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CONSTRUCTIVE VARIANTS FOR PERSONALISED FORMWORK

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Abstract: *The aim of this paper is to explore the possibility of working with a personalized reusable composite formwork in order to obtain architectural shapes for roof and wall elements without material loss. Starting with the analysis of the market needs, the definition of the functions and continuing with the conceptual and technical solution proposals, we created a formwork variant that can be reused for different complex shapes. The researches set on sight different variations of the material used, their thickness and the contact surface given by the support elements.*

Key words: personalized formwork, conceptual variant, construction variant, rod, membrane

1. Introduction

The construction industry is a domain where, although specific structural elements are strict, the desire for personalized architectural shapes is increasing. Traditional formwork requires a lot of material and quite a complex process to obtain some shapes. In the other hand, the new printing technology is mostly applied for straight elements, so the need for reusable personalized formwork is a must in this area.

2. Background

Taking into account the now-a-days approach upon architectural requirements, attempts and test were made in order to determine solutions for personalized formworks. Traditional material usage such as timber/ plywood/ tego and metal involve lot of material waste. The re-usage/ recycling are not applied in such cases, because most of the time, after concrete pouring, the formwork is useless (the same shape is likely to be used twice). The possibility of using formwork without material loss for a complex architectural shape is still an unsolved problem for the construction domain. Little has been made in this domain: starting with researches like hyperbolic shapes made with fixed wooden frames and cables plus fabric material[1], [2], upgrading to adjustable timber support for fabric [3] and closing with the modern technique of 3D printing, where also fabrics and carcass are used [4], are solutions proposed for this issue. By taking into account all these hyperbolic versions – casing and materials – we tested a variant for a personalized formwork (without formwork damage) in order to obtain different 3D parabolic shapes.

3. PLM analysis

3.1. Obtaining conceptual variants

The first step into determining a solution for the personalized formwork was the market research. By filling out forms and questionnaires, we determined which are the demands in this area. Engineers, workers, architects and sales representatives were questioned about their needs when working with a formwork and their expectations from a new product. The table below shows each type of requirement and the obtained specific function. The functions were obtained thought group brainstorming sessions.

Table 1: Demand – Function correspondent for a personalized formwork

Function n°	Notation	Demand Type/ Name ⇨	Function Type/ Name
1	F1	architectural surfaces obtained with little material loss	diversity (with equipment re-usage)
2	F2	minimum cost	cost
3	F3	quickness in execution	handiness

4	F4	safety	safety assurance
5	F5	resistance	load resistance
6	F6	formwork monitoring	control
7	F7	number of usage	viability
8	F8	concrete vibration	vibratory compaction

By using hierarchic methods (triple cross method), each of these functions were ranked in order to determine their importance and their role in the design process for the formwork variant (Figure 1, 2).

