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ORIGAMICS IN ARCHITECTURE: A MEDIUM OF INQUIRY FOR DESIGN IN ARCHITECTURE

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INTRODUCTION

The Japanese craft of "origami" has proved itself as being a valuable tool to develop various engineering and design applications in numerous fields. Several patterns developed by Dr. Nojima Taketoshi ranging from environmentally friendly containers (pet bottles, plastic containers, cans and et. al) to medical applications such as stents, catheters, from vehicle parts to new insulation material configurations, from robotics to education are sources of inspiration for many other research studies (Hagiwara 2008). These wide range of applications has been named by Ian Steward as "Origamics" demonstrating the interdisciplinary nature of these studies including mathematics, engineering, biology and many other possible disciplines which may use origamics (Stewart 2007). This paper aims to discuss the potentials of "origamics" in general, then in architecture, as an interface to gain cognitive experience on spatial transformations, computational design, form finding etc., and as a medium of inquiry for structural design in through the examples of kinetic or deployable structural designs in architecture.

FORM FINDING IN ORIGAMI

In the minds of many people, origami usually recalls skillfully crafted 2-D forms of living or non-living objects that are found in nature or in the built environment. Starting with a piece of paper and just by folding, ending up with diverse range of forms and patterns has attracted many people and resulted in hundreds of books and internet sites, origami courses. However, contemporary use of origami is not only a craft or tool for education, but also a very rich medium allowing several different and complex design applications. Though origami has evolved from being a craft to an interdisciplinary methodology "origamics", understanding the mathematics and geometrical pattern relations are essential parts of such studies. In the realm of mathematics, origami forms can be considered

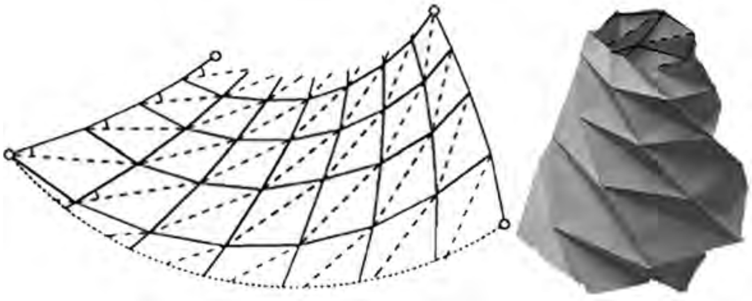

Figure 1. Taketoshi Nojima's Cone Diagram and Resulting Cone (Phillips, 2007).

as the mappings of "tessellations" into 2-D and 3-D space. In general, these tessellations are derived from applying isometric and/or similarity transformations of lines and line shapes in 2-D space (paper in traditional studies).

In the development of most of these patterns, it is possible to say that there is a grammar to be followed consisting of shapes (lines and angles) and "grammar rules" to be followed, mostly the geometry based on Huzita's Axioms (Khademzadeh and Mazaheri, 2007), Maekawa's Fundamental Theorems (Maekawa, 2008), Miura's Patterns (Miura, 1994, 13-22; 1971, 50) and Kawasaki Theorems (Hull, 2002), which has also potentials to be generalized for higher dimensions, and theorems and axioms proposed by many other mathematicians. These axioms and theorems have been first converted into successful algorithms by Robert Lang and based on these algorithms commercial software has been developed (Lang, 2008).

CONTEMPORARY APPLICATIONS OF ORIGAMI

As it is briefly introduced above, today, origamics has been recognized by many disciplines in various different studies ranging from mathematics to engineering, biology to computation and many implementations have been achieved.

The mathematical idea behind all these folding processes and their "mapping" into 2-D and 3-D space and the "grammar" of the diagrams developed in origami provides a valuable interface for education of mathematics and computation. On the way from origami to origamics, regularly held several international meetings and conferences each year (COET91; COET95; see Sorguç and Özkar, 2007) in which mathematicians are actively taking place, regulate the studies in this field and helped to found the basis of further studies. Lang studied the mathematical relations of creases and his studies and algorithms contributed to the achievement of more complex origami forms.

