Development of Stay-in-Place Formwork Using GFRP Reinforced UHPC Elements

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Abstract:
In this study, stay-in-place (SIP) formwork for structural elements subjected to aggressive environment, such as bridge columns and columns in parking structures subjected to deicing salt are developed by using prefabricated ultra-high performance concrete (UHPC) elements reinforced with embedded glass fiber reinforced polymers (GFRP) grids. Mechanical properties of UHPC and GFRP grids were determined experimentally. Novel designs of SIP formwork systems were presented and evaluated by numerical simulation in terms of strain and stress distributions and lateral deformation under gravity load and internal pressure due to concrete casting. Concrete damage plasticity model is incorporated to consider the post-cracking behavior in using the finite element analysis software ABAQUS. The proposed FRP-UHPC composite is shown to be promising for the development of lightweight, high performance, and cost-effective SIP formwork system for column elements.

Keywords: Ultra-high performance concrete (UHPC), glass fiber reinforced polymer (GFRP) grids, stay-in-place (SIP) formwork, column, accelerated construction

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1. Introduction

Stay-in-place (SIP) formwork is formwork left in place that may become an integral part of the structural element. The use of short fiber and continuously reinforced cementitious panels as stay-in-place panels for formwork has been examined by a number of researchers and organizations (ACI 347-04, 2004). These panels are typically brittle and have poor impact resistance (ACI 347-04, 2004). In order to improve their impact resistance, ductility, and durability which are the key factors for SIP formwork, advanced cementitious composites such as ultra-high performance concrete (UHPC) can be used and they can also be reinforced with a separate continuous nonmetallic reinforcement system, such as a fiber-reinforced polymers (FRP) bar, grid, or textile.

Recently, research focused on the use of SIP formwork panels for bridge decks or slabs. Kim et al. (2006, 2008) used glass fiber reinforced concrete (GFRC) for SIP formwork for bridge deck. Leung and Cao (2010) investigated a new approach for the construction of durable concrete structures. They fabricated bridge deck SIP formworks using pseudo-ductile cementitious composites (PDCC) of relatively low w/cm. With low permeability and high crack resistance, the SIP formwork acts as effective surface cover to prevent the corrosion of steel reinforcements. Yu (2014) presented that the bonding between the formwork system and concrete cast within the formwork improved significantly by treating surface of the formwork with transverse and longitudinal grooves stiffeners that can be introduced in the formwork. However, there is a lack of published work for the SIP formwork for vertical elements, such as column elements.

Ultra-high performance concrete (UHPC) is a superior fiber-reinforced, cementitioius mortar, which has good flowability and greatly-improved mechanical strengths and durability due to its dense microstructure (Graybeal 2011; Graybeal and Stone 2012). The high strength of UHPC allows the use of reduced sections, which can save materials and enable diverse design procedures. The enhanced durability enables the UHPC structure to have extended service life, and lower maintenance cost. UHPC composites are particularly suitable in thin product applications where they may be used as stay-in-place elements (Saleem et al. 2012).

Compared with conventional steel reinforcement, FRP has higher tensile strength, lower self-weight, and greater resistance to corrosion (Al-Sunna et.al. 2012; Mias et.al. 2013). Effective enhancement in flexural strength and ductility has been demonstrated by the combined use of concrete and FRP bars in panel construction (Kim et al. 2008; Kim 2006). The flexural capacity of SIP formwork panel reinforced with FRP bars can be increased by nearly four times (Kim et al. 2008). Two-dimensional FRP grids have been used to renovate or strengthen damaged structures (Yost et al. 2001). Compared with FRP bars, FRP grids are more flexible and can provide two-dimensional reinforcement, and thus they can be used to develop thin prefabricated elements (Leung and Cao 2010). The effectiveness of GFRP girds as reinforcement in UHPC panels has been demonstrated (Meng and Khayat 2016).

In this study, GFRP grids reinforced UHPC elements are proposed to produce thin and highly-durable SIP formwork. Using FRP as reinforcement can provide good cracking resistance, ductility, and enhanced durability. The durability is also assured by using UHPC, which is highly impermeable and resistant to crack. The SIP formwork was developed and evaluated under gravity load and internal pressure due to concrete casting. A three-dimensional finite element model (FEM) incorporating nonlinear material properties was established and experimentally validated.

2. Materials

The investigated panels were made of two layers of glass fiber-reinforced polymers (GFRP) grids reinforced UHPC which were optimized in authors' previous study (Meng and Khayat, 2016).

