Composite technology and integrated energy and architectural design for a new students' space

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This research fuses architectural design, energy and daylight analysis in a unique, hybrid approach to the design and fabrication of a new students' pavilion. Extreme integration brings up the opportunity to discuss about sustainability in a broader sense, as a concept which focuses more on interrelations between different design aspects rather than on single optimizations. The pavilion is made of an innovative fiber-reinforced (FRP) sandwich shell whose morphology and construction integrate structure, ornament, insulation and multiple systems in a unique element, which has been prototyped. Space and performance are modulated as part of the same system through iterative simulations. Operative temperature and daylight maps are created to support the design of heterogeneous environments, where every occupant can choose his own preferred condition in time and space. Energy consumption is minimized, while daylight autonomy is maximized, thanks to a series of design strategies involving the pavilion morphology and its relationship with solar radiation, natural ventilation and systems design.

Key words: Integrated design, FRP composite materials, energy performance, daylight, comfort, architecture, sustainability.

1. INTRODUCTION

This study started from the intent to design an experimental pavilion for students in Bologna, following the idea of extreme integration of architecture and energy in the design process. Integration was also reflected in the design of an innovative construction system, using fiber – reinforced (FRP) composite materials. This design approach was also used to implement variability inside the space, in terms of perception, usability and temperature, and to account for subjective needs and comfort preferences. Final energy and daylight performances were eventually analyzed through simulations and discussed.

1.1 Heterogenous environments

Nowadays, extreme integration of different aspects of design in the building industry seems to be an innovative concept, whereas it used to be widespread practice for most of pre-modern buildings in history. Construction methods, materials and styles were all entwined and embedded in the same architectural know-how, naturally and deeply related to the specific context.

The Modernist concept of architecture introduced the idea of democratic and universal space, represented by an ideally infinite and homogeneous open plan and ribbon windows, with the purpose of guaranteeing the same conditions for everybody [1]. At the same time, standardization and modularization of spaces and systems came together with intensification of labor division for economy of production, which in turn resulted in the heap of separately designed subsystems: each of them was designed and optimized to address a single main function, such as primary and secondary structure, covering, sun shielding, environmental control and so on. This was the rise of single-objective optimization, which led to extreme differentiation between different industries and still governs nowadays approach to building design. This idea of single-objective efficiency and standardization strongly limited the rise of variability in architecture, affecting both spatial and environmental features. Lightweight structures resulted from the quest for material optimization, while thermal systems became the only way to guarantee desired uniform comfort conditions indoors [1].

A shift towards heterogeneity in architecture is taking place in the last decades, when standardization has started to coexist with mass customization. Contemporary architecture has already embraced variability as a well-established principle for creating different opportunities of use and perception of the space, while the idea of uniformity in plan and shape has started revealing its drawbacks. In working environments, for instance, extreme uniformity - which used to be seen as 'absence of distraction' in the Modern period – is actually useless or even counterproductive [2]. Nevertheless, while variability is highly desired in spatial differentiation, still it doesn't affect environmental conditions. Understanding the potentialities of designing heterogenous environments and studying gradients of conditions without physical boundaries is key to take into account subjective needs and preferences and to avoid unnecessary electricity, heating and cooling loads [2].

In order to promote this kind of heterogeneity, energy and comfort studies need to go in parallel with architectural design and material considerations since early stages of design. In a certain sense, we need to re-unify different industries that gravitate around construction, promoting collaboration between professionals and working on inter-dependencies between different aspects. This approach deviates from single-objective optimization and approaches a new and more sustainable concept of global coherence, based on negotiation between different aspects and their inter-connections.

1.2 FRP composite materials

Rigid division of different sub-systems in buildings still characterizes the widespread practice. Even contemporary architecture characterized by curvilinear forms and fluid aesthetics, still uses framed structures concealed under the surface for load-bearing function and a jungle of different pipes and channels hidden inside unused and resulting spaces for technical systems. Integration is always sought, but never completely reached.

On the other hand, composite materials, allow for a radical shift in the way tectonics can be conceived in architecture. The word 'composite' itself means made up of various parts and elements – the analogy with cooking used by Gregg Lynn [3] is particularly explicative here, as it focuses on the transition of design perspective and scale from a mechanical to a chemical one. Composite thinking is all about layers, fabrics, glue, additives and resin, all possible materials embedded and consolidated in a unique object. Efficiency, in this case, is a consequence of integration, because surface and structure are fused together, so that the envelope can have at the same time load-bearing, insulating and aesthetic properties. This, together with FRP composites high strength-to-weight ratio, great corrosion resistance and extremely flexible formability shows a huge potential for creating highly resistant and lightweight structures. Not surprisingly, over the past decades, fiber-reinforced polymers (FRP) have been widely used in industries as automotive, marine, aerospace, wind energy and for other corrosion and chemical resistant applications. An overview on FRP mechanical, physical and thermal properties can be found in Figure 1 and Table 1.

