STEEL-CONCRETE-STEEL SANDWICH STRUCTURES IN CURRENT CONSTRUCTION – A SHORT OVERVIEW

*Roman Kubát, **

Katedra betonových a zděných konstrukcí, Fakulta stavební,
České vysoké učení technické v Praze, Thákurova 7/2077, 166 29 Praha 6, Česká republika.
`roman.kubat@fsv.cvut.cz`

ABSTRAKT

Tento článek by měl čtenáře seznámit se základními poznatky o ocelobetonových sendvičových konstrukcích, které autor nasbíral v rámci teoretické části diplomové práce. V úvodu je představena krátká charakteristika ocelobetonové sendvičové konstrukce ohledně konstrukčního řešení, statického působení a oblasti využití. Dále je zde uvedeno, jakým způsobem lze konstrukce tohoto typu rozlišovat. Článek také obsahuje výčet jednotlivých výhod a nevýhod technologie ocelobetonových sendvičových konstrukcí. V závěru jsou představeny některé příklady reálného využití ocelobetonových sendvičových konstrukcí v jednotlivých oblastech stavebního inženýrství. Konkrétně se bude jednat o příklad z oblasti jaderné energetiky, z oblasti výškových staveb a oblasti dopravní infrastruktury. Je též nastíněno, kudy se bude ubírat další výzkum autora v rámci doktorského studia.

KLÍČOVÁ SLOVA

Ocelobetonový sendvič • Ocelové plechy • Výplňový beton • Spřahující prvky • Spřažení

ABSTRACT

This paper should give the reader a basic overview of steel-concrete-steel sandwich construction (SCS), which the author collected during the theoretical part of his master thesis writing. An introduction is given to SCS construction, including construction solution, static action, and areas of use. Furthermore, the article shows a possible way, how to divide the structures of this type. Is also contains a summary of the advantages and disadvantages of SCS technology. In the end, there are a few examples of real structures from different areas of civil engineering which use this technology. The topics for further research of the author in his doctoral study are also outlined.

KEYWORDS

Steel-concrete-steel sandwich • Steel plates • Infill concrete • Connectors for composite action • Composite action

1. INTRODUCTION

A steel-concrete-steel sandwich (SCS) structure consists of two external steel plates, which are anchored to infill concrete. The composite action can be provided by shear connectors of many types. In the early days, epoxy resin was used to join steel plates and concrete. Nowadays, it is preferred to use mechanical connectors such as headed studs, J-connectors, U-connectors and so on.

The SCS works quite similar to classical reinforced concrete (RC). The steel plates carry the tension forces and the concrete increases compression strength and stability. However, the construction solution of SCS can provide much more resistance than classic RC, and that is the reason why the area of use of SCS is principally in extremely loaded structures like protective structures, offshore structures, oil storage containers, ice-resistant structures, and containments of nuclear reactors.

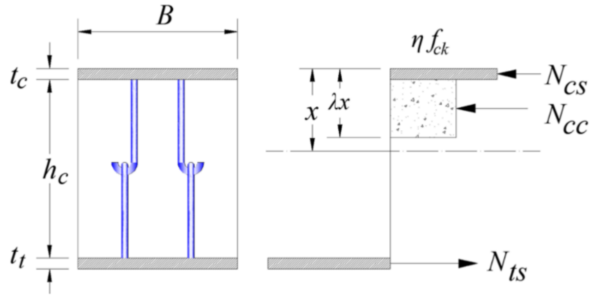

Figure 1*: Static action of SCS (Jia-Bao Yan et al, 2014).*

$$N_{cc}+N_{cs}=N_{ts} \tag{1}$$

$$x=\frac{(N_{ts}+N_{cs})}{\eta f_{ck}B\lambda x/\gamma_c} \tag{2}$$

$$M_{rd}=N_{ts}(h_c+t_c/2+t_s/2)+N_{cc}(\lambda x/2) \tag{3}$$

The compressive force of the concrete can be calculated by the following formula.

$$N_{cc}=\eta f_{ck}\lambda x\,B/\gamma_c \tag{4}$$

---

* Školitel: Ing. Petr Bílý, Ph.D.

where $\eta = 1.0$ for $f_{ck} \le 50$ MPa, $\eta = 1.0 - (f_{ck} - 50)/200$ for $50 \le f_{ck} \le 90$ MPa; $\lambda = 0.8$ for $f_{ck} \le 50$ MPa, $\lambda = 0.8 - (f_{ck} - 50)/400$ for $50 \le f_{ck} \le 90$ MPa; x = depth of the neutral axis position as shown in Figure 1; B = width of the beam.

