



SCALELESSSEAMLESS

PERFORMING A LESS FRAGMENTED ARCHITECTURAL EDUCATION AND PRACTICE

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Scaleless - Seamless

Performing a less fragmented architectural education and practice

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Origami Tessellations in a Continuum

**Integrating design and fabrication
in architectural education**

Origami tessellations populating the digital surface

In the range of projects that define the digital avant-guard of the 00s, the notion of surface maintains its overall form generating function and gains rigor through the accelerated growth of digital fabrication techniques. Advances in architectural geometry, an interdisciplinary field currently emerging at the border of differential geometry, computational mathematics and architectural design and engineering¹, (Pottmann 2007) provide solutions for the actual construction of architectural free-form surfaces, segmenting the overall surface into simpler parts, a process also known as panelization. In most experimental digitally generated projects since the mid 00s, surface becomes an integrated aggregate or a 'synathroisis' of non-standard components that facilitate overall architectural substance, each component requiring relatively simple fabrication procedures. The concept of surface as synathroisis² pertains to an assemblage of monads that individually express the common logic of the group, explicitly articulated within a computational system. The emphasis lies in the design of self-supporting, material efficient patterns that populate the surface allowing parametric part-to whole interrelations.

Surface division into a population of elements seamlessly fitting together comprises a tessellation. Our research hypothesis revisits a retro mode of tessellating, the geometry that originates in Origami, the ancient Japanese art of paper folding, in the context of the evolving computational design and fabrication methods. Origami tessellations are not uncommon in 20th century architecture. As the overview of paradigmatic projects developed in the next section makes evident, Origami tessellations in architecture are most usually encountered as static structures, folded plate shells, with applications as large spanning roofs, load bearing walls, or combinations of both. In this essay we also explore the impact of tessellating upon the kinetic behaviour of lightweight architectural surfaces focusing upon geometric transformations of architectur-

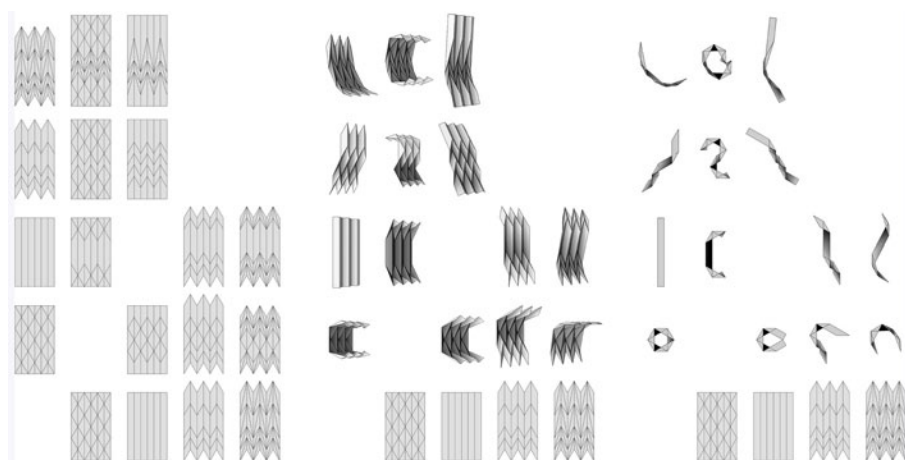


Fig. 1

Combinations of elementary Origami tessellations: Yoshimura, Pleat, Miura and Fishbone. Simulations with Rigid Origami software by T.Tachi, Sophia Vyzoviti & Pablo de Souza, 2012.

ally relevant Origami patterns - the Yoshimura, the Miura, the fishbone and standard pleats (Fig.1). We test the effect of pattern geometry upon the surface's kinematics and distinguish between two generative processes: (a) 2d pattern transformations based on repetition, arrays, and serial variability, and (b) profile generated patterns that are constructed from a desired section and further manipulated through generative modelling.

