Manufacturing, testing and construction of reinforced concrete sandwich panel (RCSP) structures

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Introduction

A reinforced concrete sandwich panel (RCSP) is composed of an EPS (Expanded Polystyrene) foam core surrounded by spray-on reinforced concrete skins on both sides. A schematic of a typical RCSP is given in Figure 1. One of the things that make the onsite sprayed RCSP buildings different from the traditional brick masonry and framed (concrete and steel) buildings is that all the structural elements (beams, columns, floor slabs, walls etc) of the building are constructed continuous with each other, without any construction joint. This is achieved by a special method of construction where first EPS foam panels encased in steel wire mesh are erected on site, as shown in Figure 2a. These panels have been manufactured in the factory and continuity is provided by connecting them with wire meshes. After fixing the utility service elements (pipes and conduits etc) the walls are then sprayed with concrete, as shown in Figure 2b. This gives an integrated RCSP system which is advantageous over pre-cast building system. As unlike pre-cast systems it is a continuous construction system and all structural elements are connected rigidly to surrounding elements. This provides extra stiffness and support to structural elements and makes the building resistant to progressive collapse (the collapse of structural elements resulting from the failure of an adjoining primary structural element) even under severe conditions. For example, a two storey house made up of RCSP system is shown in Figure 3. The strength of this building is visible in the accidentally hanging four piers carrying heavy concrete foundations, as the foundation soil was swept away by a flood wave. All weight of the hanging piers with foundations was carried by the resulting cantilever floor. And the floor joints were still capable to resist the weight of the floor and the hanging piers with the foundations, without any sign of structural failure.

This paper is based on the material collected during the site visits at RCSP manufacturing, testing and construction site in Fano, Italy during 2008 and supported by the Pai Lin Li Travel Award awarded by the IStrustE Educational Trust. This paper discusses the basic manufacturing, testing and construction techniques used worldwide.

Background

Pre-cast RCSPs were introduced in the construction industry more than 40 year ago [Craig A. Shutt (1997) and PCI (1997)]. Since long, these panels were not in practice as load bearing structural element, rather they were used as partition walls, façade cladding or some other architectural purpose. Recently, in the last decade, many private companies all over the world started manufacturing these panels commercially. Major reason behind this adaptation was an effort to develop construction system that is capable to confront natural disasters due to earthquakes and hurricanes which were observed much frequently at different places in the last few decades. There was a need to have a construction system that should be quick and permanent, so that a sustainable rehabilitation of the areas struck with natural disasters is possible. Besides being providing an earthquake-resistant and insulating building system, RCSP buildings have been constructed up to the height from single to 20 stories (Emmedue, 2006). Also RCSP building system is capable to construct architectural structures which can be constructed in a variety of shapes.

M2 Emmedue has two major manufacturing plants. One manufacturing plant situated at Dublin, Ireland head office that is specialized in manufacturing Double Panels (see chapter 2). A more advanced plant at Fano, Italy which is also equipped with testing facilities besides manufacturing all types of sandwich panels (detailed in chapter 2). At Fano, M2 Emmedue also has few construction site. M2 Emmedue and their partners have several other construction sites all over the world.

Commercially many RCSP systems are licensed by patents registered in Europe, America and other countries, aiming at protecting both the products and the machinery used for manufacturing these products. Some examples include;

- M2 Emmedue (2006) (Italy)
- ICS-3D (1991) Panel (USA)
- Tridipanels (2006) 3D/EVG (USA)
- Greensandwich (2006)panels (USA)
- ThreeDee (2000) Panels (New Zealand)

Performance studies by Greensandwich (2006), M2 EMMEDUE (2006) and Tridipanel (2006) have revealed that RCSPs are able to resist heavy gravity loads beside earthquake, fire and cyclone (heavy winds). These panels have been used for buildings up to 20 storey high (M2 Emmedue,2006). Structures built of RCSP system have been exposed to some of the most severe conditions of nature and they have been found to be able to withstand winds of up to 200 mph (Ernst, 2005) and earthquakes up to 7.6 (Threedee, 2000),6.9 (Tridipanel, 2006) on the Richter.

