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Composite Building Structures in Earthquake Engineering

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Summary

Suitable combinations of constructional materials may generate composite actions which are successfully utilized in seismic resistant building structures. The main behavioural features of such combinations, usually called composite systems, have been examined in case of new building construction as well as in case of old building retrofitting.
After an overview of the international situation both in research and codification, some example of application of composite building structure in seismic areas have been presented.

1. Introduction

The ability of structural typologies to withstand severe actions is particularly proven when the building constructions are submitted to the violence of an earthquake. The examination of damages always represents a precious source of information on the ultimate performance of constructional materials [1].

Referring to the traditional typologies, the old masonry structures are the first to prematurely fail under the seismic attack, due to their intrinsic features which are very often worsened by the age and the revage of time. They need to be upgraded by means of more ductile and modern materials, like concrete and steel, giving rise to different kinds of composite actions.

But unfortunately also many reinforced concrete structures are seriously damaged and sometimes collapse because of the earthquake, due to bad execution and poor material quality, which produce a tremendous lowering of ductility.

Looking to steel buildings the past experience show that the cases of global collapse are very rare, even if the traditional image of steel as the more suitable material in seismic resistant applications has been seriously undermined after the damages recently occurred during the Northridge (17 January 1994) and Kobe (17 January 1995) earthquakes.

Summing up, from the experimental evidence of the sad after-earthquake scenarios, it is easy to recognize that all the common constructional materials from the worst to the best used alone in the traditional typologies can badly perform under severe earthquakes, producing serious damages up to the collapse.

In order to increase the reliability of constructional materials, it can be observed that a rational combination of non-ductile (masonry, concrete) with ductile (timber, steel) materials can produce a kind of synergic effect which improves the behaviour of the construction under severe actions.

Looking back to the historical development of the seismic resistant structures, we can find that, after the catastrophic earthquake which destroyed the Calabria region in South of Italy at the end of 17th century (1783), the government imposed to build the new constructions by using a timber lattice-work inserted into the masonry walls (Fig. 1). The so-called "*casa baraccata*" (*treillis house*) represented the ancestor of a composite structure (masonry plus timber) conceived for seismic resistant purposes and its performance was largely appreciated during the subsequent earthquakes. This system is very similar to the one imposed in Lisbon after the earthquake of 1655.

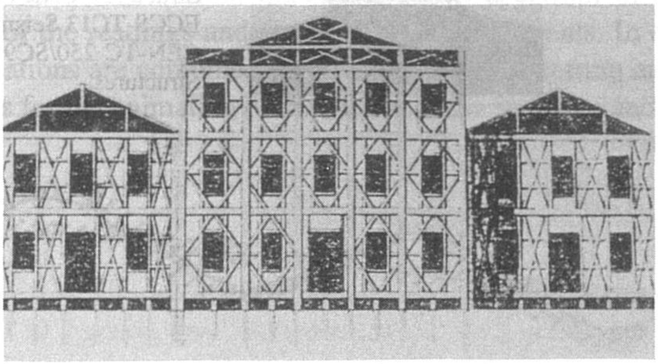


Fig. 1. Timber-masonry composite structure: the first seismic resistant composite system.

Afterwards also the consolidation activity developed in the earthquake prone areas exploited for the first time different kinds of composite actions. We can observe that the composite action has been widely experienced in the retrofitting of masonry buildings, i.e. by means of steel elements for introducing tensile resistance in walls, arches, domes [2, 3] or by using RC plates for transforming masonry walls into sandwich panels.

Only more recently the composite systems have been used for new constructions, but the original motivation was mainly based on economic aspects rather than on the requirement to improve the structural performance. Nevertheless the well known composite structures made of steel elements working together with RC elements demonstrated a good synergic behaviour also under severe seismic actions. Considering the recent damage to connections of a number of steel structures during both recent Northridge (Los Angeles) and Hygoken - Nanbu (Kobe) earthquakes and the numerous failures of new reinforced concrete structures during all the known earthquakes, it appears that the use of steel-concrete composite systems could mitigate some of the vulnerabilities of steel and reinforced concrete structures alone.

2. Main Behavioural Features

In general, the composite action can be defined as an action deriving from the combination of two or more different structural materials acting together to resist external forces. This kind of action can be performed in a single member, in the structure as a whole or in both. On the other hand, it can be derived from the integration of new materials, which are used for increasing the previous resistance of the existing construction, in case the seismic upgrading is requested.

