THE WORLD'S FIRST 3D–PRINTED OFFICE BUILDING IN DUBAI

Musa Alawneh, Ph.D, P.E, e.construct, Fz-LLC, Dubai, United Arab Emirates

Motasem Matarneh, B.S., M.S, e.construct, Fz-LLC, Dubai, United Arab Emirates

Sameh El-Ashri, B.S., M.S., e.construct, Fz-LLC, Dubai, United Arab Emirates

ABSTRACT

The Office of the Future was built in the city of Dubai in the United Arab Emirates, in January 2016, using 3D- printed concrete elements. The office is approximately 2,000 square feet and was printed using a 20-feet tall 3D printer in China. Several precast techniques were adopted in the design and construction of the Office of the Future. The 3D printed cassettes (segments) were shipped and assembled on site in Dubai. The 3D printed cassettes were supported on cast-in-place concrete strip footing. The assembling and erection of the cassettes was done in just few days. This case study will provide an overview of the 3D printed concrete technology. The properties of 3D printed material will also be presented. The special design consideration will be discussed including the shipping, handling and erection. The cassettes were tested in Suzhou (China) and Dubai (UAE) prior to erection to verify the serviceability and strength performance. The paper will be concluded with outlook on the future for adopting the 3D printed concrete in large scale projects and the required research in order to enhance the current 3D printed technology

Keywords: 3D Printed concrete, cassette, testing, Post-tensioning.

INTRODUCTION:

Three dimensional (3D) printing or Additive Manufacturing (AM) is a process of building a 3D object by adding layer-upon-layer of material based on 3D digital file. The AM first developed in 1987 with stereolithography (SL) from 3D system, a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser[1]. The 3D printed material could be plastic, metal, concrete or any other type of composite material. According to ASTM F42[2], the manufacture process of 3D printing is categorized as follows:

- Direct Metal laser sintering (DMLS)
- Direct Energy deposition
- Fused Deposition modeling
- Laser Sintering (LS)
- Material Extrusion
- Material Jetting
- Powder bed fusion

The common type that have been used in 3D printed concrete is based on material extrusion which is introduced by Contour Crafting company. The first publications on the printed concrete can be found in 1998 by Khoshnevis (University of Southern California)[3] and significant progress has been done worldwide since that date. Contour crafting methodology utilizes a robotic fabrication system that use gantry frame to deposit a low-slump composite concrete material in layers to produce structural elements for housing.

There are two schools of thought within 3D concrete printing which are best summarized as "Factory vs. Site." Previous research from the University of Southern California focused mainly on site production of 3D printed elements. This focus offers a series of advantages and disadvantages. The site based approach allows for less transport, freedom of larger units and a less modular approach. However, this approach requires significant mobilization, terrain limitations, climate limitations and concerns about the security of highly sensitive intellectual property. The factory bases approach utilized on this project provided a climate controlled environment which enabled production to proceed at any point in time, a centralized location where the project team could inspect the building elements, etc.

There are several advantages for the 3D printed concrete; 1) high speed of construction; 2) no need for formwork; 3) less number of labour; 4) great increase of freedom of design; 5) cost saving compared to conventional construction. However, several challenges still exist as the CC still in development stage.

PROJECT DESCRIPTION:

The Office of the Future is located in Dubai, United Arab Emirates (U.A.E). The office was built as part of the Dubai ruler vision to build the first 3D printed concrete office in the world in Dubai[4]. The total area of the office is approximately 2,000 square feet. It consists of 4 champers (cassettes) that arranged in the way that open to each other and provide elegant exterior perspective. In addition to two separate cassettes. Figure 1 shows the three dimensional perspective of the building. The building layout and typical cross-section of the building are shown in Figures 2 and 3, respectively.

The superstructure was 3D printed while the substructure was conventional cast-in-place (CIP) concrete. Each cassette was divided into two parts: bottom and top parts. The shape of each Cassatt is a U-shape with maximum length, height, and width of 8.1m, 2.1m and 2.1m, respectively. These dimensions were determined based on the 3D printer and shipping limitations.