Very few literature (ICS-3D 1991, TreeDee 2000, Tridipanel 2006) provides design methods for onsite sprayed RCSP, which are based on the use of design charts (ICS-3D,2001) developed from experimental observations. ICS-3D and Tridipanel also provide methods for verification of RCSP design with UBC(1997). Pre-cast and pre-stressed sandwich panels are similar to onsite sprayed RCSP with the difference that in the latter the reinforcement is not pre-stressed and there are no construction joints between the panels of the finished building. As in the buildings constructed with pre-cast and pre-stressed sandwich panels the structural elements are not continuous and are connected through flexible construction joints. These joints need to be properly designed (Bljuger 1998). This is not required in RCSPs. The literature (PCI 1997, Lindsay 2003, Kim 2004) available for the behavioural study of pre-cast and pre-stressed RCSP, only include steel connectors as the core material and ignores the EPS foam in the core as a structural material. Emmedue(2008) experimentally found that by increasing the density of EPS foam in the core of sandwich panel from 15 kg/m^3 to 25kg/m^3 the overall stiffness of the RCSP increases by around 40%. This signifies the importance of considering the mechanical properties of EPS foam while studying the overall structural behaviour of RCSPs. While in the available design methods the structural contribution of EPS foam is totally ignored.

Manufacturing of RCSP

There are two types of manufacturing techniques of RCSP that are in practice at the moment namely, factory and manual manufacturing. In the RCSP manufacturing plant at Fano, Italy, the factory manufacturing technique was observed in detail. The assembly of the EPS foam and the steel mesh with steel connectors connecting the steel meshes through the core is manufactured at the manufacturing plant shown in Figure 4. These panels are then transported and erected at the construction site before being plastered with shotcrete. There are three different systems of machineries that are used for the production of different elements of the RCSP. These machines are;

- polystyrene foam plant to produce EPS foam of the required grade
- wire meshes making machine and
- assembly plant (shown in Figure 4) to assemble the wire meshes and the EPS foam in the form of panels

The machine combines the sub-components of EPS foam blocks for the core, welded-wire trusses, and welded-wire fabric for the face mesh, into panels which are 50mm to 300mm thick. The EPS foam in the core is either centred or eccentric in the panel depending upon the thicknesses of the concrete leaves being equal or different respectively. The steel connectors in the core are either straight or inclined depending on the manufacturing plant. The connectors are placed at any desired spacing and in weights from 12 gauge (2mm) wire to #3 (9mm) rebar. The face wire meshes are manufactured in varying gauges and spacing based on the application of the panel as floor/roof or wall panel. The 25mm x 25mm, 16 gauge (1.3mm) mesh is the standard for roof and floor panels and 50mm x 50mm, 12 gauge (2mm) meshes for wall panels, as shown in Figure 5.

Concrete leaves are casted on the erected EPS + steel mesh panels using pneumatically sprayed dry concrete mix. However, the concrete skins can also be applied by hand, automatic plastering machines or shotcrete (wet-mix or dry-mix).

In the manual manufacturing technique the ready-made EPS foam panels connecting wire rolls and the steel meshes are transported to the manufacturing site and with the help of the locally available labourers the connecting wires are cut to the required connector size and the mesh and the EPS foam are assembled onsite using spot welding machines. The assembled panels are erected on the already prepared foundations and sprayed with shotcrete.

TESTING OF RCSP

Several laboratory tests have been conducted on RCSPs by the above mentioned producers, in order to patent their product and prove the strength and effectiveness of this system to get approval for public use. These tests also provide understanding of the structural behaviour of these panels for different loading conditions and helps in developing more research and improvement in the design of RCSP. The tests included flexure, shear, true-axial and eccentric-axial loading conditions. The effect of change in different design parameters (like thickness of the leaves, density of the EPS foam, etc) on the strength of the panel was also studied.

A review of the tests conducted by M2 Emmedue (2003) is given below.

