Study of Fold and Folded Plates in Structural Engineering

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Abstract: Folded plates are assemblies of flat plates rigidly connected together so as to make structural system capable of carrying loads. They provide an economical and aesthetically pleasing design. This Paper aims at studying the material used for folded plate structure, analysis of folded plate structure by finite element strip or computer programs.

Keywords: Building envelopes, Convertible roofs, Folded structures, Folded Plates, Longitudinal, Morphology, Origami and Plate loads.

Introduction:

Folded plates are used as roofing structures because they provide an economical and aesthetically pleasing design. A folded plate structure consists of a series of flat plates connected to one another along their edges usually used on long spans. Longitudinally, the plates may be continuous over their supports. Transversely, there may be several plates in each bay. At the edges they may be capable of transmitting both moment and shear or only shear.

A folded plate structure has a two way action in transmitting loads to its support, namely plate action and slab action. Transversely, the elements act as slab spanning between plates on either side. The plates then act as girders in carrying the load from the slabs longitudinally to its supports, which must be capable of resisting both horizontal and vertical forces. Folded plates have inherent resistance to fire, deterioration and to atmospheric corrosion. They allow large spans to be achieved in structural concrete which allows flexibility of planning and mobility beneath. Where ground conditions require expensive piled foundations the reduced number of supporting columns can be an economic advantage. Some architects prefer the aesthetics of folded plates to curved shell roofs. Folded plates provide good quality robust roofs.

Actions of folded plates due to loads:

The structural action of folded plates may be thought of as consisting of two parts - the 'slab action' and the 'plate action'. By the slab action, the loads are transmitted to the joints by the transverse bending of the slabs. The slabs, because of their large depth and relatively small thickness, offer considerable resistance to bending in their own planes and are flexible out of their planes. The loads are, therefore, carried to the end diaphragms by the longitudinal bending of the slabs in their own planes. This is known as 'plate action'. The analysis of folded slabs is carried out in two stages.

Transverse Slab Action Analysis:
The transverse section of the slab, of unit length, is analyzed as a continuous beam on rigid supports. The joint loads obtained from this analysis are replaced by their components in the planes of the slabs and these are known as plate loads.

In Plane Plate Action Analysis:
Under the action of 'plate loads' obtained above, each slab is assumed to bend independently between the diaphragms, and the longitudinal stresses at the edges are calculated. Continuity demands that the longitudinal stresses at the common edges of the adjacent slabs be equal. The corrected stresses are obtained by introducing edge shear forces.

Principle of morphology

Martin Trautz et al(2011) presented principle of morphology to increase the load bearing capacity in the field of design and engineering. The issue of folding is represented by different approaches to examples in nature, foldable plate structure in building and mechanical techniques and to origami. Due to their folded cross-sectional shape, palm sheets are more robust, sea shells have folded and therefore material optimized coverings and beetles protect their wings by in folding. In addition, application possibilities for rigid folded structures in engineering and architecture are presented.

Fig. 1 palm sheet

Fig. 2 seashell

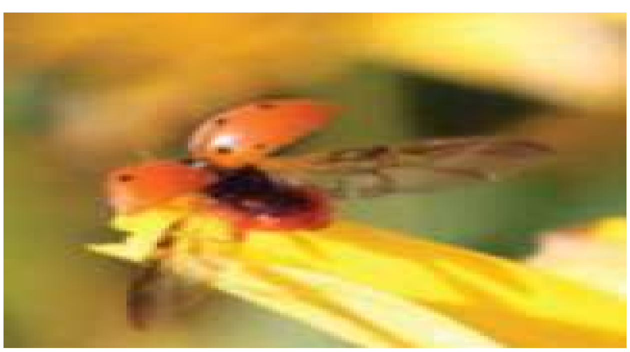


Fig. 3 ladybird with wings spread

Also in engineering the principle of folding is used. Convertible roofs of cabriolets are in-fold and out-fold. Concerning medical applications stents unfold themselves at their place of final destination. Likewise some examples of folding are found in architecture and civil engineering, e.g. at construction materials like corrugated sheets and sheet pile walls.

In Origami – the art of folding paper, folding figures are created from only one paper square and exclusively by folds – without cutting, sticking and joining. But here three dimensional Origami tendencies are presented which could have potential for the building industry and engineering. They are namely Tessellation Origami, Origami Hypars, and Modular Origami. This research and ideas in model scale need to be realized as prototypes and in building scale.

