of a structural element is reached;
no energy dissipation, due to hysteresis phenomena, can be take into account in order to reduce the seismic forces and thus to prevents the collapse of the structure, because of the impossibility of the actual plastic hinges formation (only admitted in a hyperstatic system).

Finally, it should be noted that the seismic vulnerability of industrial facilities is a very important issue, not only for the safety and safeguard of life, but also for social and economic aspects, related to the protection of content (equipment, manufactured and semi-finished goods stored in the warehouses).

2 MAIN SHORTCOMINGS IN ITALIAN INDUSTRIAL FACILITIES

Because of the territorial characteristics of the affected area, with a strong propensity for the productive activities, the Emilia’s earthquake showed all the structural weaknesses of the industrial facilities realized with prefabrication techniques (Italian Department of Civil Protection et al. 2012).

In particular, the elements that are resulted most critical were the connections in general, absent or insufficient to ensure the structural union in dynamic condition, both for the old and new industrial facilities, endorsing the results of numerical studies previously performed (Magliulo et al. 2008, Capozzi et al. 2009). As already mentioned, for these types of buildings, especially in those areas declared to low seismicity (at least until a few years ago), the friction is a technique widely used for the absorption of the horizontal forces. In fact, the use of connections attritive was banned for the first time only with the D.M. of December 1987 (Italian Ministry of Public Works 1987), although this limit was valid only for the seismic zones (according to the seismic map of that time).

Furthermore it was observed that, if mechanical connections are present, connection details are often insufficient to ensure the effectiveness of the union system (e.g. an insufficient concrete cover in the case of connections with a metallic pin). In respect to horizontal forces, this inadequate connections system leads to an increase in the vulnerability, not only of the main structure, but also of the external infill system (consisting of rc or lightweight prefabricated panels, connected to certain structural elements by means of metal inserts). More, a wrong and common practice is to perform structural analysis of a prefabricated facility with a classical frame model, considering the external infill system only in terms of seismic mass and not of stiffness, so neglecting its influence on the global seismic response: it leads to consider a more flexible frame than the braced real one, underestimating the design horizontal forces acting on the connections that support the panels.

Another deficiency is linked to the static scheme of the vertical resistant systems, cantilevers fixed at the base, and to the foundation systems of these latter, isolated prefabricated plinths: Emilia’s earthquake showed in some cases the loss of the verticality of the pillar, due to a rotation of its foundational system. Shortcomings of ductility and resistance to horizontal stresses have been observed too, because of a non-seismic design according to obsolete codes: incipient formation of the plastic hinge at the base of the pillars, during the seismic event of Emilia, is the demonstration (concrete cover expulsion and buckling of bars due to an insufficient transverse reinforcement). The damage of the pillars, finally, has been also increased by the collisions with the horizontal structural elements sustained, due to the loss of support of the latter.

Another source of vulnerability should be considered, which is leads to the shelving systems: without bracing and efficient anchoring systems, they have collapsed and have caused considerable damage to the main structures during the Emilia’s earthquake.

Following is presented a possible anti-seismic design solution for an industrial facility, that joins the advantages of the prefabrication system (construction costs and times lower) with the ones of a hyperstatic structure (strength reserve and additional ductility capacity) and the ones of an appropriate isolation system placed at the base of the construction.

3 A CASE STUDY IN L’AQULA

This paper presents a project that involves the realization of a seismic isolated building in the industrial area of Pile, few Km North-West of L’Aquila (Figure 1). The ground floor, that is spread over a surface of about 11000mq, is used for several productive functions, while the first and second floor contains offices, management activities, technical areas and services, and each of them covers a surface of 2300 mq. The ground floor has a nearly squared plant, which measures 96.8 x 100.6 m; the building presents, in height, a narrowing of the plant dimensions from the
second level, so the first and second floor have rectangular shape and a size of 18.8 x 100.8 m. The roof of the production area is inclined outwards with a slope of 1.5%. Instead, the cover of the offices area, also with the same slope, is inwardly inclined. The maximum height of the building is about 20 m from ground level.

The building is located in L’Aquila, a town of Abruzzo characterized by a high seismic risk (seismic zone 2, in the current classification of Italian seismic areas). Furthermore the investigations of seismic microzoning studies, available for the site of the intervention (Pile area), have pointed out the possibility of a significant amplification of the seismic event. So, the campaign of geognostic investigations has paid attention into the dynamic characterization of the site’s subsoil, and a ground type E was determined according to the § 3.2.2 of NTC’08 (Italian Ministry of Infrastructure 2008).

Figure 1. Render from North-West (left) and from South-West (right, down).

### 3.1 General features of structure

A prefabricated system had chosen for the realization of this structure, to reduce the duration of construction phases and to limit the weather influence to the construction process.

