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Dry Construction Systems for Sustainable Buildings in Mediterranean Context: An R&D Project in South Italy

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Abstract

The paper refers to construction engineering research and regards the development of sustainable building technologies for the Mediterranean area. It presents a work concerning the design of a modular and customizable construction system through the use of a steel structure and hemp and lime fiber components, suitable for residential buildings and offices. The system is based on dry layered technologies useful for the reuse and recycling single components (referring to circular economy principles); it contemplates the use of sustainable materials, like hemp. The R&D project aimed to increase the adaptability of lightweight construction system to Mediterranean climatic conditions, that usually prefer heavy systems (masonry and reinforced concrete), with reference to the performance of external walls, suggesting a solution to control summer overheating. The construction of a 52 square meters prototype in Crotone (Calabria region, South-Italy) allowed the assembly system to be tested and measurements to be taken regarding: construction component performance, indoor air quality, the systems which are powered almost exclusively by renewable sources. The results obtained were positive and encourage the use of light dry components even in the Mediterranean area.

Keywords: *construction engineering, sustainable buildings, steel structure, hemp fiber components, dry construction systems*

Introduction

This study presents the final results of the R&D project "*Ac.Ca. Building: Progettare e costruire in sicurezza con l'acciaio e la canapa. Tecnologie innovative per edifici ecosostenibili*" (Ac.Ca. Building: safe design and construction with steel and hemp. Innovative technologies for sustainable buildings). It was financed with European funds and was conducted in 2018-2020, the project concerned the development of an integrated system of typological and technological solutions with high flexibility for residences (collective, co-housing, mixed systems) and for advanced working spaces (co-working offices, fab-lab), destined for temporary users (Lucente 2019, Lucente 2020, Canestrino et al. 2020). The project, funded in the EU framework within the POR Calabria FESR-2014-2020, was based on a partnership that committed a working group of the Department of Civil Engineering of the University of Calabria (coordinated by Laura Greco and Roberta Lucente) and the following companies: Metal Carpenteria S.r.l. (steel structure producer), Metalinea s.r.l. (hemp fiber components producer), Irenova - Energy Solution (design and management of energy systems), Polo NET (facility, logistics, soil availability for a prototype construction), Leonardo Progetti S.r.l. for a consultancy. The work obtained a Technology Readiness Level (TRL) close to 7 out of 9 points. This paper presents the results of the research conducted at the Department of Civil Engineering of the University of Calabria with particular reference to the technological features of the system.

The recent interest in dry construction systems is inspired by the environmental sustainable approach to the building sector and by the increasing application of circular economy to the construction materials and products (Mulhall et al. 2019, Morganti et al. 2019). In fact, these systems, favouring the technical reversibility of buildings parts (i.e. floors, roofs, walls) promote a correct approach to building cycle control procedures reducing the consumption of resources, the production of waste and of polluting emissions due to transformation and demolition of buildings and parts of them (Elma 2019).

Dry construction systems were introduced in modern construction in the last century as techniques based on the use of prefabricated industrial components assembled on site using dry connections, without the use of wet binders such as concrete or mortars. With the diffusion of panels, sheets and insulating materials, these systems spread in the US and European construction mainstream. In recent decades, the features of dry construction systems advanced towards more complex configurations, where the number and the types of products and materials assembled increased, guaranteeing technological performance buildings and the control of thermo-hygrometric, acoustics, fire safety, structural strength and maintainability requirements. Generally, dry-sandwich construction systems are characterized by the ordered succession of technological parts (Zambelli et al. 1998, Imperadori 2012), forming a solution with a performance that can be graduated and modified, considering the transformations of the building over time, until its complete demolition (Greco 2017). The concept of layering, associated to the arrangement of the floors and walls characterizes the new dry construction systems (Zambelli et al. 1998). Dry sandwich construction systems are, therefore, characterized by their skill to impact the environmental sustainability of building processes (reduction of resource consumption and production of waste and polluting emissions, recovery and recycling of materials and components).

This is the background of the research developed within the Laboratory of Design and Survey of Architecture (Section of Architectural and Technological Design) of the Department of Civil Engineering of the University of Calabria concerning the use of sandwich construction systems in a warm-temperate climate, and in the South-Italian context in particular. The application of these systems in multi-storey buildings has been studied in the R&D project "*Ac.Ca. Building*".

Studies for the Use of Construction System in Italy

The use of dry construction systems presupposes the consideration of the climate context of reference, in order to optimize technological performance and to maximize the correspondence between climate features and technological choices (Greco 2019). The interaction of light construction systems with the environmental qualities of Mediterranean areas with a warm-temperate climate, is a primary issue. A building with an accurate energy performance favours solar gains in winter and limits overheating in the summer, it takes advantage of natural ventilation for the thermo-hygrometric control, generally reduces thermal exchanges with the outside thanks to the insulation of the building envelope, and uses thermal accumulation masses (walls, floors) to limit internal thermal fluctuations. This building behaviour becomes more complex in temperate Mediterranean contexts, where climate variability demands complex design solutions: defence from cold and protection from heat (Rogora 2012).

Dry construction systems, taking advantage of their sandwich structures support technological performances of floors, walls and roofs that can be modified and adapted to different energy needs during the year and/or day. The lightness of these construction systems accentuates critical questions related to their reduced thermal inertia. Typically, in Mediterranean areas a pertinent design aspect for the control of thermal oscillations concerns the integration of thermal storage elements in the building envelope, the floors and the internal walls. In fact, the reduced thickness of walls, roofs and floors and the thermo-physical characteristics of the materials generally used in dry construction systems, do not allow the control of internal thermal fluctuations in the hot season. This circumstance is one of the reasons that has slowed the spread of dry construction systems in Italy and in the south of the country in particular (Greco 2019).

Furthermore, designers and builders specialized in the masonry technique for many centuries and subsequently in that of reinforced concrete starting from the 20th century. The delay of the Italian manufacturing industry in the construction sector favored the preservation of the building masonry tradition in the 20th century, even in periods of economic well-being. In Italy, the use of dry construction systems for residential buildings spread in the first decades of the last century, with the development of the first modern prefabricated systems for serial houses. The experiments involved holiday and emergency houses, which were also exported to Italian colonies in East Africa. In these experiments, a priority was how to adapt light walls and roofs to the Italian climate (Greco and Spada 2019, Greco 2021). In these cases, the external and internal walls were built on site using a metal frame and Eternit or Cel-bes panels and an air chamber filled with insulating material in the middle. However, they showed problems of overheating in warmer climates and low durability (Valle 1938). On the other hand, in Italy there was no market demand for dry construction systems, allocating them mainly to temporary and emergency buildings, so masonry and reinforced concrete structures was preferred for housing. This mistrust was determined by a cultural climate strongly influenced by the masonry construction tradition and by technological delay of the Italian building sector, which caused the slow progress of building industrialization, which developed widely only starting from the 1960s (Greco 2021, Iori 2012). In any case, these experiences constitute a useful historical reference for today's developments, especially to highlight weak points of dry construction in the Italian context which is marked by the lack of diffusion of this technique among designers and builders and also by the Mediterranean climate.

