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THE COMBINATION OF MODULAR AND COMPOSITE CONSTRUCTION TECHNOLOGY IN GENERATION III NPP DESIGN-BUILD

(Part *2: Structural Design Provisions and Method*)

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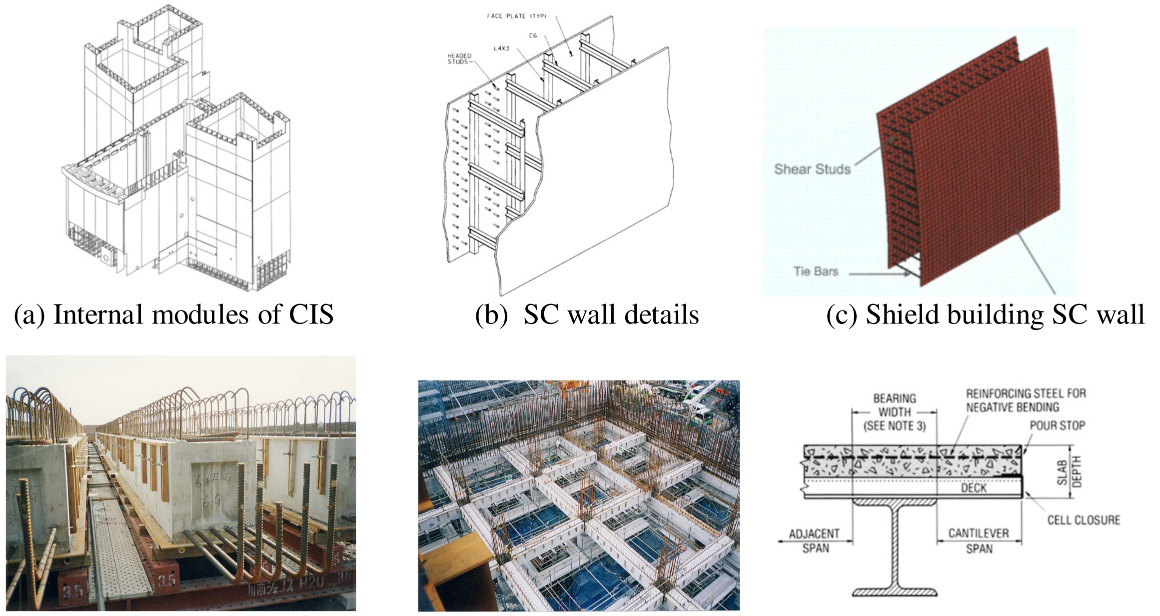
ABSTRACT

Author's same-title-paper published in the Proceedings of SMiRT-25 primarily discussed the aspect of "General Perspectives and Constructability" in this new emerging area. As the conclusions of previous investigation and research, composite and modular constructions are feasible and adequately matured for the applications in safety-related structures. Succeeding above report published on SMiRT-25, this paper will be focused on the following aspects of structural design, and intended to provide design criteria, analysis method and provisions for the application of composite and modular sections: (1) Brief review of basics of composite and modular design, (2) Example cases for composite and modular design respectively, (3) The ways to integrate composite and modular together in structure, (4) Establishment of key design criteria and analysis method, (5) General design provisions and some example structural details.

BRIEF REVIEW OF COMPOSITE AND MODULAR DESIGN

Based on investigations and discussions, this research reveals the ways through which composite and modular techniques are integrated together to provide effective solutions for new generation NPP design-construction. Since the structural configurations (SC Walls) of CIS module and shield building are quite different compared to those of precast and steel decking composite sections, the design-construction procedure and process should be carefully selected and analyzed. As such, a testing based analysis method is recommended for pre-cast pre-stressed composite sections, which referenced Japanese Concrete Codes and ACI codes. Meanwhile steel decking and SC walls design will still follow the existing codes published by AISC and AISC N690. The purposes of integrating composite and modular techniques together are intended to simplify on-site construction processes, shorten construction schedule, allowing more parallel works/jobs (which are belong to different disciplines) to be carried out in the same time or at very close time slot; further it will improve quality and reduce construction cost. Figure 1- (a) through (f) showed the schematics of modular and precast composite technologies.



