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PERFORMANCE BASED APPROACH IN DESIGN OF FREEFORM SPACE STRUCTURES

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Abstract. *This paper is related to the fact that use of computational tools for form generation, analysis and digital fabrication (CAD/CAM/CAE) in an efficient way enables accurate representation of ideas, simulation of diverse impact and production of rational design solutions. Application of geometrical and numerical computational methods and adoption of performance based priorities enables formal exploration in constrained conditions and improvement of architectural engineering design process. Implementation of advanced technologies in 3D digital design process facilitates production of unconventional complex designs, their verification by construction of physiscal models and exparimental diagnostics, as phase preceding construction of real structure. Within this work concept that provides design of non-standard, context-specific, freeform structure using rapid prototyping technology and 3D optical measurement will be reviewed. The analyzed design solution of roof structure above atrium of National Museum in Belgrade has a function to demonstate the effectiveness of this approach.*

Key words: *performance based design, freeform, space structures, CAD/CAM/CAE, rapid prototyping, 3D optical measurement*

1. INTRODUCTION

Integration of digital technologies in the process of production of space structures became a standard approach in the field of architectural engineering design. The rapid development of innovative technological approaches is becoming immensely significant, demanding our attention due to their aesthetical and technical implications.

Architecture increasingly finds its expression in freeform, deprived of impression of urban and structural topology and continuity with historical styles, ignoring conventional aesthetics in the favor of experiment based digital generation of form. Structures for covering large public spaces are more and more designed with innovative complex shapes, combinations and/or modifications of simple geometries. These innovative shapes are

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created through the interaction between practical considerations for the structures and the artistic sense of the designers, meeting complex contextual and functional influences. Freeform are generated by innovative geometric computational technologies, such as NURBS. Implementation of NURBS enabled new formal solutions, which until emergence of CAD/CAM/CAE technologies were hard to conceive, represent and produce.

Maybe more important than innovations in building's form is the change in the production process, in which, contrary to the conventional approach, design, analysis, presentation and production become a part of a collaborative process which only depends upon digital technologies, defined in (Kolarevic, 2003) as *digital continuum*. Three-dimensional digital models enabled formal exploration and analysis of generated objects of complex geometry, and implementation of digital fabrication technologies in the field of architecture enabled production of physical models both for verification of ideas and analysis. A design processes in which interdisciplinary work methodologies, traded between engineers and designers, are increasingly occurring, giving rise to hybrid technologies, new materiality and unimaginable forms (Milošević, 2014).

Performance based design (PBD) is approach in which building's performances are included in the process of form finding. Generally, performances can be defined by digital simulations, and in specific, structural performances can be modeled by finite elements (FE), common numerical computational method of stress and strain analysis. Advances in software for simulations enabled, relatively easy, accurate determination of the behavior of structures. And in the case of unconventional freeform designs, whose structural behavior is an empirical unknown, verification of numerical analysis results using digital methods of measurement, is sometimes a required step preceding construction.

This paper investigates the impact of technological advances upon architectural engineering design process. In that respect, the first part presents a brief review of the concept of integration of digital technologies in the process of architectural engineering design, with the emphasis on 3D digital design processes and digital fabrication by application of rapid prototyping technologies, as important sequences of this process. In the following part the performance based design approach and the state-of-the-art in this area will be discussed. And the final part is the case study which demonstrates the effectiveness of this approach.

2. Integration of Digital Technologies in Design Process

Permanent progress of digital technologies opens up new opportunities for their use in the contexts of research and practice in the field of architectural engineering. Advances of CAD/CAM/CEA, VR/AR and CNC technologies, particularly from the middle of 1990's, both influenced building design and construction. It should be noted that utilization of potentials of these technologies in architecture represents an answer to automated production in automotive, aerospace and shipbuilding industries.

Digital technologies overcome the limitation of conventional procedures of ideas presentation facilitating design of complex, curve geometrical forms. Unlike the conventional approach freeform are generated by geometric computational technologies such as Bézier curves, B-Splines, NURBS, Subdivision surfaces, T-Splines, etc. Currently in the field of engineering NURBS represent a dominant technology for freeform representation in CAGD. To mass application of this tool contributed advantage that freeform geometries, capable of dynamic transformations, could be represented as easily as flat shapes or conical sections

(Rogers, 2001). On the other hand, diverse computational methods, described in (Kolarevic, 2003), enabled automatic form-finding and production of series of formal solutions, their variations and transformations, thus exceeding the role of a computer as a tool that mimics the manual process of drawing (Computer Aided Drafting).

2.1. 3D digital design process

According to (Kolarevic, 2003), the process of 3D design and production of 3D digital models is considered as a beginning of digital production on the design level.

