Building's eco-efficiency improvements based on reinforced concrete multilayer structural panels

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1. Abstract

The aim of this paper is to show the environmental benefits provided by the Multilayer Structural Panels technology when applied to construct low rise residential buildings.
This is a holistic approach that takes into account the structural aspects and the environmental issues involved. Conclusions are based on the assessment of a broad set of cases and it is provided a procedure to compare the environmental impact of each one. The design space was composed of single-family houses with three different building technologies: Reinforced Concrete Multilayer Structural Panels solving, at the same time and with high level of efficiency, structural and thermal insulation requirements; Reinforced Concrete Frame structures combined with insulated cavity walls; and Steel Frames structures plus insulated cavity walls. An optimized structural analysis was applied to fulfil the load transfer requirements. On each case were evaluated the economic cost, the embodied energy and the amount of CO2 emissions during the construction phase and also the energy savings obtained along the use phase of the building due to the reduction in heat loses. The conclusions show that the more substantial improvements can be achieved when buildings are located on intense seismic activity areas or places with poor bearing capacity soils.

Keywords: Embodied energy; CO_2 emissions; Structural panels; Multilayer panels; Earthquake; Building eco-efficiency; Reinforced concrete; Thermal insulation

2. Introduction

Buildings, along their long-life cycle, not only consume large amounts of energy but also contribute substantially to greenhouse emissions. The building sector in Europe accounts [1] for the 40% of final energy consumption and is responsible for around 36% of CO_2 emissions. Moreover, the 62% of final energy consumed by buildings corresponds to the households [2] being the dominant energy end-use (around 70%) the space-heating [3]. Considering that the 75% of the total building stock in Europe [3] are residential buildings and, according to the housing statistics recently published by the European Commission [4], in 2011 the 58% of the European citizens were living in different types of single-family houses (detached, semi-detached and terraced houses), this type of buildings are the most relevant energy consumers and CO_2 emitters.

These studies [4] also predict that the housebuilding activity in Europe should rise steadily over the next few years in order to solve the housing shortage (specially social housing) in many EU countries. This scenario requires improving the eco-efficiency of the building industry and the energy performance of Europe's residential building stock not only to achieve the targets of the European Union for 2020 but also to meet the longer term objectives of its climate strategy as laid down in the low carbon economy roadmap 2050. One of the most promising approaches to reach these goals is related with building's design. Particularly, those related with the choice of appropriate wall and roof solutions for each location [5] [6] [7].

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On the other hand, the improvement of the bearing capacity of structural materials, the advance in new construction technologies and the development of structural analysis methods and tools, allows the nowadays architects and building engineers to design buildings that achieve the best structural performance by means of structural systems (frames, trusses, grids) based on linear elements, efficiently arranged and joined, and highly specialized for transferring loads (gravitational, wind, earthquake) to the ground. Unfortunately, such kind of building's structure solutions are mechanically efficient but devotes a significant amount of resources to solve only the building's load transfer requirements.

It is commonly assumed that Nature is energetically the most efficient designer because develops optimal energetic solutions on a long term basis [8]. With this purpose the constituent elements of an organism usually have a multifunctional character and satisfy diverse requirements: protection, stiffness, insulation, air/water proofing, fluid conduction, etc. This approach has a clear eco-efficient optimization objective, trying to minimize resource consumption and maximize the efficiency of the response to multiple demands.

Taking all this into account, it is possible to take advantage of building technologies inspired on Nature in order to integrate the building structure into the building envelope and partition system. This is the case of the Multilayer Structural Panels (MSP). This building technology is based on surface elements (usually flat panels) combining high insulation performance with appropriate load bearing capacity. The panels can be used to build external walls, partitions, floors or roofs. They have suitable stiffness while providing, at the same time, adequate pathways, inside the building's envelope and partitions, for energy and/or fluids distribution.

Many types of MSPs have been lately designed. Some of them are completely precast: Cross Laminated Timber (CLT) [9], Wood Structural Insulated Panels (WSIP) [10], while others are mainly cast in place: Reinforced Concrete Multilayer Structural Panels (RCMSP) [11], Lightweight Pumice Stone Concrete (LWPSC) and Lightweight Expanded Clay Concrete (LWECC) [12].

The aim of this research was to compare the eco-efficiency of the RCMSP technology with other usual options for buildings construction: structure of Reinforced Concrete Frames (RCF) or Steel Frames (SF) combined with insulated cavity walls. The analysis was focused on the above mentioned single-family standard house typologies: detached, semi-detached and terraced houses. The assessment was based on a holistic approach that took into account the ecological and mechanical efficiency of each case. The influence of the building's environmental impact (in terms of CO_2 emissions, embodied energy and thermal energy looses through external walls and roof), the efficiency of the structure to support heavy snow and seismic loads, the competence of foundations to transfer those loads to soils with limited bearing capacity and the economic costs were analysed. Only the first two phases of the building's long-life cycle – construction and use – were evaluated. The demolition phase was not included because the end-of-life stage accounts less than 5% of the total enviromental impacts [13].

3. Research samples

3.1 Types of houses evaluated

The object of study was a group of terraced houses (Fig. 1) built in 2011 by the IVVSA[†] in the town of Gavarda (Valencian Community, Spain). The building has two-storey (3 m floor to floor

[†] IVVSA is the Valencian Housing Institute, created by the regional authority – Generalitat Valenciana – and aimed to social housing construction in order to provide affordable housing either owned or rented.

height) and all the houses have similar layout and built up area (about 155 sq. m). The housing plans have been detailed in Fig. 2. The houses composition includes: living room, kitchen, one bedroom, one bathroom and garage at ground floor level, and three bedrooms, two bathrooms (one en-suite) at first floor.

On the other hand, in order to represent the typical practice of nowadays residential building construction, another two types of single-family houses have been analysed: a couple of semi-detached houses with one common party wall and a detached house. The housing plans have been detailed in Fig. 3 and Fig. 4 . Both are hypothetical models inspired in the above mentioned terraced buildings and designed using the same technical solutions.

