Shell - house steel/polyurethane sandwich systems ready to build

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Abstract

A shell formed architecture can be quickly obtained by a light steel bearing structure holding insulated polyurethane sandwich panels, shaped in shell form or straight. Lightweight façades could be shaded, in hot climates, with textile extensions and double roofs. Methodology follows very strict design phases which have brought to different systems with different, but a very simple, final shapes. Some prototypes have been realized in order to optimize the system and to verify all the theoretical calculations about wind loads and earthquake loads (above all the collaboration of the outside curved shell and the bearing structure). Many tests have been carried out to check natural lighting, optimization of spaces, static loads, dynamic loads, thermal behaviour, daylight factors analysis, logistic optimization, acoustic analysis.

One of these concepts has been named L’Armadillo® and measures 6,60mx8,00m (3,30 m is the radius of sandwich panel, frontal span of the arch is therefore 6.60 m and each arch span to next one is 4.00 m). The volume optimizes thermal behaviours and gives a high efficiency energy buildings which can be equipped with thermal or photovoltaic cells. Sandwich lightweight steel-polyurethane houses are a clear alternative to a normal house and can be quickly built with a goal to allow affordable spaces with good quality even in extreme situations. L’Armadillo® is a new system conceived from the Italian Company Brianza Plastica to find new options for its existing product Elycop® (curved sandwich panel). Therefore with a transfer of technology from an industrial product: Atelier 2 who designed it, link this project with previous experiences in design of Hospitals for Emergency (Italian NGO) with dry technology, Casa Parasol and Casa Paraiso with Dubosc and Landowski (Paris). Shell houses give multiple flexibility, are transportable as a kit in a container and easily assembled (and eventually disassembled) on site for different purposes: housing, hospitals, churches, schools, restaurants, etc. That is all those things which may disappear in a disaster contest.
Keywords: Post disaster quick built, Energy saving, Flexibility, Dismountability, Technology transfer.

1. Background

1.1 Structure Envelope (STREN) Technologies for quick construction

Simple construction principles and housing systems normally require complex processes of analysis that lead to the synthesis of their final form and technology. Industrialized systems of construction, based on sandwich panels or stratified layers supported by a frame structure, seem to offer several advantages in a quick reconstruction situation.

Jean Prouvé was the master in this area during the Modern Movement. His ability to interact with industry, opened a new era to the paradigm of the mechanical assembly of buildings. This allows to application of the the paradigm of mechanical assembly and connections to very ordinary buildings, with medium/low budgets, using a light structural skeleton and internal and external light weight envelopes. The use of steel sandwich panels with polyurethane (normally applied in industrial buildings or roofs) is an example of how existing technology can be used to make low cost homes, resistant to strong winds or hurricane, naturally ventilated and shaded, used in both normal conditions (thanks to the speed of construction) for temporary/emergency accomodation. The field of application of the stratified layer construction derives directly from vernacular buildings. Hybrid systems at low cost and low processing are possible and suitable in many emergency or post disaster situations, where is necessary a quick response to a often large amount of houses. The durability/quality of the solution is also very important considering that the temporary solution tends in most cases to become the permanent one [1]. As a consequence temporary accomodation have to fulfil higher performances than simple tents, caravans or containers. The light weight stratified layer building system is a Structure-Envelope system where the lightweight steel structure, supports the outside envelope [2]. The latter is made of sandwich steel and polyurethane panels (the inner envelope could be realized later on its own secondary structure). In the vacuum between the two main envelopes, further insulation could be added for winter and summer time. This would provide the necessary delay time of heat transfer from the outside to the inside in warm climates. Services can be applied both to the structure and/or to the sandwich panels. Close to the Tropics and to the Equator the hyper-insulation is less important because the envelope must mainly face overheating, which means shadowing the building and introducing natural ventilation are essential. A practical, technical and functional result can be obtained through aesthetical expression by using materials (such as simple wood panels or thin corrugated metal sheets or sandwich panels) used in a different way, from their normal purpose, with simple rules of stratified assembled and resistance. This shows that the value of each architecture is not contained just in the costs of the materials but also in the investment in intelligence, using very simple materials in a clever way [3].
1.2 Technology: “Shell-House”, ready made industrialized home