The development of origami diagrams in 2-D, and understanding the mathematical relations constructing these diagrams provide an invaluable medium to explore solid modeling in computational media. Construction of 2-D diagrams of origami potentially yielding "non-standard gridal forms" in plane, offers a new platform to design innovative "mesh" configurations for further form finding and modeling of m shells folded plates, or other types of structures. This relation between 2-D diagrams and the resulting 3-D solid models have also clues for the manufacturing/fabrication of these models from simple sheets of raw materials to complex forms.

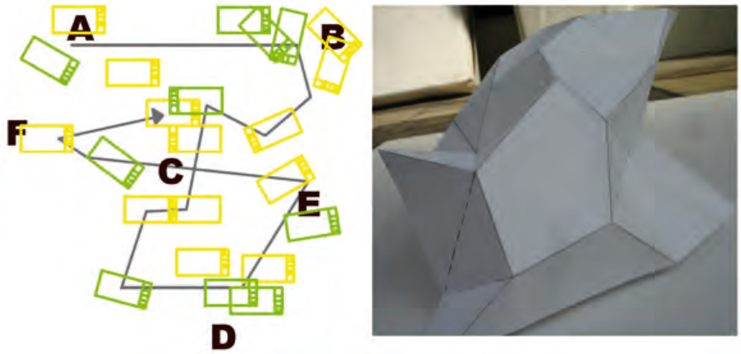

Figure 2. Computational Design by Origami, (Gönenç Sorguç and Özkar, Aalborg 2007).

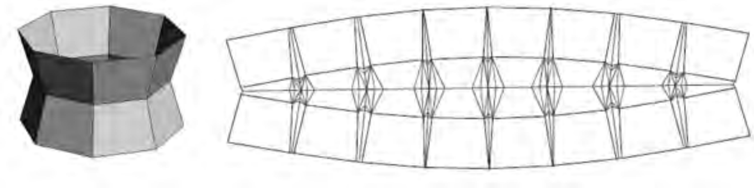

Figure 3. 3D polygonal model (left) and the crease pattern (right) (Mitani, 2009).

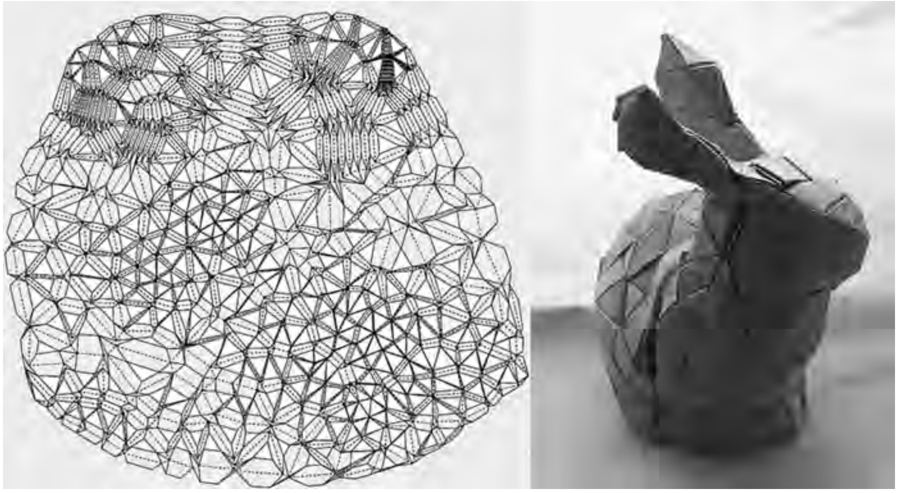

Figure 4. Full 3D origami bunny designed using 3D origami design software (http://graphics.stanford.edu/data/3Dscanrep/, retrieved December, 2009).

Hence, revising origami as a medium to inquire computational design processes as well, and considering these diagrams as a meta-language to develop visual algorithms of design patterns and forms result in new cognitive experiences as demonstrated in Figure 2, and example of computational development of a new shell structure based on 2-D patterns of Origami.

