СТРОИТЕЛЬНЫЕ КОНСТРУКЦИИ, ЗДАНИЯ И СООРУЖЕНИЯ

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Опалубка железобетонных оболочечных конструкций: проектирование и строительство

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Аннотация. Строительство железобетонных оболочечных конструкций ведётся уже более века, в результате чего получаются очень популярные архитектурные произведения. Однако интерес архитекторов и инженеров к оболочечным конструкциям, похоже, сошёл на нет из-за трудностей, связанных с опалубкой, и других различных причин. Хотя с развитием цифровых технологий строительство оболочечных конструкций, казалось бы, возобновилось, использование бетонных оболочечных конструкций всё ещё остаётся отстающим, с нерешёнными трудностями. Цель данной статьи – выявить основные трудности при строительстве бетонных оболочек и предложить их решение. Методы, используемые в статье, включают в себя аналитическое и экспериментальное моделирование. Предложенный прототип бетонной купольной оболочечной конструкции спроектирован и построен в масштабе экспериментальной конструкции. Полученные результаты подтверждают, что использование гибкой и многоразовой опалубочной мембраны может быть решением для различных кривых в структуре оболочки. Рекомендуются дальнейшие прогрессивные исследования для улучшения её характеристик и эффективности.
Ключевые слова: оболочковая конструкция, бетонные оболочки, регулируемая опалубка, многоразовая опалубка
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BUILDING STRUCTURES, BUILDINGS AND STRUCTURES

Original article

Formwork of concrete shell structures: design and construction

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Abstract. Construction of concrete shell structures has been exercised for more than a century producing very popular architectural works. And the interest of architects and engineers on shell structures seemed to have demised due to the difficulties related to formwork among other various reasons. Although, with advancements of digital technologies, shell structures construction seemed to resume, the use of concrete shell structures still remains lagging behind with unresolved difficulties. The objective of this paper is to identify the main difficulties with concrete shell construction and propose a solution. The method used in this study is analytical and experimental modelling. A proposed prototype concrete dome shell structure is designed and constructed to scaled experimental structure. And the findings confirm that the use of flexible and reusable formwork membrane can be a solution for various curves in a shell structure. And further progressive studies are recommended to refine it for better performances and effectiveness.
***Keywords*:** shell structure, concrete shells, adjustable formwork, reusable formwork

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Introduction
Concrete Shells

Thin concrete shells have long been used as structural components both from material conservation and aesthetic purposes [1]. Apart from its compressive strength to cover large spans, the concrete capacity to fit any mould and shape makes it attractive for the construction of shell structures. In the early years of the 20th century, shoeboxes, fans and houseshoe concrete shapes were commonly dominating [2]. And during those early years, material abundance and low labour cost were the main drivers of interests on concrete shell structure construction [3]. Later on, the advancements on digital and computer technologies, construction techniques and alternate material developments, enhanced the use of concrete in the futuristic curved surface structures. The period of 1925–1975 is stated to be the 5 golden decades for the popularity of concrete shell construction. Nevertheless, from the 1960s forwards concrete shells started to lose popularity mainly due to increasing costs of labour [4]. Moreover, the decrease in the construction of concrete shell was mostly connected with the cost of formworks and developments of competing materials such as steel and glass [5]. Furthermore, with the needs to meet the demands of 21st century architectural aesthetics, the fast developments of modelling and digital technologies [4], is prompting the rise of concrete shell popularity [6]. However, computer technologies can only make designing and drawing of complex forms easier, while the translation of designs in to real world projects remains with its difficulties [7]. And this paper is designed to experiment the application of a reusable surface membrane for formworks of curved surface.

Formwork of Concrete Shells

During the period of 1930–1950s, majority of the formworks used to support curved surface concrete structures were wooden materials [8], which is characterized to be complex and high skill labour demanding (Fig. 1).

Fig. 1. Wooden Formwork of 93x52 m for shell in Chiasso, Switzerland (Photo credit: Aurelio Muttoni)

The challenges of curved surface formworks are also governed by stability and safety issues against collapse [9, 10], as curved formworks created from the assemblage of material pieces are also vulnerable to horizontal sliding of failures [11, 12]. Furthermore, material wastages from shell structure formwork construction demands significant consideration. The study of Shen et. al [13] on wastages of construction reveals that timber formwork for foundation is executed with a loss of its 20% as wastage. Material waste resulted from formworks of curved surface or complex geometries is a significant challenge for the concrete construction [14]. The fact that 49% of the total cost of the construction of Centro Ovale, in Chiasso, Switzerland, was consumed by the formworks and falseworks [8], emphasizes how costly is the conventional formwork system.

