EXPERIMENTAL VERIFICATION OF PRINTED CONCRETE SHELL STRUCTURES

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Abstract

The article presents the printing technology and material used in the research. Focusing specifically on shell structures. The following section details, the application concept for bridge piers and the derived specimens for experimental verification. The testing procedure and a description of the measuring equipment is presented. Finally, an introduction to computational analyses is provided.

Keywords

Additive manufacturing, concrete, shell structure, pier

1 INTRODUCTION

Technology

Concrete additive manufacturing presents an opportunity for producing civil engineering structures and bridges employing different technologies. The most common and well-known technology is Contour Crafting ("CC"). This method is based on the successive layering of concrete layers on top of each other its shape determined by the geometry of the extruder. Each printing technology is unique presenting its own set of technological challenges and limitations. The author's research is based on the CC method utilizing a 6-axis robotic arm on a belt conveyor provided by the Czech company So-Concrete (www.so-concrete.com). The limitations of this method primarily lie in the material itself and its behaviour during the early stages. The weight of individual layers on the already printed part may lead to stability issues, undesirable creep of the mixture and thus distortion of the designed geometry. To address this, a setting accelerator is used offering an additional benefit by allowing layering in different trajectories, making possible elements with an inclination of up to 45 °. While numerous researchers and companies are involved in the printing of normal strength concrete, So-Concrete stands our as a pioneer in the printing of Ultra High Performance Concrete (UHPC). Developed in the 1990s UHPC has gained popularity in recent years. The main benefit of the material is its durability and enhanced mechanical characteristics due to its special composition and high cement content. UHPC is mostly self-compacting and requires the production of elements in a solid formwork. A printed UHPC mixture with comparable characteristics to the monolithic variant has been developed recently by the above-mentioned company. The large amount of cement causes high values of initial shrinkage of the mixture and therefore polypropylene fibres (‘PP’), glass fibres (‘PVA’) or steel wires are added to the mixture to mitigate such effects.

Appropriate applications

The development of 3D printing of concrete in the construction industry hinges on the technology itself, cost considerations and finding appropriate applications. Current applications are predominantly focused on urban furniture and hollow vertical load-bearing structures in civil engineering incorporating thermal insulation material or serving the function of lost formwork [1]. In bridge construction, the trend is toward arch structures composed of prefabricated elements [2] or segmental structures with prestressing to guarantee decompression [3].

Shells are well regarded as structures in terms of material utilisation and minimal dead mass. Structures of this type inherently take on a shape that aligns with the applied load and the specified supports. The result of the form-finding process is a curved structure loaded primarily by normal forces in the centreline thereby minimising bending moments. Despite their aesthetic appeal and elegance, manufacturing shell structures has been and is a challenging process. Italian architect Pier Luigi Nervi used these natural principles to create stunning complex structures in the past [4]. Concrete additive manufacturing eliminates these difficulties providing the means to

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produce shells quickly and easily. This opens up opportunities for applications in roofing large halls, churches, distinctive buildings, or as integral components of bridges.

The initial structure

The author's preferred bridge structures encompass a diverse range, offering many opportunities for the application of printed shell structures. A promising area of use involves the printing of the entire bridge pier or its lost formwork, which becomes an integral part of the structure after the construction process, serving as a cladding element with enhanced resistance to environmental factors. This is promising particularly in scenarios such as the construction of a multi-span stress ribbon bridge. A typical example is the pedestrian bridge designed by David Kreitzer depicted in Fig. 1. The bridge pier of this structure is approximately rectangular in shape with a variable section in height. At the top of the pier there is a saddle of the stress ribbon bridge shaped like a tendon profile effectively transferring all loads to the pier.

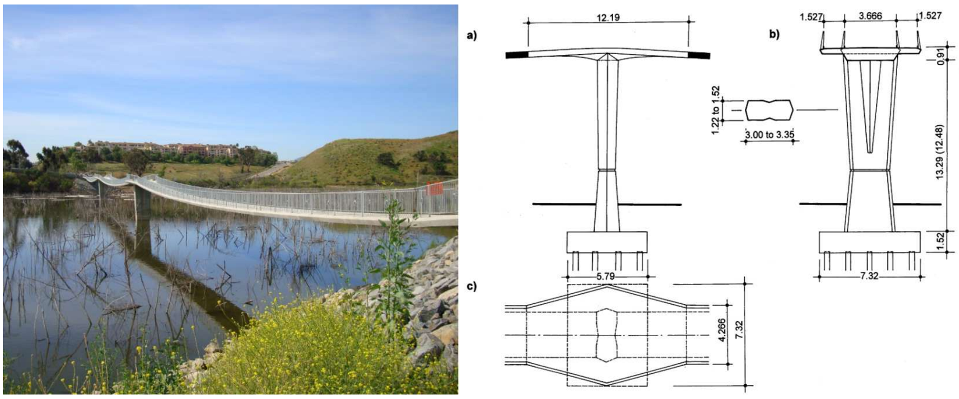

Fig. 1 Pedestrian bridge of David Kreitzer over the lake Hodges [5].