2.1 Ultra-High Performance Concrete

An UHPC mixture is designed with a water-to-cementitous materials ratio (w/cm) of 0.20. The cementitious materials were composed of Type III portland cement, ground granulated blast-furnace slag (GGBS), and silica fume (SF), whose volume fractions are 45%, 50%, and 5%, respectively. The Blaine finenesses of the cement and the GGBS are 560 and 590 m^2/kg, respectively. The sand consists of 30% masonry sand (0-2 mm) and 70% river sand (0-4.75 mm). Their specific gravities are 2.63 and 2.64, respectively. Steel fibers (0.2 mm in diameter, 13 mm in length) are used with a dosage of 2%. The fiber has a tensile strength and modulus of elasticity of 1.9 and 203 GPa, respectively. With adequate use of a high-range water reducer (HRWR), the flowability is greatly improved, and the mixture appeared self-consolidated. The HRWR is an aqueous solution with a solid mass content and a specific gravity of 23% and 1.05, respectively. The HRWR dosage was adjusted to ensure that the initial mini-slump flow of 280 ± 10 mm, enabling the UHPC to be self-consolidating. The mini-slump was measured in accordance to ASTM C 230/C 230M.

All test samples were cured for 24 h in molds covered with wet burlap and plastic sheets at 23 ± 1°C (room temperature). After demolding, the samples were cured in lime-saturated water at 23 ± 1°C until the age of testing. No heat curing was applied. The 28-day compressive strength was measured 125 MPa using cube specimens with side length of 50 mm. The flexural strength (ASTM C 1609) was evaluated using beams with four-point bending testing. The beam specimens measured 304.8 mm × 76.2 mm × 76.2 mm with a span of 203.2 mm. The 28-day flexural strength was 20.2 MPa. The cracking stress limit was determined to be 8 MPa using dog-bone specimens. The 28-day Young's modulus of elasticity and Poisson ratio were measured in compression in accordance with ASTM C469 using cylinders specimen with 100-mm diameter and 200-mm height. Their values were 50.1 GPa and 0.20, respectively.

2.2. Glass Fiber-Reinforced Polymers Grids

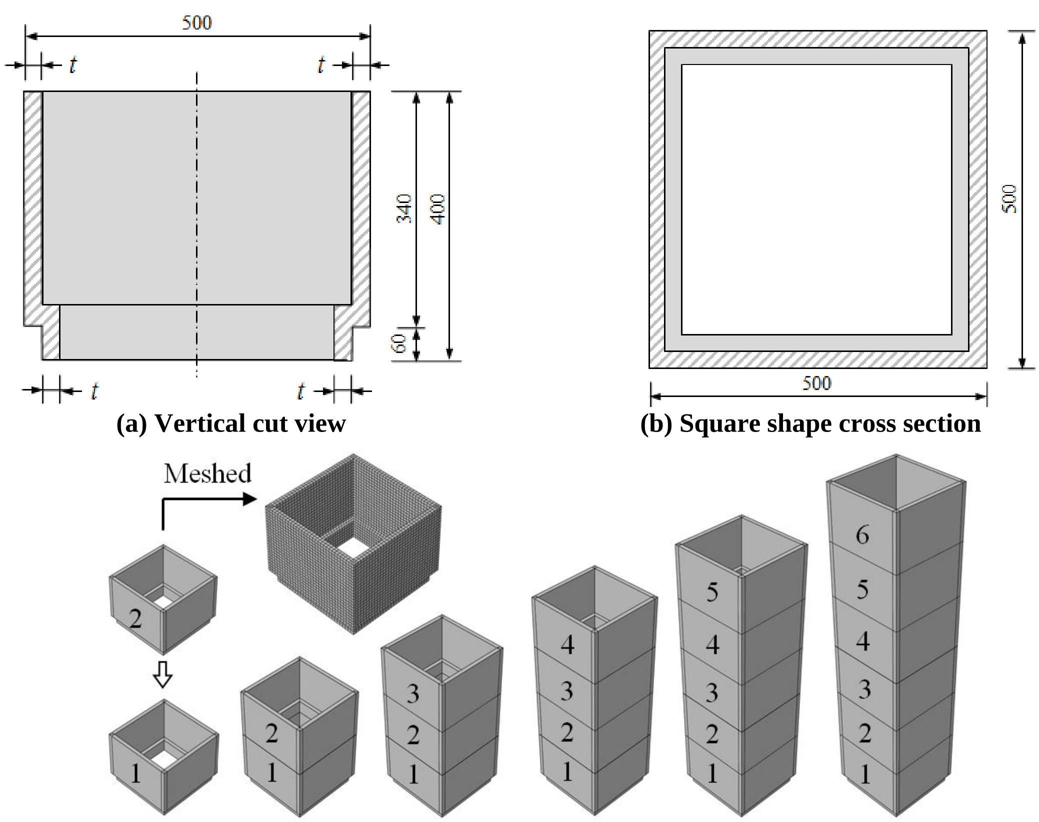
The GFRP grids have a grid size of 25 mm × 25 mm and a unit weight of 225 g/m^2. The Young's modulus and Passion ratio are 25 GPa and 0.26, respectively. The constitutive relation was determined under uniaxial tensile testing. Single FRP strip specimens were cut off from the orthogonal grids, and tested until rupture, using a load frame with a load cell capacity of 5 kN. A displacement rate of 1 mm/min was applied. The load-displacement data were recorded using a load transducer and an extensometer, respectively, embedded in the load frame.