CLT-based folded shell:

Andreas Falk et al (2012)suggested application of cross-laminated timber (CLT) in structural systems for folded façade solutions. Geometric and material properties play an important role for the enclosure, and climate and conceptual design procedures have been utilized to include these issues. A current architectural trend proposes increasing complexity of the facades and the application of folded CLT-based systems which are studied and analyzed by using combination of digital tools for structural and environmental design and analysis.

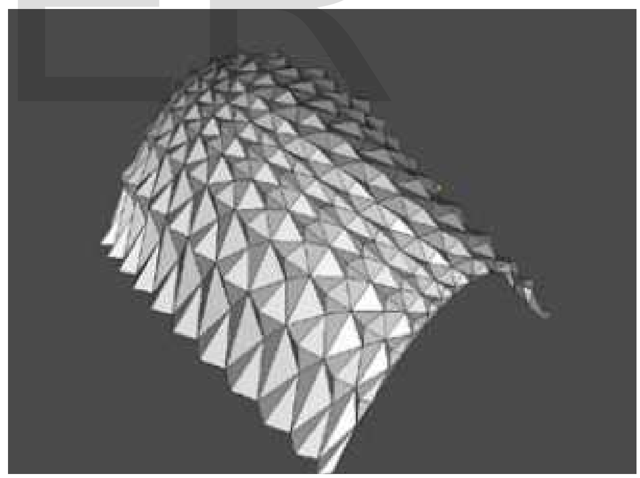


Fig. 4 Example of a CLT-based folded shell

The concept of building envelop is basically a protective layer, a climate skin which covers building and enclosed space. Plate elements of CLT provide a set of material properties – shear capacity, high strength to weight ratio, workability, tightness, heat buffering capacities etc. which enables wide variety of potential forms while maintaining structural efficiency.

Timber based folded structure:
Timber based folded structures show potential to provide robust systems for applications as facades. Rational production and construction are recognized aspects of CLT-based designs and the utilization of CLT in folded assemblies makes efficient use of material and element properties. To be able to manage effects of material properties on the environmental result relating to an object –specific geometry, the envelope design needs to be analyzed as a multi-objective problem.

The results show gainful, rational properties of folded systems and beneficial effects from an integration of architectural and environmental performance criteria in the design of CLT-based facades.

Glass folded structure:
Stefan Trometer et al(2006) presented the development of glass folded structures. Glass will not only be used as a transparent covering but as a load bearing element for the whole structure. Focus is put into the geometrical diversity and individuality. The surfaces are linked by hinges in order to follow principle of paper model and to reduce bending stress that lies on the glass. The structural analysis shows that this approach is efficient and functional.The geometrical basis for this kind of folded structure is Rhombus – wing with its fixed movement axis.

