SUBSTANCE WITHOUT FORM(WORK)

EXPLORING ALTERNATIVES FOR CONSTRUCTING FORM-FINDING CONCRETE FORMWORK

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Abstract
Currently, the process to construct the formwork for complex concrete geometry requires expert knowledge and skill of intricate construction methods. This process entails extensive labour and often perpetuates unsustainable practices. As a result of these procedures, the required formwork can often exceed 30% of the projects total cost. If current methods such as 3D printed, or Computer Numerically Controlled parts are replaced with a system that employed fabrics, the associated costs for labour and materials, would be reduced. Much of the research currently being conducted in flexible formwork aims to maintain and rely on traditional methods such as timber frames at the cost of resources and time. However, with the aid of computational simulations, the deformations of fabrics can be better understood and more accurately predicted. This research explores a form-finding solution to flexible formwork for complex concrete geometry and focuses on the influence of the materials mass on the planar, pre-tensioned surface of the fabric. Action research is implemented to iteratively test and analyse the process to improve and shape further design decisions. As a result, these strategies informed a framework for complex concrete formworks that can be used to construct intricate double curvature geometry from concrete.

Keywords. Flexible Formwork | Fabric Formwork | Form Finding Computational Design | Anticlastic Structures | Concrete

1. Introduction

Flexible formwork continues to remain both an unexplored and underutilised avenue for the production of complex concrete artefacts in the architectural, engineering and construction (AEC) industry. A major barrier impeding the adoption of this technique is "the lack of simulation utilised by current design methods" (Scherer, 2019, p. 760) and the unpredictable, multifaceted nature of fabric deformation. Very little research has been conducted on flexible formwork and it requires the fabric to be pre-defined and stretched into the bounds of a frame (Scherer, 2019), (Diederik & Block, 2014), (Torsing, et al., 2012) (West, et al., 2016), as it focuses more on how well the fabric can withstand large loads without shearing or following an unplanned deformation. These methods limit the potential of fabric as it is constrained by an additional system such as a timber frame. Contrastingly, this research claims that the fabrics form should not be pre-defined prior to the pouring of the cement, but instead should follow a form-finding process, whereby the fabric when under a load, deforms and the structure is dictated by the mass of the cement mixture. If intuitively controlled by the fabricator and cross-referenced with a parametrically driven replica, this method could be proven as a valuable extension of the construction of formwork, reducing associated labour costs and resources.

This process streamlines the fabrication of a complex concrete form through its computational model where it accurately predicts the deformation through a set of pre-defined parameters such as the extents of the fabric and the density and mass of the mixture. A process of iterative development is applied to inform a workflow of learning objectives through experimentation and physical construction. Additionally, this research explores the relationship between the density of the cement mixture and the mechanical properties of the chosen fabric and how these parameters both shape and effect the predicted result in a virtual space.

To validate this hybrid process, its reliability is evaluated through a comparative analysis between the physical model and its digital imitation. In doing so, the impacts of said mechanical properties under these circumstances are analysed and refined. To investigate these parameters and the effects they have on the method's validity, the methodology follows the structure of action-based research. The reflection and its observations and analysis allow for an iterative process, which sharpens the computational model and the process of construction with the intention of designing an efficient and simplified method for the construction of formwork for intricate concrete artefacts. The notion of form-finding adopted for this method challenges the original use of flexible formwork that predefines the shape before pouring. Instead the fabric responds to a complex range of parameters (Bell, 2012) ultimately allowing the generation of a 'naturally' found form.

2. Research Aims

This research aims to understand how flexible formwork can be constructed with the assistance of a computationally driven process and accurately translated into a physical model by gauging its fidelity through comparing the digital prototype to its physical replica. More specifically, it focuses on the construction of complex concrete geometry through a computationally simulated form-finding process. This exploration is significant as its implications in the construction industry may reduce labour costs and create a more sustainable solution for the assembly of complicated concrete structures due to a reduction of materials. Through an iterative design process this project aims to understand the limitations associated with flexible formwork and as a result, improve the fidelity of its final outcome.