For economic resource use, the devise of reusable, flexible and adjustable formwork is demanding to solve the major difficulties of many of the curved surface construction [7]. A number of researches and experiments have been so far conducted to overcome the curved surface formwork difficulties. The use of deployable (reusable) formwork is one among the others. A gridshells structure, first introduced by Russian engineer Shukhov Vladmir [4], is a system of reusable and adjustable supporting formwork, followed by the use of carbon fiber gridshell [11] and deformable gridshell [15]. The final result of the deformable gridshell, however, illustrated a flexible nature over the gridshell was observed during concrete casting. the casting is noted to be studied and addressed further.

Moreover, fabrics formworks made from various textile membranes such as Polyolefin, Nylon and Polypropylene have been used as non-conventional formworks [4]. Another innovative approach is the use of pneumatic (inflatable) formwork which is based on air inflation to air tight membrane [15]. In many cases, when this method was used to support large amounts of concrete, a significant deformation was noticed. As large amounts of concrete supported by this method are likely to induce significant deformations during casting, use of supplementary segments was demanding. Another limitation of this method is that the span of the structure is determined by the prefabricated membrane size which demands supplemented by additional conventional scaffoldings [16, 17]. Furthermore, all shapes to be casted by the use of membrane or textile formwork, which relies on viscous pressure, can only be of convex (positive) surfaces [7]. And it can be noticed that all the above investigated papers show that pneumatic (inflated) formwork to be practiced on convex or doom shaped curves only. Tang [18] argues that the use of pneumatic formwork did not gain significant popularity for its limitation to specific domed morphology which results space planning and furniture usage difficulties. A comprehensive discussion of the pneumatic formwork can be referred from Kromoser and Huber [19].

This method represents the latest and economic technology of forming manufactured foam moulds using CNC machines which historically was used to be made by hand [20]. The light weight, cheaper costs, easy milling, demoulding possibilities are the advantages of using this method. The main limitation of this method is that the formwork is extensive for large projects in which the direct reuse lacks thereby producing more wastes.

Huijben et al [4], conducted an experimental study on the application of vacuumatic structures which consists structural aggregates tightly packed in an envelope of flexible membrane.

There is a possibility of fabrication an environmentally friendly and efficient construction technology of curved surface formworks with lesser wastages of materials using the 3D printed bending technology [21]. The printing and robotic mechanism are, however, in their initial development stages in which various limitation such as economic, material recycling and sustainably are yet to be solved [22–24]. Moreover, the available experiments performed yet are limited to prototypes without large scale experiments [25].

Finally, the adjustable and flexible formwork moulds are being studied for practical feasibility. In the 1960s Renzo Piano showed up with an innovative electronic machine that can determine the height of every point of a given curved structure based on a scale model shell [26]. The invention, however, was never used in real world practices for the limitations of force analysis of that period. Most of the later developed adjustable formworks for curved surfaces were based on the principle of Renzo Piano. For example, the adjustable mould developed by the study of M. van Roosbroeck [27].

Another performance towards an adjustable mould was the idea of strip mould which is based on the arrangements of vertical pins covered by flexible smooth bed. The strip mould proposed and designed by H. Jansen demonstrates a double curved surface arranged by strips of vertical pins covered by strips of thin wood layers and rubber mat (Fig. 2).

The main limitations of this arrangement are that the distance between pins is significantly associated with the radii of curvatures and stiffness of the layers. This means the flexibility of the arrangement would be limited. The first adjustable mould developed by D. Rietbergen [26] was executed in such a way that a computer program can be used for the proposed automatic set up. Nonetheless, this development was confined to small scale tests. Similarly, a pin bed mould was developed which consists of vertical pistons of adjustable height to be covered by a flexible layer. Van

Roosbroeck [27] prepared a mould which can produce curved concrete of size not greater than 4.5x3.38 m and only up to 1.5 m of curvature. And this is accompanied with practical limitations in which large number of pin arrangements would be required in small areas (Fig. 3).

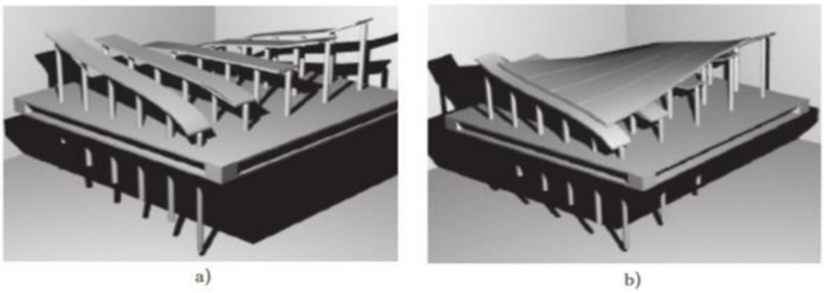
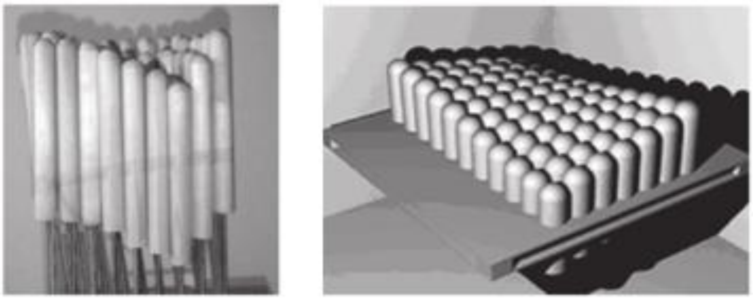