The project Ac.Ca. Building has been characterized by the definition of a flexible construction system based on the assembly of recyclable industrialized components that can be customized according to a mass customization process. The steel framed structure is combined with the building envelope and floor components made mainly of hemp fiber products, that, so far, have been almost exclusively associated with reinforced concrete structures. Dry construction systems with steel technology are currently used in combination with components for walls and slabs consisting of metal sheets or sandwich panels in gypsum or fiber cement, assembled in highly insulated packages with insulating layers inserted in special cavities. As known, panels are supported by metal frames screwed to the floors by rails and studs. The Ac.Ca. Building system involves use of innovative coating components, based on hemp fibers. These are panels of variable thickness depending on the use (external and internal walls, floors), thermal and acoustic insulation (loose and in slab), finishing (internal and external plaster). This option favors a sustainable use of the system as a whole, thanks to the characteristics of hemp-based products.

Hemp has been used in construction since ancient times; its traces can already be found in Leon Battista Alberti's "De Re Aedificatoria". It has recently been appreciated for its mechanical resistance and environmental sustainability. In fact, studies concerning its LCA (Life Cycle Assessment) highlight a negative C02 emissions balance. The plant has a speedy growth, so its biomass balances out carbon emissions caused by lime process production (it is used as a binder for hemp fibers) and the transport of finished products. The use of two biodegradable materials (hemp and lime) allows the production of construction components disposable in the soil, which increases basicity.

Ac.Ca. Building R&D project included a preliminary industrial research activity and a subsequent experimental development phase. The first action concerned the development of the typological catalogue intended for housing and working spaces and of the technological one (industrialized components of reduced number organized in sandwich sections). The second step concerned the construction of a housing unit prototype in Crotone, a small Calabrian city.

In order to reduce the environmental impact resulting from resource consumption, waste production and emissions during the building life cycle, the Ac.Ca. Building system make available construction solutions that are largely transformable and largely compatible with the recovery and/or recycling of materials and components. In fact, Ac.Ca. Building provides two levels of modifiability for the technological setting. A long-term first level of modifiability concerns the steel skeleton of the building: it allows changes in the structural set-up for specific and unplanned needs. An example of these type of transformations are the variations of the structural layout for addition, modification or subtraction of parts, like for staircases. These possibilities are offered by the steel structure; however, they are evaluated with design and construction measures on a case-by-case basis. Consequently, a long-term technological performance is assigned to the Ac.Ca. Building structural skeleton and staircases, which generally reflects the entire building life cycle. A greater second level of modifiability for the system parts provides medium-term variations; it concerns internal and external walls, roofing, floors, systems.

Ultimately, the Ac.Ca. Building is made up of parts that can be modified as a result of radical transformations of the building technological-functional structure and parts that can be modified in the medium term for ordinary and/or foreseeable actions to adapt the technological responses of the system parts.

At the end of the life of the building, the sub-systems of Ac.Ca. Building are designed to be disassembled and recycled by pieces or reused in some cases; this is possible thanks to the extensive use of dry connections. With the exception of foundation structures, connections are free of wet binder. Only some finishes require the use of glues for fixing (e.g., linoleum floor). The design choices make it possible to pursue objectives of disassembly and separability of the parts, also considering the complex technological profiles of walls and roofs, where the functional layers are composed of different products for chemical-physical and production characteristics

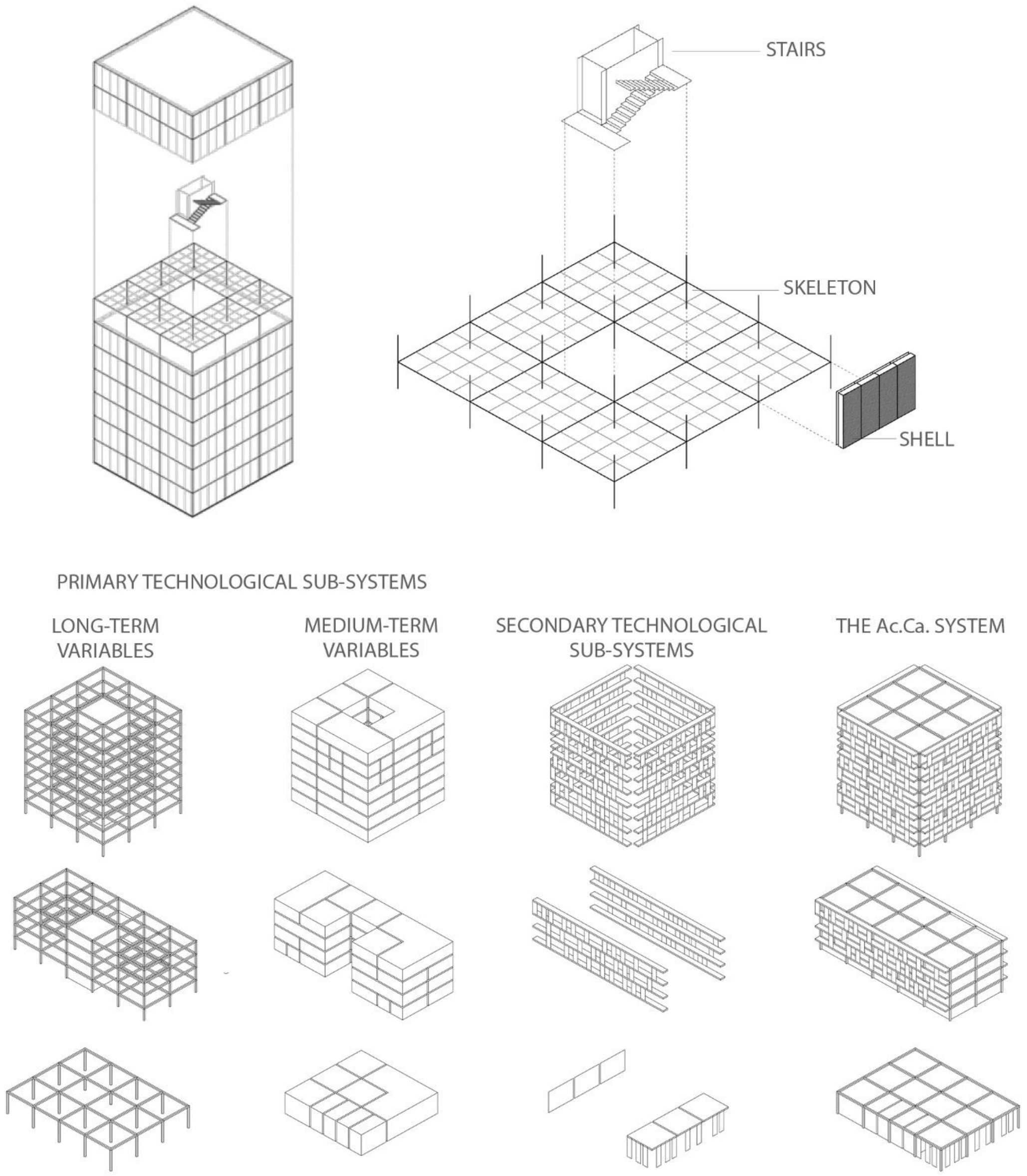
The Ac.Ca. Building System: Skeleton, Stairs, Shell

The general architecture of the Acca Building system can be referred to three functionally and technologically distinguishable parts: skeleton, stairs and shell (Figure 1).

The skeleton includes the foundation and vertical elevation structure of the building; the stairs include all parts of the stairs and the elevator block. The shell includes the external and internal walls and the floors of the building; it separates the inhabited space from the outside, defines the internal layout, provides conditions of environmental comfort for users, ensures energy savings and reduction of polluting emissions (resulting from incorrect use of the systems).

The skeleton and stairs are the editable parts with complex actions. In other words, they ensure primary functions of an invariant nature: supporting the building and ensuring circulation within it. The third part - the shell - ensures time-varying primary functions; its peculiarity consists in allowing functional and technological modifications and transformations. This design approach has made it possible to achieve six objectives, which have become peculiar features of the Ac.Ca. Building system; they are described below.

