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PHD THESIS

THE DEVELOPMENT OF CERTAIN TEHNOLOGICAL EQUIPMENTS USED TO STREAMLINE PROCESSES IN THE CONSTRUCTION DOMAIN TAKING INTO ACCOUNT THE PRODUCT LIFECYCLE MANAGEMENT

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Key words

This PhD thesis includes the following keywords: construction equipment, product life cycle management, custom formwork, complex shapes, splines, PLM analysis, optimal solution, epoxy membrane, finite element analysis, formwork management, Augmented Reality.

SUMMARY

INTRODUCTION

The field of construction is constantly changing through new architectural perspectives, modern technologies and customized requirements.

Of all construction equipment, formwork, although not an integrant part of the construction itself, has a significant influence, up to about 20% of the cost of common concrete works and 40% of labor consumption (where the costs include both the modifications and the purchase of wooden formwork and wooden plywood, as well as investments for simple or complex metal formwork – for example, sliding or climbing formwork).

Investments in this sector are high, technology in countries with financial power is developed, and concrete constructions have complex architectural forms. Alignment to these results must be done efficiently, productively and according to the context of the macro environment.

EQUIPMENT EVOLUTION

The need for survival and safety led to the emergence of living spaces. Since ancient times man has been preoccupied with finding and later building a shelter for the family (starting with the Stone and Bronze Ages). This was the starting point and development of constructions.

Beginning with 600 BC the Romans used a concrete "opus caementicium" (a mixture of volcanic ash, lime mortar, sand and gravel) on a large scale. During this period, many edifices were built with arches, vaults and domes as a distinctive sign. After the fall of the Roman Empire, the period that followed was especially marked by invasions and attacks. The main constructions erected were of the military type. After the end of this period, after 1000 AD, during the Middle Ages, people started building places of worship and later urban residential buildings. Thus, during that period, construction equipment such as digging (wooden and metal screeds), lifting (wooden systems based on pulleys), transporting (wooden carts with wooden wheels, stone or metal) and then scaffolding, scaffolding and formwork which were predominantly made of wood and metal.

After this period followed the Renaissance, a cultural movement conducive to the development of art and literature, the discovery of new geographical territories, a period dominated by revolts and the delimitation of new borders. Continuing with the 1700s, the Industrial Revolution begins, a milestone in the evolution of construction equipment, based on the inventions of the era. Therefore, after the discovery of concrete, the construction of monuments with special shapes began again, with techniques that tested the engineers of the time.

THE PRODUCT LIFECYCLE MANAGEMENT (PLM) APPROACH FOR THE DESIGN OF NEW FORMWORKSOLUTIONS

Developing the bibliographic research part, the minuses resulting from the study of current formwork can be covered by using the PLM concept in the design of a product. Here, material resources will be used efficiently and it will be ensured that the time required for manufacturing, use and maintenance is minimal.

Because from year to year the requirements imposed by technology develop, and the current needs to build a space differ from one developer to another and from one beneficiary to another, it is necessary to create an equipment that satisfies these demands.

In other words, after the analysis of the types of formwork used today, the need to develop new formwork solutions to meet market requirements appears.

In order to obtain an effective constructive variant for the construction equipment, the PLM concept will be used, where, in the process of designing new solutions, the product will be followed throughout its life, starting from market requirements, design, constructive solution optimization, manufacturing, exploitation to recycling, from the idea till reintegration into the environment.

In the first stage, that of market research, it is desired, first of all, to identify the aspects that need to be improved, in the formwork elements, by determining the needs/requirements for such a product.

After establishing the requirements, the next step is to determine and analyze the functions:

- the identification of functions based on the requirements of the beneficiaries (respectively the enumeration of functions and their ranking);

- the selection of functions with significant weight.

The triple cross method was used to establish the hierarchy and select the most important functions.

Then, the selected functions are broken down into primary functions, for which a number of technical implementation solutions are proposed. To validate the technical solutions found, the TRIZ method and related software were used.

