3D PRINTING FOR PRESTRESSED CONCRETE

Ibrahim Huthman, Grad. Research Assistant, Ohio University, Athens, OH
Ali Semendary, Grad. Research Assistant, Ohio University, Athens, OH
Eric Steinberg, PhD, PE, Professor, Ohio University, Athens, OH
Kenneth Walsh, PhD, Associate Professor, Ohio University, Athens, OH

ABSTRACT

3D printing is rapidly growing from the printing of small objects or scaled models, into full scale large objects. 3D printers were first developed in 1986 and were initially used for prototyping. Now 3D printing is being developed and utilized for the structural area to fabricate buildings and bridges. Oak Ridge National Laboratory printed a vehicle and small building. A design and engineering company printed an 11,840 square foot concrete mansion and a six story apartment building near Shanghai. A 10-foot high concrete villa as an addition to a hotel has also been printed in the Philippines. Multiple other structures are being planned including a metal footbridge by a Dutch company, an office building in Dubai, and houses. The ability of 3D printing and its rapid advancing technology necessitates the prestressed concrete industry plan for its future. This paper looks at some of the advantages that 3D printing will bring to the prestressed concrete industry and primarily focusses on the advantages of the versatility in the usage of formwork.

Keywords : 3D Printing, Prestressed Concrete, Formwork, Bridges

INTRODUCTION

Today, 3D printing, also known as additive manufacturing, is a rapidly growing technology. Commercial desktop 3D printers now exist which enables individuals to start an industry from home. However, 3D printing is not a new technology. The first 3D printer was invented as far back as 1986 by Charles Hull. The purpose of his invention was to aid engineers and designers to realize their ideas by developing solid prototypes from CAD drawings[1]. The process of 3D printing is relatively straightforward. A design of an object is made on a CAD software and saved as a "stl" file. The "stl" file is then fed to a 3D printer. The 3D printer constructs the final object by depositing layer by layer of a chosen material until the final product is formed. From its onset, 3D printing was very popular amongst the manufacturing sector because it fabricated complex designs before they went into mass production, thereby saving significant costs. The medical sector was also one of the early benefiters of this technology. Wake Forest Institute for Regenerative Medicine 3D printed the first human organ in 1999[2]. Since then a prosthetic leg, a fully functional miniature kidney and more innovative life changing organs and body parts have been printed[2].

Early limitations of 3D printing technology included small scale printing and few materials available for printing. Plastics were the most common materials used then and now. However, 3D printing materials are expanding, from the most common plastics: Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA) to metals, wood, glass and even concrete[3]. In addition, large scale 3D printing has also evolved. The University of Southampton 3D printed the first robotic aircraft[4]. Also, the first 3D printed car has been produced[5]. These are just a few examples of the evolution of 3D printing from small scale to large scale.

However, the evolution that is more pertinent to the precast prestressed concrete industry is what is currently happening in the civil engineering construction industry. 3D printing technology is advancing at a rapid rate and changing the way we think about construction. This change is due to the development of 3D concrete printers. These printers work similar to how regular 3D printers work. These automated machines can form a final structural element by producing layers of concrete. Two research teams at the forefront of this exploration with one being out of California and the other being primarily out of England[6].

The team out of California has a process of developing structural elements and full scale buildings by layering of concrete using automated systems. The system can be compared to how a typical 3D printer functions. A model of a building or structural component is designed on a CAD software and then fed to the 3D printing machine. This machine in turn produces layers of concrete through a nozzle, using a sophisticated tool path optimization system[7]. The research team out of England uses a method similar to the one employed by the California team. It involves the processes of 3D printing high performance concrete in layers to form integrated structural components. This method is mainly focused on the flexibility and functionality of developing complex structural components,[8] whereas, the method by the Californian team can go a step further to 3D print an actual building. In addition, a research group in Paris, France have used Ultra-High Performance Concrete (UHPC) to 3D print large scale structures. Their refined technology enables the production of complex geometries. They achieve this by using a 6 axis robot. They have produced a multi-purpose wall with complex geometries to demonstrate this technology[9].While these teams of researchers are fine tuning 3D printed technology to become commercially viable in construction, companies around the world have gone a step further to undertake practical projects using 3D concrete printers.