Methodologically it is possible to differentiate two procedures (Striech, 1996). (1) The first procedure includes translation of digital model dates, created on the basis of sketches or ideas, to CAM software which generates CNC instructions which are then transferred to equipment for production of physical models such as 3D printer. (2) Second, inverse process, is *reverse engineering*, which includes development of the concept on work physical model, and then by the means of 3D scanner its translation to digital model. Scanning of physical models results in a scheme called point cloud, which is then interpreted by conventional software with the aim of creation geometry approximation of the work model.

Independently from selected procedure the point is in production of 3D model which defines geometry, main elements, dimensions and other relevant data necessary for following phases of the design process.

2.2. Digital production - rapid prototyping

Generally, the process of digital production is performed in several steps. (1) The first step is analysis of information of all parts of a three-dimensional CAD model by application of CAM software. (2) The second step is transfer of all analyzed information to CNC code which is in the form of specific instructions for different production machines. (3) And the final step is the production which is realized by application of some of the techniques such as: two-dimensional cutting, subtractive, additive or formative fabrication (Kolarevic, 2003).

Rapid prototyping (RP) is a term used to denote diverse technologies, conditionally speaking, for fast production of 3D physical models (prototypes) based on geometry defined by CAD software (Snaches, 2005). The term rapid should be taken relatively, giving that procedure is considered rapid in comparison to the time necessary for conventional methods of model production, causing reduction of the production cost. The models produced by this technology are widely used for freeform visualization, whose understanding by conventional methods of presentation is insufficient. The technology is also suitable for visualization of different phases of a design process - from conception proposals to verification of assembly components and details of final solution, thus enabling designers to test ideas. RP could represent the step preceding digital production of a real structure.

Initially, RP was developed for advancement of industrial production, but it found application in different fields such as medicine, architecture, art and design, etc. Considering that by RP it is possible to produce models based on CAD generated geometry, accuracy up to 0.1 mm, its suitability for different applications is clear. In addition to verification of formal solutions, the technology could be used for verification of assembly, composition of joints, and different required functional tests. Application of models produced by RP as a medium of communication between designer with other participants in design and construction processes or clients represents another possible use.

All RP technologies have in common that physical models are produced progressively by addition of thin layers of material - process of Additive Fabrication (AF). Digital models necessary for this fabrication process are composed of two-dimensional layers, obtained by division of three-dimensional CAD model in thin parallel slices, where distance between the slices represent the layer thickness. Information about each individual layer is specifically transferred to the production machine head, and that process repeats until the end of model production. The layer is produced by depositing, sintering or stiffening of material, and model so that each subsequent layer deposits directly on the previous. Because of described production process technology is also referred as Layer Manufacturing (LM).

Currently available technologies greatly differ depending on the time required for the model production, mechanical properties of material used for model production (epoxies, paper, polyester, ABS, polyamide, wax, etc.), cost of production, finishing quality, etc. Selection of adequate technology depends upon purpose of the model (Pham, 1998), (Karapatis, 1998). According to (Sanches, 2006) it is possible to make following classification of modeling devices: (1) Concept Modeler - 3D Plotter (3DP), Multijet Modelling (MJM), 3D Printing; (2) Format Modellers - Stereolithography (SLA), Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), PolyJet; (3) Functional Modellers - Selective Laser Sinterinl (SLS).

Production of a model by 3D plotter technology is fastest, cheapest and consequently of less accuracy and poor finishing. The second group devices are highly precise, they can use wide range of materials, and produced models have good quality of finishing, production is more expensive, but models beside for visualization cloud be used for testing of assemblage, and certain functional experiments. The third group devices have characteristics greatly similar to the second group devices, with the difference that applied materials possess mechanical properties that enable their use in functional tests, the production is more expensive, though model's finishing of models is poorer then finishing of models produced by the second group devices.

The advantage of RP for freeform structure model production, comparing to traditional methods of production of architectural mock up and considering various parameters (precision, prize, production time, model purpose, etc.) is undoubted. Assumption is that in the future digital production technologies will have wider application in building industry (Kurth, 1998), implying many positive consequences and overcoming standardized production rigidity in favor of mass-customization, unaffecting production economy and efficiency.

3. PERFORMANCE BASED DESIGN APPROACH (PBDA)

Different scientific methods were used for developing innovative structure systems. A well known example is that of wire models used by Gaudi for realization of his famous buildings, and by Otto for form-finding of his hanging roofs. Designers like Fuller, Nervi, Candela, Toroja, Isler and others also experimented by producing physical models in order to realize innovative structural solutions (Nestorović, 2000). Application of digital 3D modeling, analysis, simulations and production of physical and virtual prototypes represents a logical continuity.

