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3D Concrete Printing of Pedestrian Arch Bridges

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ABSTRACT

Today, 11% of the global carbon emissions are associated with the materials and construction processes of structures. For purposes of construction, 3D Concrete Printing (3DCP) was proposed to help mitigate these carbon emissions significantly. Carbon emissions of construction is directly related to the amount of concrete used and the material used to create a viable concrete mix design. This document aims to determine the mix design necessary for a 3DCP pedestrian arch bridge, a possible design method to use, and how carbon emissions are affected by employing 3DCP. It is expected that the use of a supplementary cementitious material will replace Portland Cement, a new method of design will be used for 3DCP purposes, and that 3DCP related carbon emissions will be significantly lower than normal cast-in-place methods. Within the 11% of carbon emissions related to materials and construction is the concrete and cement industry. About 10% of the 11% is related to the concrete and cement industry, with 8% coming from Portland cement alone. Researched supplementary cementitious materials include: Alkali-Activated Metakaolin, Fly Ash, Slag, and Silica Fume. Out of the four, Alkali-Activated Metakaolin, Fly Ash, and Silica Fume were selected. A new method of design called the SMART Method, a fatigue analysis method of design, was determined to be the best candidate for the design of 3DCP structures since 3DCP and masonry structures are built similarly. Finally, it was discovered that a 44% decrease in carbon emissions was achieved using 3DCP rather than a normal cast-in-place method. To summarize, the use of 3DCP will have significant environmental benefits, saves material, use supplementary cementitious materials, and will soon be a recognized construction method for concrete structures.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Chapter 1

Concrete Mix Design

The concrete mix design for 3DCP is unlike all other typical mixes. 3DCP mix design requires some more thought in order for the mix to properly flow through the pumping system and must have the ability to be continuously built upon and support continuous layers of the concrete mix. In order to properly design a 3DCP, it is imperative to consider the following: flowability, extrudability, buildability, and potential clogging of the concrete mix. It is also important to understand the material components and properties. With all of this information a valid concrete mix design can be created.

Three-Dimensional Concrete Printing (3DCP) Considerations

Flowability is the ability for the concrete mix to flow through the pumping system. A concrete mix with high flowability is more suitable to flow through the pumping system because it is less viscous and more easily transferred through the pumps and pipes. It is also worth noting that low flowability could cause the pumping system to ramp up pressures within the pipes because the concrete must be continuously extruded onto the flat printing surface in order to construct 3DCP elements.

In effect, the concrete must be able retain its shape uniformly in order to properly extrude onto the printing surface. The material that comes out of the pumping system must also be able to properly lay on top of the previous layer, so a consistent and proper extrusion shape is required for proper construction of the 3DCP elements. Therefore, a high enough flowability is required to form a nice consistent extrusion of material, but also must be low enough to prevent the pumping system from failing due to astronomically high pressures. All while also having enough strength to hold up the preceding layer of concrete.

The ability of the concrete to hold up these continuous layers of material is known as buildability. The material that is used in the 3DCP must have the strength to provide enough resistance to hold up the layer being placed above it. This would mean that the material requires a certain amount of open time to set just enough so that the next layer can be printed on top without disrupting the below extrusion in any way.

Finally, it is important to note that there are many elements of the mix design that could potentially clog the pumping system. The biggest concern would be a low flowability of material causing the pumping system to potentially clog because the material is not transferring through the pipes properly. Another concern is if a fiber was to be added to the concrete mix design. A fiber has the potential to stick to the walls of the pipe at random angles which could cause a buildup of material inside the pumping system. Similarly, only fine aggregates should be used not only to prevent clogging, but to also prevent the extruded shape from being irregular.

Mix Components and Properties

Continuing on to the mix design components and properties, starting with binder material, aggregate, fibers, additives, and the W/C ratio. The binder is synonymous to cement material in the aspect that it is the paste that holds the mixture components all together through a chemical reaction with water. There are several supplementary cementitious materials that satisfy this component. The most known is Portland Cement, but for the purposes of reducing carbon emissions significantly, it is important that an environmentally friendly material is picked. All of the following materials can satisfy this binding function need: Metakaolin, Fly Ash, Slag, and Silica Fume.

Metakaolin is a low embodied energy material that will reduce the carbon footprint of the construction industry, and it still has the necessary mechanical properties as well as durability for printing 3DCP bridges. What makes it stand out from the rest of viable alternative binders is the notable ability to strongly resist acid, which would be desirable for resisting chemical weathering of the concrete elements (Rashad, A. M. (2013).).

Another supplementary cementitious material is fly ash, which is an extremely fine binder material that can flow into tight spaces effectively because of its incredibly small size. So the fresh properties of this binder material can be expected to be favorable when pumping through a 3DCP machine. Additionally, fly ash has the mechanical and durability properties necessary to be an effective binder material. The biggest advantage that fly ash has is that since it has such a fine particle size of .5µm-150µm, it can flow easier as a fresh material and it creates a highly tight bonding matrix, which gives the hardened material very low permeability. Again, an extremely low permeability will be significant for resisting freeze thaw cycles at which the material is exposed while being used in bridge applications (Siddique, R., 2003).

The next supplementary binder looked at was slag. Slag is a more average size particle, with respect to binders, at about 3µm that also has the mechanical and durability properties necessary for 3DCP bridge construction. However, it's very resilient to acid attacks similar to metakaolin, but shows signs of having a higher compressive strength than that of metakaolin (Bakharev, T. et. all, 2003).

Finally, silica fume exhibits similar properties to that of a high strength, high performance binder material. It has a very high early compressive strength, high flexural and tensile strength, modulus of elasticity, high electrical resistivity and low permeability. The particle size is also very fine like fly ash at <1µm, which gives it its naturally low permeability. However, high early compressive strength adversely effects the 28-day compressive strength, and therefore would be more useful in the mix for its buildability properties for 3DCP (Siddique, R., 2011).

The next component of the mix is aggregates. However, due to the extrudability factor and 3DCP pumping system a coarse aggregate should be negated from all possible mix designs, unless rightfully justified. Coarse aggregates could easily cause the pumping system to get clogged and will most likely misshape the extruded material from the nozzle of the machine. Fine aggregates, on the other hand, are an effective and efficient choice because of their smaller size, which leads to the conclusion that fine aggregates will be used for 100% of the aggregate material use since coarse aggregates can adversely affect the constructability, and shape of the final product. Therefore, a fine aggregate sand (0.25mm – 0.06mm) will be selected.

Another consideration is fiber reinforcement used primarily to reduce shrinkage in the concrete material, which prevents cracking at early stages of setting, ultimately increasing the durability of the material, but it can also increase some other mechanical properties. However, too much of it can cause the pumping system to clog as stated earlier, and should be carefully put into the mix to prevent this from happening.

Additionally, additives can be put into the mix design. These additives are most likely not going to be necessary for 3DCP purposes, but could help if needed. Superplasticizers are added to the concrete mixture design to help liquefy the mixture and make it more flowable in the pumping system. Retarders are used to increase the time the concrete needs to set, so if the mix design entails a very short setting time, then a retarder should be added to allow for more fresh material time. Comparatively, accelerators are used to decrease the time the concrete needs to set, so if the mix sets too slowly it could affect buildability of the 3DCP material.

The final necessity for every mix design is a W/C ratio, which can be manipulated to increase and decrease the flowability of the material and the reaction time of the binder material. Lower W/C ratios are typically preferred since the final product comes out stronger; however with the continuous concern for pumping and clogging of the 3DCP machinery, a slightly higher than preferred W/C ratio may be necessary.