Fig. 1 Front and back façades of terraced houses in Gavarda

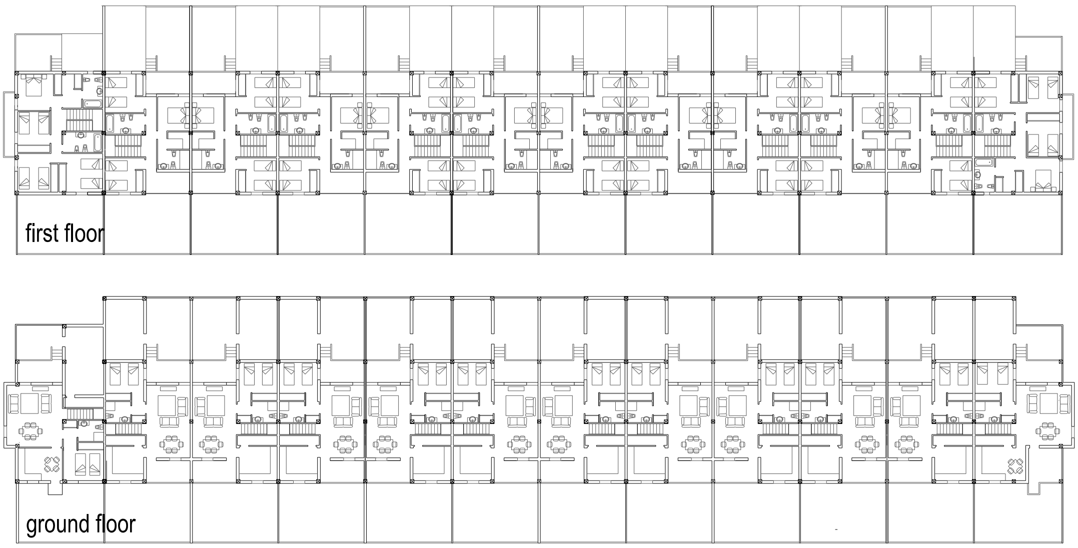

Fig. 2 Terraced houses floor plans

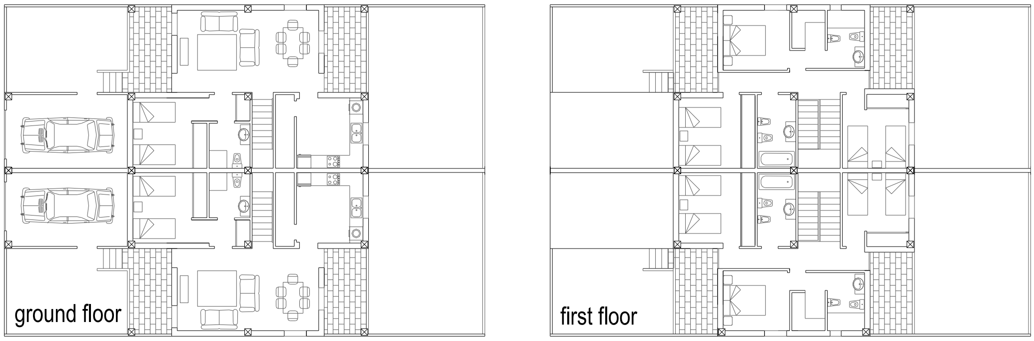

Fig. 3 Semi-detached house floor plans

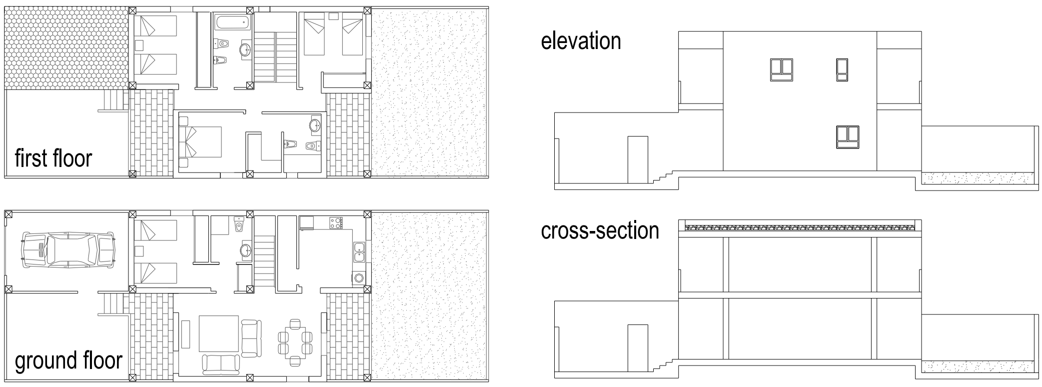

Fig. 4 Detached house floor plans, elevation and cross-section

3.2 Construction and structural solutions analysed

The three types of buildings (detached, semi-detached and terraced houses) were designed and analysed using three alternative structural systems: Reinforced Concrete Frames (RCF), Steel Frames (SF) and Multilayer Structural Panels (MSP). Details about the structure, foundation, walls, partitions and roof solution for each case follow.

3.2.1 Brick walls and reinforced concrete frames

In this case, the facades were designed as brick cavity walls insulated by filling the cavity with expanded polystyrene foam panels (EPS). In order to meet the standard performance fixed by the Spanish Building Code [14] the thickness of the panels was set to 40 mm for the external walls and 50 mm for the roof panels. These walls were finished with mortar at the external side and plaster at the internal side. The party walls and partitions were also brick walls. The inverted flat roof was insulated using extruded polystyrene foam panels (XPS) laid over the concrete floor and protected with a thin layer of gravel. See Fig. 5. In both cases, the thermal conductivity of the polystyrene foam was 0.039 W/m·ºK.

Fig. 5 Cavity wall and inverted flat roof solution

The RCF structure was solved using rectangular columns joined to wide beams through rigid joints. The floors of first level and the roof were one-way systems composed of inverted T-joists of reinforced precast concrete and hollow lightweight concrete blocks (Fig. 6). The thickness of these concrete slabs was fixed in 28 cm and the strength of materials was: concrete 25 N/mm^2 and steel rebars 500 N/mm^2. The foundation was made of reinforced concrete using isolated spread footings tied with strap beams.

Fig. 6 Wide beams and one-way reinforced concrete floor

3.2.2 Brick walls and steel frames

The floors, roof, walls and foundation of the SF configuration are identical to the original RCF case. However the structure is composed of rectangular hollow section columns formed with two rolled steel channel beams and girders made of rolled steel I-beams (see Fig. 7). The yield strength of the rolled steel was 275 N/mm^2.