Both tension force N_{ts} and compressive force N_{cs} in the steel plates are governed by either the yield resistance of the steel plate or maximum shear resistance of total shear connectors in the tension or compressive zone of the concrete. These forces can be determined by

$$N_{ts}=\min\left(n_t P_s,\ f_{yd}\, A_{ts}/\gamma_{M0}\right) \tag{5}$$

$$N_{cs}=\min\left(n_c P_s,\ f_{yd}\, A_{cs}/\gamma_{M0}\right) \tag{6}$$

where, n = number of the shear connectors (n_c = in the compressive zone, n_s = in tension zone); P_s = shear resistance of the shear connectors; f_{yd} = yield strength of the steel plate; A_s = area of the steel plate (A_{cs} = compression steel plate area, A_{ts} = tension steel plate area).

According to balance equation (1), it is possible to determine the depth of the neutral axis position via equation (2) and then also the bending resistance via equation (3).

2. DIVISION OF THE SCS

Generally, it is possible to divide the construction solutions of SCS into three types according to the connectors used for the composite action. Specifically, the division is 'Direct Link', 'Semi Link' and 'Indirect Link' (Jia-Bao Yan et al, 2014).

2.1. Direct Link

This type of construction solution uses transverse bars as connectors, which join the steel plates to each other by welds on both ends of the bar. This solution is practical, because it allows to prefabricate the semi-rigid steel panels, which are just welded to each other and filled with concrete. Furthermore, there is no need to evaluate the possibility of the pullout failure of the connector from concrete or concrete breakout failure due to tension force in connector.

A classic case of the direct link solution is British Bi-steel, which was developed by Hugh Bowerman in1998 (Bowerman, H. et al, 1998) and which is used for the construction of immersed tunnels in these days.

Figure 2: *Direct link type (Jia-Bao Yan et al, 2014).*

2.2. Indirect Link

The difference between the indirect link and the direct link solution is that the steel plates are not joined by their connectors. It brings a series of disadvantages of the indirect link compared to the direct link. For example, there is a problem with holding the steel plates in position during the concrete placement. Another disadvantage is the requirement of resistance to pullout failure and concrete breakout failure. On the other hand, in the case of indirect link, there is no problem with a complicated process of connectors welding to both steel plates.

Typical construction, which uses the indirect link is called the Double steel (Jia-Bao Yan et al, 2014). It consists of two independent steel plates with headed studs as connectors. After fixing these plates in the final position, the space between them is filled by concrete.

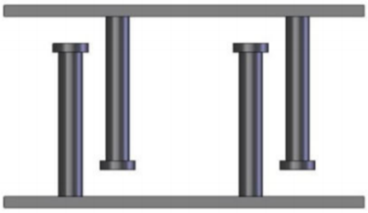

Figure 3: *Indirect link type (Jia-Bao Yan et al, 2014).*

2.3. Semi Link

Semi Link connects the advantages of both previous variants. The steel plates are not joined by connectors to each other during the prefabrication, but straight before the concrete placement. The connection of the steel plates is provided by the closed shape of the connectors or by some kind of linear element (steel bar or wire threaded through the closed shape of the connector).

Typical connectors for semi link solution are for example J-hook or U-connector with steel wire (see Figure 4.).

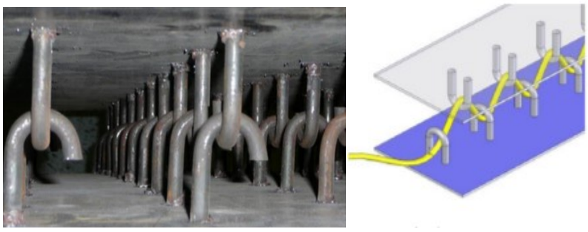

Figure 4*: Semi link type (Jia-Bao Yan et al, 2014). Using J-hook on the left side, using U-connectors on the right side*

3. ADVANTAGES AND DISADVANTAGES OF SCS

SCS technology brings several advantages and also a couple of disadvantages in comparison to RC. Most of the advantages relate to the resistance of construction and construction speed. On the other hand, the disadvantages relate rather to design and realization.