Potential Mix Design

Keeping all of the previous information in mind, and after reading articles on tested mix designs used in 3DCP, a viable option becomes clear and more defined. For starters, we are focusing on designing a mix with low carbon emissions, good acidic defense, and low permeability for freeze/thaw cycle defense. In order to achieve low carbon emission, Portland Cement is instantly taken out because of the high carbon footprint it creates. Based on the remaining binders, metakaolin really stands out from the rest because it both provides excellent acidic defense and produces very low carbon emissions. In order to satisfy the final necessity, a choice of fine particle sized cementitious material will be provided. The additional binder will either be silica fume or fly ash. Le, T. T. et. all, 2012, give information about running several tests on concrete mix design for 3DCP. The run 5 trials containing 75% sand : 25% binder, 70% sand : 30% binder, 65% sand : 35% binder, 60% sand : 40% binder, and 55% sand : 45% binder respectively, each having a W/C ratio of .28. The binder consisted of 70% Portland Cement, 20% fly ash, and 10% silica fume. It was found that the final mix of 55% sand : 45% binder and W/C ratio of .28 had the best material properties for 3DCP. However, for the purpose of our mix design it is necessary to limit carbon emissions and maximize acidic defense. Therefore, in exchange for the 70% Portland Cement, it is appropriate to substitute it with metakaolin. More specifically, from the literature, it is found that alkali-activated metakaolin performs much better and inhibits much larger strength in compression.

To summarize, after running the numbers of the given mix design values, a final mix design comes out to have 49% sand (0.25mm – 0.06mm) + 40% binder + 11% water. Where the binder consists of 70% alkali-activated metakaolin, 20% fly ash, and 10% silica fume. Additionally, if a fiber reinforcement is added to reduce temperature and shrinkage effect of the concrete, then a new combination can be used, 48% sand (0.25mm – 0.06mm) + 40% binder + 11% water + 1% fiber. If a fiber is used then it is best to provide steel fiber reinforcement, or a hybrid fiber reinforcement of steel and synthetic fibers since hybrid fiber is less expensive than solely steel fiber reinforcement.

Chapter 2

3D Printed Bridges in Use

Several 3D Printed Bridges are in use today, but are simply for pedestrian use only. The first of these bridges to be built was a plastic 3D printed bridge located in China. Although this is not a 3DCP bridge the design process and fabrication are very useful to understand. Some actual 3DCP Bridge are located in Baoshan, China and another in the Netherlands. Learning from each of these designs an idea for proper design and construction can be acquired.

Plastic 3D Printed Bridge

Design Process

Most of the information regarding this bridge is more useful for the design process. The design of the plastic 3D printed bridge is taken as a three step process. The first of the steps is using the catenary equation. The catenary equation is an equation that can be used to determine the shape of a cable being suspended between two points in a state of pure tension. Theoretically, by flipping the shape of the line produced using the catenary equation, a shape can be produced to be in a state of pure compression. By using this shape the bridge will be designed to prevent bending failure and all loads can be transferred through the curve as an axial force. By keeping all forces transferred as axial, it reduces the necessity for all sources of reinforcing steel.

The second step in their design process is to use a computer based program call Rhino3D to optimize the topology of the design. By using the topology optimization process a much lighter structure can be obtained; the lighter structure is obtained by simulating loading combinations and observing where material experiences negligible stresses and forces. Essentially, all inefficient material is being taken out of the design of the structure. There are three key elements in the topology optimization process, object function, design variable, and boundary conditions. The object function in this case is to minimize the structure's weight. The design variable is the limitation of the structure's stiffness. The boundary conditions include load region, load applied, support types, etc.

The final step in the process is to use finite element analysis of the structure, which step is absolutely necessary to finalize the design as it ensures that the previous step, topology optimization, is safe, and to ensure the bridge is not exposed to high local concentrations of stresses. This step will also allow the designers to properly segment the bridges for constructability and transportation purposes (Yuan, P. F. et. all, 2018).

Fabrication and Limitations

After design was complete, the use of three 6-axis robots were used to print the final product. Limitations of the design include approximate values, and approximations based on 2D analysis rather than 3D reality (Yuan, P. F. et. all, 2018).

Baoshan 3DCP Bridge

Design Parameters

Before leading into the design of the bridge, it is important to understand the design parameters and which one is most important. Verbatim from the *Fabrication and Application of 3D-Printed Concrete Structural Components in the Baoshan Pedestrian Bridge Project*.

1. "According to the local geology, an abutment was set on each side of the pool, based on which the span and maximum side thrust of the bridge was determined;"
2. "Bridge gradient is limited to less than 8% considering pedestrian comfort;"
3. "Material performance data;"
4. "Preliminary design of handrails and deck panels is developed first to estimate the dead load of the bridge;"
5. "Width of the bridge is determined based on the surrounding roads."

Out of the following design parameters, the most notable one is the first. This is a parameter that can be used for all 3DCP bridges (Xu, Weiguo et. all, 2020).

Design

The structure is designed to be a circular, segmented arch bridge based off of the ancient stone arch Anji Bridge in Zhaoxian, China. A structure simulation is conducted using two software known as Grasshopper and Midas, using these software allows the designer to optimize the design of the arch and its voussoirs, which is the segmented blocks shape, which could be described as a "keystone" shape. A total of 44 voussoirs are to be staggered in 4 rows, with each voussoir having an internal shape of a double-X (Fig.1) (Xu, Weiguo et. all, 2020).

Figure 1. Printing process of concrete components. (Xu, Weiguo et. all, 2020).

Printing Process

The printing system used consisted of six components, a mixer for the concrete, a pump for extrusion, a six-axis robotic arm used to print, a special printing tool head that is described to have a cylindrical storage silo with an auger flight inside to prevent clogging of material, a controller, and programming and controlling software to make the robotic arm print the correct shape. It was noticed that the printing of concrete around the edges of the design needed to be printed slower than the other elements of the design because it can be misshapen if printed too fast (Xu, Weiguo et. all, 2020).

Construction Process

For the construction of the bridge, first and foremost, each individual component of the bridge was inspected and moved to the construction site. Four steel arch angles were installed as temporary supports for the voussoirs. Each voussoir was lifted by crane to its proper location in the final construction of the bridge. A real-time monitoring system with vibrating wire stress sensors and high-precision strain monitors were installed to collect data about the structure's sustainability and strength. After completion, it was learned that the cost of construction was roughly 2/3^{rds} the cost of a typical bridge that would have taken its place had it not been a 3DCP bridge (Xu, Weiguo et. all, 2020).

Netherlands Box Segmental, Post-Tensioned, 3DCP Bridge

Design

The cross-section of this bridge is a series of 2 liter bottle shapes connected together and alternating from right-side-up to up-side-down continuously connected at the bottom by a straight line of concrete (Fig. 2). The shape provided for this design enables the bridge to resist the bending moment and shear forces applied to the structure. On the ends, bulkheads were provided on top of traditional abutments. These bulkheads were used to provide the post-tensioned cables with a place to anchor at the ends so the post-tensioned cables can work properly and put the bridge cross-section in a state of compression. These cables were also designed to be tightened at any time to prolong the life against the everlasting effects of creep. Steel parapets were also provided on each side of the bridge essentially to be a set of railings (Theo A. M. et. all, 2018).

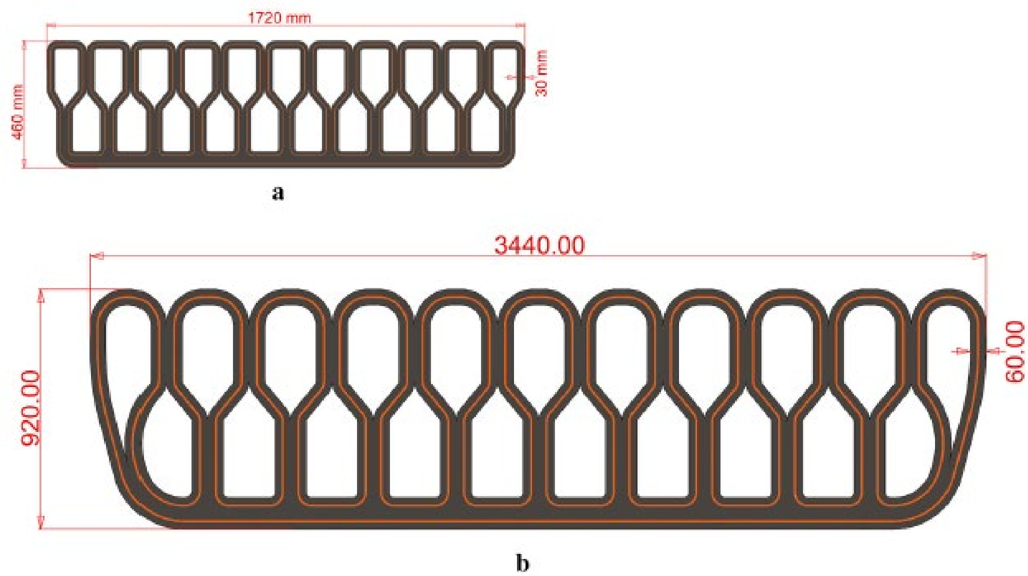

Figure 2. Print paths of the 1:2 scale model for testing (a) and the actual bridge section (b). The optimised pattern of the latter with regard to the former saves 4% of print path length. (Theo A. M. et. all, 2018)

Printing Process

The printing process is similar to all the prior printing processes in the bridges mentioned above. However, unique to this project was that a cable was introduced in the concrete printing process. With the use of a hybrid down-flow, back-flow nozzle, which allowed a cable and concrete to properly be extruded from the nozzle simultaneously. With their unique design, the cable can correctly be placed in the middle of the concrete extrusion to allow for full bonding between each consecutive layer of concrete and between the cable and concrete interface. Similar to the Baoshan Bridge, it was noticed that at curved portions of the bridge a reduced speed is necessary to prevent misshapen extrusions (Theo A. M. et. all, 2018).