The concept of the printed structure

The concept of the printed structure involves an alternative design for the upper saddle, which can be configured as a curved plate in the longitudinal direction and supported in the transverse direction by the shell pier structure. The shape of this structure can be derived using solvers based on membrane theory, seeking a shape that bears only compressive and tensile stresses. The process begins by creating the initial geometry of the elliptical pier with curved parabolic plate (the saddle of the stress ribbon bridge) at the top. For the purposes of the study, only the upper part of pier with expanding cross section is considered. This part is 9.0 m in height. The initial geometry is covered by a mesh using the Kangaroo membrane solver implemented in the Grasshopper editor in Rhinoceros. Subsequently, a vertical load is applied to the nodes at the bottom of the pier, and boundary conditions are specified at the nodes on the edge of the saddle as described earlier and illustrated in Fig. 2. The reduction of bending moments in the shell structure depends on the value of vertical load applied in the solver. In this case, the force was chosen so that the original and new piers have the same width at the bottom. Similarly derived structures are suitable for 3D printing of concrete aligning with natural principles to efficiently utilize material and achieve cost savings. The proposed concept of the saddle with specific boundary conditions can be freely modified, as the principle of structure form finding is universal as depicted in Fig. 3.

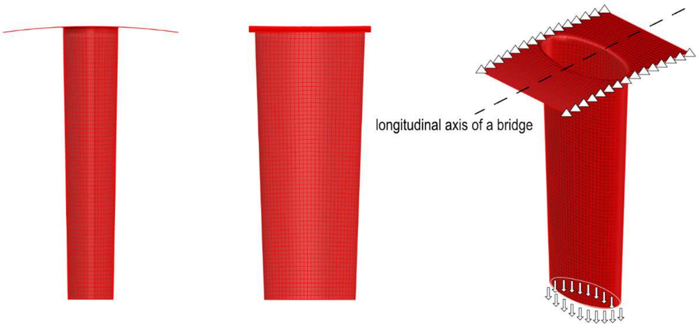

Fig. 2 Original shell structure of the pier before form finding analysis.

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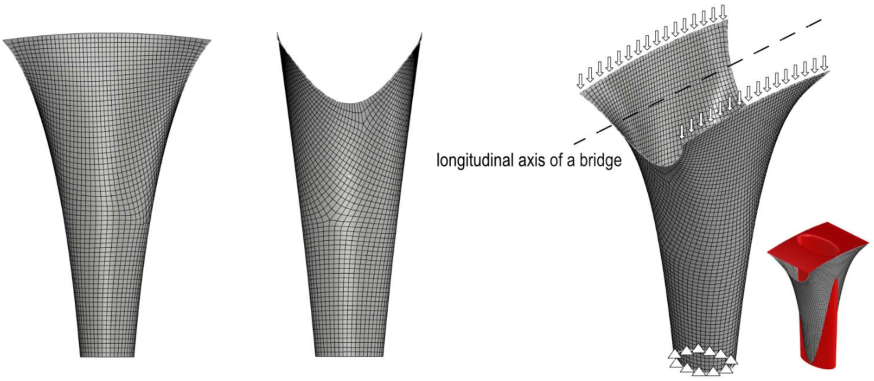

Fig. 3 The new shell structure as a result of form finding analysis.