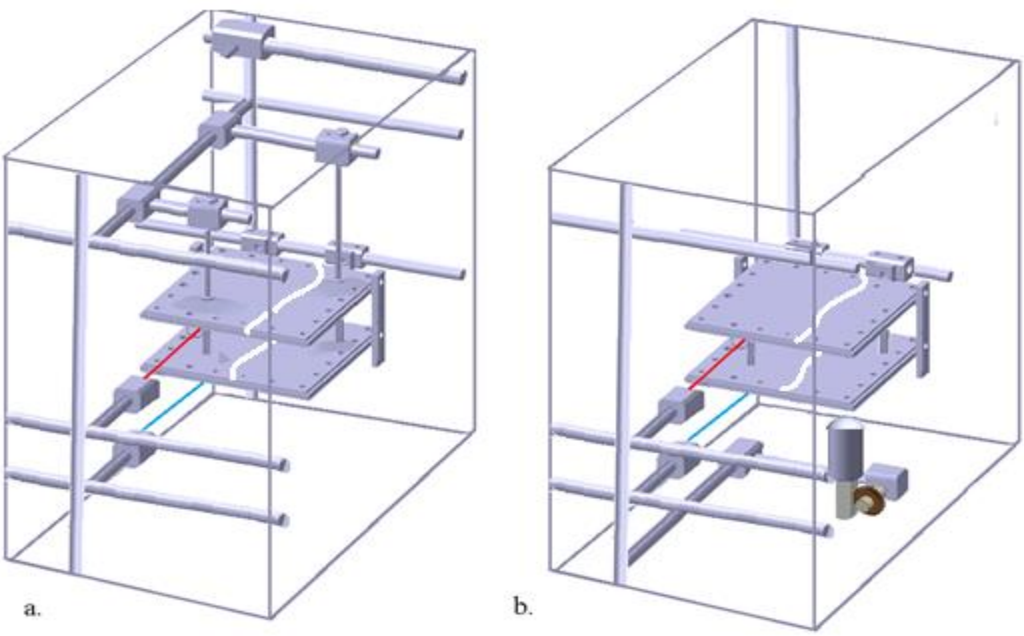
To develop the optimal solution, the morphological matrix method is used, where based on the established evaluation criteria (and their weights), the possible constructive solutions are analyzed and the best ones are identified.

Two solutions with the highest score are proposed for testing, verification and validation. These solutions are presented, analyzed and the operation is described and the component milestones are detailed.

The two optimal solutions proposed for testing, verification and validation are:

- variant 1 with cable system, composed of a fixed frame, on which the cable-type modeling elements are positioned and locked and which, for superior strength, has stiffening elements positioned under the lower membrane. Fastening the cables to the membrane is done without perforation by using glued or perforated discs, crossing the two membranes and spacers. To limit the stresses in the perforated area, washers are placed above and below the coupled membrane (Fig. a).

- variant 2 with plunger, composed of a reusable equipment that allows, on a fixed frame, the positioning of adjustable plungers (with double role - pushing elements and support rod), equipped with heads of different diameters and acting on the formwork panel - a composite elastomeric membrane. Fixation of the rods is done at the base of the fixed frame by locking elements. In the case of reinforcements, in the version of active reinforcement, meshes/rings welded/glued to the spacing elements are used or connecting pieces are used (Fig. b).



DETERMINATION OF THE MATERIAL CHARACTERISTICS FOR THE FORMWORK PANEL

Because in the equipment verification stage, both in the numerical calculation section and in the finite element analysis section, certain material characteristics of the component elements of the equipment are used as input data, the exact determination of their values was desired - for membrane formwork panel.

Thus, the materials used are established, the experiment is designed, the experimental program sheet is drawn up (with the presentation of: the purpose, the type of test-respectively tensile stress, the specimens, the equipment used and with the establishment of the variables and the range of variation of the independent variables) . The INSTRON 5587 universal testing machine was used for the tests.