At the lead is a company in China. In April of 2014, they 3D printed a 6-story apartment building with a 20 ft. tall, 33 ft. wide and 132 ft. long 3D printer using recycled construction material and a patented ink[10]. A similar project has also been accomplished with 3D printers in the Philippines. The world's first 3D printed hotel villa was completed in July of 2015 in the Philippines. The villa measures 34.5 ft. by 41 ft. by 10 ft. and it is an addition to the Lewis grand hotel in Angeles City in Pampanga, Philippines[11]. In the United States, the Oak Ridge National Laboratory developed an integrated building and vehicle, which where both 3D printed. It is an energy efficient project which enables energy to be transferred from the vehicle to the building and vice versa. The building is about 38 ft. by 12 ft. by 13 ft.[12]. The projects highlighted above are projects that have already been undertaken and show the practicality of 3D printing in construction. However, the technology is still developing and there are still some innovative projects in the works using 3D printers in construction.

One of these innovative projects is the planned 3D printed steel footbridge over a canal in Amsterdam[13]. The company printing the footbridge uses robots to 3D print steel structures using different types of metal. The steel bridge will be 3D printed as a whole structure without any assembly. The construction of the steel bridge will be completed in the fall of 2017. In addition, the first 3D printed office structure is to be printed in Dubai. This project will be undertaken by the Chinese company group. The building will be about 2000 sq. ft. and will be constructed with Special Reinforced Concrete (SRC), Glass Fiber Reinforced Gypsum (GRG) and Fiber Reinforced Plastic (FRP)[14].The different types of projects highlighted above exemplifies the numerous benefits of 3D printing. These benefits include but are not limited to:

- Elimination of formwork
- Reduction in construction time
- Reduction of labor and construction cost
- Reduction in waste[7,10,11,14]

3D PRINTING IN THE PRESTRESSING INDUSTRY

In the previous section, the benefits and practicality of 3D printing in construction, are highlighted. The pertinent question now concerns how 3D printing benefits the prestressing industry so it can remain at the forefront of the construction industry. A challenge to stakeholders in the prestressing industry is to investigate the practicality of 3D printing in various processes common to the production and usage of precast prestressed concrete. The research team has begun this investigative process and documentation of this initial research will be explained later in this paper. Different research methodology and tests have been executed to seek potential benefits of 3D printing in the precast prestressed concrete industry. Some immediate benefits include the elimination of formwork, reduction of girder end cracks, and increasing the span lengths of girders. The elimination of formwork will lead to more flexibility for designers. Currently, designers are constrained by the economic cost of form modification. An analysis on form modification suggests that the most ideal girder shape design is one with a wide top flange, large bottom flange and narrow web[15]. However, with 3D printing this ideal shape could be attained because 3D printing does not require formwork. This would thus enable designers to make changes to the top flange, web, and bottom flange as deemed necessary.

The end zone cracking in the precast prestressed concrete I girders are a common issue as the size of the girders and magnitude of prestressing has increased. The end zone cracking is caused by the transfer of significant prestressing forces to the concrete. Different types of cracks have been observed at the end zone of I girders such as inclined cracks, web cracks, bottom flange cracks or cracks at the web-flange interface. An example of inclined cracks which was observed at end zone of an I girder is shown in Figure 1.

Fig. 1: End cracking marked on I girder

The cracks develop when the prestressing forces at release generate tensile stresses from Poisson's effect which exceed the concrete tensile strength. The amount of the prestressing force and the girder depth are considered the most important factors which impacts on the length and width on the end zone cracks[16]. The end zone cracks can cause a durability issues especially if the cracks are located close to the strands. Cracks are often accepted whenever they are within allowable crack widths. The girder could be accepted whenever crack widths are less than 0.012 in. However, girders are typically rejected if crack widths exceed 0.05 in. If the crack widths are between 0.012 in. to 0.05 in., the girder could be repaired[17]. Partial debonding of strands[18,19], changing the web reinforcement details,[20] and vertical end region posttensioning strands[19] are solutions that have been suggested to reduce or eliminate the end zone cracking. However, a change to the section dimensions near the end of the girder to reduce or eliminate the end zone cracking has not been suggested. This solution has not been investigated in the past due to the difficulty in modifying the forms. However, 3D printing technology could be a valid option to reduce or probably eliminate the end zone cracking by modifying the section dimensions at the end zone. Another benefit from 3D printing is the span length of the prestressed concrete girder which may be increased by using a variable depth along the span. The main objectives of this paper are to demonstrate small scale modeling and performing analysis on effective I-girder shapes that can be prestressed and 3D printed.