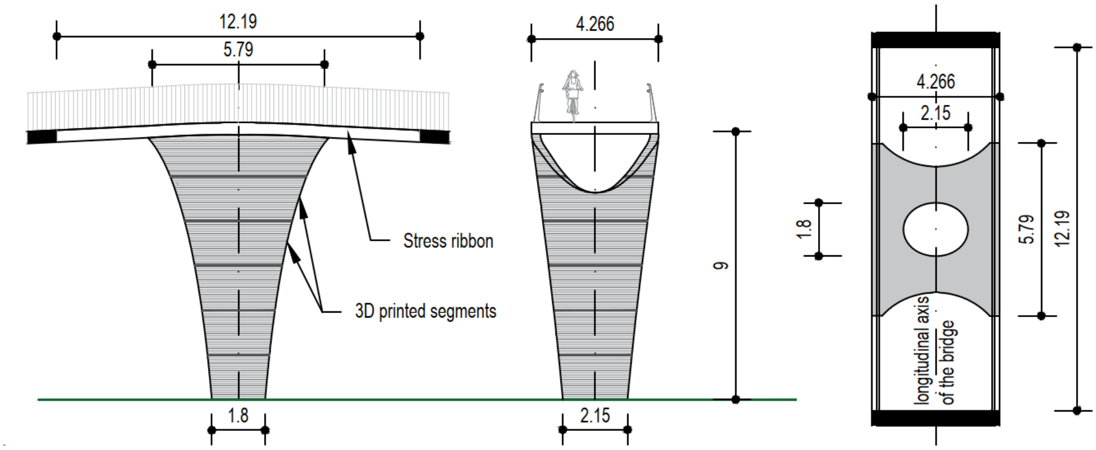

Fig. 4 Longitudinal, transverse cross section and plan of the bridge.

The printing process for such a pier or his lost formwork is most convenient when done horizontally, step by step from heel to head. Given that the pier's geometry may exceed the height capabilities of the factory or transport, it is advisable to divide the structure into prefabricated segments as shown in Fig. 4. A fundamental design is ensuring sufficient ductility. While the printed filament may contain dispersed reinforcement effective in the longitudinal direction, its tensile capacity perpendicular to the layers is greatly reduced. Technical Specification TP07 for Ultra High Performance Concrete [6] shows that ductility can only be considered if the volume of steel dispersed fibres is at least 1.5%. At the same time, the reduction in tensile capacity perpendicular to the layers poses challenges in segmental production, where the connection between precast layers is not guaranteed. An additional challenge is the impossibility of fitting the vertical reinforcement into the filament. To address this vertical/inclined continuous closed ribs on the inside of the pier are design. After segment assembly, continuous reinforcement is fitted and the internal space of the ribs is filled with concrete. Trajectories of the main stresses are generally oriented in the shell structure, as illustrated in Fig. 5, and the arrangement of the ribs can be derived from them.

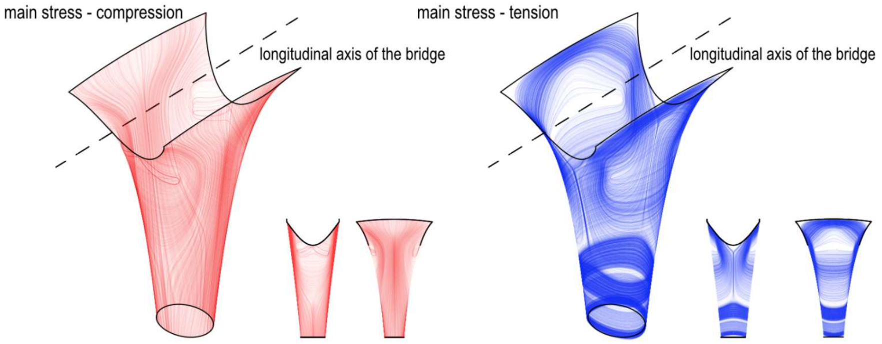

Fig. 5 Pier main stresses.

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As the shell must be anchored into the foundation structure, the concept of post-cast concrete ribs with reinforcement is a suitable production option. The horizontally oriented forces can be captured by dispersed reinforcement within a certain limit or by horizontal closed rings of steel reinforcement inserted into or between the concrete filaments during printing. The horizontal connection of the printed precast elements outside the vertical ribs can be achieved through concrete joints or more elegantly with adhesives. Prefabrication considers a pair of filaments that together form the shell thickness. The inner one protrudeds locally at the ribs, creating sufficient space for the vertical reinforcement. During the tensile loading of the reinforcement of the ribs, an additional local radial effect on the shell is produced caused by the spatial curvature of the shell and reinforcement. In compressive loading, the forces are distributed to the concrete and the reinforcement by the modulus of elasticity ratio and do not produce additional problems. The activation of the inserted horizontal reinforcement is essential for the reliability of the structure in terms of global behaviour and local additional radial effects, and therefore experimental verification is convenient for further work.