Next is the conduct of the experiment, the collection of data (results) and their interpretation.

The results obtained for each individual membrane, more precisely, the specific material characteristics, which will be used in the analytical calculation and the finite element analysis of the behavior of the modeled membranes, under the stresses of concrete loading.

VALIDATION AND DEVELOPMENT OF THE IMPROVED SOLUTION

The next step is to verify the proposed equipment and validate it.

Thus, it is checked for the acting forces that may occur during the pouring of concrete:

- plunger type modeling elements;
- cable-type modeling elements;
- stiffening elements;
- the membrane.

The equipment is verified using analytical calculation (plunger, cable, stiffener) and numerical finite element modeling (membrane).

For the analytical calculation, an algorithm for dimensioning the formwork equipment components is proposed.

The calculation of the membranes is done in the elastic domain, at the limit state of normal operation.

For the finite element modeling (FEM) part, two calculation programs were used: Simulia and Abaqus.

As input data for modeling, the following were noted: membrane type (material characteristics), membrane length, membrane width, membrane thickness, concrete layer thickness, position of modeling elements, level difference between modeling points, applied forces.

When using finite element analysis (with "Simulia"), the value of the maximum deformation height of the membrane in the elastic domain and its resistance to concrete pressure was determined.

Based on the data provided by the calculation program, the elastic range of the composite material was established. Through this analysis, the reusable character of the proposed solution is demonstrated. Thus, insert membranes work in the elastic medium up to a deformation of up to 43 cm. By using a stiffening (mesh type) in the lower area of the membrane, displacements are blocked and loads can be much higher.

In parallel, an analysis was carried out in the Abaqus program, where a more detailed analysis of the request of the membrane-type formwork panel was desired, applying several modeling points

After the equipment is dimensioned, it is analyzed: the mode of operation, the use, the maintenance of the formwork and the recycling of its landmarks (according to the PLM stages). Finally, based on the feedback from the completed stages, the improved solution of the formwork is obtained.

Thus, the proposed formwork solutions are analyzed and each milestone is targeted to identify what needs to be manufactured and what needs to be purchased from the market (such as: formwork frame, formwork panel, fasteners, membrane, elements plunger-type molding elements, cable-type molding elements, plunger locking elements, cable locking elements, spacers, reinforcement and stiffener locking elements, stiffeners, etc.).

In order to determine how to carry out the assembly, it is necessary to detail the location where the concrete is poured.

The chosen solution, for the previously analyzed equipment, is that of casting the element in a production hall. Then, the order of its assembly operations is presented.

For a correct execution of the installation of the equipment parts, it was proposed to develop a formwork manual with a description of the component elements, the necessary equipment and the steps to follow for its realization.

Another criterion taken into account is that of the way of use. The formwork proposed for the creation of the architectural surfaces will be used in a production hall, for the creation of prefabricated elements, which will be mounted directly on the construction site. Two variants of use are proposed. But it is shown, that another, more demanding one is also possible, with the use of warning or information sensors.

Another aspect, for which the equipment must be analyzed, is that of maintenance. Thus, it is shown that the component parts must be checked, cleaned, degreased and properly stored.

Following the efficiency of the proposed solution, the need for a correct management appears. In this sense, a logical scheme of the management of the equipment milestones was created.

Knowing that each item can be purchased from a supplier or ordered for manufacture at an executed, the scheme takes into account the necessary supply times, for each of the items that define the formwork equipment. Thus, it is necessary to have permanent knowledge of the stock of equipment components and the condition of each one. The selection is usually made according to the stock: the necessary available equipment is chosen, which can perform the "task". It is worth noting the development of a formwork selection diagram from management.

The following shows the advantages of using augmented reality through barcodes (QR), which is done for each shape - material - size - supplier.

And, for better product management, a product catalog was proposed that includes all types of formwork in the warehouse.

The last stage of the analysis of the equipment is that of taking it out of use - recycling.