Performance based architecture design represents an approach in which building performances are used for design conception. In the broadest sense performances (form financial, spatial, social to technical - structural, thermal, acoustical, etc.) are defined by digital quantitative and qualitative simulations (Grobman, 2012). Structural performances, which are the focus of this work, are commonly modeled by Finite Elements Method – FEM (Hughes, 2000). Diagnostic of structural behavior directs thinking about next steps (i.e. modification of form or reorganization of structure) in iterative structural design procedure. In that respect, primary suggested geometry can be a subject of transformations with an aim of optimization of determinate criteria. FEM, relatively easy, enables superposition of different analytical estimations and comparisons of alternative solutions thus helping selection of solution with optimal performances. This design approach differs from the conventional one in the sense that the structural performances are used in the process of design conception, and not after the form is defined.

3.1. Simulation and modeling

Simulation as a scientific method enables acquisition of knowledge based on the replication of reality. An advantage of this method in PBDA is used for verification of structural behavior of real engineering structures by their replacement by adequate digital, virtual or physical models. Digital simulations are implemented by computer software for structural analysis (CASA), based on FEM. And in the case of physical models analysis, models constructed by adequate technology, in adequate scale and from adequate material, are analyzed by selected measuring procedure, with the aim of obtaining results which will guide corrections of design solutions. Modern CAD/CAM and RP technologies offer different possibilities for production of physical models in terms of accuracy, materialization quality and rate of development. These models could be used as functional models for reliable determination of structural behavior. In accordance with the analyzed problem, it is necessary for models to represent as accurate as possible replicates, in order to obtain reliable analysis results. In the context of this work physical models constructed by RP technology will be used as functional models for conducting 3D optical measurement analyses. Technologies are selected due to their reliability, efficiency, accuracy and economy.

3.2. Structural analysis of physical models - 3D optical measurement

3D optical deformation analysis is an advanced procedure that can be used for analysis of real structure's physical models. The technology provides insight into behavior of the structure, its components and materials. Determination of static and dynamic behavior of the structure and its components under the impact of different influences is a required verification step. Effective methods and accurate apparatus -for implementing such analysis are developed.

The advantage of 3D optical analysis is in use of equipment which is not in direct contact with the subject of analysis, it is independent of the material and with high precision can measure 3D surface coordinates, 3D displacements and drift rate and the value of the surface deformation. Using this method can enable specification of material characteristics (elastic modulus, Poisson coefficient, etc.); components analysis (crash tests, vibration analysis, resistance, etc.); and verification of FEA. Unlike conventional measurement methods that use different measuring devices (strain gauges, extensometers, etc.) application of this technology enables to obtain information about the displacements and deformations in different conditions.

Considering that the design process of structures is usually iterative, the fact that 3D optical measurement system reduces the measurement procedure is also an important advantage of this method. Another advantage is software application which supports system and which enables measurement, analysis, creation of report documentation, and even visualization of results by advanced techniques such as animation.-

Usually calculations done by FEA software are highly reliable, however in the case of non-conventional freeform designs an empirical verification is a necessary step preceding their construction. In this work 3D optical deformation analysis of physical model constructed by RP was implemented in the design process of a freeform roof structure.

4. CASE STUDY

The analyzed design represents the design solution for reconstruction and extension of the National Museum in Belgrade (Fig. 1). The design proposal for freeform roof structure above atrium represents an example of design solution conceived by using PBDA, and confirms its effectiveness in design of non-standard complex geometry structures.

Fig. 1 Mock up of the roof structure above atrium of National Museum in Belgrade

The used design procedure is iterative and has the following algorithm: (1) Phase of conceiving idea; (2) Phase of production of three-dimensional model by using ACAD system, taking into account the modeling methodology (i.e. models must be made of solid elements); (3) Phase of conversion of three-dimensional computer model data to STL format; (4) Phase of production of physical model by selected RP technology - 3DP; (5) Phase of strain and stress analysis of the model by 3D optical measurement procedure - recording of deformation by stereo cameras and processing the results by ARAMIS and PORTOS software applications; (6) Phase of conclusion based on the obtained results - approval of proposed design solution for further elaboration or return to the stage of conception and modification of suggested geometry (Fig. 2).