The technological systems allowing the development of a composite action give rise to composite constructions, which can act at two different and separate levels:

A - **member level**: different materials (usually steel and concrete) can form parts of the cross-section; it comprises beams, columns, slabs, walls;

B - **structure level**: sub-systems made of different materials can compose the whole structure; it comprises the possible combinations of frames, bracings, walls and cores, which can be made of simple (steel or RC) as well as composite elements.

Level A leads to the so-called "**composite members**" and level B gives rise to the so-called "**mixed**" or "**hybrid structures**", but all together they belong to the family of composite systems.

From the point of view of seismic resistance, composite systems are suitably used both in the construction of new buildings as well as in the refurbishment of old existing buildings. The main advantages of a composite system in seismic resistant applications, respect to structural steel or reinforced concrete alone, can be identified in the following points:

- high stiffness and strength of beams, columns and moment connections;
- satisfactory performance of all members and the whole system under fire conditions, which can arise after an earthquake;
- high constructability for floor decks, tubolar infilled columns, moment connections;
- increase of ductility for encased beams, encased columns and beam-to-column connections;
- satisfactory damping properties for the whole system.

Due to these synergic properties, it seems logical to utilise the two basic materials (steel and RC) in tandem and to consider, therefore, both composite and mixed structures as an attractive solution to seismic design problems.

Many research results [4, 5, 6, 7, 8, 9, 10, 11, 12, 13] have shown the interest of using composite structures in seismic areas, particularly due to the presence of concrete, which increases the resistance in the elastic field up to 50%, contemporary increasing the stiffness and largely preventing local buckling. After complete concrete crushing, the structure behaves always like a bare steel structure when submitted to very large displacements.

Due to the complexity of the stress state in composite connections many experimental and design-oriented research project have been developed in USA, Japan and Europe for several types of connection details, which demonstrate their potential for use in seismic resistant applications [12, 13, 19, 20]. In terms of seismic design, composite connections often avoid or minimize the use of stiffners comparing to structural steel design.

3. New Building Construction

3.1 Composite Elements

In seismic resistant structures the most commonly used steel-concrete composite elements are: beams, columns, slabs and walls.

In multistory buildings it is very frequent the use of floor structures made of composite beams and composite slabs, which are obtained by casting reinforced concrete on steel trapezoidal sheetings supported by double T beams (Fig. 2). In these cases the main structural advantage of the composite action versus the seismic performance is due to the diaphragm effect which allows to rigidly connect in plan the vertical bracings under horizontal seismic forces.

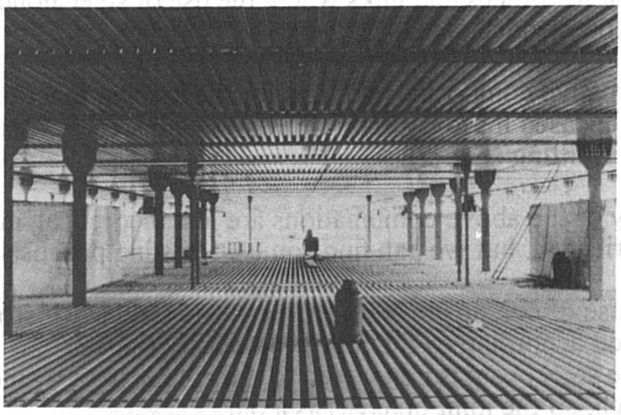


Fig. 2. Steel trapezoidal sheetings before the concrete casting in a composite floor.

Among the composite beams types, the encased beams (Fig. 3) represent a suitable system which provides a good performance under cyclic loading due to the presence of the concrete mass which avoids or at least postpones the local buckling phenomenon in the web of the double T section. This increases the rotation capacity of the member and therefore the ductility of the whole structure. The behaviour of encased beams has been proved by many monotonic and cyclic tests [6, 11].

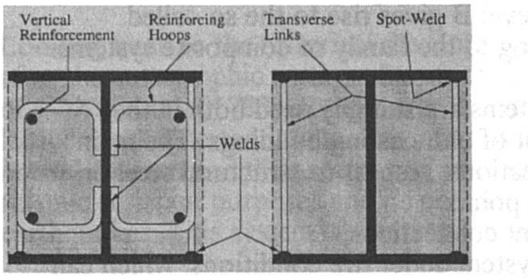


Fig. 3. Partially encased beam-column sections (Elnashai, 1996).