3. Research Question(s)

Due to the issues identified within the broader scope of this research regarding the process of digitally simulating both the deformation and construction of flexible formwork for the production of concrete forms, the questions this research seeks to address are:

- To what extent does flexible formwork accurately replicate intricate concrete geometry that is digitally simulated through a form-finding process; and

- How can fabric be implemented as the formwork for the construction of complex concrete geometry and directed towards achieving a high fidelity through a form-finding process.

4. Methodology

The notion of action research drives a dynamic and agile approach for establishing a procedure where objectives become iterative and improvements are sought through simultaneous processes. Consistent developments are made to a process to achieve an outcome through "intervention experiments that operate on problems or questions perceived by practitioners" (Baskerville, 1999 p. 9). Each stage is critically assessed through observation and reflection, prompting a cyclical correlation. This process aims to construct and incite change through understanding and critically questioning each stage through a repetitive repertoire. This research implements the paradigm of action research to inform future design-based decisions until a desired outcome is achieved (O'Brien 1998). Recently, this notion has been adopted into other interdisciplinary investigations that employ digital technologies and forms of fabrication to refine processes based on a reflective and iterative process. Labeled as the “learning by doing” approach, flexible formwork revolves around this domain because of how the changes to the digital model are confirmed once the observations have been made to the physical prototype(s). The iterative production of artefacts as solutions to the identified problems, through a dynamic process where reflections and observations lead to future developments, positions this research in the field of action research (Cole et al. 2008). By understanding the issues associated with this research, the developed process can “also provoke change” (Foth et. al, 2005), necessary for any future developments within the scope of formwork construction for intricate concrete structures.

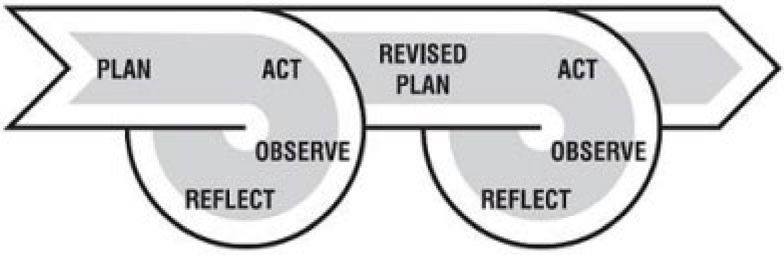


Figure 1. An Action-based research diagram by Stephen Kemmis

5. Background Research

As design has evolved, it has become far more complex in nature, often being the catalyst of organic geometry and effecting how individuals act and perceive in space. It has far surpassed the development of the construction sector. The AEC industry has substantial potential for improvements, particularly if new systems could provide the capacity to “adjust to a site in a dynamic way” (Bell, 2012 p. 2). Particularly within construction, long-standing methods could potentially be replaced with contemporary techniques as a result of computational simulations. However, due to an inherent complexity with achieving double curvature concrete forms and a lack of experimentation and simulation, these well-versed traditional standards are not being replaced. The applied procedures in many areas of construction are thus inefficient.

One sector where these concerns are particularly felt is in the realm of formwork for organic concrete forms. As noted in Scherer’s paper (Scherer, 2019) the industrial fabrication technique tends to default to planar and uniform cross sections due to its predictability and its implicit nature. These established methods of formwork contain a handful of disadvantages. This includes:

- Labour-intensive practices
- Inefficient construction
- Rendering a space inaccessible until the formwork is removed

The above issues each require review to further explore and understand the studies of fabric as flexible formwork.

Known as the process of creating a temporary mould, formwork is the construct into which cement is poured and formed. When architectural works become more intricate, this structure becomes increasingly difficult to fabricate, "requiring a full and generally rigid formwork" (Diederik & Block, 2014 p. 39), or 3D printed or Computer Numerically Controlled (CNC) parts. These methods typically demand an extensive quantity of supplies and time to fabricate.