Construction Process

The construction process starts off by laying 2 of the 6 elements of the 3DCP portion of the bridge onto a wooden scaffolding. This wooden scaffolding is to keep all the elements in place while the epoxy-based interface material is added to connect the individual elements. As this is happening, the team is simultaneously aligning two elements to ensure there is minimal deviation between the two elements positions. They then proceed with the same process to connect the next element until all 6 are connected. Some time is elapsed before adding the bulkheads of the design to ensure the interface material has set properly. The post-tensioned cables are then fixed to the bulkheads with typical post-tensioned construction processes. Once the bridge is completely assembled, the entire bridge is moved by crane onto the abutments and tested on site using large water-filled containers as a final test (Theo A. M. et. all, 2018).

Takeaway

From the research on 3D printed bridges in use today, a proper design procedure and construction procedure can be defined. The entire design process expressed in the plastic bridge design seems to be very fitting. First by using the catenary equation, we can define a shape of the arch required for design. That is followed up with topology optimization to reduce material that is inefficient to the design and minimize the weight of the structure overall. Ending with verifying the design using finite element analysis to ensure the design is safe and does not have any localized stresses and to figure out where to segment the bridge efficiently. For construction, it is absolutely necessary to have some form of steel shoring to keep the bridge in place while connecting elements together. A proper interface material must be designed to make the interface between elements smooth. A smooth interface is essential to ensure that the interface between elements does not induce localized stresses that could be detrimental to the integrity of the structure. Elements will need to be placed by crane, or at least that appears to be the common theme in constructing the 3DCP bridges.

Notable information:

1. The use of the extrusion tool mentioned in the Baoshan Bridge would be valuable to projects that would require a larger granular aggregate as their unique auger flight nozzle prevents clogging
2. The use of the hybrid back-flow, down-flow nozzle in the Netherlands Bridge can be an effective way to add cable wire elements to the internal aspect of each layer of the 3DCP process.

Chapter 3

Masonry Arch Bridge Design

In order to come up with a process for designing a 3DCP arch bridge, research has been conducted to correlate masonry arch bridge design to 3DCP arch bridge design. The two are similar in respect to smaller components being combined together to create one single structure; masonry is made of small, individual bricks, stones, or CMU's, and 3DCP would be made of larger, individual 3DCP segments. Both would bonded together by some sort of mortar or epoxy type material to complete the structure. Since both are similarly constructed, the design process of both should also be similar, if not the same.

Euro Code

Masonry arch bridge design has never had a very structured and formal set of steps to design the final product, and most of the work presented on design is experimental and theory based. However, the CD 376 Euro Code published in 1991 established a design process that was used for years. This code is similar to those found on concrete and steel design and employs many of the same steps and procedures to get to a final design. These design codes all have one thing in common and that is they generally focus on the ultimate limit state (ULS) of the design. While ultimate state design method is the conventional approach for concrete and steel design because of the high level of understanding of their material properties, for masonry systems, particularly the masonry arch bridge design, it may not be an effective process because masonry materials are not heavily researched, relatively. For example, ACI 318 first edition was originally release in 1910 for design of concrete, while the first edition of what is now known as TMS

402/602 was release in 1973. The difference of 63 years lets you know how much less research has been put into masonry codes, which is why design of masonry is based on experimental and empirical methods more so than concrete. Due to the lack of research and understanding of the masonry material properties, specifically the uncertainty of the mortar joints, it is more appropriate to design based on the permissible limit state (PLS) design method in addition to the ULS (Melbourne, C. et. all, 2007).

SMART Method

The PLS design focuses more on the modes of fatigue failure that can occur over several millions/billions of stress cycles. Some modes of failure are, but not limited to, four-hinge mechanism formation, ring separation, horizontal displacement in the abutment, and failure of radial mortar joints. The PLS is typically the controlling factor in masonry arch bridge design because modes of failure associated with the PLS will likely occur before any ULS failure modes occur. The reason most ULS failure modes do not occur first is due to the fact that the mortar joints in masonry arch bridges create a discontinuity in the material strength. Due to this lack of understanding in designing for a PLS, the Sustainable Masonry Arch Resistance Technique (SMART) method was introduced (Melbourne, C. et. all, 2007).

The SMART method proceeds as follows:

1. Determine the geometry of the bridge and form of construction
2. Determine project loadings
3. Determine materials to be used.
4. Perform structural analysis

5. Determine ULS
6. Determine PLS
7. Assess carrying capacity and life expectancy with the use of S-N curves (S-N curves are graphs that show stress vs. the number of cycles until failure)

Step one begins the process by coming up with a reasonable geometry for the final product and a form of construction, this can range from using wooden supporting arches or steel arches depending on the weight of the masonry being held up. Step two then introduces the preliminary dead, live, snow, wind, and earthquake loads that are applicable to the design of the bridge. Step three is a determination of the materials being used, whether that be CMU or clay brick, and the type of mortar mix being used. Step four, structural analysis, is to complete calculations of maximum bending moment, maximum shear force, maximum axial load, shear strength of materials, bending moment capacity, etc. After finding these values from the structural analysis, step five is to compare these values to the ULS's such as shear failure, punching shear failure, bending moment failure, etc. Similarly, step six compares the structural analysis values to those found to be PLS values. The PLS values are found with the use of S-N curves, which are significantly hard to create because it is all based on experimental analysis of the finished bridge itself. Therefore, the permissible stresses are compared to the safe capacity of masonry, currently assumed to be 50% of the ultimate load carrying capacity of the bridge. Step seven is the assessment of the life expectancy of the bridge. The life expectancy is found with the use of the S-N curves and Miner's Rule. Miner's rule states that a certain amount of useful fatigue life, of anything, is directly proportional to the number of repeated stress cycles experienced at a certain stress level. Again, the determination of this lifecycle is very hard to obtain because it us only found in conjunction with the S-N curves (Melbourne, C. et. all, 2007).

S-N Curves

S-N curves are graphs that compare a minimum stress level that incurs fatigue to the number of cycles required to cause the minimum stress level to increase to a higher value. These graphs can then be used to determine when the stress level will reach the PLS value of stress. At this stress level, a fatigue failure will form and the structure will be structurally determinate and unsafe to continue using. Unfortunately, these curves are hard to model because they are based off of experimental data. As found in Joan R. Casas 2010 article, an equation that can be used to find these curves for plain concrete can be used. The equation proposed takes into account the minimum value of repeated stress, and is as follows:

$$S = A \times N^{-B(1-R)} \tag{1}$$

Where, S is the ratio of maximum loading stress to the strength σ_{max}/σ_u, R is the ratio of minimum stress to the maximum stress $\sigma_{min}/\sigma_{max}$, and A and B are coefficients determined by Table 1, where SF is the survival probability, synonymous with confidence level (Casas, J. R., 2011).

Table 1. Parameters of fatigue Eq. (1) depending on the required confidence level

SF	A	B
0.95	1.106	0.0998
0.90	1.303	0.1109
0.80	1.458	0.1095
0.70	1.494	0.1023
0.60	1.487	0.0945
0.50	1.464	0.0874

Proposed Design Process

After understanding the interest in designing masonry arch bridges for the PLS, an appropriate design process for 3DCP arch bridges can be understood. An example of the SMART Method is run through in the article by Melbourne, C. et all 2007 p. 7-10. The process is the same as what is described in the subchapter "SMART Method" of this paper, except numbers are used to solve the design.