Composite columns made of round, square or rectangular hollow steel sections filled up with concrete present also the advantage to improve the local buckling resistance of the steel wall, allowing to increase the b/t ratio of the section.

Composite walls are derived from the insertion of vertical steel profiles into a reinforced concrete wall. The presence of steel improves the ductibility of the element.

3.2 Composite Sub-Systems

The classification of seismic resistant structures is usually done according to how the bracing system faces the horizontal quakes [14]. The same format can be followed in case of composite structures and, therefore, the main categories of MRF (moment resisting frames), CBF (concentrically braced frames) and EBF (eccentrically braced frames) can be considered.

Referring to MRF composite systems, the following combinations are possible: beams can be simple (steel) or composite (steel plus RC); columns can be simple (steel or RC) or composite (steel plus RC). Figure 4 shows a seismic resistant system composed by RC columns and steel-RC composite beams.

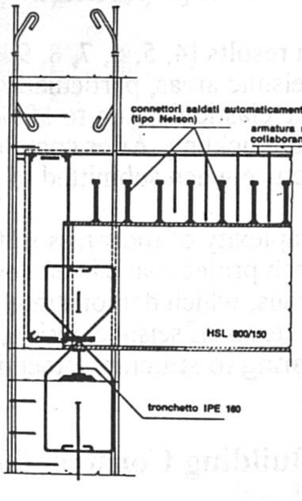


Fig. 4. Composite MRF subsystem made of RC columns and steel-RC composite beams.

In case of CBF composite systems, beams and braces can be in steel or in composite (i.e. encased sections); columns have the same possibilities as in the previous case of MRF. The EBF leads to the same typologies, eccept for braces and links where the use of steel alone is recommended.

Alternative composite solutions for the bracing function can be obtained by means of RC frames with encased masonry and RC frames with steel braces, the last being particularly suitable in case of retrofitting (Fig. 5).

Many of the above combinations are just theoretical; in practice only few cases have been experienced, but we can find some interesting proposals, like the one shown in Fig. 6.

The use of composite steel-RC beams in steel MRF structures provide interesting results when applied according to the following phases (Fig. 7):
- the steel beam is connected to the column tree by means of a bolted cover plate only in the web, so the joint behaves as a pin;
- the concrete slab is casted excluding the part corresponding to the joint, so the dead lead of the floor does not produce bending moments in the columns, except for the affect of eccentricity in the frame node;
- also the beam flanges are connected by means of cover plates, leading to the complete scheme of frame.

The advantage of this constructional procedure (so-called *disconnection technique*) is to provide the structural scheme to absorb negative moments produced by seismic horizontal actions in the nodes by increasing the capability.

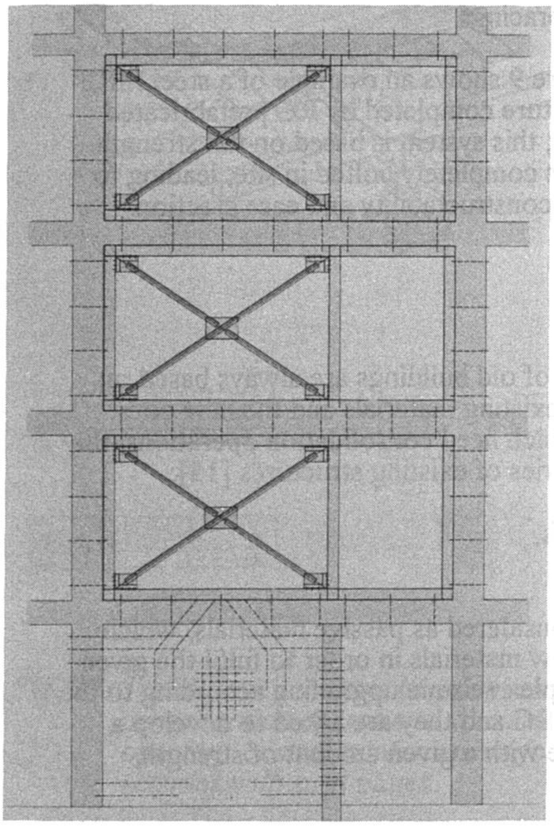


Fig. 5. RC frames with steel bracings.