With the development and integration of fabrics as structural reinforcement as well as formwork comes a variety of challenges and opportunities that benefit the AEC industry as a whole. This application of fabrics into the design realm would generate a superior system, allowing "flexible formwork to be more readily accessible to designers" (Scherer, 2019, p. 760). This benefits all parties in the AEC industry, ranging from, but not limited to its elevated sustainability, degree of design freedom, shortened time frame for construction and cheaper overall costs for material and labour.

As shown in several existing studies (Scherer, 2019), (Diederik & Block, 2014), (Torsing, et al., 2012) (West, et al., 2016), a major limitation in the current realm of flexible formwork methods is "the lack of simulation utilised by current design methods" (Scherer, 2019, p. 760). Computational simulations are invaluable in this process as they can be synthesised with a physical process to establish a dynamic workflow. Where the process of constructing physical models is sometimes "not within the fabricators control, but a behaviour-based approach, allows an understanding of this not as a problem of precision, but rather as a generative potential." (Menges, 2015 p. 32). This comparison between realms was something that Block's research (Diederik & Block, 2014) failed to fulfil and thus, in theory, lost results that could have further improved the design and construction processes. Block's research features limited reflection on the extensibility of his methods to the mainstream construction industry.

Whereas Torsing's exploration (Torsing, et al., 2012) demonstrates how hypar (Hyperbolic Paraboloid curve) shell construction costs can be drastically reduced, as stated "the formwork system drops from 31% to 4% of the costs." (Torsing, et al., 2012 p. 350). This is a clear link to the necessity for change in the construction industry, especially in the development of formwork as much of the resources can be spared with the application of fabrics. Furthermore, it is noted that a "conventional structure with two 45m spans costs between $1600 and $3000 per m^2" (Torsing, et al., 2012 p. 350). However, with fabrics it is reduced to a maximum of $940 per m^2. By contrast, the system that Torsing developed saw the geotextile require a supporting structure costing 54% of the total formwork construction.

Several scholars have studied the area of flexible formwork utilising a *pre-casting* method (two ends are stitched to form the desired shape before pouring the mixture into the hollow mould), such as Ron Culver and Joseph Sarafian, and the Bartlett School of Architecture (Griffiths, 2014), (Morby, 2016). These projects interweave the digital and physical models through 6-axis robot fabrication. Whilst this form of fabrication will not be explored in this project, it is important to extrapolate the notion of an inter-related computational system where the outcome of the physical model can "lend itself to parametric design, where dramatic forms can be achieved by digitally altering a set of variables." (Morby, 2016). The structure was not hollowed and optimised to use less material in areas where it wasn't required. Therefore, it is unlikely that this method will be adopted in this project due to its failure to efficiently consider the use of materials.

This literature review accentuates the difficulties within this field of study through a limited number of published literature resources and the identification of reoccurring complications. Parametric design will continue to develop and with it, a need for modification. The use of flexible formwork has been studied in several ways and as a result has demonstrated the many flaws within the systems that need to be addressed before feasibly being implemented in the construction industry. Whilst the concept has been investigated, it hasn't been explored to its richest potential as it continues to rely on other materials for structural formwork. This is primarily due to the physical and digital models not being interweaved to extrapolate data to further inform design decisions to supplement this concept. Nevertheless, these findings have informed the "traditional construction methods' failure to adapt to new digital technologies" (Morby, 2016). This may be bridged with the introduction of flexible formwork and its computational workflow as a more efficient, sustainable alternative to formwork construction.

6. Case Study

The examined case study investigates what limitations confine the adoption of flexible formwork into the industry and how the final product is impacted by various strategies and applications, which are informed by a computationally constructed model. An iterative procedure is applied to the workflow to identify the concerns that have a significant impact on the precision of the designed method when replicating the computational model throughout its physical construction phases. As well as understanding the negatives, this methodology will assist in understanding areas of strength, which will benefit further experimentation as it informs future iterations and offer new insights into other case studies.

