Structural Morphology of VACUUMATICS 3D Formwork Systems: Constructing Thin Concrete Shells with 'Nothing'

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Vacuumatics consist of unbound particles inside a flexible membrane enclosure of which the internal air is removed to create a pressure difference with the ambient (atmospheric) pressure. This ‘externally’ acting ‘vacuum pressure’ stabilises the unbound particles into their present configuration. The ability to adjust the level of under-pressure, referred to as the ‘flexibility control’ of Vacuumatics, enables vacuumatics structures to be ‘freely’ shaped into almost any thinkable shape. From practical point of view the shaping of Vacuumatics is considered by deforming an initially flat structure. Furthermore, by locally changing the configuration of the unbound particles imprints can be made into the surface texture of the structure. Also, objects can be added in between the particle filling and the membrane envelope, which enables additional customisation of the structure. By effectively utilising this adaptability of shape as well as surface texture, Vacuumatics can be applied as a self-supporting formwork structure to produce ‘freely’ curved concrete structures with customised surface textures. The flexibility control of Vacuumatics is considered in this paper from a structural as well as morphological point of view, elaborating two shape design methods referred to as the ‘suspension method’ and the ‘lifting method’. A real-time concrete shell construction illustrates the effectiveness of using Vacuumatics as a flexible formwork technique.

1 Introduction

Since the 1990’s the contemporary building industry is eagerly looking for ways to realise ‘freely’ curved building shapes in order to anticipate to one of the most important architectural trends of the past two decades, referred to as ‘blob-architecture’ or ‘free-form design’. Through vast developments of advanced digital design systems, literally all ‘thinkable’ shapes can easily be modelled 3-dimensionally by means of Computer Aided Design (CAD) software. The construction process of these ‘free forms’ on the other hand seems to have ‘lacked’ the same degree of development. Where liquid-like, yet curable, materials – like concrete – have practically unlimited form possibilities, often traditional formwork techniques are used (Figure 1), which are considered labour-intensive, time-consuming and therefore financially unattractive.

As part of the ongoing PhD research ‘Vacuumatics 3D Formwork Systems’ – carried out at the Eindhoven University of Technology (TU/e), in commission of ABT Consulting Engineers – the idea is put forward to utilise Vacuumatics as a flexible formwork system to produce customised ‘free-formed’ concrete structures (Huijben \textit{et al}, 2009).

This paper illustrates the flexibility of Vacuumatics, focusing on the formability and adaptability of the overall shape as well as the surface texture. Furthermore, the construction process of a customised ‘free-formed’ concrete shell structure is described, using Vacuumatics as a fully self-supporting formwork structure.
2  Flexibility of Vacuums

Vacuums, or simply vacuumatic structures, are a theoretical counterpart of pneumatic structures as they rely on the negative difference in air pressure for their structural integrity. By pumping out the air from a closed flexible envelope filled with granular material an internal under-pressure – or (partial) vacuum – is induced. This pressure difference can be interpreted as the ambient (atmospheric) pressure acting externally onto the skin, which is then tightly wrapped around the unbound particle filling. For practical reasons the ‘externally’ acting atmospheric (air) pressure will be referred to as ‘vacuum pressure’. As the skin is wrapping the particles, these are tightly compressed, hence retaining whatever configuration they were put into. This phenomenon is referred to as ‘vacuum prestressing’ and partly determines the flexibility or ‘mouldability’ of vacuumatic structures.

2.1 Adaptability of Shape

The possibility to vary the vacuum pressure, often indicated in terms of percentage of the atmospheric pressure, is considered to be one of the most valuable characteristics of Vacuums. The level of vacuum pressure can be varied between 0% and 100% of atmospheric pressure (or 0bar to 1bar). It must be noted, however, that an under-pressure of 1bar is physically not attainable on earth, although values up to 0.98bar were measured using a membrane pressure sensor and a diaphragm vacuum pump during laboratory measurements. The principle of varying the vacuum pressure is referred to as the ‘flexibility control’ of Vacuums (Huijben et al, 2009), which enables these structures to be repeatedly re-shaped into ‘any’ given form (Figure 2). By lowering the level of vacuum pressure the consistency of the unbound particles inside the skin envelope decreases, which causes the overall structure to behave ‘plastically’.