Within the context of digital fabrication advances architects are concerned both with tectonics of assembly and with synthetic surface and material effect resulting to intricate patterns through the aggregation of building materials³ (Iwamoto 2009). Iwamoto (2009) classifies folding as one of the state of the art digital surface fabrication techniques. Certainly as a method for digital fabrication folding entails the development of three dimensional components into two-dimensional patterns ready for cutting by lazer, water-jet or plasma cutters. While geometric development in two dimensions has been employed in pre-digital tectonics, arts, and crafts it is today largely facilitated by software. The pre-digital unfold or crease pattern which traditionally required intensive geometric calculations can be easily achieved in modelling software – by the unroll or smash commands in Rhino and employing applications like Pepakura Designer. Despite the fact, the design generative potential of folding has been neglected in computational architecture during the past few years. In this paper we intend to revisit the design generative potential of folding, by embedding it within advances in digital modelling, exploiting its digital fabrication facility and enhancing its performance potential.

Evolution of Origami tessellations in 20th century architecture

During the 20th century many architects have explored the structural capacities, the conceptual symbolism and spatial possibilities of creating architectural forms by importing the knowledge of Origami art into architecture. The paradigmatic projects we

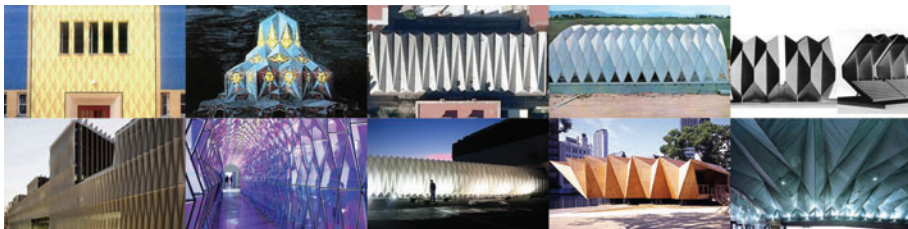


Fig. 2

Origami tessellations in contemporary architecture (top row from left) (1) Facade detail by Bruno Taut, Berlin-Grunau, 1912, (2) Kultusbau by Wassili Luckhardt, 1920. (3) Decks of the dining room of the Technical College of Tarragona by Eduardo Torroja, 1956 (4) Experimental timber cover by Renzo Piano, Genova, 1965 (5) Stadium and sports complex by Jorn Utzon, Jeddah, 1967 (bottom row from left) (1) Biomedical Research Center by Vaillo & Irigaray & Galar, Navarra, 2011. (2) One way colour tunnel, by Olafur Eliasson, San Francisco Museum of Modern Art, 2007. (3) Foldable Plastic Tube by Mats Karlsson for Stockholm Design Week, 2008. (4) Wooden Pavilion in Nakanoshima Park by Ryuichi Ashizawa, Osaka, 2009. (5) Passenger Terminal by Foreign Office Architects, Yokojama 2001.

display here (Fig. 2) provide a chronological evolution of Origami applied into architecture, focusing upon the form-generative, ornamental and structural properties of the most architecturally celebrated Origami pattern, the Yoshimura.

The conceptual transformation of a two dimensional surface into a patterned, rhythmic and multiply folded plate structure comprised a recurrent theme in architectural avant-garde. The facade made by Bruno Taut at Falkenberg in 1912 represents the geometric pattern of Yoshimura. Taut used to emphasize the surfaces of facades by using prolifically contrasting brilliant colour ranges. Taut was probably familiar with this design through the many publications of the beginning of the century that explored these new knowledge that connect crease patterns with mathematics, geometry and consequently with architecture. We use this example as the very first direct reference of Origami art imported, though only graphically into architecture.

Drawings of Wassili Luckhardt, at the time of the “Gläserne Kette”, started from a crystallographic abstraction of Switzerland Mountains⁴ (Nerdinger & all, 2002). In a few of his projects the influence of geometric exercises of representing primary figures by folding paper is evident. That kind of exercises probably inspired the ability of finding and imagining complex and innovative forms made by folding that emphasizes internal spaces in contrast to the mass of an opaque crystals and minerals. Using sequences of folds W. Luckhardt created spaces full of rhythm and vivid contrasts of light and shadows.