Fig. 1: 3D architectural Perspective

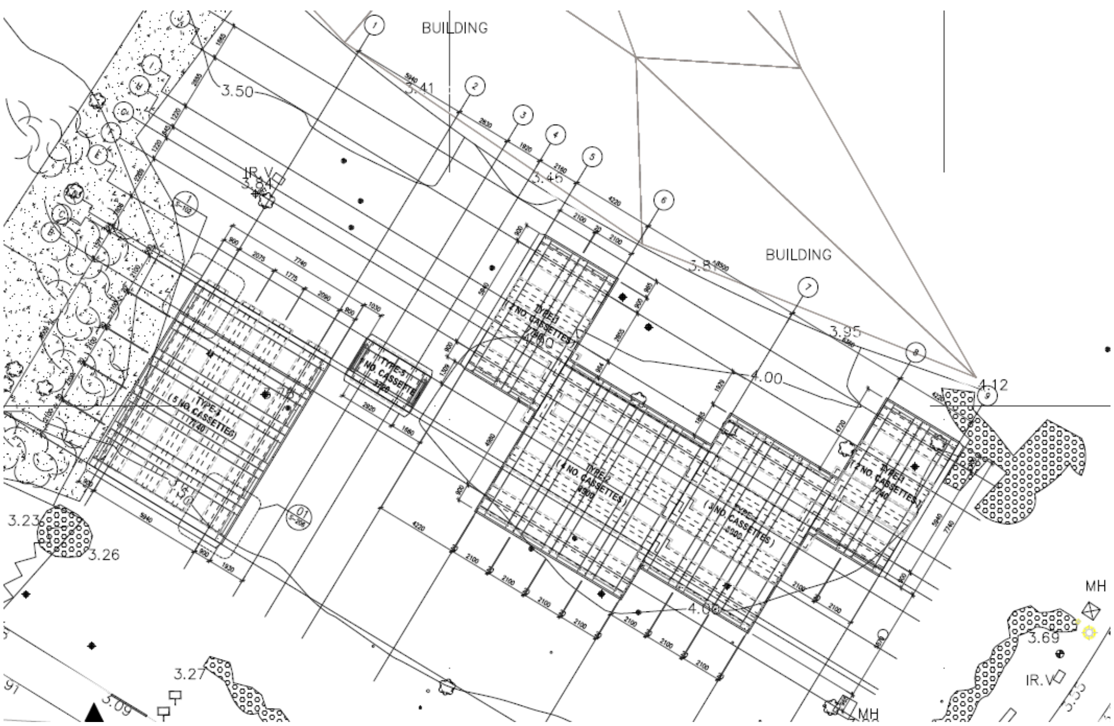

Fig. 2: Office Building Layout

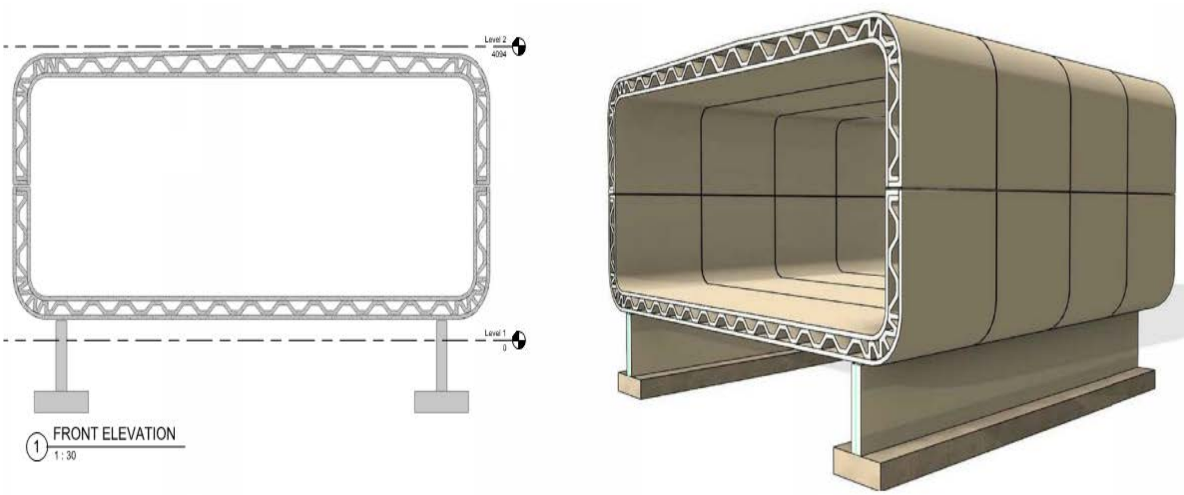

Fig. 3: Building Cross-section

STRUCTURAL SYSTEM:

The member size and geometry were selected to suit the 3D printer capabilities. The concrete layer dimension that can be printed depends on the printer nozzle size. The available printer can print concrete layer up to 50mm wide by 20mm thick. Accordingly, the structural system was formed by a concrete truss with member size of 50mm wide. There was no limitation on the member geometry since the printer nozzle would follow the geometry from the 3D digital model.

The superstructure of The Office of the Future was designed to be fully 3D printed concrete. Each cassata was divided into segments. Each segment consists of two parts: bottom and top parts. The shape of each segment is a U-shape with maximum length, height, and width of 8.1m, 2.1m and 2.1, respectively. These dimensions were determined based on the 3D printer and shipping limitations. Joints between segments were filled with grout and longitudinal post-tensioning (PT) were used to connect the segments together. The longitudinal PT were passed within the void of the cassette which later filled with grout.

The available current printer is capable of printing concrete paste which has a low tensile concrete strength (about10% of its compression strength). The challenge was how to enhance the 3D printed concrete element to sustained the flexural stresses. Therefore, it was proposed to add steel reinforcement manually between the concrete layers during the printing process. The steel reinforcement was also prefabricated and welded to form the shape of the concrete truss, refer to Figures 4 and 5 for concrete and steel truss dimensions; respectively.

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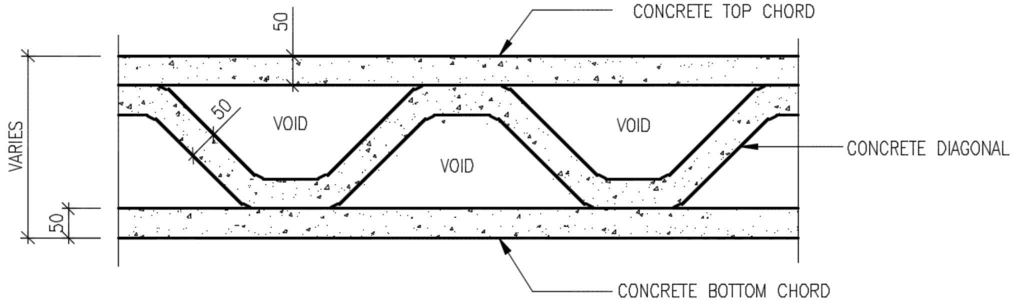


Fig. 4: Concrete truss dimensions (mm)

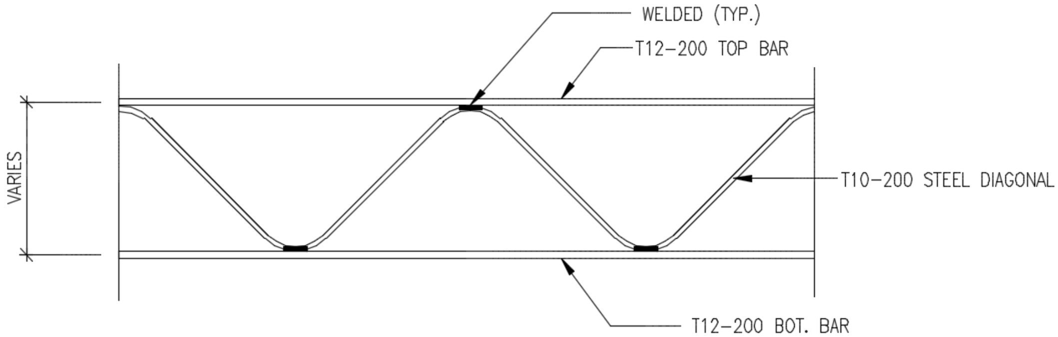


Fig. 5: Steel truss

Fig. 6: Prefabricated rebar steel truss

Fig. 7: 3D printed cassette during fabrication. Steel rebar truss was placed manually between the 3D printed concrete layers

The design was not finalized until the full scale testing of typical cassettes was carried out. This was due to the fact that there were highly uncertainty in material mix consistency, printing layer dimensions, curing, and bond between steel truss & concrete printed layers.

After printing a few cassettes, a team of structural engineers from e.construct[5] visited the production facility in China and carried out full inspection and full scale testing. One cassette was tested to failure load and two cassettes were tested as per ACI318-11 testing load recommendation. Refer to Figures 8 to 10 for cassette during testing load.

Fig. 8: 3D printed top cassette during testing

Fig. 9: 3D printed bottom cassette at the failure testing load

Fig. 10: cracking pattern at the mid span during testing.