At this point, it is necessary to clearly emphasize that the way origami, either with its diagrams or as with its final "object classes", show variations in different design studies.

In industrial and architectural design when the final form has importance, origami provides both a prototype and also a "computational design algorithm" through the diagram for further design processes. In some cases origami is capable of producing "die/mold" for manufacturing in which machining sequences as well as nesting of parts are integral part of the diagrams manifested in 2-D plane. In computational point of view origami can also help "decomposition" of virtually constructed objects for manufacturing. Banghay in his study illustrated the process of the projection of a 3-D solid model into plane for the CAM manufacturing by using polygon nets together with basic principles of origami (Banghay, 2000). In another study, algorithm is proposed for obtaining 3-D origami models from a single plane by using polygonal representations for CAD applications (Mitani, 2004).

No matter how origami involves, it is seen that experiencing and re-experiencing the design process is possible in this way, in other words the set of "design products" produced by origami also facilitates reverse engineering applications.

Another important field of application of origami studies can be considered under the discipline of "Biomimesis" as named by Benyus (Benyus, 1997). The deployable/foldable nature of origami provides a very powerful medium in understanding several deployment modes existing in nature and thus the structural relations among different components.

Hachim, Karni and Hanaor studied some sampled deployable forms in nature, their morphologies and their potentials to be used in man made structural systems (Hachim, 2004). The studies of folding/unfolding process of hornbeam and beeves leaves by using origami models together with simulations explained kinetic energy requirement in these processes and contribute to developments of solar panels (Kobayashi, 1997). Several studies conducted by Nojima provided 3-D origami forms based on various forms in nature like cactus flowers, nautilus shells and many others resulted in the development of new lightweight high strength plate configurations and different applications from engineering to medicine (Hagiwara, 2008).

Today origami has also found application in the development of nano-materials and electronic devices and/or components. Jurga et al., proposed a method to develop 3-D nanostructures by folding 2-D nano-patterned membranes for manufacturing purposes (Jurga et al., 2003). Sokolowsky and et al. in their study developed an interactive image based modeling system called as image origami allowing construction of 3-D images from 2-D image data (Sokolowsky et al., 1999). Stellman and his co-workers proposed a kinetic and dynamic analysis technique in nano-patterning process used in the production process of nano-materials (Stellman, 2005).

STRUCTURAL INQUIRY FOR BUILDINGS OF THE 21ST CENTURY

Today, in one hand, rapidly developing design tools and construction/manufacturing technologies, the demands for more responsive spaces and as a consequence IT and AI applications, and on the other hand serious environmental problems (depletion of energy sources, pollution, disasters, etc.) and thus demands for performance based solutions, rapid population growth and etc. make architectural design process much more complex than ever before and force architects to develop new approaches through trans-disciplinary studies. Recently, there are examples of architectural designs with their innovative forms/form finding processes and structures together with their functional efficiencies revealing this complexity. However, the difficulty of finding optimized form-structure-function trilogy still imposes difficulties and researchers seek for new methods/tools to develop new structures and thus new forms.

It is no doubt that structural design is an integral part of many engineering and architectural design processes and has a direct effect on the final configuration of the "designed product". However it is the process which constrains the design most; light weightiness, static and dynamic stability, long life span, construction/manufacturing easiness, low cost, high strength but environmentally friendly materials and many more. Thus, searching for the proper structural configuration which satisfy the constraints but yet allow designers to develop their "product" is a general problem experienced in any design process.

ORIGAMI AND THE STRUCTURAL DESIGN PROCESS

As briefly summarized in the previous section, architectural design in today's practice has become a trans-disciplinary issue and the "design" should satisfy many requirements. The complexity of the design problematic and the process itself force architects to explore new methods and new media to provide suitable solutions. While the use of computational medium offers architects a great extent of freedom in exploring new forms, these forms with their flexible features and temporal and/or spatial transformability potentials are mostly incompatible with conventional structures. Hence, architects and engineers are seeking for new "structural configurations" to achieve architectonics with the required stability and "flexibility".