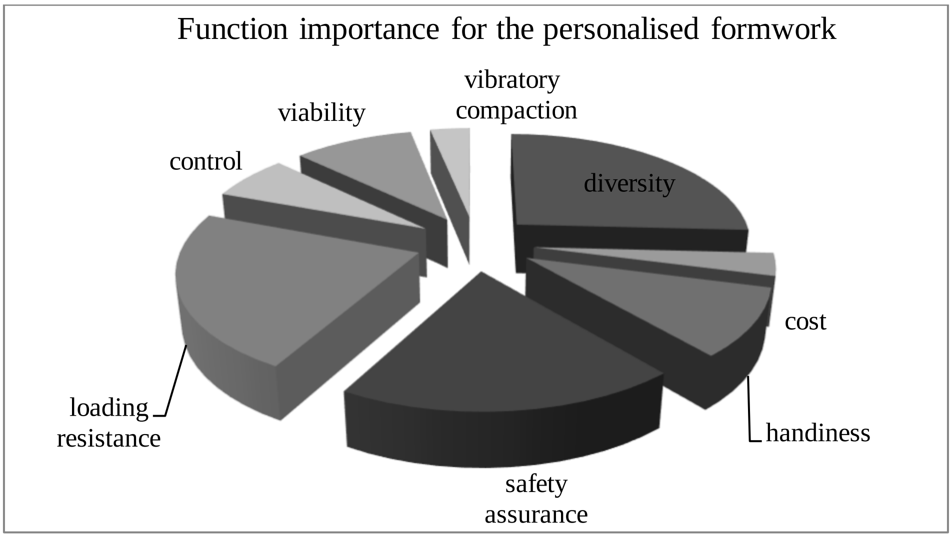


Figure 1: Function importance - chart

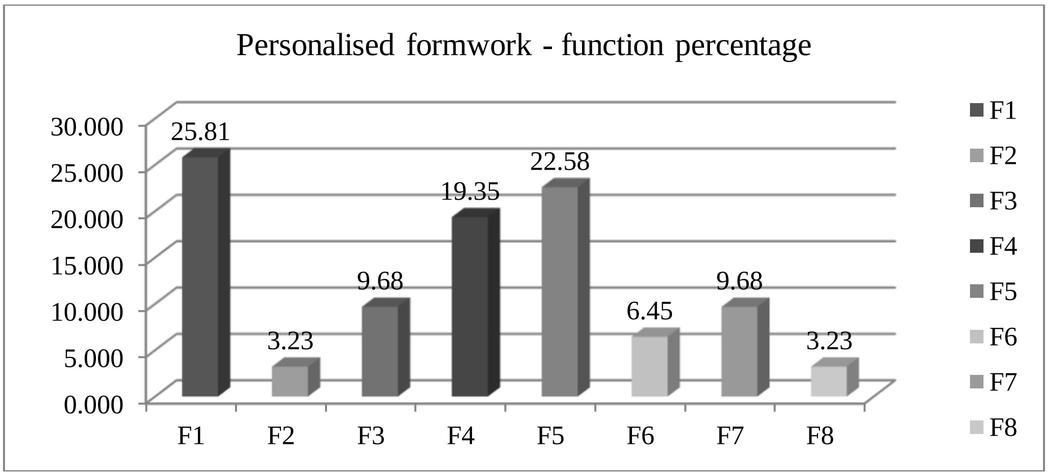


Figure 2: Function percentage for personalized formwork

By analyzing the above data, the top 5 functions kept for the final part of the PLM approach were:

- the diversity - with equipment re-usage;
- load resistance;
- safety assurance;
- viability;
- handiness.

In order to determine possible conceptual solutions for each type of function, a new set of brainstorming sessions was organized. After the conceptual solution enunciation, a focus group was put together in order to sort the proposed ideas, to find other solutions for gaps and to determine which one is the optimum one. Table 2 sums up the proposed conceptual solutions for the personalized formwork's functions.

Table 2: Possible conceptual solutions for a personalized formwork

Function name	Possible solution
Diversity (with equipment re-usage)	Shape formation by using pressure
	Shape formation by using heat
	Shape formation by using other base materials as mould
	Shape formation by pushing
Deviation control	Peg system
	Overlapping system
Deviation control	Poka Yoke system
Load resistance	Tie-rod
	Spring rod
	Transverse lamella
Viability	Timber
	Metallic
	Aluminum
	Fabric
	Composite
Handiness	Multiple simple modules
	One single (large) module
Safety assurance	Blockage system
	Mechanical pouring
	Monitoring and alarm devices

The CPS diagram method revealed the optimum variant for each named conceptual solution by deciding how benefic is the proposition taking into account the criteria and summing up the weight factor to it. The biggest value implies the best choice (Tables 3-7). Hence, we obtained the so called specification book for the personalize formwork.

Table 3: Diversity with equipment re-usage – process type

		Pushing	*Pressure/Heating*	*Traditional materials shaping*
Criteria	**Weight (*)**			
Multiple use	5	+1	0	-1
Ease in usage	3	+1	+1	0
Endurance	2	+1	+1	+1
Price	4	0	0	+1
	Total	10	5	1

Table 4: Deviation control – fixing system between modules

		Peg system	*Classic overlap system*	*Poka Yoke control system*
Criteria	**Weight (*)**			
Sealing	4	0	+1	+1
Ease in usage	3	+1	0	+1
Warning	5	0	0	+1
Price	2	0	0	0
	Total	3	4	12

Table 5: Load resistance – support and fixing of formwork

		Interior + exterior fixing (tie-rod)	*Interior fixing (pressurising rod)*	*Exterior fixing (transverse lamella)*
Criteria	**Weight (*)**			
Multiple use	3	+1	+1	+1
Ease in usage	4	0	+1	-1
Endurance	5	+1	+1	+1
Price	2	0	0	0
	Total	8	12	4