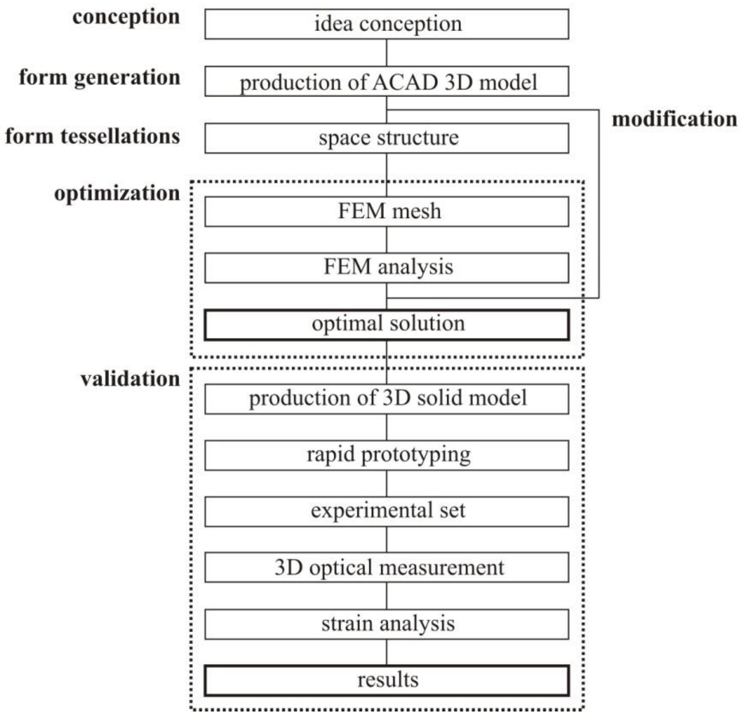


Fig. 2 Flow chart of the design process

4.1. Geometry modeling of structure

The final design proposition is freeform roof steel lattice structure constructed by application of NOVUM Free Form (FF).

The model of this structure is composed of crossed orthogonal mesh of steel beam girders. The modular grid has dimensions 1.44 x 1.44 m. In X-direction, the length of the structure is X=37.44 m, in Y-direction Y=34.56 m. The designed roof surface over the atrium slightly ripple in height of Z=6.10 m. The entire surface of the dome above the atrium is 1355 m² and it is stiffened with beam supports which are rested on 12 reinforced concrete columns. The test of the vertical and horizontal loads is supported by side supports in reinforced concrete slab located at the entire perimeter of roof structure.

The surface shape was generated in ACAD (Cucakovic, 2010), (Nestorovic, 2010), by translation of two projected mutually orthogonal curved lines which are formed in the domes apex (Fig. 3).

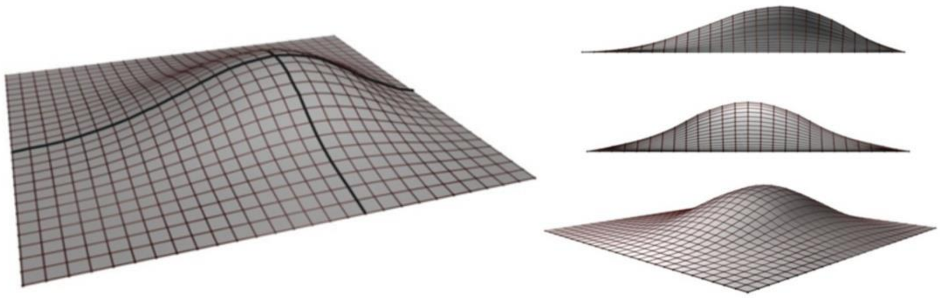


Fig. 3 Initial geometry of the model of roof structure above the atrium of the National Museum in Belgrade

The steel roof structure is designed as a single-layer, uniaxial symmetric structure. Curved, orthogonal steel beam mesh will support glass panels covering. For the reasons of setting up planarity (only very small perimeter of the network has planar geometry) of the system mesh is transformed in triangular. Introduced diagonals at the same time increase the stiffness of the system (Fig. 4).