3.1. Advantages of SCS related to construction resistance

- Concrete is hermetically closed between the steel plates during the whole service life, which means that the shrinkage is limited.
- Steel plates keep concrete safe from external conditions (carbonation, chlorides, chemically aggressive environments).
- Theoretically, there is no limit for the reinforcement ratio. In real, the thickness of steel plates is limited by the weldability of every unit.
- Concrete core increases the fire resistance, which is better than in the case of pure steel construction.
- Steel plates provide the watertightness of construction.
- It is possible to use lightweight concrete as the core, which reduces the self-weight of the final construction.

3.2. Advantages of SCS related to construction speed

- The most used solution called Bi-steel provides the possibility of modular construction, so it is very similar to prefamonolitic construction.
- Steel plates work as permanent formwork.
- Because the formwork is not removed, there is no need to cure concrete.

3.3. Disadvantages of SCS related to designing

- Currently, there are only few findable codes, which provide the design methods for SCS. The author of this paper found just two. The first one is Japanese called JEAG 4618 (Architectural Institute of Japan, 2005). It is possible to find some mentions about this code on websites mostly in Japanese, but the whole text is not publicly available. The second one is American and it is called ANSI/AISC N690-18 (American Institute of Steel Construction, 2018). The American code also contains a commentary summarizing the knowledge from the existing results of experiments, which makes it useful for both design of structures and understanding the underlying principles.
- For the structures of great importance like primary containments of nuclear reactors, there is also a problem with the certification of a brand new solution.

3.4. Disadvantages of SCS related to realization

- For curved structures like containment walls and dome, there is a strict requirement for the production accuracy of single modules.
- Another problem is welding. It is very hard to weld single modules to each other in the space between the steel plates with connectors or it is even not possible. In the case when it is not possible to weld from the inside, it is necessary to make it from the outside only, which can be a problem for steel plates with larger thickness.
- For the structures of larger dimensions, there will be a need to solve the connection of the older concrete with the newer concrete from the other interval of concrete placement, because it is slower to build the next floor from Bi-steel modules than from the classic removable formwork.

4. REAL EXAMPLES OF USE OF SCS

As mentioned above, SCS technology is determined principally for structures of great importance. Nowadays it is possible to see a couple of cases of the use of SCS all over the world. The following text will introduce a few of them.

4.1. Secondary containment of nuclear reactor AP1000 from Westinghouse company

The purpose of this structure is to keep the reactor safe from possible external extreme loads like aircraft impact, terrorist attack or extreme natural influences like tornado, hurricane and so on.

The design of Westinghouse containment includes SCS cylinder wall and conical roof, which consists of reinforced concrete supported by radially arranged steel beams. At the top of the roof there is a water tank for passive reactor cooling in the case of an accident. The cylinder SCS wall is mostly 914 mm thick. In the upper level, the thickness is increased to 1370 mm. The thicker part includes the penetration for air inlet and stiffeners for beams to support them. Construction from SCS uses Bi-steel technology. The steel plates were designed as 19 mm thick using steel ASTM A572 Grade 50 with a yield limit of 345 MPa. The composite action is provided by headed studs with 19 mm in diameter. The spacing of headed studs is 216 mm vertically and 213 mm horizontally. Furthermore, one of four headed studs is replaced by a connecting bar (Bi-steel technology). In the areas with higher values of stress, the composite action is provided only by connecting bars with 152 mm spacing. The infill concrete with the thickness of 876 mm has 41.6 MPa nominal compressive strength.

