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Shrinking the Construction Site

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Abstract

Construction operations are loud, dangerous, and often remote. So, taking a field trip to a construction site for a class period is almost never feasible. Nowadays, zoom and various multimedia technologies provide convenient opportunities to visually bring the construction site to the class room, but these can be cumbersome, and less engaging than a site visit.

In conjunction with the visual stimulation of going to the site, or bringing the site to the class room through video, it is important for students to have tactile stimulation as well. This work aims to provide the means for this tactile stimulation with three dimensional scaled models of construction projects, a process we call "shrinking the construction site." Through careful and accurate design of the 3D models, it is possible to show construction processes and step by step procedures for the construction of various building elements all while providing visual and tactile stimulation for students in a classroom environment.

This paper describes the procedures taken in order to design and construct a 3D model of the processes taking place during the construction of a reinforced concrete building, such as excavation, installation of formwork, installation of reinforcement, pouring concrete and removing the formwork. The aim of this model is to provide a tactile experience for students during the instruction of formwork temporary structures, and other construction operations. It can also be used to instruct topics such as construction site safety, site logistics, and resource management among others. The researchers aim to expand the 3D model to include steel building construction models, and representative utility installation components.

Key words: Construction, 3D printing, Education, Tactile, Kinesthetics

Introduction

As educators we strive to find new and interesting ways to engage with students and deliver content. In construction engineering education, the curriculum ranges from the means and methods for a construction process, to line items required for estimating a task, the time it takes to schedule an activity, to the required temporary structures for the completion of a construction project. As such, faculty should be engaging with a variety of learning styles in developing their class activities. Students in Construction Management/Engineering, and Architecture programs generally prefer two learning styles; visual and kinesthetic [1]. For this reason, the researchers decided to develop an educational prop to instruct the means and methods required to construct a one-story concrete building, focusing on formwork, and placement of reinforcement and concrete, using 3D printed elements.

Background

It is becoming evident that with the decreasing cost of 3D printing technology and the increasing comfort faculty have with the use of the technology [2], 3D printed props are finding their way into the classroom environment. Examples of 3D printed educational props range from topographical maps used in a topographical engineering course [3], to 3D bronchi used for the instruction of bronchoscopy [4]. Specifically, for Civil and Construction Engineering instruction, 3D printed props included trusses used for mock testing [5], and abstract blocks used for the instruction of spatial reasoning [6].

In construction related classes, the use of 3D printed props for instruction of course material relating means and methods, safety, constructability, and productivity is very limited. In the pertinent literature search for this manuscript, no references were identified. Furthermore, models that depict the sequence of construction are limited to virtual or digital models, that rely on specialized software.

To overcome these difficulties, the researchers decided to test the possibility of creating 3D scale models of construction processes, in a way that depicts the means and methods involved in their construction, while being as true as possible the relative dimensions, and the interactions between the model parts. In this paper, the development of the first model is outlined, which consists of the steps to construct a one-story concrete building. The model incorporates the excavation of the site, the placement of the foundations and reinforcement, the placement of the columns and a wall, and the floor slab. The model also added the steps of placement and removal of formwork so that the model can be used in the instruction of temporary structures.

Methodology

For the creation of the model, the research team decided to use SketchUp [7] because of its ease of use, and the quick and straightforward capability to create the files necessary to 3D print the various model pieces. The process of creating the building model began with a broad investigation of internet photos, printed educational resources on the construction processes involved, in addition to the existing knowledge on the topic from the researchers. Our research team then brainstormed and outlined the basic design of a model that would represent a real construction project, and decided to concentrate on the main structural elements and the foundations. Thus, only the column foundations, strip footings, columns, walls, and slabs were modeled, with the associated reinforcement, and formwork necessary to compete a one-story concrete structure. In future iterations of the model, the team will add additional elements. After evaluation several possible scales, the team decided to use a 1:50 scale for the representation of the real structure in the model, since that scale produces pieces that can be 3D-printed and in dimension that fit within the capabilities of the majority 3D-printers. In addition, these 1:50 scale pieces are large enough to efficiently represent construction operations, and sturdy for handling in a classroom demonstration environment.