In the quest for structural solutions, architects have been searching for new form-structure relations, different modes of structural solutions in terms of responsiveness and thus they explore new design tools or media. Origami, which provides form and structure at the same time, with some spatial qualities has become a subject of interest among the designers. Hence, it is inspiring to inquire potentials of origami as a medium to design and develop new architectural structural forms (kinetic or static) satisfying the requirements outlined above.

Origami as described in previous studies provides "diagrams" from 2-D space into 3-D space and resulting forms are free from any plastic deformations. Moreover, the structural stability of these folded configurations has been considerably improved. Recent examples developed by Dr. Nojima for automotive and aerospace industry illustrates the achievement of structural stiffness of these planes by preserving their lightness as well. In addition to structural stability of origami forms which are potentially "kinetic", a single type input (i.e. force, torque or moment) is adequate to deploy or collapse (fold and unfold) these forms (Krishnan, 2003). Deployment observed in origami has been a subject of interests in decades.

Hunt and Aria studied one of the common modes of deployment in origami, twist buckling encountered in cylindrical origami forms (Hunt and Aria, 2005). Ebara and Kawaguchi applied origami to the design of 3-D deployable solid structures and presented some structural models obtained with their approach (Ebara, 2003). Vincent in his studies related with biomimesis also analyzed deployable structures found in nature in the forms of tubes, membranes, folded plates observed in plants and insects and discussed how these structures can be applied to man-made systems contributing future studies on origami as well (Vincent, 2000). Deployable structures has found applications in large extend in designing space antennas. Among several researchers, Pellegrino and Guest developed a space antenna with deployable features and built a fully working prototype (Pellegrino, 2008). There are also new studies in field of medicine and related engineering. In this context, **Figure 5** shows an innovative study

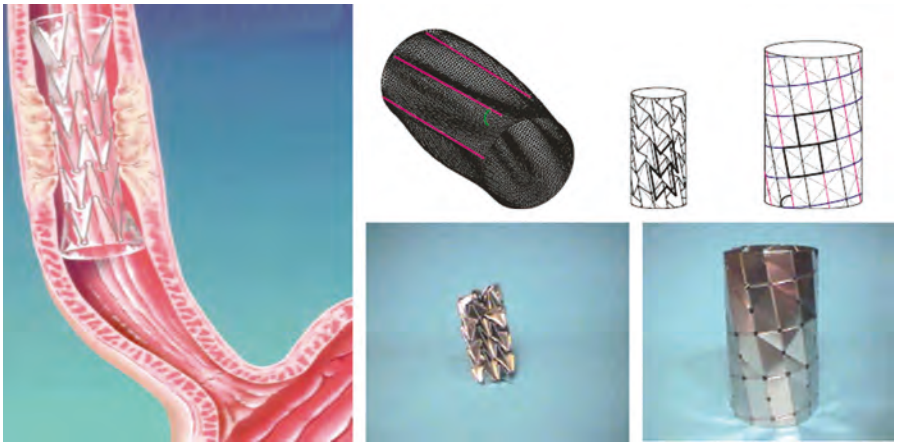

Figure 5. Expandable stents inspired by origami (http://www-civil.eng.ox.ac.uk/people/zy/old/research/stent.pdf, retrieved December 2009).

called "Innovative Origami Expandable Stents" by Kaori Kuribayashi, a research student in the Department of Engineering Science, Oxford.

Studies briefly introduced above are some well known examples structural design by using origami. The number of these studies in literature is numerous and many other interesting examples are developed at different scale. However, in architecture thus in building scale, such innovative structures have not been encountered yet despite the need of them. But the present examples in literature have proved that origami with all its latent features can be considered as prospective medium/tool for architectural designers to explore new structural forms static or kinetic structures for further application both to achieve new forms, "responsiveness" and "performance" which are expected qualities of today's architecture.

a. Origami in Shell and Plate Design in Architecture

The relations or rules to be followed in the organization of crease patterns (valleys and hills) given in origami diagrams can be considered as a meta-language for different disciplines and their applications. In the case of structural design, these diagrams have potentials to provide "mesh networks" of structural forms. When these "mesh networks" are augmented into 3-D space, it can easily be seen that 2-D forms generate "classes of structural elements" with a proper structural stabilities. The patterns developed in the diagrams i.e. "mesh networks" can be experienced in virtual or real medium i.e. in paper with which architects are very familiar.