METHODOLOGY

SMALL SCALE 3D PRINTED GIRDERS

The aim of small scale 3D printing was to demonstrate the functionality of 3D printing systems in the prestressing industry. Using a desktop 3D printer, a prestressed girders was 3D printed on a scale of 1 to 20. using plastic. To achieve this, structural dimensions of an actual prestressed bridge girder were obtained. The girder was an AASHTO Type 1 girder spanning 20 ft. It had 6 strands at 2 in. spacing. To 3D print this girder in plastic it was scaled down using a shrinkage factor. The length of the scaled down girder was controlled by the build volume of the 3D printer. Two printer options existed. They both varied in size and precision of print. After 3D printing and testing several different specimens, the 3D printer with the larger print volume was chosen.

The chosen 3D printer had a build volume of 11.8 in. in length, 12 in. in width and 18 in. in height. The build volume controlled the length of the girder that could be 3D printed. Thus, the shrinkage factor used to scale down the girder was obtained from this limiting factor. After the actual girder was modeled in Solid Edge software with its original dimensions, the shrinkage factor was applied. The new span length was 12 in. Attempts were made to print the strands as a different material, but were unsuccessful. Therefore, holes were placed at strand locations to model prestressing ducts. Several difficulties were encountered in producing the holes in the full length of the scaled girder. Finally, 0.06 in. diameter ducts allowed usage of 0.025 in. diameter wires throughout the scaled girder's length. This was equivalent to 0.5 in. diameter strands in full scale. The modeled image of the scaled down girder can be seen in Figure 2.

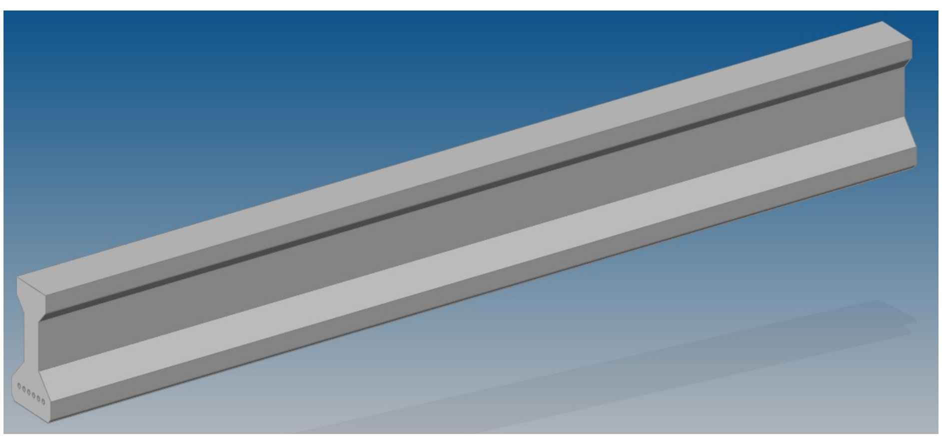


Fig. 2 Scaled-down model of an I-Girder

The next step after completion of the model was to 3D print the girder. The model was saved as a stl file and fed to the 3D printer. Figure 3 shows the completed 3D printed girder. To prestress the girder, steel wires modeling the strands were run through the ducts. Figure 3 also shows these holes at the end of the girder.