Fig. 7 Girders, columns and one-way reinforced concrete floor on SF configuration

3.2.3 Walls and floors built with multilayer structural panels

This alternative was designed with Reinforced Concrete Multilayer Panels [11] because this technology (see Fig. 8) combines high insulation performance with appropriate load bearing capacity, especially against seismic loads [15]. These panels were used not only for external walls but also for party walls, partition walls, floors and roof.

This type of MSP is composed of an EPS core surrounded by two grids of electro-welded steel wire connected through the polystyrene by steel ties, as shown in Fig. 8. Depending on the insulation capacity requirements the thickness ranges from 40 to 240 mm. Later, a final coating layer of cast in place shotcrete (from 30 to 60 mm thick) is sprayed in both faces with the polystyrene panel acting as a support for the concrete casting. On the other hand, in order to guarantee the complete transmission of loads, additional grids of electro-welded steel wire ensure monolithic connections between walls and between walls and floor slabs, as shown in Fig. 9 providing the structure of high ductility and global box-like behaviour under seismic forces. The MSP construction process is shown in Fig. 10. In this case, the thickness of the EPS panel was set to 140 mm for the external walls and 40 mm for the internal walls. Floors were designed with the same kind of panel but using 200 mm thick EPS and adding extra steel rebars (to supplement the underside electro-welded steel mesh where needed) and increasing the thickness of the upper layer to a minimum of 50 mm. Both configurations exceed the requirements fixed by the Spanish Building Code [14] for the worst climatic area in Spain and have an insulation capacity much higher than other cases.

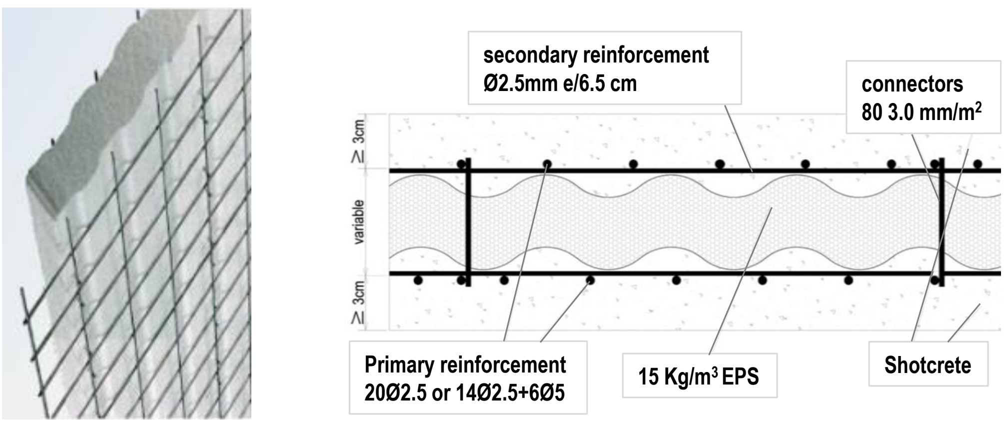

Fig. 8 MSP configuration. Structural panels with EPS with electro-welded steel mesh for walls and floors

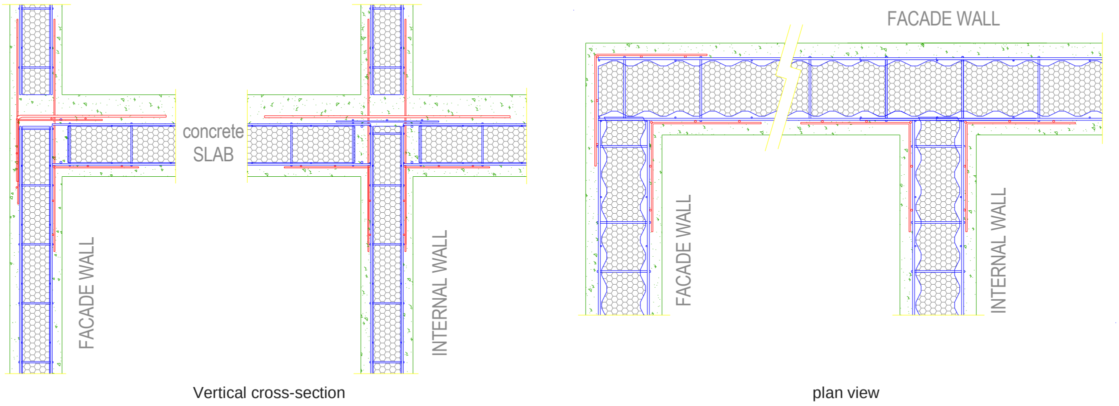

Fig. 9 Detail of the connections between walls and wall-floor slabs in MSP (additional electro welded steel wire grids in red)

Fig. 10 MSP Construction system
(a) Assembly of panels (b) Shotcrete sprayed on walls. (c) Concrete pouring on floor slabs.

Additional reinforcements are also added around openings and at the edges of the bearing panels. Finally, wall footings were designed with reinforced concrete strip foundations.

3.3 Structural analysis: models and load patterns

The structural models analysed for each configuration (RCF, SF and MSP) of the semi-detached houses are shown in Fig. 11. These models have been analysed using the software Architrave® (Universitat Politècnica de València 2013) [16]. Similar models have also been elaborated and analysed for the detached and terraced houses.

The RCF and SF models were defined as three-dimensional frames with rigid joints. Although the seismic loads in such structures are basically supported by the stiffness of the columns, the floor and roof slabs connect all columns on a given level and act as diaphragms. The staircase slabs, modelled as planar finite element meshes, also helps to bear the seismic shear forces. On the other hand, the role of the enclosure walls and partitions as stiffening elements is currently under study [17–19]. Such walls, usually built filling the frames, are not designed as structural elements but are reasonably stiff and strong. As a consequence, the stiffness and strength of the entire system increases. However, this stiffness increment also reduces the period of vibration and increases the magnitude of the earthquake forces and its effects. The lack of final conclusions prevented the inclusion of this additional stiffness on the structural model. Nevertheless, the inertial forces due to earthquake acceleration of walls were included into the analysis.

In the MSP model, all the walls (facade and partitions), floors, roof and their openings were modelled as connected planar finite element meshes. The result is a very stiff and lightweight *cellular structure* that behaves like a bundled-tube and is characterized by intrinsic superior performances with respect to the seismic loading. Moreover, as can be seen on Fig. 12, the MSP inertial mass being accelerated by the earthquake is always smaller than that of RCF or SF. It means that not only is a stiffer and stronger structural system but also it will be submitted to smaller seismic forces.