Given the initial length of each specimen, the load-deformation relationship can be converted into a force-strain relationship. The force-strain relationship remained linear until shortly before rupture. The slope of each line represents the tensile stiffness. The average slopes corresponding to force versus strain was 60 kN/ε. The average peak load was 1.2 kN. The rupture strains was approximately 2×10^4 με.

3. Design of SIP Formwork System

Novel designs of SIP formwork systems were presented and evaluated by numerical simulation in terms of strain and stress distributions and lateral deformation under gravity load and internal pressure due to concrete casting.

There were some critical considerations for the design of SIP formwork systems: (1) Connection: connection details should be considered to overcome problems of mating precast members to each other and to the existing or cast-in-place structure. (2) Bonding conditions between SIP formwork and post-poured concrete: reliable bonding between formwork and post-poured concrete is essential and can be achieved by: a) special treatment, such as grooving or roughening the form face in contact with the structure concrete; b) use of anchoring devices extending across the interface between form panel and structure concrete; c) a combination of a) and b); and d) use of paint-on or spray-on bonding chemicals. (3) Code requirements: Precast concrete forms used in composite design with cast-in-place concrete in buildings should be designed in accordance with ACI 318. With these considerations, a SIP formwork system is proposed, as depicted in Figure 1. A square cross section is considered, which represents a typical column used in building. The outer side length is 500 mm. The wall thickness is denoted by *t*, which is investigated and the optimum value is discussed in this study. The total height of each element is 400 mm, of which a 60-mm bottom height is inserted into the adjacent element. Thus, each layer is 340 mm in height. The elements are assembled in site layer by layer (Figure 1c).



(a) Vertical cut view **(b) Square shape cross section**

(c) Assembly layer by layer

Figure 1. Illustration of the SIP formwork system.

4. Numerical Simulations

4.1 Description of the Finite Element Model

A three-dimensional nonlinear finite element model was developed using ABAQUS to investigate the mechanical performance of the designed formwork. The thin and flexible GFRP grids were modeled using 2-node linear 3-D truss (T3D2) elements. Each T3D2 element has 2 nodes, and each node has 3 degrees of freedom. The UHPC matrix was modeled using 8-node linear 3-D brick reduced integration (C3D8R) elements. Each C3D8R element has 8 nodes, and each node has 3 degrees of freedom. The contact between GFRP and UHPC was defined using the keyword 'embed,' without considering interfacial debonding. Surface-to-surface hard contact was defined for the contacting surface pairs using a basic Coulomb friction model, namely penalty friction model. The coefficient of friction was assumed to be constant 0.8 for the contact between UHPC surfaces. The concrete damaged plasticity (CDP) model is employed to consider potential damages in UHPC. Assuming that steel fibers are uniformly distributed in the cementitious matrix, the mechanical properties of the UHPC are considered to be homogeneous. Since no significant concrete crushing was observed in the experiments, the UHPC was assumed to be elastic under compressive stress. This assumption can be checked in the stress distribution results. The formwork pressure due to fresh concrete casting is considered as hydrostatic pressure, which is linearly distributed throughout the height of formwork, as illustrated in Figure 2. The density of fresh concrete is assumed to be 2400 kg/m^3. The bottom of formwork is fixed.

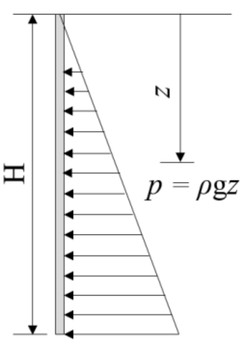


Figure 2. Illustration of static hydraulic pressure applied on SIP formwork.

