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Flexible Physical Body by Blending Architecture and Structure Using Origami

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ABSTRACT

Flexibility is one of the key concepts in the formation alphabet of architecture but it is less frequently taken into account in the area of physical body and it has more been dealt with of the diversity or free plan designing types in micro-scales. When the architectural spaces' context needs flexibility, the structure, as well as the architectural form, should be both designed because the most important challenge in investigating flexibility in architectural context is structure and flexibility has to be granted to the body of structure and that in a macro-scale. The present article aims at investigating flexibility in the architectural context for which the structure should be coordinated with the behavioral architecture. Origami technology solidifies and renders flexible its structure to be followed by physical flexibility and structural stability and this is why it has drawn the attention of the structural and architectural engineers. In this regard, origami is utilized as a factor linking the structure and architecture. The diamond origami pattern possesses the intended properties in terms of architectural flexibility and structural stability and it was subjected to loading in the form of a model made of steel plates in finite element software. The findings indicated that the diamond origami pattern provides the required flexibility for adaptation to the various environmental conditions by blending architecture and structure in the building's physical body and that the diamond pattern's adaptability is feasible in all the sub-branches.

Keywords: Flexibility, Adaptability, Physical Body, Structure, Origami.

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1. INTRODUCTION

Architectural flexibility means responding to the new conditions that are always integral necessities of architecture (Mahdavinejad, Farajollahi, & Karam, 2011, p. 1). This can be actualized when the structure is not found baring the architec-tural flexibility from being objectified. Nowadays, the traditional methods of construction are no longer responding to novel conditions. This is while the industrial methods of construction are not always found successful and generally cause inflexibility in the building for attentions are solely paid in them to the current common needs expected to be satisfied by the building and the prospective requirements are mostly neglected (Einifar, 2003, p. 65). In order to render the building physical body flexible, use should be made of the technology when designing the structure because three topics, namely structure, architecture and technology, have been the same in their primary significations since the beginning of the recorded architectural history (Bagha'ei, 2009, p. 28) and it is clear that architecture and structure are closely interrelated in such a way that the functional structural systems are envisioned as main systems of building axis and have been usually honestly expressing the architectural forms (Ching, Onouye, & Zyber-buhler, 2013, p. 134). Flexibility in architectural designing substantially pertains to the designing of "spatial forms" and their construction. This way, architects often tend to develop diverse and uncommon architectural forms.

Structure is the most important challenge in the flexible architecture for preserving the building's stasis and features a fixed form and position parallel to the controlling of the static and dynamic forces (Moore, 1999, p. 10). Therefore, in order to create flexibility in the physical body, the structure should be also designed flexibly so that coordination can be brought about via the spatial context be-tween the structure and architecture.

Featuring structural solidarity and formability, origami causes the bond between structural engineering and architecture (Schenk & Guest, 2011, p. 4). Such a composition leads to a strong and efficient structure with more advantages in contrast to the traditional forms of construction (Ahmed, Wan Badaruzzaman, & Wright, 2000, p. 126). Origami has been used as a solution in numerous sciences and its applicability is undeniable but the goal of this study is taking advantage of the flexibility attribute of diamond origami for creating physically flexible architecture. Such flexibility can be actualized in an applied manner and on a macro-scale when the structural requirements are observed in line with the achievement of a balanced structure.

Therefore, types and scales of flexibility in architecture, as well as the structural re-quirements and various kinds of the structure-architecture interrelationships, were investigated following which the effect of such a technology on the structure and physical flexibility was determined based on the conceptualization of origami and investigation of its properties. In the end, the best method for coordinating structure and architecture was specified.

2. THEORETICAL FOUNDATIONS

In order to design a flexible space, it is necessary to recognize the flexibility's definition and factors involved therein. Thus, the following sections deal with the definition of flexibility and various kinds of flexibility in architecture.