The testing results indicated low structural performance of the printed concrete cassettes. It has been noted that the thickness of the chords is variable. It was ranged between 35 to 45mm, so in the design, 35mm width was considered as a structural stiffness and 45mm was used for self-weight calculation. The flexural capacity of the cassette was very low compared to the theoretical predication. The specimen also had a lot of cracks under initial testing loading and undergone large deformation. The failure mechanism has been largely influenced by the bonding of the reinforcement with the printed concrete. A flexure failure occurred at the bottom/base of printed cassette and compression block failure occurred at the top pf the printed cassette. The bonding was good at bottom/base of the print where the chords size was the largest (45mm) due consolidated under the self-weight of the upper layers. The top of the print showed less bonding where concrete consolidation was minimal and chord size reached as low as 35mm.

As a conclusion from the testing results, it was decided to add external transverse post-tensioning (PT) to enhance the flexural capacity of the top cassette. In the bottom cassette, two strip footings were introduced between the original two strip footings. Furthermore, it was decided that all the cassette shall be full scale tested on Dubai before can be approved to be erected on site.

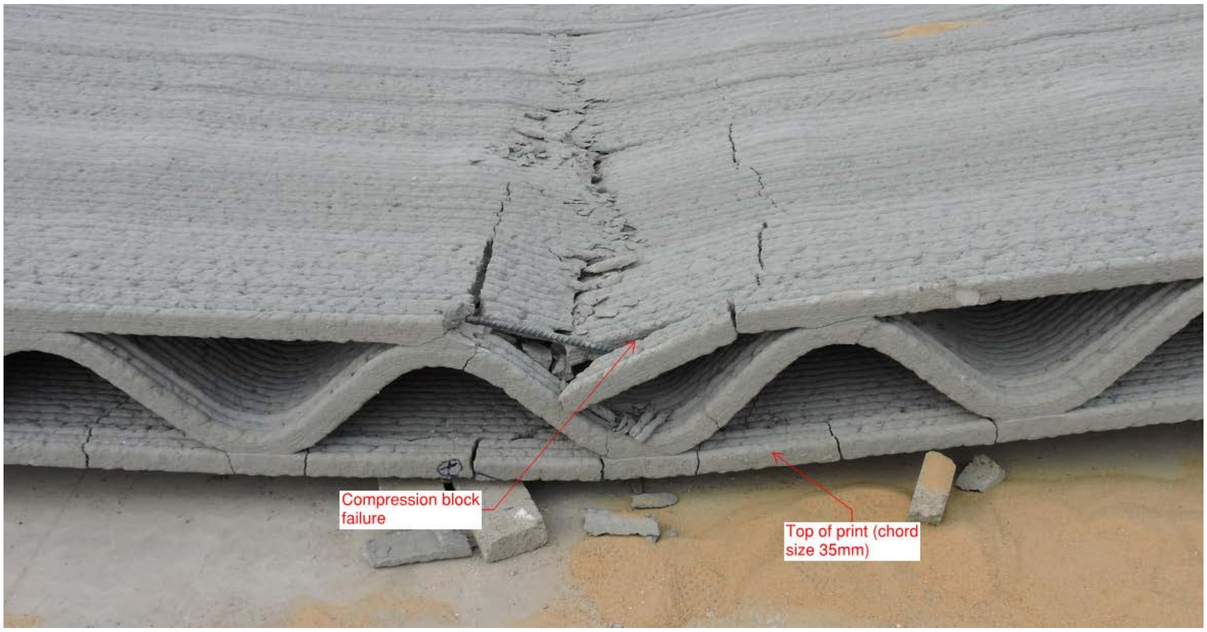


Fig. 11: Failure mechanism at top of the print.

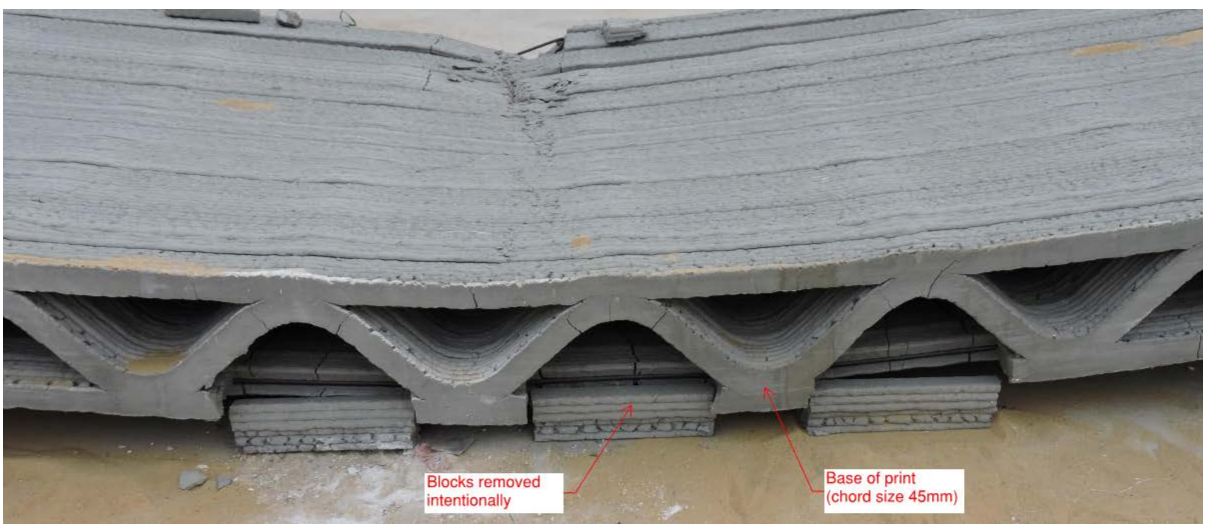


Fig. 12: Failure mechanism at base of the print.

3D CONCRETE PRINTER:

The concrete cassettes were printed in China by Chinese based company Winsun [6]. The 3D Printer is 20 feet tall, 33 feet wide and 132 feet long. The printer is used robotics head connecting with computer that fusion concrete paste material that laid layer by layer. The width of the concrete layer is around 50mm by 20mm thickness. Due to confidentially, no photo was allowed to be taken for the printer; however, refer to Figure 11 for the schematic diagram for the printer.

e.construct the design engineering firm based on Dubai was developed the 3D digital model using Rhino software that can be translated to the 3D printer language. The printing process takes up to 12 hours to build each cassette.

3D PRINTED CONCRETE MATERIAL:

The concrete mix was developed by WinSun which they have been used it in their projects. All of their projects were built in China. The office of the Future was the first project for them to be built outside china. The concrete mix consists of cement, water, glass fibers, and additives.