FRPs have already shown long term durability and good weathering resistance in many architectural applications and in the boat industry, where they have been largely used in environments where traditional materials would have failed. Anyway, Knippers et al. [5] pointed out that loadbearing fibers should never be exposed to the attack of chemicals, damaged

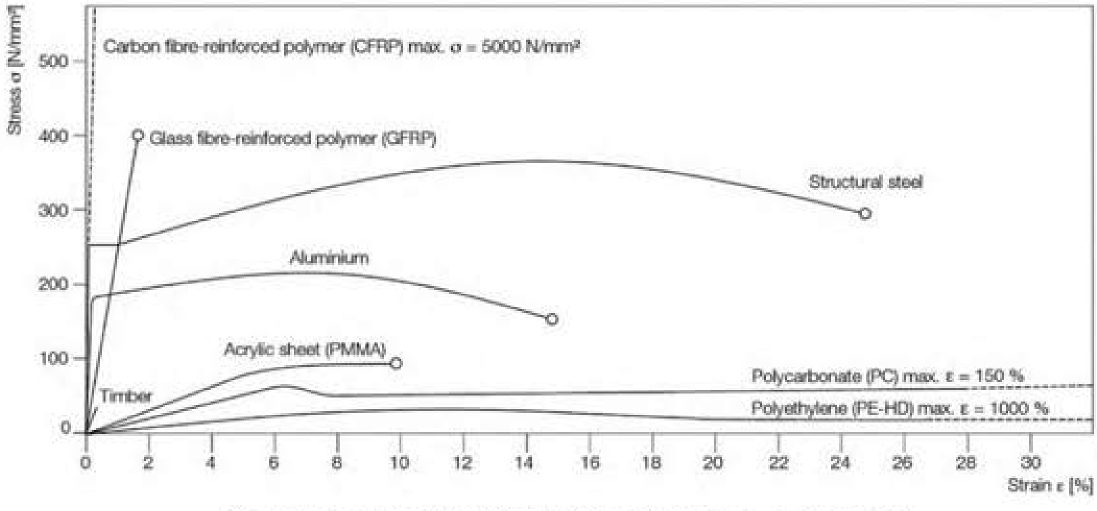


Fig. 1. : FRP compared to traditional building materials: stress - strain curves [5].

Table 1. FRP compared to traditional building materials: physico-mechanical and thermal properties [4]

Characteristics	Tensile strength [MPa]	Flexural strength [MPa]	Density [kg/m^3]	Thermal conductivity [W/m°C]
FRP	170-270	205-240	1550	0.57
Steel	450	450	7500	46.55
Wood	low	80	200 -1400	0.15 - 0.04
Concrete	2 to 5	3 to 5	2200	0.8

by UVs or corroded by moisture. Stabilizers can be used to inhibit degradation of the polymer in case of continuous exposure to heat or UV. If water penetrates the outer layer, the surface could show blisters; this problem can be solved by eliminating the old coating and applying new gelcoat. Reaction to fire and high temperature depends on the type of resin used and has to be demonstrated by means of fire tests. Anyway, heat resistance of resins can be improved by fillers and additives [5].

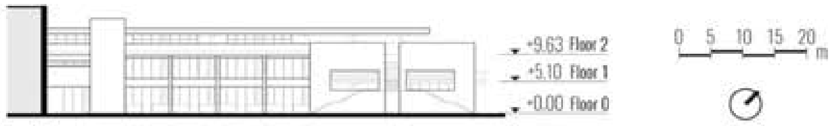
However, the physical, mechanical and thermal properties of FRP composites highly depend both on the type of polymer matrix and on the fibers used as reinforcement, as well as the kind of filling material which is chosen for the core and the specific production method. Because of its own nature, this material is highly customizable and can be designed and produced to address the project specific needs.

2. CASE STUDY

This research investigates the aforementioned concepts by applying them to the design of a new pavilion for University students in Bologna. The pavilion was designed to host students' spaces at the School of Engineering and Architecture in Via Terracini, out of the Bologna city center. This is an isolated and uninviting place where the lack of services and leisure spaces is evident. The new spaces were meant to fill that gap and create socialization opportunities for the students' community. The chosen location was on top of the existing University building, giving function and purpose to an easily accessible yet unused terrace and avoiding occupation of new land (see Fig.2) [6][7].

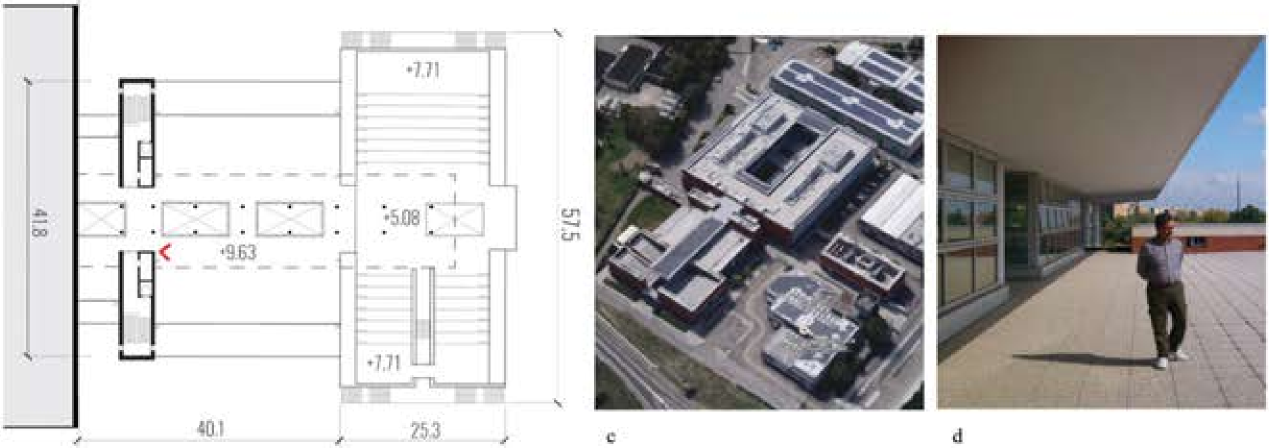
2.1 Construction system

In the present case study, an extremely lightweight and resistant pavilion was needed, primarily because of its position on top of the existing building. At the same time, the pavilion had to be designed for being used all over the year, offering a good level of thermal comfort and daylight and keeping low operating costs: that is why a good insulating material was required and space for systems had to be considered. Moreover, because the construction site was located within the University facilities, it was crucial to keep the construction



a

Elevation South-East



b Plan of the Roof Terrace, 2nd floor

c

d

Fig. 2. : Existing building. a: Elevation of South-East facing façade. b: Roof terrace plan. c: View of the existing building and surrounding University facilities. d: View of the roof terrace where the pavilion is located, point of view is referenced in the plan by means of a red symbol.

period as short as possible, possibly prefabricating as many components as possible.