This research, however, did not focus on the improvement of a single form for the validation of its method and instead it observed the production of several forms to understand the design extents that this method could replicate. This did not prevent past lessons being enforced into future iterations as they provided more results into what the best individual strategies were under certain circumstances when constructing a physical model that was similar to its physical counterpart.

Figure 2. Main stages of development; digital, physical and the scanned comparison

The forms developed are examples of anticlastic surfaces; both follow a double-curved geometry as this would offer an insight into the capabilities of this method and validate whether or not this system is as valuable as the systems currently being explored (Diederik & Block, 2014). As mentioned above, this study challenges the methods previously used to construct flexible formwork due to its cost and labour-intensive nature. This project made use of suspending the fabric by a set height, previously defined in the grasshopper script and the mass of a pre-defined mixture of cement, which is then applied in layers over the top of the surface in an attempt to construct a surface with a consistent thickness.

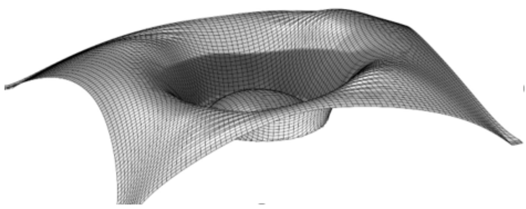


Figure 3. An example of the forms generated by the computational method using equations based from the mechanical properties of the fabric

The weight of this material naturally deforms the fabric, creating an innately durable and efficient structure. As a result, the mixture was kept consistent as to not cause large fluctuations in weight that differed from that used in the digital model. Thus the recommended ratio for the sand and cement mixture was recorded and repeated for each iteration. Figure 4 demonstrates a portion of the formwork required to construct a complex geometric form from concrete by Philippe Blocks team at ETH Zurich (Block, 2017)**.** With this in mind, the developed system was designed to reduce the complex and laborious construction process, whilst still being able to accurately construct key details and curvatures. Before prototyping could commence the system was designed and tested within the bounds of a virtual space to understand and predict how the fabric would deform under the stress from the application of the cement mixture. In order to hone the parametrically generated model in grasshopper, preliminary tests were performed with wax as a substitute for the cement mixture.

Figure 4. A portion of the required formwork for Philippe Block's HiLo shell roof, ETH Zurich

6.1 PRELIMINARY PROTOTYPES, UNDERSTANDING MATERIAL BEHAVIOUR (ITERATION 1)

The wax prototypes offered valuable insight for future iterations as they identified the need for a high viscosity mixture as well as something that contained a large mass. When pouring the wax onto the surface of the fabric, it seeped through the gaps between each thread as its viscosity was far lower than that of water, which did not permeate through the fabric. But, as the intended purpose of this research was to use cement mixtures, this wasn't a concern due to the constituent parts that create the cement and sand mixture, by nature, giving it a high viscosity.

Figure 5. Preliminary wax models that gave valuable insight to how the material properties of the mixture, particularly the viscosity and how this impacted the model

Multiple materials were tested and chosen based on a few key mechanical properties:

- The young's modulus *(a measure of elasticity, equal to the ratio of the stress acting on a substance to the strain produced)*
- Thread count *(the number of horizontal and vertical threads per square inch)*
- Weave type *(two distinct sets of yarns or threads are interlaced at right angles) described in figure 6.*

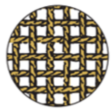
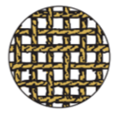
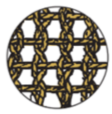
FABRIC	WEAVE COUNT	WEAVE TYPE	DESCRIPTION	
Calico	Low	Plain	Simplest pattern, alternating warp and weft threads, under and over.	
Chino Drill	High	Twill	Weft is woven over three or more warps and then under one. Next row, the pattern is shifted over one to the left or right.	
Spandex, nylon	Medium	Leno	Two warp threads and a double weft thread, adjacent warp threads cross over. The weft travels left to right and is woven between warp thread	

Table 1. Properties and details of the fabrics used for the models, essential for the continued development of the process

The materials tested were Calico, Chino drill and Spandex nylon thread. Noted in the first iteration as seen in figure 6, the method produced a structurally sound model using chino drill fabric that was very swift and simple to construct. However, a major unforeseen issue with this method was ensuring the thickness of the surface was consistent across the fabric.