On the SketchUp software, the team modeled the various pieces in real dimensions, starting with the pieces closer to the ground, and moving upwards. Once the design of each model piece was completed, it was scaled by a factor of 0.02 to achieve the desired model size and exported as a Stereolithography (STL) file, ready for printing. As the model progressed in SketchUp, pieces were periodically printed to ensure that they would fit together as intended. Often these “quality control” prints led the team to modify tolerances or geometry, to improve the model’s ease of use and representative qualities.

The equipment used during the drafting and prototyping phase of this project included two different 3D printers available in Bucknell University's Maker-E space; the Pulse XE [8], and the Fusion3 F410 [9]. Their specifications are shown in Table 1 below. The filament used for this model was Polylactic Acid (PLA), but it is possible to print with many other types such as Acrylonitrile butadiene styrene (ABS), and Polyethylene terephthalate (PET).

Table 1: 3D Printers Specifications

Specification	Pulse XE	Fusion3 F410
Build Volume	250 x 220 x 215mm	355 x 355 x 315mm
Print Speed	60mm/s	250mm/s
Layer Height	30-350 microns	20-300 microns
Filament Diameter	1.75mm	1.75mm
Nozzle	Hardened Steel, 0.4mm	Hardened Steel, 0.4mm
Max Hotend Temp	>295C	300C
Max Heated Bed Temp	120C	140C
Print Surface	Heated Bed	Heated Glass
AC Input	24V	110V/230V

The team also color coded all the model components with different colored filament, where red color was reserved for ground and backfill, black for reinforcement, grey for concrete, orange for formwork, and green for insulation/vapor barriers. This distinction and color coding of the pieces, allows for the model to be easier understood, and leads for a clearer distinction between the materials and functions of these components of a real construction site, during classroom demonstrations.

Results – Model Assembly Sequence

As mentioned earlier, the final model consists of a one-story concrete building set up in an arrangement of 3 by 3 columns. It is possible to construct the model in an arrangement of 2 by 2 columns, but within this narrative only the 3 by 3 is shown. The aim is to identify the construction processes required to construct this one-story building and allow students to add and remove parts, simulating the steps that are necessary to construct a real concrete structure.

As shown in Figure 1, the site starts with the excavation, marking for the placement of the formwork for the foundation. The site consists of a 3 by 3 grid, and each piece interlocks with its neighbors for stability, and their dimensions are roughly 4.5in by 4.5in. In total, the base is made up of 1 center piece, 4 corner pieces, and 4 edge pieces. The site pieces are also etched with the layout of the foundation. This etching is intended to allow model users visualize where subsequent pieces fit, and to allow for a sturdy placement of these pieces.

After the excavation, the site is ready for the formwork for the columns and strip footings. In Figure 2, shown in orange, the formwork is made of three types of pieces (for placement convenience) but the idea is conveyed that a contractor would require to build a perimeter of formwork around the foundations and strip footings. The reinforcement pieces for the strip footings were printed in two parts and connected using epoxy glue.

