



AN INNOVATIVE FORM OF STEEL-CONCRETE (SC) STRUCTURES FOR NUCLEAR POWER PLANT

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ABSTRACT

SC construction has been recognised for over 25 years as an attractive structural concept for the design and construction of nuclear power plant, offering both structural efficiency and potential savings in construction time. In order to manufacture modular self-supporting SC units, it is necessary that the two steel plates are 'tied together' at regular intervals for handling, transportation, erection and concreting. Many attempts were made over the past 25 years to devise practical, economic and safe methods of connecting the plates. They have included the use ribs, trusses or bars welded to both plates. The welding is largely manual giving rise to issues of economy and health and safety due to the confined space between the plates.

This paper describes work undertaken to develop manufacturing and construction processes using an innovative form of composite steel-concrete (SC) modular construction. The basic building block of the system is a steel plate folded into a U-shape with a concrete infill. Individual building blocks (referred to as 'Steel Bricks') can be joined together to create larger units that make up structural modules. Holes cut into the plates allow the concrete to flow between Steel Bricks during concreting. The work addresses all the key manufacturing operations including plate folding, joining of units together, lifting of units, stability during erection, alignment and manipulation, joints between panels, connection to reinforced concrete foundations and QA/inspection techniques. The concept has been demonstrated at full scale through the construction of a section of a diesel generator building.

INTRODUCTION

Most buildings and containment structures in nuclear power plant (NPP) have been built from reinforced or post-tensioned concrete in the past. This has placed heavy reliance on cast in-situ construction. It has led to lengthy site operations to accommodate the time spent in assembling the shuttering and reinforcing steel and stripping the shuttering after curing of the concrete. Attachments to the walls and floors which are used to support electrical and mechanical equipment (e.g. piping, cable trays, etc.) require the installation of either embedded steel plates or concrete expansion anchors into walls, floors and ceilings. Installing embedded steel plates is difficult because anchor rods and their end plates need to be inserted in the very dense reinforcement, requiring the displacement of the reinforcement bars. Installation of concrete expansion anchors entails locating reinforcing bars in the concrete to avoid cutting them followed by drilling into the concrete and inserting anchors for bolting steel plates to the concrete surface to attach supports. As there are around 100,000 plates in a typical NPP (see for example Meiswinkel and Schnell (2013)), this is a very costly and time-consuming operation.

New generation NPP manufacturers have been developing modular construction techniques that make greater use of pre-fabrication and factory assembly and reduce reliance on site activity. Most have adopted a technique that uses composite steel/concrete (SC) modules made by pouring concrete between two steel plates. The plates serve the dual purpose of reinforcement and permanent formwork to the concrete. Shear studs welded to the inside surfaces of the plates ensure composite action between the steel and concrete and can be spaced such that the compression steel plates do not buckle under load. They also

provide the means for easy attachment of support points for equipment, eliminating the need for embedded steel plates or concrete expansion anchors.

Previous research has shown that SC structures exhibit greater stiffness and strength as well as toughness when compared with that of conventional concrete structures. Another advantage is that the steel plates act as impermeable membranes in SC structures, removing any leakage problems which is an important requirement in some parts of NPP. For these reasons, a number of reactor manufacturers have made SC construction an integral part of their new designs (see for example Schultz (2006), Toyama (2009) and Massayoshi (2009)).

To support the surface plates during assembly, lifting, transportation, concrete pouring and curing, the two plates must be connected together to form a self-supporting unit. In this way, parts of modules may be fabricated off-site and transported as units to be assembled on-site and connected together. Many attempts have been made over the past 25 years to devise practical, economic and safe methods of connecting the plates. They generally use bars, ribs or trusses welded to both plates. When the concrete sets, these ribs, trusses or bars provide out-of-plane shear reinforcement to the concrete. **Figure 1** shows an example of a SC panel prior to concreting with shear studs and bar connectors.

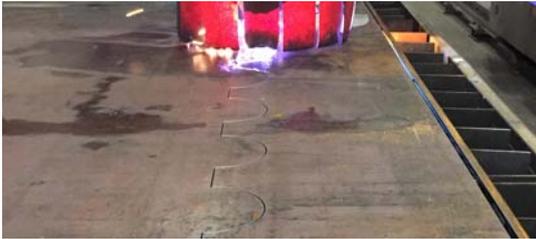


Figure 1. Typical SC panel with bar connectors and shear studs.