To start, the masonry arch bridges were all designed to withstand ULS type failures by following standard practices found in the CD 376 Euro Code published in 1991. Since 3DCP of arch bridges would be built in a similar way, as in both masonry and 3DCP are built up in segments and glued together by some form of mortar, it can be observed that designing for the ULS still applies. However, given that 3DCP bridges are segmental, they would also require more care in design like the masonry arch bridges. Therefore, incorporating design for PLS is crucial for structural safety of 3DCP arch bridges. By understanding these similarities in material construction, I will propose a design process for 3DCP that is the SMART method, but with extra steps, as follows:

1. Determine the geometry of the bridge and form of construction
2. Determine project loadings
3. Use approved mix design
4. Perform structural analysis
5. Determine ULS
    a. If design does not resist ULS failure, restart and adjust geometry as needed
6. Determine PLS
    a. If design does not resist PLS failure, restart and adjust geometry as needed

7. Assess carrying capacity and life expectancy with the use of S-N curves
    a. Obtain S-N curves using Eq. (1) and Table 1.
    b. Ensure life expectancy of 100 years or more
    c. If life expectancy is lower, restart and adjust geometry as needed.

The first change to the SMART method is the determination of materials. Since 3DCP needs more fine aggregates to prevent clogging in the system it is appropriate to already use a mix design that is approved to work in the system. Preferably, the mix design identified earlier should be used. After comparing values to the ULS and PLS, the geometry of the design should be adjusted to prevent these types of failures in the final product. A suggestion would be to increase the materials extrusion cross-section to lessen internal stresses. Create S-N curves using Eq. (1) and Table 1 that follows the 95% confidence level values. Since the design process is new to 3DCP a higher confidence level is more conservative, and should be used until more knowledge of 3DCP arch bridge design is introduced. My final remark is to design for a 100 year lifespan or more, this is so the bridge can survive for a person's entire life.

Chapter 4

LCA of Normal Construction Bridge vs. 3DCP Bridge

Parameters

To promote the use of 3DCP, a Lifecycle Assessment (LCA) was conducted. The LCA is an evaluation of embodied energy or carbon emissions associated with all equipment, material, and maintenance of, in this case, the bridge. For the purpose of this research, carbon emissions were evaluated for all four stages of the bridges life: Concrete Manufacturing, Construction, Maintenance and Use, and End of Life. Stage 1: Concrete Manufacturing deals with the materials, and transportation of those materials, to create a concrete matrix. Stage 2: Construction is what equipment is needed to construct the bridge, and how far the ready materials need to be transported. Stage 3: Maintenance and Use covers all of the equipment and transportation associated with maintaining an operable bridge. Finally, Stage 4: End of Life deals with how the bridge is demolished and where it is transported afterwards. The results will be important because they help visualize the significant difference in carbon emissions of normal versus 3DCP constructed bridges. Please note that this LCA was conducted using the free online program called openLCA using the IMPACT+ (Default Recommended Midpoint 1.29) database and reported all values in units of $kgCO_2$ (GreenDelta GmbH, 2021). Within OpenLCA users must create flows that would define a material, machine, transportation method, etc. These flows would then be placed into a process which would allow the user to define what emissions are related to what process, such as how much carbon emissions are released due to transportation of an aggregate, emissions related to using a hose for water, emissions related to 3DCP, etc. Finally the user could create a product system to create a flow chart of steps taken to come to finalize a stage in the process and output results in $kgCO_2$.

In order to come up with estimations for concrete and transportation carbon emission values, a location for the bridge was selected to be at the Penn State University Arboretum. The bridge that is currently roughly 120' long, 4.5' wide, and 10' tall. An arch bridge made of 3DCP segments, and compared to a normal cast-in-place construction. A rough estimate of concrete volume used is $200yds^3$ for normal construction and $110yds^3$ for 3DCP construction. This is based off of a visual estimation of a 45% material reduction for 3DCP, and on approximate dimensions of 120', length, 4.5', width, and 10', height. In this scenario, it is assumed that all raw materials will be purchased and shipped to Penn State's Civil Infrastructure Testing and Evaluation Laboratory (CITEL) where it will be 3DCP into segments, and then ready-to-construct segments will be transported from CITEL to the Arboretum (4mi). All other necessary equipment is assumed to be located at CITEL, and for maintenance purposes a Type A Rapid Repair Material will be used. Finally, the concrete mix discussed in Chapter 1 will be used for construction.

Transportation distances will be as follows:

1. Alkali-Activated Metakaolin / Fly Ash / Silica Fume
    a. Transported from R-E-D Industrial Products to CITEL (140mi)
2. Sand
    a. Transported from Hanson Aggregates to CITEL (36.4mi)
3. Concrete Mix / 3DCP Segments
    a. Transported from CITEL to Arboretum (4mi)
4. Type A Rapid Repair Material

a. Transported from Centre Concrete to CITEL (6.4mi)

5. Demolished Materials

a. Transported to Wayne Township Landfill from Arboretum (44mi)

Note that all transportation values are based on 0.3kgCO_2/tonne of material (Smith, S. H., & Durham, S. A., 2016).

Stage 1: Concrete Manufacturing

To begin, each material in the mix design generates a different amount of carbon emissions specific to the process of obtaining / creating them (Table 2). For normal construction, mixing of materials was complete based on the value of 0.0636 kgCO_2/tonne of material (Sun, H., & Park, Y., 2020). For 3DCP construction, mixing is considered in Stage 2 during the printing process with a value of 9.88 kgCO_2/yd^3 of material (Mohammad, M. et. all, 2020). Note that the printing process also includes mixing, pumping, and the robotic arm extruder. For both normal and 3DCP construction, refer to Table 3 for material volume distribution. (O'Brien, K. R. et. all, 2009) (Maddalena, R. et. all, 2018) (Korre, A., & Durucan, S., 2009) (Botto, S., 2009). Reference Figure 3 and Figure 4 for the process flow chart of Stage 1: Concrete Manufacturing for 3DCP construction and normal construction, respectfully.

Table 2. Carbon Emission Equivalent for Mix Design Materials

Material	Carbon Emission Equivalents [$kgCO_2$ / tonne]
Alkali-Activated Metakaolin	236
Fly Ash	0.006
Silica Fume	$7x10^{-6}$
Sand (0.25mm-0.06mm)	2.39
Water**	$9.10x10^{-4}$
** Measured in $kgCO_2$ / 1.5L	

Table 3. Concrete Mix Material Volumes for Normal and 3DCP Construction

Material	Normal Volume [yds^3]	3DCP Volume [yds^3]
Alkali-Activated Metakaolin	56	30.8
Fly Ash	16	8.8
Silica Fume	8	4.4
Sand (0.25mm-0.06mm)	98	53.9
Water*	22	12.1
Total	200	110

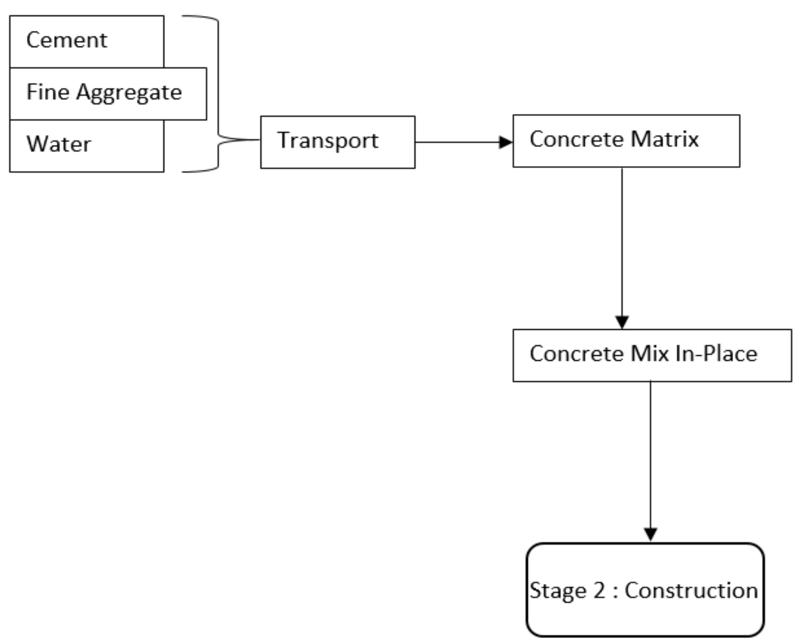

Figure 3. Stage 1: Concrete Manufacturing Process Flow Chart for 3DCP Construction

