

***Origami* inspired timber structures – construction and numerical modelling**

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Abstract: *Origami inspired timber structures – construction and numerical modelling.* The paper is dedicated to show the possibility of application of timber folded structures based on the concept of the *origami* art of paper folding. Small scale timber models as well as numerical analysis by the finite element method are described as a base for future building scale structures. Some problems and critical factors for timber applications are discussed with connections between member panels included.

Keywords: origami, timber structures, finite element method

INTRODUCTION

Origami is an old art of paper folding developed in Japan with origins in China. The term is a combination of two Japanese words: ‘oru’ – to fold and ‘kami’ – paper. There are several typical folds in the *origami* art. Some of them are presented in Fig. 1: ‘mountain fold’, ‘valley fold’. After change of the direction of mountain fold one can receive the ‘inside reverse fold’ or ‘outside reverse fold’. A detailed description of *origami* folds and patterns can be found in [3].

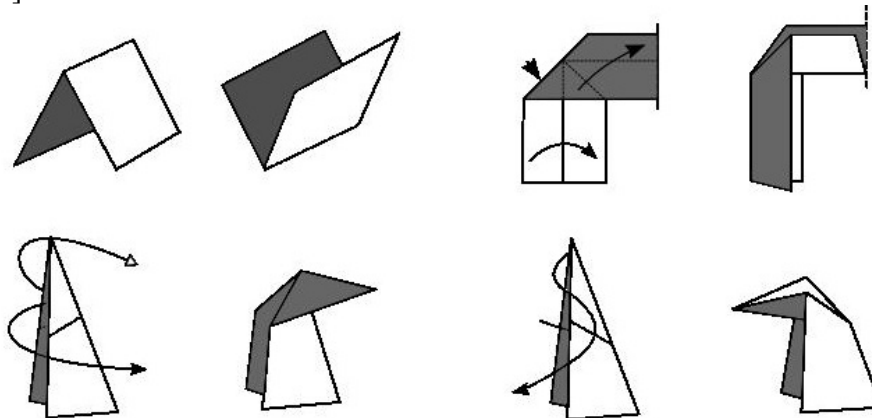


Figure 1. Origami – paper folding art

Origami is an inspiration for engineers in the fields of civil engineering, architecture, biotechnology, medicine, space engineering and other technical applications [5-8], including timber structures and constructions..

From mechanical point of view the correct theory to describe folded plates is a six parameter shell theory [2] with three displacements and three rotations in the displacement field. The third rotation is necessary because of folding the structure. Each fold is flat, so the equations of the theory can be simplified. For numerical analysis it is necessary to use the finite element method because of complex character of folded structures. Finite elements with six d.o.f. per node are to be used.

The present paper is dedicated to the study of possible civil engineering applications of timber folded plates inspired by *origami* art. Several patterns of folded plates are considered to answer the question if those structures are attractive from mechanical point of view. The authors tried to select the most convenient (for engineers and architects) *origami* based folded plate pattern. Small scale prototypes are built from balsa wood and analyzed

experimentally in the Faculty of Civil Engineering at Warsaw University of Technology. The most critical problem on connections of timber members is presented. Numerical analysis is done with the use of the Abaqus professional software.

SMALL SCALE PROTHOTYPES

Small scale models of folded plates made of balsa wood have been developed and analysed in the Division of Timber Structures at the Faculty of Civil Engineering, Warsaw University of Technology. Balsa wood sheets of thickness 2-5 mm were connected by modeler glue. Typical example is presented in Fig. 2 – Miura-Ori pattern on left and its wooden model on right.

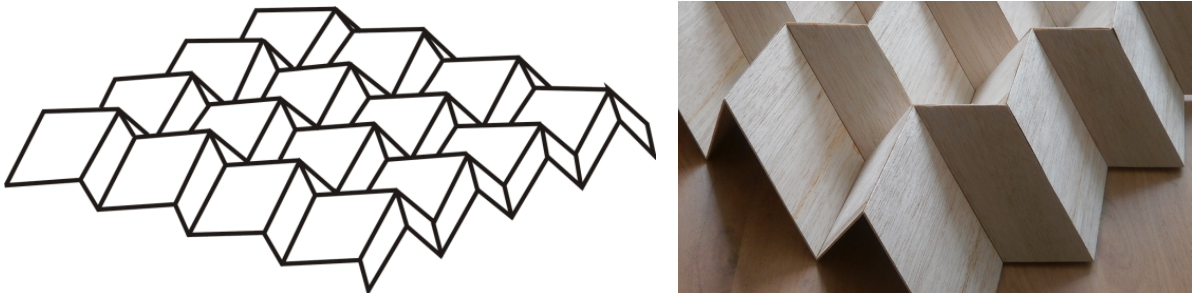


Figure 2. Miura-Ori pattern and small scale prothotype

Two other prothotypes of tessellation and egg-box patterns are presented in Fig. 3. The analysis and experiments with the small scale models can help to understand the specific structure of folded plates based on the *origami* concept, evaluate their stiffnesses, sensitivity of dimension changes and problems with connections of panels. According to the author’s opinion development of small scale prothotypes is a good introduction to numerical analysis as well as to building scale projects.