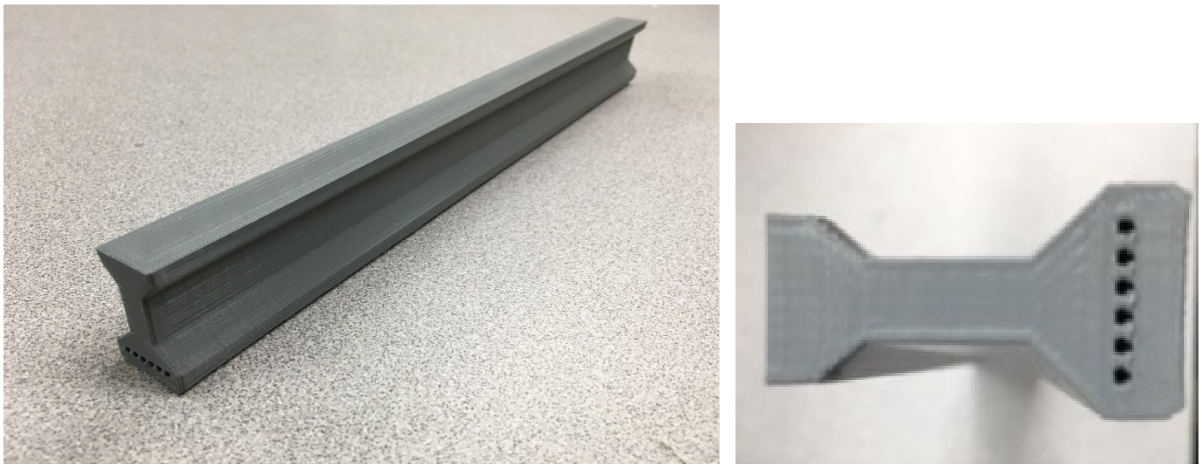


Fig. 3 3D printed model of a scaled-down I-Girder

The prestressing wires had a diameter of 0.025 in. which was equivalent to 0.5 in. in full scale. These wires were then prestressed using a scaled prestressing device. The prestressing device can be seen in Figure 4. The prestressing device was about 2 feet long. It was made of steel and had a customizable end fixture, which could be modified depending on the amount of wires to be prestressed. The end fixture also allowed for movement in order to prestress the wires. After the prestressing was done, the wires were bonded to the girder using an adhesive. Future work on this project includes using longitudinal and rosette strain gages to record the strains occurring on the prestressed girder and device. Also, a modeled simulation of this test will be developed using finite element software. The parameters used on the model will be similar to that of the plastic girder. Analytical and modeling results will be compared and analyzed for similarities and differences.

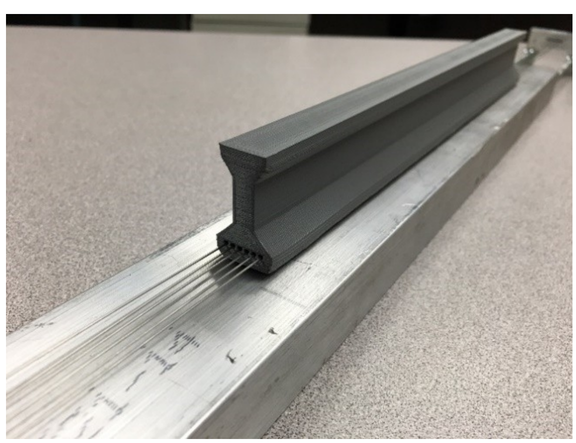


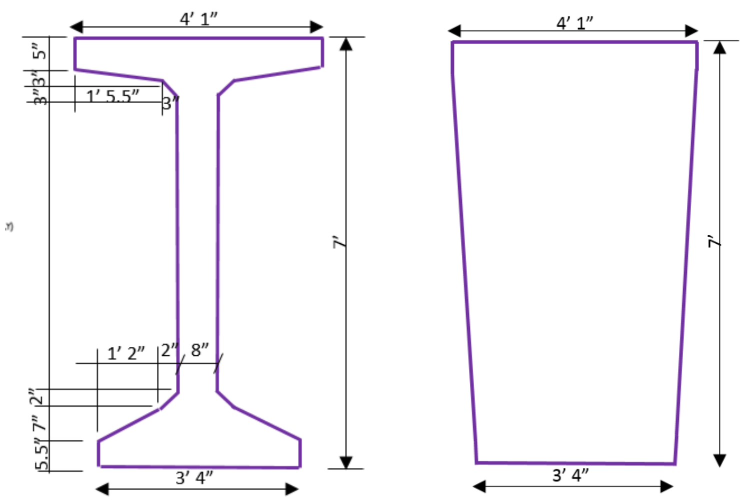
Fig. 4 Prestressing device

FINITE ELEMENT MODEL

Finite element models were created using commercial software to study the benefits from using 3D printing in precast prestressed concrete industry.