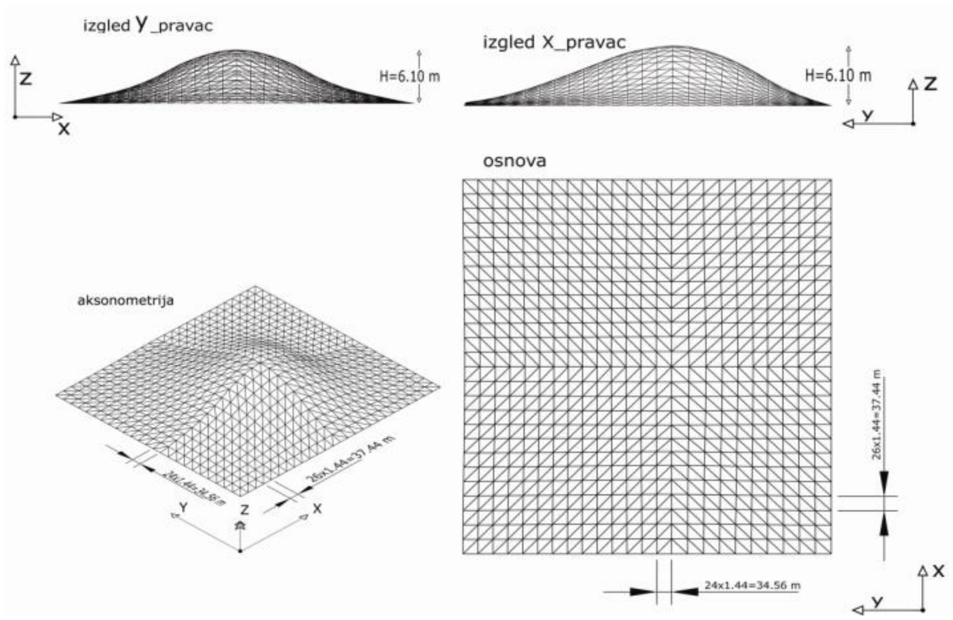
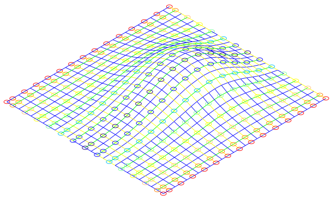
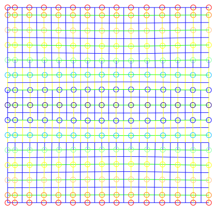
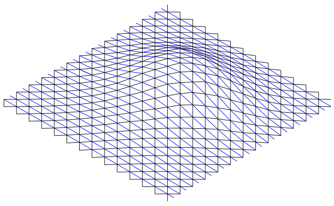
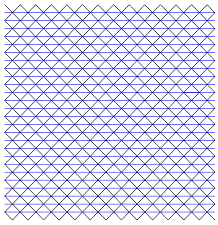
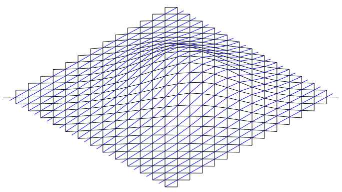
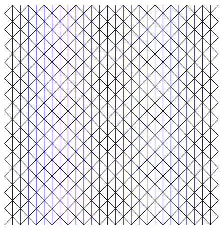
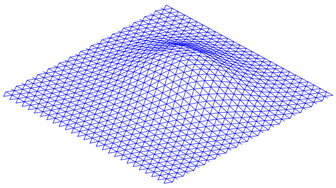
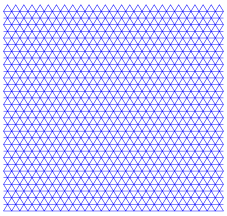


Fig. 4 Geometry of the model of steel roof structure above the atrium of National Museum in Belgrade

One of the main tasks was to find an optimal geometry solution, which will both satisfy structural and aesthetic demands. In that respect, the modeling of the structure was done. Four geometrical concepts, presented in Table 1, were suggested.

Table 1 Geometrical concepts

No	Concept description	3D view	Plan view
1	Uniaxial symmetrical, uni-layer steel structure of orthogonal mesh grid - crossed beam steel girders are placed directly at angle of 90° and parallel to X-Y directions. To obtain triangular system, smaller secondary rods - carriers of cladding glass panels, could be set between non-plane rods, and in this manner directly involved in supporting construction;		
2	Uniaxial symmetrical, uni-layer steel structure of orthogonal mesh grid - crossed beam steel girders which are placed directly at 90° and then rotated by 45° rests on X-Y directions. For the need of network planarity, secondary rods (carriers of glass panels) are set parallel to X direction;		
3	Uniaxial symmetrical, uni-layer steel structure of orthogonal mesh grid - crossed beam steel girders placed directly at 90° and then rotated by 45° rely on the X-Y directions. For the need of network planarity, secondary rods (carriers of glass panels) are set parallel to Y direction;		
4	Uniaxial symmetrical, uni-layer steel structure of triangular mesh grid.		

4.2. Materialization of structure

For the materialization of glazed roof structure over the museum atrium NOVUM Freeform (FF) system was envisaged - pipe profiles with the spatial adapters on their ends rigidly bolted to cylindrical node connections.

NOVUM Structures GmbH, offered to re-design, develop, deliver and build the cupola and all the elements of the glazed roof: material for the complete system NOVUM FF (steel pipe, beam profiles, nodes, connectors, supports for the glass panels) as well as material for the support beam assembly that carries the designed beam structure. All material is protected from corrosion by RAK standard color. The used steel has a quality S234 or S355 according to EN 10025 and EN 10210 or equivalent.