2.1. Definition and Concept of Flexibility in Architecture

Literary, flexibility means bending and pliability and elasticity and flexible is the thing that is bendable, pliable and elastic (Dehkhoda, 1998, p. 3765). In English, flexibility means the changeability in the objects and things and it is lexically an adjective referring to the elasticity of an object in such a way that it is found easily changeable according to the conditions hence it is considered as an equivalent to the term changeability (Cambridge Dictionary, 2013). The term "flexibility" is used in architecture to mean a manmade space accountable to the novel conditions and needs. Flexibility means adaptation to the changes in the space and points to the issues related to the users' present time and future needs (Schneider & Till, 2005, p. 287).

2.2. Types of Flexibility

Flexibility can be categorized in either of the following groups:

2.2.1. Diversity

The ability to provide various uses of space is called diversity which is defined as the freedom in making choices for diverse uses enabling the users to make choices based on their needs (Albotan, 2009, p. 1). In other words, diversity is the very multifunctional property of a space serving various functions at various times. In general, the two concepts of time and space are in interlocking association with one another and cannot be separated as also pointed out by Herman Minkowski: "time alone and space alone are condemned to destruction and only their unity facilitates their survival" (Ching, 2014, p. 134). Every space is capable of being converted to a place and this is formed over time and by human beings (Erabi, 2011, p. 14).

2.2.2. Changeability

The ability of space for development or summation in the form of its substructure's quantitative increase or decrease or the ability of space's separation and restoration to the preliminary plan after expansion and/or area reduction is called changeability. This attribute is directly related to the type of spatial function, form, shape, and dimensions of the collection wherein space is located. Changeability may be observed in structural, functional or spatial forms (Einifar, Shayan, & Garipour, 1989). This property is more engaged with physical body of space because it is via the physical development and summation that the area and capacity can be changed. Thus, space's physical body should feature changeability so as to be flexible as held by Lang, "flexibility in architecture is the attribute of a space that can be changed for responding to the various needs" (Lang, 1987, p. 201). In other words, "flexibility means adapting to the spatial changes" (Schneider & Till, 2005, p. 2). In general, spatial flexibility and organization of the manmade space and the changes therein serve the achievement of new conditions and needs and applications (Einifar, Shayan, & Garipour, 1989).

2.2.3. Adaptability

The ability of space for adjusting to the new and required conditions is called adaptability. This space can respond to the various functions at one time and at different times (Venturi & Scully, 1977, p. 49). Following the primary pattern and geometry enables the designing of a flexible space that is also capable of getting adapted to the conditions during various times (Einifar, Shayan, & Garipour, 1989, p. 70). Adaptability includes factors of spatial organization, functional factors, and physical factors. Figure (1) illustrates the types of flexibility.

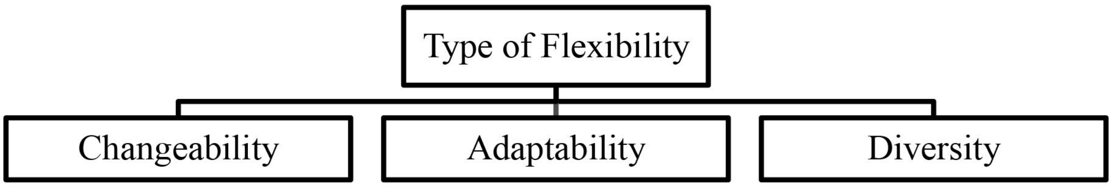

Fig. 1. Diagram Showing the Flexibility Types

2.2.3.1. Physical Factors

According to the study objective, the forthcoming section solely deals with the physical aspect of adaptation. Physical body refers to the format of the building, i.e. everything touchable and observable in a building. One of the factors influencing the creation of "adaptable" space is the physical body of building that gets adapted to the conditions in the course of designing process and depends on factors like dimensions and size, geometry, form and shape, diversity and space's variegation (Sheppard & Town, 1974, p. 86).