Figure 1. *The Functionally and Technologically Parts of the Ac.Ca. Building System*



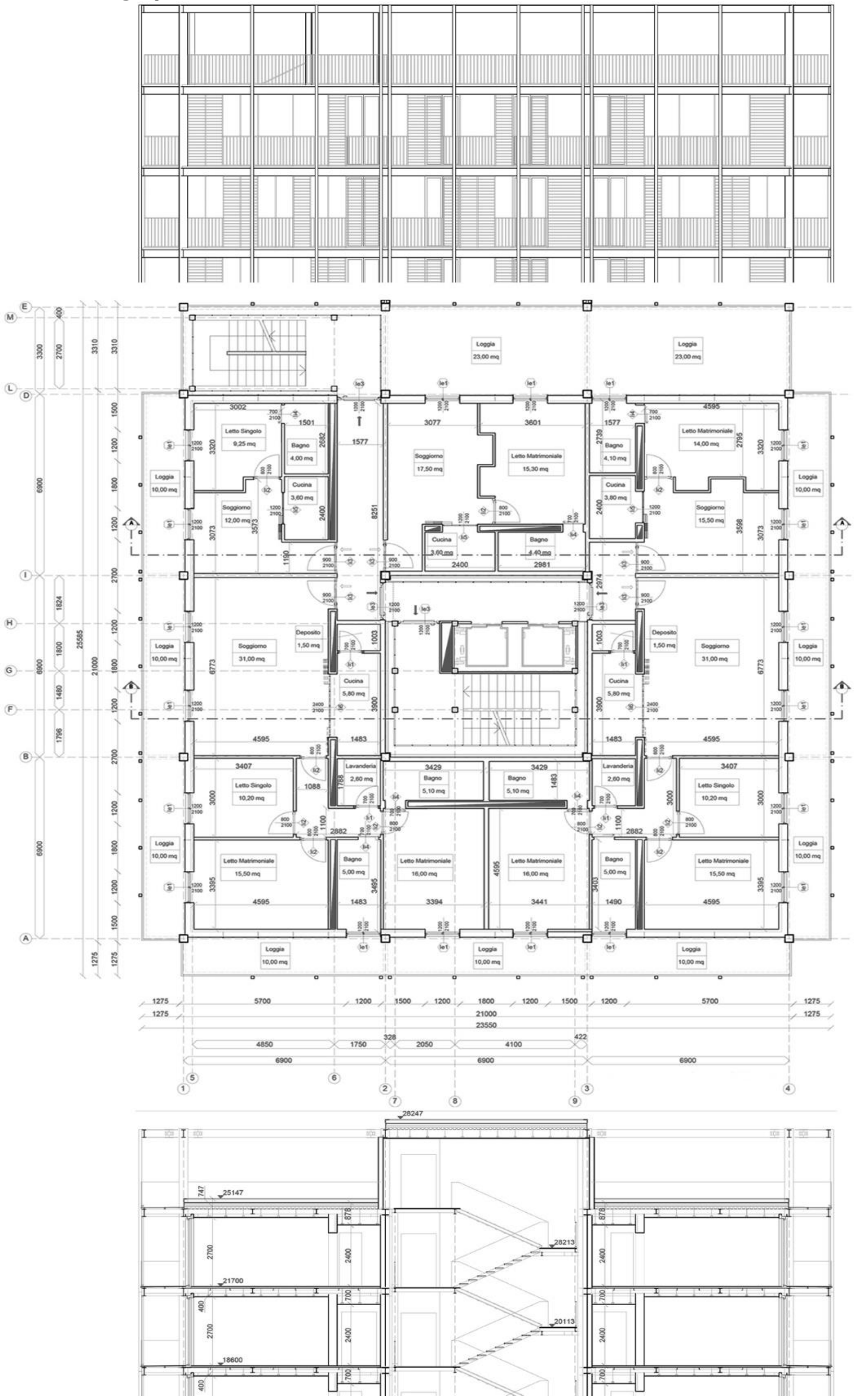
A first feature is the Ac.Ca. Building modularity, aimed at simplifying the construction method. The use of modular components and sub-systems allows the saving of materials and products, the standardization and optimization of the processing cycles, the standardization of the assembly sequences and the types of connections. Furthermore, the modularity of components and sub-systems allows the disassembly and relocation according to different configurations of the same elements, contributing, also in this case, to a sustainable management of the building process. The square structural module is equal to 6600x6600 mm; the inter-floor is equal to 3100 mm (net height is 2700 mm, floor is 400 mm including false ceiling). The structural elements (beams, sheets, columns) conform to these dimensions. The hemp panels used for internal and external walls have a standard width of 600 mm and 1200 mm, with special elements for corner connections and the positioning of openings, or junction fittings (Figure 2).

The second characteristic of the Ac.Ca Building system is its good energy performance. As is known, the steel structure presents problems of thermal bridges which risk worsening the performance of highly insulated casings. For this reason, the envelope was positioned flush inside the structure, which is therefore exposed and advanced, whatever the dimensions deriving from the design calculations. This relationship between the structure and the envelope is combined with the use of insulated walls and floors. The thermal bridges between the structure and the envelope are resolved by insulating the shell (walls, floors, roofing) with an insulating layer placed both on the intrados and on the extrados of the floors and roof and in the panels used for the external walls. This configured a construction system with non-thermally insulated skeleton and internal spaces enclosed by insulated envelope.

The retraction of the shell referred to the structural skeleton has further objectives. The shell defines a perimeter that can be modified independently of the structural set-up. This is very important for multi-storey residential buildings. In fact, the exposed structure allows the assembly of cantilevered parts both during the construction phase of the building and for any subsequent extensions. In the "basic" configuration of the building there is a cantilevered walkway with a minimum depth of 600 mm which can be equipped with a service bridge, capable of facilitating maintenance of the facade, as well as being a private or common balcony for residential units. This space can also be used for extensions of the internal space by moving the external walls. In any case, the rear position of the shell with respect to the skeleton allows to obtain a service bridge on all levels of the building, offering a useful working platform for maintenance, reducing costs and times.

Furthermore, the independent position of the external wall with respect to the structure allows change (number and type) of the layers composing the envelope, both in relation to the use (residential or industrial) or to future and changed performance of the technical elements. The use of mechanical connections facilitates the replacement or addition of individual layers (thermal and acoustic insulation, system pipes). This allows the sub-system, or parts of it, to be modified over time, limiting economic and environmental burdens. In addition, this approach facilitates plant integration, with the possibility of carrying out monitoring and adaptation works of the plants, thus reducing costs and construction times.

Figure 2. *Plan, Elevation and Section (Pieces) of a Tower Building Designed with the Ac.Ca. Building System*



The Ac.Ca. Building Sub-Systems and Technological Profiles

The skeleton, stairs and shell of the Ac.Ca Building system are divided into primary technological sub-systems and secondary technological sub-systems (Figure 1). The primary technological sub-systems respond to primary functions of the building construction: supporting the parts of the building, closing and separating the internal space from the outside, defining the internal layout. The secondary sub-systems complete the building in the external parts (balconies, stairs), ensuring conditions of comfort and safe use. This articulation has been optimized by reducing the number and type of parts.

"Technological profiles" have been defined for the more complex sub-systems; they are useful in responding to diversified environmental conditions and functional structures and various uses (residential and industrial). The technological profile defines a specific operating mode of the sub-system, which is distinguished by a set of technological requirements controlled by one or more technological layers/parts included in the sandwich of the sub-system and/or its components. Each profile can be modulated in relation to the conditions of use and the specific climatic context through geometric-dimensional characters typical of the entire sub-system or component and through the constituent parts. This methodology made it possible to offer a versatile technological response through a reduced number of system parts.