Laboratory testing for flexure

A schematic of the flexure tests conducted by M2 Emmedue (2003) in accordance with ASTM (2005) E72-05 guidelines is given in Figure 6. Six panels were tested, three with a core thickness of 60mm and the other three of 80mm. Both concrete leaves of all these panels were 35mm thick. The panels were 1.11m wide and 2.4m long. The length “L” of the panel between the two supports was 2.13m, with 0.235m overhanging portion over the supports. Similar flexure tests were conducted by Emmedue (2008), on eight 4m long and 2.25m wide panels used as floor slabs, four with 80mm and the other four with 160mm thick EPS foam core. The top leaf of all the panels was 55mm thick while the bottom leaf was 35mm thick. Two from the 80mm and two from the 160 mm thick panels had EPS foam of density 15kg/m^3 and the rest had a density of 25kg/m^3. The geometrical properties of the panel are given in Figure 1.

The material properties of the panels tested were evaluated by M2 Emmedue(2003). The reinforcement consisted of two electro-welded steel meshes made up of 2.5mm diameter steel wires with an average tensile yield strength of 700MPa. The spacings of the wires in the mesh were 62mm longitudinally and 67mm transversely. The average 28 days cube strength of concrete was found to be 51.0MPa. The vertical steel connectors joining the two meshes were 3mm in diameter with a density of 80 connectors per square metre. The yield strength of the connectors was also 700MPa.

These tests have shown that the same panel can sustain loads above 1.7 kN which is far greater than that of comparable traditional masonry structures in Europe (EMMEDUE, 2003).

Laboratory testing for in-plane shear

Two types of tests on RCSP for in-plane shear have been performed namely, diagonal tension test and racking shear test. Diagonal tension test is one of the standard methods for evaluating the shear strength. ASTM (1999) E 519-81 gives a test method for “Diagonal tension (shear) in masonry assemblages”, which is used to evaluate shear strength parameters for masonry. M2 Emmedue (2003) used this method for the shear strength evaluation of RCSP. A schematic for the shear test performed as per ASTM (1999) E 519-81 regulation by Emmedue (2004) is shown in Figure 7a. The diagonal tension test setup and the results obtained by M2 Emmedue (2003) are discussed in this section. The purpose of the diagonal tension test is to evaluate shear strength and stiffness of a standard size panel element. The strength values obtained from this test does not include the effect of wall size. To evaluate the effect of panel size on the shear strength, racking in-plane shear test was also performed by Emmedue (2008), shown in Figure 7b.

In real structures, the walls that are constructed as shear walls are under racking shear load when the lateral loads such as the wind load or the earthquake load are applied on the structure. Wind and earthquakes are devastating natural hazards and it is evident that in past these calamities are responsible for disasters including total structural collapse. Therefore, racking shear strength check is a very important part of the wall element design.

Laboratory testing for axial and eccentric loads

A schematic for the true and eccentric axial load test performed as per ASTM (2005) E72-05 regulation by M2 Emmedue (2003) is shown in Figure 8. Six such panels were tested with core thickness of 80mm. Three of these panels were tested with a true axial compressive load, two panels with an eccentricity of 52.5mm and one panel with an eccentricity of 57.5mm. The setups of the distributed load required achieving the eccentricities of 52.5mm and 57.5mm are shown in Figure 8b.

From the axial and eccentric load no separation (bulging) or indentation of panel leaves was observed before the failure. This shows that for design purpose there is no need for considering the local failure check and it is sufficient to perform global design for the axial or eccentric loading conditions.