Welding of ribs or bars is manual and raises issues of economy, quality and health and safety due to the confined space between the plates, particularly where wide panels are concerned. The only example in which simultaneous automatic welding of the bars to the two plates was achieved is Bi-Steel (Corus (2003)). In Bi-Steel, both ends of each bar are simultaneously friction welded to both plates. However, fabrication requires specialist equipment and there are several manufacturing constraints; for example the panel thickness is limited and the friction welding process places limitations on the plate thickness to avoid ‘burn through’ of the plates and on bar diameter to avoid distortion of the bars during welding.

THE STEEL BRICK CONSTRUCTION CONCEPT

‘Steel Brick’ is a new generation of SC modular construction protected by international patents. It overcomes the manufacturing problems of earlier SC systems. A Steel Brick is made by cutting a pattern into a flat steel plate (Figure 2(a)) and then folding the plate to form an ‘L’ shape (Figure 2(b)). Shear studs are welded to the sides of the ‘L’ section (Figure 2(c)) and then two ‘L’ shaped plates are welded to form a ‘U’ shape) as shown in Figure 2 (d).



(a) Pattern cut into flat plates



(b) Plates folded into an 'L' shape



(c) Shear studs welded to the sides of the 'L' sections



(d) Two 'L' sections welded to form a 'U' shape

Figure 2. Steel brick concept.

The pattern cut into the plates creates circular holes in the base of the 'U' to allow concrete to flow between bricks joined side-by-side (Figure 3(a)) and Steel Bricks can be welded together to create large structural modules. The base of the 'U', which is integral to the Steel Brick, provides the means of holding the two sides of the panel together and acts as out-of-plane shear reinforcement to the concrete. Corner bricks are fabricated with holes in the vertical side of the 'U' to allow concrete to flow round the corner as shown in Figure 3(a). It is also possible to use different plate material on the two sides of a wall (e.g. stainless steel and carbon steel) to provide greater corrosion resistance on one side as may be required in some parts of a NPP. The same concept is also used to manufacture module floors in which the unit brick has holes in both the base of the 'U' and in one of the vertical sides to allow flow of concrete in the plane of the floor during concreting (Figure 3(b)). This enables the floor to have a finish similar to conventional floors by allowing the concrete to rise above the plate to create a 'topping'. These features enable Steel Bricks to overcome the manufacturing problems of earlier SC systems.



(a) Steel Brick wall/corner modules



(b) Steel Brick floor module

Figure 3. Steel Brick modules.

STEEL BRICK MATERIALS AND GEOMETRY

Design, manufacturing and workshop and site trials have been carried out on materials with the following specifications:

- Steel plates: S355, plate thickness $8 \leq t \leq 15$ mm.
- Shear studs: 19 mm diameter, with ultimate strength $f_u = 450$ N/mm² and as-welded height ≥ 75 mm.
- Concrete: normal weight, grade C40/50.

WORKSHOP AND SITE TRIALS

A series of plate bending tests was carried out on 8, 10, 12 and 15 mm plates in lengths up to 10 m. Clause 4.14 of BS EN 1993-1-8 (BSI (2005)) prohibits welding within $5t$ of a cold-formed corner unless either the cold-formed zones are normalised after cold forming and before welding or the r/t ratio satisfies the relevant value obtained from Table 4.2 of the code (where r is the bend radius). Tests demonstrated that internal bend radii can be achieved that exceed the minimum specified values.

Comparative welding trials were performed to assess whether edge preparation was required when welding the two halves of a Steel Brick together. Both metal inert gas (MIG) and submerged arc welding were investigated. The welded specimens were subjected to a series of non-destructive and destructive tests (visual, magnetic particle inspection (MPI), radiography, Vickers hardness survey, Charpy, tensile bend test and macro test). In the case of MIG welding, all test pieces without edge preparation failed due to the lack of weld fusion, whereas all test pieces with edge preparation passed. The submerged arc welded specimens, on the other hand, all passed and this welding process has therefore been adopted.