A) Dimensions and Sizes: all of the architectural dimensions are formed of form and space, meaning and concept, performance and efficiency depending on the human being's nature and destiny, wants and needs. The proportions of space are influenced by masonry materials (brick, block and so on), structural issues and systems (covered span), standardized elements and components (door, window, carpet and so forth) and their limitations and facilities. Moreover, the human proportions, human perception, and mentality, number of individuals, behavior, performance and furniture play determinant roles in the dimensions and sizes of the architectural spaces (Erabi, 2011, p. 212). Dimension and size can be investigated in the depth and height of the physical body and the size of the interior space and architectural elements and the more the access to space is easier, the more space enjoys adaptability (Bentley, 1985, p. 178).

B) Architectural Elements' Siting: physical properties depend on other factors like the placement location of doors and windows, as well, that largely influence the space's adaptability (Lang, 1987, p. 119). Essentially, the method of light's infiltration and passing through the shell into the interior parts for lighting the space causes the formation of the building's form and façade so form and space would be indiscernible without light (Erabi, 2011, p. 138).

C) Shape and Form: although the creation of space is the primary goal of architectural designing and it is the space the encompasses us and also it is the space wherein our behaviors and activities occur, we need designing the proper form for the creation of this space. In general, the embodiment and appearance of a phenomenon are called form which, in line with the expression of the present study's subject, is a meaning or content formed of certain materials. The effect of the constituent materials on the formation of form as well as the abilities and constraints of every material in formability, as well, are expressive of the interaction and effect of special contents and raw materials on the formation of the form (Erabi, 2011, p. 64). Cambridge believes that the performance of the objects can be defined via their representation in mind. In Sullivan's mind, "form manifests performance". "Form enables performance and functioning". Venturi realizes multipurpose buildings as physically a space that is complex in terms of plan and form but at the same time acceptable as a whole. Complexity causes the creation of ambiguity which per se results in the creation of adaptability (Venturi & Scully, 1977, p. 49). One of the properties of complex systems is the nature of their adaptability. These systems are not passive rather they exhibit reactions in an active form so as to exhibit every incident in their favor and make various kinds adapted to the environment (Bemanian, Amirkhani, & Leilian, 2010, p. 91).

D) Diversity and Variegation: diversity and variegation in space are effective in space in line with bringing about adaptation to the environment and performance during various times. Such variegation can take place in number, size, and area, shape, and form as well as color and so on in such a way that, according to Hertzberger, the users can choose the space based on what they want (Albotan, 2009, p. 74). Production of space can be carried out by propagation of a repetitive element in a free manner. If various solutions are created for the method of the volumes' interference with one another, diversity can be created. Though featuring a modular basis, this task is diverse in composition for it is done freely. In parallel, the specifications of the segments, type of interference and amount of infiltration in one another by them are very effective in the final composition's diversity (Erabi, 2011, p. 132).

2.3. Scales of Flexibility

Recognition of various scales of flexibility contributes to a better understanding of flexibility. In an article titled "investigation and comparison of flexibility in Iran and Japan's residential architecture", Einifar et al. (1989) analyzed the flexibility scales of the traditional houses' spaces and, as put by them, these scales can be generalized to the urban spaces, as well (Einifar, Shayan, & Garipour, 1989, p. 70). They have divided flexibility scale into several sets, including the followings:

1) Micro-Scale: in this scale, flexibility is defined in the spatial and functional dimensions and components (service-providing, service-receiving and communication spaces). In fact, on this scale, the spaces acquire their names from the formation of the space and space is not given a specific name so that it can respond to the various performances.

2) Medium Scale: in this scale, flexibility is engaged with the functional layers. Getting the elements organizing a space coherent and creating unity between them as well as the quality of these elements' interrelationships and the type of their relationships inside and outside the building are discussed in this scale. The use of light and ventilation and openings on this scale is of great importance.