A “Shell-House” is based on a simple concept but it is the result of integrated design among architects, engineers and building industry. This helped to achieve different goals: the use of products already available on the market, the weight optimisation and the logistic, transport optimisation, simplicity and speed of assembly, and last but not least important, pleasant architecture. The design approach has similarities to the one used in the automobile industry, where options can be added to the basic version. Self supporting corrugated steel shells have also been used by the military for many decades but a “Shell-House” is a different thing for many reasons. It is a “mechano kit” and this allows transport in rather small parts. On the contrary self supporting shells needed big spaces to be transported, therefore only using military trucks and never stored in a container like the “Shell-House” is. That is why there is no need for making the arches self supporting but using them only as envelope and using the steel “skeleton” structure as the bearing frame. This solution also allows the reduction as much as possible of the foundations to few points instead of being obliged to design a foundation platform (therefore using much water which can be a problem in some regions). Anyway, in case of need, also a concrete platform could be realized as foundation.

The first “Shell-House” prototype, using curved and linear sandwich steel-polyurethane panels, was designed by Atelier 2 (Gallotti and Imperadori - Milano) with the Company Metecno. In that first case the unit was designed, free of charge, for the Italian NGO Emergency, organization which supports civilian war victims. It was meant to be a FAP (first aid post, or a small hospital unit in severe climates and dangerous war sites) and it has been erected and disassembled twice time (without any damage) before being given as a gift to another NGO who have built the unit for the third time (therefore showing its power of flexibility) as a site Hospital in the Rumanian countryside. This NGO is also italian, “Gruppo 29 Maggio”, and they are building a orphanage village. The “shell-house” Emergency unit will function as small hospital for this new community. This unit was designed using a trapezoidal, self bracing, hollow tube steel structure which bears a secondary hollow structure and then the curved sandwich panel. This is the panel “Oyster” (thickness 80 mm, radius 3.50 m) produced from Metecno and normally used for industrial roofs. All façades and floors (formed by a steel beam optimized grid) are in structural sandwich steel-polyurethane panels (named “Glamet” – thickness 80 mm). Interior finishing is in wood but all the shelves and partitions are also made in sandwich panels. Each structural frame has an inter axis of 3.50 m, therefore with a frontal diameter of 7.00 m (“Oyster radius is also 3.50 m) the final units measure in ground around 100 sqm. The building is equipped as a small hospital unit [4][5].
Figures 1, 2, 3 Delivery and construction of Emergency unit in Rumania as small hospital in 2007.

1.3 “L’Armadillo”, ready made industrialized home

Figure 4 – L’Armadillo housing unit in Carate Brianza (Milano) integrating photovoltaic cells on the roof.

“L’Armadillo” is a clever evolution of the “Emergency” unit into a house or other living space. In this case it has been designed by Atelier2 (Gallotti e Imperadori – Milano) with the Company Brianzaplastica using their existing roof panel “Elycop” (sandwich with 40 – 80 mm thickness,
radius 3.30 m). Bearing structure has been optimized into a 3 hinged arch (each frame is at 4.00 m span to the next one) supporting a secondary hollow section steel structure and then the sandwich “Elycop” panels. This solution, compared to the previous one used for the Emergency unit, allows a totally free space on the ground floor to be divided for any customized purpose. The building system is made of a light weight dry assembled kit. Foundations are in concrete on single elements (or platform/raft, depending on wind loads). Due to the light weight of the module the wind load becomes the critical factor to the foundation design. The principal bearing structure is made of galvanized steel profiles, shaped in a semi circular frame (linked at the base with a main beam to hold the secondary beams and the floor) which holds 2 secondary square tubes. Structural elements are connected with simple bolted connections. The curved Elycop sandwich panels are fixed to the secondary structure with steel screws. Sandwich steel panels are fixed to the ground floor secondary beams with steel screws. façades panels are fixed to the sandwich floors and to the sandwich shell. The floor is totally above ground where only 3 steel supports for each main frame descend to concrete foundations and are fixed to them with simple bolted connections. Façades are completed with 2 sunshading made of textile that protect the building from sun radiation, which is much more intense on the vertical surfaces than on the curved shell, except from the top third where it is necessary to fix also a further metal sheet to ventilate the upper part of the sandwich arch. The main steel structure is made of three hinged arches that support square steel sections that act as purlins. The main arches are connected with a floor beam that distributes weight to three fitted stabilisers. Over the master beams there are secondary beams supporting the sandwich panel floor, suspended above ground and therefore ventilated, made of 80 mm-thick sandwich panels in pre-painted steel filled industrially with polyurethane hardened foam. Outer covering consists of end window walls made of aluminium pre-painted windows and doors inserted in the 80 mm-thick sandwich panels. Elycop panels are modular. Normally they are used for industrial roofs and their commercial dimension is 40 mm. For the “Armadillo” a new evolution of Elycop’s use has increased the panel thickness to 80 mm in order to give better thermal, acoustic and static performances. This product improvement has been introduced to guarantee the same performances are achieved by both the vertical façades and horizontal bearing floor (which are also made by 80 mm sandwich panels). To increase the thickness to 80 mm accurate studies in the fluidity of polyurethane foam and time of expansion have been undertaken. This permitted the adaptation of the same machines used to produce the 40 mm panel without the requirement of expensive technology. This has given very good results in terms of economy of the solution and the distribution of polyurethane in the curved sandwich has been successful without air voids.
Figures 5, 6, 7, 8 The 3 hinged main arches are in ordinary steel profiles HEA 120 mm and they carry the secondary rectangular beam section profiles on which is fixed the curved Elycop panel. On the floor a sandwich panel of 80 mm which acts as bearing structure fixed on main steel beams. The final shape allows energy equipment to be integrated.