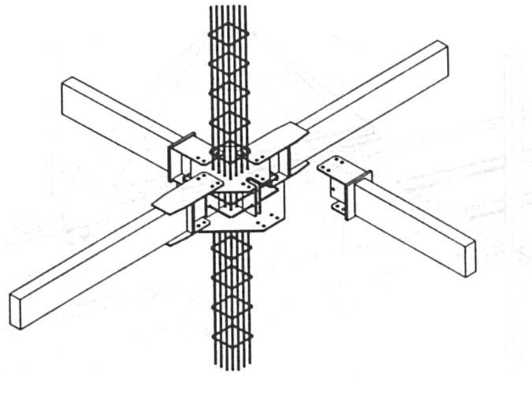


Fig. 6. Composite subsystem composed by RC columns and steel beams for a MRF scheme (Carannante Joints, 1995).

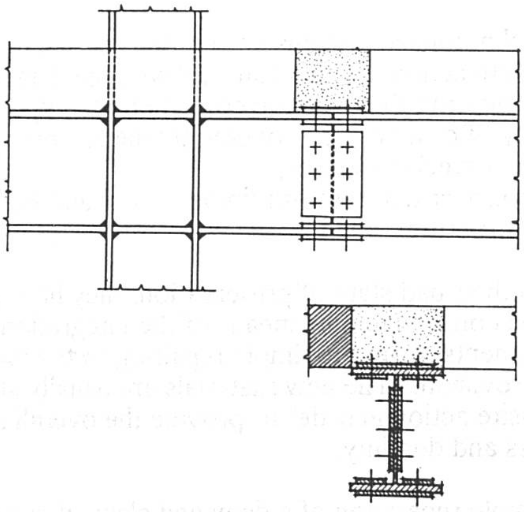


Fig. 7. The disconnection technique of a composite MRF structure for improving the seismic resistance.

3.3 Composite (Mixed or Hybrid) Structures

They can be derived from a combination of different sub-systems which can be simple (RC walls or cores, steel bracings) or composite (like the ones mentioned above in section 3.2).

A very common typology is the one composed by pinned steel frames and reinforced concrete cores and/or walls, in which the two materials play different functions in withstanding the external actions: steel frames provide the carrying capacity of vertical loads and reinforced concrete elements maily resist the horizontal seismic forces (Fig. 8).

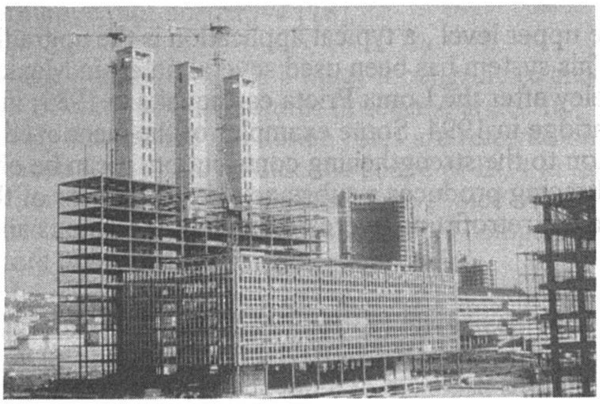


Fig. 8. Composite structure with RC cores and pinned steel frames.

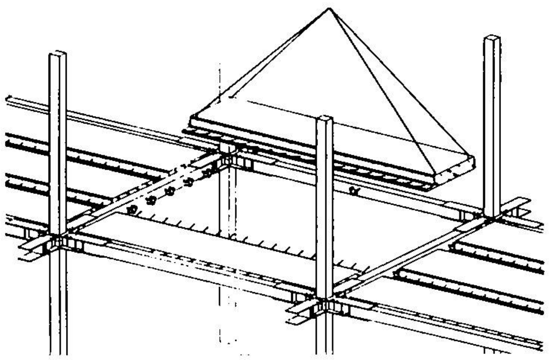


Fig. 9. A composite structure with steel MRF and RC prefabricated slabs.

From the global ductility point of view this solution is not eccellent, because the dissipative zones are concentrated into the RC elements. Nevertheless due to its economical advantages, this type of composite structures is very often used in low seismicity regions. An improvement to this solution can derive from the combination between steel MRF and RC bracings.

Figure 9 shows an example of a steel MRF structure completed by RC prefabricated slabs; this system is based on full strength joints completely bolted in site, leading to high constructability and ease erection.

4. Old Building Retrofitting

The technological systems used in the seismic upgrading of old buildings are always based on composite actions, which can be developped among the existing materials and the new ones. By considering the common constructional typologies which need consolidation operations, the majority of cases can be covered by the following categories of existing structures [15]:
- iron or steel structures;
- masonry structures with timber floors and timber roofs;
- RC structures.