3) Macro-Scale: this scale incorporates functional, structural and spatial flexibility. Vertical and horizontal development of the space and the type of its relationship with the peripheral neighborhood are important in this scale (Ibid, p. 71).

The flexibility of the space's physical body in terms of the scale falls in a subset of the macro-scale because the micro- and medium scales mostly deal with the space's internal layers and macro-scale largely deals with the changes like the space's physical separation and connection and the method in which the physical body is connected to the environment (Ibid, p. 71). The important subject in the macro-scale is the creation of coordination between the architectural physical body and the building's body. Therefore, it is necessary to become familiar with various kinds of relationships between structure and architecture.

2.4. Various Kinds of Relationship between Architecture and Structure

In general, there are three types of relationships between the structural form and architectural form:

A) Paradox: it is seen between the architectural and structural forms when there is occurred a sort of adjacency like geometry, masonry, scale, and texture between some parts of the architectural qualities. The geometrical dissimilarity between the architectural and structural forms is the most common quality sourcing the paradox.

B) Blending: structure plays the role of the building's body and architecture grants function thereto. The shell structures are the purest combinations of the structure and architecture.

C) Symbiosis: while being independent, structure and architecture peacefully live at one another's side and do not cause any barriers for each other. Most of the buildings fall in this set (Charleson, 2014, p. 42).

Based on this classification, the blending of the architecture and structure creates the highest amount of flexibility in the physical body of space. In fact, it is via the creation of a flexible structure as the body of a typical building that a flexible architectural context is created. To do so, the structure and architecture should be simultaneously designed and this adds to the precision in the architectural designing but entails paying attention to the structural designing requirements.

2.5. Essential Factors and Requirements in Structural Designing

Recent advances in the area of materials production, techniques of building construction and methods of structural calculations have brought about novel freedom in architectural designing the realm of which has also been extensively expanded accordingly. But this new freedom does not exempt the modern structures of the supply of the essential and required principles that have always been the foundation of good architecture. These factors are balance, stability, strength, performance, economy, and beauty (Salvadori, Heller, & Oakley, 2017, p. 32). Therefore, paying attention to balance and stability is considered amongst the requirements in every sort of formal and physical designing hence these have to be somehow tested.

2.6. Origami Conceptualization and Application in Architecture and Structure

Origami is a Japanese word made of two terms "oru", meaning folded, and "kami", meaning paper. Origami is the method of offering shapes and it is substantially obtained by folding the used material, i.e. paper.

Origami is the art and thought of folding paper for creating various shapes (LaFosse & Alexander, 2008, p. 5). The folded plates of the fixed or movable panels as inspired by origami are widely applied for motive architectural plans. The structure of the curved and folded plates in origami has drawn the attention of two groups of architects and structural engineers due to their possession of massiveness and continuousness, creation of applied spaces as well as the plastic and flexible characteristics. The diversity and scattering of light and shade along the folded plates emphasize the formability and flexibility of space and covering in architecture. These folds not only create protruded and indented structures but also enable a subtle perception of the space (Schenk & Guest, 2011, p. 3). The folded origami sheets have more strength and solidarity against the imposed forces as compared to the flat papers. In Origami and by the assistance of a collection of resistant folds and layers capable of being hardened, the thin surfaces not only cover the space but also act as the load-bearing element, as well. The diamond pattern is a sort of origami the folding of which is essentially based on a diamond's shape which was invented by a Japanese scientist after subjecting a cylinder to pressure and its compression. This pattern features solidarity and flexible form as shown in Figure (2) (Buri & Weinand, 2008, p. 2).