Among the following decades 30, 40 and 50s crease geometric patterns inspire plenty of artistic works, lighting fixtures, furniture and interior designs as the circular Yoshimura dome of the dining room of the restaurant “El Coto” in Madrid, made by the architect Luis Gutiérrez Soto. In the early works by Eduardo Torroja, Pier Luigi Nervi and Felix Candela we encounter folded plate concrete shells, material efficient structurally active surfaces that are extremely thin in proportion to their load bearing capacity⁵ (Bechthold, 2007). Since the late 60’s folded shells also appear in timber, pvc, as well as cardboard. While the structural and plastic qualities of Origami tessellations in architectural surfaces prevail, little has been achieved with respect to kinematics.

According to Fernando Cassinello not only were the complexities of calculation that halted the application of folding patterns into architectonic structures, but also the aesthetic prejudices in a new way that would break with the doctrines in vogue, giving the spectacular triumph of aggressive, dynamic and personal architecture of Frank Lloyd Wright, as a favourable factors to acceptance. To this would be added the expressiveness and movement of the forms developed from crease patterns in contrast with the clean and pure rationalist, purists, and neo-classical volumes, in which the inclined line and planes had no place in its immutable creed of parallelism and orthogonality (Cassinello 1961).

The completion of the construction of the passenger terminal at the port of Yokohama in 2002, directed by Alejandro Zaera and Farshid Moussavi of Foreign Office Architects - based on their first prize in the international competition held in 1995- has re-established within architectural practice the implementation of geometries derived

from faceted surface elements inspired by Origami. In the past decade, folding has fruitfully expanded its popularity among students of architecture as a resource for formal exploration. Conducting working models through folding and cutting paper has helped the understanding and development of complex geometries as well as their corresponding spatial mechanisms.

From Fröebel to Tachi: Origami as a teaching tool in architectural design education

Material driven form generation experiments have a long tradition in the architectural avant-garde. At the preparatory workshops led by Joseph Albers at the Bauhaus during the 20's form generation was directly done with material handling⁷ (Bergdoll & all 2009) intending to familiarize students with abstract spaces deriving from surface transformations caused by the stress and strength of paper. Since the mid 90s surface transformation morphogenetic studies in paper and other sheet materials have been exacerbated and associated with strategies of folding, surface manipulation and the creation of artificial terrains⁸ (Allen 2011). Material computing is a recent discipline specific term that describes the analogue form-finding processes complementing the new digital design tools that might in fact be described as quasi-physical form-finding processes⁹ (Schumacher 2007). Following the evolution of the notion of surface in contemporary architecture, we observe that digital design methodologies have paradoxically revamped physical modelling, in an expanded notion of material computing which not only complements but also challenges the overall form, distinct component, and texture generation.

The course *Folding Architecture*ⁱ taught by the authors at the Department of Architecture, University of Thessaly during the spring semester of academic year 2011-12 is embedded in the tradition of material driven form generation processes in architectural education and investigates combinatorial methodologies that employ both computational tools and material processes outlining interdependencies between the two. The course focuses upon the design generative potential of folding as a retro-novel genre of tessellating the digital surface. The didactic methodology of the educational project interweaves thematic research in Origami, papyroplastics, folded plate and deployable structures, single surface architecture and advanced architectural geometry.

In the introductory exercises, the drills that complement the four lectures embedding the scientific relevance of the design assignment, the didactic methods of Friedrich Froebel and Joseph Albers are combined with traditional Origami techniques and state of the art digital simulations (Fig. 3).

The first thematic lecture *Vanguard Childhood: A new educational paradigm, Friedrich Fröebel and the abstract Origami* demonstrates the origins of the relation between Origami Japanese art and European artistic culture in early 20th century. The corresponding drill entails the construction, of a number of Origami objects such as the dove, the tulip, the crane, the waterbomb, the swan, chicken as well as the geometric construction of the several regular geometric flat figures that can be made by different folding positions of the equilateral triangle displayed in the *Fröebel album* (Fig. 3).



Fig. 3

Folding Architecture course didactic references (from top left) spread from Fröebel Album with Folding exercise¹⁰ (Bordes Caballero, 2007) spread from Senba-zuru Orikata 1797, preparatory course directed by Josef Albers (Bergdoll et al, 2009) covers of publications by Sophia Vyzoviti.