All these features brought to the choice of a continuous, double curvature FRP sandwich shell (see Fig.3): the outermost layer was a carbon FRP, the inner one was a glass FRP, while systems were placed in the gap between the two, together with polyurethane filling. The latter created a thermal insulating core and separated the two load bearing elements.

From the structural point of view, the sandwich is composed of two thin, strong and stiff skins separated by a lightweight, low-strength and thick core. The skins resist the tensile and compressive stresses resulting from the flexure induced by out-of-plane loadings, while the core resists shear forces and keeps the FRP layers at a desired distance to provide the required moment of inertia to the overall structure. Moreover, in this case, double curvature helps stabilizing the shell geometry, while ridges on the outermost CFRP laminate act as stiffeners [7]. The two FRP skins were composed of a thermosetting polymer matrix and fibers, which usually came in the form of woven fabrics. The former surrounds, supports and protects the fibers and is strong in compression but weak in tension, while the latter provides an excellent tensile strength. The fibers elastic modulus had to be carefully considered in order to avoid excessive deformations of the structure or to have elongations which would make the polymer brake before the fibers. In general, FRP technology allows for great freedom and flexibility in the skins shape. In fact, changing the laminate thickness, the fibers direction or the way they are entwined can make the structure resist differently without significantly affecting the overall shape. Surface finishing is a white gelcoat, which determines the final appearance and, at the same time, serves as a protection from external media.

2.2 Prototype

A small part of the pavilion shell was selected and prototyped as shown in Figure 3. A scale of 1:2 was chosen for this prototype, resulting in a 0.6m x 1.2m fabricated panel. The prototype used the same material system as the pavilion: a FRP sandwich as described above. The idea was to test in a smaller scale and with the same workflow, techniques and know-how that could be used for the entire pavilion fabrication off-site. This system was extremely light and resistant, it was load-bearing and thermal insulating. Moreover, electrical systems, part of the drainage and conditioning pipework were integrated inside the PUR core, as well as a LED lighting system. The latter was placed adjacent to the GFRP laminate, exploiting their typical translucency to create a glare effect in the evening hours [7].

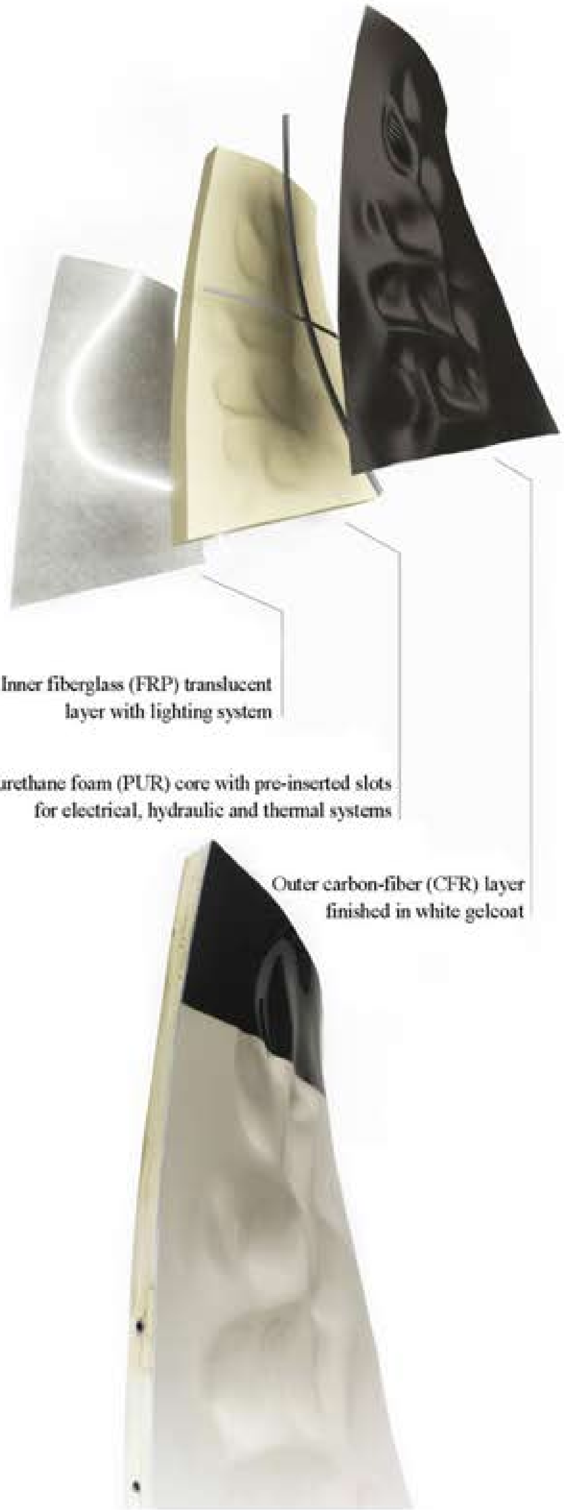


Fig.3: Picture of the fabricated prototype and exploded view showing the different layers [7]

2.3 Design strategies

Performance criteria had paramount importance on the pavilion design since the beginning. After having carefully analyzed the existing context, a step-by-step iterative approach comprising design decisions and simplified simulations was adopted to quickly assess the consequences of those choices. The pavilion geometry as well as the choice of materials and systems were part of the same design workflow, without separating architectural concepts from engineering considerations and, instead, exploring their interdependences.