Where Steel Bricks are welded together to form large panels, the weld is between the free edge of a side plate and a rolled corner. The shape of the rolled corner provides a natural edge preparation, and the free edge of the side plate needs no further preparation. This forms a 'single prep butt weld' as defined in detail 1.9.2, Table 1, BS EN 9692-1:2013 (BSI, 2013) for MIG welding, and detail 1.4, Table 1, BS EN ISO 9692-2:1998 (BSI, 1998) for submerged arc welding. All welds passed the test and the inspection criteria (visual, MPI, radiography, Vickers hardness survey, Charpy, tensile bend test and macro tests). Similar welds are used to create T or L joints between wall elements. Figure 4 shows submerged arc welding of Steel Bricks in progress to create a wall panel.

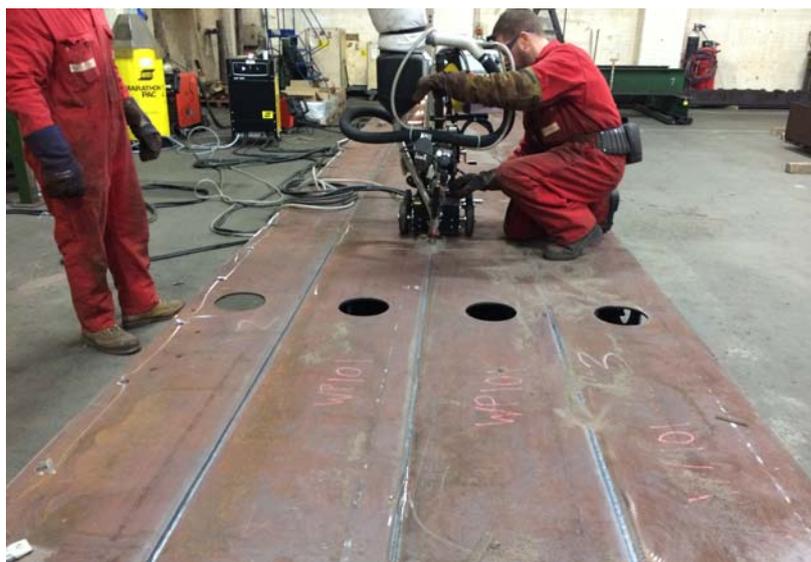


Figure 4. Submerged arc welding of Steel Brick panels.

A range of wall to floor connections, both welded and bolted were investigated. Although both are technically feasible, the trials showed that bolted site connections provided an easier option for construction. An example is shown in Figure 5.

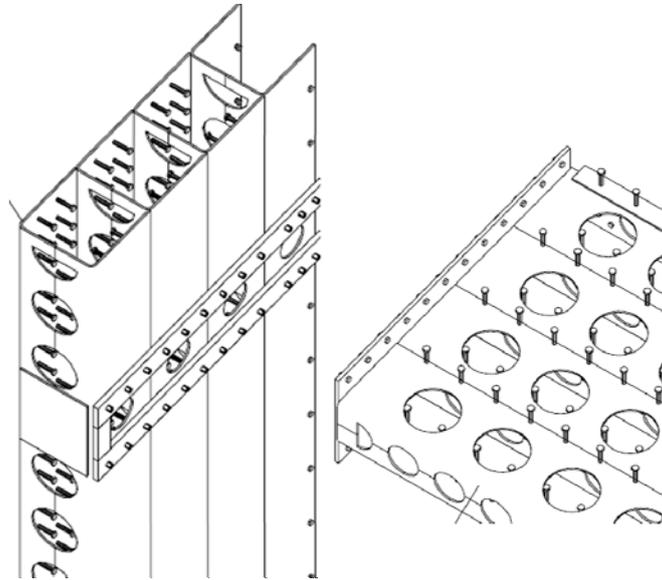


Figure 5. Example of a floor to wall connection.

A concrete mix was designed to ensure good flowability of concrete. This included the use of well-graded aggregates (with a maximum aggregate size of 20 mm, 60% of aggregates with diameter < 5 mm and 30% with diameter < 0.5 mm), as well as the use of additives. Concreting trials were performed on isolated elements, a structure comprising a series of connected walls and structure comprising a combination of two walls and a floor. The quality of the concreted specimens was checked by testing four core samples from the concreted structures as well as by visual inspection after cutting up large sections of the concreted structures. The $\Phi 100$ mm core test results (performed 3 months after the specimens were cast) were all satisfactory as shown in Table 1. A concreted wall assembly is shown in Figure 6(a) and a section through one of concreted elements is shown in Figure 6(b).

Table 1: Concrete core strength.