2 DESIGN OF THE SPECIMENS

The pier design offers a versatile array of shapes to cater to specific bridge design requirements and construction details. For these reasons, in this research, focus is directed towards the horizontal cut-out one segment of the pier for analysis, particularly when subjected to horizontal tensile stresses. To emulate real-world structures, an ellipse is chosen as the particular shape, with three distinctive geometries designed. The first has a ratio of lengths in a major and minor axis of the ellipse equal to 1.0 and it degenerates into a circle. The second considers a major and minor axis ratio of 1.5 and the third a ratio of 2.0. The specimens exhibit a variable section along the height. The shell is deflected 20 ° from the vertical axis on the main axis of the ellipse. The size of the major and minor axis of the ellipse is based on their constant ratio in all layers. By applying this principle, the same curvature is guaranteed at each horizontal level to ensure minimal bending moments and constant normal force around the circumference [7]. Two specimens of each type will be produced, one without and one with vertical ribs, to determine the stiffening effect on the horizontal tension distribution along the height of the specimens. The design incorporates 8 evenly spaced ribs around the circumference, creating space for the insertion of straight reinforcing bars. The designed shell thickness is 30 mm. The filament width is 15 mm and the height is 5 mm. The ribs locally extend the section to 60 mm. The specimen geometry is illustrated in Fig. 6.

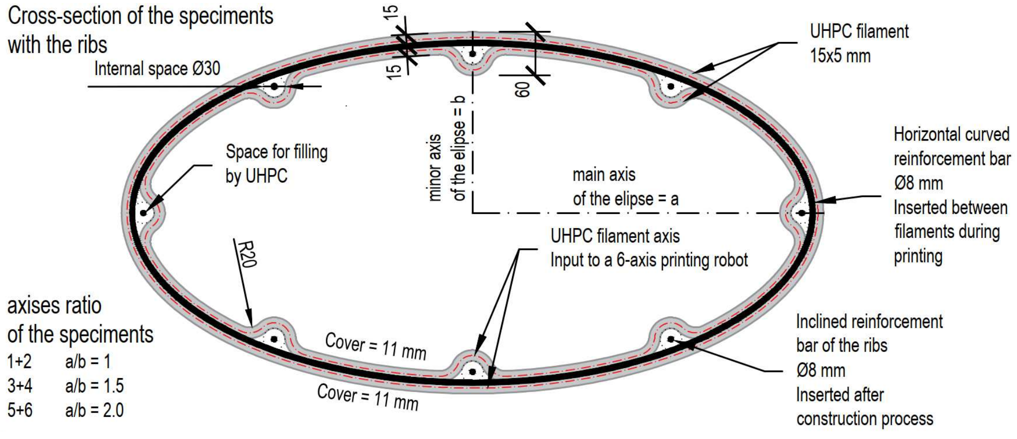

Fig. 6 Cross section of the specimens with the ribs.

The shown specimen geometry is not bound to the pier design and is used solely for testing the concept in a horizontal tension scenario. Uniform rib spacing, a rarity with respect to general principal stress trajectories, can be designed especially at the bottom of the pier to ensure a uniform force application into the foundation structure.

Furthermore, this rib spacing is suitable for precast lost formwork. The design of the specimens is carried out considering the manufacturer's capabilities to create the slenderest element minimising material consumption. The specimens are designed using 3D parametric modelling using Grasshopper in Rhinoceros motion trajectories of a 6-axis robot carrying a concrete extruder are easily and accurately obtained according to the specified geometry of the specimens. Contour lines and derived volumes for computational analyses can also by obtained. Considering the available hydraulic cylinders, the minimum internal dimension (on the minor axis) of the smaller base was chosen to be 0.33 m. The circular specimens have an axis length (radius of the circle) to the shell centreline of 0.180 m while the other elliptical specimens have a minor axis length of 0.180 m and a derived major axis size. All specimens have a uniform height of 0.5 m as depicted in Fig. 7.