In this plastic-like phase the structure can be moulded relatively easy, but will retain its newly given shape, analogous to modelling clay. When the desired shape is obtained the level of vacuum pressure can be increased to its maximum (roughly 1bar), which further stabilises the structure.

Figure 2: Illustrating the shape adjustability of a vacuumatic structure using cylindrical wooden elements in a Low Density Polyethylene (LDPE) film envelope
One of the questions that rises when shaping Vacuumatics is how to determine the initial configuration of the unbound particles inside the flexible envelope. Therefore, from practical point of view, the shaping of vacuumatic structures is considered by deforming an initially flat structure.

2.2 Adaptability of Surface Texture

The principle of using unbound particles inside a flexible envelope skin, benefits not only the formability and adaptability of the overall shape, but also enables the customisability of the surface texture. By locally changing the configuration of these particles imprints can be made into the surface of the structure (Figure 3). Furthermore, by adding certain objects in between the particle filling and the skin envelope a surface texture or pattern can be created (Figure 4). These characteristics are regarded especially useful when using Vacuumatics as a flexible mould for producing concrete elements or structures with customised surface textures.

3 Structural Flexibility

At the Pieter van Musschenbroek laboratory of the Eindhoven University of Technology, a large number of four-point bending tests have been conducted on beam-shaped vacuumatic structures in order to explore the flexural rigidity in relation to the specific characteristics of the filler and skin materials used. These tests pointed out that the flexural rigidity is aided by using a membrane skin with a low elasticity and a particle filling that possesses high mutual frictional characteristics (Huijben et al, 2010).

3.1 Adapting the Flexural Rigidity

As mentioned before, the level of vacuum pressure also partly determines the mouldability – or in this case rather the adaptability of the flexural rigidity – of Vacuumatics. In order to explore the influence of the induced pressure difference on the flexural rigidity and load-bearing capacity of vacuumatic structures, a series of four-point bending tests have been conducted where the level of vacuum pressure is varied in several steps (Figure 5). In this particular study sand particles are used ranging from 0.5mm to 1.0mm in size, enveloped by a plastic film of Low Density Polyethylene (LDPE), 90micron in thickness. The accuracy of the level of under-pressure during these experiments varies within a range of approximately +/-0.1bar. Nevertheless, these values are considered adequate for this research as we are mainly aiming at discovering behavioural trends.

The force-displacement graphs of the conducted flexural tests (Figure 6) – representing the average results of at least three similar bending tests – are used to give an indication of the flexural rigidity. At the initial stage of the bending process these graphs show a variation in bending stiffness, which is indicated by the inclination of the graphs, dependent on the level of induced vacuum pressure. Furthermore, these graphs clearly illustrate that there is no linear relationship between the level of under-pressure and the load-bearing capacity (or yielding strength). An important outcome of these bending tests is that all specimens behave plastically at some point, where yielding turns out to be a geometrically determined phenomenon. The horizontal branches of the graphs start at comparable values of deformation not related to the level of induced vacuum pressure. The level of under-pressure does however determine how much force it takes to deform an initially flat vacuumatic structure into a curved shape.
3.2 Increasing the load-bearing capacity

As vacuumatic structures in general tend to behave relatively ‘weak’ in bending – which of course can be used beneficially when considering the formability of Vacuumatics – a way to enhance the flexural rigidity of the structure in fully deflated state might be desirable for several structural applications. Analogous to reinforced concrete, a layer of ‘reinforcement’ can therefore be added in the tensile zone of the structure to increase both the flexural rigidity as well as the load-bearing capacity of Vacuumatics. In theory any sheet-like material can be used as reinforcement in between the particle filling and the envelope skin. The ‘only’ requirement the reinforcement layer needs to have to be used efficiently in free-formed vacuumatic structures – self-evidently apart from restricting the elongation of the structure in its tensile zone – is that it needs to be flexible so it can be formed along with the particle filling in its (partially) un-deflated state, analogous to the membrane covering.

A series of flexural tests of beam-shaped vacuumatic structures – identical to the ones described in the previous section – are conducted at 100% vacuum pressure, using pieces of a steel wire mesh (ST), Polypropylene fabric (PP) and Nylon textile fabric (TX) as reinforcement. These tests show that great enhancements in flexural rigidity are attainable, even resulting in an increase of the yielding strength of up to 300% to 600% (Figure 7).