Table 6: Viability

		Composite	*Fabric*	*Timber*
Criteria	**Weight** (*)			
Multi use	5	+1	+1	+1
Ease in usage	3	+1	+1	0
Endurance	4	+1	-1	0
Price	2	-1	+1	0
	Total	10	0	5

Table 7: Handiness

		Multiple imple modules	*One large module*
Criteria	**Weight (*)**		
Multiple use	4	+1	+1
Ease in usage	5	+1	0
Sealing	3	0	+1
Price	2	0	0
	Total	9	7

3.2. Obtaining technical variants

The last step in a PLM analysis is attaining the technical constructive variants.

The "635 Method" was used as a creative instrument in order to obtain as many technical solutions as possible.

The evaluation was made by using decision matrix analysis.

The table below shows all the proposed solutions and the final chosen ones.

Table 8: Constructive technical solutions for a personalized formwork

Conceptual solution	**Technical solution**	**Chosen solution**
Shape formation by pushing	Adjustable needles	Adjustable needles
	Volume growth	
	Overlapping	
Poka Yoke control system [5]	Exterior frame dado/finger joint/ connection with blocking system	Exterior frame miter joint connections with blocking system
	Exterior frame pinned connections with blocking system	
	Exterior frame miter joint connections with blocking system	
Interior fixing solution	Adjustable rod	Adjustable rod
	Permanent formwork spacing elements (lost inside)	
Composite [6]	Elastomers (Rubber)	Elastomers (Rubber)
	Metal matrix composites	
	Polymeric matrix composite (Plastics)	

	Polystyrene foams (Polyfoams)	
Multiple simple modules	Frame/ cases + membrane	Frame/ cases + membrane
Monitoring and alarm devices	Failure/ crack sensor in the frame	Failure/ crack sensor in the frame
	Failure/ crack sensor in the membrane	Failure/ crack sensor in the membrane
	Positioning sensor and alarm	Positioning sensor and alarm
	Interior and exterior temperature	Interior and exterior temperature

Hence, the variant will consist of a re-usable equipment that allows, on a fixed frame, the positioning of adjustable support rods (they have double role - pushing elements and sustaining rod), with different dimensions, that act upon diverse composite elastomeric membrane types, in order to obtain the desired shape. For large elements, simple modules are suggested connected among them by using a control Poka Yoke control system, namely a miter joint connection with blockage. The proposed monitoring devices insure up to date attributes.

By finalising this PLM step, the table below is an enunciation of the basic formwork functions and their corresponding obtained solutions.

Table 9: Function fill check

Function	Solution
Diversity	Fix frame with adjustable rods of different dimensions
Re-usage	Rod recoil and repositioning to a new surface
Usage facility	The usage of manual/pneumatic/hydraulic systems
Security	Blockage joining system
Load resistance	Adjustable rods for concrete support
Viability	Composite (polymeric) membrane
Handiness	Simple modules

Figure 3 is a representation of the chosen technical solution for the personalised formwork. The base frame acts as a support for the adjustable rods. The membrane is fixed on the upper frame and a cassette is put over in order to assure concrete pouring shuttering conditions. The surface remaining free is the mould surface, where the rods act. They are controlled manually (for this test) and push the polymeric membrane. The rods act as support for the concrete, maintaining the membrane to its given shape. During concrete pouring the system is blocked. After the concrete hardens, the equipment can be unblocked, the rods can be retract and the upper frame loosen from the membrane. At this stage the concrete element can be removed and the formwork used for another project.