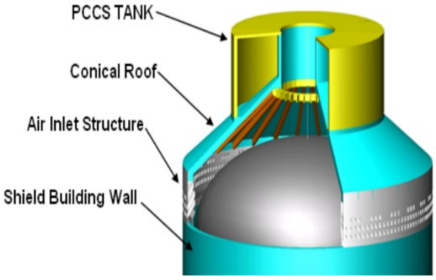

Figure 5: *Particular parts of the secondary containment (European Nuclear Society, 2010)*

For the shield building (SCS part) (Bílý, P., 2020), it was used over 160 semi-rigid Bi-steel panels for the construction of containment wall. Typical panel was 3 m high and 11.5 m long, which corresponds to a 30° segment of the final cylinder wall. It means that one floor was built from 12 panels.

Figure 6: *Lifting up of steel panels by the crane (Vogtle Plant Construction Photos).*

4.2. Rainier Square Tower´s SCS core

Rainier Square Tower is 259 m high skyscraper, which makes it the second highest structure in the centre of Seattle. Let´s say that Rainier Square Tower is a pioneer of high rising buildings in relation to construction speed by using SCS technology for stiffening core.

When the skyscrapers are built the classic way using RC for core construction, there is a problem with the connections between concrete core and the neighbouring lightweight steel construction, which can be realized after the formwork was removed. But if the SCS technology is used, this problem disappears and the core and other structures of the floor can be built at the same time. The result is the reduction of construction time by almost half. The real time of construction of raw structure of Rainier Square Tower was 10 months, which is truly half the time in comparison to expected construction time of RC variant of the core (21 months).

The thickness of the core walls was designed from 1143 mm to 533 mm, depending on the height level. Steel plates are 13 - 19 mm thick and the composite action is provided only by the connecting bars with the diameter of 25 mm arranged in 305 mm spans in both directions. Furthermore, there were added a series of trusses in the space between the steel plates to increase the stiffness of the panels during the transport. The infill concrete has 68.9 MPa nominal compressive strength.

Figure 7: *Rainier Square Tower (Magnusson Klemencic Associates).*

The stiffening core consists of 3 modules (each approximately 12.2 x 9 m). In every third of height of the structure, one of the modules is removed, ending with one module at the top. Every module consists of 3 types of panels. It is a corner column panel, a pure wall panel and a wall panel with construction hole (respectively, steel beam frame).

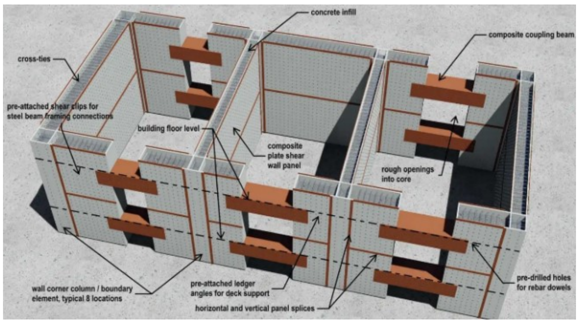

Figure 8: *Scheme of the core (Magnusson Klemencic Associates).*

4.3. Minatomija Immersed tunnel in Kobe

Immersed tunnels made from SCS are typical for Japan. Generally, immersed tunnels are always partly or wholly immersed under the water (meant in the longitudinal direction). In Japan, the main use of the immersed tunnels is transport structure between the islands. Immersion of construction under the water brings some specific requirements in design. The construction has to be watertight and has to be resistant enough to hydrostatic pressure. That is the reason why the SCS is ideal. Because the steel plates provide watertightness and great load resistance too.

Immersed tunnel Minatomija is 1.6 km long, 34.6 m wide and 9.1 m high. The span of one field is 13.3 m including the extension and 9.7 m without the extension. The thickness of the circumferential construction is 1.1 m except the floor structure, which is 1.2 m thick. The centre wall is 800 mm and the side walls are 500 mm thick. The composite action is provided by steel angles 150/150/12 mm. The space between the steel plates is further provided with diaphragms, which increase the stiffness of steel segments before concrete infill.