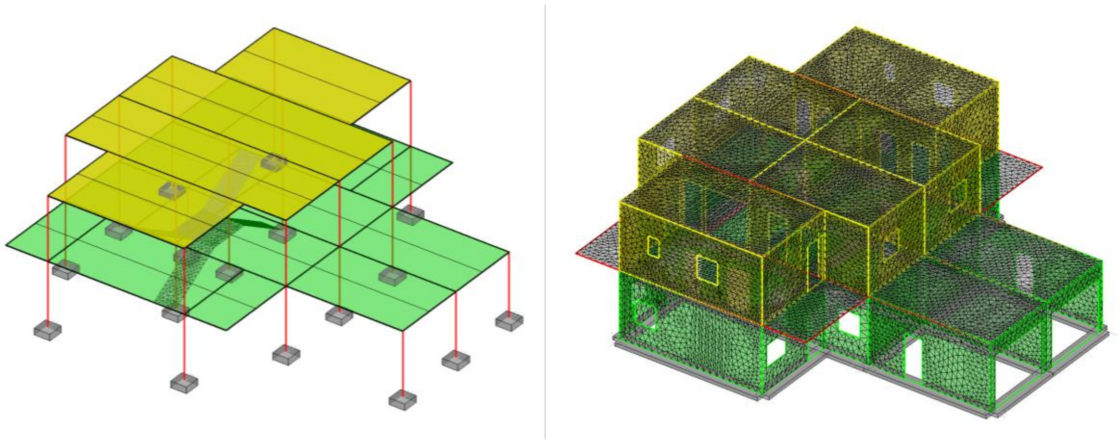

Fig. 11 Structural and foundation models. RCF and SF (left) MSP (right)

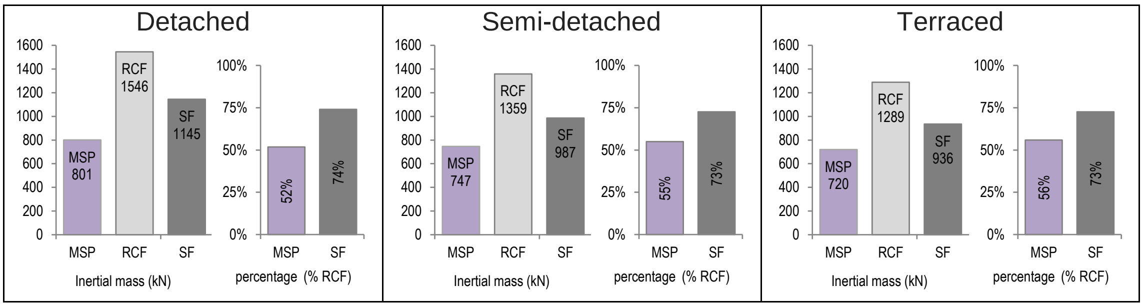

Fig. 12 Inertial mass generated by the seismic acceleration forces (per dwelling unit)

Each structure was calculated and designed to be able to withstand the static and dynamic actions generated by dead, live and seismic loads associated with the Ultimate Limit States (ULS) and Serviceability Limit States (SLS) established in the Spanish Codes [20,21][‡].

Magnitudes and characteristic of permanent gravitational loads (self-weight and dead loads), live loads (imposed and snow loads) and earthquake basic ground acceleration have been detailed on Table 1. A modal analysis was conducted on each case applying the spectral parameters shown in Fig. 13.

Dead loads		
Floor self-weight [kN/m²] Flooring [kN/m²] Partitions [kN/m²]		2.80 (RCF and SF) 2.00 (MSP) 1.20 (all cases) 1.00 (RSF and SF) 1.50 (MSP)
External walls	[kN/m]	7.00 (RCF and SF) 5.00 (MSP)
The structural elements self-weight is automatically obtained considering the structural element material and dimensions		
Live loads		
Imposed	[kN/m²]	2.00 (inner floor) 1.00 (roof floor)
Snow	[kN/m²]	from 0.40 to 1.20
Seismic loads		
Basic ground acceleration / gravity		from 0.04 to 0.20

Table 1 Considered loads RCF, SF and MSP structure and foundations

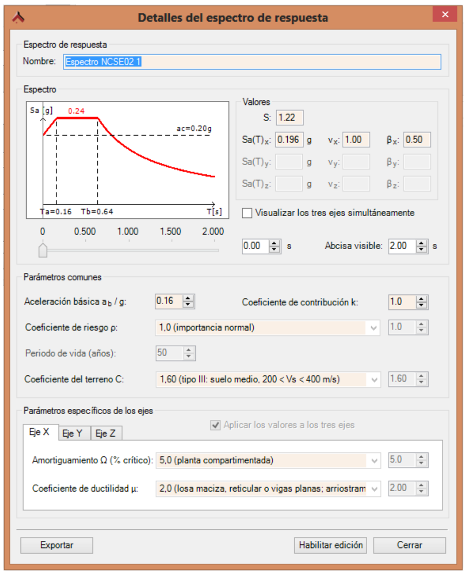

Fig. 13 Seismic spectral parameters

The foundations were designed considering a cohesive soil which bearing capacity could range between 0.6 and 2.4 kg/cm^2.

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‡ based on Eurocodes

4. Assessment methodology based on a holistic approach

The procedure followed to reach conclusions was based on three different areas of assessments: the structural performance, the environmental impact and the economic cost. A set of parameters were established for each appraisal area in order to configure the design space of analysis. The structural parameters were: type of structure (RCF, SF or MSP), magnitude of the snow load, earthquake basic ground acceleration and soil bearing capacity. The evaluation of environmental impact and economic costs in housebuilding activity is usually divided into three stages: construction, building use, and demolition. In the following analysis only the first two have been taken into account. The environmental impact was evaluated accounting the embodied energy and CO_2 emissions generated by the building's construction phase and the expected energy consumption savings to be obtained during the using phase of the building. The economic cost appraisal was also restricted to the construction phase.

Later, a detailed study of the space of analysis of every type of house – detached, semi-detached and terraced – showed the holistic quality of each case, fixed the trends of the problem and lead to conclusions and design recommendations.