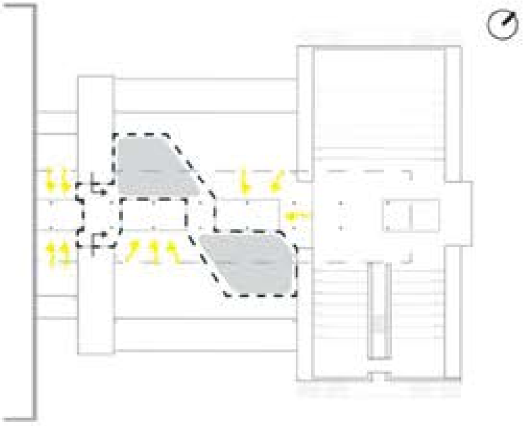
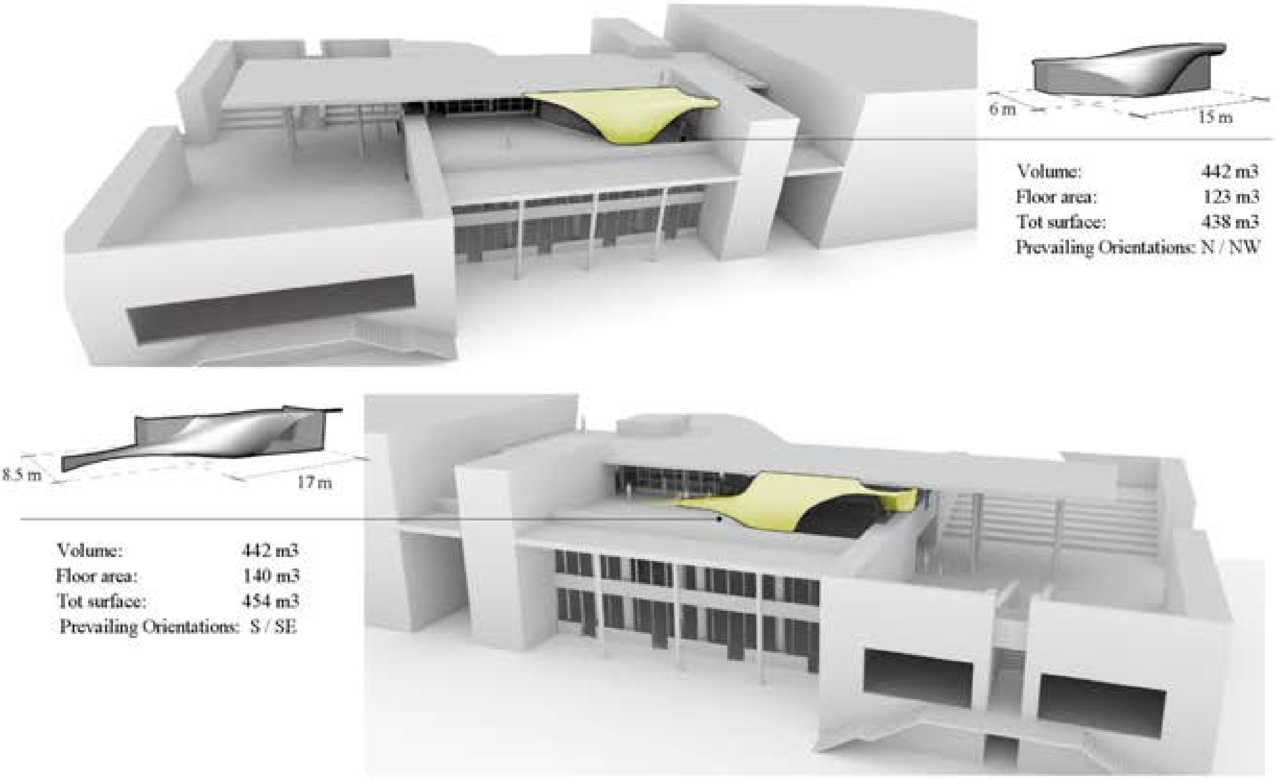


Fig. 4.: Pavilion volumes (dashed line): influence of sunlight on the shape (yellow arrows).

After having planned the activities performed there, schedules were created for the expected pavilion occupancy, predicting peaks during lunch time and expecting regular Saturday openings for events or social and studying activities.

The pavilion was conceived to be completely autonomous from the existing building and was equipped with a Variable Refrigerant Flow (VRF) HVAC system with two pipes and heat pump for either heating or cooling. Given the potential high variability in occupancy levels, an air system was preferred over radiant heating because of its capability to quickly condition the space when needed. A series of sensors like thermostats, humidistats and CO_2 detectors were employed to control the VRF system.

Considered the pavilion location - on top of an existing University building - the relationship between the pavilion and the building underneath was one of the first challenges. The terrace was situated exactly on top of the main classrooms and it was interrupted by three full height internal glazed bodies. In the middle, along the longitudinal symmetry axis, a long, white framed structure with roof dominated the terrace and the whole building. Adjacency to the existing building was privileged when possible. In fact, putting a conditioned pavilion on top of



Volume:	442 m3
Floor area:	123 m3
Tot surface:	438 m3
Prevailing Orientations:	N / NW

Volume:	442 m3
Floor area:	140 m3
Tot surface:	454 m3
Prevailing Orientations:	S / SE

Fig. 5.: Overview of the two shells that form the pavilion and the exhisting building.

an already conditioned building reduced the pavilion heat transmission through the floor and, for the same reason, advantaged the zones underneath. The indoor space of the pavilion was designed to be accessible from the existing internal stairs, while the pavilion shell was conceived as an extension of the building walls and the terrace concrete framed structure (see Fig.5).