Individual tensile tests on the tensile behaviour of the reinforcement materials indicate that Polypropylene fabric (PP) in particular is regarded to be extremely suitable to be used in vacuumatic structures. This is mainly due to the fact that it has a relatively high tensile strength in combination with a high ductility (Figure 8) and therefore doesn’t result in abrupt tensile failure, like it is the case with steel wire mesh (ST) reinforcement. The tensile tests are carried out using strips of fabric of 5cm in width, which are clamped at both ends and axially loaded using a basic fabric tensile test setup (according to ASTM D822-91 and ISO 527).
4 Morphological Flexibility

In line with the aforementioned investigations of the structural flexibility of Vacuumatics, this section focuses on the morphological flexibility of vacuumatic structures. Like the shaping of any semi-rigid object, the simplicity of the shaping process itself is aided by using as little ‘control points’ as possible to manipulate the initial (flat) structure. In this part of the paper, two different shape design methods are discussed for ‘freely’ shaping Vacuumatics by effectively utilising the ability to vary the level of vacuum pressure (or ‘flexibility control’). Although the focus in this specific study lies on the construction process of a single curved shape, the same principles applies for the construction of double curved structures.

4.1 Suspension Method

The first – and assumedly most intuitive – shape design method is referred to as the ‘suspension method’ (Huijben et al., 2011), directly related to the design approach of several well-known engineers/designers using funicular structures, like weights on strings (Antoni Gaudi), cable nets (Frei Otto) and suspended cloths (Heinz Isler). The inverted shape of these tension-only structures leads to compression-only structures when subjected to the (predominant) gravitational loading case. As the structural behaviour of Vacuumatics is considered relatively weak in bending, this principle in particular is regarded effective regarding the construction of ‘structurally efficient’ thin shell structures by means of Vacuumatics 3D Formwork Systems.

The beneficial characteristic of vacuumatic structures to regulate their flexural rigidity can be used to its fullest potential in case of the ‘suspension method’. An initially flat vacuumatic structure is only marginally ‘deflated’ – only to prevent the particle filling from shifting inside the flexible enclosure – after which the structure is lifted at its ends to form a funicular structure (Figure 9). The length of the structure and the final position of the two suspension points (or rather ‘control points’) determine the final shape of the structure, which in this case closely resembles a catenary arch as the vacuumatic structure has practically ‘no’ flexural rigidity. After full ‘deflation’ (just under 1bar), the now rigidised vacuumatic structure can be flipped over to form a self-supporting temporary load-bearing structure to function as a formwork onto which the fresh concrete mortar can be sprayed. No additional supports are required. When the concrete mortar is sufficiently hardened the Vacuumatics formwork can then easily be demoulded by ‘re-flating’ it – as in letting the air back into the structure and thus decreasing the level of vacuum pressure – which causes the formwork to simply drop down from the concrete structure, enabling it to be re-used again.

Figure 8: Stress-strain graphs of tensile tests of strips of ‘reinforcement’ material of 5cm in width (ST = steel wire mesh, PP = Polypropylene fabric, TX = nylon textile fabric)
4.2 Lifting Method

Considering the fact that flipping the formwork structure can be regarded impractical in case of relatively large-scale structures a second shape design method is considered, referred to as the ‘lifting method’ (Huijben et al, 2011). From structural point of view a close relationship can be found with gridshell construction (Hennicke and Schaur, 1974) as the intended shape is obtained by locally lifting (or lowering) an initially flat semi-rigid surface into its desired (equilibrium) shape (Figure 10). The obtained form is then stabilised by simply fixing the boundary conditions of the structure.

In general the self-weight of the structure is effectively used to force the structure ‘downwards’ when lifting it locally, although additional local forces can be applied to reach the desired curved shape. From mechanical point of view the lifting method of a structure lifted at a single (mid)point can be interpreted as two (symmetric) cantilever beams loaded mainly by the deadweight of the structure. Additional point loads at the ends of the cantilever represent the vertical constraints of the ends of the structure when lifted (Figure 11).

The flexibility control of Vacuumatics aids the shaping process as the yielding strength can be effectively lowered (by decreasing the internal air pressure), which minimises the effort needed to force the structure into its intended shape. When the final shape is obtained the flexural rigidity of the vacuumatic structure can be ‘restored’ to its maximum by fully deflating the structure. Similar to the ‘suspension method’ (after flipping), now the fresh concrete mortar can be applied to produce the free-formed concrete structure.