Due to their bad state of preservation, they have to be considered as passive materials, which must be consolidated by means of the integration with new materials in order to fulfil the given requirements, from the simple repairing to the more complex seismic upgrading according to the code provisions. The new materials are usually steel and RC and they are asked to develop a composite action in order to provide the overall structure with a given amount of strength, stiffness and ductility.

The simple reparation of a damaged element can be made in different ways. Some examples are given in Fig. 10, dealing with the main systems using steel as active material for strengthening masonry walls, RC beams, wooden floors [16]. RC can be also used for repairing masonry walls, steel floors, wooden floors.

The main technological systems used in case of retrofitting of existing structures give rise to different composite elements belonging to level A, like: masonry - steel; masonry - RC; RC - steel; timber - steel; timber - RC.

At the upper level , a typical application is the upgrading of RC frames by means of steel braces [3]. This system has been used several times: in Mexico City after the earthquake in 1986; in Berkeley after the Loma Prieta earthquake in 1989; in Santa Monica after the earthquake of Northridge in 1994. Some examples of the mentioned applications are given in the Fig. 11. In addition to the strengthening contribution, it can be observed that in many cases the addition of steel bracing produces a substancial improvement of the aesthetic aspects of the façades, which, before the retrofitting, were completely anonimous and sometimes ugly.

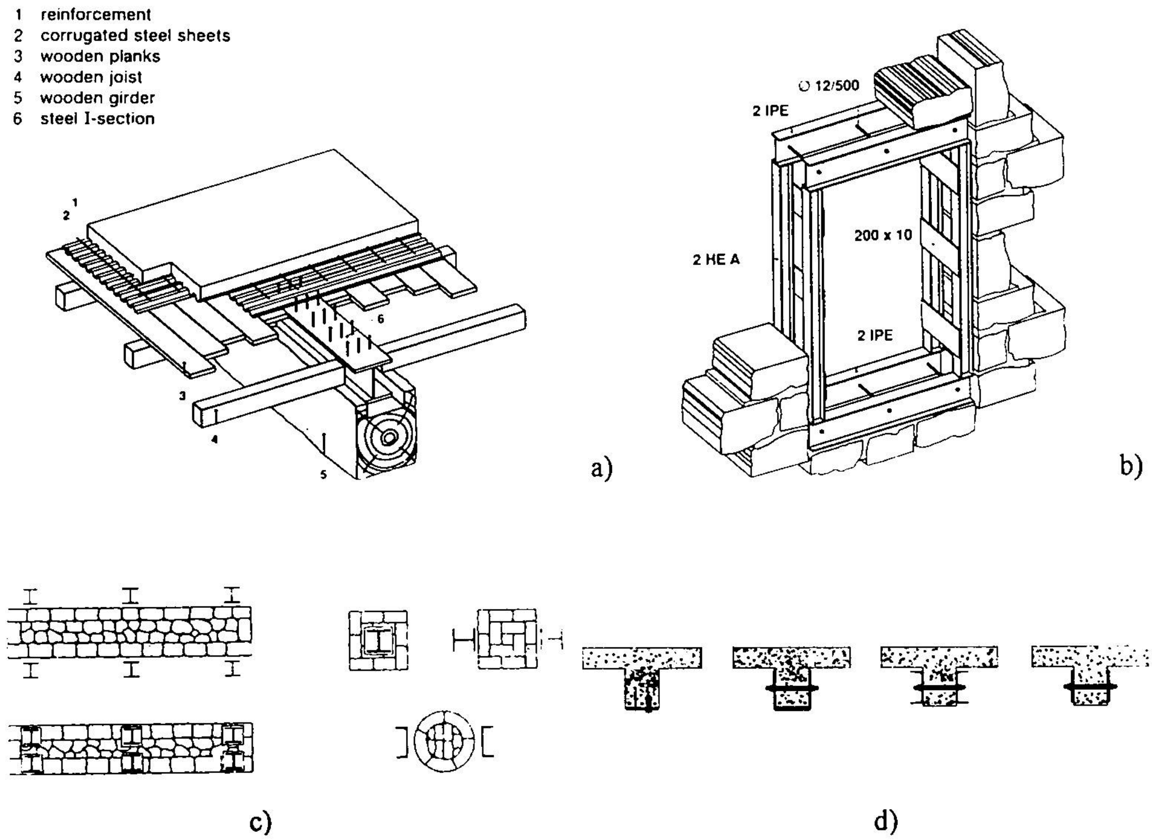


Fig. 10. Technologial systems based on composite actions, which are commonly used in consolidation operations: a) composite steel-timber floor; b) steel frame in a masonry opening; c) steel reinforcement for masonry walls and columns; d) integration of RC sections with steel plates.