Figure 6. Outcomes of fabricated iteration 2, the first attempt at creating complex geometry using flexible formwork

6.2 EXPLORING CEMENT APPLICATIONS, MIMICKING SHOTCRETE (ITERATION 2)

Iteration 2, noted in figure 7, was formed using chino drill and stemmed from the observations made from the previous stage, so, attempts to mimic the application of shotcrete (sprayed concrete) at a small scale were tested. An *Ozito 400W spray gun with* a 2mm diameter nozzle was used to replicate this application however it could not spray a mixture that contained an aggregate, so, a pure cement mixture was used instead. By applying the cement mixture in several intervals prevented cement from pooling at troughs. This iteration was successful as it applied a consistent thickness across the fabric surface, however, will not be used for future iterations as the available equipment could not spray a slurry containing cement and an aggregate of sand or glass fibres without clogging.

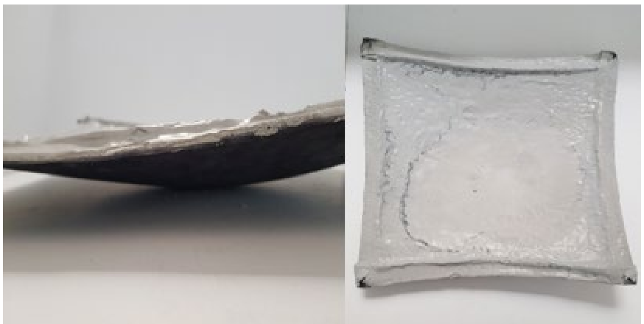


Figure 7. Outcomes from iteration 2 that utilised a spraying technique on flexible formwork to achieve curved concrete geometry

6.3 EXTENDING DESIGN FREEDOM WITH FABRICS (ITERATION 3-5)

The strategy of extending design freedom utilising fabrics involves a far more elastic material, spandex, from nylon threads as shown in figure 8. Iteration 3 reflected on the final outcome achieved from the prior prototypes and explored how the mechanical properties of the fabric could potentially broaden design freedom and the range of applications this process can be applied to (Diederik & Block, 2014). Spandex was used to exaggerate the curvature of the form due to its elastic nature. This test garnered comparable results to the first iteration where the cement slumped toward the centre, creating an uneven surface of concrete. However, this pooling effect was far more noticeable as a result of the high elasticity of the spandex, creating stress fractures in areas where the concrete was less than 1cm thick, ultimately causing the model to fail, delineated in figure 9.

Figure 8. Iteration 3 whilst achieving a very defined form, was unsuccessful due to an inconsistent surface, thinner areas cracked as a result

Figure 9. The result of an uneven surface across the flexible formwork caused cracking throughout the thin shell.

With the approach of continuously refining the previous established strategy and the observations from the previous iteration, prototype 4 was refined as to limit the deformation of the fabric and create a self-supporting structure *(point must deform and meet the ground)* to reduce the stresses occurring along the arcs in the surface. As seen in figure 10, the artefact is in contact with the ground and is self-supporting, due to the implementation of a hose clamp to funnel material into a given area.

Figure 10. Iteration 4 reveals the complexity of the forms that this process can replicate

However, as a result of the addition of the hose clamp and its required support (*in this case 20mm rope*) the model failed. This was because of the interference created by the rope and clamp when undergoing a natural form-finding process, which resulted in stress cracks as highlighted in figure 11**.**

Figure 11. Depicts the stress cracks that lead to the failure of design iteration 4

The final strategy undertaken involved refining the process from the previous iteration to minimise the interference with the fabric, allowing gravity to naturally construct the desired shape. As noted in figure 12 below, four small incisions were made in the fabric to feed the rope through to eliminate the interference with the fabric whilst pouring the cement. The outcomes of this strategy were successful, demonstrating how this process could result in a fully realised model, that is, by sight, similar to that of the digital construct. Having exhibited the potential of flexible formwork to construct complex concrete geometry, the final stage of this research was analysing and comparing the digital and physical models to understand the reliability of this fabrication process.