In order to examine the morphological flexibility of the formwork, several similar shaping tests were conducted with various levels of pressure difference. The obtained shape of the formwork is analysed by measuring the vertical distance from the ground to the bottom side of the curved structure at several intermediate points and comparing it with a parabolic curve (Figure 12). Each test was carried out up to the point where the ends of the structure – fixed with steel clamps – started to be lifted from the ground. The total applied force is therefore similar for each test and clarifies the different amplitudes of the obtained curved shapes.
The aim of this study is to find out whether the ‘flexibility control’ of Vacuomatics can be utilised to benefit the shaping process as assumed before. What these tests point out is that the structures mainly deform locally near their lifting point. The ends of the structure remain almost perfectly straight. Furthermore, it illustrates that the level of vacuum pressure has hardly any effect on the derived overall shape of the structure, apart from the vertical displacement of the lifting point. This indicates, however, that the force needed to curve the structure decreases with the lowering of the vacuum pressure. In an attempt to create a more evenly distributed curvature along the ‘span’ of the structure a piece of Polypropylene (PP) fabric is added in the tensile zone of the structure to function as a ‘reinforcement’ layer, which increases the yielding strength of the structure. As expected, the newly derived shape is more evenly curved and now closely resembles the reference parabola (Figure 13). This obtained shape will be used for further analysis.
5 Structural Shape Analysis

Although Vacuumatics behave relatively weak in bending the shapes obtained in the previous sections are considered ‘structurally efficient’, which causes the structure to be mainly subjected to compressive forces when externally loaded by concrete mortar. For the aforementioned shape design methods as well as this specific study a vacuumatic structure is composed out of lightweight expanded clay aggregate (Liapor) of 2.5mm to 8.5mm in size and Low Density Polyethylene (LDPE) film of 150micron in thickness. The initially flat vacuumatic structure (Figure 14), which measures approximately 2.3m in length, 0.7m in width and 0.06m in thickness, is shaped by lifting its midpoint. The particles used are considered extremely suitable for this study, as the particles are relatively light weight – which benefits the final load-bearing capacity determined by the self-weight of the formwork plus the concrete mortar. Furthermore, the coarse surface texture of the particles leads to large mutual friction of the particles, which results in an enhanced interlocking action and thus a relatively higher flexural rigidity as well as load-bearing capacity (Huijben et al., 2010). Furthermore, as coarse particles behave relatively rigid under axial compression (Huijben et al., 2010) it is assumed that the formwork structure will fail due to global instability – like in-plane buckling – rather than due to local plastic capacity failure.

For the load-bearing tests we loaded the structure with cylindrical sand bags (2.1m in length and 25.5kg in weight each) to simulate the load of the (wet) concrete mortar. As expected, the Vacuumatics formwork structure fails due to asymmetric in-plane buckling of the shell (Figure 15). The minimum load-bearing capacity of three identical tests was found to be 229.5kg (9 sand bags), analogous to 1.6kN/m². This corresponds to a layer of 65mm of concrete to be safely applied onto the formwork. As the span of the formwork structure is approximately 2.0m, the thickness-to-span ratio of the intended concrete shell would be about 1:30. Compared to shells build by Heinz Isler – with thickness-to-span ratios of 1:360 or less – this proportion would seem more than acceptable for larger scale shell construction. However, the thickness of the formwork itself would grow significantly when scaled up, which would lead to significant increase of self-weight. Further research is therefore required to verify the use of Vacuumatics for constructing large-scale (concrete) shell structures.

![Figure 14: Lightweight expanded clay aggregate (Liapor) filling and a Low Density Polyethylene (LDPE) film envelope](image1)

![Figure 15: In-plane buckling failure of a self-supporting Vacuumatics formwork structure](image2)
6 Concrete Shell Construction

Based on the aforementioned considerations and analyses, now a similar ‘efficiently shaped’ (reinforced) Vacuumatics formwork structure will be used to produce a customised concrete shell structure.