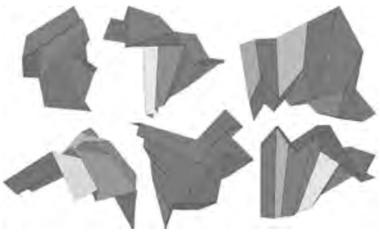

Figure 6. Spatial Exploration of an Arbitrary Folding .

The possibility of changing the depths of creases and/or their frequencies, allows the exploration of different structural stabilities and also different spatial qualities. Here in such studies, origami provides the "functions" for the transformation from plate to shell or from plate to folded plate. **Figure 6** shows how computer visualization can be used to explore the potential applications of ideas from borrowed origami for the conceptual design of plates and shells.

Figure 7. Origami Crease Patterns and exploring its Structural Performance, METU experience.

From this point of view, in the department of architecture at METU, Ankara, several courses which allow students to explore form-structure-space concepts both in real and digital world, have been designed. Among them in Arch 333 Mathematics in Architecture and in Arch 470 Digital Design Studio, students have experienced and shared spatial and structural potentials of a sheet of paper by hands on workshops. **Figure 7** shows a student work, how successfully a piece of paper turns into a structure by simple origami folds. On the left is seen the geometric configuration of valleys and hills on a sheet of paper before folding, as well as the topology of an origami work, that have been recently addressed in such courses to be used as medium and guide not only to design new forms, but also to explore the potentials of a plate and a shell structure.

There are also hands on studies/inquiries' in architectural schools in different countries such as **Figure 8** shows a cardboard structure designed by students from the Department of Architecture at The University of Cambridge for a banquet, and **Figure 9** shows another study from Siracusa, İtaly by Prof. Luigi Alini's studio. Similarly in **Figure 10**, the "Packaged" designed by Miwa Takabayashi is a temporary pavilion built with cardboard, to be installed at various malls.

In the practice of architecture it is not surprising to see the impact of origami as a medium to generate different shell forms. In this context, Yokohama Port Terminal by FOA Architects and Colorado Springs Air

Figure 8. Students works from Cambridge (http://www.arplus.com/9298/cardboard-banquet-cambridge-uk-by/ retrieved December 2009).

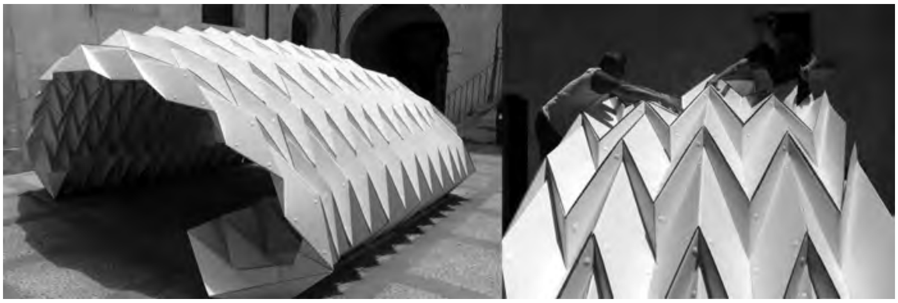

Figure 9. CardBoard Pavilion http://europaconcorsi.com/projects/112669-Cardboard-Pavilion-Costruire-Col-Cartone/images/1596828/slideshow, retrieved December 2009).

Figure 10. "Packaged" an artwork designed by Miwa Takabayashi's (http://blog.bellostes.com/media/packaged-cardboard-pavilion.png, retrieved December 2009).