Before starting the design of The Office of the Future, six concrete samples were tested in Sandberg Laboratory[7]. The test program comprised of five parts:

- Compression and tensile strength
- Bond strength/adhesion
- Modulus of elasticity and thermal coefficient
- Density, water absorption and permeability, drying shrinkage, wetting expansion, and freeze thaw
- Chemical composition (petrographic and SEM examination)

The structural design was based on the results of the testing for the main design parameter:

- Compressive strength after 28 days = 31.6 MPa,
- Tensile splitting strength after 28 days = 3.0 MPa,
- Modulus of elasticity after 28 days = 19,500.0 MPa

Fig. 13: Side view of sample of 3D Printed wall material. It shown that the printed layer is 20mm

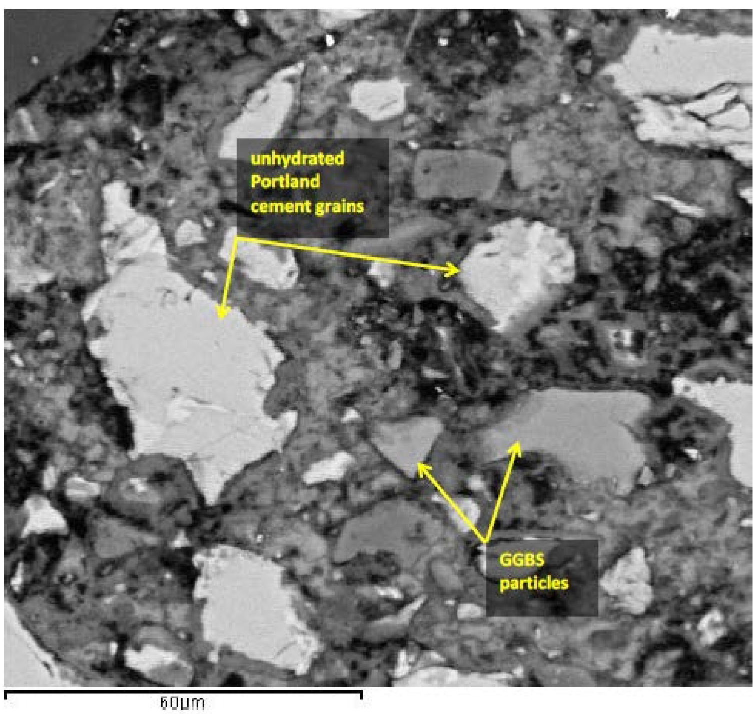


Fig.14: Polished surface, backscattered electron image: view showing an area of paste with abundant un-hydrated cement grains and two un-hydrated GGBS

CONSTRUCTION SEQUENCE:

Stage 1: Printing the Cassettes:

The digital model was developed for each segment and sent to printing facility in China. The reinforcement truss was prefabricated in China and delivered to printing facility. The printing was taking 12 hours to complete each cassette.