**Fig. 2. Two strip mould designed by H. Jansen:
a) one layer strip; b) two layer strip mould**



a) b)

**Fig. 3. Pin bed moulds:
a) by M. Van Roosbroeck; b) by Hans Jansen**

Finally, the above-mentioned studies and practices demonstrate that the implementation of adjustable mould has not yet reached the verge of producing real world curved surfaces of concrete shell formworks [28].

That is where this paper focuses to conduct an experimental study on devising a reusable and adjustable formwork structure for curved surface concrete structures.

Methodology

The hypothesis of this paper for feasible use of the adjustable and re-usable formwork is tested by practical construction experiments.

Practical prototype formwork of a dome shape and concrete casting were conducted. The model of the concrete dome shell experimented has a thickness of 7 cm with the dome dimensions denoted in Fig. 4.

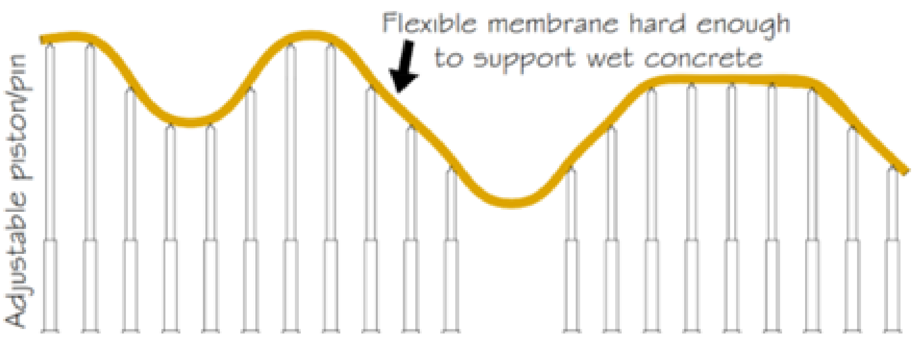


**Fig. 4. Rigidity of formwork membrane and spaces of vertical supports
In this study, an arrangement, timber panels of 25x7x2 cm sizes were arranged to create continuous surface**

Materials used for the formwork

Generally, the material to be used as a surface membrane for any curved surface has to fulfill two important requirements: Rigidity and flexibility for smooth surface curvature. The rigidity of the formwork surface membrane is governed by the minimum space between consecutive vertical supports pins (Fig. 5).

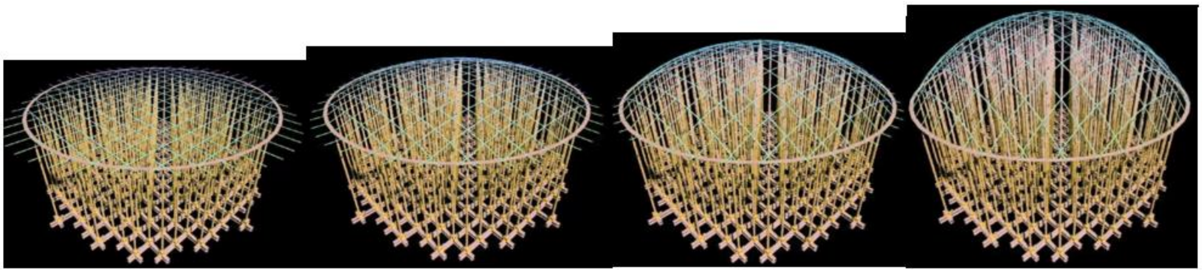


Fig. 5. 3D Simulation of adjustable support pins and flexible plate strips

Membrane Strength Compatibility

Referring to the European strength class systems of timber structure, the bending strength ranges 14 MPa -50 MPa or C14–C50 for soft woods [29]. And considering the effects of knots and other defects that reduce strength of timber, this paper takes low strength up 8 MPa for ultimate safety. And to analyze the timber panel carrying capacity to support a specified concrete thickness, the following empirical analysis is conducted.

Timber panel dimensions: l = 250mm width, b = 70mm, thickness t = 20mm.

Timber bending strength, fb = 9.8 MPa shear strength, fv = 1.0 MPa.