4.2 Investigated Cases

In total, 12 cases were investigated, as listed in Table 1. Four assembly layer numbers are considered, which are 3, 4, 5, and 6, respectively. Six layers of element give a total height of 2.04 m for one casting. Three wall thicknesses are considered, which are 15, 20, and 25 mm, respectively. The corresponding volumes are 0.0124, 0.0162, and 0.2 m^3, respectively. Given the density of UHPC, which is 2500 kg/m^3, the masses are determined to be 30, 40, and 48 kg, respectively.

Table 1. Investigated cases

Case	Assembly layer number	Wall thickness (mm)
1-3	3	15, 20, 25
4-6	4	15, 20, 25
7-9	5	15, 20, 25
10-12	6	15, 20, 25

5. Results and Discussion

5.1 Strain Distribution

Figure 3 shows the distribution of maximum principle strain within the six layers of formwork. The maximum principle strain is the largest at the inner surface of corners. The outer surface of wall is also subjected to relatively large tensile strain in the middle. The strain distributions indicate that potential damage may be initiated at the corners. Strengthening the corners by increasing the thickness can reduce the maximum tensile strain. Using round cross section is another possible alternative to reduce the maximum tensile strain. Due to page limit, it is not elaborated in this paper.

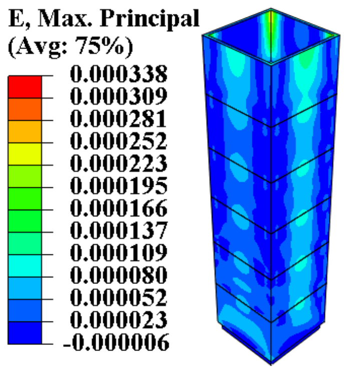


Figure 3. Distribution of maximum principle strain.

Figure 4 shows the effects of assembly layer number and wall thickness on the maximum principle strain within the formwork elements. The maximum principle strain linearly increases with the assembly layer number, indicating that the assembly height for each cast should be limited. Excessive one-time assembly can potentially lead to damage in formwork. At the same time, the maximum principle strain decreases with the wall thickness. For a specific UHPC mixture with determined tensile strength, it is essential to select an appropriate wall thickness and one-time assembly height.

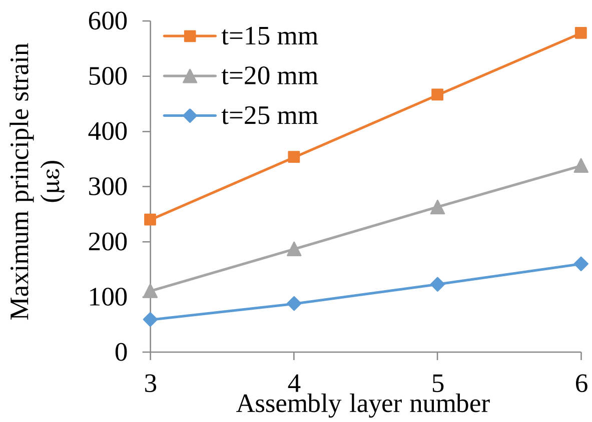


Figure 4. Effects of assembly layer number and wall thickness on maximum principle strain.

5.2 Stress Distribution

Figure 5 shows the distribution of maximum principle stress within the six layers of formwork. Within the elastic range of UHPC, the strain and stress distributions are alike. The maximum principle stress is the largest at the inner surface of corners. The outer surface of wall is also subjected to relatively large tensile stress in the middle. The strain distributions indicate that potential damage may be initiated at the corners. Strengthening the corners by increasing the thickness can reduce the maximum tensile strain. However, when the strain is large enough to cause inelastic behaviors in UHPC, the strain and stress distributions will be quite different. For the sake of safety, the formwork is designed to operate in elastic range, although it can experience inelastic behaviors in the case of extreme events, such as earthquake, during construction.

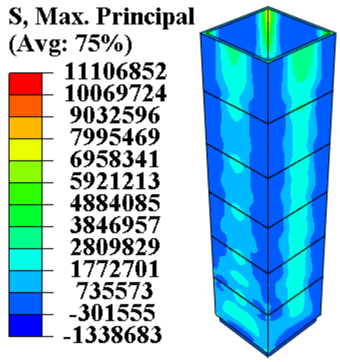


Figure 5. Distribution of maximum principle stress.