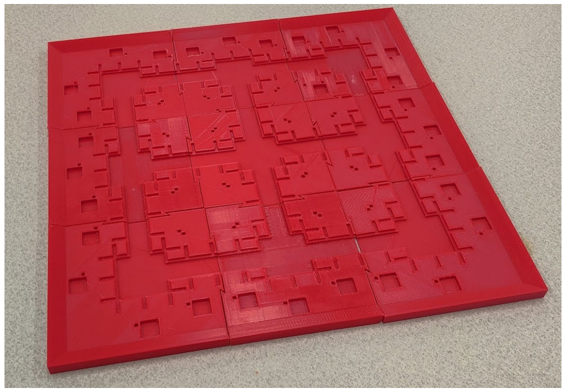

Figure 1: Site Layout for 3X3 set-up

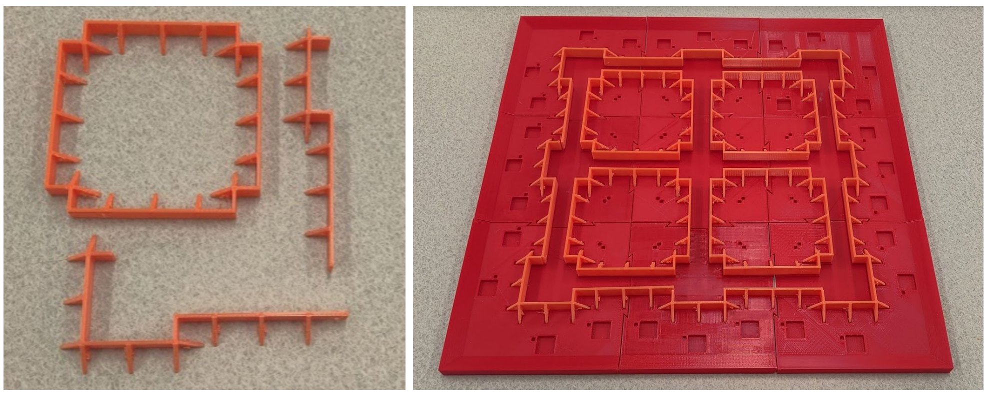

Figure 2: Footing Formwork Pieces (left), and Footing Formwork on the Site (right)

Once formwork for the foundations is complete, the next step requires the placement of the reinforcement for the column foundations and the strip foundations, shown in black in figure 3. One section of the building will have a concrete wall, and that is reflected in the foundation as well, where the reinforcement has reinforcement extended to be connected to the wall. That portion of the foundation is shown in the upper corner in Figure 3.

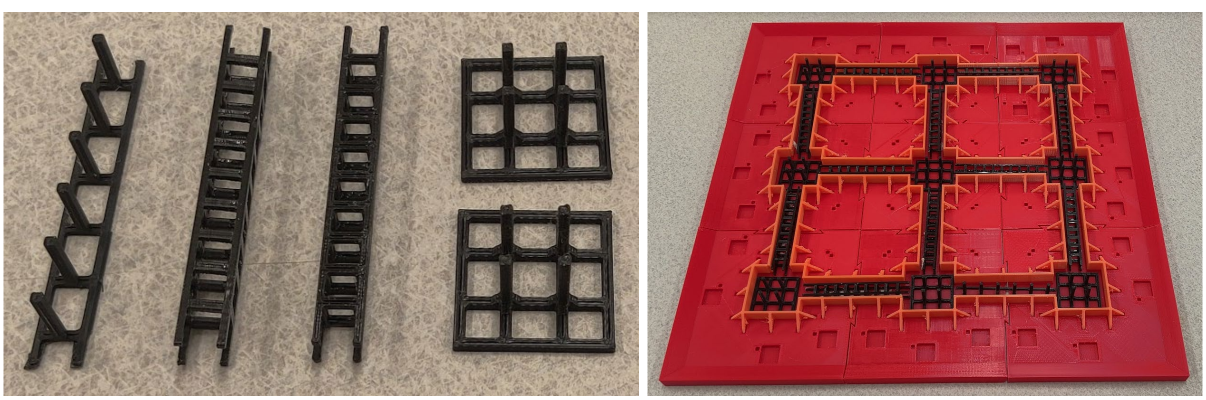

Figure 3: Foundation Reinforcement Pieces (left), and Foundation Reinforcement on the Site (right)

After the placement of the reinforcement, the next step requires the pouring of the concrete, shown in grey. The process is represented by the placement of the concrete pieces as shown in Figure 4. The process does not require the removal of the reinforcement, but holes in the concrete pieces allow for their placement in the model.