The second thematic lecture explores the early influences of Origami art in Modern architecture. The corresponding drill focuses on devising experiments that activate potential transformations of paper into a three-dimensional surface. The exercise refers to the methodology of the preparatory workshop by Joseph Albers at Bauhaus, where the exploration of potential forms is directly related to physical models. According to morphogenetic experiments outlined by Sophia Vyzoviti in her publication *Folding Architecture*¹¹ (Vyzoviti, 2003) paper surface is considered as an operational field where discipline in time, sequences of transformations are applied by folding, pleating, creasing, scoring, cutting, pressing, rotating, twisting, bending, wrapping, interweaving, compressing, enfold, extending, and balancing.

The third thematic lecture focuses upon the influence of Yoshimura patterns on folded plate shells as demonstrated in the work of Torroja, Candela, Breuer and Nervi. The corresponding drill focuses on tessellated shells produced by direct folding in sheets of paper. This technique generates shells by profile manipulation that manifest kinetic behaviour in terms of rotational and translational deployment.

The fourth thematic lecture focuses on current development of surface architecture in the context of the evolving computational design and fabrication methods. The corresponding drill focuses on digital representations of Origami tessellations on the basis of developed crease patterns employing the open source application Rigid Origami Simulator created by Tomohiro Tachiⁱⁱ. The particular drill familiarizes students with a technique of transferring physical to digital object data, generating computable models from direct folding experiments that enable their further architectural calibrations in terms of digital design and fabrication.

Architectural Design Development

Having established their computable geometry, the fundamental question is how Origami tessellations become productive in architectural design development. Design processes, valuable as they are in terms of didactics, need to be substantiated by their results. The section demonstrates design development processes and design outcomes, making evident the range of applicability of Origami tessellations in integrating design and fabrication in architectural education.

Design method

The notion of generative modelling as a shift of focus from objects to operations, defining form as a sequence of processing steps, rather than the end result of applying operations, is employed in the design development method. Based on a model of workshop teaching, the studio process relies primarily on modelling and prototype fabrication and explores the design potential of Origami tessellations integrating geometry, materiality, and performance.

The sequence of steps in the design development oscillates between physical and digital modelling (Fig. 4) and in an outline includes:

- Analogue form-finding based on Origami principles by direct folding that leads to intuitive, freeform, pattern variations

Fig. 4

Characteristic phases in design development process making evident operational shifts from physical to digital modelling. University of Thessaly, Department of Architecture, Design Studio Folding Architecture, Sophia Vyzoviti (faculty) Pablo de Souza (teaching assistant), Giorgios Amvrazis, Irgen Saliani, Apostolia Sofiadi (students) 2012.



- Developed crease patterns, processed according to the two colourable Origami rule
- Deployment simulation in Rigid Origami Simulator
- Transformation of digital objects in Rhino
- Revised developed crease patterns
- Fabrication of models with cutting plotter and laser cutter
- Prototypes in soft and hard material combining paper, plastics, meshes, and fabric
- Kinetic behaviour study of the prototype, physical deformations that exceed simulation
- Evaluation and preliminary design development.

Range of applicability

Research outcomes in terms of architectural design that were produced during the *Folding Architecture* course include three classes of architectural products: static shells in the genre of folded plate structures, kinetic shells in the genre of architectural textiles, and polymorphic reconfigurable objects.

Static shells in the tradition of folded plate structures make evident the versatility of digital morphogenesis facilitated by computational modelling and fabrication tech-

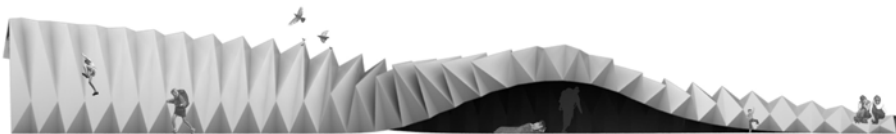


Fig. 5

Forest shelter. University of Thessaly, Department of Architecture, Design Studio Folding Architecture, Sophia Vyzoviti (faculty) Pablo de Souza (teaching assistant), Artemis Papachristou and Tatiana Vasiliadou (students) 2012.