FE MODEL OF SOLID END PRESTRESSED CONCRETE I-GIRDER

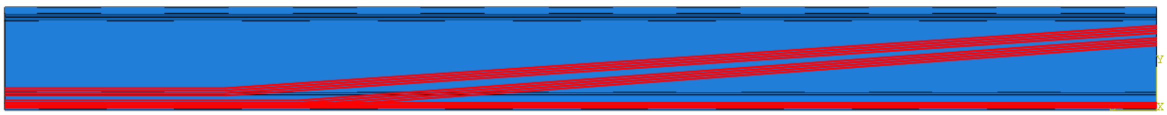
In order to investigate the advantages of using 3D printing in the precast prestressed concrete world, a three dimensional (3D) finite element model was created using commercial software. The effect of a solid rectangular cross sectional end of a girder on the end zone cracking was investigated for a prestressed concrete I-girder. The 3D finite element model was created for prestressed concrete I-girder which was chosen from a bridge in Montgomery County on Interstate Route 75. The prestressed concrete girders of this bridge were inspected in the yard to evaluate the changes in the standard design of the end zone reinforcement details of prestressed concrete girders by the Ohio Department of Transportation. The inspected girders exhibited inclined cracks in the web close to the harped strands. Linear and nonlinear finite element models were created and calibrated with both field observation and available experimental data and the results showed the ability of the model to identify the location of the end zone cracks observed in the field[21]. The same model was used in this paper in order to evaluate the effect of the solid rectangular end of the girder on the end zone cracking. The solid rectangular portion of the beam extended from the end of the girder to different lengths (10, 20, 30 and 36 in.).. Only, linear finite element model was considered in this paper for simplicity. The girder’s dimensions are shown in Figure 5. The total span length of the girder was 157 ft. The girder was 84 in. deep, and the top flange width was 49 in. with a thickness of 5 in. The bottom flange width was 40 in. with thickness of 5.5 in.



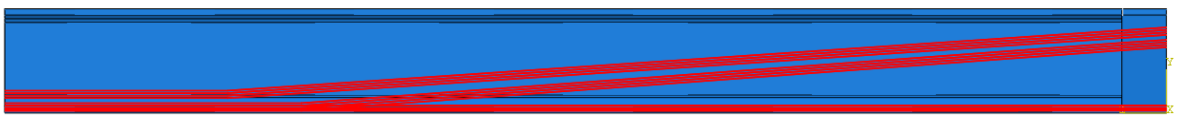
(a) (b)

Fig. 5: Cross section details for prestressed concrete I girder:(a) Original section, and (b) Solid end section

The strands were 0.6 in. diameter seven wire low relaxation with an ultimate capacity of 270 ksi. and consisted of 38 straight and 16 draped. Seven of the straight strands were debonded for distance 10 feet from the end of the girder. The model was created using commercial software. Each part in the model was drawn using commercial software and extended the length equal to the half of the span because the girder was symmetrical about the mid-span. The draped strands were drawn with an angle to obtain an accurate representation. The web reinforcement was drawn and distributed with spacing as defined in the bridge plans. The materials were defined by using parameters in the elastic range. The concrete compressive strength was 6 ksi. The modulus of elasticity of the concrete was calculated to be 4415 ksi, and Poisson's ratio was taken as 0.2. The modulus of elasticity of strands was taken as 28,500 ksi and Poisson's ratio as 0.3. For the web reinforcement, the modulus of elasticity was taken at 29,000 ksi and Poisson's ratio was set equal to 0.3. The embedded constrain option in the finitie element software was applied to the model for the interaction between concrete and reinforcement. In order to define the boundary conditions according to the symmetry condition about the mid span, no movement was assumed in the longitudinal direction at one end. The vertical movement (Y direction) was restrained at the other end. The girder was modeled to be free to rotate or deflect in all other directions. In the longitudinal direction, the girder was seeded to approximately 3 in. Reinforcement and strands were also seeded to 3 in. in order to allow embedment elements to be accurately embedded in concrete girder. The concrete was modeled using four node linear tetrahedral elements (C3D4) because of the shape of the girder. The reinforcement and strands were modeled using two node linear three dimensional truss elements. The prestressing force of 44 kips was applied to each strand. The prestressesd force was applied as a negative temperature through the predefined field in the software. A linear equation was used to model the prestressing force along the transfer length in the software in order to accurately represent the stress. After the transfer length, a uniform negative temperature was applied. The details of the models are shown in Figure 6.



(a) Standard end



(b)Solid end

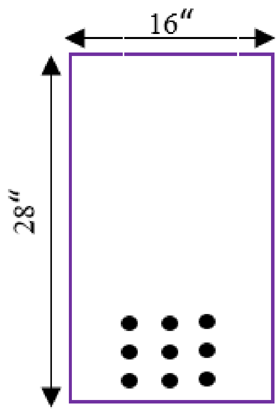
Fig. 6 FEM of precast prestressed concrete I girder

FE MODEL OF VARIABLE DEPTH PRESTRESSED CONCRETE RECTANGULAR BEAM

A precast prestressed concrete rectangular section 16 in. wide by 28 in. deep was assumed to investigate the effect on varying the depth of the section. The span length was 40 ft. There were 12 straight ½ in. diameter low-relaxation Grade 270 strands as shown in Figure 7. The stress in the strands at release was assumed to be 190 ksi. The cross section in the first model was assumed to be uniform for the whole length. However, the girder depth was reduced to half its original depth, and the strands were harped for the non-uniform cross section along the length. The harped distance was assumed to 0.4 L from each end. The same strands patterns and spacing was assumed in both models.