For the formwork equipment, four categories of waste have been identified that can be introduced into the circuit: non-ferrous materials, metals, electrical and/or electronic equipment and wooden components.

Thus, following the analysis, possible new more efficient technical solutions are identified, which satisfy the imposed standards.

The feedback sent to the designers leads to an improved constructive solution, which is analyzed from the idea to recycling.

EXPERIMENTAL RESEARCH

After the development of each stage within the life cycle, after the part of analysis, verification and validation of the solution(s), the experimental stage is carried out which reproduces on a certain scale the operation and the way of use of the customized formwork.

in the first part of the chapter, the elasticity of the membranes is analyzed, which are subjected to equibiaxial tension, using two spherical plungers of different diameters.

The aim of the study is to determine the maximum value of the deformation of the membranes. For a 1m x 1m membrane, the maximum strains in the elastic range are around 200mm, confirming the results from the FEM analysis and the tensile experiment.

Thus, the possibility of reusing the membranes is validated within a value of ±200 mm of their deformation (with mounting eyes at one meter). The best membranes, according to the data obtained, are SBR 3mm and SBR 3mm with insert.

Next, experimental determinations are made for the membrane-type formwork panel without stiffeners. This experiment verified the resistance of the membrane taking into account the weight of the concrete, using plungers with adjustable heads for modeling. For this test, the membrane type and the distance between the molding elements were taken as variables, and the tests were for one, two or three plungers. Here, no stiffeners were used at the base of the formwork, and the forces acting on it were previously calculated for the weight of the 5cm thick concrete.

The results highlight how the membrane type influences the strain value. For the same value of the distance between modeling points, lower deformations are obtained when using membranes with higher characteristics, and decreasing the distance between modeling elements leads to a lower value of deformation.

The following experimental research concerns the membrane-type formwork panel with stiffeners, using paired cables for modeling and where the forces taken into account are the ones of the weight of concrete with a thickness of 5cm. For this test, the membrane type and the distance between the modeling elements were taken as variables, and the membrane modeling was performed using one cable, two cables, and three cables.

Comparing the solution with and without stiffeners, one can highlight the high precision when using the mesh cable system for stiffening, where the height differences (deformations) after casting tend to zero.

For each type of research, the research program sheet was developed (with the definition of the problem, the classification of variables, the type of investigation, the method, the type of analysis and conclusions), the experimental stand was presented and based on the experimental program, the experiments were carried out, collected the data and analyzed and interpreted it.

Experimental research confirms the correctness of the constructive solutions proposed for the customized formwork.

GENERAL CONCLUSIONS PERSONAL CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

General conclusions

In order to reach the objectives proposed in the thesis, we started from a market research, which highlighted the fact that the "formwork area" is slightly developed, then, that the requirements of the beneficiaries regarding the structural forms in the constructions are diverse, and the formwork used, in general, today, do not fully satisfy them.

PLM analysis was used in terms of developing effective solutions for a new product - formwork, which would satisfy the needs, respectively the requirements of the beneficiaries, from the idea to recycling and reintegration into the environment.

In the analysis, through the lens of PLM, the stages of market research for the correct identification of requirements, which is essential for a new modern product, were insisted upon.

Thus, the macro-environment was studied, because it essentially influences the demand. This is why studies must be carried out permanently, consistent with the real situation on the market.

Based on primary and secondary research, market requirements were identified.

The proposed methodology, by selecting the requirements and establishing their weight (importance), leads to the establishment of functions for a new product. This ultimately allows the division into primary functions and their ranking in order to find constructive solutions.

Thus, the evaluation criteria were chosen, which support the request: high productivity by reducing times (of assembly, use and maintenance) and costs (by reusing formwork).

The development of the optimized solution, for the product, was done starting from the selected functions, so that, then, using creative methods and evaluating the multitude of possible variants generated, to finally arrive at the solutions that satisfy them the best.