(a) Internal modules of CIS (b) SC wall details (c) Shield building SC wall

(d) Pre-cast units (e) Installation of units (f) Decking-steel configuration

Figure 1 Schematic of SC wall and precast composite structures

Basics of Precast Composite Structure Design

- The application of partial-precast and cast-in-place concrete composite members

In order to make construction more reasonable, shorten construction period, improve construction quality and cut the cost of construction, precast elements are often designed and widely used in reinforced concrete and prestressed concrete structures in recent decades. By this way, part of the member's section was constructed in a separate placement and then installed at its structural position beforehand; taking these precast elements as formworks, the remaining part of that section was constructed (which often times is called the cast-in-place concrete)

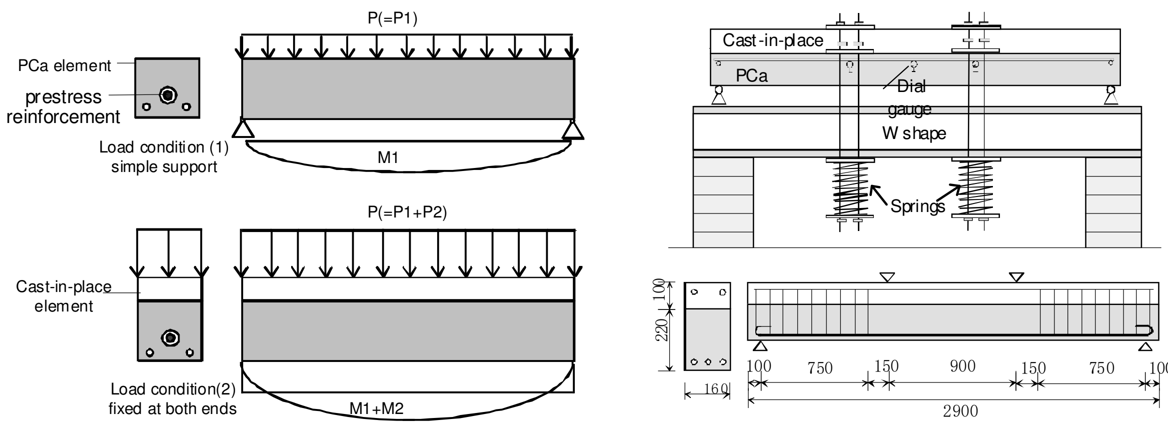
- The problems arising from conventional partial-precast design

To ensure that cracks will not occur during the construction stage, often times full-prestressing need to be induced on precast elements (this could lead to problems of "cost" and "camber" issue), or in other way specific shoring systems are designed instead to perform supporting; the reason to do so is because the designer could not precisely evaluate the crack width and deflections in the service stage if precast elements had been cracked during the construction phase. So the above conventional composite design cannot make precast elements demonstrating their function in pursuit of structural integrity, meanwhile, in the same time, reduce the construction time and cost.

- The advantages of half-precast (prestressed) and cast-in-place composite members

In order to change the concept of design of the precast structure and make the precast elements more widely and conveniently used to construction, half-precast partially prestressed concrete (PPC) composite members (with reinforcements) can be used to replace the conventional precast elements utilized previously. The advantages of such type of composite structural member can be summarized as following: (1) it can eliminate the complicated and time consuming formworks at the site; (2) half-precast parts manufactured by the shop can improve the quality of structural members; (3) the inducing of controlled partial prestressing force on half-precast unit can effectively control the cracking and

deflection of structure not only in its construction phase but also in its service-life stage; (4) such half-precast composite construction possesses both the features of full cast-in-place construction and full precast construction.
Following Figure 2 showed some conceptual configurations of half-precast partially prestressed composite members.



(a) Half-precast member with partial prestress and loading history due to construction

(b) The testing specimens and configuration

Figure 2 Schematic of new half-precast and cast-in-place composite members

Basics of SC Module Design

- SC section configuration and applications

Steel concrete composite section (SC-section), as a new emerged lateral load bearing structural type, is introduced as a new construction technique in recent years to substitute the RC wall in some GEN III NPP design-construction to satisfy new safety requirements and reduces the cost as well. As an advancement of conventional composite structure, SC-Wall is comprised of two face-plates on both sides, concrete as infill is poured in between and hardened to become a "sandwich" type component. The advantages of using SC-Wall come from the fact that the construction is simplified, faster and can be executed in a way of modularization. This greatly save on-site works and total construction time; also through the way of using workshop manufacturing and installation it can result in high quality of structural components. Author's same title paper published in SMiRT-25 Proceedings described the early employment of SC modular construction in Japan and the recent application (Figure 3) in AP1000 projects in the U.S.