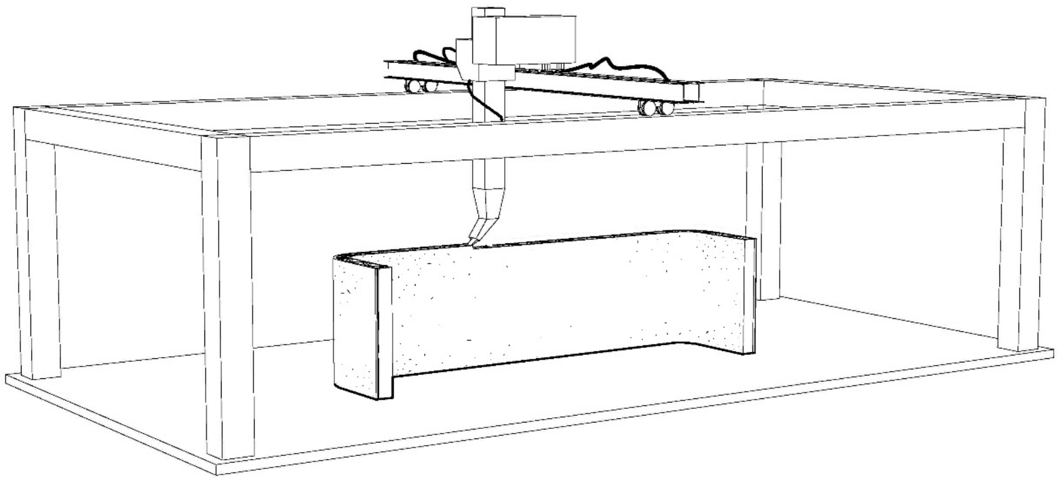


Fig.15: schematic diagram for concrete printing process

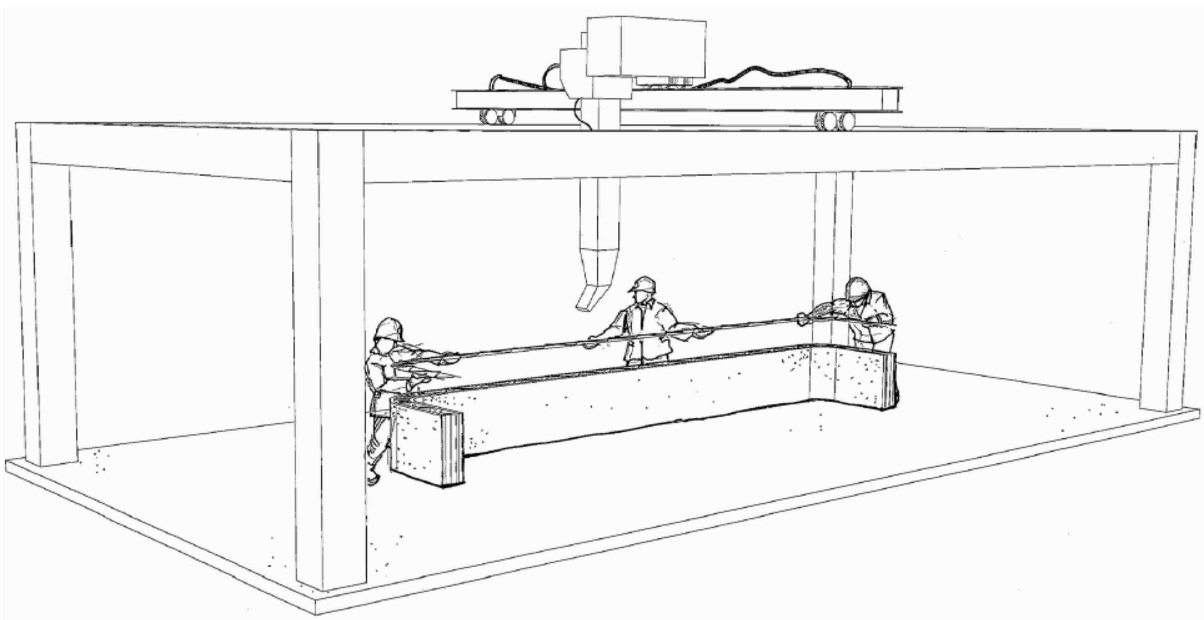


Fig. 16: placing prefabricated steel truss during printing process

Stage 2: Ship the Cassette

Each two cassettes were loaded in container and shipped to Dubai

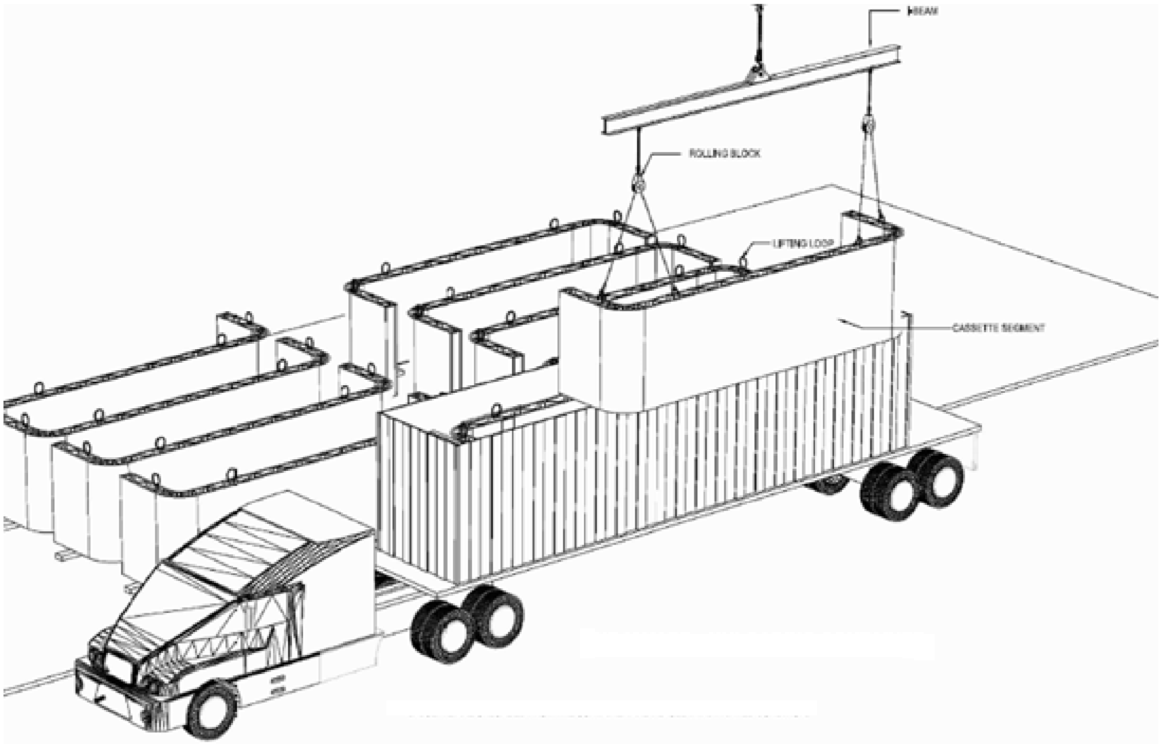


Fig.17: Schematic Diagram showing the shipping of the 3D printed cassettes

Stage 3: Inspect the cassettes prior erection

After delivering the printed segments to Dubai, detailed inspection was done for each cassette. Post-tensioning rebars were added for the top cassettes to enhance the flexural capacity.