Other laboratory tests

To test the performance of RCSP for other forces of nature, the following tests were also conducted;

- Fire resistance: The quality of the EPS foam used in RCSPs is F type which is self-extinguishing in compliance with the DIN 4102 (1998) rules and enhances fire resistance of these panels. The test report by M2 EMMEDUE IBERICA S.A of July, 2003 reported that buildings constructed with RCSPs are mechanically stable for the fires beyond the duration of 60 minutes.
- Earthquake resistance**:** In the report by M2 Emmedue (2000), the laboratory tests carried out on a full scale two-storey prototype shows that the RCSP structures can resist a First Category Earthquake (which is the maximum level provided by the Italian Seismic Standards) without damaging the structure. The results obtained with these tests represent the scientific evidence of what has been already naturally experimented at several sites in the world where structures of RCSP were constructed.
- Cyclone resistance: Buildings that were constructed by M2 Emmedue with RCSP system in the areas of high risk of cyclones have demonstrated their ability to withstand the most devastating cyclones throughout the years which verify the results obtained by the tests on RCSP. In which wooden missiles with speeds up to 200mph were shot on the panel to simulate flying objects in the condition of a cyclone. The missiles only caused the external damage and the internal side of the panel remained unaffected.
- The rain tests carried out by on RCSPs by M2 Emmedue shows very good results, giving the suitability of the panels under the most difficult weather conditions.

Construction with RCSPs

In Italy, the use of single panels (three layer panels i.e. concrete-EPS-concrete) as structural (or load bearing) element is not permitted by the Italian Building Authorities. Hence, only double panels (five layer panels i.e. concrete-EPS-concrete-EPS-concrete) are used in load bearing wall in Italy. Efforts are on for approving single panels for structural use. Contrary to this, in Spain and other place in the world, where the building authorities only requires the strength test results to be acceptable, several multi-storey buildings are constructed with single panels only.

Shuttering for erecting RCSP structure

Special methods of shuttering are developed for construction of building with RCSPs. The method of installation depends upon the type of shuttering frame. If a hollow metal masonry type frame is being used as shown in Figure 9, the frame can be grouted in place when the concrete skins are being applied to the panels. If a wood frame is being used, an anchoring member of sheet metal or treated wood may be embedded in the panel. If vinyl frames are used they may be temporarily tied in place and then grouted solid when the concrete skins are placed.

Panel placement on foundation

The panels are secured to the foundation in a variety of ways but generally, the panels are attached to the foundation through the use of dowels as shown in Figure 11.

RCSP construction

Being light, these panels are transported and erected onsite by one or two operators, as shown in Step-1 in Figure 10.

Hot-air generator is used to melt EPS foam to produce chases behind the steel mesh for electric wiring and piping as shown on Step 3 in Figure 10. For rigid or semi-rigid pipes that cannot be bent to be inserted behind the steel mesh, the mesh is cut in the required length and then covered with plane steel meshes as shown in Step 3 of Figure 10. Openings for door and window frames are cut and the frames with fixations are placed and tied to the panels.

After the whole structure of EPS foam and steel mesh with wiring and piping is erected, the concrete plaster is applied directly onto the panel either by hand or pneumatic spray. Finally, the floors and roofs are poured with concrete using cranes (as shown in Figure 12) or by hand.

Observations and Conclusion

Tests on RCSPs by M2 Emmedue (2003,2008) have been reviewed and discussed with reference to load-displacement characteristics and modes of failure. These tests were used by the author to validate the numerical models of RCSP, which were developed to be used in conjunction with the experimental results to develop a better understanding of the behaviour of sandwich panels under different loading conditions.

The structural behaviour of RCSP to different loading conditions is found to be very different from the wall and floor behaviour provided in the international building codes (BS 1997, UBC 1997, Eurocode 2004, ACI (2002), etc). For downward bending, the building codes consider the concrete in the bottom as fully cracked and all the tensile stress is taken by the reinforcement in the bottom. This is not the case in RCSP (Lindsay 2003), where the bottom leaf is also capable to resist bending moment.

Among the few design methods available for onsite sprayed RCSP, the ICS-3D (1991) design approach is very crude as it uses the ACI 318-95 design code while ignoring the presence of the EPS + connector core and the bending stiffness of the bottom leaf. The other methods are limited to specific type of shear connectors and provide less flexibility in the design parameters (thickness of leaf and core, diameter of connector and density of EPS core etc).