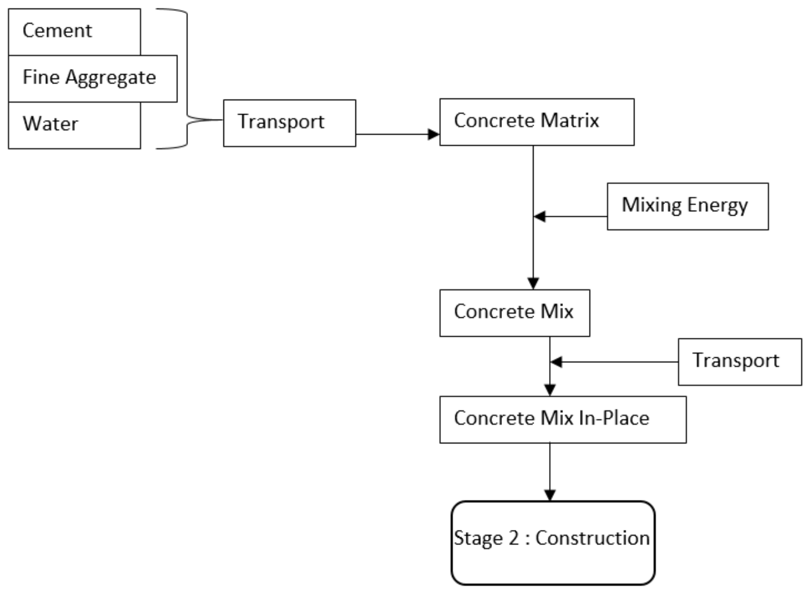

Figure 4. Stage 1: Concrete Manufacturing Process Flow Chart for Normal Construction

By simply observing the different process flows of each type of construction it can be inferred that the 3DCP construction will generate less CO_2 emissions. The result values are shown in Table 4 and graphically shown for ease of comparison in Figure 5.

Table 4. Stage 1: Concrete Manufacturing Carbon Emissions

Process / Material	3DCP [$kgCO_2$]	Normal [$kgCO_2$]
Alkali-Activated Metakaolin	4943	8988
Fly Ash	2.20E-02	4.00E-02
Sand_Fine Aggregate	129	234
Silica Fume	3.08E-06	5.60E-06
Transport Alkali-Activated Metakaolin	1543	2806
Transport Fly Ash	268	488
Transport Sand_Matrix and In-Place	1228	2233
Transport Silica Fume	32	59
Transport Water	19	35
Water	6	10
Total	8169	14853

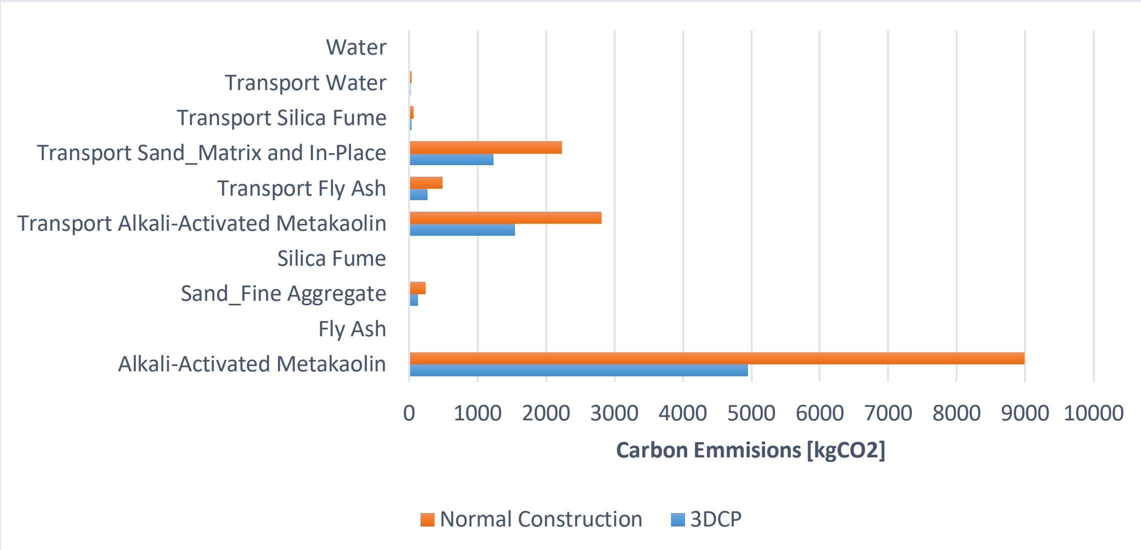

Figure 5. Stage 1: Concrete Manufacturing Carbon Emissions

As expected the results are in favor of 3DCP, primarily due to the 45% reduction of materials necessary for construction. It is apparent that the Alkali-Activated Metakaolin is a significant factor in the carbon emissions: had Portland Cement been selected, the carbon emissions of the binder would have increased 70%. Bringing this into the discussion shows how significant it is to use Metakaolin rather than Portland Cement when it comes to protecting our environment.

Stage 2: Construction

Stage 2 deals with the getting all of the concrete into place. In order to do that for normal construction, a mixer truck is necessary to transport the concrete to the site, but pre-printed segments will be transported to site for 3DCP construction. Mixer trucks emit a total of 1989 kg CO_2/yd^3 of material; these emissions come from the power necessary to continuously mix the concrete in the back of the truck and is based off of an average of values (Sun, H., & Park, Y., 2020). The concrete is the poured into the formwork, typically a wooden material for cast-in-place construction that can only be reused up to 10 times. Formwork also has innate emissions in its processing lifetime and emits 588.7kgCO_2/yds^3 of material (Dong, Y. H. et. all, 2015). 3DCP construction starts off with printing the material at CITEL and is then transported on site to be put together. The printing process emits 9.88kgCO_2/yds^3 of material printed (Mohammad, M. et. all, 2020). It was unknown how much the 3DCP formwork would emit, so it was assumed that pre-cast formwork was used to put the 3DCP in-place. The pre-cast formwork is steel rather than wood and can be reused 100-200 times. This type of formwork was found to generate 529.05kgCO_2/yds^3 of material (Dong, Y. H. et. all, 2015). The formwork carbon emission value of the 3DCP segments at the completion of Stage 2 is most likely dramatically over estimated, but for representational purposes will be used. Reference Figure 6 and Figure 7 for the process flow chart of Stage 2: Construction for 3DCP construction and normal construction, respectfully.