Figure 12. Highlights the 4 small incisions made into the fabric to achieve the overall structure

"Meshroom", a Photogrammetry software was used for scanning the physical model back into the digital space as it is the most reliable for translating images into an accurate 3D model. The models below in figure 13 are the benchmark models to be compared to their digital counterparts as they were the most successful products from the process that they transpired from. Minimal post-processing was required for this method in comparison to lidar scanning. The scanned models were spot checked against points of interest such as vertices from the physical model to validate this method of 3D scanning.

Figure 13. Three benchmark models chosen for analysis. Left: iteration 1, Middle : iteration 2 and Right: iteration 5

After confirming the scans, the digital form was directly compared to the physical artefacts scan through a confidence interval. Using the confidence interval test identifies what points are within a particular bracket. For example, a confidence interval of 95% at 10mm suggests that 95% of the points from the digital model accurately align with the scanned object. This technique allows for the identification of outliers, highlighting areas that differ substantially from the digital version.

Whilst each iteration provided valuable insights into the process and the development of future practices, unintentional errors as a result of the fabrication technique *(for example, inconsistent thickness)* detrimentally altered the final output as noted in iteration 3. Extrapolating the results from the comparisons made describes a successful process, but some of the strategies may need additional interrogation and understanding to refine and detail the outcomes. However, the developed strategy offers judgement into the potential techniques that could be carried out for formwork for larger scale intricate concrete projects.

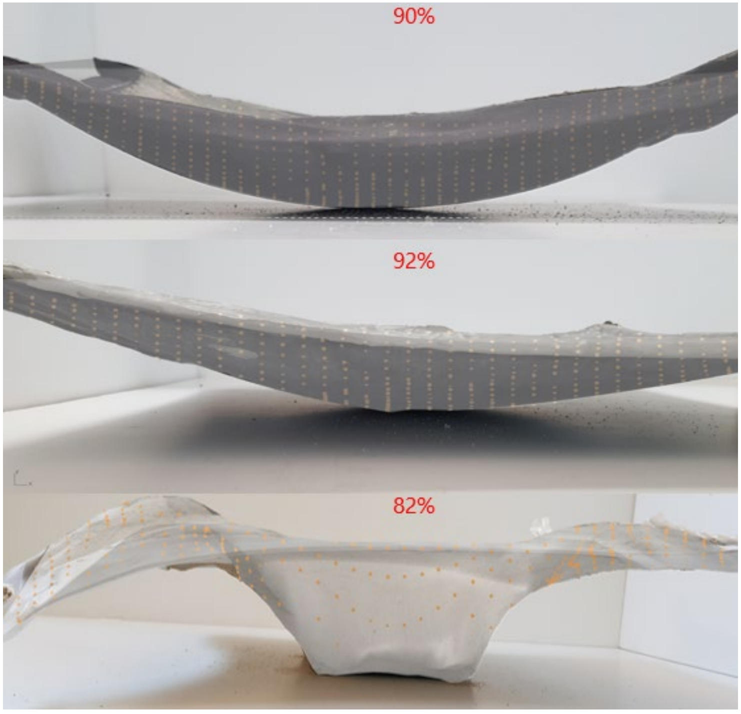


Figure 14. Showcasing the results after a confidence interval test of a tolerance of 10mm was performed, in order from top to bottom, iteration 1, iteration 2, iteration 3

7. Discussion

Due to the adoption of experimentation and an iterative process of flexible formwork fabrication strategies, contrasting levels of fidelity were accomplished. A comparison between the physical model's scan and its digital replication by way of a confidence interval reveals the reliability of this method for potential larger scale sophisticated concrete projects. Iterations 1 through to 3, recognised properties within the fabrics and mixture, that were essential to future developments (Iterations 4 and 5) as they substantially impacted the performance of the final product. These initial tests with flexible formwork under the form finding process produced results that were predicted from the digital model, validating this method for the construction of complex concrete forms and directed future developments.