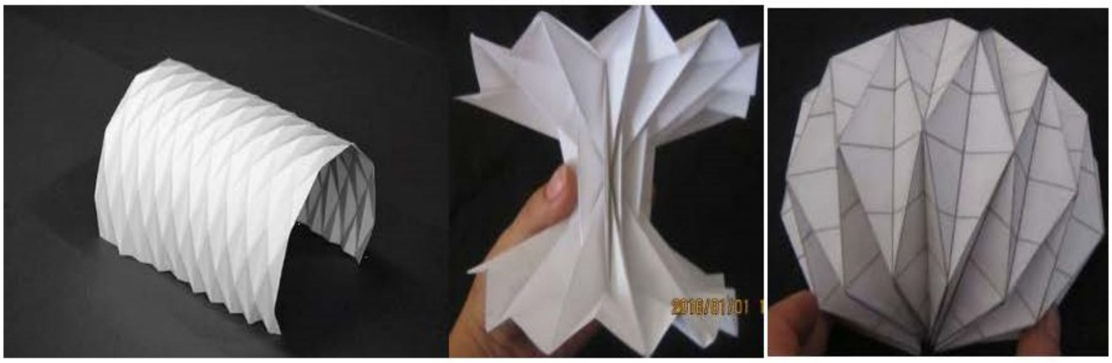

Fig. 2. Flexibility in a Diamond Pattern

Considering the factors influencing the physical flexibility of the space in Figure (2), origami features diversity as well as flexibility required for creating the physical body of a space. According to the fact that the structural stability is one of the most important challenges in the flexible architecture for creating flexibility in physical body, application of flexibility in the diamond origami pattern and its production using steel plates, as flexible materials, within the format of space-constituting shell provides a sort of mixture between architectural and structural forms making the structure and the body of the building. Steel plates with the capability of changeability in the architectural context facilitate flexibility through folds in the origami plan. On the other hand, origami folds on space's shell cause more solidarity in the steel plates for withstanding the loads. To prove this hypothesis, it is necessary to model the diamond pattern and subject it to loading so that its flexibility and stability can be assessed.

3. RESEARCH METHOD

Most of the plans are modeled and calculated before implementation by the assistance of software (Matcha & Ljubas, 2011, p. 327). Origami modeling can be generalized based on the geometry of its paper patterns to real-world cases (Buri & Weindnand, 2008, p. 2). The modeling process is carried out by the use of software simulating the real world's specimens in the virtual space enabling the designers and engineers to investigate the model's flexibility (Felbrich, Nönnig, & Wiesenhütter, 2014, p. 174). The diamond pattern was modeled based on the geometry obtained in the prior research using finite element software using 0.6mm steel plates and subjected to subsequent analyses. In order to analyze the structure's stability and changeability in various axes, use was made of Abaqus/Standard, version 6.10, for its high speed and accuracy in structural modeling. Abaqus/Standard Software utilizes the Newton-Raphson Method for solving the nonlinear problems in which, unlike the linear problems, the answer cannot be calculated via solving a single equations' system. In other words, in the nonlinear method, the software divided the entire simulation problem into several loading steps and determines the approximate static balance configuration at the end of each step. Generally, the calculation of the balance conditions and the acceptable answer in every loading step necessitates the running of a trial and error and consecutive reiteration process. In the end, the sum of answers found in various steps gives an estimation of the nonlinear problem's solution. Resultantly, Abaqus/Standard Software concomitantly implements repetitive processes and performs load dividing to calculate the answer to the nonlinear problem (Musavi, 2013, p. 60). In this test, the stress in orthogonal (gravitational) loading has been investigated in line with the determination of the tolerance to the vertical loads, stress in lateral (cyclic) loading and maximum displacement and force (pushover) to figure out the reaction of the diamond pattern's structure to the physical body's flexibility as well as the structure's stability and changeability.

4. STUDY FINDINGS

Pattern modeling using Abaqus/Standard Software was investigated subject to various kinds of stress loading in the forms of orthogonal (gravitational) loading, lateral (cyclic) loading and maximum force and displacement (pushover) so that the accuracy of the stability and architectural flexibility acquired for the structure can be determined.