Stage 4: Erect the Cassette on CIP Foundation

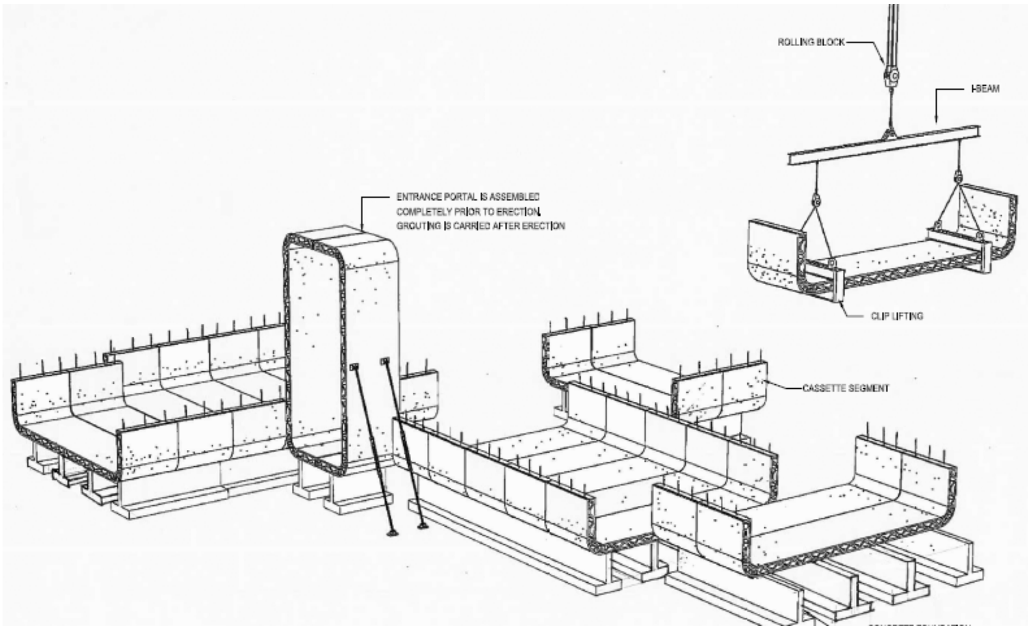


Figure 18: erection of the segment on CIP foundation

Stage 5: Add Transvers Post-tensioning to Connect the Cassettes

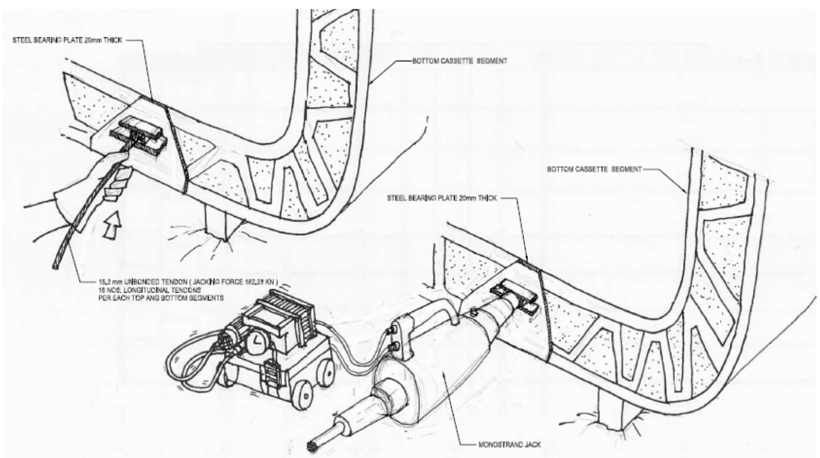


Figure 19: add PT to connect the segments together

Stage 6: Grout the dowels bar between the foundation and cassette

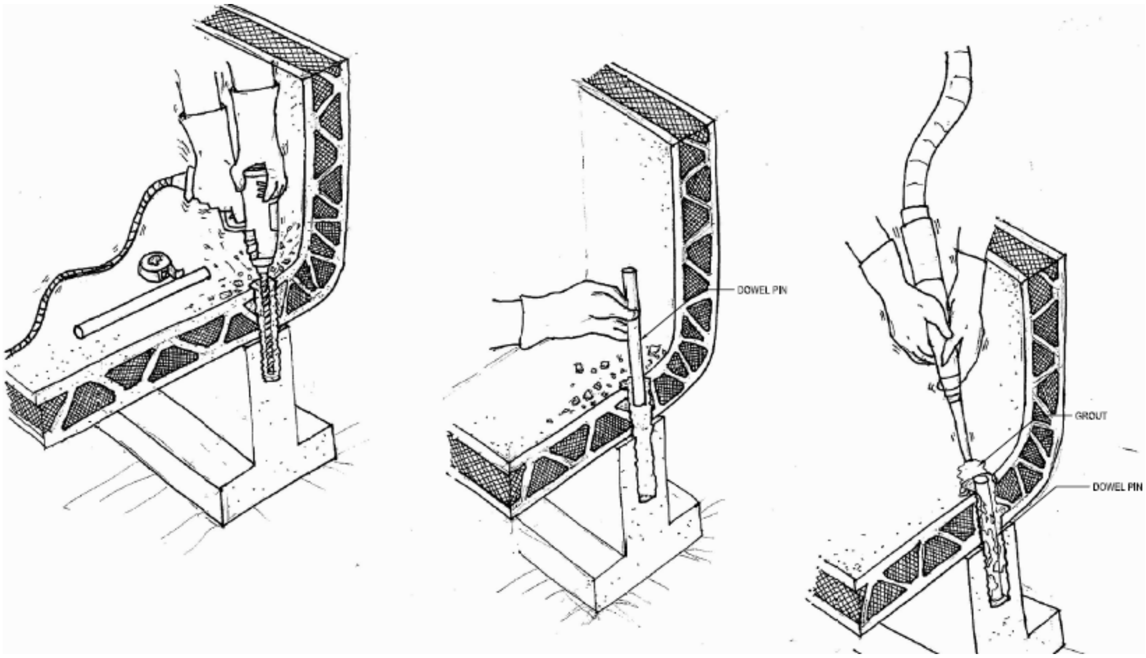


Fig. 20: grout dowel bars between the cassette and CP foundation

Stage 7: add finishing and attach non-structural elements

Fig. 21: 3D printed office during applying the external finishing. Insulation was attached from outside and external finishing was applied.

Refer to Figure 19 for the 3D printed cassette during construction. Figure 20 shows the typical connection details.

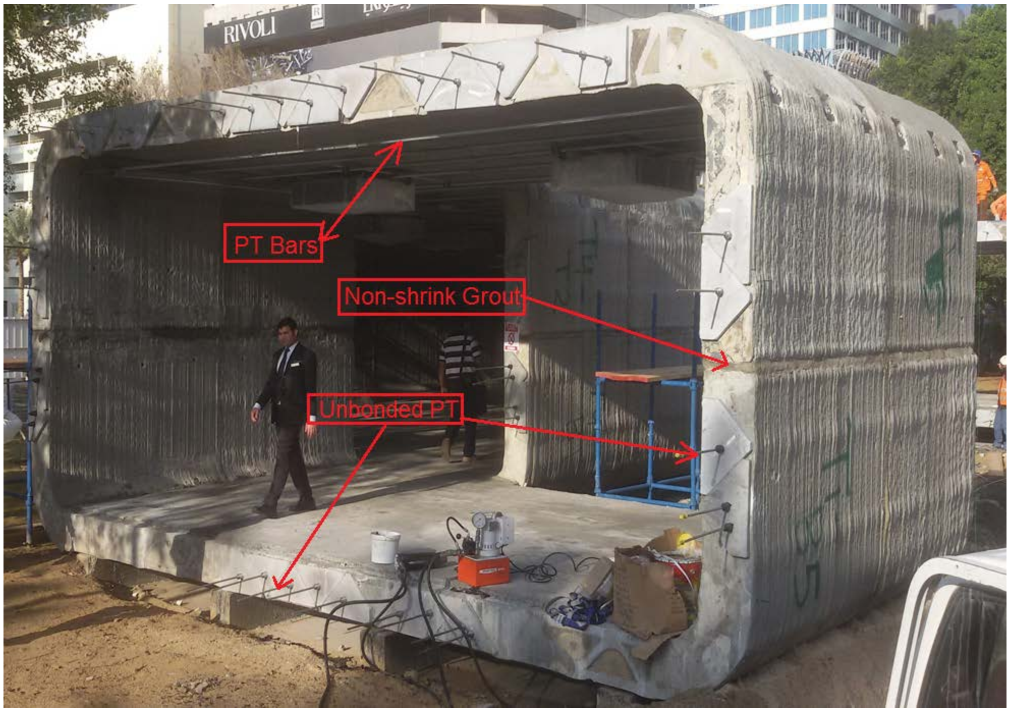
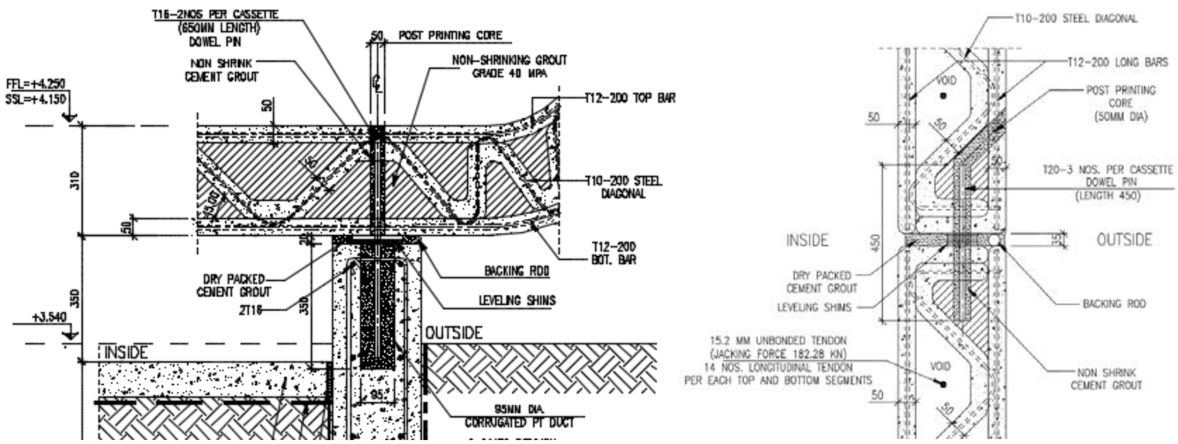
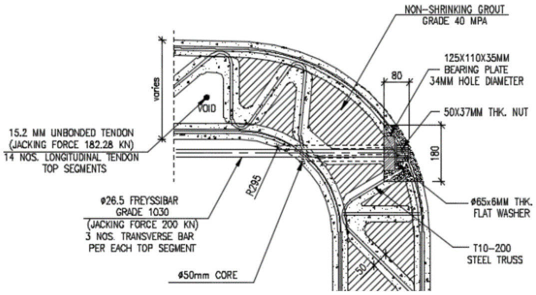