Fig. 6

Kinetic shell prototype. University of Thessaly, Department of Architecture, Design Studio Folding Architecture, Sophia Vyzoviti (faculty) Pablo de Souza (teaching assistant) Vasilidiki Dimou, Kostis Maniatis, Beatriz Borrego and Vasilidiki Berberidu (students) 2012.

niques. While their architectural calibration maintains an elementary space enclosing capacity compared to their historic precedents their regulating geometry is variable. Digital modelling enables a seamless integration of scaled, tilted, rotated components within a continuous system. A parametrically differentiated Origami tessellation accentuates architectural performance by enhancing morphological flexibility and therefore diversifying possible modes of habitability (Fig. 5).

Kinetic shells in the genre of architectural textiles are tested in the studio with a range of material substances combining rigid and soft sheets. The groups explored the deployment ability of each shell in an indeterminate series of transformations alternating overall enfolding of the pleated shell in order to produce minimum inhabitable spaces (Fig. 6).

In terms of kinematics, Origami tessellations commonly manifest translational and rotational deployment, flat packaging, axial rotations, and more rarely axial revolutions. Translational deployment produces the spatial effect of oscillating tubular forms that contract and expand maintaining constant enclosure. Rotational Deployment produces the spatial effect of oscillating spherical forms that allow for variable boundary enclosure. Flat-packaging produces the spatial effect of a diminishing footprint. Revolutions and axial rotations produce the spatial effect of alternating concave and convex enclosures. Two formal states comprise minimum and maximum values the object achieves: developed state and flat package state. In between the two, objects acquire a variety of vault configurations producing an oscillating tubular spatial effect. Translational deployment was evident in all steps of the transformation from vault to flat package.

The third kind of design derivatives - the polymorphic reconfigurable objects-transgress the mandate of single surface. Origami tessellations provide the regulating geometry for component formation allowing for assemblage flexibility and multiple recombination options. In this genre of objects we observe the similarities between Origami and Tangram.

Prototyping

Fabricated prototypes confronts the geometry of surface transformations with material effects, incorporating factors such as gravity, time, and human participation. The full spectrum of shape change in the physical, animated by human activation prototypes was not evident in the digital simulation. Formal instability and plurality is triggered by the interaction between individual and kinetic prototype (Fig. 7).

While testing the fabricated prototypes we observed that Origami tessellations, in performance bare the potential to generate shape changes autonomously, operating as a morphological automaton. This emergent performativity, which is open to interaction and integrates the unpredictable, can be attributed not only to the systems' intrinsic geometry or its material consistency but also to the artefact's potential appropriation by human agency.



Fig. 7

Transformable furniture prototype performance at the kindergarten. University of Thessaly, Department of Architecture, Design Studio Folding Architecture, Sophia Vyzoviti (faculty) Pablo de Souza (teaching assistant) Eleni Marinakou, Stavroula Psomiadi and MariaTsilogianni (students) 2012.

Conclusion

The traditional disciplines of artistic expression are reinvented every day, transformed under the influence of technological advances that offer us greater accessibility to fields of action and reflection that were far away socially and physically until now. Architecture has traditionally been known as the art that covers the three major artistic disciplines. In the current contemporary context of creation and thanks to the influence of the new artistic languages and means of creation, the architectural project may be ephemeral, ethereal and audiovisual, a temporary urban installation, and no longer exclusively eternal heavy and immobile. Cross disciplinary of artistic genres that today represent diversified cultural production offers new opportunities for action and reflection, research and creation.

The course Folding Architecture partakes in this new phase of hybridization and cross-breeding inherent to contemporary creative trends, in which the act of creation has shifted from the individual to a practice of commons, a multidisciplinary community of creators, where collective work is a priority, focusing in the collaborative nature of artistic processes. Traditional art of Origami which has served and still serves as creative inspiration enhances its maximum expressiveness as a medium and as a catalyst for research. As a field of interference between innovations in artistic media, spatial geometries and building materials that enable multiple and heterogeneous applications of architecture, it offers to us a global vision and at the same time a focal point, a thread of narrative intensity and creative potential.

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Notes

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i Course description available on <http://www.arch.uth.gr/en/studies/course/482/8>

ii Available on <http://www.tsg.ne.jp/TT/software/>

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