The Outer shell consists of three modules (a middle unit and two side units) which are shaped to fit at the joints after they have been made water tight; the conjunction of the curved panels is located always at one third of the arch. The internal space can be partitioned with gypsum board dividers or wooden panels. The underflooring is made with plywood planking, which allows for gluing the floor finish. In general aesthetic and functional characteristics of Armadillo make it available for a wide range of uses. It can be used as a single unit or assembled with other units in both of the main axis of expansion to create larger, living spaces, emergency hospitals, first aid, temporary houses, schools, emergency food storage areas or restaurants. The living unit, realized as a prototype and tested, is a small curved shell measuring 6.60 x 8.00 m, which can be divided into sub-units of 6.60 x 4.00 m, or enlarged into units measuring 6.60 x 12.00 or 16.00 m, by adding one or two spans to the basic module. Since the interior of the shell is completely empty, and can therefore be fitted according to the client’s needs, many different configurations, both for residential uses and other functions, are possible. Also different modules can be joined together along the transversal axis to obtain open spaces for different purposes. “Armadillo” is surprisingly spacious inside, and so any arrangement is possible. Internal dimensions clearly
show the difference between this and other industrialised homes (especially containers or caravans), and also demonstrate its adaptability to different requirements. It can be assembled like a “mechano” construction system, in just a few days, on a simple loadbearing foundation. Elycop panels are fastened over the light, durable metallic frame, also to increase the whole structure’s level of rigidity. The system can be supplied in separate kits, depending on the project requirements. They can also be autonomously devised by the client who has the option of buying only the building frame and order separately the other components. Reliable insulation and the correct position of openings results in high savings on fuel for heating/cooling needs and also on electricity. “Armadillo” can also easily be equipped with photovoltaic systems or solar panels, and therefore be totally independent of fuels. The majority of the building components are made from recyclable, environmentally friendly materials [6].

1.3 Prototype and site tests

A prototype has been constructed and was tested in 2005 in Carate Brianza (Milano). Dimensions are 6.60 m x 8.00 m (more than 50 sqm), which is the surface corresponding to the base unit. Interiors have been conceived as kitchen/living room, bedroom, bathroom and a terrace. 2 sun shading screens have been integrated with the front and rear facades. The 3 hinged main frames (spaced 4.00 m) are in ordinary steel profiles HEA 120 mm. The arches carry the secondary box beam section profiles. Main arches are linked with a base beam ILS 200 mm, connected to the foundation with 3 short steel legs, bolted in concrete. Secondary floor-beams ILS 140 sit on the main beams and carry the sandwich panel of 80 mm as a bearing floor. Thermal resistance of the 80 mm polyurethane panel has been shown to perform very well in winter-cold conditions and in summer-hot condition the system can rely on natural ventilation and the presence of a further ventilation layer on the shell improves the overall condition. The curved panel overlapping guarantees water and wind tightness and all the connections with vertical facades or floors are carefully protected for the same reason (in some cases also with additional polyurethane foam). In the prototype the internal space has been partitioned with gypsum board panels. The finished floor is a rubber layer glued on a wood layer which is fixed with screws to the floor bearing sandwich panel. The structural system has been calculated firstly with Straus automatic finite elements program both for stress and strains and the
prototype has been tested to verify the structural calculations. Design and testing on site have been undertaken following the Italian Building regulations\(^1\).