Moment resisting capacity of timber, M_{res} is given by:

$$M_{res} = \frac{\emptyset f_b * I}{y} = \frac{0.9 * 9.8 * \frac{bt^3}{12}}{(\frac{t}{2})} = 41{,}160\ N - mm. \quad (1)$$

For simply supported panel, bending moment maximum is given by:

$$M_{max} = \frac{w * l^{\,2}}{8} = \frac{w * (250)^2}{8} = 7812.5\, w\, mm^2\,, \quad (2)$$

where w = linear loading of concrete supported by the timber panel.

Equating equations (1) and (2), max value of w is found to be, w ≤ 5.27 N/mm.

With the given length and width of the panel, the maximum than taking specific density of concrete, γ_c = 24000 N/m^3, the maximum height of concrete that can safely supported by the timber panel is computed as:

$$h_{con} = \frac{w}{\gamma * b * l} = \frac{5.27\ N/mm}{2.4 * 10^{-4} N/mm^3 * 7mm} = 3137\ mm.$$

The computation above demonstrates that a timber panel of 25 cm long can support up to 3.13 m thick concrete. And this justifies that prototype panel 25x7x2 cm used is structurally safe to support wet concrete up to 20 cm thick shells.

The panels were arranged side by side with a space of 1mm and nailed to fixed to three parallel rubber ropes. The plasticity of the rubber provides the desired flexibility of the membrane to fit various curvatures as shown in Fig. 6.

And to meet the requirement of smooth curvature, the size of the panel is main parameter. The shorter the spans and widths of the panel produces the smoother the curvature. However, it is crystal clear that the length of the panels determines the space between the pin supports. This means shorts lengths lead to closer supports, which increases the number of the supports and thereby the overall cost of the formwork.

Fig. 6. Formwork supports and membrane laying

As discussed in section 1, the formwork mould prepared by Van Roosbroeck [27], had pin bed spacing 3-5 cm which demands large number of support pins. Accordingly, a mould of 2x2m, for instance, would on average require about 2500 pin supports. And to minimize the number of the supports and to keep a relative smoother surface, this study randomly selected 25 cm long and 7cm wide timber panels. And the 2 m diameter dome is supported by less than 64 supports made from timber sized 5x5 cm which are erected from a ground surface. A steel plate of 30mm wide was laid over successive supports to provide support to the timber panels and lateral ties as well as shown in Fig. 7.

Fig. 7. Formwork membranes in position

Results and Discussion

The construction of the formwork for the intended curved surface was successfully erected and fitted model shape. As it can be noted from Fig. 8, the smoothness of the surface showed some irregularities and gaps at the joints between successive panel strips.

Fig. 8. Final Dome model

And to create a smoother finish, a thin layer of wet gypsum coat was applied which provided a smooth surface finish. Finally, the concrete paste was applied, which was cured for 28 days. And after the curing was over the formwork surface membrane was recovered without for further use. Despite the fact that the model was tested for the dome shape, the membrane arrangement is found to be applicable to be curved in any direction. The feasibility of fitting in to both the sagging (concave) and hogging (convex) shapes is demonstrated to be practical. Moreover, significant carpentry works were required to make cuttings and fitting modifications of the panel shapes at the ends of the panel strips with smaller arc lengths. This can be described to be the main challenges with the arrangement at the end edges.

Conclusion and recommendation

The arrangement of the timber panel was found to be flexible to fit any curves (of positive, zero and negative curvatures). And the optimum dimensions of the prototype panel determined the smoothness of the surface membrane. The panels retrieved after the curing are retrieved to reusable for farther use. The arrangement of the timber panels with a rubber lining to be flexible to various curves demonstrated the feasibility of using such reusable formwork membranes. And this can save the formwork cost from use and throw. The difficulty of fitting at the end edges created from the rigidity of the timber panel needs further refinement with adjustable panel designs. For the future, the paper recommends further study to be made to automate the vertical support pins with a computer-controlled stepper motor driver. Moreover, studying the cost and economic impacts of the reusable formwork with adjustable vertical supports are the future focus of study.

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ВКЛАД АВТОРОВ | CONTRIBUTION OF THE AUTHORS

Х.Й. Дамир – теоретические и конструктивные аспекты систем опалубки, а также изучение передовых материалов и технологий для изготовления бетонных оболочечных конструкций; М.И. Рынковская – анализ материалов для статьи, результатов; И.А. Сереке –тематические исследования и реальные примеры, иллюстрирующие лучшие практики в области опалубки бетонных оболочек.

H.Yo. Damir – theoretical and design aspects of formwork systems, as well as the study of advanced materials and technologies for the manufacture of concrete shell structures; M.I. Rynkovskaya – analysis of materials for the article, results; I.A. Sereke – case studies and real examples illustrating best practices in the field of concrete shell formwork.

КОНФЛИКТ ИНТЕРЕСОВ | DISCLOSURE

Авторы заявляют об отсутствии конфликта интересов.
The authors declare no conflict of interest.

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