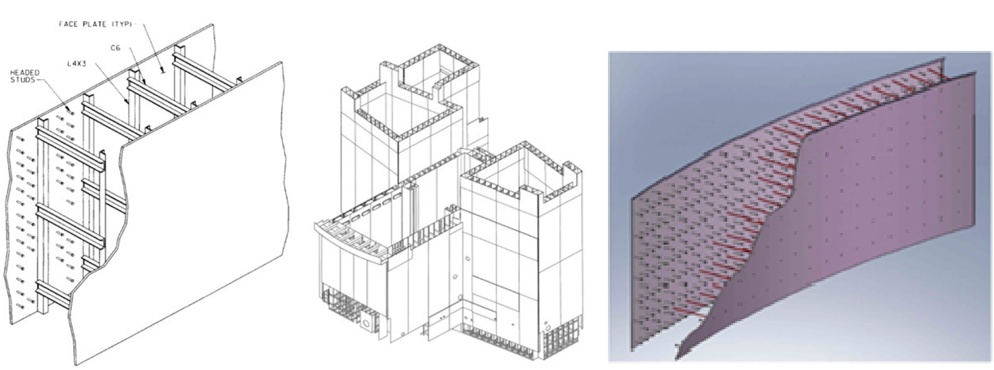


Figure 3 SC section application as SC-Wall inside containment and shield building

- General aspects of SC sections design

Current practices for SC-section design are largely based on the provisions originally given in ACI 318 & 349 codes, in which SC-section is either considered as an equivalent RC member or considered as actual steel-concrete composite member. But in either way the basic principles and assumptions are identical or similar.

(1) Design requirements based on ACI349

Design for axial load, in-plane bending and out-of-plane bending shall be in accordance with the requirement of ACI-349 Chapter 10, 14 and 17. The axial force and the bending moment are resisted by the tension of the faceplate, the compression of the faceplate and concrete. This design approach recognizes that the behavior of the SC module is similar to that of RC. The surface steel-plate (face plate) is similar to standard tensile reinforcement in each of two designing orthogonal directions.

Design for in-plane shear for SC wall should be in accordance with the requirements of ACI349 Chapter 11 and 14. Based on above methodology, the in-plane shear is resisted by faceplate and concrete. The bearing mechanism of the in-plane shear is a combination of the bearing mechanism of diagonal tension of steel-plate and diagonal compression of concrete plus pure shear capacity of steel-plate.

Design for out-of-plane shear for SC wall should be in accordance with the requirements of ACI349 Chapter 11. The out-of-plane shear force is resisted by concrete and the effect of shear reinforcement bars if shear reinforcement is appropriately arranged. As stated previously, the design approach is based on the premise that the behaviour against out-of-plane shear and the effect of shear reinforcement of SC wall are similar to those of a RC member. In detail design out-of-plane shear should also consider combined shear and torsion in accordance with ACI349 Section 11.6, no concrete shear cracking is allowed, and therefore shear reinforcement should be included in the design.

(2) Design requirements based on AISC N690 App.N9

AISC N690 App.N9 "Design of Steel-Plate Composite (SC) Walls" is a new established requirement dedicated for steel concrete composite structure. Its basic philosophy remains following the principles given in ACI 318 and 349. To account for composite-action states between steel material and concrete material, the level of composite-action need to be investigated in all working stages especially in ultimate working stage. Figure 4 and Figure 5 showed some of the mechanisms utilized in composite-action evaluation.