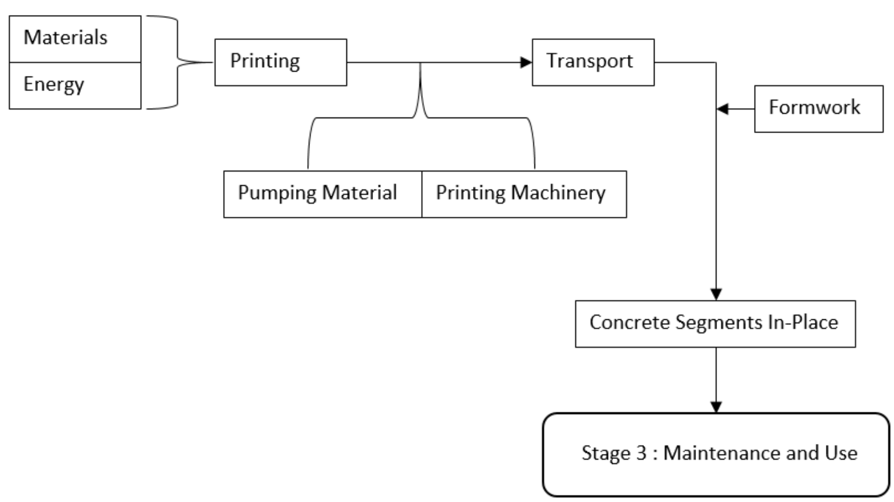

Figure 6. Stage 2: Construction Process Flow Chart for 3DCP Construction

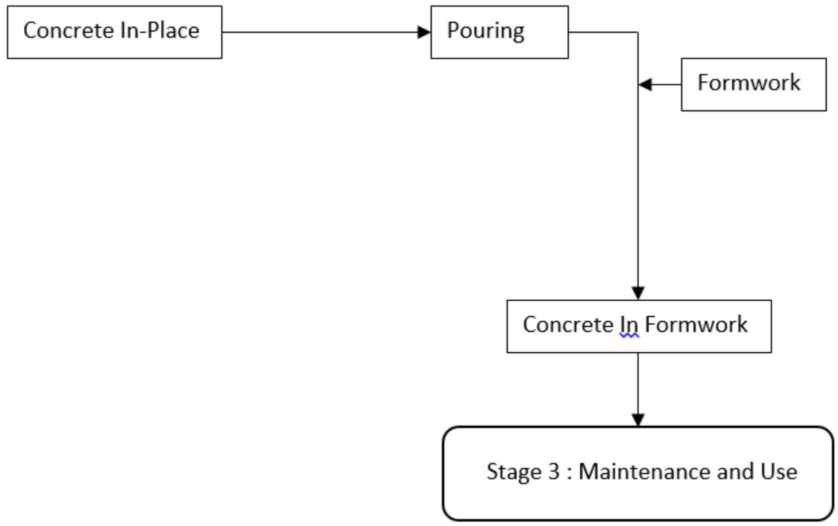

Figure 7. Stage 2: Construction Process Flow Chart for Normal Construction

The carbon emission results of Stage 2: Construction are shown below in Table 5 and graphically shown for ease of comparison in Figure 8.

Table 5. Stage 2: Construction Carbon Emissions

Process / Material	3DCP [kgCO_2]	Normal [kgCO_2]
Printing Process	173723	--
Mixing Concrete Matrix	--	18484
Transport 3DCP Segments	192	--
Mixer-Truck	--	397800
Formwork	58196	117740
Mixing / Printing Total	173723	416284
Total	232110	534024

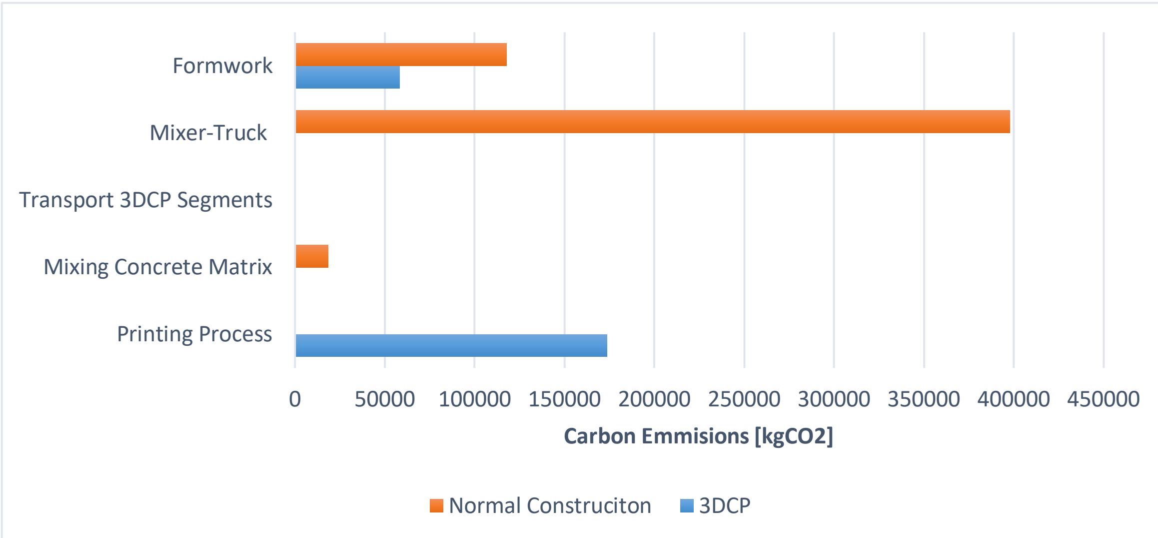

Figure 8. Stage 2: Construction Carbon Emissions

As seen above graphically the values are still in favor of 3DCP significantly. Please take note that the emissions of Mixing / Printing in Table 3 is representative of the Printing Process for 3DCP, but Mixing Concrete Matrix and Mixer-Truck for normal construction. By doing this, it can be easier to see that normal construction produces over 2x the amount of carbon emissions than 3DCP.

Stage 3: Maintenance and Use

Stage 3 is for maintaining the bridge throughout its entire life time. Since this is a pedestrian arch bridge, see Figure 9, the bridge will be inspected and maintained every 2 years as stated by the Pennsylvania Department of Transportation. Given that the bridge is a low-threat to human life if failure occurs, minimal maintenance and repairs will suffice for keeping the bridge in good condition. At a minimum, the bridge will need to be power washed clean and Type A

Rapid Repair Material will be used to fix cracks. The power washer was determined to be run at 8 gallons per minute and consumes 1 gal of gasoline per hour. Liquid gasoline emits 2.87 kgCO_2/gal (Sudiro, M., & Bertucco, A., 2009). Values for Type A Rapid Repair Material could not be found, so only transportation of the material is accounted for. Although the creation of the repair material carbon emissions was not found, it should not cause significant changes in the final values because maintenance and use is anticipated to be the smallest portion of the total emissions. Reference Figure 10 for the process flow chart of Stage 3: Maintenance and Use for all types of construction.