5. Codification

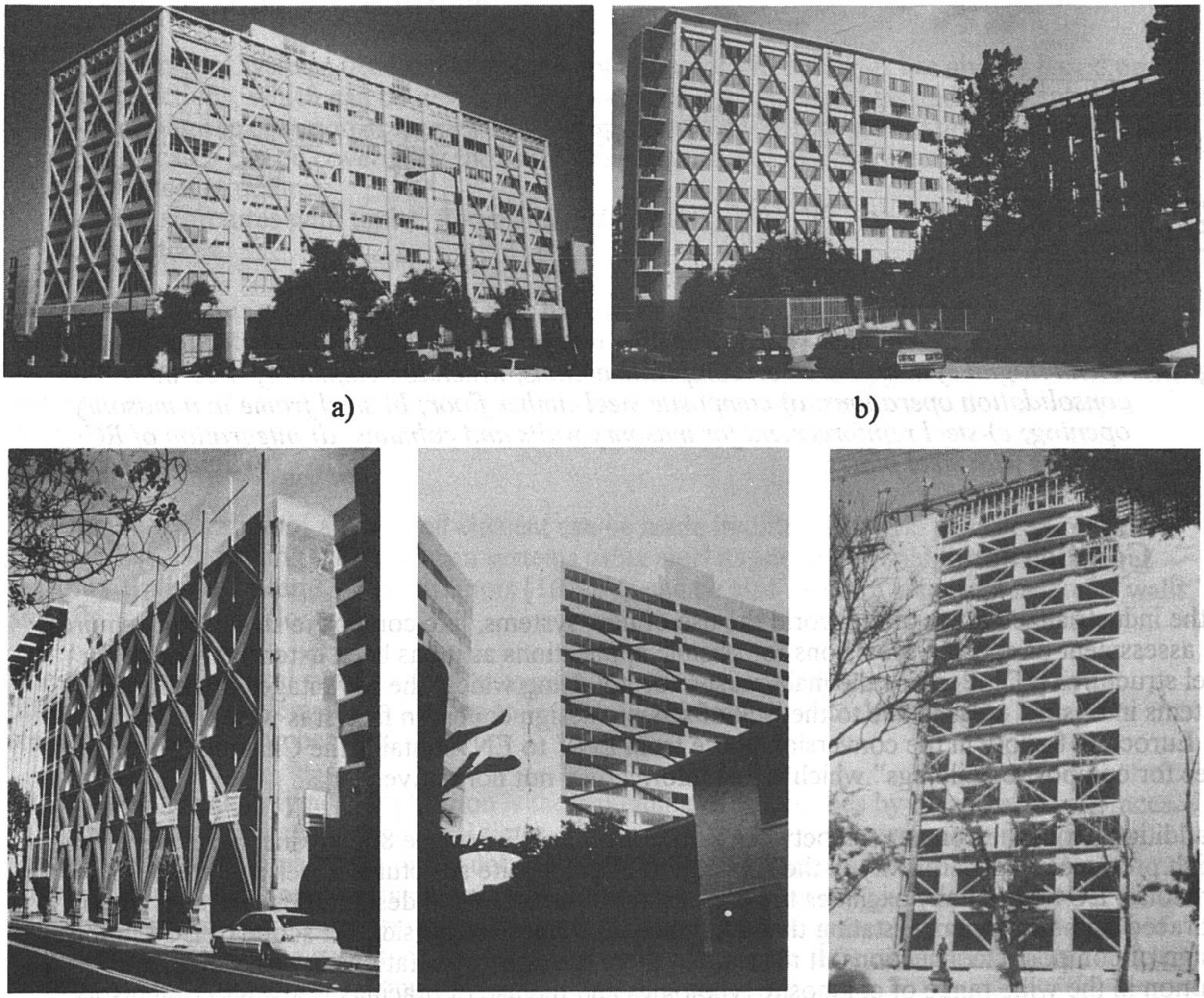
In the industrialized areas of the world the use of new systems, like composite structures, requires the assessment of specific provisions for seismic applications as it has been extensively done for steel structures [17]. Perhaps the main reason for not using widely the advantages of composite systems in seismic areas is due to the lack of seismic design codes. In fact, it is well known that the Eurocode 8, now in the conversion phase from ENV to EN, contains the Chapter "Specific rules for composite buildings" which is just informative, not normative [18].