Specimen	Density (kg/m ³)	Core strength (N/mm ²)
A1	2321	58.2
A2	2339	63.3
B1	2242	59.1
B2	2235	56.7



(a) Concreted wall module



(b) Section through a concreted specimen

Figure 6. Concreting trials.

FULL SCALE CONSTRUCTION TRIAL

The use of Steel Bricks at full scale was trialled by designing and building a part of a building used on NPP sites. The building selected for this purpose was the ‘Diesel Ultimate Secours (DUS)’, which is a post Fukushima safety measure being constructed on all EDF nuclear reactor sites in France. The DUS building is rectangular on plan (23 m x 13 m) and 20 m high constructed over 5 levels (Figure 7). It houses two sets of diesel generators, two fuel tanks, electrical rooms, air intake rooms and ventilation rooms. The two generators provide electrical power for up to 72 hours to the buildings that contain equipment necessary for removing the heat generated by the nuclear fuel contained in the spent fuel pool and in the vessel of the reactor building. Power from the DUS generators is required in the event that all other means of electrical power supply, including all the existing emergency diesel generator sets, have failed.

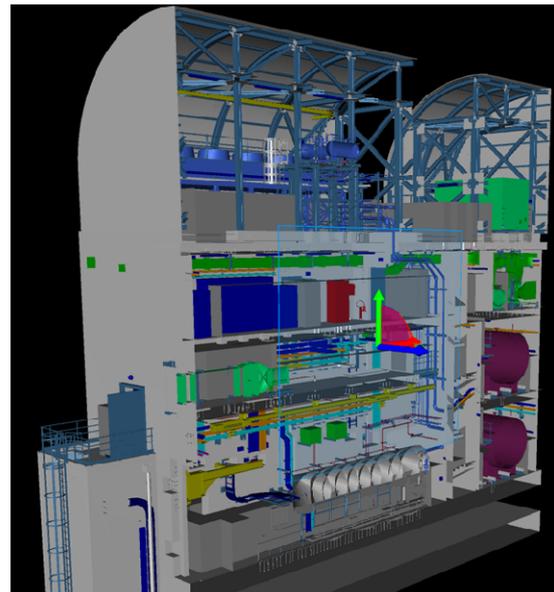
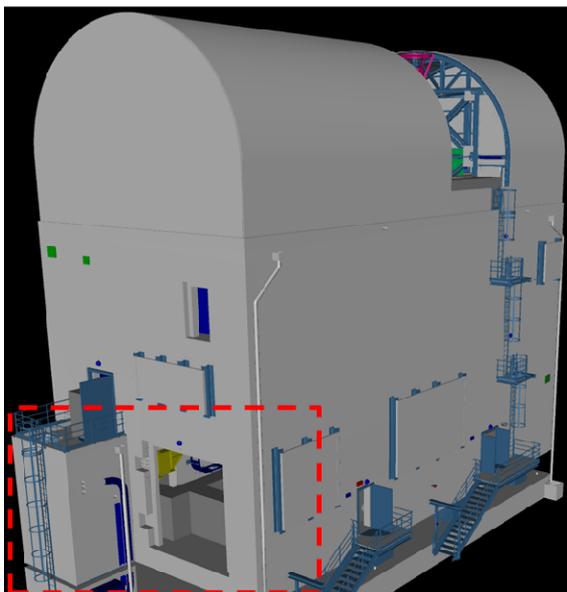


Figure 7. The DUS Building.



Figure 10. Erection of one of the large floor modules.



Figure 11. Completed structure prior to final site welding and concreting

CONCLUSION

This paper has summarised ongoing work performed to develop and prove the technical feasibility of a new generation of SC modular construction technique for use in building new NPP. Practical trials were conducted addressing all aspects of construction. The application of existing Eurocode design rules at the construction and final stages as well as the new AISC specification to the design of Steel Bricks was examined.

Steel bricks were shown to overcome the manufacturing difficulties encountered with earlier generations of SC construction, while retaining the advantages. The work has demonstrated how existing design rules can be conservatively applied to this form of construction. The manufacturing trials have shown that individual steel bricks and their assembly into sub-modules can be achieved using existing and relatively simple technologies. The work showed that the complete trial structure, which utilised part of the EDF DUS building design, was possible to construct with relative ease and without site fit-up issues.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of Innovate UK. The assistance of EDF in providing design information and building layouts for the DUS diesel generator building is also gratefully acknowledged.

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