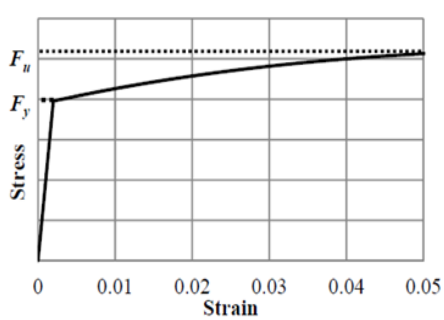


Figure 4 Interfacial shear force-slip curve

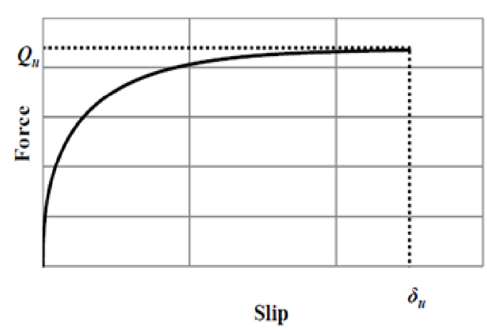


Figure 5 Shear stud stress-strain curve

In normal working condition, the section globally acts as a one-piece (monolithic) material; both stress and strain hold the form of plain distribution. Normal working condition practically is related to service level A/B or OBE load. As an overall the SC wall is in elastic stage (stress level is within the elastic limit of materials)

In ultimate working condition, the section globally still keeps a plain strain distribution, but since stress level (such as concrete) exceeds elastic limit, the plain distribution does not apply to section stress.

Ultimate working condition practically is related to service level C/D or SSE-LOCA load. As an overall the SC-Wall exceeds elastic range, and enters a stage of elasto-plastic, this state is close or might exceed the yield point of materials. In the end of this stage, composite section often times exhibits pretty much transition from fully composite to partially composite due to above elasto-plastic deformation. The member design capacities are reduced because of the decreasing of composite-action. So the level of composite-action shall be investigated in all working stages especially in ultimate working stage.

KEY DESIGN CRITERIA AND ANALYSIS METHOD

Section Analysis for Precast Concrete Composite Structures

Just as described in author's same title paper published in SMIRT-25, precast composite structure is comprised of precast parts (or units), this will be assembled firstly in early construction phase to serve as formworks; then commercial concrete be poured above precast parts to designed thickness; rebars at jointing points or layers will be specially treated to assure they can perform in the similar way like the full cast-in-place construction. Among the all structural members and components design, the section analysis is always critical to establish stress-strain relationships for further design purposes. Following Figure 6 provides the section analysis mechanism for half-precast (partially prestressed) concrete composite beam member given in Figure 2.

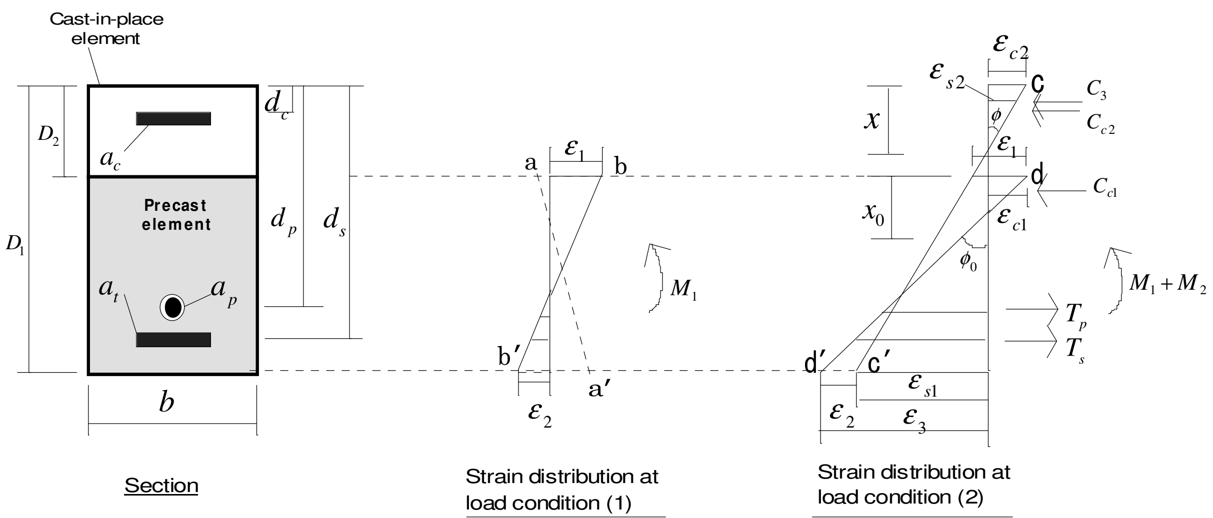


Figure 6 Section analysis mechanism for half-precast (partially prestressed) concrete composite beam