The realized system allows a high reduction of the transmitted energy and acceleration during an earthquake, from the ground to the whole structure, thanks to a decoupling of the structure motion from the ground motion, introducing a discontinuity along the height of the structure itself (immediately below the ground floor slab), which is thus divided into two parts: the substructure, rigidly connected to the ground, and the superstructure, above the isolation system. Vertical structural continuity, so the transmission of the vertical loads to the ground, is ensured by the isolation devices placed between superstructure and substructure, which are characterized by a significant stiffness in the vertical direction beside a high deformability in the horizontal direction.

The substructure (Figures 2,3) is formed by a grid of foundation plinths of square cross section, 200 x 200 cm, each of these realized above a bored pile of great diameter (150 cm) and variable length from 15 to 37 m; all isolated plinths are linked by a reinforced concrete slab of 20 cm thick, which is also the floor of the basement technical compartment.

The superstructure, instead, includes the structural elements listed below.

- Basement level: rc piles cap positioned above the isolation devices (Figures 3,4), with a square cross section of 200 x 200 cm, in correspondence to each plinth of foundation.
- Structural elements of diaphragm (for each level): grillage of precast beams of rectangular, “L” or “inverted T” (Figure 5) cross...
section, which link pillars in both directions, with a height of 127 cm (max) for the ground level, from 60 to 100 cm for the first level and of 60 cm for the second-third levels; prestressed “double T”-beams (Figures 5,6), supported by grillage of principal beams, with heights from 60 to 90 cm, 40 to 60 cm and 40 cm respectively for ground, first and second-third levels (dimension depending on the area and the loads acting); supplementary rc slab cast in situ, 10 cm thick for the ground level, 8 cm for the other ones.

At the ground level, portions of separated floor are designed to individually support very heavy equipment, through foundation elements and seismic devices properly dedicated. Particular joints, shock transmission units, are installed in correspondence to these discontinuities: they allow vertical decoupling in serviceability conditions but became a rigid link during an earthquake.

- Vertical structures and vertical connecting elements: prefabricated rc pillars (Figures 4,6), with a rectangular cross section of 80 x 80 cm, hinged and fixed respectively at the lower and upper diaphragm; rc walls, 40 cm thick, placed in correspondence of the two stairwells and elevator shafts, and between some of the pillars along the building perimeter. The rc internal stairs are cast in situ, while the external stairs are realized in steel.

The continuity of the prefabricated elements, thus the monolithic of the structures, is guaranteed by the realization at each level of a rc slab over the prestressed “double T”-beams and, especially, by the wet joints in correspondence to the pillars (Figures 5,6): starter bars end new reinforcing bars are positioned between the precast beams and an integrative casting is realized. The diaphragm system so realized allows to consider the horizontal elements in a rigid plane.

Figure 2. Reinforcement of bored piles and foundation slab; cut away of piles’ head; reinforcement of plinths.

In the basement level, plants and distribution lines are positioned in both directions, at the intrados of the ground floor. This space is also functional to the accessibility and inspection purposes of the isolation devices, which are directly settled on rc rectangular plinths, representing the lower substructure fixed to the ground.

The perimetral joints are designed for a maximum displacement of 250 mm at the life-safety limit state. They are realized using two galvanized steel plates, the upper one sliding through an arrangement allowing bi-directional movements. This plate, 1cm thick, is bolted to the isolated structure, and is connected through slotted holes (60 cm long) to the bottom plate, which is fixed with a Halfen-type binary to the head beam of the external retaining wall. The same solution is adopted with thicker plates in correspondence to the access gates for forklift trucks, where concentrated loads are higher.

Figure 3. View of the basement level.
3.2 Characteristics of the isolation system

An isolation system is constituted by a set of devices which, combined together, allow to obtain a system characterized by the following capabilities (Dolce et al. 2010):

- support capacity for the gravity loads both in static and seismic conditions;
- high deformation capacity due to a very low stiffness in horizontal direction during an earthquake;
- a sufficient dissipation capacity;
- a suitable stiffness for the horizontal non-seismic loads (wind, impacts, etc…).

An important additional capability is the re-centring capacity: among the main functions of seismic isolation systems, this is the least taken into account by designers. This capability allows to obtain, after a seismic action, a null or not significant residual displacement.