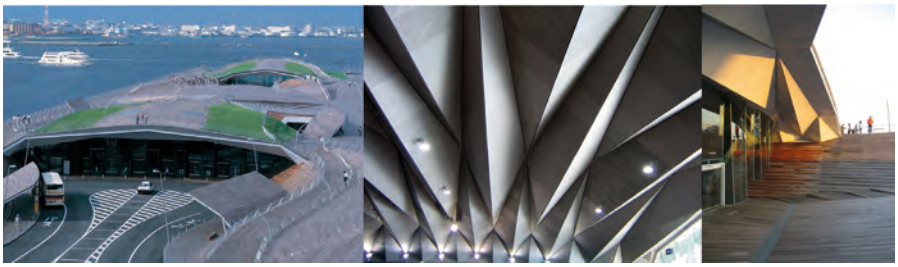

Figure 11. Yokohama Port Terminal by FOA (http://www.boliviaarquitectura.com/img/architecture%20now/FOA/projekt-foa-yokohama-06.jpg, retrieved December 2009).

Figure 12. Colorado Springs Air Force Academy Chapel (http://www.dgrin.com/showthread.php?t=132729, retrieved December 2009).

Figure 13. Automobile Museum in Nanjing, China

(http://www.worldarchitecturenews.com/index.php, retrieved December 2009).

Force Academy Chapel by SOM are a well known examples of shell buildings in which the diagrams and structural relations of origami can be traced easily (**Figure 11**, **12**). Recently, "Car Experience" project has been announced as the winner of the international invitation competition for the Construction of the Automobile Museum in Nanjing, inspired by origami is being constructed in China (**Figure 13**).

However, when these diagrams are analyzed to extend further, it can be seen that these diagrammatic relations guaranteeing structural order and stability can also be used to explore new forms for steel structures and space frames which are not easy to be realized with the present vocabulary of these structures. Hence it is possible to claim that the idea of origami helps structural engineers and architects to extend the present "vocabulary" of structural elements.

b. Origami in Design of Kinetic Structures in Architecture

> "If architects designed a building like a body, it would have a system of bones and muscles and tendons and a brain that knows how to respond. If a building could change its posture, tighten its muscles and brace itself against the wind, its structural mass could literally be cut in half…"
>
> Guy Nordenson, Ove Arup and Partner (Fox, 2000).

In today's architecture, conventional static space is no longer adequate to describe the "contemporary space" and more efforts has been spent to

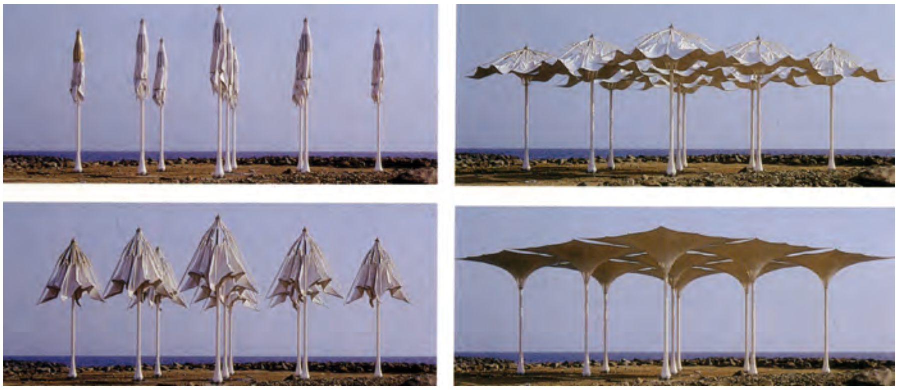

Figure 14. Convertible umbrellas by Frei Otto (Otto, 1995).

provide “flexibility” in order to achieve responsiveness and thus the idea of “intelligence”. Moreover, structures should be lighter and “transformable”. This trend has been named as Kinetic Architecture but it should be emphasized that the definition of “kinetic architecture” should be revised with the definition of new kinetic structures which are expected to be an integral part of the building structure rather than part of the structural “installations”.

Membrane packing is the earliest prototypes of kinetic architecture and can be observed in the tents of many tribal cultures. Traditional tents were revived by Otto as a leading prototype for lightweight adaptable buildings and his early forms in 1950s on retractable covering which had minimum surface during the construction and extending to a large area is still an important example for deployable structures (Otto, 1995).