In addition, from the comparison between Eurocode 4 and Eurocode 8 many incongruicies arise, which produce some perplexity in the application of composite structures in seismic areas. In particular, EC4 esplicitally excludes the use of sway frames and the design rules are referred only to braced non-sway frames, stating that the unbraced frames are outside the scope of EC4 in the design of composite connections. It means that there are strong limitations in the choice of a solution in the wide range of composite typologies and the use of bracings is always compulsory, what vanishes the meaning of the behaviour factors given in EC8 for other typologies.

The first U.S. seismic design provisions for composite constructions (NEHRP) have been developed by the Building Seismic Safety Council (BSSC) within the National Hazard Mitigation Program in 1994 [19]. The most challenging parts of this code are devoted to establish seismic force reduction factors and drift amplification factors. In estabilishing reduction factors, the available research data have been integrated by engineering judgment and phisical understanding of the behaviour of these systems. The basic composite structural framing systems identified in the NEHRP code and the corresponding force reduction factors (R) and drift amplification factors (Cd) are the following:

COMPOSITE SYSTEMS	R	Cd
Special moment frames	8.00	5.50
Ordinary moment frames	4.50	4.00
Partially restrained frames	6.00	5.50
Eccentrically braced frames	8.00	4.00
Special concentrically braced frames	8.00	4.50
Concentrically braced frames	6.00	5.00
RC shear wall with steel elements	8.00	6.50
Shear wall reinforced by steel plates	8.00	6.50

For these systems specific design requirements are provided, with particular reference to connections and detailing.



a) b)

c) d) e)

Fig. 11. Seismic upgrading of RC frames by means of steel bracings: a), b), c) Berkeley; d) Santa Monica - Los Angeles; e) Mexico City.

6. Applications in Building Construction

It is difficult to collect all the existing examples of building with composite structure erected in earthquake prone areas. Some informations have been obtained from the current technical literature.
It seems that in the highly seismic areas of United States the use of composite systems is limited to steel structures with composite floors and more recently to steel structures with concrete-filled composite columns [19]. However, despite the construction of many spectacular high-rise buildings with composite superframes in less seismically active areas, the use of such composite system is going slowly in highly seismic areas such as in California. Nevertheless many research activities have been developed and are now in course in USA [19, 20].

A different situation appears in Japan, where the advantages of composite steel-concrete structural systems are well-documented, thanks to many investigations on different typologies of composite members, connections and frames. In the last twenty years the floor area in square meters of mixed structures rose from 10 to 40 millions about [21].

In Europe an extensive research work has been recently carried out to focus on the cyclic behaviour of composite members and connections [4 to 13]. These studies have confirmed the feasibility of composite frames designed to resist seismic actions, but very few applications for building construction in the European earthquake prone Countries seem to derive from these theoretical basis. As an example, a new steel-composite structure has been recently built in Timisoara - Romania [22], according to the Romanian Seismic Code, which is largely ispired to Eurocode 8.

In Italy the majority of composite (hybrid or mixed) structures have been erected in the area of Naples city and surroundings. Due to the damages produced by the bradyseism phenomenon, the old town of Pozzuoli was completely evacuated in the early eigthies and a new town has been erected for 25.000 people. The pressing need to give hospitality the population in the shortest period of time oriented the choice of the structural typology on prefabricated solutions for low-rise buildings of 4 to 6 stories. The mixed system composed by concrete cores and steel skeleton has been selected in the majority of cases, because of both quick erection and seismic reliability. This can be considered an interesting example of extensive use of composite structures in low seismicity areas.

Fig. 12. General view of the new Management Centre of Naples.

Parallel to this actvity, many multi-story building have been erected within the area of the the new Management Centre of Naples (Fig. 12) in the last 15 years by using mixed solutions [23]. The high rise buildings from 50 to 100 m high have maily a structural system composed by reinforced concrete cores and steel skeleton (Fig. 8). The cores have the main structural function to resist the horizontal forces produced by earthquake or wind and they usually contain stairs and elevators. The surrounding skeleton, being simply pinned, is completely braced by the core and therefore its structural function is to resist the vertical forces only. The floor structures are usually made of both precasted concrete elements lightened with polystyrol and trapezoidal steel sheetings infilled with casted concrete. Beside to this current typology, also some special systems, always composite, have been conceived with innovative solutions; three of them merit to be mentioned [23].