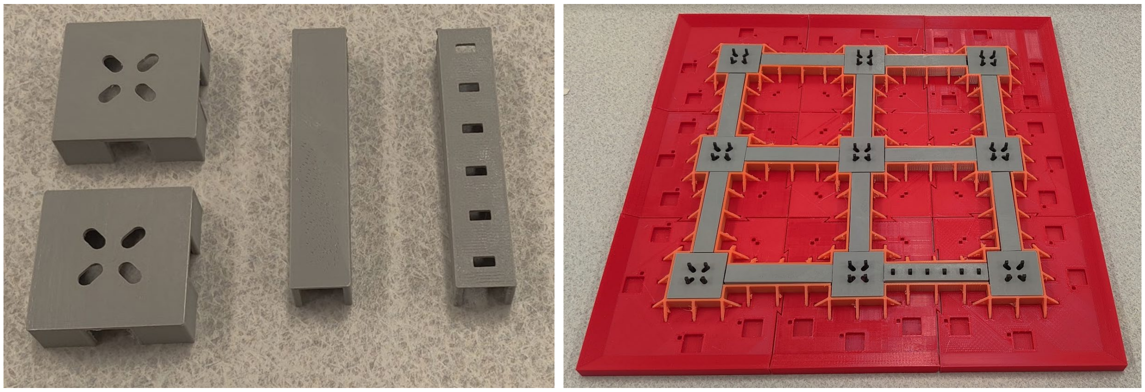

Figure 4: Foundation Concrete Pieces (left), and Foundation Concrete on the site (right)

The next step in the process is the placement of the reinforcement for the vertical members; columns and wall, as shown in Figure 5. For convenience in the model, the reinforcement for the columns and the strip footings are the same.

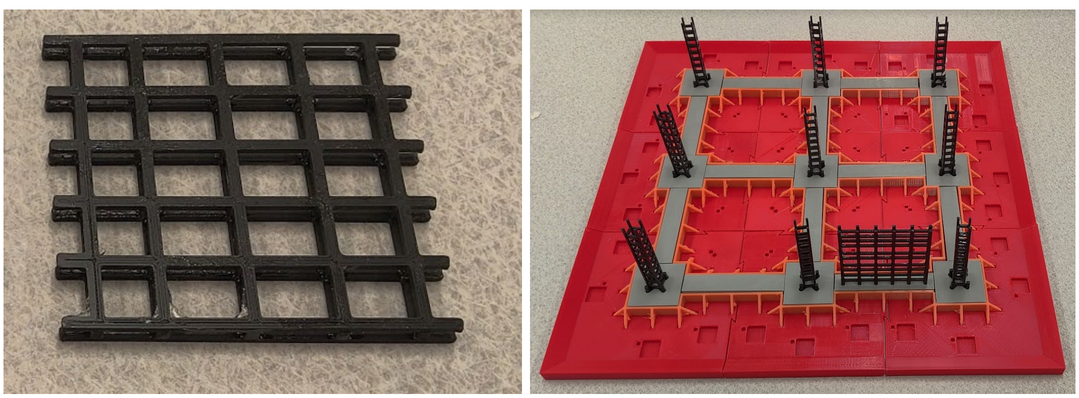

Figure 5: Wall Reinforcement (left), Wall and Column Reinforcement on the site (right)

The next step requires the placement of the formwork for columns and the wall as shown in Figure 6. The wall formwork is in two parts, and the formwork for the columns connected to the wall have a “C” shape to suggest that the wall and the columns are poured together. The formwork for the columns that are not connected to the wall are in 2 pieces that interlock as they are placed around the column reinforcement. Also shown in Figure 6, are bracing pieces that are resting on the columns/wall, and are supported by blocks set on the site pieces, or by stakes on the site.

The next step requires the pouring of the concrete for the walls and columns (Figure 7). The columns that are connected with the wall, have an interlocking connection to suggest the pour happens at the same time. The column/wall pieces slide through the formwork, and the reinforcement protrudes through openings at the top of the concrete pieces.