The thermal properties and fire resistance of the sandwich panel largely depend upon the thickness of the concrete leaves and concrete cover to the reinforcement. This limits the design for minimum thickness of concrete leaves.

The construction of RCSP buildings is easy, fast and clean, since it does not require any masonry work. Compared to other construction systems, the advantages of the RCSP building system are as follows;

- Lightness and workmanship: These panels are easy to handle, transport and assemble. The lightness of the panels matches with the stiffness of structure, even prior of the completion with structural concrete that provides integrity to the panels and correspondence between the panels and their use. Prior of the concrete application, the weight per square meter changes according to the type of panel: from 3.5 Kg/m^2 to 5 Kg/m^2. A worker can easily handle over 3 m^2 of wall without difficulty.

- Quick construction: The time required to construct a fully functional building using RCSP technology is much shorter compared to the conventional systems.

- Inexpensive: Economic comparisons between these buildings and other traditional systems having equal performances have shown a saving exceeding 20% as for the double panel and 40% as for single panels. Furthermore, it should be taken into account the considerable saving of time due to the use of an industrial product that optimizes the assembling sequences and reduces at the minimum the work of the building site staff.
- Versatile: These panels can be used for building almost any kind of structure. The panels can be employed as load bearing vertical elements, partitions, curtain walls, floors and staircase flights. In all of these cases it is easy to obtain all the geometrical shapes both plane and curved, just cutting the elements on site. Few examples are given in the appendix. The characteristics of heat insulation, sound-proofing, fire resistance, handling and easiness of assembling make these panels suitable for all kinds of uses.
- Choice of finishes: The walls constructed by RCSPs can be completed with a variety of finishes. It is possible to apply a thick coating right on the raw plastering or, as an alternative, ordinary painting on the smooth plastering. Almost any type of coating is possible, without exception.

Once the complete building is sprayed with concrete plaster and it dry to gain strength, the whole structure becomes monolithic. This makes all structural elements of the building over supported thus reducing the chances of progressive collapsing as a case in precast construction. The steel mesh is dense enough to reduce the chance of creep, shrinkage and other mechanical and thermal problems.

Architecturally and aesthetically, buildings constructed with RCSP have no patches of the system chases which are always visible in the traditional systems. Also as the concrete plaster is homogeneous all over the structure it also improves the aesthetics of the building.

In RCSPs the use of wood or metal stud framing as required in masonry block construction, precast and tilt-up construction is not required as the EPS foam serves this purpose which after construction provides insulating, and structural purposes. As these panels are reinforced and encapsulated by a layer of concrete on both sides, they are also resistant to pests, mold and vermin, and are fire and water resistant.

The value of the K (total heat transmittance of a wall) provided by a panel made up of a polystyrene slab of 4 cm (density 15 kg/m^3) applied with plaster 3 cm thick on both sides for a total thickness of 10 cm, is equal to 0.78 W/m^2 K. For the wall panel of 8cm thick polystyrene slab (density 15 kg/m^3), the calculated value of the K heat transmittance is equal to 0.49 W/m2 K. Such a heat insulation degree exceeds in a remarkable way the peculiar values of the partitions or curtain walls obtained with the traditional systems; this produces energy saving equal to 40% both while heating and while cooling.

The soundproofing of these panels is one of the advantages of the building system.

The author is currently undergoing research in developing methods of strength estimation for RCSPs and has successfully developed a numerical model to achieve this purpose (Mohammad, 2008). The objectives of the research includes;

- Understanding the structural behaviour and performance of RCSP under various loading regimes
- identifying and recommending the basic design parameters of RCSP walls and
- establishing the methods for strength estimate of RCSP in flexure, in-plane shear and axial loading conditions

M2 Emmedue performed dynamic tests of a two storey structure in 2002 and 2008 in order to prove the seismic load capacity of RCSP buildings. It is important that this and similar data from other producers may be used for research in developing methods to estimate the dynamic behaviour of RCSP systems to further improve the design and understanding of the structural behaviour of RCSPs.

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