Equilibrium of horizontal forces gives:

$$C_{c1} + C_{c2} - T_p - T_s - C_s = 0 \tag{1}$$

The equilibrium of moments gives:

$$M = M_1 + M_2 = -C_{c1} \cdot (D_2 - x + \frac{x_0}{3}) + C_{c2} \cdot 2 \cdot \frac{x}{3} + T_p \cdot (d_p - x) + T_s \cdot (d_s - x) + C_s \cdot (d_c - x) \tag{2}$$

Unknown x, ϕ (as shown in Figure 6) can be obtained by using numerical analysis method at above two equations, and all section stresses can be computed subsequently.

SC-Wall Section Analysis (Example)

Following Figure 7, based on Japanese code - JEAC4618 (2009), provides the schematics for SC-wall section analysis when subjected to the loading of out-of-plane moments.

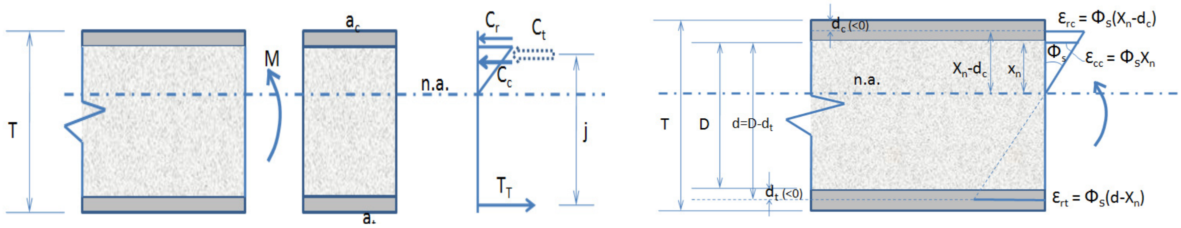


Figure 7 SC-wall section analysis subjecting to out-of-plane moments

GENERAL DESIGN PROVISIONS AND PROCEDURES

Integration of Precast Composite Design and Modular Design

When looking at the applications of precast composite / or steel decking concrete design, we find that the combination of these two design-construction techniques can almost simplify all vertical force bearing structural systems, such as beam, column, slab and / or slab-beam system etc. Meanwhile modular design, on the other way, is perfectly tailored for taking the role of lateral force resistance shear wall system, which as we well known is primary structural system to maintain stability and integrity of the global structure. So the good integration of precast composite design (including steel decking concrete design) and modular design together can definitely lead to great benefit and efficiency on construction execution.

Recommended Procedures for Design Practice

By keeping the above thoughts in mind, follows are some recommendations to this approach of integration process and related procedures for design practices.

- <u>The integration of SC-walls and steel decking / precast composite for CIS structues</u>

Containment internal structure (CIS) design is a very typical application of SC-wall integrated with steel decking and / or precast composite floor. Since basically CIS located in the centre part of nuclear island, due to the highly concentrated design of SSCs in very limited space, the construction and installation always are facing challenges at the site. Through the integration of above three unique designs, the structural constructions can be executed in a similar way like the systems and mechanical components, that means conventional civil scope of work can be performed by the means of pre-manufactured structural installations; therefore the trivia on-site civil works are greatly simplified, the remaining focuses will be largely left on the joints and connection handling. Following Figure 8 showed some of the recommended joint connections when use this type of integrated construction.