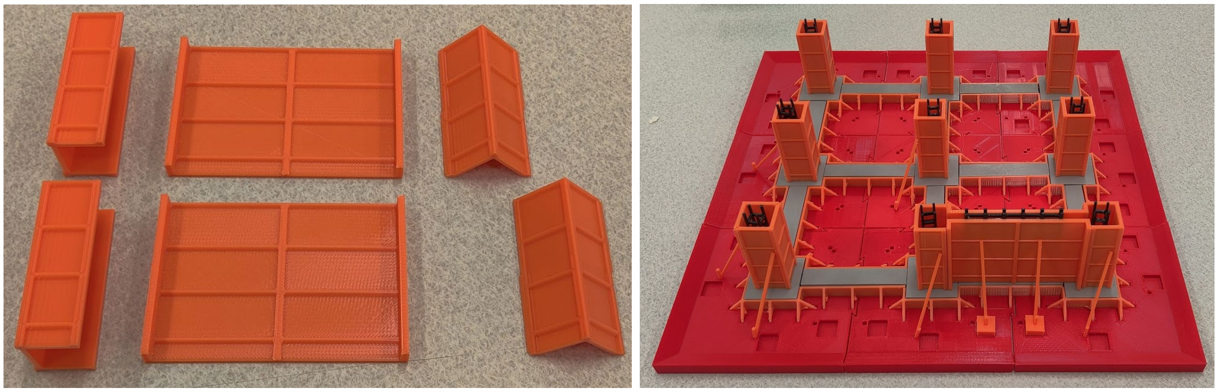

Figure 6: Wall/Column Formwork Pieces (left), and Formwork Pieces on the site (right)

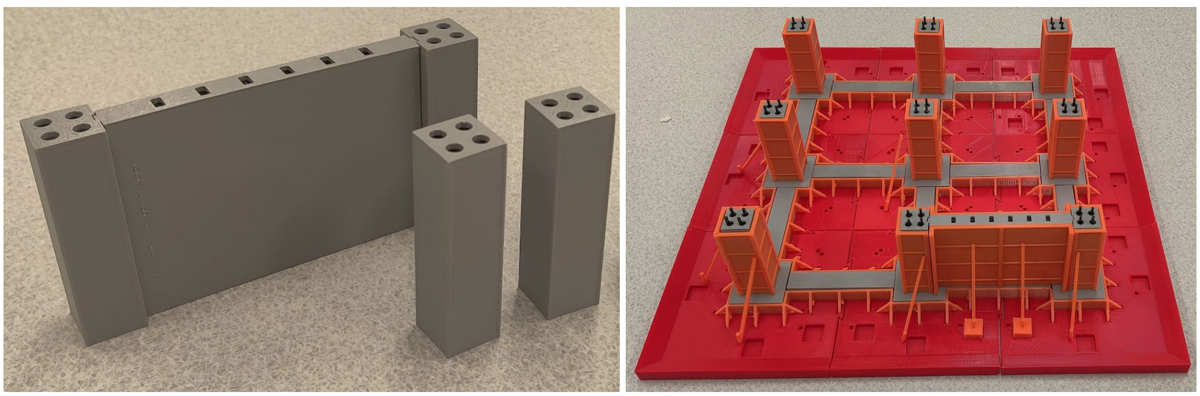

Figure 7: Wall/Column Concrete Pieces (left), and Concrete Pieces on the site (right)

The next step requires the removal of the formwork, and the placement of the slab-on-grade. Figure 8 (left) depicts the pieces for insulation and moisture (green), floor reinforcement (black), and floor concrete (grey), while on the right the pieces are all placed on the site.