In the early 1960s, Emilio Pinero pioneered the use of scissor mechanisms to make deployable structures. A mechanism can expand in a horizontal direction, in both horizontal and vertical directions, and with a fabric covering, which unfolds with the mechanism to complete a deployable roof. Chuck Hoberman who has followed Pinero’s way is another “inventor”. He calls himself the designer of several kinetic structures and seeks for new spatial organizations based on the idea of motion in nature. In his structures “the idea of mechanism” can be clearly seen both in the structural relations and the way deployments are achieved with successfully. But the majority of those structures are “installations” rather than they are part of the structural design in building scale. There are also several recent examples of other deployable and retractable systems

Figure 15. Pinero’s scissor mechanisms for deployable structures (Robbin, 1996).

Figure 16. Hoberman’s Iris Dome (Architecture, June, 1994, 103).

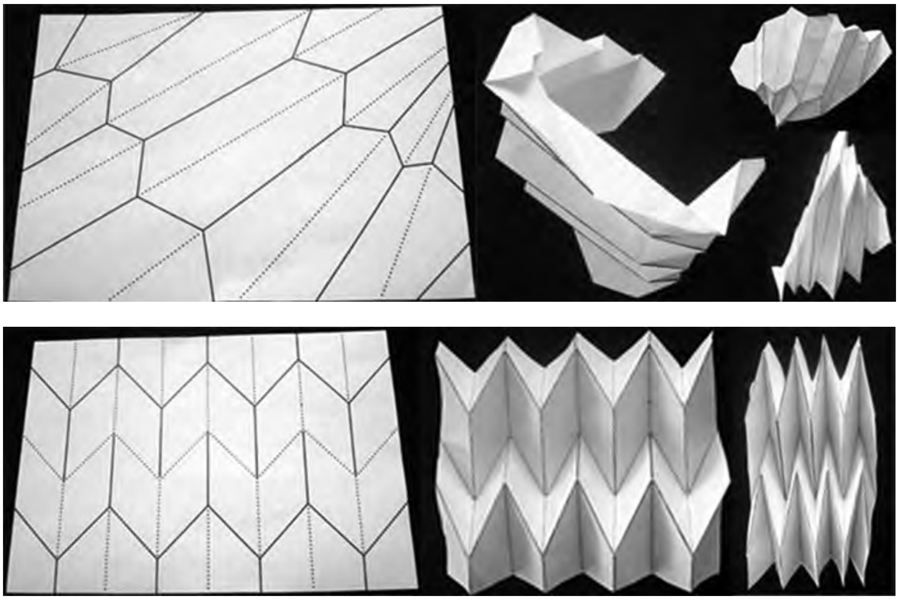

Figure 17. Demonstration of kinetic properties of an arbitrary folding.

Figure 18. Folding egg, sectional prototype (Fox, 2004).

in architecture from small scale shelters to roofs covering very large spaces as well as antennas and solar panels, yet number of applications and their performance are limited. It is possible to claim that although kinetic architecture has much potential in building design and achieving interactive/responsive built environments, compared with other kinetic design examples in different disciplines; it is still in its infancy. The main reason of such discrepancy is the way kinetic structures designed in the field of architecture; mostly by intuition and inspiration or through some trial and error processes.

However, design of kinetic structures requires trans-disciplinary approaches and architects should overcome many difficulties faced by mechanical and control engineers and he/she should provide dynamic and structural stability, forces to be applied and many more in the design process. Hence architect should find some new tools and medium to experience such complex behaviors of kinetic structures in order to use them efficiently in their design.

Origami has also potentials to be used in the search for kinetic structures, and understanding the kinetic behaviors. In this sense, the diagrams developed in origami can also be considered as the relation of "links" which are designed to yield either a translational or rotational displacements without any "locking" problem which is an important obstacle in the design of "mechanisms". When the design of a simple four bar mechanism is thought, even the calculation of the force to be applied, the dimensions of links and their proportions may not be very straightforward in the initial phase. However, any origami folding, even with a very complex folding diagram, can easily be fold and unfold with a single stroke of a force or torque in a stable way.