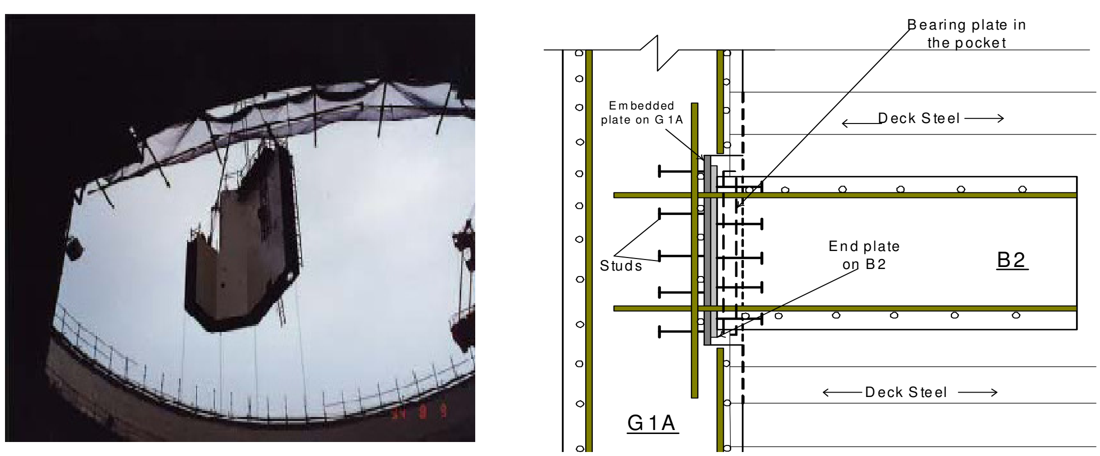


Figure 8 SC-wall-module precast-beam and deck-steel joint connection example

- <u>The integration of SC-walls and precast composite / steel decking for strucural systems within or outside nuclear island</u>

If look at the plan of a NPP, we can find that many safety-related buildings / facilities are outside containment vessel, such as shield building, auxiliary buildings and conventional island facilities etc. These buildings actually are even bigger in dimensions, the reason to design as such is because there are more operation systems, devices, valves and switches etc. within them. So to meet these needs, more floor areas are designed for accommodation purposes, and staffs' daily working and access as well. To reduce construction costs, shorten construction period and improve quality, the utilization of above integrated techniques can serve as the best solution for all challenges in design-constructions of such facilities. Following section provides some detailed examples to illustrate the advantages of this innovation.

- <u>Some Example Structural Details</u>

As the summary of this paper, here gives further examples to illustrate the ways through which integrated modular design and precast composite design come together to function as highly improved structural systems.

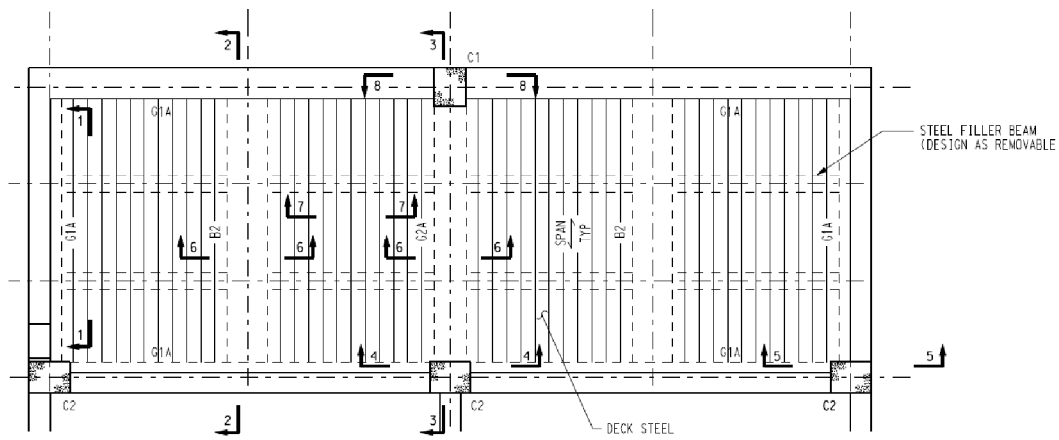
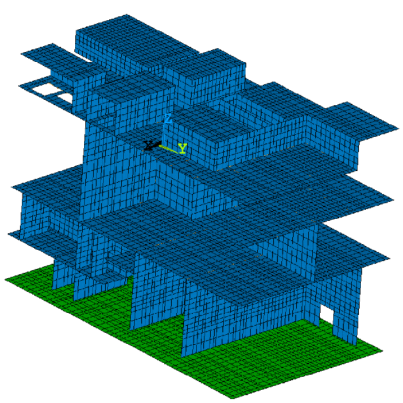
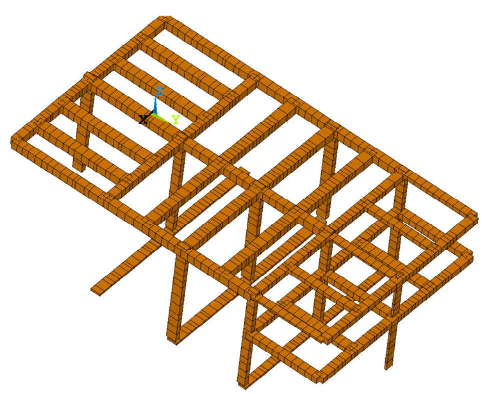