Fig. 22: 3D Printed cassette after erection. external PT bars were added to top cassette and longitudinal PT were added to connect the segments together



a) cassette to foundation connection b) cassette to cassette connection



c) external PT bar to cassette connection

Fig. 23: Typical connection details

ANALYSIS AND DESIGN:

The analysis of the panel was done using a 2D frame analysis. Chords were modelled as beam elements with 35mm thickness by 1000mm width. Filling grout was modeled as shell elements with stiffness reduction of 0.5 to consider the effect of shrinkage cracking. External PT bars were modeled using dummy frame element and the tendon profile is modeled on its center[8]. Refer to below Figures for the geometry of the analysis model.

The design live load was considered as 5.0 KN/m^2 and 0.6 KN/m^2 for office area and an inaccessible roof, respectively. Additional superimposed dead load for finishing were considered as 1.5 KN/m^2 and 2.0 KN/m^2 for office finishing and water proofing, respectively. Three external PT bars 25mm diameter are used for each cassette (2.1 wide).

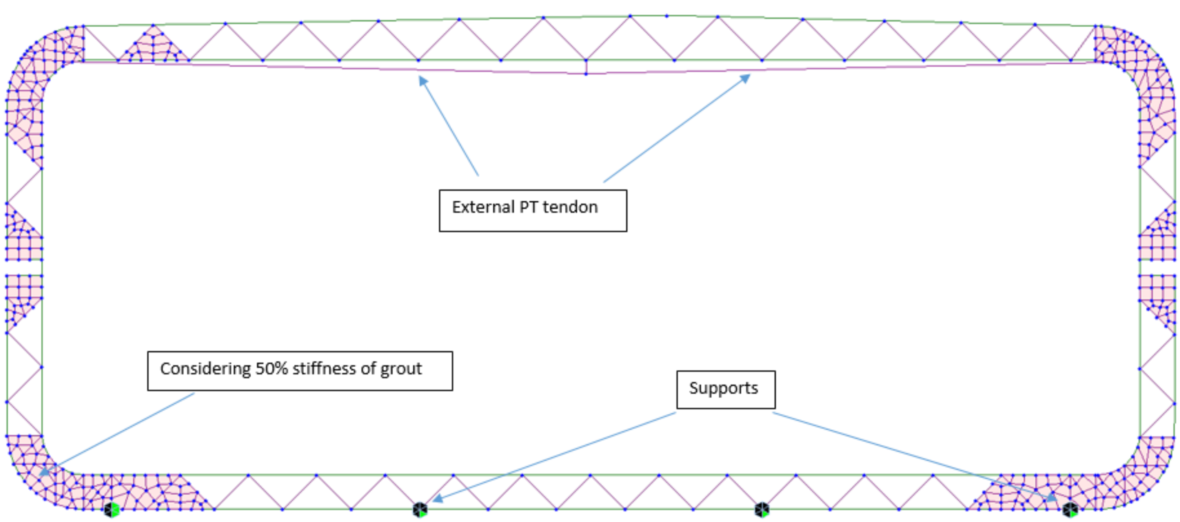


Fig.24: Geometry of 2D Model

The analysis results are shown in figures 23 to 26.

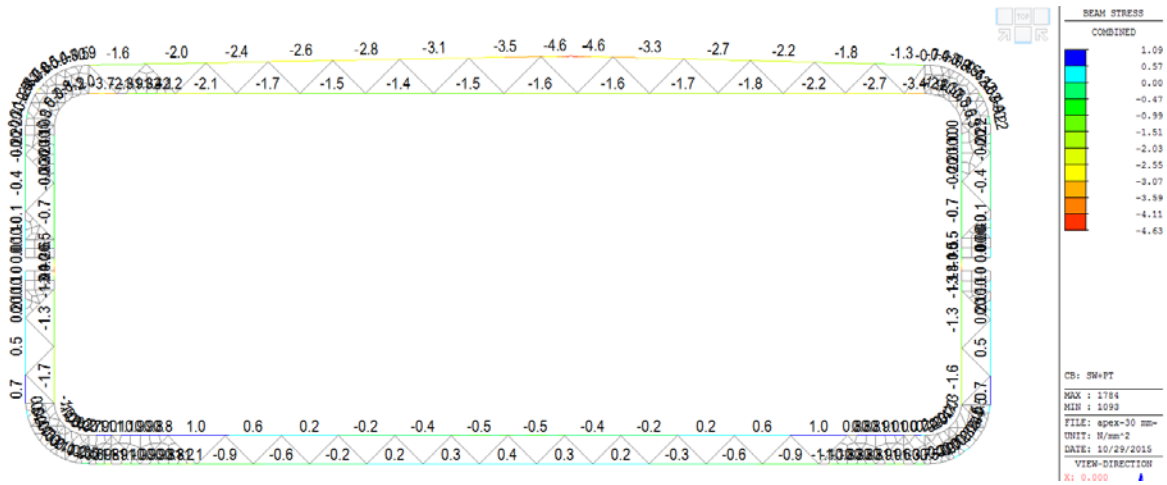


Fig. 25: Beam stress under PT + SW (MPa)