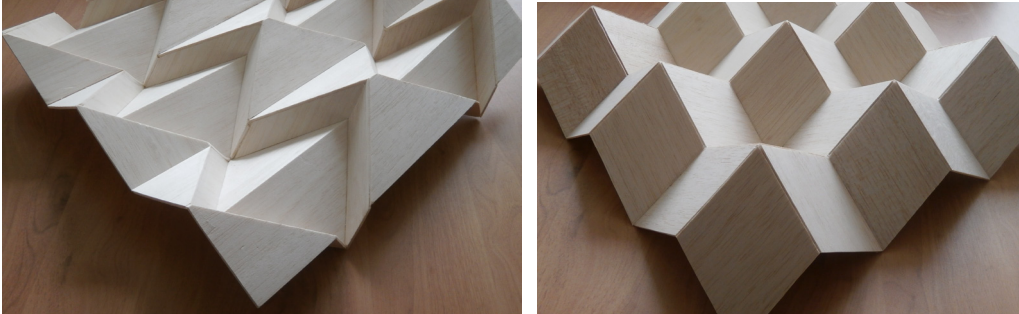


Figure 3. Small scale prothotypes – tessellation and egg-box patterns

BUILDING SCALE STRUCTURES

The concept of extension the *origami* inspired structures to the building scale was successfully developed in the Federal Polytechnic of Lausanne [1]. Two examples are presented in Fig. 4 – hospital chapel in Waatland (Switzerland) and large scale experiment in IBOIS laboratory. Several examples of *origami*-inspired buildings made of timber, metal, concrete and glass are studied in [8]. The concept is attractive for architects and engineers.

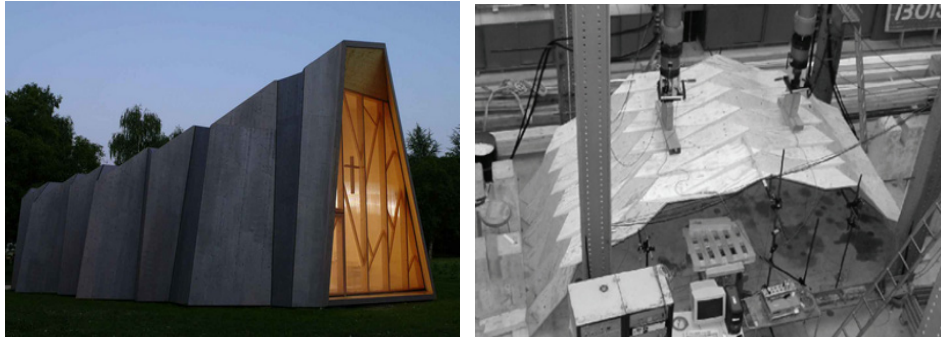


Figure 4. Building scale examples – hospital chapel in Waatland and IBOIS laboratory experiment [1]
CONNECTIONS AND GEOMETRY OF TIMBER FOLDS

There are several concepts of connections of timber panels which are cross-laminated in the building scale. The main problem is that the panels are connected to each other on various angles (Fig. 5). The angled panels can be connected during construction the real structure or some segments can be pre-fabricated. In building scale the panels are relatively thick and can be screwed (Fig. 6). Because the laminated timber is used it is possible to use internal metal connectors glued inside the panels (Fig. 6). The problem of connections suitable for selected geometry is a subject of scientific research to provide tools that allows economic and easy realization of folded constructions made from cross glued timber panels.