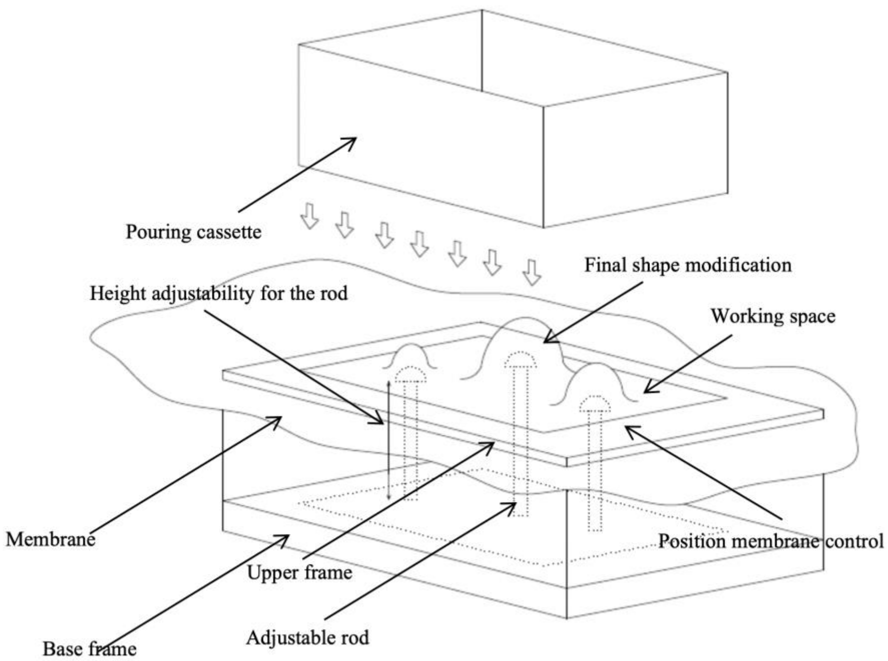


Figure 3: Technical constructive solution - sketch

4. Technical solution tests

In order to determine which and in which way the variables modify the membrane shape and to establish the formwork segment of the usage, we established as variables the parameters named in table 10.

Table 10: Variable parameters

Variable name	Variable type
Material type	SBR , NBR, EPDM membranes
Material thickness	1 mm, 2 mm, 3 mm
Diameter rod	120 mm, 150 mm
Deformation height	up till 230 mm (function of the rupture height)

The fixed frame (considered both upper and base) was made out of steel members, and the rod was positioned in the center. The tests were made upon a single simple module, so no connections were necessary. Also, the monitoring devices were not discussed in this part of the test. The composite materials used as membrane for the concrete are detailed in the following table.

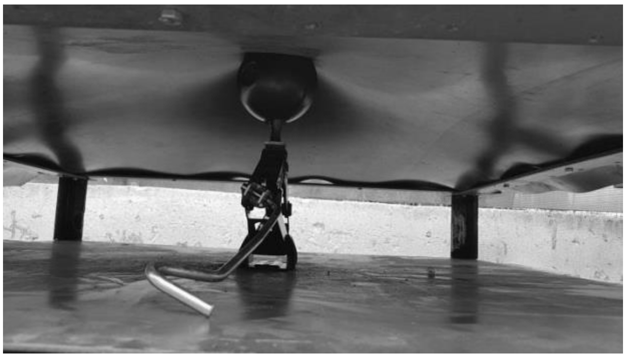
Table 11: Composite materials – input data information

Type/ Name	Thickness [mm]	Specific weight [gr/cm^3]	Rupture/yield resistance [MPa]	Stiffness [ShA]	Yield elongation [%]
SBR	1	1.7 ± 0.05	1.8	65 ± 5	180
SBR	2	1.7 ± 0.05	1.8	65 ± 5	180
SBR	3	1.7 ± 0.05	1.8	65 ± 5	180
NBR	1	1.5 ± 0.05	3	65 ± 5	300
NBR	2	1.5 ± 0.05	3	65 ± 5	300
EPDM	1	1.5 ± 0.05	4	65 ± 5	300

Input data:
- rod used = 150 mm diameter and 120 mm diameter;
- base and upper frame dimensions = 1200 mm x 1200 mm, with a working space (the mould surface) of 1000 mm x 1000 mm;
- maximum deflection height = 230 mm;
- rod positioning = at 500 mm on horizontal axis and 500 mm on vertical axis (taking as the origin the marginal end of the working surface).