The results obtained have been illustrated (see Fig. 16, Fig. 17, Fig. 18 and Fig. 20) for each type of house and structure. The parameters of the reference case presented in these figures were: basic ground acceleration 0.16·g, snow load 0.4 kN/m^2 and the soil bearing capacity of 0.8 kg/cm^2. Nevertheless, a mathematical expression (1) has been developed for obtaining the cost, the embodied energy and the CO_2 emissions on each case within the ranges shown in Table 1.

4.1 General assumptions

The thermal transmission losses or solar gains through windows and doors have not been taken into account, assuming that thermal bridges are properly solved and that the size, position and orientation of windows and doors, the material of the frames and the type of glazing is the same in all cases. Nor have been considered possible improvements from the thermal inertia of each solution.

The wall coatings (external cement plaster and gypsum internal plaster), being the same for the three technical solutions, have not been considered in the analysis.

In order to obtain comparable values, the functional unit considered in the construction costs and CO_2 emissions comparative analysis has been the dwelling unit, notwithstanding having designed and calculated the whole structure for each of the analysed buildings.

On the other hand, despite energy use and CO_2 emissions of a building also depend on the climate and socio-economic characteristics of the territory where the building is located [22] and the economic situation of the inhabitants, this variables were not taken into account.

Construction costs for each part of the buildings have been obtained from the database BEDEC [23] developed by the Institute of Construction Technology of Catalonia[§]. Nevertheless, these

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[§] The foundation Catalonia Institute of Construction Technology - ITeC, is an independent non-profit-making organisation that carries out its work in the area of operations intended to further the progress of construction.

information has been checked with other authors' results [24] and technical reports provided by industry manufacturers. This database provides not only the cost of materials and building components but also their environmental impact based in resource consumption (raw and basic materials), embodied energy and amount of CO_2 emitted into the atmosphere to construct each building component.

Finally, for the use phase analysis, a lifespan of 50 years has been taken into consideration, being this value the average of the life-cycle studies of residential buildings performed from 1997 to 2012 [22], is also the lower boundary established in the Spanish Building Code (CTE DB SE)[21].

4.2 Structural performance

The structure and foundation type (RCF, SF and MSP) of each class of building (detached, semi-detached and terraced) were designed heuristically with the aim of fulfil the code requirements (strength and stiffness) and also to provide optimized solutions. Compared results of deflection, movements, membrane stresses and bending moments corresponding to a semi-detached house of the reference case can be seen in Fig. 14 and Fig. 15.

Deflections and movements obtained for RCF and SF configurations were qualitatively similar and were in the same range of magnitude. It was expected than the MSP will provide a level of structural performance better than the RCF and SF configurations. The achieved results confirmed this expectation not only in terms of strength (stress levels and bending moments for the worst ULS were always very far away from the material limits and flexural capacity) but also in terms of stiffness (displacements for RCF and SF were always more than twenty times greater than MSP movements).

Moreover, the MSP configuration lightness, the greater extent and continuity of the contact area with the ground and the system ability to distribute the load between external and partitioning walls help to minimize the size of the foundation needed to support the building. The volume of reinforced concrete required on each case was calculated and could be established that similar quantities are needed for RCF and SF. However, using MSP the amount of reinforced concrete was halved while, at the same time, the capability of the foundation to withstand differential settlements was increased substantially. As an example, Fig. 16 shows the quantities required to design the foundation of the reference case.

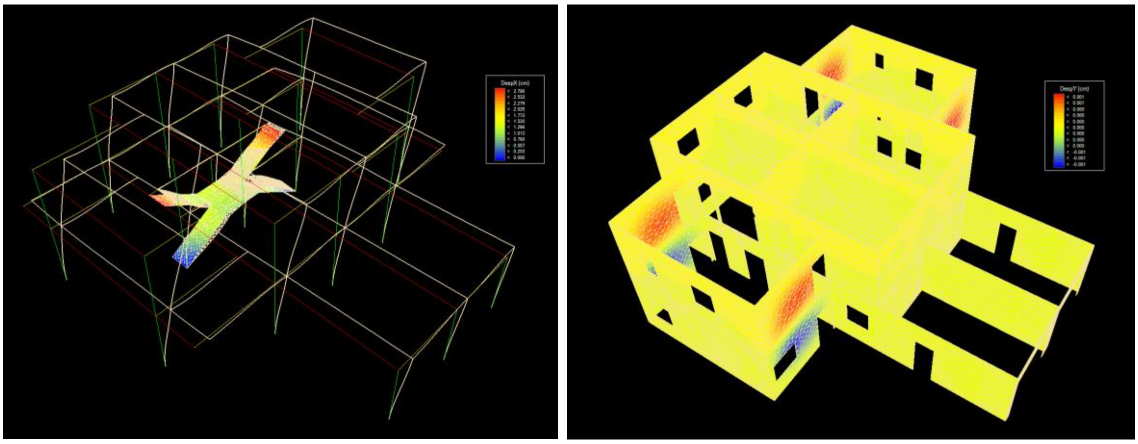

Fig. 14 Deflections and movements of the structure of a semi-detached house for RCF (left) and MSP (right) configurations. Depicted images correspond to the first mode of vibration for a basic ground acceleration of 0.20·g (maximum value of the analysed range)

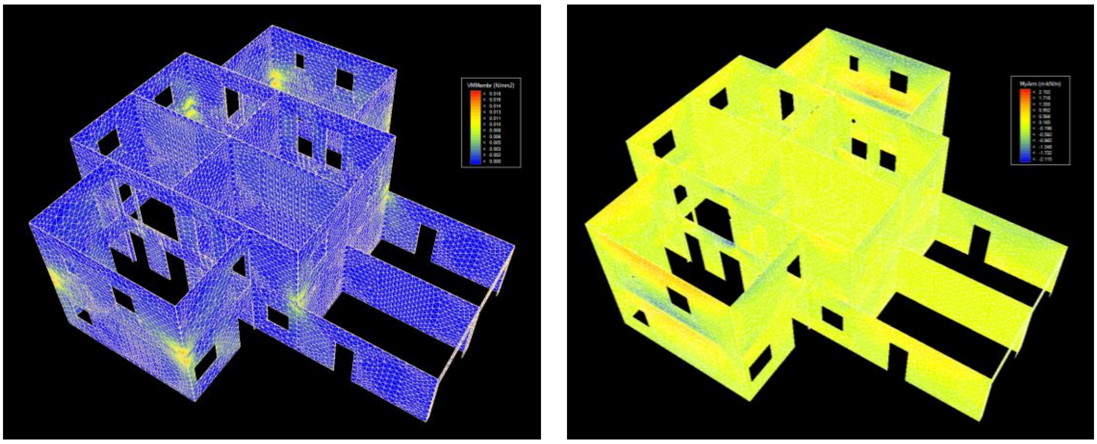

Fig. 15 Semi-detached house designed with MSP. Basic ground acceleration 0.20·g
Membrane stresses (left) and bending moments (right) have been depicted for the worst ULS