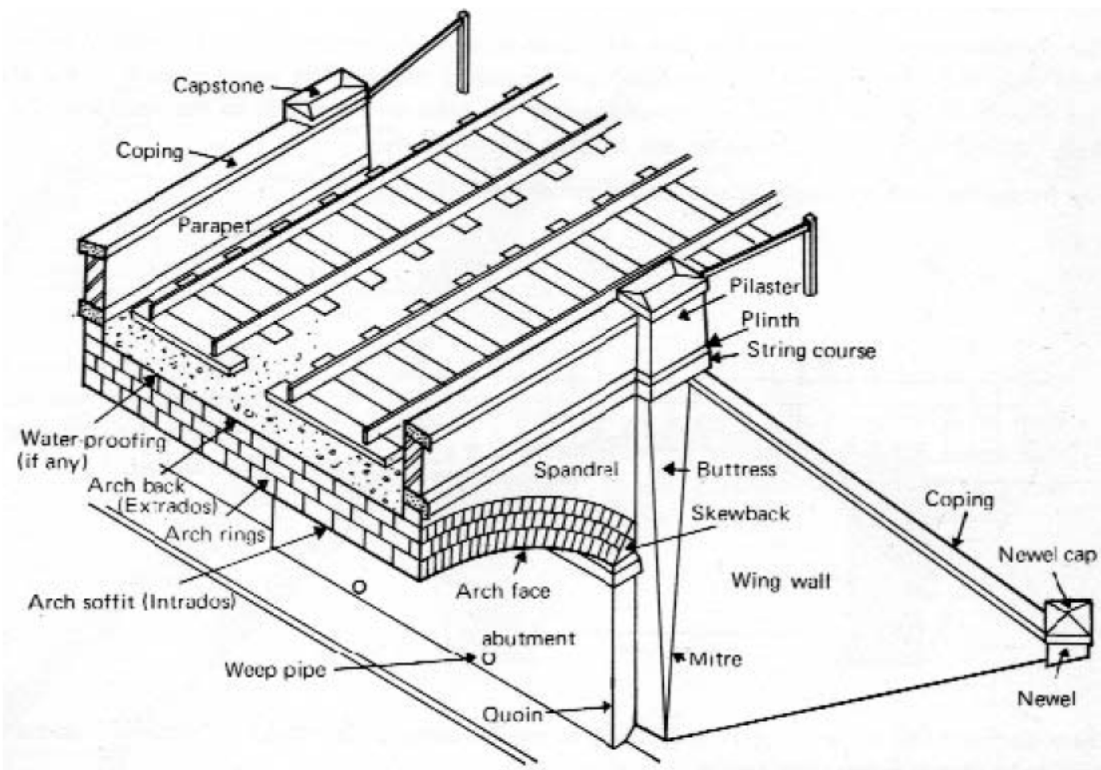

Figure 9. Typical arch bridge construction Melbourne, C. et. all, 2007

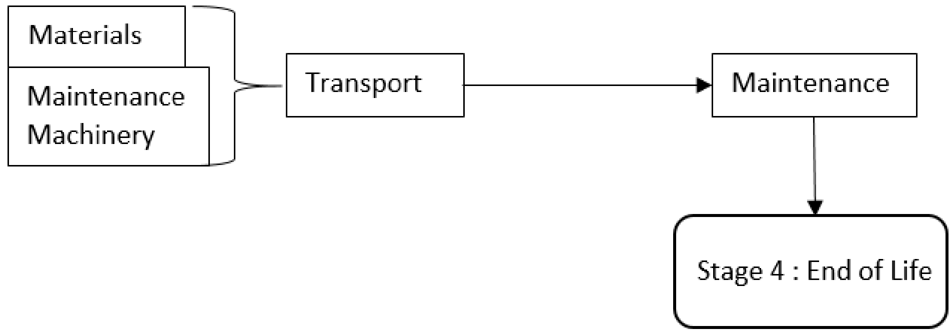

Figure 10. Stage 3: Maintenance and Use Process Flow Chart for All Constructions

The resulting carbon emissions of Stage 3: Maintenance and Use are shown below in Table 6 and graphically shown for ease of comparison in Figure 11.

Table 6. Stage 3: Maintenance and Use Carbon Emissions

Process / Material	3DCP [$kgCO_2$]	Normal [$kgCO_2$]
Maintenance Machinery Gasoline	77.5	51.7
Transport Maintenance Material	39.0	39.0
Transport Water	102.1	68.1
Water	30.2	20.1
Total	249	179

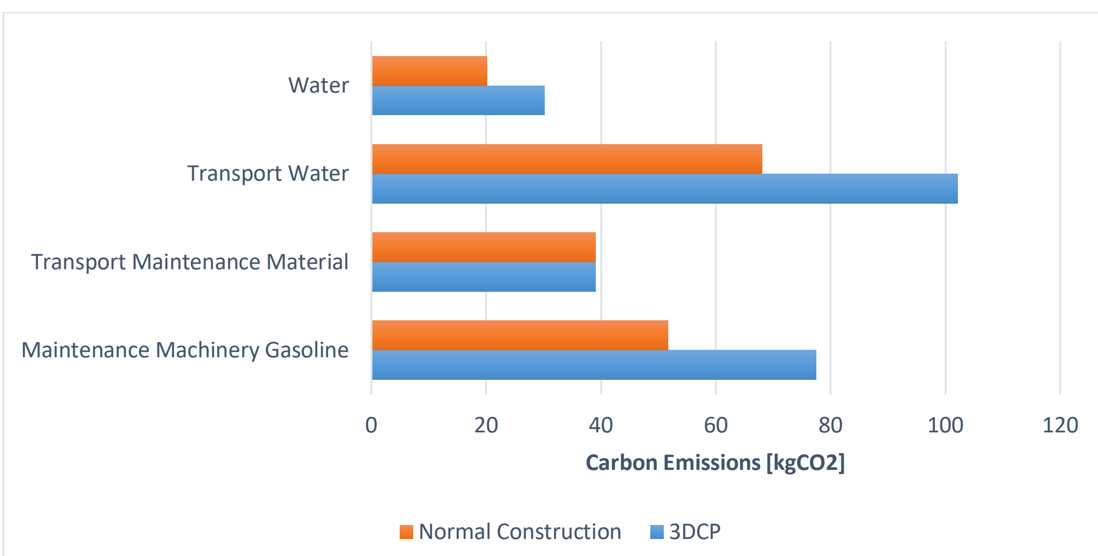

Figure 11. Stage 3 Maintenance and Use Carbon Emissions

Notice how for maintenance and use there is a clear change in favor of normal construction. The situation occurs because a 3DCP bridge will have more exposed surface area. This is due to the concrete optimization to reduce material unnecessary for structural stability. Again, the Maintenance and Use stage is fractional compared to the other stages of the process, so spending more emissions on maintaining a bridge is worth it.

Stage 4: End of Life

The final stage is the End of Life where the bridge structure gets destroyed and transported to either a recycling facility or a landfill. For ease of calculations, it is assumed that all demolished materials are transported to a landfill and not recycled. There are several different methods to demolish a structure, but the most fitting for the pedestrian arch bridge is by using a Jaw Crusher machine (Abudayyeh, O. et. all, 1998). The Jaw Crusher generates 0.28kgCO_2/tonne of material crushed (Mah C.M. et. all, 2017).Using conversions and density values of all the materials used, 1440kg/m^3 for Sand, 890kg/m^3 for Alkali-Activated Metakaolin, 540kg/m^3 for Fly Ash, 130kg/m^3 for Silica Fume, and 1000kg/m^3 for water at STP, it is determined that a total of 290,632kg of material was used for normal construction and 159,848kg of material for 3DCP construction. This material is then loaded onto a truck and transported to the nearest landfill. Reference Figure 12 for the process flow chart of Stage 4: End of Life for all types of construction.

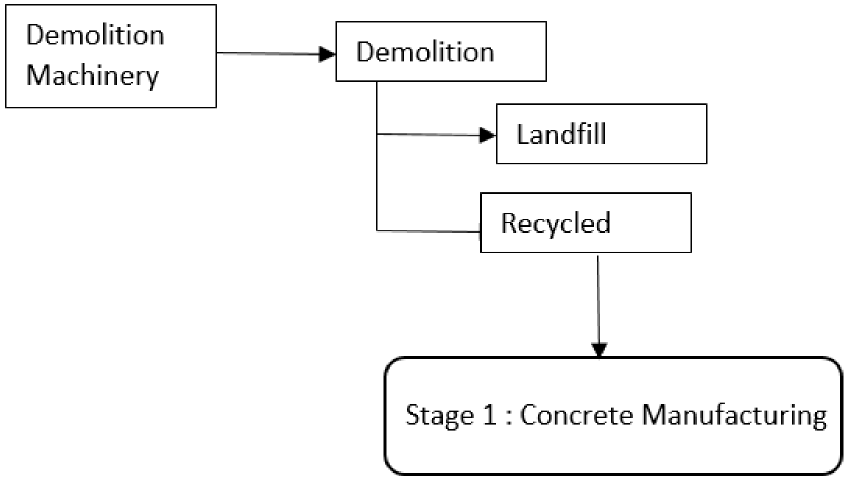

Figure 12. Stage 4: End of Life Process Flow Chart for All Constructions

The resulting carbon emissions of Stage 4: End of Life are shown below in Table 7 and graphically shown for ease of comparison in Figure 13.

Table 7. Stage 4: End of Life Carbon Emissions

Process / Material	3DCP [$kgCO_2$]	Normal [$kgCO_2$]
Demolition Machinery	45	81
Transport Demo to Landfill	2110	3836
Total	2155	3918

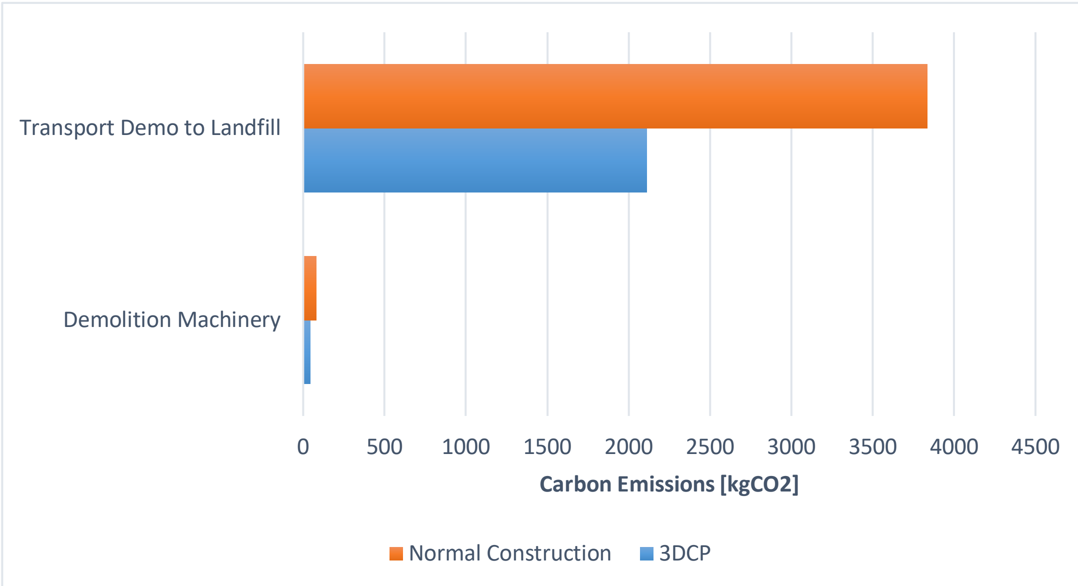

Figure 13. Stage 4: End of Life Carbon Emissions

Finally, the end of life stage is in favor of the 3DCP construction process because the 45% reduction of materials is significant throughout the life of a 3DCP structure.