The technical solutions for the implementation of the functions, chosen on the basis of rigorous evaluations, allow the construction of the new product – customized formwork used to create complex shapes by using elastomeric membranes shaped with plungers or cables.

This was followed by the "simulation" of the following stages in the life of the product, which through "substitution" allow, through questions, answers and feedback, to finally obtain an improved solution of the formwork product, which meets the expectations during the entire life cycle.

Thus, the following are checked: operation, dimensioning of technical solutions (through analytical calculation and finite element numerical simulation), manufacturing, assembly, use and recycling.

It should be noted that a management of equipment milestones was proposed using R.A. and specific maintenance.

The final stage was the validation of the proposed solutions, by carrying out experimental tests, which would confirm the possibility of implementing such equipment.

<u>Personal contributions</u>

The originality of the scientific research is conferred by the personal contributions brought to this work. These can be noted throughout the doctoral thesis through analyses, syntheses, proposed constructive solutions, laboratory experiments and applications of augmented reality.

From the analysis of the chapters of the doctoral thesis, a series of own contributions can be distinguished:

- The study of the field, of the research carried out here and the original analysis of the formwork systems;
- Analysis through the prism of PLM of the development of a new product - namely an effective formwork for the creation of complex surfaces, where it is noted:
    - the SWOT analysis;
    - the use of creative methods for finding new ideas (brainstorming, brainwriting, Ishikawa fishbone diagram);
    - requirements analysis (Pareto chart);
    - creation of the diagram of ideas (simple or mind-map type);
    - conducting primary market research through field work (questionnaire);
    - analysis and ranking of functions (triple cross method);
    - finding possible solutions (TRIZ method, morphological matrix method);
    - determination of original formwork solutions for complex shapes: the use of auxiliary materials as a support base (liquid column, granular materials – talc, sand), the use of composite strips shaped and fixed by reinforcing agents, modeling by pulling or pushing elements (plunger, cables) etc.;
    - determination of the optimal solution (Pugh method);
    - numerical simulation of the behavior of the proposed solutions;
    - analysis of the operation, manufacture, assembly, use, maintenance and recycling of the new product;
- The original approach to formwork equipment modeling;
- Experimental research to validate the proposed constructive solutions;
- Elaboration of a case study analyzing the assembly of a formwork using Augmented Reality;
- Formwork management using QR codes.

In the thesis, both the theoretical analysis of the solutions and their applicative nature were pursued.

Thus, the analytical calculation regarding the formwork allows the optimal pre-dimensioning of its components, and the study of the spline lines leads to the correct establishment of the membrane modeling points.

The numerical analysis of the behavior of the formwork, respectively of the membrane required under the forces of the weight of the concrete, led to the validation and determination of the field of applicability of this equipment. The in-depth study highlights the most unfavorable situations regarding the dimensions and elasticity of the membrane, but also the rigidity of the formwork.

As shown above, experimental studies validate the constructive solution that uses membranes as a formwork panel.

Proposal for future research

The development of technological solutions, the discovery of new materials and in general the dynamics of the environment allow the development of new constructive solutions.

The following researches are proposed for the future:

- studies regarding the automation of the adjustment, respectively the modeling of the membrane (spline curve-modeling points-computer-motion command-step by step motor-cable movement-automatic blocking-repeat...);
- studies regarding the establishment of the optimal realization technology for complex sculptural surfaces, with variations in height greater than 300 mm, using composite materials "cast" on modeled surfaces with the help of mesh-type systems, as in the case of the proposed solution;
- studies regarding the establishment of the optimal realization technology for ruled (regular) sculptural surfaces using formwork that uses the proposed solution.

This work, elaborated during several years of research, leaves the way open for the development of innovative experimental systems in this field.

In the future, new algorithms, new methods and programs can be developed which, used for analysis, allow obtaining much more precise solutions for structural elements with complex shapes.

We hope that the topic addressed in the doctoral thesis will arouse the interest of specialists in the field and be a starting point for other applications.

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