In an attempt to convey and analyse a simplified construction method for complicated concrete systems, these iterations have explored the accuracy of a physical product through a direct comparison of its digital replica to quantify its reliability. Through an in-depth engagement throughout the method, the computational model has been vital as it anticipated the deformation of the fabric at key intervals, allowing the maker to adjust the process and increasing tension in the fabric and mixture adjustments, to achieve desired results. A major concern with this issue stems from applying the cement to the fabric's surface evenly which was difficult to accomplish pouring, if the end result was to be a thin shell structure. However, spraying multiple thin layers at a time, over a dynamic form prohibited the occurrence of the wet mixture from slumping toward troughs in the structure and assisted in creating a consistent thickness. It was observed that this method minimised significant errors due to the reduction of human error as it could be more consistently applied to the surface, at the expense of efficiency *(time)*. Although, this method is superior and has been employed in larger projects (Diederik & Block, 2014) it was not further employed in this research due to the equipment available being unable to spray a thick slurry.

A key contribution to the success of the benchmark models chosen for analysis was the accuracy at which the digital model was able to predict the deformation and the precision of the identified parameters needed for construction. The reference of the digital model throughout the construction process assisted in producing functionally successful models in most cases, excluding iteration 3. This research extends the understanding of the application of fabric as formwork as it has established a simplified process for the making of complex concrete geometry, where it has significantly reduced the initial labour required for setup. This has been authenticated from the results drawn from the confidence interval as each model had a confidence factor of 90% or higher within a tolerance of 15mm. Simply, 90% of the points from the scanned object were inside a distance of 15mm from the points that constructed the computational model, thus validating this hybrid process and proving its reliability.

Subsequently, whilst the results obtained from the experiments encouraged and validated the feasibility of upscaling this procedure, the models used to obtain these results were only $0.5m^2$. Further research into large scale objects is still necessary before implementing this method into the construction industry to quantify changes regarding time for construction and labour and costs for the production of complex organic forms.

However, it answers the main questions raised. Further exploration into the relationship between the mixture and its method of application is required to adequately replicate what has been modelled in a digital context. Whilst functionally, this research was quite successful, it was limited due to constraints in gaining access to equipment that could imitate the application of shotcrete at a smaller scale. This method of experimentation focuses on streamlining the understanding of a complex process to overcome various limitations associated with fabric formworks. Subsequently, this leaves a solid foundation for future praxis in fabric formwork as it suggests how the fabrication of formwork can benefit from the experimentation of a hybrid method through a comparison to a standardised digital model.

8. Conclusion

This research documents the examination of a hybrid process and its impact on the construction of a computationally generated complex concrete structure through the medium of flexible formwork. Whilst the form-finding process utilised, established a few concerns with the construction of anticlastic structures, the assistance of a computational model predicted the behaviours of the fabrics accurately. Thus, overcoming many fabrication challenges due to a foreseeable and in-depth understanding of the stages of deformation. The results extrapolated from the flexible formwork models developed through an iterative process that took into consideration the mechanical properties of the fabric, could simulate the deformation of a physical process in a digital space.

Despite a lack of experience with cement construction and achieving the appropriate ratio for the mixture, the prototypes yielded high similarities to its digital counterparts, particularly when employing a spray application for the cement. Whilst this hybrid process has only been tested on a small scale, the key contribution that this research presents is the need to reconsider how individuals, particularly within the AEC industry, engage and confront the construction of complex concrete forms through the medium of flexible formwork. Doing so, would benefit all involved parties as costs can be significantly reduced, labour hours lessened, and the construction process simplified producing a comparable, structurally sound and aesthetic organic concrete form. As a result, the research project has begun the discussion for flexible formwork applications. It has explored methods to not only hone the outcome but also overcome challenges throughout the construction phase through an understanding of fabric deformations by means of a computationally driven model.

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