Figure 3. *A Part of the Abacus Referred to the Primary Technological Sub-System*

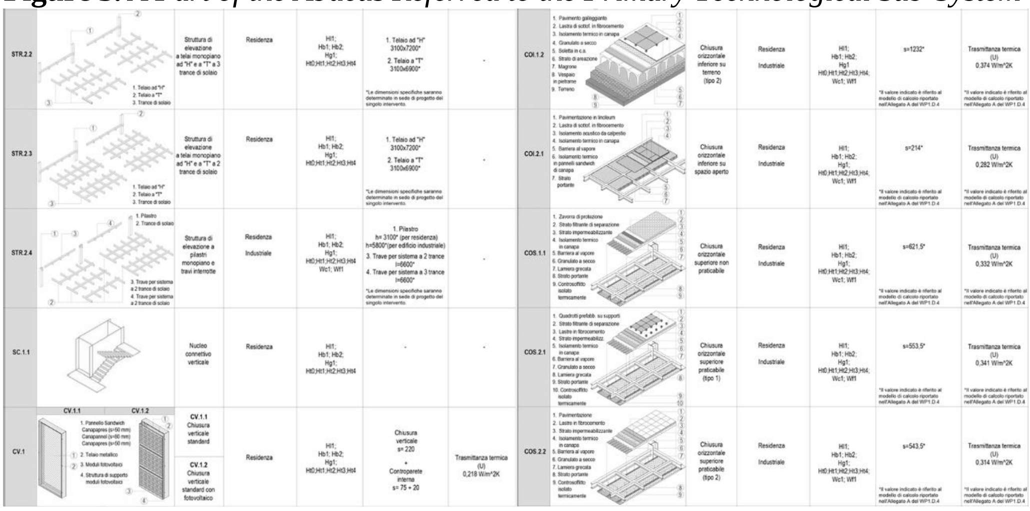
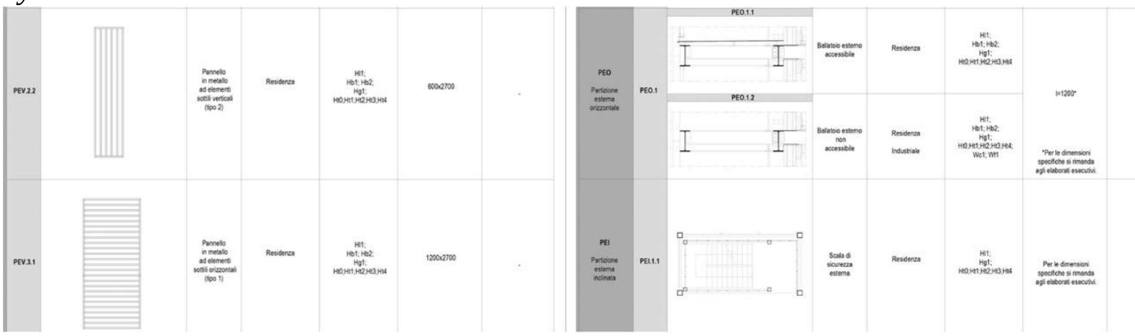


Figure 4. *A Part of the Abacus Referred to the Secondary Technological Sub-System*

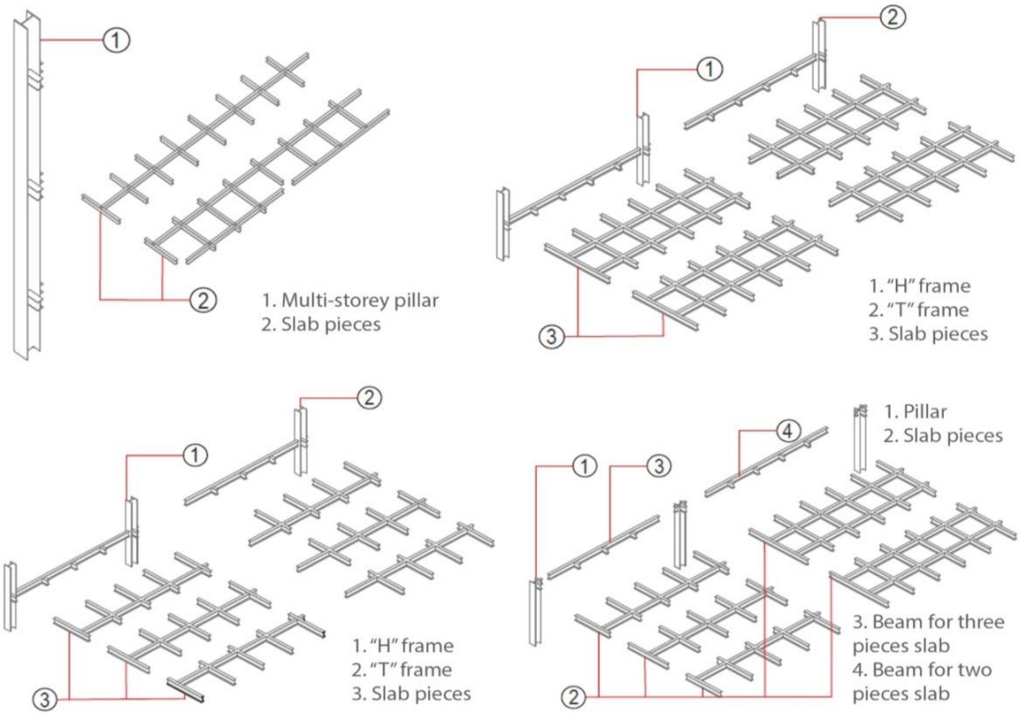


In fact, the Ac.Ca. Building is made up of 11 technological sub-systems which correspond to 42 technological profiles (Figures 3-4). The Ac.Ca. Building is of the "open" type, therefore the grid of primary and secondary modifiable technological components and sub-systems allows additions and modifications in response to changed or new demand conditions in the building market.

Skeleton

The structural types can be: frame schemes, multi-storey pillar, simple elements (pillar, beam). The study has favored a high level of prefabrication, therefore the elements can be transported by ordinary vehicles. Buildings (single and multi-storey) and different uses (residence and work) are possible. In any case, the square geometry of the base module (6600x6600 millimeters) does not change; it optimizes the mechanical response of the steel components, the methods and costs of transport and movement, the compatibility with the Ac.Ca. Building typological layouts. To this end, two hypotheses for the structures have been developed. The first alternative, suitable for multi-storey buildings, considers the use of multi-storey pillars (also called "passing pillars"), i.e., linear elements 9.30 meters high to serve three floors, and large elements for floors (2x12 meters). The second alternative concerns "H" and "T" frames, of dimensions equal to 3.10x6.60 meters, while the floors are composed of three elements of 2.20x6.60 meters or, alternatively, of two elements of 3.30x6.60 meters (Figure 5).

Figure 5. *Structural Types of the Ac.Ca. Building System*



The choice is made by evaluations on the type of construction site. In all cases, welded connections are used for the beam-column joints (made during the production of the elements in the factory) and bolted connections for the beam-beam and column-column joints (carried out on site). Connection between beams and pillars are rigid (welded in the factory) so as to reduce the need for bracing. These choices were made for the production approach developed so far by Metal Carpenteria S.r.l. and to enhance the company's know-how in a new sector (housing). Additionally, connections welded in the factory speed up assembly times on site, reducing the on-site connection to the head-to-head type. While considering that the solution with multistorey pillars (9.30 meters high) and slabs reduces the number of connections on site, it should be noted that the solution with frames and slabs pieces is more efficient related to construction, since the lighter elements are more easily moved on site.