The single layer steel roof structure will be covered with 1248 triangular insulation glass and/or aluminum panels. Insulating triangular glass panels are leaning at a point and are made of 10 mm thick UV surface protected outside glass, 12 mm air space, and inside 16 mm thick laminated glass, composed of two 8 mm thick glasses glued with a 1.52 mm layer of PVB. All edges of the glass panels and tolerance will be in accordance with DIN12150-1:2000.

All the joints shall be made of one-component un-structural silicon Dow Corning Building Sealant or equivalent in black color. All gaskets shall be made of black silicon.

Simple joints and channels between the covers will be made of insulating aluminum. Finish shall be such as to match the color of steel structural parts.

The drainage is mainly through the roof surface directly in gutters, located between the flat part of roof and dome. For smoke extraction in terms of fire protection twenty separate motorized movable triangular windows with frames will be embedded.

4.3. FEM modeling of structure

For FEM analysis of digital models KOMIPS package (by prof. dr Taško Maneski, Belgrade University Faculty of Mechanical Engineering) was used (Maneski, 1998). In addition to the supporting structure's own weight and the weight of glass panels roofing, loads of snow and wind were in the total sum of 2.0 KN per node area, and temperature changes in structure were included in calculation (Fig. 5).

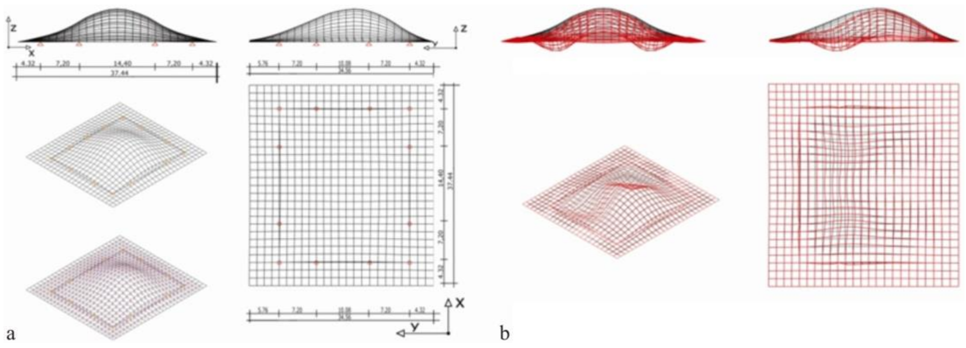


Fig. 5 FEM analysis: Model of analyzed steel roof (a) and image of deformation by FEM analysis (b)

On the basis of the obtained results the solution was adopted (Fig. 4). The total weight of supporting structure is Q=78 t, the maximal stress is 8.5 KN/cm² (6.1 KN/cm² of force and 2.4 KN/cm² of own weight) and deformation is 1.622 cm (1.167 cm from forces and 0.455 cm from own weight). Finally, this resulted in steel structure of 60 kg/m² basis.

4.4. Rapid prototyping of structure

For physical model construction we used MakerBot Replicator 2 Desktop 3D Printer (Fig. 6) supported by its software MakerBot MakerWare™ Bundle 1.0. Used 3DP, in possession of University of Belgrade Faculty of Architecture (Nestorović, 2013), is low-cost, multitask tool which can make fast accurate, highly complex and professional-quality prototypes.

Applied printing technology is fused filament fabrication. As printing material MakerBot Replicator 2 uses PLA. PLA is renewable bioplastic that can reliably stick to the platform with practically no peeling, curing, sliding, or shrinking. The material is environmentally friendly and enables production of high-quality prototypes and huge pieces with dimensional stability. It is worth noting that construction with PLA achieves 32% energy savings comparing with ABS filaments.

MakerBot Replicator 2 Desktop 3D Printer is accurate device which produces models of good finishing. The capacity of a 100-micron layer height enables smooth surface without any post-production. Building volume is: 28.5L x 15.3W x 15.5H cm, while filament diameter is 1.75 mm, and nozzle diameter is 0.4 mm.

The used device quickly prints projects with optimized hardware and software, out of 3D solid CAD digital models. Required file types are STL, OBJ or THING.