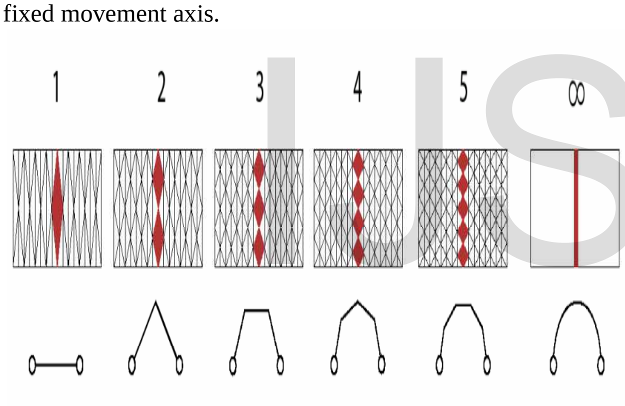


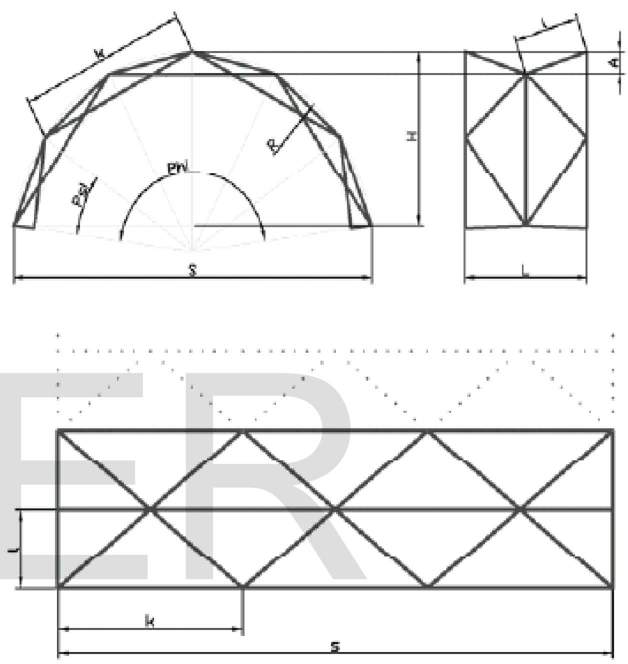
Fig. 5 Geometrical diversity

To provide an insight into geometrical correlations and their dependencies, a simplified geometry basing on a rectangular base is examined. This geometry is defined by the parameters Span (S), Height (H), Length (L) and System Field Number (N), according to Figure. These input parameters match with requirements of the conceptual design and lead to the geometry definition according to following formulae:

$$R = \frac{H}{2\sin^2\left[\arctan\Theta\right]} \quad with \quad \Theta = 2\cdot\frac{H}{S} \qquad (1)$$

$$\psi = \frac{\phi}{2N} = 2\cdot\arctan\frac{\Theta}{N} \quad with \quad \phi = 4\cdot\arctan\Theta \qquad (2)$$

$$A = 2\sin^2\frac{\psi}{2}\cdot R \qquad (3)$$



The construction height (A) depends on N and the relation H/S, but not on L. Parameter study shows that fundamental bearing capacity of glass is sufficient. Also it can be inferred that the construction height (A) has direct influence on the load bearing capacity. At a low height (H) up to 2m and the System Field Number (N) = 5, stability failure occurred.

R J Jiang et al (A general finite stripe for the analysis of folded plates) suggested semi-analytical finite strip analyses of folded plates. The geometric constraints of the folded plates, such as conditions at the end and intermediate supports are modeled by very stiff translational and rotational springs. A complete Fourier series including constant term are chosen as longitudinal approximating functions for each of the displacements.

Numerical examples are presented for comparison with available numerical results. The results show that this kind of strips is versatile, efficient and accurate for analysis of folded plates. The method is especially useful in analysis of folded plates with complicated support conditions, such as box girder bridges.

Prof. Dr. Ing Martin Trautz et al presented the two main folding plate principles of pointed folding plates forming an facet texture and longitudinal folding plates forming the typical fold texture imply different fields of application. A method of developing folded plate principles on spatial structures also with irregular and freeform geometries is presented.

Algorithm of triangulation, originally applied in Finite element analysis is used for discretisation and form finding of the textures of folded plate shells.

The example of leaf of Chamaerops Hunilis shows the process of optimization of the employed folding principle.

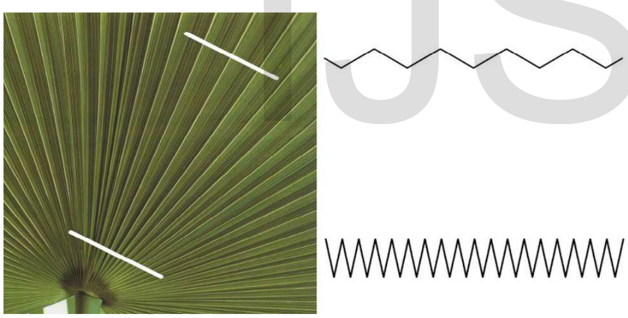


Fig. 6 Leaf of Chamaerops Hunilis

The structural characteristics of folding structures depend on the shape of the folding (longitudinal or pyramidal), on their geometrical basic shape (plane, hoppit, cupola, free-form), on its material (concrete, timber, metal, synthetics), on the connection of different folding planes and on the design of the bearings.

Structural behavior of folding:

The inner load transfer of a folding structure happens through the twisted plane, either through the structural condition of the plate (load perpendicular to the centre plane) or through the structural condition of the slab (load parallel to the plane). At first, the external forces are transferred due to the structural condition of the plate to the shorter edge of one folding element. There, the reaction as an axial force is divided between the adjacent elements which results in a strain of the structural condition of the slabs. This leads to the transmission of forces to the bearing.

Using numerical digital method, it is possible to make tessellation and triangulation of arbitrary shapes. Due to this method, almost any folding structure can be constructed.

There is a future scope in context of the sustainable use of material and to gain new impulses for the principle of structural shaping.

Conclusion:

Using the concept of folding, as seen in nature and origami, to increase load bearing capacity, folded plates are used as roofing structure for long span. Glass, timber or R.C.C. are the material used for folded plate structure. Folded plates are analyzed considering plate action and slab action. Analysis of folded plates can be done by finite element strip or computer programs or manually by moment distribution method.

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