For this specific study a layer of approximately 60mm of concrete mortar is applied onto the vacuumatic structure by means of hand lay-up. Shotcrete would be the method of choice for this particular formwork application, but as this study mainly focussed on the construction process of the Vacuumatics formwork itself rather than on the produced concrete shell, this technique serves the cause. To explore the adaptability (or rather customisability) of the surface texture, cardboard characters are added on top of the reinforcement layer in between the membrane and the particles (Figure 16). During the entire curing process of the concrete (approximately 2 days), a vacuum pump was attached. The demoulding of the cured concrete shell was simply done by disconnecting the vacuum pump, which almost instantly eliminates the pressure difference. Without the level of under-pressure the Vacuumatics formwork loses its structural integrity and becomes fully flexible. The use of a plastic film envelope further beneficially contributes to the demouldability of the formwork, as the concrete does not attach to the oily contact surface of the Low Density Polyethylene (LDPE) film. The formwork therefore simply drops down from the shell when the vacuum pump is disconnected.

The final result is a ‘freely’ curved concrete shell structure (Figure 17). The cardboard characters which are added to the formwork leave smooth imprints into the somewhat rough concrete surface – mainly due to the size of the particles used – enabling a wide range of (aesthetically pleasing) customised surface textures (Figure 18).

Figure 16: Cardboard characters added inside the Vacuumatics formwork before application of the concrete mortar

Figure 17: ‘Freely’ curved concrete shell structure after demoulding of the Vacuumatics formwork structure

Figure 18: Variations in surface texture of the final concrete shell structure
7 Conclusions and Discussions

The flexibility of Vacuumatics 3D Formwork Systems is discussed, focussing on the adaptability of the overall shape as well as on the adaptability of the surface texture. The aim is to effectively utilise vacuumatic structures as a flexible formwork for the production of ‘freely’ curved concrete structures with the ability to customise the surface texture of the concrete structures. One of the most valuable characteristics of vacuumatic structures is the ability to vary the so-called ‘vacuum pressure’, referred to as the ‘flexibility control’ of Vacuumatics, between approximately 0bar and 1bar. This vacuum pressure represents the ‘externally acting’ ambient atmospheric pressure – or rather under-pressure – induced by removing the internal air from the enclosed flexible membrane with a filling of unbound particles. Due to the unbound character of the particles Vacuumatics can be literally ‘moulded’ into almost any shape. Their current configuration is fixed upon deflation of the structure. For practical reasons, however, the shaping of vacuumatic structures is considered by deforming an initially flat structure.

A series of four-point bending tests points out that the flexural rigidity as well as the yielding strength of vacuumatic structures can be adjusted by varying the level of vacuum pressure. Although the yielding of the structure turns out to be a geometrically determined phenomenon – as it occurs at comparable values of deformation not directly related to the level of induced vacuum pressure – the level of under-pressure does determine the amount of force needed to manipulate an initially flat structure into a desired curved shape. The addition of a (flexible) ‘reinforcement’ layer in between the particle filling and the membrane envelope at the tensile zone of the structure significantly increases the flexural rigidity as well as the yielding strength. In order to obtain a ‘freely’ curved shape using as little ‘control points’ as possible, two shape design methods are elaborated referred to as the ‘suspension method’ and the ‘lifting method’. The ‘flexibility control’ of Vacuumatics has practically no direct effect on the shape obtained by means of the lifting method, but can effectively be applied to decrease the efforts for manipulating the initially flat surface into its desired curved shape. Whereas the structure tends to mainly deform locally at the lifting point, the addition of a reinforcement layer results in a more evenly distributed curvature along the span of the structure. Although this particular study results in the production of single curved structures, the exact same principles apply for double curved structures. It would be interesting, furthermore, to investigate how digitally modelled curved shapes can be translated into methods to shape Vacuumatics.

The load-bearing test of a self-supporting curved Vacuumatics formwork structure, as well as a real-time concrete shell construction, illustrates that vacuumatic structures can effectively withstand the load of (wet) concrete mortar up to a certain degree. Further research is required however, to verify the use of Vacuumatics for larger-scale formwork applications. Customised surface textures in concrete can easily be realised by adding objects inside the formwork in between the particle filling and the membrane envelope. The demoulding of the formwork is carried out by simply detaching the vacuum pump, which is connected during the hardening of the concrete mortar to ensure the structural integrity of the vacuumatics structure. When detached the formwork simply drops down.

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9 References


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