Similar considerations can be made for the floors. Larger and heavier elements are more expensive to move on site, even if they have fewer connections. Therefore, the structural typology must be decided case by case, in relation to the specific work. The availability of more options is part of the open industrialization vision that is the assumption of Ac.Ca. Building. The choice of a 3100 mm center distance between the floors combines easy transport and the possibility of an internal height of 2700 mm; the floor has a thickness of 400 mm, including false ceilings for systems.

External Wall

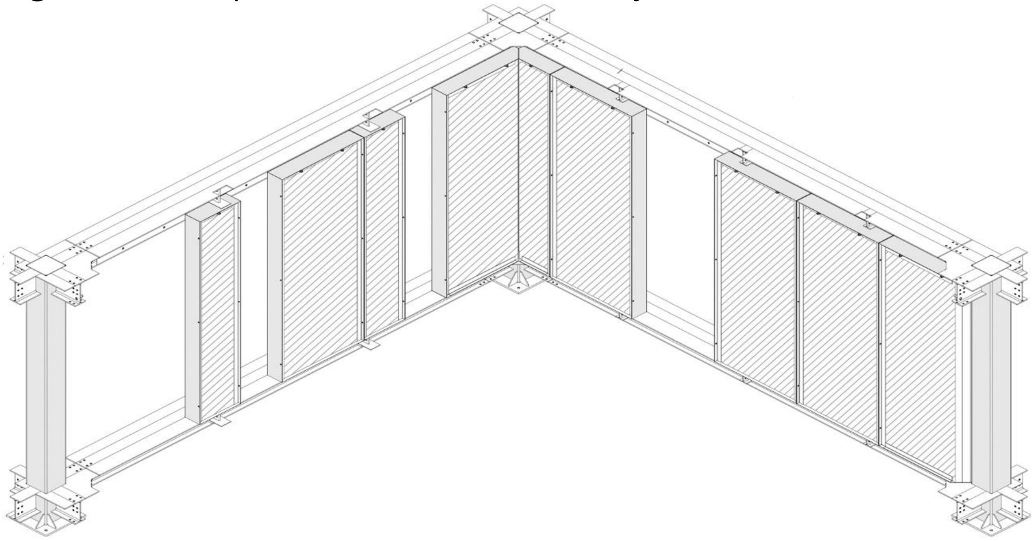
The external wall is mechanically fixed to the structure and completed by an internal counter-wall for the passage of the systems. The connection is made with a metal frame. The wall thickness changes depending on the climatic zone and the required thickness of thermal insulation. The special pieces were limited to the half module panel (i.e., 600 mm wide) and to the one for correcting the thermal bridge of the pillar (internal side) (Figure 6). The system is quick and easy to assemble thanks to metal plates welded to the beams. The plates are used for fixing the external wall elements and the internal counterwall. This is made up of a metal frame (50 or 75 mm thick) and hemp panels. This solution (metal frame and hemp panels) is also used for the interior walls.

Roof

Roof is defined as an element composed of three macro-parts: an upper package that ensures thermal insulation, impermeability and accessibility (if provided) of the roof; an intermediate package consisting of a double-frame steel floor and folded metal sheet; a lower package with cavity that can be equipped for systems. Layers are assembled with dry technique. The modifiable parts of the sub-system concern, in particular, the extradosal and intradosal technological packages. The advantages are: adaptation of the thermal-acoustic insulation requirements, maintenance of the intermediate layers and external cladding, maintenance of the intrados systems.

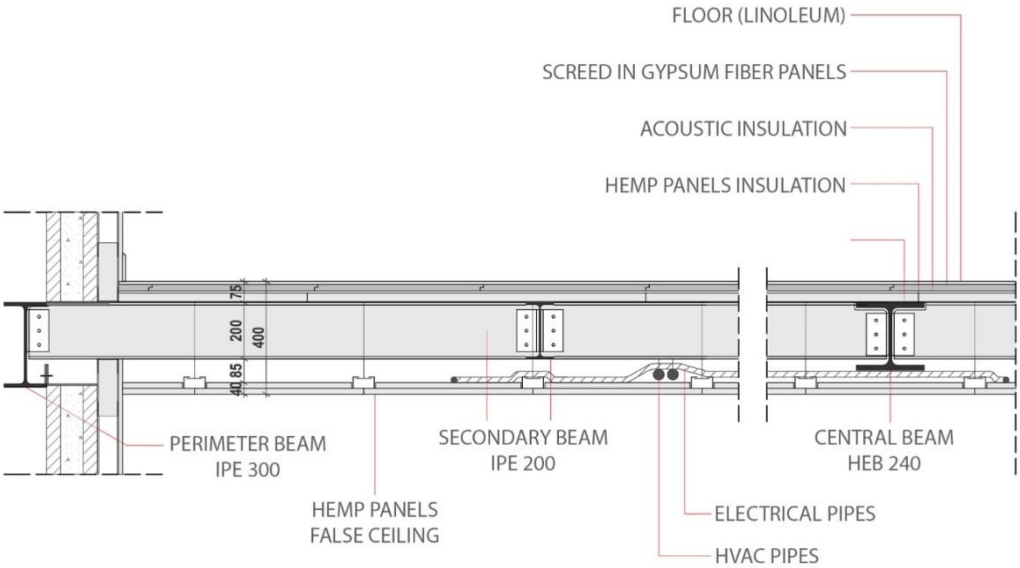
There are four technological profiles deriving from this sub-system architecture, corresponding to accessible/non-accessible roof models, with visible systems. Unlike the intermediate slabs, the upper layer of the folded sheet is a dry granulate which allows to create the slope to the roof (therefore of variable thickness), thanks to the type of material.

Figure 6. *Panels of the External Wall, Mechanically Fixed to the Structure*



Above are positioned: vapour barrier, hemp thermal insulation (thickness at least 50 mm), waterproofing layer (a sheath of 3 or 4 mm). In the case of a non-accesible roof, the stratigraphy is made up of a separating filter layer and gravel; if accesible, the layer under the floor is made of fiber cement panels (thickness 22 mm) which is not damageable by rainwater. The floor can be placed on thermoplastic supports creating a floating floor that can be equipped for the systems installed on the roof (solar thermal and photovoltaic).

Figure 7. *Section of the Slab*



Slab

Floors are rigid (as regards the statics) thanks to the bidirectional joists. This choice also made it possible to move the elements of the system while maintaining the two-dimensional geometry without the need to break down the floors into single linear elements during both the transport and assembly scheme.

An easy-to-assemble scheme has been designed for the floors, both in terms of the type of elements and materials, and also light and performing from a thermal and acoustic point of view. It is composed of a thin sheet metal (4 mm) welded on the bidirectional joists, on top are placed: a hemp panel for thermal insulation (30 mm) and a sheet for acoustic insulation (thickness 8 mm), then a sheet of gypsum fiber substrate (thickness 23 mm) to support the finishing layer (floor). Below, the slab is completed by a false ceiling with double hemp panels (20 + 20 mm). The choice of using a layer of thermal insulation below beams and joists and another above is necessary to obtain the insulation of all parts of the shell (in addition to increasing the performance of the technical element). The space between the lower and upper coatings can be used for systems.