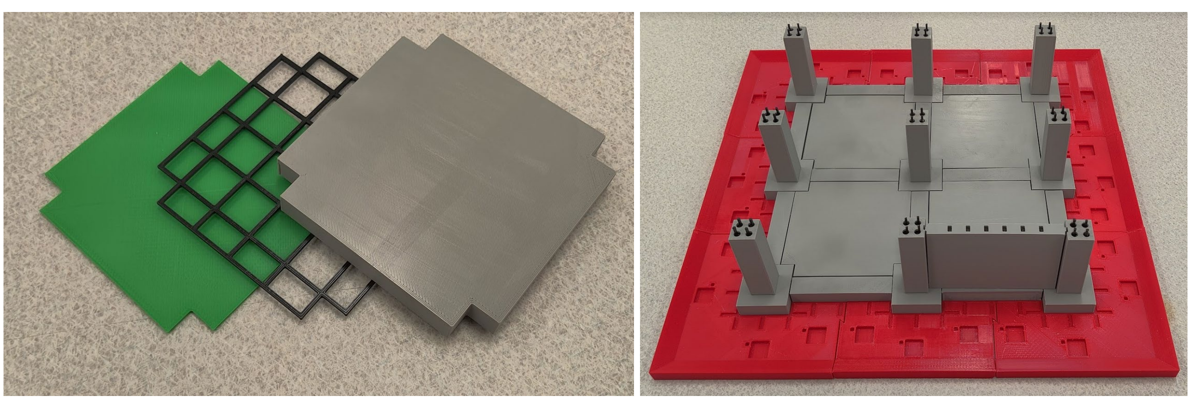

Figure 8: Slab-on-grade Pieces (left), site with Formwork Removed (right)

The next step requires the placement of the formwork required for the first-floor slab. This is made up of several pieces that represent the formwork sills, shores, stringers, joists and plyform, as shown in Figure 9. The assembled formwork is placed on the site as well as the perimeter formwork for the first-floor slab as shown in Figure 10.

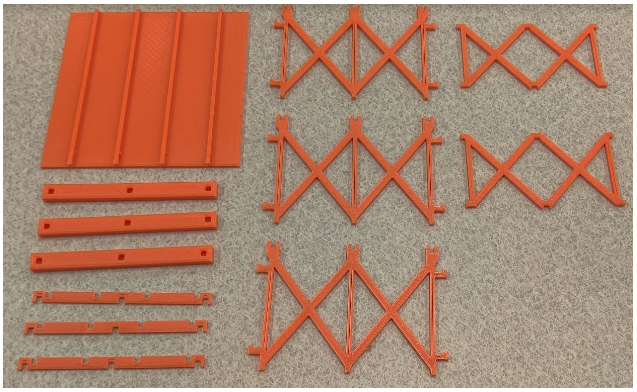


Figure 9: Slab Formwork Pieces (left), and Slab Formwork Assembled (right)

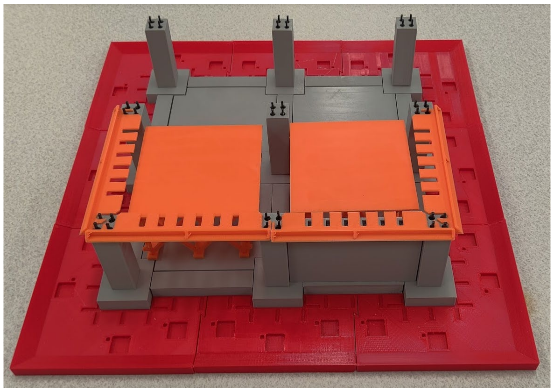

Figure 10: Slab Formwork Reinforcement Placed on the Site

The next step in the model handles the placement of the floor slab, that includes the concrete and the reinforcement. The bottom part of the slab (ceiling) is placed first and out of sequence from the real construction process, and it is followed by the reinforcement and the concrete slab, as shown in Figure 11.