There are other characteristics that could influence the choice of the more appropriate isolation system, such as the devices cost and durability, the ease of installation, the actual plan dimensions: these characteristics, in case of proper maintenance, don’t affect the mechanical performance of the isolation system.
A lot of devices have been studied, proposed and applied in the last 20 years (Housner 1998, Buckle and Mayes 1990) and, nowadays, some of them are widespread all over the world. The devices of an isolation system can be classified in two principal typology: isolation devices and auxiliary devices. The isolation devices, as principal functions, have to sustain the vertical loads of the building with a high stiffness in vertical direction, and have to allow high deformability in horizontal direction through a very low horizontal stiffness; the other functions, i.e. energy dissipations, suitable horizontal stiffness against non-seismic loads and re-centring capability, could be associated or not to the isolation devices, while these are own functions of the auxiliary ones. The seismic isolators currently used can be divided into:

- steel-reinforced elastomeric seismic isolators, i.e. multi-layer rubber bearings with (generally) steel plates as reinforcing elements, based on the high elastic deformability of rubber;
- sliding seismic isolators, i.e. multi-directional bearings based on the low friction resistance which develops between the (flat or curved) surface of some appropriately treated materials.

A seismic isolation system can be realized only with elastomeric devices or only with sliding devices, if these isolators incorporate sufficient energy dissipation and re-centring capacities; otherwise, it could be also obtained through a suitable combination of both isolation devices and/or auxiliary ones.

In this case study is used an hybrid isolation system (Naeim and Kelly 1999), composed by 84 elastomeric isolators and 27 sliding devices (Figures 7,8).

This configurations generally presents interesting advantages from technical and economical point of view. It allows to obtain low stiffness system (long period), with significant reduction in seismic effects, independently from the structural mass on each isolator. Another technical advantage is related to the possibility to design the position of the centre of stiffness getting it closer to the centre of mass, appropriately combining rubber devices (with a certain horizontal stiffness) with flat-surface multi-directional sliding (without horizontal stiffness): the result is a reduction or an elimination of the torsional effects due to the eccentricity between the position of the resultant of inertial loads and the centre of stiffness. The economic benefit consists in a cost saving, due to the fact that the cost of a flat-surface sliding device is significantly lower than the rubber isolator one. The main problem for this hybrid system, instead, is given by different vertical deformations, instantaneous and time dependent (creep), which leads to different vertical settlements where isolation devices are placed, both in static and seismic conditions. So, a particular type of elastomeric device, the lead-rubber bearing (LRB), was used to counteract this negative phenomena: whit the insertion of a lead core in the rubber bearing we can obtain a higher initial stiffness, so that creep deformation of rubber, and so different vertical settlements, aren’t allow. With LRB devices (Robinson 1982, Kelly 1992), three other important functions are achieved: a high dissipation capacity that reaches the damping value of 25% in this case (it depends on dimension of the lead core and on design displacement of device (Naeim and Kelly 1999)), seismic displacements not excessive in value and a sufficiently horizontal-stiffness for non-seismic loads (wind and impact).

![Figure 7. Lead-rubber isolator positioned on site (left) and flat-surface sliding device (right)](image)

![Figure 8. LRB isolator acceptance testing](image)

2.3 Modelling, seismic action and seismic response of structure

Using the software MIDAS-CIVIL, the 3D model briefly described below has been realized.
Foundations: constraints are placed in the real position of the foundation piles; they have a rigid behaviour in vertical direction, and a variable and finite value of stiffness in both horizontal direction, depending on depth and soil characteristics (determined by geognostic investigations).

Rc walls: 4-nodes “plate” finite elements.

Diaphragms: specific diaphragm elements of the software, with infinite stiffness.

Isolators: specific isolator elements of the software, equivalent to springs with horizontal stiffness given by manufacturers’ specifications (and vertical stiffness of higher order of magnitude).

Rc pillars and beams: 2-nodes “beam” elements, with geometric sections and material characteristics that represent the actual design typology, appropriately released at the ends in accordance to the design static scheme.

The linear-elastic modelling of the isolation device has been adopted because its characteristics fulfil the restrictions required by Italian structural code (§ 7.10.5.2, NTC’08); thus the seismic analysis of the building has been performed with a linear spectral analysis with modal superposition (CQC method).

In accordance with NTC’08, three limit states were taken into consideration: “damage”, “life-safety” and “collapse” limit states, respectively SLD, SLV and SLC. The first is a “serviceability limit state”, that was considered to verify the damage to non-structural components, limiting the storey drifts (§ 7.3.7.2, NTC’08). SLV and SLC, instead, are “ultimate limit states”: while SLV was used to design the structural elements, SLC was used to verify the seismic devices.

The characteristics of the isolation system, high vibration period (T≈3s) and high damping (ξ=25%), determine a strong reduction in spectral design accelerations, calculated following § 3.2.3.2 (NTC’08).

In Table 1 is reported the principal parameter of the spectra used for SLV (Figure 9) and SLC, and is shown the spectrum for the “life-safety” limit state, with and without the seismic isolation effects.

The behaviour factor (or Strength Reduction Factor) used in the calculations, in according to the code, is equal to 1 for the substructure and 1.5 for the superstructure.