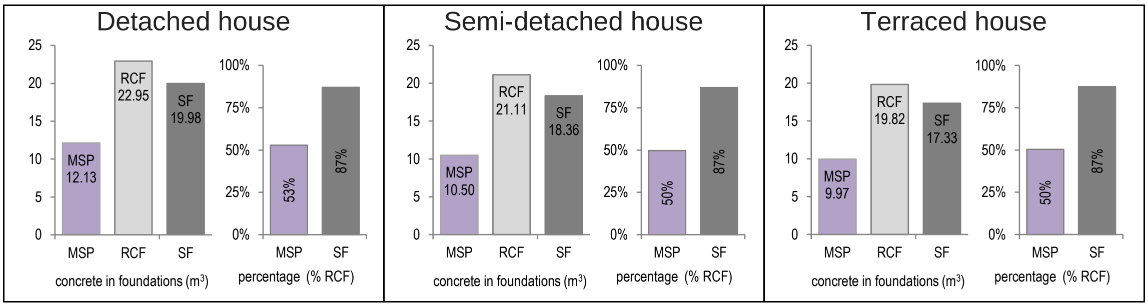

Fig. 16 Volume of reinforced concrete required for foundations (per dwelling unit and being the basic ground acceleration 0.16·g, the snow load 0.4 kN/m^2 and the soil bearing capacity of 0.8 kg/cm^2)

4.3 Environmental impact

Recently, an extensive research effort has been devoted to study the ecological footprint of buildings along their life-cycle [24–30]. A similar approach has been applied in this study but specially focussed on the benefits of technologies based on holistic structural systems.

It is quite evident that the less energy is used in the construction phase of the building the more energy resources will be available for being used during its use phase. Equally relevant is, for measuring the eco-efficiency of each case, the amount of greenhouse gas emissions associated with each technology. Finally, the economic cost of each solution could also help to improve the affordability of housing.

The performance of each building was analysed considering the technical solutions designed for the structure (MSP, RCF and SF), foundation, roof and wall characteristics (internal and external) being the thermal envelope designed to achieve thermal insulations well above the requirements fixed by the Building Regulations [14].

In the following sections results about embodied energy, CO_2 emissions and economic cost, considering the type of building and its structural system, are shown. The calculated amounts and percentages refer only to the building components specified for each configuration: foundations, structure, envelope (external walls and roof) and internal walls. It was assumed that additional building components like: flooring, plaster, painting, carpentry, windows, plumbing, heating, and electricity systems, etc., had the same cost for every configuration and have not been included.

4.3.1 Embodied energy

The embodied energy on each building was calculated by measuring the energy consumed to execute the building components analysed (foundation, structure, external walls, party walls, partitions, floors and roof). This amount included the energy needed to produce the materials and also the energy consumed during the transport and construction process.

The embodied energy was calculated using the BEDEC [23] database. The quantity obtained for each case was compared considering the different types of structures and classes of buildings. The results showed that similar quantities of energy were embodied into the RCF and SF configurations. However, the houses built with MSP embodied less than a 60% of the energy trapped into the houses constructed with RCF or SF. As an example, Fig. 17 shows the quantities required for the reference case.

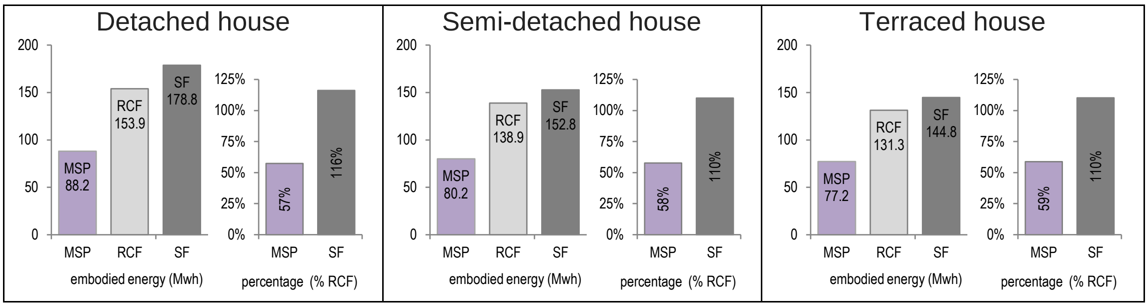

Fig. 17 Embodied energy in MWh (per dwelling unit and being the basic ground acceleration 0.16·g, the snow load 0.4 kN/m^2 and the soil bearing capacity of 0.8 kg/cm^2)

4.3.2 CO_2 emissions

The amount of CO_2 emissions have also been obtained for each configuration using the BEDEC [23] database. In this case the calculated emissions are also referred to the construction phase (products manufacturing, transportation and building process). The results, measured in tonnes of CO_2 emitted into the atmosphere, are shown in Fig. 18. It can be observed that the CO_2 emissions of all configurations were substantially equivalent (the small differences are ranging from -10% to +15%). The lower values correspond for MSP solution and the higher for SF.

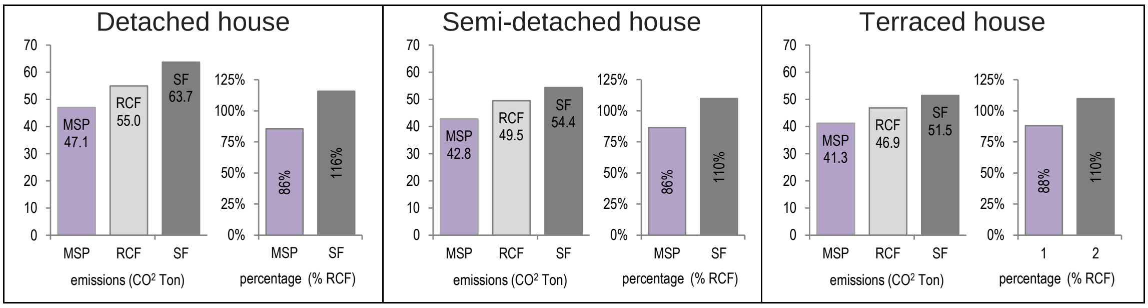

Fig. 18 CO_2 emissions in tonnes (per dwelling unit and being the basic ground acceleration 0.16·g, the snow load 0.4 kN/m^2 and the soil bearing capacity of 0.8 kg/cm^2)

4.4 Energy efficiency along the lifetime

The thermal insulation of the building envelope is, along with the energy efficiency of the appliances and equipment, one of the two main parameters for measuring the eco-efficiency of a building at the utilization phase [5] [7].