(a) Uniform depth

(b)Non-uniform



Section A-A Section B-B

Fig. 7 Details of precast prestressed concrete rectangular section

Three dimensional (3D) finite element models were created using commercial software. The cross section was drawn using the finitie element software and extended to the length equal to the full span. Then, the strands were drawn and extended for the same length. The materials were defined by using parameters in the elastic range. The concrete compressive strength was 5 ksi. The modulus of elasticity of the concrete was calculated to be 4031 ksi, and Poisson's ratio was taken at 0.2. The modulus of elasticity for strands was taken as 28,500 ksi and Poisson's ratio as 0.3. The interaction between concrete and strands was modeled as an embedment constraint. All strands were modeled as embedment elements. The boundary conditions were defined as pin at one end and roller at the other end. The girder cross section was seeded to approximately 2 in. with the same size in the longitudinal direction. In order to allow embedment elements to be accurately embedded in concrete girder, and strands were also seeded to 2 in. Eight node linear brick elements were used to model the concrete. Two node linear three dimensional truss elements were used to create the model for the strands. The prestressing force was calculated based on the prestress at release. The prestress force was applied as a negative temperature through the predefined field in the model. A linear equation was used to model the prestressing force along the transfer length in the finite element software in order to accurately represent the stress. After the transfer length, a uniform negative temperature was applied.

RESULTS AND DISCUSSION

FE RESULTS OF TAPERED PRECAST PRESTRESSED CONCRETE I GIRDER

The results from the finite element model for the original shape is shown in Figure 8. The maximum principal tensile stresses were used as indication of the crack's location whenever the value of maximum principal tensile stresses were greater than the tensile strength of concrete. The theoretical cracking stress was calculated according to the AASHTO LRFD (2012) Bridge Specification C5.4.2.7. The cracking strength was found to be 0.56 ksi. The results showed that the end zone had maximum principal tensile stresses which were greater than the cracking strength. The results also show that the maximum principal stress in the web reinforcement was 7.2 ksi at the web cracks location.

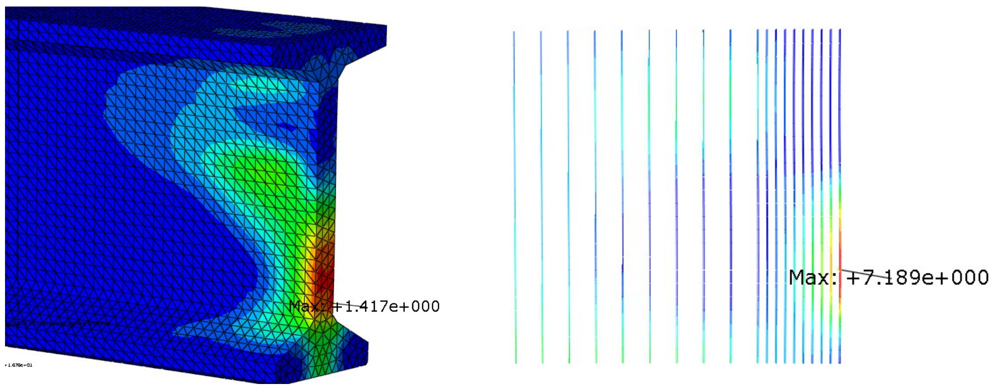
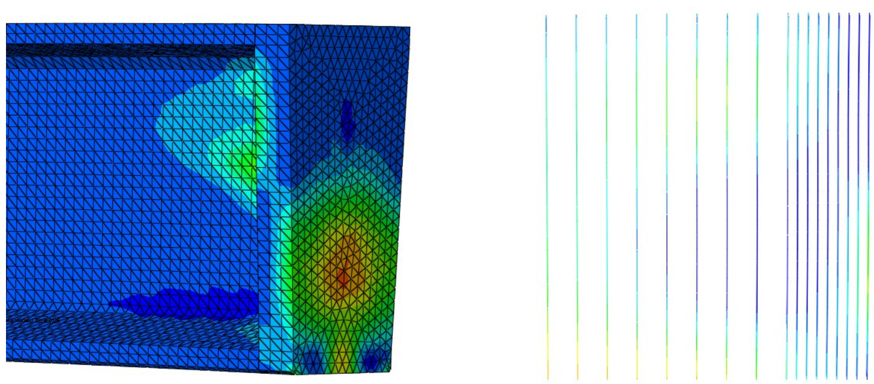
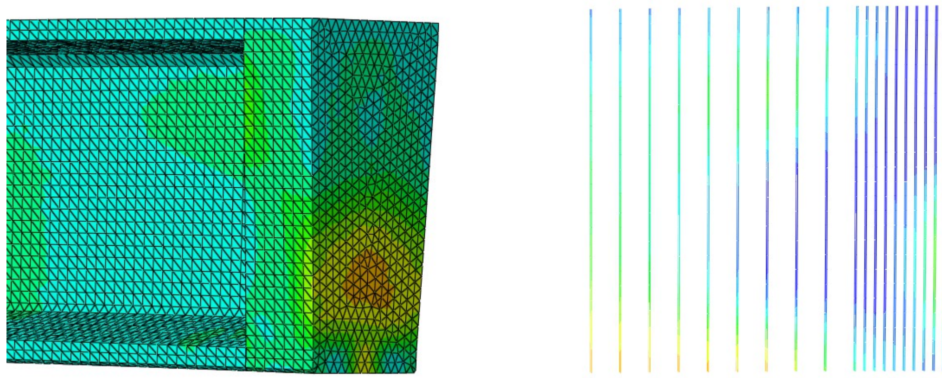