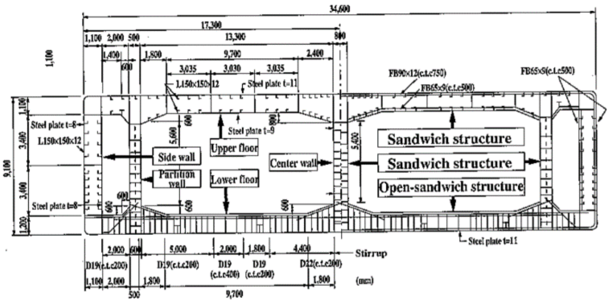

Figure 9: *Cross section of Minatomija Immersed tunnel (Kimura H. et al. 2002).*

5. FURTHER RESEARCH

During the masters study the author of this paper has participated in project Allegro, whose purpose is to design the key components of helium-cooled fast demonstration reactor. His master thesis´s task was to give an elementary design of primary containment using SCS technology.

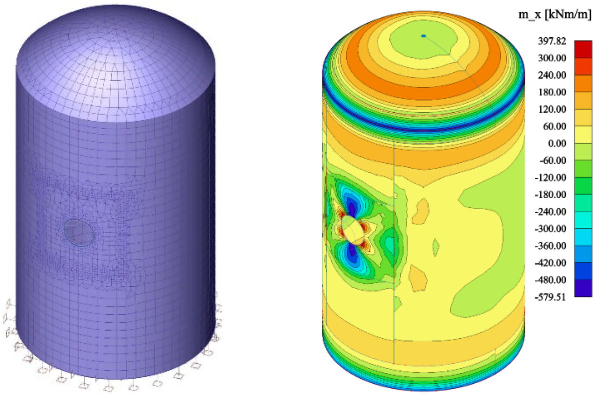

Figure 10: *FEM model of containment on the left side, bending mement around axix x on the right side (Kubát, R., 2020)*

The present goals are to explore the American code deeper, to solve the problematical areas of the design, to modify the thermal loads correctly and to optimize the global design related to shape, dimensions and all critical details. All results of the research will be discussed with ÚJV Řež continuously and according to that the design will be edited.

In the later stages of the research the questions of the realisation (see disadvantages of SCS) and of the decommissioning will be solved too.

6. CONCLUSIONS

Quite unusual construction solution of SCS has been introduced together with its division, advantages and disadvantages. Especially the summary of disadvantages raises the topics for future research. Furthermore, the real structures make a good resource of inspiration, because we can be sure their design actually works.

ACKNOWLEDGEMENTS

The author would like to thank once more to Petr Bílý Ph.D. for great leading during master thesis writing. The research activities were supported by the Technology Agency of the Czech Republic under the THETA program, project no. TK01030116 “Conceptual design of safety-important components of helium-cooled fast demonstration reactor ALLEGRO”, and by the Czech Technical University in Prague under student project no. SGS20/109/OHK1/2T/11 “Testing methods and application of cement composites”.

References

Kubát, R. (2020), Analysis of response of composite steel-concrete guard vessel of fast reactor to design accident conditions, Master thesis. CTU in Prague.

Bílý, P. (2020), Tlaková obálka Allegro – varianta OB. Technical report. CTU in Prague

Jia-Bao Yan, Min-Hong Zhang, Jat Yuen Richard Liew, K.M.A. Sohel (2014), Experimental and analytical study on ultimate strength behavior of steel–concrete–steel sandwich composite beam structures, Materials and Structures, pp. 1523–1544.

Bowerman, H., Pryer, J. (1998), Advantages of british steel bi-steel in immersed tunnel construction, IABSE reports, pp. 395–403.

JEAG 4618-2005 (2005), Technical guidelines for seismic design of steel plate concrete structures: for buildings and structures. Architectural Institute of Japan.

ANSI/AISC N690-18 (2018), Specification for Safety-Related Steel Structures for Nuclear Facilities, American Institute of Steel Construction.

European Nuclear Society (2010) ENC 2010 - European Nuclear Conference, pp. 1356-1360

Vogtle Plant Construction Photos. Available online: https://www.georgiapower.com/company/plant-vogtle/showcase/construction-photos-2018-12.html. [citation 16.3.2021]

Magnusson Klemencic Associates. Available online: https://www.bdcnetwork.com/structural-engineer-speeds-skyscraper-construction-novel-building-core-design and https://www.djc.com/news/search.html?action=get&id=12108174&print [citation 16.3.2021]

Kimura H., Moritaka H., Kojima I. (2002), Development of Sandwich-Structure Submerged Tunel Tube Production Method. Technical report.