In this study, the indoor-outdoor heat energy flow has been evaluated in accordance with the results obtained by other authors [6] for detached residential buildings over a 50 years period. In Fig. 19 can be seen the thermal pathways through which such flows occur. It was assumed that all analysed buildings were in the same climate zone, had the same building orientation and the openings were solved using the same doors/windows technical solution. Similar assumptions were made about the ventilation systems, the building's airtightness and the lower level floor design. Nevertheless, the external walls and roof still account for one third of the total flow and any reduction on the envelope transmittance improves substantially the building's eco-efficiency along its lifetime.

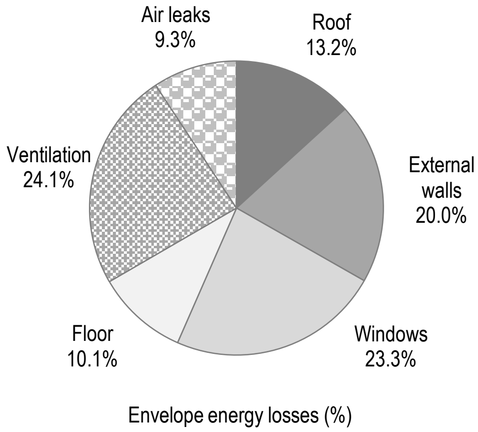

Fig. 19 Detached residential buildings envelope energy losses

The transmittance of the brick cavity walls insulated with 40 mm EPS panels (RCF and SF cases) is 0.563 $W/m^2{\cdot}K$ while MSP external walls (140 mm EPS insulation) have a transmittance of 0.264 $W/m^2{\cdot}K$ (nearly a half). For the roof the difference is even greater. The RCF and SF system (floor of one-way joists and hollow lightweight concrete blocks) plus 50 mm EPS insulation has a transmittance of 0.625 $W/m^2{\cdot}K$ while the MSP roof (200 mm EPS insulation) has a transmittance of 0.187 $W/m^2{\cdot}K$ (nearly one third). Then, taking into account that all the envelope surfaces (MSP, RCF and SF cases) had, basically, the same dimension it is possible to calculate the percentage of energy savings due to the improvements on the envelope transmittance. Considering that the savings are referred only to one third of the heat flows shown on Fig. 19, the MSP building technology will reduce around the 20% of the energy losses. Details can be seen in Table 2.

	RCF & SF configurations	MSP configuration	Subtotal	TOTAL
External walls	RCF & SF. Cavity wall + EPS 50 mm	MSP 35-EPS140-35 mm	10.6%	19.9%
Roofs	RCF & SF lightweight concrete blocks floors + EPS 40 mm	MSP 50-EPS200-35 mm	9.3%	

Table 2 Energy savings due to the transmittance reduction of the MSP envelope

4.5 Economic appraisal

Economic costs due to the construction of each configuration can be seen in Fig. 20. The calculated amounts only include the cost of the building components specified for each configuration: foundations, structure, envelope (external walls and roof) and internal walls.

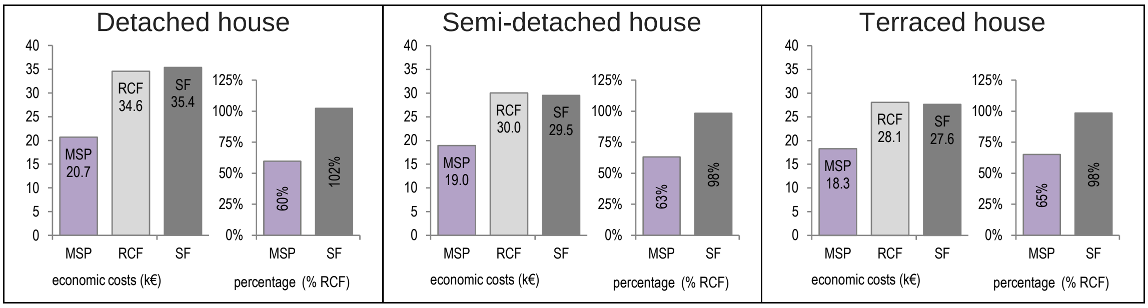

Fig. 20 Economic costs in k€ (per dwelling unit and being the basic ground acceleration 0.16·g, the snow load 0.4 kN/m^2 and the soil bearing capacity of 0.8 kg/cm^2)

As shows Fig. 20, the costs of foundations, structure, envelope (external walls and roof) and internal walls in RCF and SF configurations are similar. However, the MSP technology is around 60% to 65% cheaper, depending on the house typology. As was likely to occur, the terraced house cost is lower in all the three structural systems, due to the sharing of the foundations, beams, columns, bearing walls and party-walls.

5. Synthesis of results

A multiple quadratic regression – based on the results obtained in 510 cases – has been developed (1) in order to obtain the relative amount of embodied energy, CO_2 emissions or the economic costs for a given type of building. The function always refers the values of MSP or SF configurations to the corresponding value of RCF and returns the ratio between those values. This mathematical expression depends on three variables (see domains in Table 3) and eleven parameters (p_n, where n ϵ [0,10]) which values can be find in Table 4 and Table 5 for SF results compared with RCF, and in Table 4 and Table 6 for the MSP solution compared with RCF. The function can be checked using the values shown in Fig. 17, Fig. 18 and Fig. 20 and its maximum deviation from the calculated values is less than 1.5%.