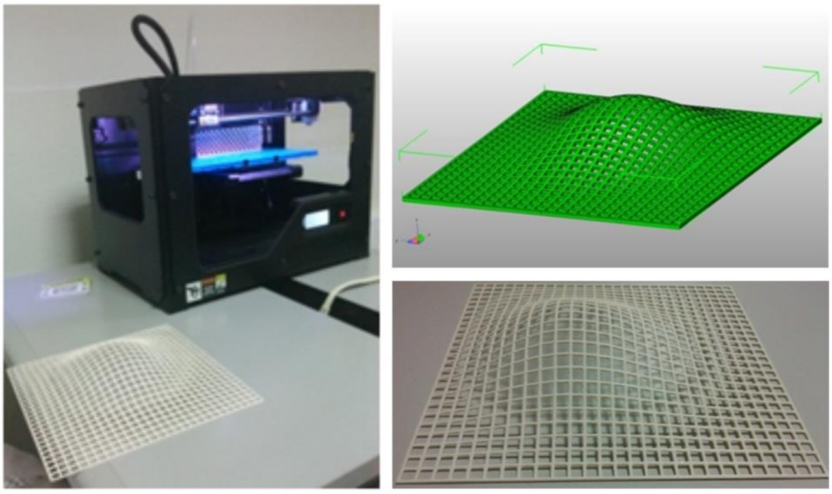


Fig. 6 Construction of physical model by MakerBot Replicator 2 Desktop 3D Printer

4.4. 3D optical deformation analysis of structure

Validation numerical modeling with 3D optical measurement is an experimental method for determination of deformation and calculation of stress of physical models. In the particular it is used for analysis of physical models constructed by MakerBot Replicator 2 Desktop 3D Printer (Fig. 7). Created model represent replication of strength of real architectural structure. For the process of measurement GOM equipment and software application ARAMIS, were used.

The procedure was undertaken in order to verify the structural behavior, previously determined by FEM, and to confirm that experimental results could be predicted by using FEM.

The equipment used for 3D optical analysis is in the possession of the University of Belgrade Faculty of Mechanical Engineering (Maneski, 2011). The equipment consists of two optical digital mobile stereo cameras with 2 Megapixels resolution, which can measure volume dimensions of 2000 mm x 1500 mm x 1500 mm. The cameras are supported by ARAMIS and PORTOS software applications that are used for measuring of 3D shape changes of model and determination of deformation distribution under static and dynamic loads. ARAMIS application analyzes and calculates deformations of the whole structure or its parts, while PORTOS analyzes, calculates and reports of the structure's deformations, rigid movements and display the dynamic behavior of analyzed structure. Advantage of ARAMIS software is the ability of integration into the standard analysis process due to the many export and import data possibilities. The software also enables calculation of the deviation between measured and referred data, and comparison with data obtained by FEM.

The procedure of analysis involves the following steps: (1) camera recording of the structure; (2) automatic calculation of results - fast calculation of all phases of loading, automatic calculation of the 3D surface coordinates, 3D displacements (in Cartesian and in radial coordinates) and plan strain tensor, stress calculation on the basis of data on material; (3) report creation.

Fig. 7 Validation: experimental set (a) and measurement equipment (b)

5. Conclusion

The paper is based on the point that use of potentials of advanced digital technologies and multidisciplinary approach improves - the design process. Numerous examples of successful architectural designs realized on these principles are justification for this approach. Continual development of digital technologies, in terms of performance improvements, opens the possibility for the introduction of certain technologies, not initially developed for the process of architectural design, in the process of solving architectural and engineering problems. Having in mind that achieving quality results is conditioned both by knowledge about the problem and technology which is used for its solution, It is important to constantly improve architectural production tools and design methods. Within this paper performance based design process, that steps out of standard profession frame and utilizes scientific methods, was reviewed and possibility of its application in freeform structure design.

It should be stressed that suggested design methodology is justified only in specific cases of design of non-standard complex structures. When it comes to unconventional solutions additional analysis is a required step preceding construction of a real-structure. Usually, structural behavior of geometrically complex, original design solutions is empirically unknown. Though there is a high correlation between results obtained by standard computer FEM simulations and empirical tests, experimental analysis should be undertaken.

On the other hand, RP represents a technology that is constantly evolving, which potentials, at this point, are still not enough exploited in the process of conception of architectural solutions. In that respect suitability of RP technology for production of accurate models for formal verifications and analysis of freeform structures, was reviewed within this work. A prototype constructed by 3DP was utilized as functional model in structural tests. Diagnostic of structural behavior by 3D optical measurement was used for verification of FEA results.

Technological advances, development of digital production technologies and digital methods of measurement facilitated this approach, making it more available, efficient and economic, overcoming existing limitations and enabling realization of rational design solutions.