The "folding egg" is a prototype kinetic folding sheet structure that is constructed from a low-cost recyclable material by Bryant Yeh in Kinetic Design Group in MIT (**Figure 18**) Advantages are low cost, low weight, structural stability, high insulation value and many possible configurations.

It is easily experienced that any origami structure can be folded or unfolded regardless the complexity of the form without any plastic deformation or "locking" which avoids deployment. Thus the networks provided in these origami diagrams also provide the schema of the "mechanism" with proper proportions among "links" which are crease patterns of the whole configuration. Therefore, the study of these diagrams grants an initially wise search for a kinetic structure and acts as a medium which facilitates further applications of control and eventually realization of the proposed network of mechanism. Moreover, the form-structure duality of origami will help architect to control the spatial relations and allow kinetic structure to be an integral part of the architecture.

CONCLUSION

Origami, from an ancient Japanese craft to today's recently recognized "engineering discipline", offers many opportunities to mathematicians, designers and engineers to explore mathematical relations, new forms and dynamic or static structures.

During the last decades, studies conducted in Japan have shown the transformation of origami from 2-D to 3-D and has found important fields of applications in industry. These studies have also contributed to the recognition of origami as an "engineering discipline" allowing trans-discipliner studies from biology to nano-technologies, from automotive to structural design.

As presented in the previous sections, while the involvement of IT and computational technologies has led architects to explore new form-function structure relations, architectural design problems become more and more complex and an architectural design should satisfy both environmental requirements/constraints with high spatial and formal qualities and also respond to human needs. In achieving this complicated task, architects need to explore new forms, structures and propose solutions integrated and/or compatible with the state of art technologies without losing architectural qualities. Therefore, developing new media and/or tools allowing architects for such inquiries becomes a very important issue.

Hence, the art of origami in architecture has been re-visited in this new context. Examples manifesting the potentials of origami in architectural design and manufacturing processes have been presented and some clues on how origami can serve to design education are given. Increasing number of new examples, researches, exhibitions demonstrating the use of origami have proved that this ancient art has still have many prospects to be investigated.

In this context, origami and it is potentials have been explored in computational design, form finding for shell and plates as well as for design of new kinetic structures in architecture should be emphasized that, the mathematical idea behind folding and their organizations and resulting networks in the diagrams are today's "algorithms" for further design development processes which are generating several designs keeping form and structure intact. Thus, authors believe that origami should be questioned more in architecture as well and its concise use will provide very valuable information in their quest for "complex designs".

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Anahtar Sözcükler: origami; mimarlıkta origami; tasarım eğitimi; biçimsel araştırmalar.

MİMARLIKTA ORİGAMİ: MİMARİ TASARIM İÇİN YENİ BİR ARAŞTIRMA ALANI

Bu çalışmada, 'origami' bir öğrenme ara yüzü olarak ele alınmış ve bu bağlamda farklı disiplinlerdeki uygulamaları incelenmiştir. Benzer biçimde, mimarlık alanında bu potansiyeller araştırılmış ve örneklenmiştir. Makale kapsamında 'mimarlıkta origami', form strüktür ve mekânın bir arada şekillendiği güçlü bir keşfetme ortamı/aracı olarak sunulmuştur. Bu keşif sırasında üretilen şemalar/diyagramlar ise düzlem-levha ve kabukların keşfedilmesi ve tasarlanması, bir sonraki aşamada ise etkileşimli akıllı ya da edilgen sistemlerin tasarlanması, dönüşüme olanak veren kinetik yapıların geliştirilmesinde çok boyutlu bir araç olarak ele alınmıştır. Süreçte bir ara yüz olarak origaminin hem tasarım eğitimindeki çok boyutluluğu öğretmek, hem de öğrencilerin mimari tasarım projelerinde ileri morfolojik araştırmalar yapmalarını sağlamak amacıyla eğitimdeki olası kullanımlarının neler olabileceği de örneklenmiştir.