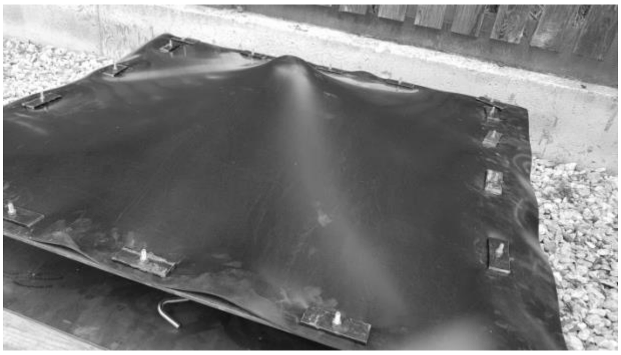
For this test a single rod of variable diameter was used. The membranes were tested successive for each diameter and strained until composite rupture. The concrete was poured at the maximum determined deflection height for each case apart.

Eighteen tests were made. For each membrane type and thickness a series of three tests: one for membrane rupture (in order to determine the maximum deflection height – with the 120 mm rod), one for the rod of 120 mm diameter, and one for the 150 mm hydraulic rod. In figure 4 one can see fractions from the controlled experiments.

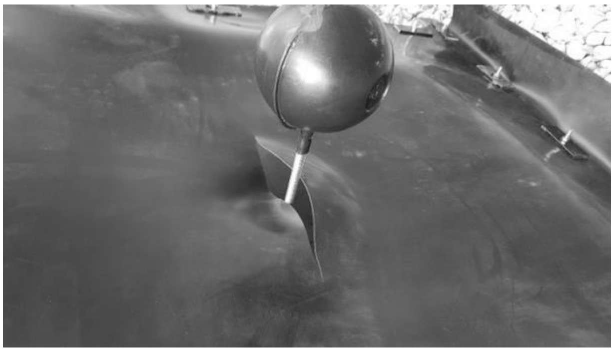


A

B



C



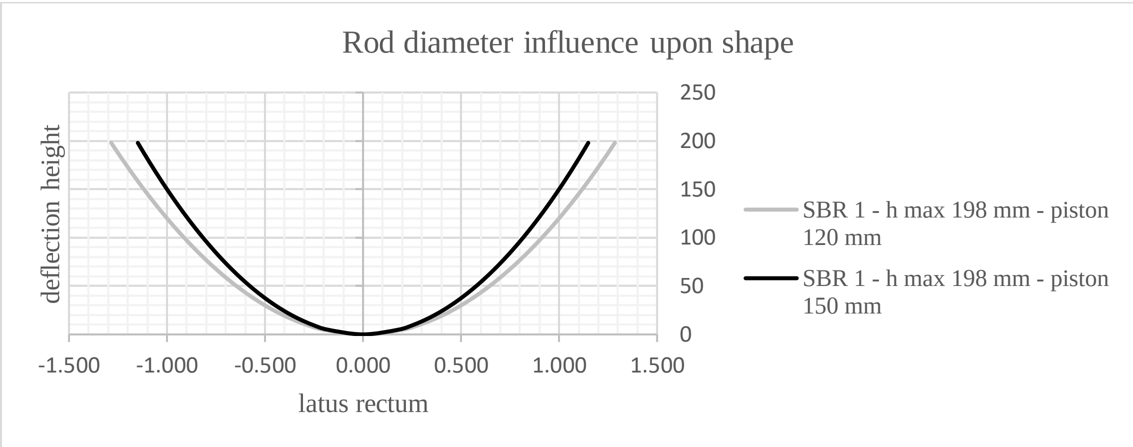
D

Figure 4: Personalized formwork – one rod tests: A. rod view; B. deformation height; C. overall deformation view; D. membrane failure/ fracture