Figure 9 Part of the floor system plan designed in auxiliary building of NPP



(a) Shear wall



(b) Column and beam

Figure 10 The finite element model of the whole structure

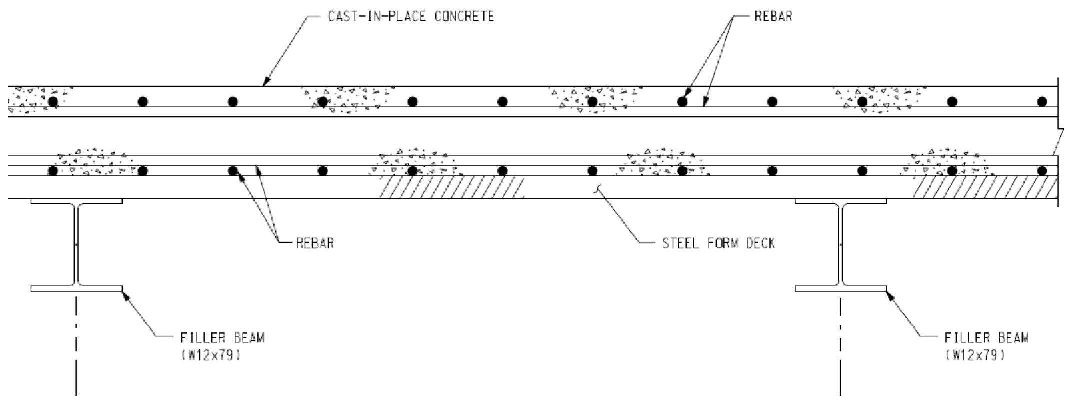


Figure 11 Section 1-1 detail

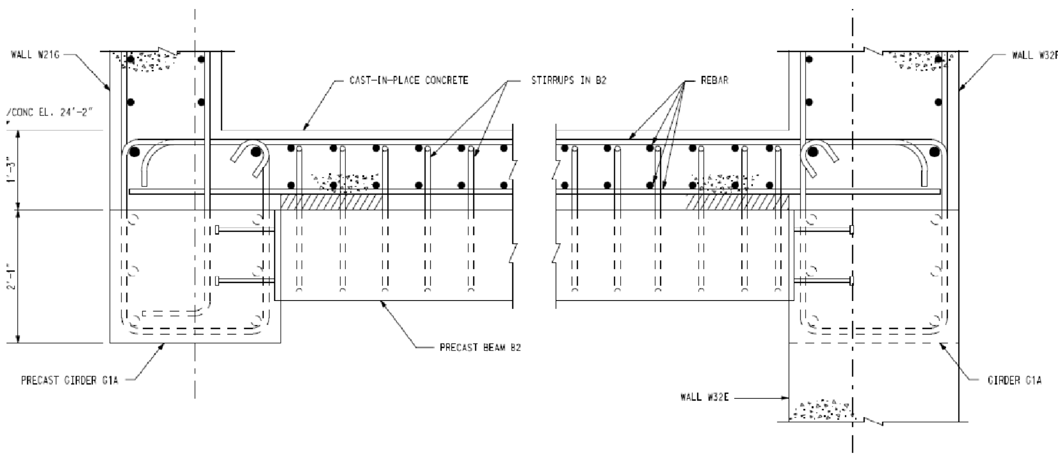


Figure 12 Section 2-2 detail

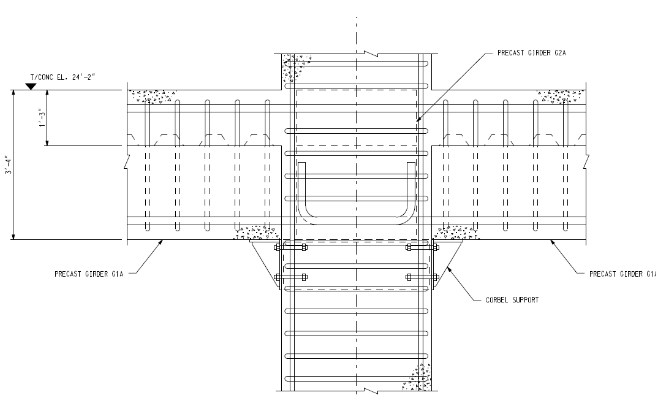


Figure 13 Section 3-3 detail

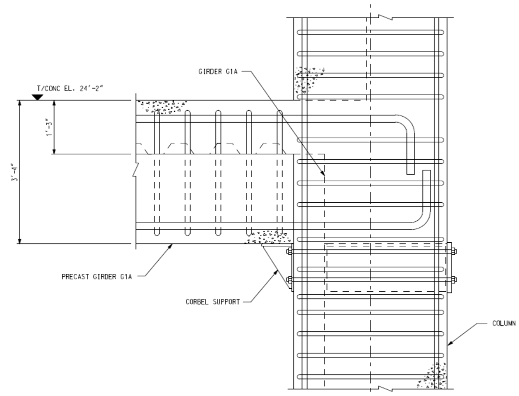


Figure 14 Section 4-4 detail

CONCLUSION

By the above investigation and discussion, this research reveals the ways through which modular and composite techniques are integrated together to provide effective solutions for new generation NPP structural design-construction. Since the sectional configurations of CIS modules and shield building modules are quite different compared to those of precast and steel decking composite sections, the design-construction procedure and process need to be carefully selected and analyzed. To consolidate and reconcile all these differences, testing based analysis methods are provided to evaluate precast composite section and SC-wall section, which referenced Japanese Concrete Codes, ACI codes and AISC N690 code. Further, to facilitate the applications of this innovated design-construction approach, a true design example is presented at the end of this paper.

REFERENCES

Shang, Z., Zhu, J. and Zheng, M. (2013). *"CONSIDERATIONS AT BEYOND DESIGN-BASIS PHENOMENON DESIGN FOR NEW NUCLEAR POWER PLANT - Seismic and Tsunami",* SMiRT22, San Francisco, USA