If system ducts are particularly bulky (for example in case of controlled mechanical ventilation service) it is possible to increase the slab equipment capacity by using perforated metal core beams capable of allowing the passage of larger systems. In any case, the total thickness of the floor must not exceed 400 mm, in order to make the height of the vertical supports (3100 mm) compatible with the minimum habitable height (2700 mm) (Figure 7).

Ground Floor Slab

The ground floor slab includes a reinforced concrete layer cast on site (minimum thickness 40 mm) to connect the plastic domed formwork (the so called "igloo"). The use of concrete cast on site is limited to this part of the building and to the foundations. The two phases are connected, so they do not interfere with the general planning of the building-site based on dry-systems technologies. Finally, section is composed of dry granulate, hemp thermal insulation, fiber cement panel and linoleum floor. The sub-system includes two technological profiles: slab on open space (e.g., on a porch) and on ground.

The Ac.Ca. Building Prototype

In 2020 a prototype of the Ac.Ca. Building was built in Crotone, a small city on the Calabrian east coast (Figure 8). It consists of a structural module (6600 x 6600 mm) within which the layout of a single-family residence has been defined. The construction allowed a verification of the assembly of the structure and of the main technological sub-systems of Ac.Ca. Building, on which technological performance monitoring was also performed. The modularity of the system made it possible to create a test model consisting of a single structural span (the layout consists of the base module 6600x6600 mm); it is an example of the design and assembly conditions for the construction of multi-storey buildings with a larger plan area.

Figure 8. *A Prototype of the Ac.Ca. Building: Rendering and Realization*

The prototype is a single-storey building, so the solution with frames and pieces of slab was chosen. This solution is considered the most efficient from the point of view of transport and moving of the elements on site. The section of the pillars is box-like, with dimensions 300x300x6 mm. This choice is consistent with the technological repertoire, it also follows a consolidated know-how of the company-partner producing metal carpentry (Metal Carpenteria S.r.l.) and has proved successful for the reasons set out below.

The structural calculations show that the same external geometry (300x300 mm) can be maintained even in the case of a residential tower building (up to 9 decks above ground) by increasing the thickness of the profile. In addition, the square geometry (instead of an IPE or HE profile) facilitates the bolted connection of the beam.

Structural calculations prove that the same external geometry (300x300 mm) can be maintained even in the case of a residential tower building (up to 9 floors above ground) by increasing the thickness of the profile. In addition, the square geometry (instead of an IPE or HE profile) facilitates the bolted connection of the beam.

Figure 9. *Pillars of the Ac.Ca. Building Prototype: The Beam Connections is bolted Head-to-Head, Thanks to the Pillars Capital*

Figure 10. *Pieces of the slabs for the Ac.Ca. Building Prototype*

Each pillar is produced in the factory and has a capital. A first, short, section of the beam attached to the pillar is welded to this (Figure 9): a sort of support, which allows the creation of the beam-pillar union far from the node (which remains rigid, thanks to the capital welded in the factory) or to ensure that the connection is bolted head-to-head, easily assembled on site by lifting the pieces with a crane (or mobile crane) and lifted workers. The two floors of the prototype (the base one and the roof one) are each made with three pieces (Figure 10). The bidirectional framework guarantees a rigid deck, so bracing in the horizontal plane are not required; furthermore, the use of two-dimensional elements (instead of single linear joists) reduces assembly time. Also in this case, assembly of the three pieces is obtained with bolted joints; those welded (necessary for creation of two-dimensional elements) are used exclusively for production in the factory).

The Assembly of the Structure

The assembly sequence follows an optimized scheme for a smart movement of the pieces. Once foundations have been completed, pillars are bolted to the plinths by means of anchoring bolts. Subsequently the perimeter beams of the base and the three pieces of the slab of the first deck are mounted (by bolting). At this point, the perimeter beams of the roof are connected to the pillars (Figure 11). These are mounted after the three pieces of the first slab so that they can be moved more easily (by crane or mobile crane). To facilitate assembly, the external wall modules are mounted before the pieces of the second deck (Figure 12). By mounting the various dry layers of the roof, the building envelope is complete (except for the windows): it is possible to work both externally (on the finishes) and internally, so climatic conditions do not affect the construction site phases.

The external wall modules are a sandwich type. The layers are joined by a metal frame, which is also useful for connecting modules to the steel structure. The package consists of three layers. The two exposed faces are each made up of three hemp and lime slabs (three pressed panel of hemp and lime, called Canapres) with a consistency that provides mechanical strength to the sandwich; the layer in the middle (also in hemp and lime, called Canapannel) has a soft consistency. The metal frame of the wall modules is equipped with plates on the upper border and on the sides. The first plate is useful for connection with the upper beam; the lateral ones guarantee the connection between each module or guarantee union between them, so the global response of the wall to external stresses.

The second deck is then assembled. It is a lower horizontal closure on open space, one of the options provided in the system repertoire. The prototype is in fact raised to the ground (+90 cm at the highest point). This made it possible to test a type of floor very similar to that for the intermediate slab envisaged in the repertoire for multi-storey buildings and a roof slab.

The two slabs differ for layers and for factory production: the one used for the first deck arrives on site already equipped with thin metal sheet (4 mm, with underlying stiffening substructure) to support the various layers up to the finishing, unlike the roof deck on which the folded containment sheet for dry granulate useful for slopes is placed.

Figure 11. *The Assembly of the Structure: The Perimeter Beams of the Roof are connected to the Pillars*

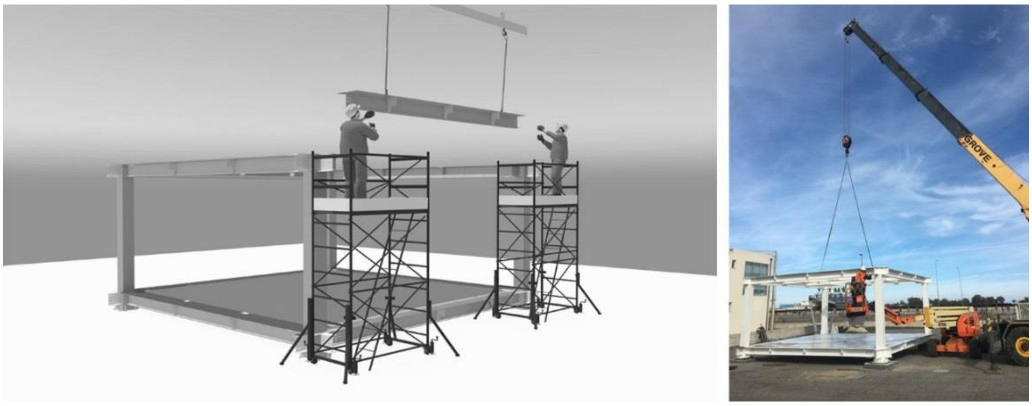
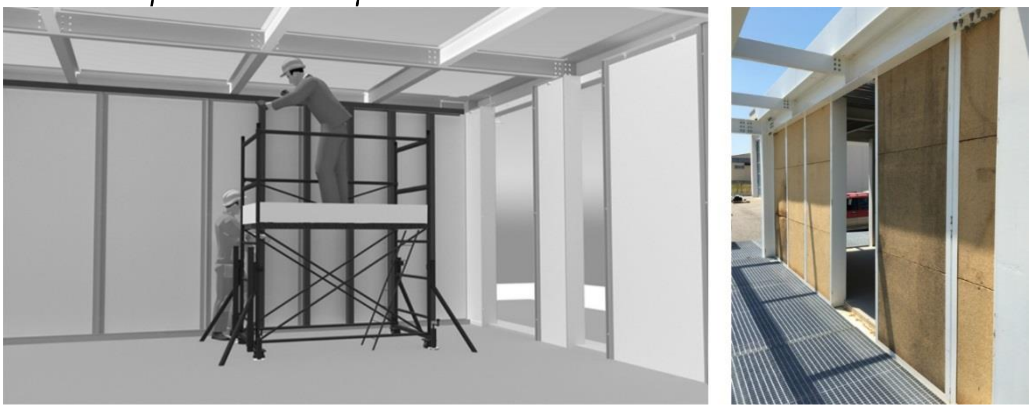