First, the Law Court Building, composed by three towers, which are equal in plan but have different height varying from 78 to 177 m (Fig. 13). For each tower the structural system is composed by reinforced concrete curved walls, which provide strength and stability under horizontal loads, and a steel skeleton resisting vertical loads only. The floor slab is connected to the upper flange of beams by means of studs, giving rise to a composite horizontal diaphragm connecting the steel structure to the reinforced concrete walls.

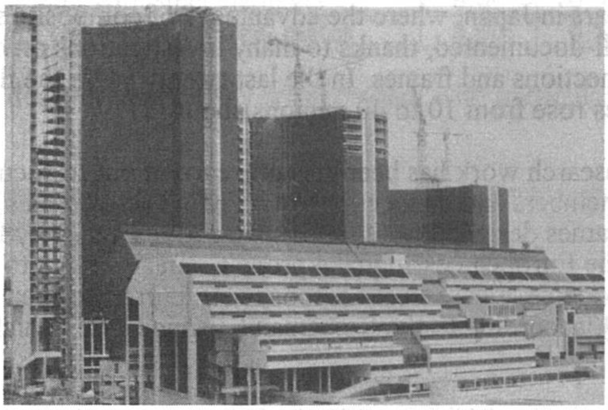


Fig. 13. The new Law Court building of Centre of Naples.

The second example is given by the two twin towers of the Electrical Department Headquarter (Fig. 14). Each tower has a lozenge shape 58x14 m and its structure is composed by two reinforced concrete cores connected at the top by a box-section girder which the 29 stories are suspended to. The suspended structure is made of steel ties and steel-concrete composite floor beams. The horizontal connections between cores and suspended structure are provided by means of elasto-plastic dissipative devices, which allow for a significant reduction of seismic effects, mainly at the base of the cores, where bending moment and shear are reduced of 30%.

Fig. 14. The National Electrical Department of Naples.

Finally, mention must be done to the main building of the new Fire Department, which is important at least for two reasons: first, because this building, initiated in 1981 and completed in 1985, was the first example in Italy of a base isolated structure; second, because it received the award of the European Convention for Constructional Steelworks in 1987. The structural scheme is based on a mixed structure [24], in which the concrete cores are spaced about 18x18 m and the steel skeleton is suspended to the top grid by means of vertical ties (Fig. 15). The top grid is connected to the upper part of the concrete cores by means of special devices, which isolate the steel skeleton from vertical and horizontal motions transmitted by the earthquake [25]. The bearing devices are made of a combination of rubber and teflon, which plays the double role to allow for free movements under serviceability conditions and to provide damping and energy absorbtion during an earthquake (Fig. 16).

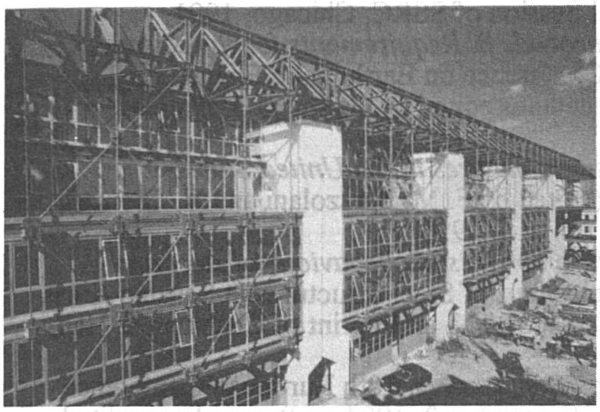


Fig. 15. The main building of the new Fire Department Centre in Naples.

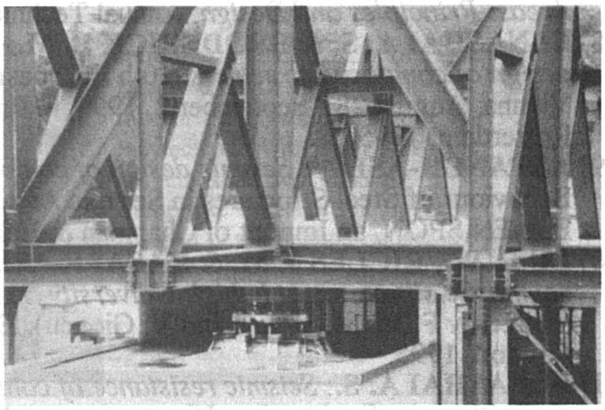


Fig. 16. Special devices to provide base isolation in the building of Fig. 15.

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