Shang, Z., Sun, Y., Huang X., Gou, H., Wu, C., Chang, C. and Han B. (2019) *"THE COMBINATION OF MODULAR AND COMPOSITE CONSTRUCTION TECHNOLOGY IN GENERATION III NPP DESIGN-BUILD (1: General Perspectives and Constructability)"*, SMiRT25, Charlotte, USA

Shang, Z., Ohno, Y. and Li, Z. (2001), *"Flexural behaviors of PPC composite beams with precast units cracked due to construction load (Short-term flexural behavior)",* JOURNAL OF STRUCTURAL AND CONSTRUCTION ENGINEERING (Transaction of AIJ) Architectural Institute of Japan, No.542, pp. 131-138.

Shang, Z., Ohno, Y., Li, Z. and Li, W. (2006), *"Flexural behaviors of reinforced concrete composite beams with precast elements cracked due to construction load (long-term flexural behaviors)",* Proceedings of the 2nd fib International Congress, Session 15-23, Durability of Concrete Structures, Naples, Italy

Shang, Z., Lv, Z. and Wang, X. (2005), *"Investigation of stiffness evaluation and deflection calculation of PCaPPC members",* JOURNAL OF ARCHITECTURAL STRUCTURE, Architectural Institute of China

ACI 349, Code Requirements for Nuclear Safety Related Concrete Structures.

ASME Boiler and Pressure Vessel Code Section III Div.2,Code for Concrete Containment

Shang, Z., Huang, X., Chu, M., Zhang, L., Wu, C. and Chang, C. (2016), *"THE APPLICATION OF PSHA METHOD IN THE DETERMINATION OF BEYOND DESIGN BASIS EARTHQUAKE FOR NEW NPP DESIGN"*, ICONE24, Charlotte, USA

Shang, Z., Huang, X., Sun, Y. and Chu, M. (2018), *"A RECOMMENDED METHOD FOR SC WALL DESIGN-EVALUATION REGARDING THE ELASTO-PLASTIC BEHAVIOR UNDER BEYOND DESIGN BASIS SEISMIC LOADING",* ICONE26, London, UK