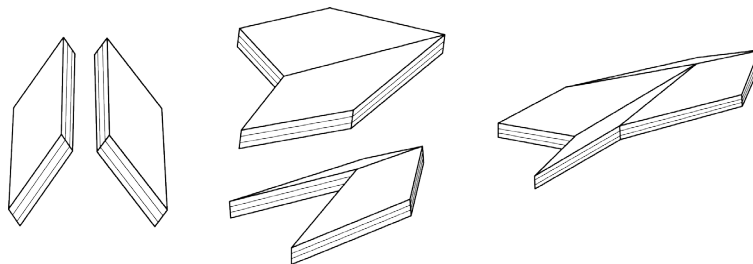


Figure 5. Connections in a folded plate

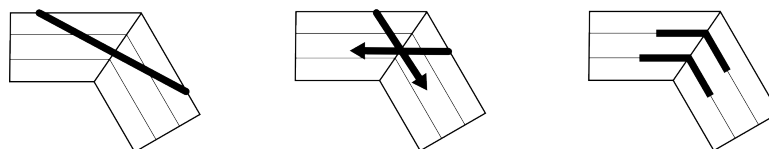


Figure 6. Internal connections of timber members

NUMERICAL MODELLING

Numerical analysis is done with the use of Abaqus programme. Shell finite elements are used for numerical calculations. Selection of the correct element with convergence analysis for *origami* inspired modules are presented in [4,8]. 4-noded S4R shell element with 6 d.o.f. per node with hourglass control is used for calculations. The subject for numerical analysis is a timber folded plate roof on a square. 36 modules are used for each *origami* inspired folded plate. Constant thickness plate, as well as folded plates with longitudinal, Facet, Eggbox and Mura-ori patterns are clamped on two opposite edges with free boundary conditions on two other edges. Parametric study of several patterns was considered and compared with the experimental results [4,8]. An example of typical module, finite element model and deformation/stresses presented in Figs. 7 and 8 for Miura-Ori pattern [8].

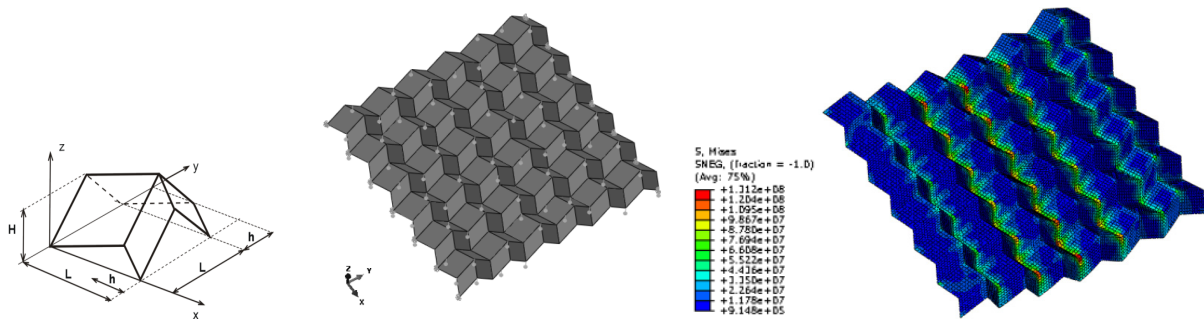


Figure 7. Miura-Ori pattern – finite element model, deformation and stresses

It is typical for the origami based models that the structures are very stiff even for thin panel members and the stress concentrations are local through the bends (see Fig. 7).

CONCLUSIONS

The analysis and evaluation of the possibility of application of folded plates inspired by the *origami* art in the building scale, for which a part is presented in the paper, provides the following observations and recommendations:

- six-parameter moderately thick shell theory with the finite element formulation based on Abaqus software is suitable for the numerical analysis of folded plates,
- small scale models and experiments are useful to understand the specific aspects of folded plates as a base for numerical analysis and building scale projects,
- folded patterns based on the concept of *origami* are recommended because of their large stiffness and specific distribution of forces through the bends,
- the most recommended pattern is the Miura-Ori,
- cross-laminated timber panels are recommended for the building scale,
- connections of timber panels are a critical point for folded plate structures.

Applications of timber folded plates inspired by *origami* art are strongly recommended from the point of view of mechanical properties as well as of architectural value.

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Streszczenie: *Budowle drewniane inspirowane origami – konstrukcja i modelowanie numeryczne.* W pracy przedstawiono możliwość inżynierskiego wykorzystania drewnianych struktur tarczowniczych budowanych na zasadach zgodnych ze starożytną sztuką składania papieru *origami*. Jako podstawę do projektowania i budowy konstrukcji w skali rzeczywistej wykorzystano modele w małej skali oraz modelowanie numeryczne przy zastosowaniu metody elementów skończonych. Przedstawiono także najważniejsze cechy rozważanych konstrukcji z punktu widzenia materiału, jakim jest drewno, w tym opisano techniki połączeń płatów tarczownic.

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