$$f = p_0 \cdot (p_1 + p_2 \cdot bga + p_3 \cdot sl + p_4 \cdot ss + p_5 \cdot bga \cdot sl + p_6 \cdot bga \cdot ss + p_7 \cdot sl \cdot ss + p_8 \cdot bga^2 + p_9 \cdot sl^2 + p_{10} \cdot ss^2) \quad (1)$$

	bga	sl	ss
	Seismic load (Spanish NCSE-02) Basic ground acceleration for Modal Response Spectrum Analysis	Snow load	Soil type: cohesive Soil strength
	bga/gravity	kN/m^2	kg/cm^2
upper boundary	0.20	1.2	2.4
lower boundary	0.04	0.4	0.6

Table 3 Range of each variable

	Detached		Semi-detached		Terraced	
	SF vs RCF	MSP vs RCF	SF vs RCF	MSP vs RCF	SF vs RCF	MSP vs RCF
Cost	1.04082	0.96103	1.00000	1.00000	1.00305	1.04012
CO_2 emissions	1.05130	0.99534	1.00000	1.00000	1.00185	1.02124
Embodied energy	1.05420	0.98132	1.00000	1.00000	1.00215	1.01713

Table 4 Type of building parameter p_0

	SF vs RCF									
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
Cost	0.93546608	-0.65870906	0.11199692	0.04158580	-0.58288861	0.00442331	0.00215675	5.18013649	-0.02581504	-0.01090438
CO_2 emissions	1.01531101	-0.98080361	0.15881675	0.08783704	-0.88405084	0.00277974	0.00477887	7.61745690	-0.03404530	-0.02252354
Embodied energy	1.04406629	-0.97703629	0.14493508	0.07242220	-0.87355788	-0.00788916	0.00369540	7.03340517	-0.02465235	-0.01818116

Table 5 Parameters (p_1 to p_{10}) for comparing SF vs RCF

	SIP vs RCF									
	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8	p_9	p_{10}
Cost	0.58341700	0.00231474	-0.00962647	0.10128657	0.00690526	-0.02052374	0.00527087	-0.90535201	0.00202397	-0.02472408
CO_2 emissions	0.77072951	0.01476742	-0.02748906	0.20438529	0.01645317	-0.06012399	0.01019661	-1.77137213	0.00853926	-0.04899709
Embodied energy	0.53902333	-0.00674664	-0.02337219	0.11385212	0.01098819	-0.04128353	0.00541620	-1.40319684	0.01033029	-0.02697077

Table 6 Parameters (p_1 to p_{10}) for comparing MSP vs RCF

6. Discussion

A closer observation of the results obtained shows that MSP configuration achieves its best against RCF on those cases where the structure was submitted to a high seismic activity (bga = 0.20·g) and a low or moderate snow load (sl = 0.40 kN/m^2) being the soil cohesive and of poor quality (ss = 0.60 kg/cm^2). In this scenario, the MSP economic cost is 59.5% of a RCF configuration, CO_2 emissions of MSP are the 79.5% of RCF and the embodied energy of MSP is only the 53.0% of the amount embodied on RCF.

However, the lesser benefit corresponds to those cases where the building is located in areas with low seismic activity (bga = 0.04·g) and the structure bears heavy snow loads (sl = 1.20 kN/m^2) but is supported by a cohesive soil of good quality (ss = 2.40 kg/cm^2). This time the MSP economic cost is the 68.8% of a RCF solution, the emissions of CO_2 are nearly the same (98.0%) and the embodied energy is only the 65.3% of the energy enclosed in the RCF configuration.

On the other hand, when comparing the SF cases with the RCF, the differences are on the opposite side. The worst results of SF against RCF correspond to locations of high seismic activity (bga = 0.20·g) with low or moderate snow load (sl = 0.40 kN/m^2) but with cohesive soil of good quality (ss = 2.40 kg/cm^2). In this case the SF economic cost is 104.6% of the RCF cost, the embodied energy is the 118.3% and the CO_2 emissions rise until the 119.8% of the RCF.

Though, very small differences are obtained SF vs RCF when the buildings are located in moderate seismic activity places where the snow load is low or moderate and the soil has poor quality. In these cases SF offers worse results than RCF bus the differences are always lesser than 8%.

From the point of view of the structural performance, the MSP has shown against RCF or SF configurations even a better behaviour because of its high strength and stiffness. These properties are especially interesting when the structure must support relevant seismic loads and/or the foundation must transfer the loads to soils with poor bearing capacity. The reason of this good response is the surface distribution of the structural material (reinforced concrete) forming a three-dimensional, monolithic, continuous and lightweight system. This configuration is very common in many organisms in Nature and it seems to be advisable at least for low or medium rise structures.

The reduction of heat loses through external walls and roof is also substantial (20%) when comparing a well-insulated RCF or SF solution with the even better insulated configuration provided by the MSP. This is especially important when taking into account that the 70% of the household energy consumption is devoted to space-heating.

7. Conclusions

The use of Reinforced Concrete Multilayer Structural Panels improves substantially the long-life eco-efficiency of the most common residential buildings: the single-family (detached, semi-detached and terraced) houses. During the construction phase, these types of houses embody more energy and emit more CO_2 per unit of dwelling than any other residential typology because of its size and high ratio of envelope surface to inhabited volume. Reductions up to 20% in CO_2 emissions and 35% to 45% in embodied energy can be achieved building these houses with this technology.

At the same time, during the use phase, these types of buildings are avid energy consumers because of the heat lose through its envelope (external walls and roof). Reductions up to the 20% can be attained using Multilayer Structural Panels to construct the structures and the building's envelope. Furthermore, this technology can provide more affordable housing because its economic cost is, at least, a 30% less than the solutions based on Reinforced Concrete or Steel Frames combined with insulated brick cavity walls.

Reinforced Concrete Multilayer Structural Panels are highly efficient in structural terms because its lightness reduces substantially the self-weight and the earthquake inertial forces. Its eco-efficiency is more remarkable for buildings (low or medium rise) located on places with high seismic activity, low or moderate snow load and cohesive soil of poor quality. This building technology provides not only highly energy efficient envelopes but also structures substantially stiffer than those built with Reinforced Concrete Frames or with Steel Frames. Moreover, multilayer structural panels have the ability to accommodate – without experiencing significant damage – the movements generated by earthquakes or due to differential settlements.

Finally, the uncoupled building technologies composed of structural systems based on highly specialized and efficient elements but devoted only to the load transfer requirements and envelopes (external walls and roofs) providing only thermal insulation are substantially less eco-efficient than the coupled technologies were the building's envelope fulfil not only the thermal insulation requests but also the structural ones.

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