*Figure 10,11 The structural system has been calculated with Straus automatic finite elements program both for stress and strains. A test programme has been carried out to verify the theoretical calculations.*

Horizontal load tests have been carried out on the prototype by applying hydraulic jacks to the main frames and to the secondary structure in order to verify the theoretical model and also to prove that the presence of the sandwich permitted the structure in the direction of the load not to be braced. The introduced stiffness without additional bracing maximises the usable space and reduces costs. Different scheme tests have been carried out by adding curved panels to the bearing structure in order to prove the enhancement of stiffness thanks to the contribution of the sandwich shell. The 2 hydraulic jacks applied were driven by a oleodynamic system controllable and measurable with pressure manometer. Structural deformations have been evaluated with a tolerance of 0.5 mm and the results show a substantial elastic behaviour with some plastic corrections very probably due to a small plastic behaviour of the connectors and joints (bolted or screwed). Static analysis on the simple automatic model has given very good results compared with the real behaviour of the prototype. After analysing a partial model and testing the prototype on site, under horizontal loads to verify the increasing rigidity of the system due to shell panels, a full complex model automatic has been completed. This model has been finally checked under single or combined load actions (permanent loads, variable loads, snow, lateral winds, frontal winds, earthquake). All stress and strain outputs have been within the limits of safety and functionality, for this typology and for the applied materials.

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Figures 12 Horizontal load tests have been carried on the prototype by applying hydraulic jacks to the main frames and to the secondary structure.

2. Temporary Pub “Pian Cafè”

Figure 13 “Pian Cafè” has been quickly constructed in an existing square in Piancamuno – Italy.

“Pian Cafè” is the direct application of “L’Armadillo” for a different purpose of temporary and dismountable unit. It has been conceived to be a Pub in a small town in northern Italy (Piancamuno) where Atelier 2 (Gallotti and Imperadori – Milano) also designed a new contemporary square for the town’s open air market.
A Pub with public toilets (also for disabled people) was then needed and the low budget of the community led to the application of a “Shell-House” concept. A corten steel skin applied with rivets on the Elycop panels was added to L’Armadillo. This was for an aesthetic reason (all the square walls has corten steel as a final layer) but also because it creates a ventilation layer between it and the corrugated Elycop panel. Façades have been conceived to be protected from summer sun by 2 huge existing trees and to be able to save energy in winter.

Figure 16 South Façade and corten steel high durability outer shell
Foundations are on concrete plattform to resist winds prevailing in the Valley where it is placed. In winter the building profits of passive sun energy, through south façade, and also from all internal thermal loads (coffee machine, fridge, washing maschine) therefore doesn’t use any extra heating source during the cold season.

Figures 17,18,19 Daylight factors and sun gain studies for the South façade.
3. Conclusions

Figure 20 Politecnico di Milano students visiting the prototype “L’Armadillo”. A real vertical load test which shows the huge space of the single unit.

This building system shell-shaped, is a house composed by existing industrial products, the result of a commitment to specialization, research and product innovation between the company policy and a pool of designer and consultants always led by Atelier 2 (Gallotti and Imperadori, Milano).

The Shell House realized are modular units designed and built with quality products, present on the market and often used for non-residential purposes. “L’Armadillo” is designed to be shipped in a container, erected and dismantled, if necessary, through simple, quick procedures. It’s streamlined conformation optimises the heat loss and win ratios between the internal volume and the outer surfaces. Application of solar and photovoltaic panels can transform the unit and make it independent from other energy sources in case of need.

This extremely durable living unit was even designed to be used in areas where seismic activity and high winds are acting, according to Italian regulations, and therefore can be used in areas with extreme climate conditions. The use in other specific areas will request to verify the specific wind loads in order to verify the bearing and bracing structure (which is the shell itself) for the area selected to the application, as well as the dimension of foundations or concrete platform.
Figures 21,22  The modular nature of L’Armadillo allows a wide range of project solutions. Basic unit can be enhanced with a vast selection of complements and accessories, that make various applications possible in relation to the different needs and conditions.

References