Figure 6 shows the effects of assembly layer number and wall thickness on the maximum principle stress within the formwork elements. The maximum principle stress linearly increases with the assembly layer number. The maximum principle stress decreases with the wall thickness. For the UHPC mixture in this study, which has a crack stress limit of 8 MPa, the assembly layer number can be 3 when t = 15 mm, 4 when t = 20 mm, or higher than 6 when t = 25 mm.

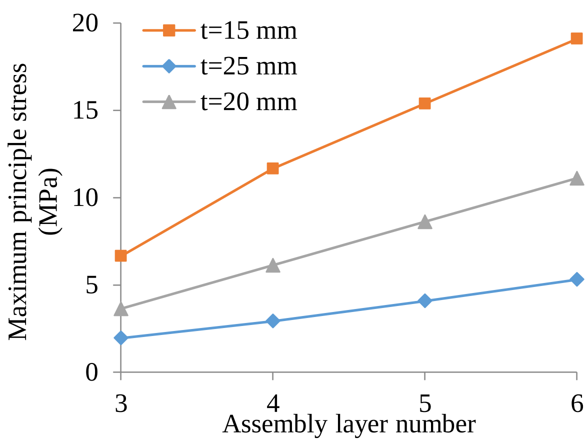


Figure 6. Effects of assembly layer number and wall thickness on maximum principle stress.

5.3 Lateral Deformation

Figure 7 shows the distribution of lateral deformation of six layers of formwork. The formwork exhibits lateral expansion, which is the largest in the middle of wall at the top where the deformation is subjected to less constraint. The maximum deformation is an indicator of the ability of formwork to retain the designed shape and dimensions during concrete casting. Besides, the distribution of lateral expansion allows the monitoring, control, and assurance of construction quality. Displacement sensors can be deployed at the top of formwork assembly, to monitor the deformation most effectively. Excessively large lateral deformation could indicate damage or dislocation of UHPC elements, or instability of the assembly.

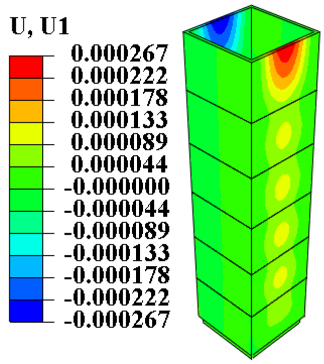


Figure 7. Distribution of lateral deformation.

Figure 8 shows the effects of assembly layer number and wall thickness on the lateral deformation of formwork. The maximum lateral expansion linearly increases with the assembly layer number, and it decreases with the wall thickness. Overall, the lateral deformation is adequately small. With an assembly consisting of 6 layers of UHPC elements, the maximum lateral deformation is 0.8 mm when t = 15 mm, or less than 0.2 mm when t = 25 mm.

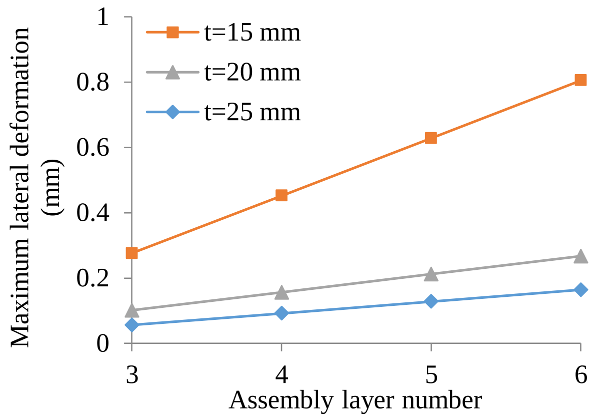


Figure 8. Effects of assembly layer number and wall thickness on lateral deformation.

6. Conclusions

Based on the above investigations, conclusions can be drawn as follows.

Stay-in-place UHPC formwork reinforced with embedded GFRP grids is designed for column of buildings with square cross section. The performance of the designed formwork is evaluated using a three-dimensional nonlinear finite element model, in terms of the strain and stress distributions, and the lateral deformation, during concrete casting. Sensitivity studies were conducted for the wall thicknesses of 15, 20, and 25 mm, at different assembly heights. With the use of the proposed UHPC element reinforced with GFRP grids, the assembly height can be 1 m when the wall thickness is 15 mm, or 2 m when the wall thickness is 25 mm. The largest lateral deformation is less than 1 mm.

Acknowledgements

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