Fig. 8 Maximum principal tensile stresses at the end zone of precast prestressed concrete I girder with standard shape

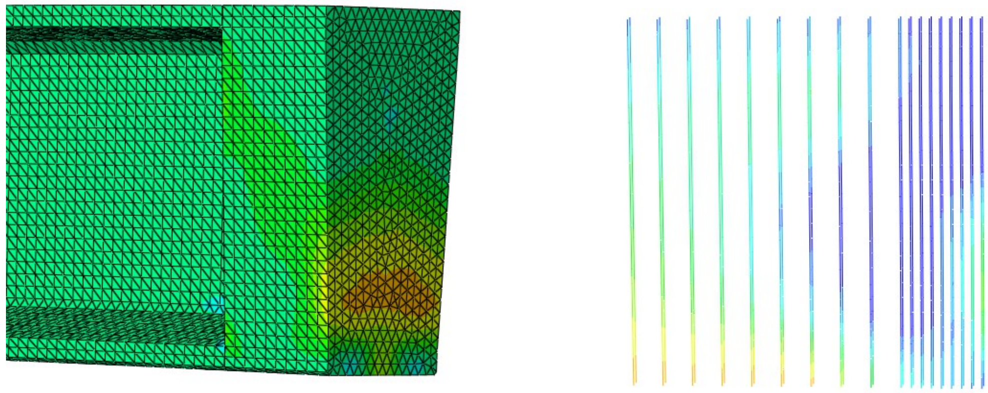
In order to investigate the effect of solid end of the girder on reducing the end zone cracks, the end of the girder was solid for distances of 10 in., 20 in., 30 in., and 36 in. The maximum principal tensile stresses in both concrete and web reinforcement was investigated as shown in Figure 9. The results show that the maximum principal tensile stresses were reduced by approximately 50% in both the concrete and the web reinforcement when the end of the girder was solid for 20 in. This implies that the amount of vertical reinforcement could be reduced for a congested area. For solid distances above 20 in., the decrease in the maximum principal stresses for both the concrete and the web reinforcement was insignificant.