4.1. Investigating Stress in Orthogonal (Gravitational) Loading

The highest stress is observed in the apices of the structural format's geometry highlighted in red in Figure (3). The more the structural parts tend towards dark blue, the more they are found stable. The exerted gravitational force was equal to 280182 Newtons and the displacement was found equal to 9.3179 centimeters meaning that the diamond origami structure features the required balance and stability.

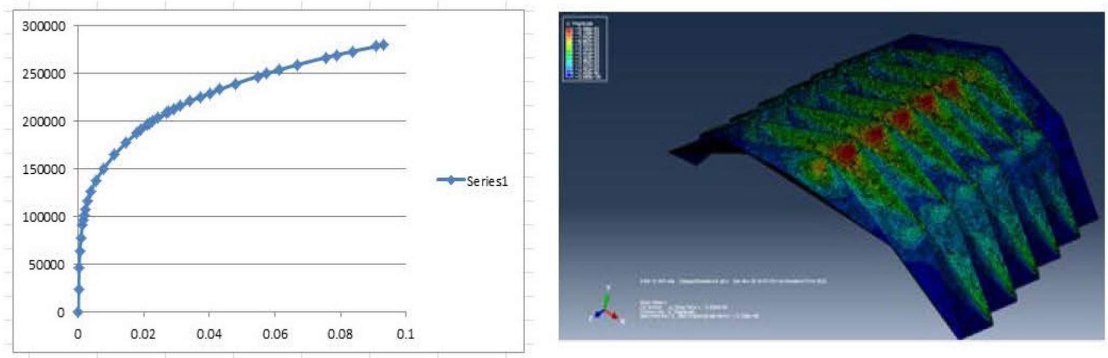

Fig. 3. The Capacity of the Diamond Model Following the Orthogonal Loading

4.2. Investigating Stress in Lateral (Cyclic) Loading

To delineate the hysteresis diagrams, use was made of cyclic loading to clarify the stress caused by lateral loads on the cross-sections. In all of the models, loading's effect is calculated in the form of displacement. This type of loading was carried out on two axes.

A) Cyclic Loading in X-Axis:

Stress caused by reciprocal (cyclic) loading on x-axis shows that the structure undergoes displacement for 9.5cm up to a load equal to 258481 Newtons (Fig. 4).

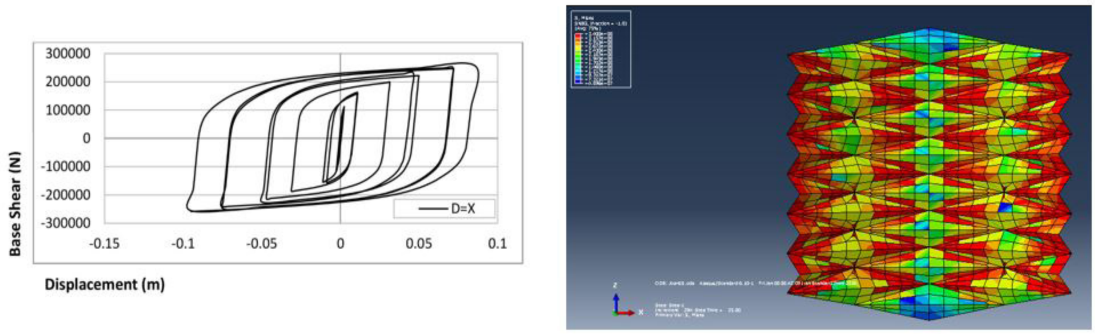

Fig. 4. Distribution of Stress on the Surface of the Diamond Model Subject to Cyclic Loading on X-Axis

B) Loading on Z-Axis:

Reciprocal (cyclic) loading was exerted in the form of lateral force on z-axis for 144981 Newtons as a result of which displacement by 0.15 meters was observed (Fig. 5).