The full height glazed bodies let diffuse sunlight come inside the building, so it was important to avoid covering or shading these bodies as much as possible. At the same time, the pavilion had the potential to be highly exposed to sunlight and it was clear since early stages of design that this feature had to be exploited to achieve excellent daylight in the internal space and consequently reducing the need for artificial lighting. These considerations led to the choice of a high transparent-to-opaque surfaces ratio as well as to the idea of splitting the pavilion in two parts, alternatively covering one side or the other of the glazed bodies, keeping a certain amount of diffuse light able to penetrate the lower floors all day long, as shown in Figure 4. Then, daylight simulations were carried out to assess the pavilion Daylight Autonomy and verify these assumptions. Moreover, glare was avoided as much as possible and checked through simulation.

On the other hand, the pavilion location suggested possible issues during the summer time, due to overheating. In order to minimize cooling loads, several different strategies were tested and combined together to assess the most effective and feasible ones and how they could meaningfully coexist:

- The first one was to lower solar gains, choosing low solar heat gain coefficient (SHGC) glasses, orienting them Northwards and creating appropriate shading devices in order to block direct sunlight (see Fig.5 and Tab.2).
- Given the great amount of people who will potentially stay in the pavilion and the air quality requirements, ventilation losses were found to be considerable. For this reason, the second strategy was to introduce a heat recovery system which passed the exhaust air through a sensible and latent heat exchanger with the fresh outdoor air before exhausting it.
- The third idea to reduce cooling loads was to implement a fan-driven ventilation strategy during the night: this was preferred over stack / wind-driven ventilation because of uncertainties and inaccuracies connected to weather data and the simulation itself. In this case, fans started ventilating when indoor temperature was above 23°C and, at the same time, outdoor temperature was less than 24°C. This approach was very effective to reduce cooling loads, especially in the morning.

In order to decrease heat loss during winter, instead, a good insulated external envelope was needed. In this case, the composite material and its sandwich structure comprising PUR foam core played a fundamental role in keeping thermal transmittance low. Ventilation losses in winter were also lowered by introducing the aforementioned heat recovery system. Transparent surfaces were chosen to be double glazed with low U value, similar to the composite one, in order to keep low winter heat loss. At the same time, low solar heat gain coefficient (SHGC) was chosen to avoid excessive overheating during summer, which was found to be the most critical period of the year. A medium-high visible transmittance (VT) ensured excellent daylight, without glare. Precise data are listed in Table 2 and 3. [6]

Table 2. Opaque surfaces constructions and material properties.

Constructions	Materials	Thickness [m]	Conductivity [W/mK]	Density [kg/m^3]
Concrete roof	plaster	0.02	0.9	1400
	concrete	0.30	2.3	2400
	polystyrene	0.10	0.035	35
Concrete wall	bricks	0.08	0.2	1700
	concrete	0.3	2.3	2400
	plaster	0.02	0.9	1400
Floor	concrete tiles	0.04	1.5	2000
	concrete slab	0.30	2.3	2400
	plaster	0.02	0.9	1400
FRP sandwich	FRP skin	0.01	0.57	1600
	PUR core	0.10	0.034	40

Table 3. Transparent surfaces properties.

	U value [W/m^{2}K]	SHGC	VT
Single pane window	5	0.70	0.79
Double pane window filled with Argon, low E-coating	1.3	0.30	0.70

2.4 Simulations and results

Energy simulations were performed using EnergyPlus 8.4 and the plug-in Honeybee for Grasshopper, a visual programming language which runs inside the Rhinoceros 3D application. As shown in Figure 6a, the simulations focused on the second floor where the pavilion was located. The model was subdivided in seven main thermal zones while other shading surfaces were considered as context. The pavilion floor and all other surfaces which were adjacent to the already conditioned existing rooms were considered adiabatic: this approximation exempted the simulation from considering all the other floors as well, which would have resulted in much slower simulations. For each thermal zone, all boundary surfaces - both existing and new - were analyzed one by one (see Fig.6b) and separately assigned specific construction and material properties. A new 10 cm polystyrene layer was added to the existing concrete roof which otherwise would have caused great heat losses. Inefficient existing single pane windows separated the pavilion indoor environment from the internal glazed bodies, which were already conditioned: this was the reason why they did not need to be replaced or improved. Other external surfaces were the FRP sandwich shell and double pane windows filled with Argon with low E-coating and frames integrated inside the FRP shell, to reduce heat loss along the frame. Transparent surfaces were chosen to be double glazed with low U value.