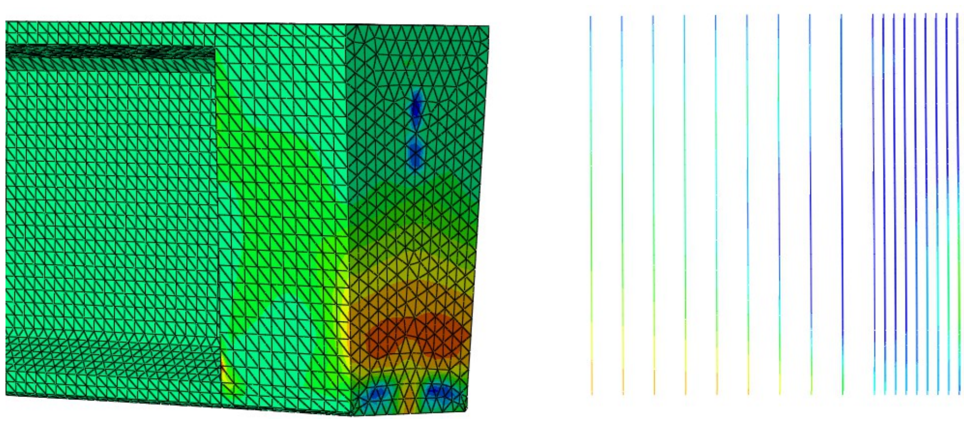
(a) Solid end for 10 in.



(b) Solid end for 20 in.



(c) Solid end for 30 in.



(d) Solid end for 36 in.

Fig. 9 Maximum principal tensile stresses at the end zone of precast prestressed concrete I girder with modified shape

FE MODEL OF VARIED DEPTH OF PREAST PRESTRESSED CONCRETE RECTANGULAR SECTION

The effect of the varied depth of the cross section along the length was investigated. The finite element results from both uniform and non-uniform rectangular section is shown in Figure 10.

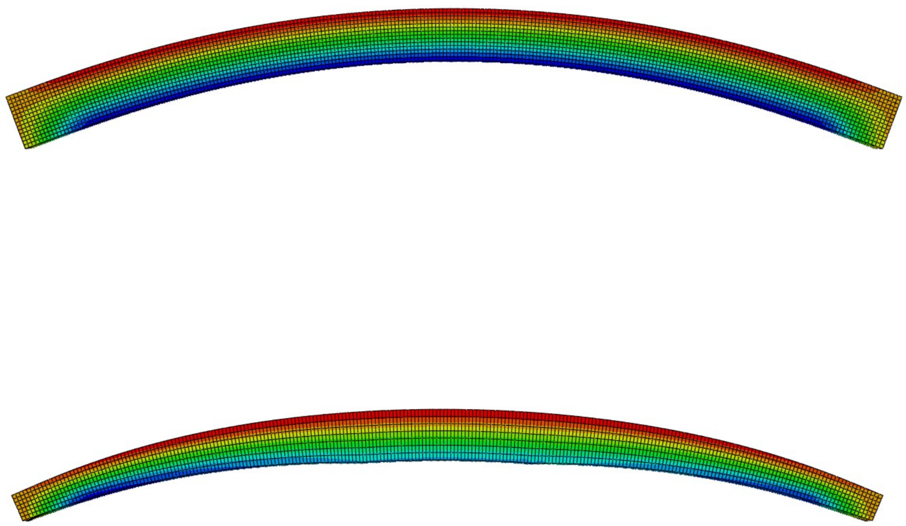


Fig. 10 Longitudinal stresses in precast prestressed concrete rectangular girder

The results show that the longitudinal stress in concrete due to the prestress force at release were decreased when the non-uniform cross section was used. However, the longitudinal compressive stresses were increased at the transfer length as shown in Figure 11b.

(a) Longitudinal stress distribution across the depth at mid span

(b) Longitudinal stress distribution across the depth at transfer length (30 in. from the end)

Fig. 11 Longitudinal stresses in precast prestressed concrete rectangular girder

CONCLUSION

In summary, 3D printing technology has proved its ability in construction through some of the diverse projects highlighted earlier in the paper. The technology is also continually improving to provide a cost effective alternative to conventional methods of construction. The scope of 3D printing can be extended to the precast prestress industry which could benefit tremendously with the various kinds of innovation 3D printing promises. Small scale 3D printing of I-girders and finite element analysis of different girder shapes were investigated and the following conclusions were drawn:

- The challenge to change forms of existing prestress I-girder shapes can be answered by using 3D printing which does not require any formwork.
- Many solutions have been used to eliminate end cracks in girders but no solution has involved modification of the shape either at the end or along the length of the girder. However, 3D printing is an option to modify the shape of the girders.
- Solid rectangular ends of an I-girder reduced the stress at end by almost 50% which is a potential solution to eliminate end cracking in the girder.
- Tensile stresses at the end of a girder were reduced when the girder depth was varied along its length. This reduction in cross-section reduces overall dead weight and may allow higher superimposed loads or increases in span length.

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