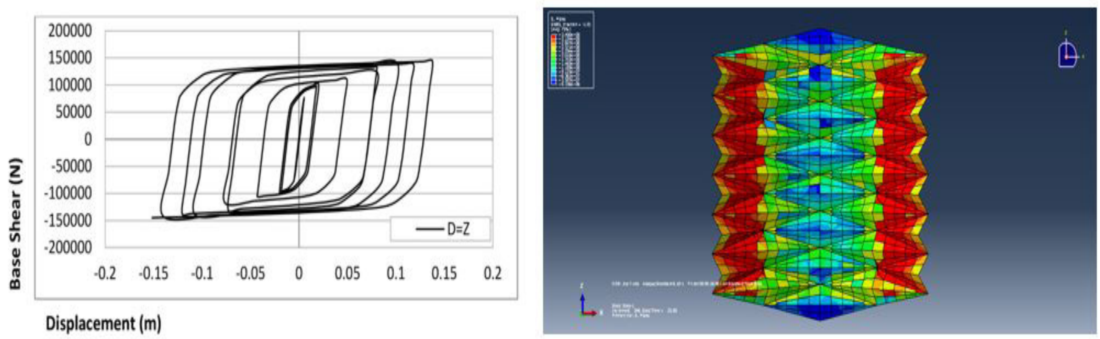

Fig. 5. Distribution of Stress and Its Diagram for Z-Axis after Subjecting the Diamond Pattern to Cyclic Loading

As it is observed, the amount of stress caused by lateral force is lower on x-axis in comparison to z-axis meaning that x-axis exhibits better structural behavior and z-axis shows the physical body's changeability.

4.3. Investigating Maximum Force and Displacement (Pushover)

In this section, two perpendicular axes were analyzed following being subjected to loading in terms of the structure's maximum ability.

A) Pushover Loading along x-Axis:

The load-bearing amount on x-axis was maximally equal to 196782 Newtons with the maximum displacement being equal to 0.063m (Fig. 6).

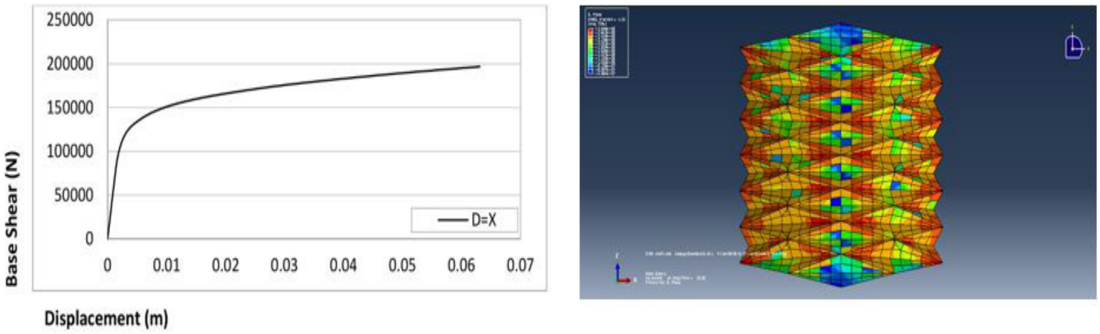

Fig. 6. Distribution of Stress along the Model's Surface with Pushover Loading along X-Axis

B) Pushover Loading along Z-Axis:

In this axis, the maximum force was 108309 Newtons and maximum displacement was 0.10m (Fig. 7). So, it can be discerned in a comparison of the two x- and z-axes that x-axis demonstrates structural strength and z-axis shows the changeability of the architectural context.