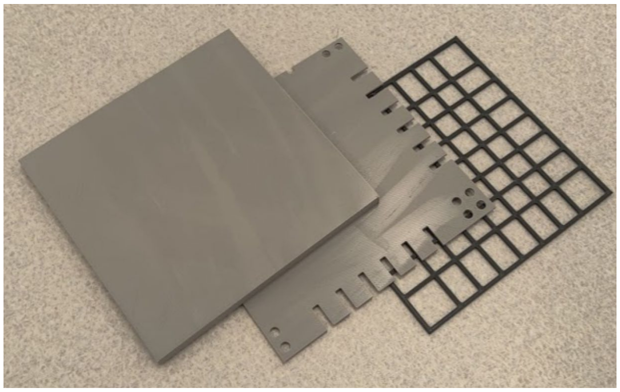
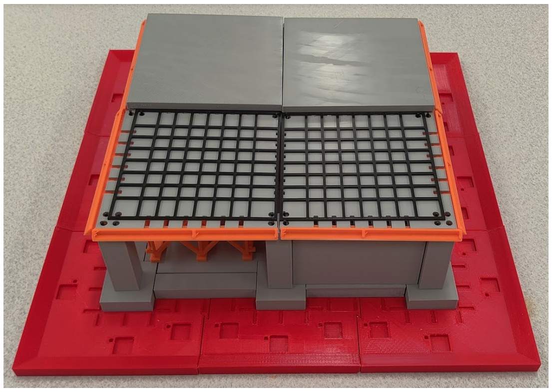

Figure 11: First floor Pieces (left), and First Floor Placed on the Site (right)

The final step requires the removal of all the formwork (Figure 12), and the backfill of the excavation as shown in Figure 13.

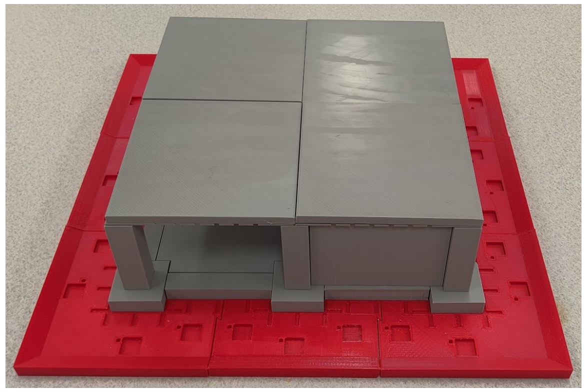

Figure 12: Site with all Formwork Removed

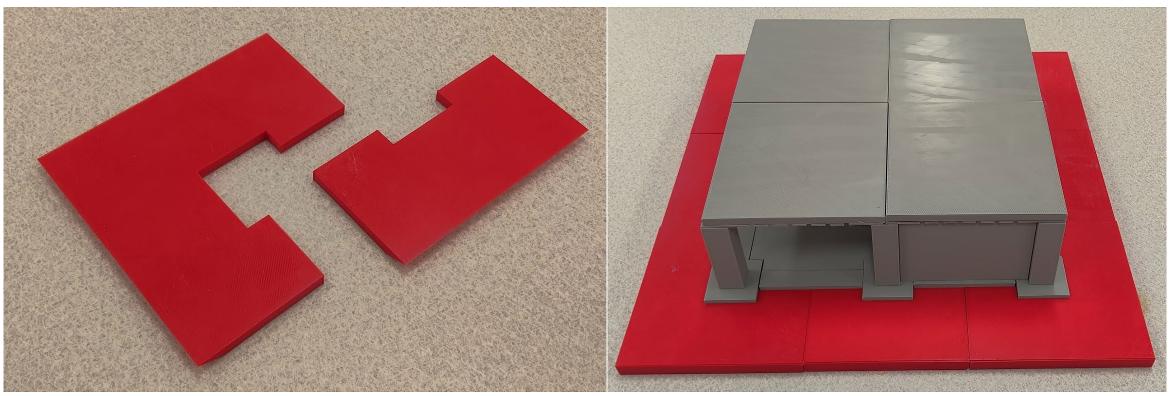

Figure 13: Site Backfill Pieces (left), and Completed Site (right)

Limitations

Similar to many other educational props, this model does have limitations. Due to the time it takes to print all the pieces in the model, this prop requires some forethought and planning, and it is not meant to be prepared the day before the demonstration.

The version of the model consisting of the 3 by 3 grid of columns requires the printing of 126 distinct pieces, as shown in Table 2. Similarly, the 2 by 2 grid of columns requires 61 pieces. The total time required to print these pieces is estimated to take several days, depending on print speed, and print surface.