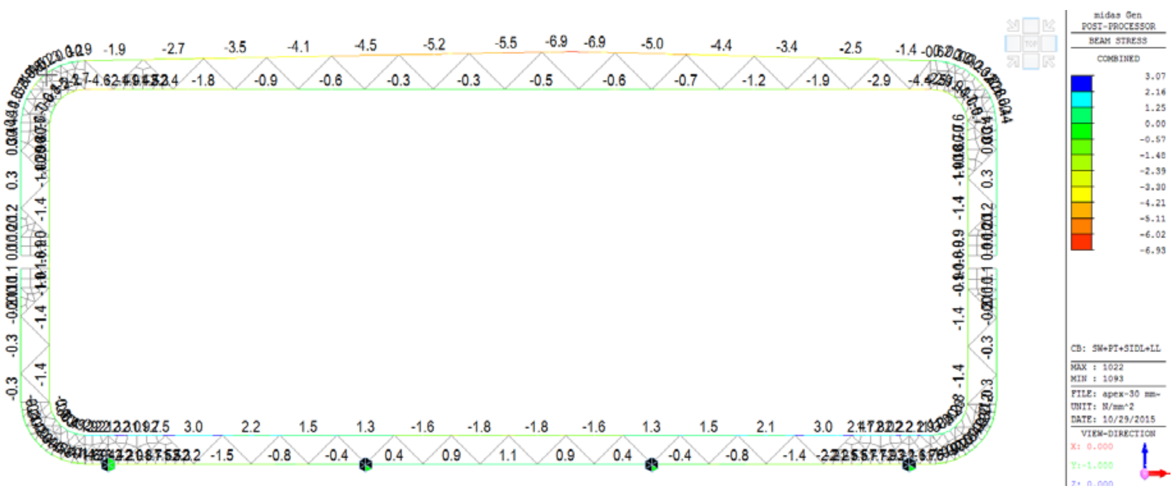


Fig. 26 Beam Stress under Load case [SW+PT+SIDL+LL] (MPa)

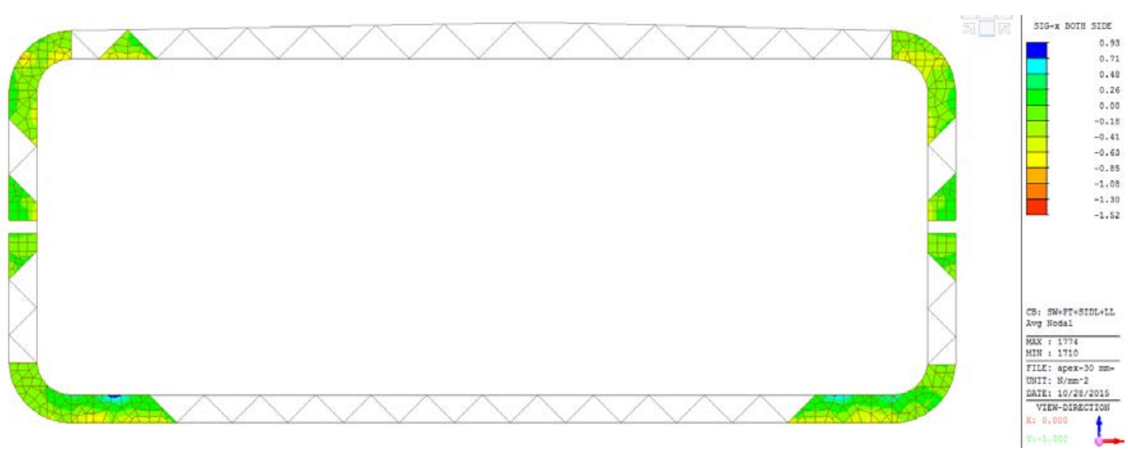


Fig. 27 Plate stresses under Load case (SW+PT+SIDL+LL) (MPa)

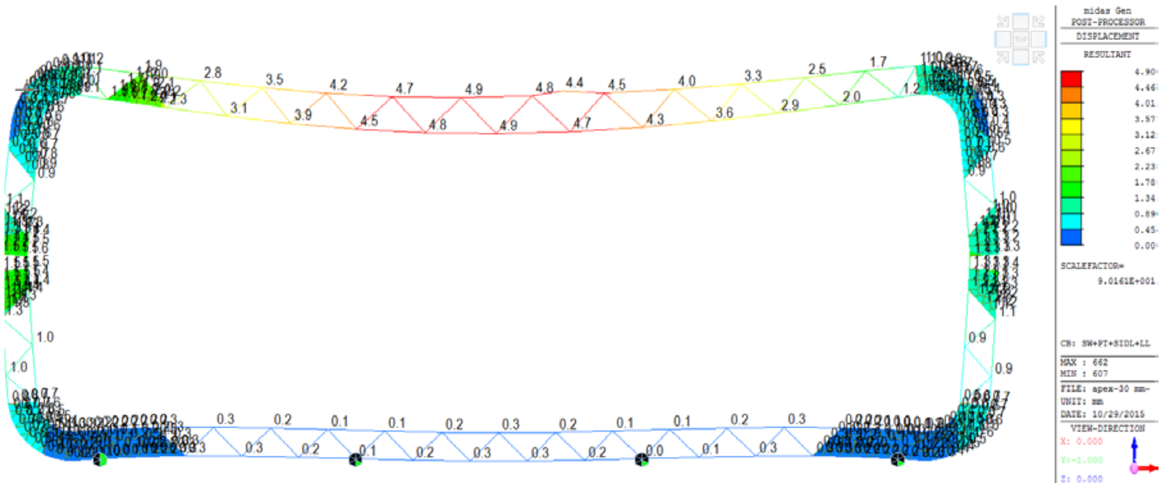


Fig. 28 Deformation values in mm due to SW+SIDL+LL+PT

CONCLUSIONS:

The 3D printed concrete is a new term in structural and construction engineering. The 3D printing technology has started in the late of last century in different industries. Recently, there were several attempts in different locations worldwide to adopt the new technology in civil engineering applications. The 3D printed concrete offers great flexibility of element geometry. Dubai has just built the first 3D printed office building in the world. The authors believe that building “The office of the future” is one of major milestones in 3D printed concrete technology; yet a lot of improvements can be achieved:

1- Concrete mix need to be improved to enhance the tensile capacity and hence eliminating the need to add conventional reinforcement manually during printing process. More research required to explore the using of ultra-high strength concrete (UHPC) in 3D concrete printing.
2- Quality control procedure is required to ensure the consistently of the concrete mix.
3- Curing procedure is required.
4- Design methodology and new code standard is required especially for designing concrete composite element without reinforcement.
5- Connection details between printed elements shall be developed as part of printing process.

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