Conclusion of LCA

In order to see what the most carbon expensive stage is, an evaluation of the total values is presented below (Table 8, Figure 14). What is observed is that Stage 2: Construction is the most expensive stage in the process which is attacked by 3DCP significantly. The whole point of 3DCP is to reduce the amount of material necessary for structures to be complete. Overall a 44% reduction in carbon emissions was obtained. To reiterate, by reducing materials used by 45%, a 44% decrease in carbon emissions will result.

Table 8. All Stages Totaled Carbon Emissions

Stage Label	3DCP [$kgCO_2$]	Normal [$kgCO_2$]
Stage 1: Concrete Manufacturing	8169	14853
Stage 2: Construction	232110	534024
Stage 3: Maintenance and Use	249	179
Stage 4: End of Life	2155	3918
Total	242683	552974

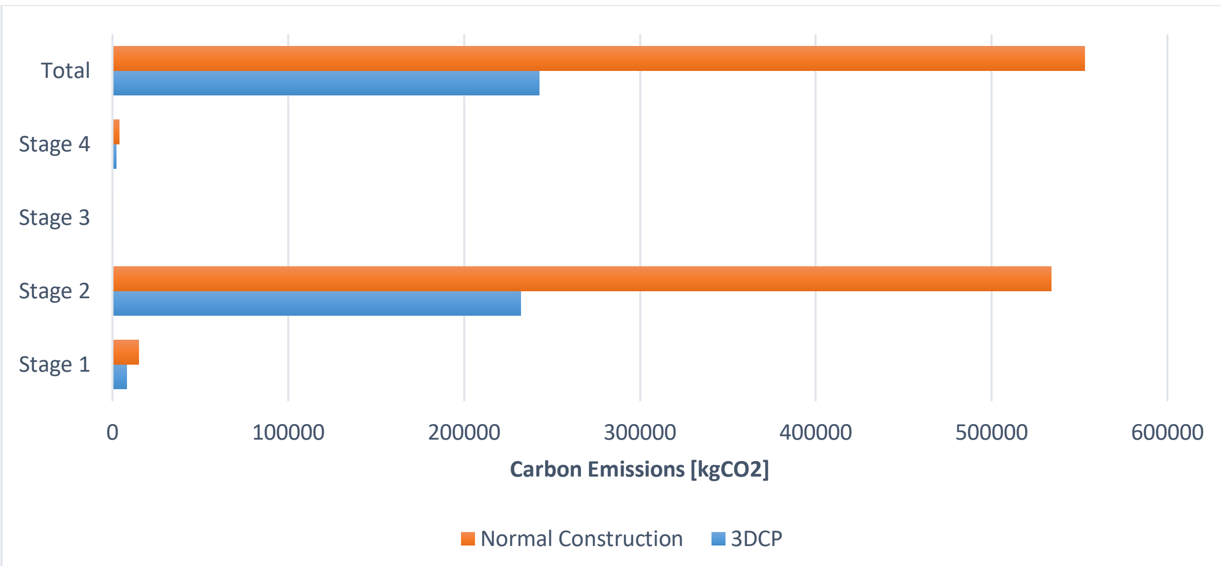

Figure 14. All Stages Totaled Carbon Emissions

Using OpenLCA did have some limitations as a free database was selected that had minimal process flows premade and available. This leads to more research to find carbon emission values for each stage. These carbon emission values were based off of some case studies and may not represent the overall average of carbon emissions for each step. With further and more in-depth study, a stronger database can be obtained, which would lead to more up-to-date product systems, while generating more realistic results. These results were also based on an estimation of bridge size and 3DCP reduction capabilities. The reduction capabilities of each bridge is unique and could have been less, or more depending on the loading conditions it would experience over its lifetime. Overall, for the purpose of this research, the LCA was generated to provide incentive towards 3DCP structures and was able to express how carbon emissions are reduced when 3DCP construction is employed.

Chapter 5

Conclusion

In conclusion, 11% of the global carbon emissions are associated with the materials and construction processes of structures. As a way to decrease this percentage, 3DCP should be employed everywhere when the technology is available to do so. 3DCP has the ability to reduce carbon emissions by 44%, as seen in the LCA conducted in Chapter 4, but it requires a more tailored concrete mix design due to technological limitations. The proposed mix design consists of 49% sand (0.25mm – 0.06mm) + 40% binder + 11% water, and it would be desirable if an additional 1% fiber could be incorporated. It is important to note that this mix is only theoretical and has not been used in practice. The design of 3DCP Bridges should be constructed in accordance with the SMART Method seen in Chapter 3 so that the design will be sustainable. The use of SN-Curves is necessary for the SMART Method to be complete, which makes this method difficult to conduct. However, future research should make these curves readily available for designers everywhere. The SMART Method is a design based on fatigue analysis and may not be applicable to 3DCP applications, but it is well worth considering it when conducting a design. Overall, the use of 3DCP will have significant environmental benefits, saves material, and will sooner be a recognized construction method for concrete buildings.

Appendix A

Citations

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BIBLIOGRAPHY

My name is Justin Scheidler and I am currently studying at Penn State University as an undergraduate. I am pursuing a Bachelor's in Civil Engineering and will be moving onto graduate school pursuing a Master's in Engineering in Structural Engineering. I am very passionate about the work I do and have always wanted to ensure the safety of the public through proper design of structures. I have interest in new and upcoming structural processes and design, which is why the paper before you is all about how using 3DCP is beneficial for the environment and society. I am originally from the Pittsburgh area and would love to stay there and design/redesign buildings for the people of Pittsburgh as a way to give back to the place I grew up at. Aside from that, I love to teach people about my work and degree. I feel that the more you teach someone, the more you understand the information so it can be retained much easier than before. Plus, you get to teach someone something new and I absolutely love to do that. Helping others has always been trait of mine and that's why I have chosen to pursue Structural Engineering as a career path, because I love to do it and would like to teach it years down the road after I have helped redesign Pittsburgh.

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JUSTIN SCHEIDLER

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Education

--Pennsylvania State University, University Park, PA **May 2021**

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--*Schreyer Honors College Scholar and Dean's List* **3.89 GPA**

Coursework

--Statics, Strengths, Dynamics, Structural Analysis Matrix Methods

--Structural Analysis, Concrete/Foundation/Masonry/Steel Design, Mechanics of Soils

Professional Experience

Structural Engineering Intern (CDM Smith) **May 2020 – August 2020**

--Designed 3 different foundational square footings, w/ and w/o applied moment

--Learned about concrete containment tank design using ACI 350 and PCA Tables

--Learned AutoCAD drafting and 3D modeling in Revit

--Navigated through ASCE 7, ACI 350 and 318, and TMS 402

--Learned to read structural construction and shop drawings

Engineering, Scientific and Technical Intern (Pennsylvania D.E.P., Pittsburgh, PA) **May 2019 – August 2019**

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--Leading a team to design a concrete canoe for structural and stability presentation

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Engineering Design Class **August 2018 – December 2018**

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--Designed and programed a line following robot

--Worked in a multi-disciplinary team of engineering students

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--National Honor Society Member **2015 – 2017**
--Walter J. Kinsey Honors Scholarship **2019 – 2020**

Skills

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--C++
--Microsoft Office
--Surveying