Figure 12. *The Assembly of the Structure: Panels of the External Wall are Mounted before the Pieces of the Second Deck*



The Assembly of Insulation and Cladding Layers and Finishes

The first deck includes: a layer of thermal insulation in hemp panels arranged on the thin sheet, a separating layer (non-woven film), a concrete layer to support resilient flooring (Figure 13). The use of a separator layer and linoleum allow the separation of the concrete layer from the underlying components (panels), so a selective demolition is allowed at the end of building's life. The roof slab includes: a folded sheet for laying the slope layer (granular), thermal insulation, waterproofing layer, protective gravel.

Walls facilitate systems integration and maintenance. In fact, the solution involves metal studs and rails (on the ground and on the ceiling) to which pressed panels of hemp and lime (20 mm thick) finished with hemp plaster and paint are screwed (Figure 14). The external wall is also equipped with an internal counterwall. These measures, in addition to the false ceiling, allowed the creation of a hollow internal “lining” on the whole vertical elements (internal and external walls) as well as horizontal (ceiling) inside which all systems have been arranged: air conditioning, water, electricity (Figure 14). In addition, wall panels can be drilled using a cutter in order to speed up the insertion of electrical boxes as well as to facilitate future systems implementation and maintenance. In general, the high level of plant equipment makes the construction method very flexible. In addition, a finish in recycled plastic laminate panels was partially adopted for the bathrooms (up to the height concerned by the pipe crossing) so as to allow quick assembly/disassembly without demolition (Figure 15).

Figure 13. *Layers of the First Deck (on the left), Internal Wall (on the right)*

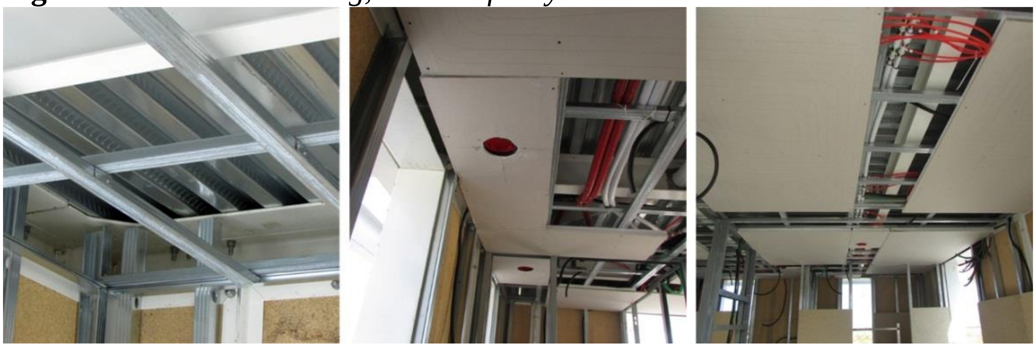
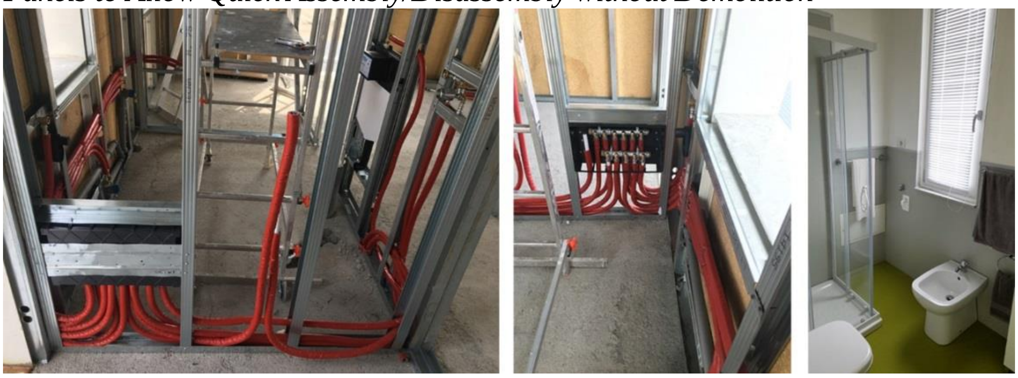

Figure 14. *The False Ceiling, Suitable for Systems*


Figure 15. S*ystems of the Bathroom: Walls Have Recycled Plastic Laminate Panels to Allow Quick Assembly/Disassembly without Demolition*


In some cases, windows are full-height type, so as to totally replace a module of the external wall. In other cases, they are installed on a window sill made with the same sandwich as the external wall.

Internal and external wall finishes are made with hemp and lime plaster and natural hemp-based paint. This allows to obtain materially continuous elements, which can be disposed of without first separating the parts (with the exception of the metal support ones) despite finishes being made on site by wet processing.

The prototype includes accessory elements. The shelter on the second slab allowed an assembly verification of the cantilevered structures expected in the tower building design (where they can be used as an external balcony and/or as scaffold for façade maintenance operations). The perimeter platform creates an extension of the usable space, as well as allows a better view of the prototype.

Monitoring

Between May and August 2020, a measurement and monitoring campaign was conducted on the prototype building. The goal was to evaluate the Indoor Environmental Quality (IEQ) by testing performance of the building shell and systems, in order to guarantee good indoor environment values. The IEQ classification considers four parameters: visual comfort, thermal-hygrometric comfort, acoustic comfort, air quality. Monitoring took place in two phases: in a single room (bedroom) during the building assembly (May-June) in order to improve the weak points during construction and on all rooms when the building was completed (July-August). Thermal imaging cameras and heat flow meters were used for instant measurements, environmental monitoring station and multisensors control unit were used for the long-term ones.

During building assembly, an excessively high illuminance value was measured in the afternoon (on average 170 lux) so it was necessary to install Venetian blinds to avoid glare. The thermo-hygrometric comfort was borderline (between second and third comfort class). However, in this phase, tests were performed with an incomplete shell: there were no windows nor internal walls (except for those in the room being tested). The acoustic comfort values did not highlight any risks; observed values above 35 dB are referable to work in progress on remaining parts of the building. Even the air quality did not highlight risk values, the average internal value of carbon dioxide being equal to 447.74 ppm.

When the building is finished: glare phenomenon had been corrected by Venetian blinds, absence of acoustic risk had been verified (works have been completed, so average values below 30 dB ha been recorded), no risk values for air quality were highlighted (average internal value of carbon dioxide measured was equal to 445.98 ppm).

More considerations are needed regarding hygrometric comfort. Monitoring (completed building) took place between July and August 2020. As is known, dry (light) layered systems perform well in cold climates (materials have very low values of thermal conductivity) but do not guarantee as much comfort in Mediterranean climates, where grounded (heavy) systems are preferred. Monitoring in the hottest months and in a location (Crotone) where torrid days are recorded, made it possible to test the Ac.Ca. Building in the worst conditions. In fact, in July (average monthly temperature recorded equal to 28.9 °C), in the time period between 12:00 - 16:00 (peak of maximum external temperature recorded on 7/31/2020 equal to 37 °C), the indoor temperatures were not tolerable. The building shell is unable to maintain a good thermo-hygrometric comfort with only natural ventilation. The average IEQ class recorded was the IV, so it was necessary to switch on the cooling system, consistent with the design provisions.