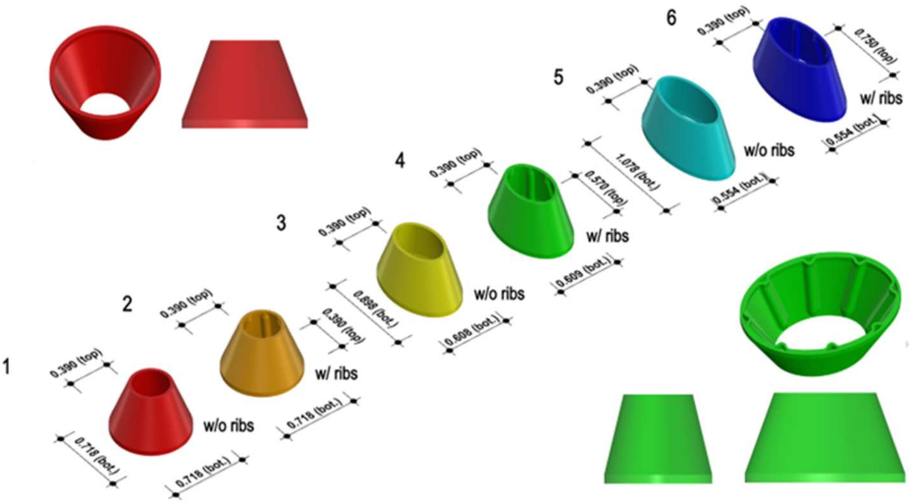

Fig. 7 Designed shape of specimens using Rhinoceros program.

For stability and economy reasons, the specimens will be tested upside down allowing the smaller of the bases to form the loading area and the larger area to rest on the floor. Vertical loads will be applied to the sand using a hydraulic cylinder over an auxiliary printed concrete block of precise geometry. The loading of the shell will be carried using fine sand with a grain size of 0–0.5 mm filling the surface irregularities in the inner space of the shell. The concrete block will ensure that the load is evenly distributed to the loading area. A total of 3 block sizes are designed. The block height is 50 mm for circular shells, 100 mm for 1.5 axis ratio specimens and 200 mm for 2.0 axis ratio specimens. Due to the expected vertical deformation of the loading surface (sand), the ribs of the specimens are modified at the top to prevent contact with the concrete block in case of settlement. Given the potential risk of the whole specimen being lifted by sand entering the joint between the shell and the floor, 50 mm high concrete vertical bottoms are designed. Furthermore, the shell itself is in this part also vertical. The bottom as well as the concrete block consists of a printed lost formwork with an additional reinforced concrete inner space. A safety gap of 5 mm in relation to the shell is maintained for both auxiliary elements. Specimens 1 and 6 at a scale of 1: 7.5 are printed in plastic and shown in Fig.8.

Fig. 8 3D model of specimens 1 and 6 in plastic at a scale of 1:7.5 with visualisation of the experiment.

The concrete used in the research is classified as C110 according to TP07 [6] with a characteristic compressive strength of 110 MPa, tensile strength 14.3 MPa and a modulus of elasticity 50 GPa. Steel reinforcement B500B, with a diameter of 8 mm, will be inserted as reinforcement for the ribs and horizontal closed rings created in a precise shape and closed by welding. The spacing of the rings is 150 mm in height.

3 FEM ANALYSIS AND MEASURING EQUIPMENT

The vertical load applied by the hydraulic cylinder on the sand induces earth pressure and radial deformations, and accompanying tensile stresses along the shell structure's centreline around the circumference are expected.

Different behaviour patterns for specimens with and without vertical stiffening ribs are expected as well. While the circular specimen can be analysed using a rotationally symmetric problem, the others require 3D volumetric analysis. The Midas FEA NX software, as shown in Fig. 9, is employed for a uniform approach in order to handle this strongly nonlinear problem. To model the system effectively, it is necessary to ensure free deformation from the specimen's vertical axis. The vertical supports are located at the bottom of the specimen, while loads and horizontal supports are applied to the auxiliary concrete block. The interaction between sand and concrete elements is ensured by contacts. Following experimental verification, all the input data to the calculation will be updated to ensure compliance. The results of the numerical models and their comparison with experiments will be the subject of future papers dedicated to this topic.

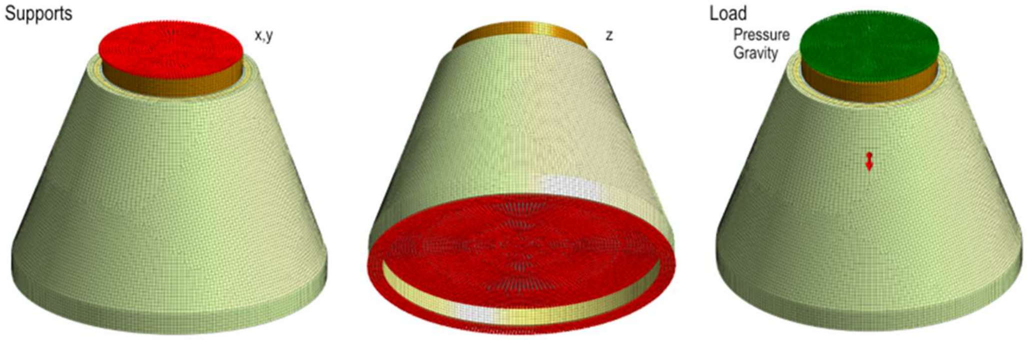

Fig. 9 FEM model at Midas FEA NX.