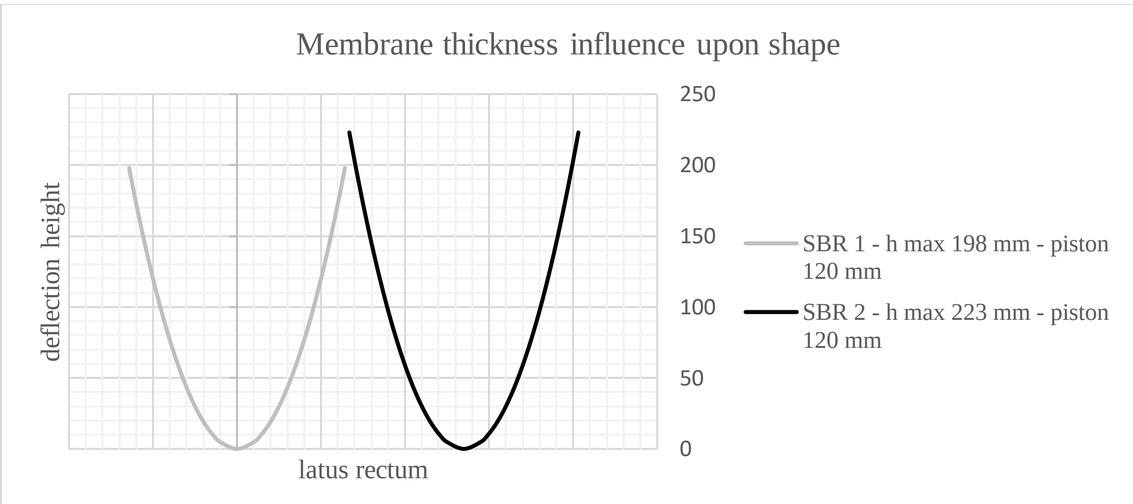
Conclusions regarding the test:

- the rod diameter influences the paraboloid's Gaussian curvature;
- the thickness of the composite influences the height of the deflection;
- the elongation of the material influences the height of the deflection;
- the height of the deflection influences the paraboloid's Gaussian curvature.

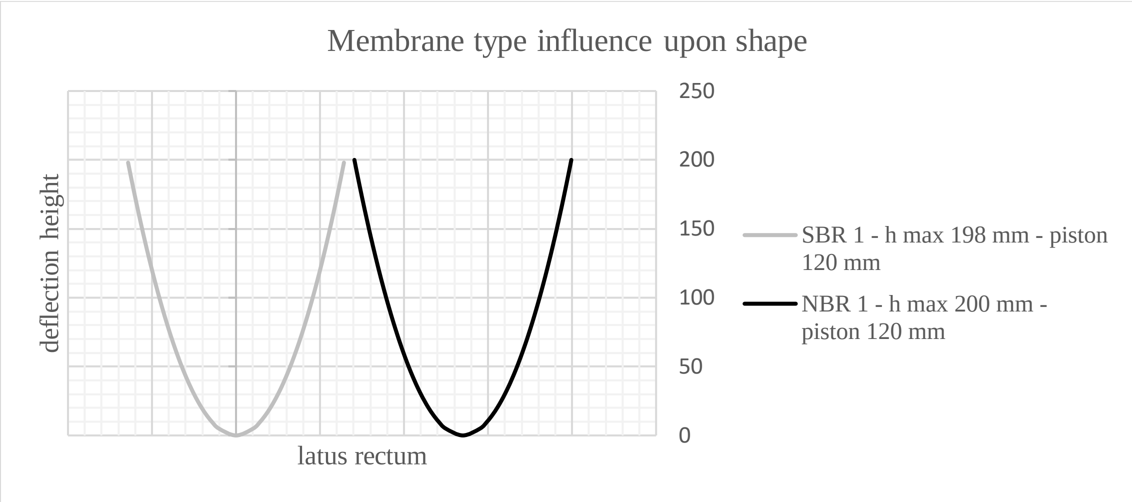
An analytical representation according to the test result was made to observe the notate conclusions (Figure 5).



A – Rod diameter influences the Gaussian curvature (the latus rectum value)



B – membrane thickness influences the deflection height



C – membrane type has little influence upon the deflection height

Figure 5: Result analysis A. rod diameter influence; B. composite thickness influence; C. composite characteristics influence

5. Conclusions

By analyzing the variants for the personalized formwork, one can say that the single rod solution is appropriate for a parabolic architectural surface that does not exceed a fifth of the membrane's length. Function of the rod's diameter, the chord (latus rectum) of the parabola can be modified function of the desired shape by taking into account that an unit diameter is inversely proportional to the chord. Reinforce fiber polymers was established as the proper solution for the membrane, in which case the fraction thickness variables did not modify significant the data. Also, in order to maintain the parabolic shape of the formwork, the peak of a nearby rod must be at a minimum distance of at least the own length of the latus rectum. As future directions, the transposing on larger scales is next be observed and also the membrane's thickness for significant greater values may be put up to test. Also, new tests for concrete pouring variables (height, thickness and class) are on the verge of preparation.

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