In fact, the building is equipped with an HVAC system: mechanical ventilation and heating/cold air conditioning by means of radiant ceiling panels. This allowed the testing of a further configuration of the slab - with a radiant false ceiling instead the hemp one - not specifically included in the technological repertoire. The ventilation system is used to automatically control indoor humidity, to avoid formation of condensation on the ceiling: if cooling is switched on in unfavorable hygroscopic conditions (there are two pairs of temperature/humidity probes), the ventilation system first cuts down humidity then allows cooling system activation. Ventilation blows air into the living room and bedroom while extracting it from the bathroom and kitchen.

In the last three weeks of August (average monthly temperature recorded equal to 29.0 °C, maximum outdoor temperature peak recorded on 8/1/2020 equal to 35 °C), comfort levels equal to IEQ class I were recorded, thanks to activation of HVAC systems in the morning and afternoon (temperature set to 26.0-25.5 °C). The building is equipped with an electricity production system (photovoltaic panels) and even mass buildings require a cooling system to equal levels of comfort (in hot climates such as Crotone in summer months). During the night, building shell responded very well, registering comfort classes equal to I and II level without the cooling system power on, provided a minimum and constant natural ventilation is guaranteed (typical of the summer months in Mediterranean climates).

The heat transmission value (U) measured for the external walls is very low (about 0.220 W/m2k), the phase shift (calculated as the time lapse between the moment when the maximum temperature is recorded on external surfaces of the structure and the moment when the maximum temperature is recorded on the internal surfaces) is approximately 9 hours in moderate external conditions (temperatures between 18-26 °C). Ultimately, the Ac.Ca. Building, despite being a light system, guaranteed good thermo-hygrometric comfort in the Mediterranean climate. The recorded parameters made it possible to make the building compliant with IEQ class II, following indications adopted by the UNI EN 15251 certification procedure during the project.

Conclusions

The aims of the Ac.Ca. Building Research and Development project are the optimization of construction process during assembly phase on site (manpower and economic resources) and the sustainability of the entire building life cycle (from design to the end of its useful life). The project takes into account the productive and climatic context of Southern Italy and the difficulties that held back the development of industrialization in the last century.

A dry layered system must be combined with a industrialized construction process that requires the definition of a rigorous scheduled operative plan already in the design phase, with a level of detail corresponding to a specific assembly plan for the prefabricated components. Such a detailed plan requires combination of design and production, the main feature of the Ac.Ca. Building system. This combination reduces the craftsmanship of traditional construction site and thrusts the construction process towards an industrial production approach that can also be used by small and medium-sized companies with a good level of specialization, capable of ensuring efficiency, quality, safety and ease of monitoring and check. This is an important feature, considering that in Italy in the last century the spread of industrialization was held back by a delay of industrialization level and unfamiliarity of companies with on-site assembly procedures and with industrialized construction site management.

Dry construction minimizes work on site, as elements to be assembled are transported (almost completed) from the factory to the assembly site. For example, in the Ac.Ca. Building, the use of hemp-based modular panels allows the reduction of the number of pieces and connections. A careful organization of construction site and transport planning allows minimization of storage areas, greatly shortening time span between components delivery and their assembly. Evaluating the R&D project, the building is like an assembly box: organized by an operational plan, it allows quick and sustainable construction thanks to the modularity and standardization of the singular elements and their connections. In fact, thanks to repetitiveness concept, it was possible to test the Ac.Ca. Building system through the assembly of a single structural bay (6600x6600 mm), exemplifying a large number of elements, connections and assembly schemes provided in the system repertoire.

In the past, the reduced thermal inertia of light systems discouraged the use of dry construction systems in the Mediterranean area. The Ac.Ca. Building (although overheating problems persisted in some summer periods) highlighted a good performance of the thermal phase shift, which allowed a good thermal performance during the night. In any case, the use of air conditioning systems powered by renewable sources allows a good balance between improving thermal comfort and energy consumption. Finally, for the sustainable disposal of the Ac.Ca. Building components, the extensive use of elements based on hemp fibers and dry connections between the parts are good peculiarities for implementing recycling processes of components and materials. Project solutions were tested in the prototype assembly, largely confirming forecasts including the environmental sustainability performance of the R&D project.

References

Canestrino G, Greco L, Spada F, Lucente R (2020) Generating architectural plan with evolutionary multiobjective optimization algorithms: a benchmark case with an existent construction system. In N B Escobar, D A Torreblanca-Díaz (eds.), *Conference Proceedings of XXIV International Conference of the Iberoamerican Society of Digital Graphics.* Medelin: Universidad Pontificia Bolivariana de Colombia, 149-156.

Elma D (2019) *Design strategies for reversible buildings.* Netherlands.

Greco L (2017) I sistemi costruttivi a secco. Una traiettoria di innovazione del processo edilizio sostenibile. (Dry construction systems. A trajectory of innovation in the sustainable building process). In L Greco, P Piane, *Costruire a secco. Metodi, tecniche e realizzazioni dal progetto al cantiere*. Roma: Aracne Editrice, 27-37.

Greco L (2019) Dry construction systems for sustainable design: issues and perspectives for the use of dry construction systems in the Mediterranean context. In: *Sustainable Built Environment Conference Proceedings Book*, 209-216.

Greco L (2021) Italian temporary prefabricated constructions (1933-1949). Projects, Patents and Prototypes. *Tema* 7: 42-53.

Greco L, Spada F (2019) The invulnerabile prefabricated construction system for Italian temporary buildings in the 1930s. In J W P Campbell et al. (ed), *Water, Doors and Buildings: Studies in the History of Construction*. Cambridge (UK): Construction History Society, 535-548.

Imperadori M (2012) *La meccanica dell'architettura.* (The mechanics of architecture). Milano: Gruppo24ore, 3-40.

Iori T (2012) Préfabrication et industrialisation made in Italy. (Prefabrication and industrialization made in Italy). In F Graf, Y Delemontey (eds), *Architecture industrialisée et préfabriquée: connaissance et sauvegarde*. Lausanne: Pu Polytechnique, 73-85.

Lucente R (2019) Architectural quality and typological flexibility: the role of buffer spaces in warm climates. An application in a steel and hemp construction system. In *Sustainable Built Environment Conference Proceedings Book*, 43-48.

Lucente R (2020) *Abitare Acciaio. Esperienze di ricerca progettuale*. (Living Steel. Project research experiences). Siracusa: LetteraVentidue.

Morganti R, Tosone A, Abita M, Di Donato D (2019) Learning from Finland: from circular economy to circular building, *Tema* 5: 68-83.

Mulhall D, Braungart M, Hansen K (2019) *Creating Buildings with Positive Impacts.* Technische Universität München.

Rogora A (2012) *Progettazione bioclimatica per l'architettura mediterranea. Metodi, esempi.* (Bioclimatic design for Mediterranean architecture. Methods, examples). Milano: Wolters Kluwer, 6-8.

Valle C (1938) *Corso di edilizia coloniale con particolare riferimento all'A. O. I. R.* (Colonial building course with particular reference to the A. O.I.R). Pioda.

Zambelli E, Vanoncini P A, Imperadori M (1998) *Costruzione stratificata a secco. Tecnologie edilizie innovative e metodi per la gestione del progetto.* (Dry layered construction. Innovative building technologies and methods for project management). San Marino: Maggioli editori.