The experimental setup, involves 16-channel measurements. The applied force, 8 deformations, 4 stresses on the outer surface of the shell and 3 in the reinforcement at different height levels will be monitored. In case of displacement of the specimen in one direction, the positions of measuring equipment are strategically chosen to ensure accurate responses for evaluation of deformation and stress . The positions are illustrated in Fig.10.

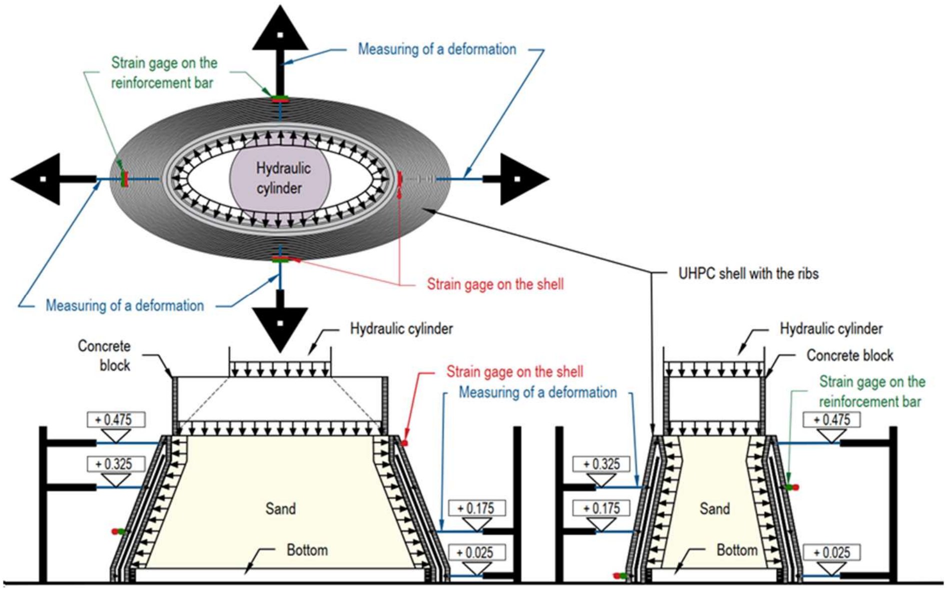

Fig. 10 Positions of measuring equipment on the specimen with the ribs.

4 DISCUSSION

The studied approach represents a novel concept in the global context of construction. The innovation lies in the use of printed Ultra-High-Performance Concrete (UHPC) and its application to shell pier structures. This research is based on the author's experience with additive manufacturing of UHPC and the understanding of key structural stresses gained from the recent construction of a tram stop in Prague, where the author actively participated. Similar interests are evidenced in the work of other researchers dealing with natural shaped ceiling structures using curved plastic formwork [8], 3D printed foam [9] or steel mesh and plastic membranes [10] forming formwork.

The production of shell elements with stiffering ribs and space for reinforcement, without the need of auxiliary elements, has not been explored in current research. The findings presented in this research contribute to minimizing material consumption and its results can be used in the early stage of the adaptation of additive manufacturing to the construction industry. Specifically, it may find application for the production of prefabricated lost formwork for piers. The function of the horizontal reinforcement within the shell structure and the effect of the stiffening ribs on the overall durability of the element will be fundamental to future research. The limitations of the research are mainly observed on the fabrication side. The application of a setting accelerator to the concrete mix may pose challenges such as delamination of the partial layers and the formation of shear surfaces, particularly at the level of the embedded reinforcement. The main assumption of the experiment is the application of a horizontal load using fine-grained sand. A different sand behaviour may lead to rethinking of loading method.

5 CONCLUSION

This paper introduces the design of a pier suitable for concrete additive manufacturing. The concept of its design which includes the placement of horizontal and vertical reinforcement has been presented as well. The specimens were derived from the conceptual design of the pier. The proposed experiment will experimentally verify their function. The aim of the experiment, the measuring equipment and the numerical modelling of a geometrically and materially complex problem were briefly outlined.

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