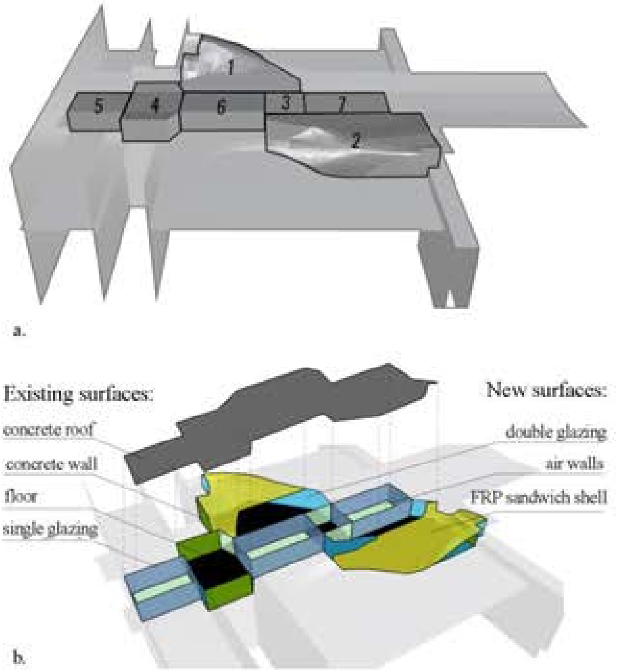


Fig. 6.: a: Division in 7 thermal zones;
b: Different surface types and materials.

Moreover, appropriate schedules were created for occupancy. The pavilion was considered closed on Sundays and open on Monday-Friday from 7 a.m. to 20 p.m. and Saturday from 7 a.m. to 21 p.m. Occupancy peak was expected for lunch hours (12 a.m.- 2 p.m.). HVAC was designed to run Monday-Saturday following the actual occupancy, with heating set point at 21°C, set back at 15°C. Cooling set point and set back were at 24°C.

As previously discussed, a fan-driven ventilation was designed to operate in case of high indoor temperature (above 23°C) and low outdoor temperature (less than 24°C), that is during the summer, at night. Ventilation for fresh air inlet was calculated based on occupancy, considering 40 m^3/hour per person. A heat recovery system was essential for recovering heat from exhaust air, its effectiveness was assumed around 70%.

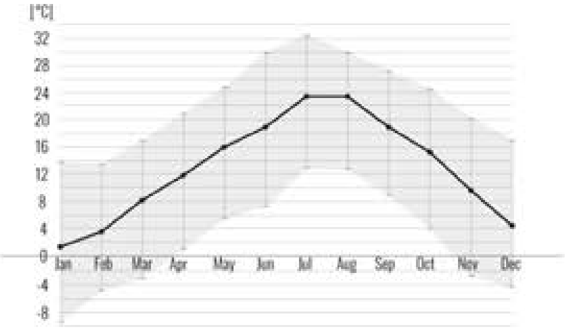


Fig. 7.: Monthly average drybulb temperatures in Bologna (black dots) and range from min to max temperatures (in grey), from epw file for Bologna.

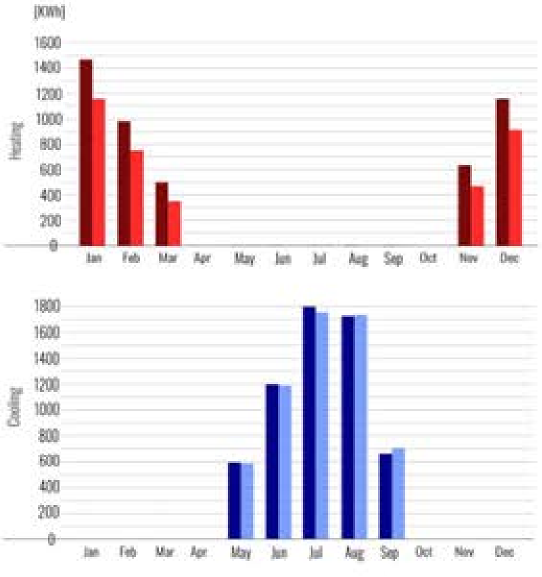


Fig.8: Heating and cooling energy consumption all over the year. Zone 1 in dark, zone 2 in light color.

The main areas where people were supposed to stay longer were zones 1 and 2; for this reason, these two zones were conditioned, while zones 3 and 4 were not. Simulation results showed that temperatures in zones 3 and 4 were acceptable. Internal units were integrated inside the FRP shell, allowing the users to adjust the temperature according to their comfort preferences. Tiny refrigerant gas pipes run through the FRP shell and under the suspended floor, while heat pump was located inside an accessible and ventilated shaft in zone 2. Figure 7 shows heating and cooling energy required to condition both zones 1 and 2 during a year; total heating energy per area is 24.12 KWh/m^2 year, while total cooling energy per area is 34.38 KWh/m^2 year. Figure 9, instead, represents an example of some results regarding zone air, mean radiant and operative temperatures and analysis maps for the month of June.

Daylight simulations were carried out using Daysim, Radiance and Evalglare, together with the plugin Honeybee. The same model used for energy simulations was used here. In addition, Radiance definitions were applied to materials, including color, specularity and roughness values. Annual daylight simulations tested indoor levels of illuminance on a plane 1 meter distant from the floor, with a grid size of 30 cm. These data allowed the creation of annual lighting schedules for each thermal zone, to be used as inputs for the energy simulations. In addition, Daylight Autonomy (DLA) was calculated for each test point, resulting in values between 20% and 90%, with an average of 74.6% (see Fig.10a). DLA