One more limitation is that for more effective instruction, and to engage all the students in a class, the researchers suggest multiple sets be printed so that students can separate into groups, allowing them to engage with the model. For small classrooms, this limitation might not be an issue, but for large lectures, printing multiple copies might not be feasible.

Table 2: Break-up of all the pieces for the 2 model set-ups

	3X3 layout		2X2 Layout	
	Description	**Quantity**	**Description**	**Quantity**
Site (red)	Center Edge Corner	1 4 4	Corner	4
Backfill (red)	Corner Edge	4 4	Corner	4
Foundation Formwork (orange)	Center Edge Corner	4 4 4	Center Corner	1 4
Foundation Reinf. (black)	Column Strip footing Wall found.	9 11 1	Column Strip Footing Wall found.	4 3 1
Foundation Concrete (grey)	Column Strip footing Wall found	9 11 1	Column Strip footing Wall found.	4 3 1
Vertical members formwork (orange)	Wall Columns	1 pair 9	Wall Columns	1 pair 4
Vertical members reinforcement (black)	Columns Wall	9 1	Columns Wall	4 1
Vertical members concrete (grey)	Wall Columns	1 9	Wall Columns	1 9
Slab on grade	Insulation (green) Reinf. (black) Concrete (grey)	4 4 4	Insulation (green) Reinf. (black) Concrete (grey)	1 1 1
Slab formwork (orange)	Set (sills, shores, stringers, joist, plyform) Slab edge	4 8	Set (sills, shores, stringers, joist, plyform) Slab edge	1 4
Floor slab	Conc. ceiling (grey) Reinf. (black) Conc. floor (grey)	4 4 4	Conc. ceiling (grey) Reinf. (black) Conc. floor (grey)	1 1 1
Total		126		61

Observations, Conclusions, and Future Work

This prototype model for concrete and formwork is still in its testing stages. The researchers plan to evaluate the model with industry professionals to identify any errors in the representation of the model elements as they relate to real building elements, and then produce a final model that would be available for anyone to download.

The team also plans to create models for other types of construction such as a precast concrete structure, a steel frame structure, and a structure with a steel joist roof system. In addition, the researchers plan to assess if the models can be used in class instruction to help students identify other aspects of the construction process such as productivity, and hazard recognition.

References

1. Nelson, J. and J.W. Lawson, *Teaching Architecture, Engineering and Construction Disciplines: Using Various Pedagogical Styles to Unify the Learning Process*, in *120th ASEE Annual Conference and Exposition*. 2013: Atlanta, GA.
2. Berman, B., *3-D printing: The new industrial revolution.* Business Horizons, 2012. **55**(2): p. 155-162.
3. Wang, C., et al., *Topographical survey engineering education retrofitted by computer-aided 3D-printing.* Computer Applications in Engineering Education, 2018. **26**(6): p. 2116-2130.
4. Osswald, M., et al., *Facilitation of bronchoscopy teaching with easily accessible low-cost 3D-printing.* Trends in Anaesthesia and Critical Care, 2017. **15**: p. 37-41.
5. Blake, N. and F. Adam, *Integrating a 3-D Printer and a Truss Optimization Project in Statics*, in *2016 ASEE Annual Conference & Exposition*. 2016: New Orleans, LA.
6. Huang, T.-C. and C.-Y. Lin, *From 3D modeling to 3D printing: Development of a differentiated spatial ability teaching model.* Telematics and Informatics, 2017. **34**(2): p. 604-613.
7. Trimble. *SlketchUp for Web*. 2020 [cited 2020 Feb 25, 2021]; Available from: https://www.sketchup.com/products/sketchup-for-web.
8. MatterHackers. *Pulse XE - NylonX Advanced Materials 3D Printer*. 2020 [cited 2021 Feb 25]; Available from: https://www.matterhackers.com/store/l/pulse-xe-nylonx-advanced-materials-3d-printer/sk/MFG0HF92.
9. Fusion3Design. *F410 3D Printer*. 2020 [cited 2021 Feb 25]; Available from: https://www.fusion3design.com/f410-3d-printer/specs/.