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REFERENCES

1. Cucakovic, M. Nestorovic, B. Jovic, "Free Form Structure Surfaces", Proceedings of the 14th International Conference on Geometry and Graphics, Kyoto, Japan, 2010, pp. 330-331.
2. Kolarevic, Architecture in Digital Age - Design and Manufacturing, New York&London: Spon Press, 2003.
3. Striech, "3D scanning and 3D-printing for media experimental design work in architecture", ACADIA ’96: Design Computation: Collaboration, Reasoning, Pedagogy, 1996.
4. F. Rogers, An Introduction to NURBS: With Historical Prospective, USA: Academic Press, 2001.
5. T. Pham, R. S. Gauit, "A comparison of rapid prototyping technologies", International Journal of Machine Tools and Manufacture 38, 1998, pp. 1257– 1287.
6. J. Milošević, Z. Šobić, M. Nestorović, "Towards Generative Convergence in Design of Architectural Structures", 1st International Academic Conference Places and Technology, Belgrade: University of Belgrade Faculty of Architecture, 2014., pp. 744-751.
7. J. P. Kruth, M. C. Leu, T. Nakagawa, "Progress in additive manufacturing and rapid prototyping", CIRP Annals-ManufacturingTechnology, vol. 47, no. 2, 1998, pp. 525–540.
8. J. Sanches, "Rapid Prototyping and Architecture", Proceedings of Rapid Prototyping Development Conference, RPD 2006, Marinha Grande, Portugal, 2006.
9. J. Snaches, J. Gonzalez, A. Oyarbide, "Using Rapid Prototyping for Free-from Shapes in Architectural Scale Models", Proceedings of the International Association for Shell and Spatial Structures, IASS 2005, Bucarest, Rumania, 2005.
10. M, Nestorović, Konstruktivni sistemi - principi konstruisanja i oblikovanja, Beograd: Arhitektonski fakultet Univerziteta u Beogradu, 2000.
11. M. Nestorović, A. Čučaković, B. Jović, "Geometric Analysis Variant of Free-Form Dome", Proceedings of 3rd International Scientific Conference moNGeometrija, Belgrade, Serbia, 2010.
12. M. Nestorović, P. Nestorović, J. Milošević, "Rapid Prototyping: Constructing Physical Models of Architectural Geometry", Applied Geometry and Graphics Issue No 91. The Interdepartmental Collection of Proceedings of SED-13, Kyiv: Ukraine Association for Applied Geometry, 2013., pp. 187-192.

13. N. P. Karapatis, J.-P.S van Griethuysen, R. Glardon, "Direct rapid tooling: a review of current research", Rapid Prototyping Journal vol. 4, no. 2, 1998, pp. 77–89.
14. T, Maneski, Kompjutersko modeliranje i proračun struktura, Beograd: Mašinski fakultet Univerziteta u Beogradu, 1998.
15. T. J. R. Huhges, The Finite Element Method: Linear Static and Dynamic Finite Element Analysis, Dover Publications, 2000.
16. T. Maneski, B. Nestorović, "Validation Numerical Modelling With 3D Optical Measurment Deformations of deformations of foldable plastic packaging buckling failure". Serbian architectural journal (SAJ), Structural Systems, No. 2, 2011, pp. 152–162.
17. Y. J. Grobman, E. Neuman, Performalisam: Form and Performance in Digital Architecture, New York: Routledge, 2012.

PRISTUP ZASNOVAN NA PERFORMANSAMA U PROJEKTOVANJU PROSTORNIH STRUKTURA SLOBODNE FORME

Rad je povezan sa činjenicom da je korišćenjem alata za generisanje forme, analizu i digitalnu proizvodnju (CAD/CAM/CAE) na efikasan način omogućena precizna prezentacija ideja, simulacija različitih uticaja i produkcija racionalnih projektnih rešenja. Primena geometrijskih i numeričkih kompjuterskih metoda i usvajanja prioriteta zasnovanih na performansama omogućava formalna istraživanja u ograničenim uslovima i unapređenje procesa projektovanja u oblasti arhitektonskog inženjerstva. Implementacija naprednih digitalnih tehnologija u 3D proces projektovanja omogućava produkciju nekonvencionalnih kompleksnih oblika, njihovu verifikaciju konstrukcijom fizičkih modela i eksperimentalnu dijagnostiku, kao faze koja prethode izgradnji relane strukture. U okvirima ovog rada razmatraće se koncepti koji omogućavaju projektovanje nestandardne, kontekstualno specifične strukture slobodne forme primenom tehnologije brze proizvodnje prototipova i 3D optičkog merenje. Analizirano projektno rešenje krova iznad atrijuma Narodnog Muzeja u Beogradu u funkciji je potvrđivanja efikasnosti ovakvog pristupa.

Ključne reči: *projektovanje zasnovano na performansama, slobodne forme, prostorne strukture, CAD/CAM/CAE, brza izrada prototipova, 3D optičko merenje*