The principal results of the modal analysis, performed on the 3D model previously described (Figure 10), are summarized in Table 2 and shown in Figure 11. It can be observed that, due to the isolation system, the structure presents only two principal modes, either translational and prevalent in one horizontal direction; the third mode, instead, represents the torsional component, which is limited.

The results from the modal analysis with response spectrum, performed for each limit state considered, satisfied the necessary prescriptions of [NTC2008]. In particular, the verify of the tensile stress presence in seismic devices was carried out: only in two cases it was observed, but always with acceptable values (lower than 1 MPa, in accordance to § 7.10.4.2, NTC’08).

From the analysis results and the discussion above, we can summarize the principal advantages of the isolation system adopted in this case study as follow:

- the superstructure moves essentially as a rigid body over the isolation system, where most of the displacement in seismic phase concentrates, with consequent reduction of storey drifts;
- due to the low horizontal stiffness of the isolation system, the period of the first vibration mode of the structure is higher (T≈3s), with a consequent decrease in design spectrum ordinates;

<table>
<thead>
<tr>
<th>Table 1. Parameters of SLV and SLC spectra</th>
</tr>
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<tbody>
<tr>
<td>( \xi_{el.} = 5% )</td>
</tr>
<tr>
<td><strong>Spectral parameters:</strong></td>
</tr>
<tr>
<td><strong>SLV</strong></td>
</tr>
<tr>
<td>( a_{g} )</td>
</tr>
<tr>
<td>( F_{0} )</td>
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<tr>
<td>( S )</td>
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<tr>
<td>( T_{B} )</td>
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<tr>
<td>( T_{C} )</td>
</tr>
<tr>
<td>( T_{D} )</td>
</tr>
</tbody>
</table>

Figure 9. Effects of period shift and damping on SLV spectrum.
Figure 10. Three-dimensional view of the Finite Element Model

Table 2. Eigenvalue analysis: principal modes of vibration

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency [Hz]</th>
<th>Period [s]</th>
<th>Tran-X Mass (%)</th>
<th>Sum (%)</th>
<th>Tran-Y Mass (%)</th>
<th>Sum (%)</th>
<th>Tran-Z Mass (%)</th>
<th>Sum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3282</td>
<td>3.0465</td>
<td>32.15</td>
<td>32.15</td>
<td>66.32</td>
<td>66.32</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.3285</td>
<td>3.0444</td>
<td>66.04</td>
<td>98.19</td>
<td>32.26</td>
<td>98.58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.3307</td>
<td>3.0236</td>
<td>0.4</td>
<td>98.58</td>
<td>0</td>
<td>98.58</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 11. Visualization of first vibrational modes (from left to right): translational-Y; translational-X; torsional.

- the high damping ($\xi \approx 25\%$) provided by LRB seismic devices contributes to a furthermore reduction;
- the isolation system used allows the decoupling of the principal translational modes (of the superstructure) and the limitation of the torsional components;
- deformability demand of the structure is concentrated into seismic devices, allowing to design the building to remain fully elastic: so the calculation according to the capacity design isn’t necessary;
- with the high reduction of the spectral accelerations and the elastic design, damage of structural and non-structural elements are avoided, preserving the functionality of the industrial facility;
- there is an increase in flexibility in the design of the spaces, due to lower resistant cross sections demanded to the structural elements.
CONCLUSIONS

Seismic vulnerability of industrial facilities is a very important issue, not only for the safeguard of life, but also from social and economic points of view: the protection of content and the continuity of the productive activities are crucial aspects too: the terrible effects of the recent seismic events in Italy (L’Aquila, 2009 and particularly Emilia, 2012) have pointed out this fact. This vulnerability is closely related to the following aspects: the seismic hazard has been only recently recognized by the national structural codes; the buildings, designed with rc prefabricated elements, are in accordance with isostatic schemes (no strength reserve, no possible redistribution of inertial forces and no energy dissipation capacity are possible in this building systems).

This article presents a possible solution for these matters, whose aim is the substantial reduction of the principal weaknesses in new design industrial facilities. This solution acts on both terms of the fundamental disequation of the structural design, “Capacity > Demand”:

- **Demand**: the seismic isolation system at the base of construction filters the seismic action transmitted to the superstructure, greatly reducing the spectral accelerations.
- **Capacity**: the prefabrication is still used, but associated with wet joints system, which allows to restore the structural continuity at the internal nodes of the rc frame, moving from an isostatic structure to a hyperstatic one; additional strength reserve, capacity of inertial forces redistribution and ductility capacity are obtained.

The result is a seismically protected building with a good behaviour under seismic actions, both for the structure and the content, being removed the typical weaknesses of rc prefabricated building.

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