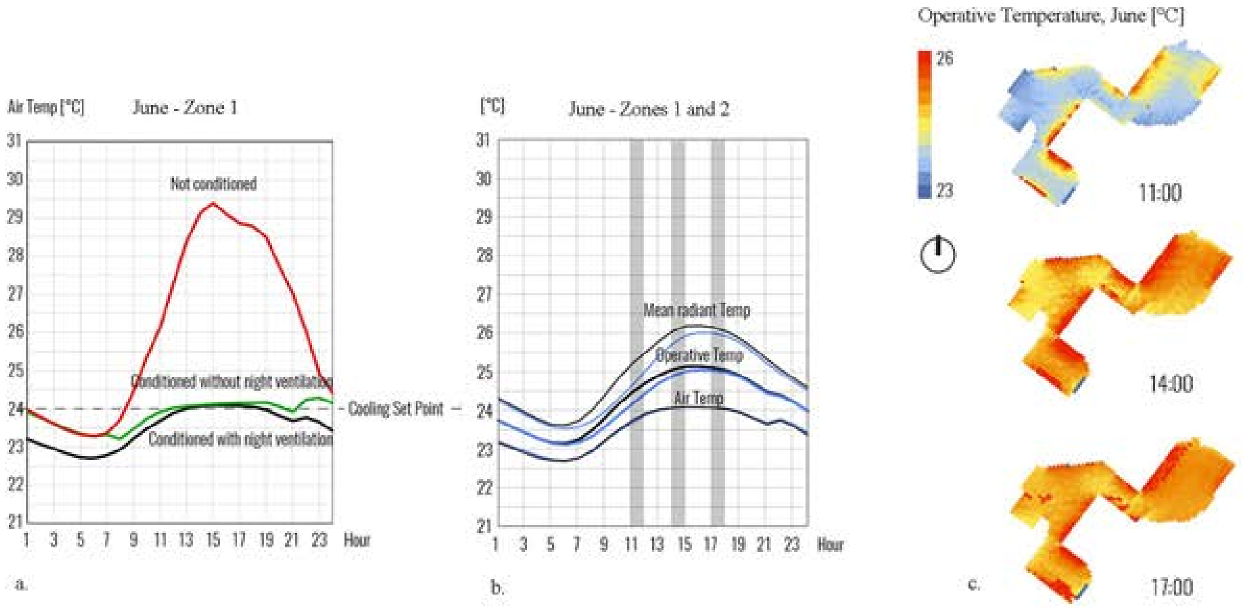


Fig. 9.: a: Mean air temperatures in June; red curve: HVAC off; green curve: HVAC on; black curve: HVAC on with night ventilation. b: Relationship between mean air temperature, mean radiant temperature and operative temperature for zone 1 (in black) and zone 2 (in blue). d: Operative temperature maps in June at 11:00, 14:00 and 17:00, calculated at a distance of 1 meter from the floor.

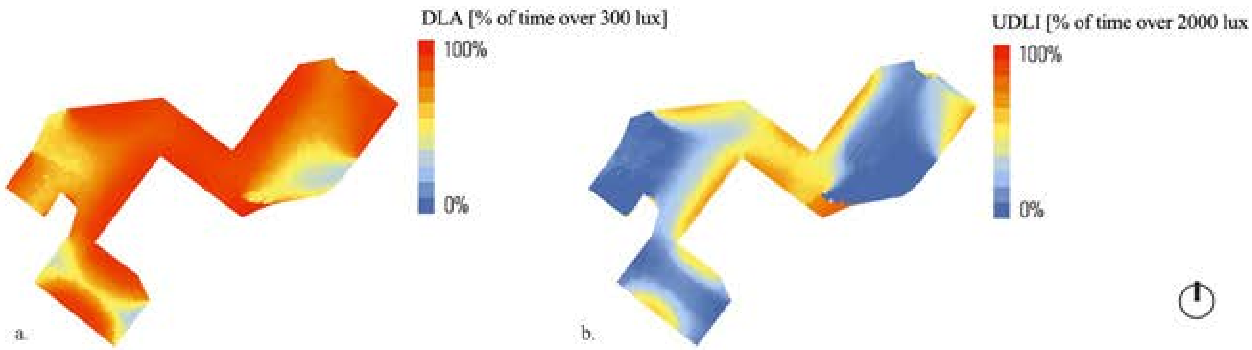
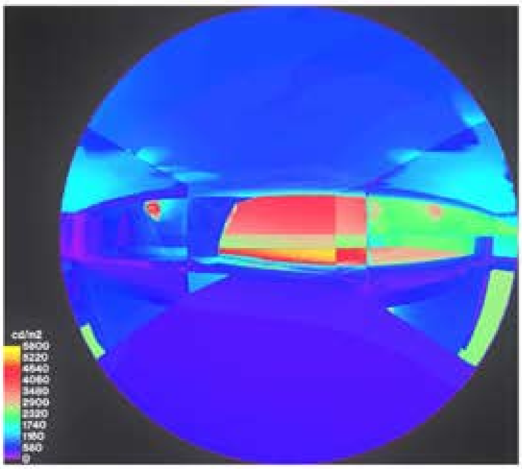


Fig. 10.: a: Daylight autonomy map indicating the percentage of active occupancy hours during the entire year when the test point receives more than 300 lux. b: Useful daylight autonomy map, indicating the percentage of active occupancy hours during the entire year when the test point receives more than 2000 lux.



DGP = 0.339 1st June, 1 pm

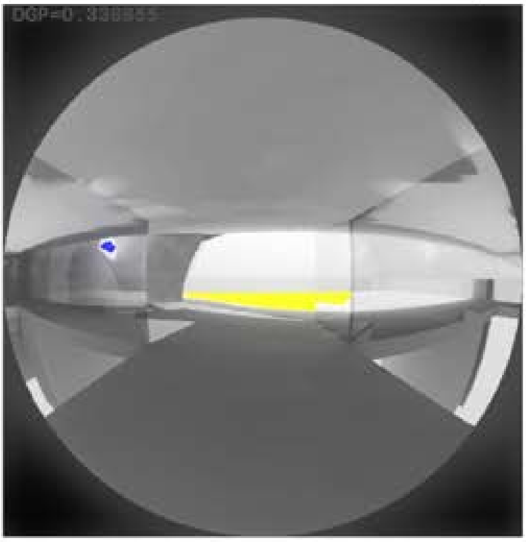


Fig. 11: Example of glare analysis using Evalglare inside Grasshopper; this one represents the situation in zone 3 in June at 1 p.m. Daylight glare probability (DGP) here is 0.339, which is less than 0.35 and therefore not perceptible (Reinhart et al., 2012).

represents the percentage of active occupancy hours during the entire year when the test point receives more than 300 lux. Spatial Daylight Autonomy ($sDA_{300/50\%}$), instead, indicates the percentage of test points which exceed 300 lux for at least 50% of the yearly occupancy hours. In this case, sDA was 100% for zones number 1 and 3, 91.3% for zone 2 and 90.4% for zone 4. Figure 10b shows the Useful Daylight Illuminance over 2000 lux ($UDLI_{2000}$), that is the percentage of time when each test point has more than 2000 lux. Glare analysis was then performed for the red areas of Figure 10b for some specific hours of June, July and August. Figure 11 shows an example of image-based analysis of glare; results show that Daylight Glare Probability (DGP) is under 0.35, which is the threshold under which glare can be considered not perceptible [6].

3. DISCUSSION

As predicted during early stage design considerations, the highly solar exposed location, as well as the lightweight, well insulated FRP construction system with low thermal inertia resulted in cooling loads higher than the heating ones. In fact, simulation results showed a total cooling energy required for the whole year of 34.38 KWh/m^2, while the heating one was 24.12 KWh/m^2. Heating energy loss was mainly due to ventilation (40 m^3/hour person). During the summer, instead, the adopted night ventilation strategy helped keeping air temperature low during the night with some advantages during the off-peak hours; however, being a lightweight pavilion with low thermal inertia, its temperatures tended to vary quickly according to outdoor conditions. Given this, the chosen air conditioning VRF system appeared to be the best choice for its ability to adapt to rapidly changing conditions, occupancy situations and needs. Operative temperature maps showed the possibility to have variable comfort conditions available in the pavilion space: these, together with the possibility for the user to control the different internal units, assured heterogeneity and variability to the space conditions. In the future, thin film photovoltaics could be studied and integrated in the FRP shell, in order to provide the required energy for the pavilion and make it autonomous.

Daylight simulations resulted in excellent Daylight Autonomy (DLA), values and a Spatial Daylight Autonomy ($sDA_{300/50\%}$) near to 100%. Glare image-based simulations showed that this phenomenon is not a threat for the pavilion, as many of the transparent surfaces are North-East oriented and very few of them are hit by direct sunlight. Nevertheless, an accurate evaluation of Annual Solar Exposure (ASE) could be added to the sDA metrics, in order demonstrate compliance with LEED daylight requirements [8].

Software use was of paramount importance in the development and simulation of interdependencies between different elements. In this case study, the author used EnergyPlus 8.4 together with the plugin Honeybee for Grasshopper, a visual programming language which runs inside the Rhinoceros 3D application. This connection was really useful to implement a step-by-step iterative approach comprising design decisions and simplified simulations, in order to quickly assess the consequences of those choices. The pavilion geometry as well as the choice of materials and systems were part of the same design workflow. This approach had some weaknesses which were mainly connected to software limitations. In fact, EnergyPlus is not able to easily handle extremely complex 3d models and, therefore, many details were lost passing from the architectural model to the simulation one. This approximation is acceptable on a macro-scale and for common building applications, but makes new explorations over small geometric details hard to develop [6].

4. CONCLUSION

A lightweight pavilion for University students was designed following the principle of extreme integration of architecture, energy, structure and technical systems, as a driver for globally coherent and sustainable design. Single sub-systems optimization was substituted by an approach that promoted inter-dependency among different aspects, so that architectural spaces were also shaped according to energy and daylight considerations, structural elements had also thermal insulating and decorative features and so on, in a way that blurs the boundaries between different disciplines and components. This research also highlighted the importance of modulating energy and architectural features to create heterogenous environments, created to both stimulate creativity and enable a range of different acceptable conditions among which the user can choose, according to his subjective preferences and needs, in time and space. For instance, operative temperature maps showed the possibility to have variable comfort conditions available in the pavilion space: these, together with the possibility for the user to control the different internal units, assured heterogeneity and variability to the space conditions. Moreover, the pavilion realization could help creating an informal space to enhance communication, social relations, dynamic activities, temporal and accidental occasions. At the same time, it could also help raising awareness about integrated design approach towards sustainability.

The use of FRP composites for the pavilion shell showed promising results that could lead to a radical shift in the way of conceiving the building itself and its sustainability in the future. A 1:2 scale prototype of a portion of the pavilion shell was fabricated to test materials, workflow, techniques and know-how that could be used for the entire pavilion fabrication off-site.

The pavilion energy and daylight performances were designed and analyzed, in a continuous iterative approach involving architectural design, considerations about materials, aesthetics and relationship with the existent building. The highly solar exposed location, as well as the lightweight, well insulated FRP construction system with low thermal inertia resulted in cooling loads higher than the heating ones. In order to reduce cooling loads, a fan-driven ventilation strategy during the night was implemented, along with a VRF system. Final simulations showed a total cooling energy required for the whole year of 34.38 KWh/m^2, while the heating one was 24.12 KWh/m^2. Heating energy loss was mainly due to ventilation (40 m^3/hour person). Daylight simulations resulted in excellent Daylight Autonomy (DLA), values and a Spatial Daylight Autonomy ($sDA_{300/50\%}$) near to 100%. Glare image-based simulations showed that this phenomenon is not a threat for the pavilion (DGP is under 0.35).

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