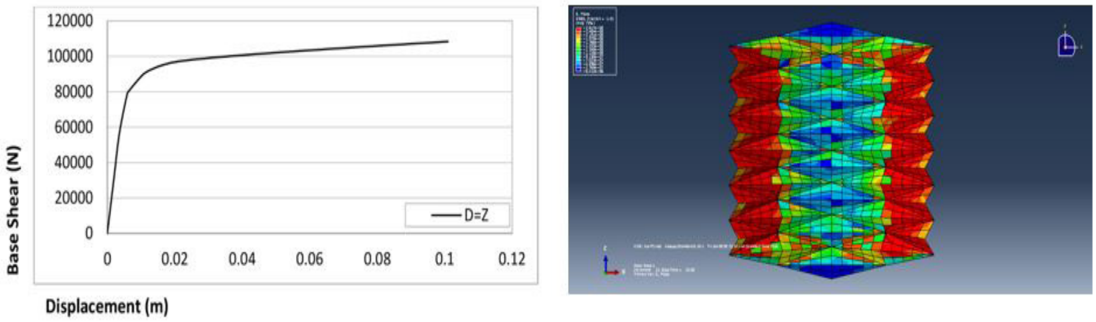

Fig. 7. Distribution of Stress Along with the Model with Pushover Loading Along X-Axis

Based on the results given in Table (1), D-Z axis of the origami pattern is the weak direction but it exhibits flexible behavior. D-X axis is the strong direction of the origami pattern that also features balance and stability. The extra loading analysis, as well, reflects the bi-dimensional nature of this pattern's performance in response to architectural flexibility and structural stability. Y-axis, as well, showed the highest resistance against the gravitational forces.

Table 1. The General Results of Various Kinds of Loading in Various Axes

	Loading Direction	Orthogonal Loading	Pushover Loading
Maximum Force (Newton)	X	-	196782
	Y	280182	-
	Z	-	108309
Maximum Displacement (Meter)	X	-	0.063
	Y	0.093	-
	Z	-	0.10

Therefore, using this pattern as physical body of space gives the required structural strength on an axis (x) for stability and physical balance and the required flexibility and changeability along with the other axis (z) for the context's adaptability to the peripheral environment.

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5. DISCUSSION AND CONCLUSION

• Factors influencing the space's physical flexibility can be obtained based on the analysis of the adaptability of the physical factors and their sub-branches.
• Based on the results, use can be made of a diamond origami pattern to figure out models for constructing the building's physical body most capable of adaptability to the various environmental conditions.

The various models of space's physical adaptability to the various conditions include the followings considering the use of diamond origami pattern based on the adaptability sub-branches:

A) Adaptability in Dimensions and Size:
In a diamond pattern, the change in the length and width dimensions of the folding patterns enables the creation of structures with dimensions and sizes matching with the intended needs.

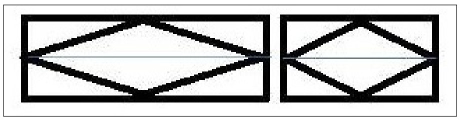

Fig. 8. Kinds of Diamond Patterns

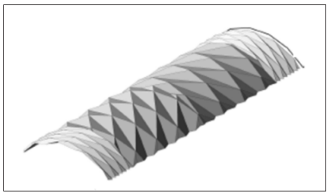

Fig. 9. Adaptable Structure Based on Diamond Pattern

B) Adaptability in Shape and Form:
In creating the spatial covering using diamond origami, various forms can be created that possess adaptability in proportion to the environment.

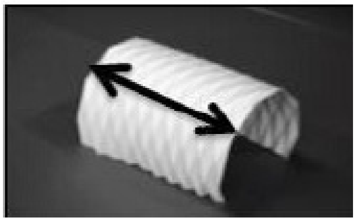

Fig. 10. Diamond Pattern with the Axial form Enabling Linear Motion

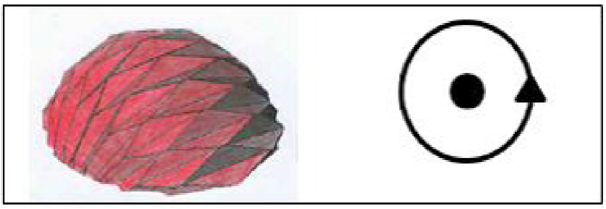

Fig. 11. Diamond Pattern with Circular and Central Form

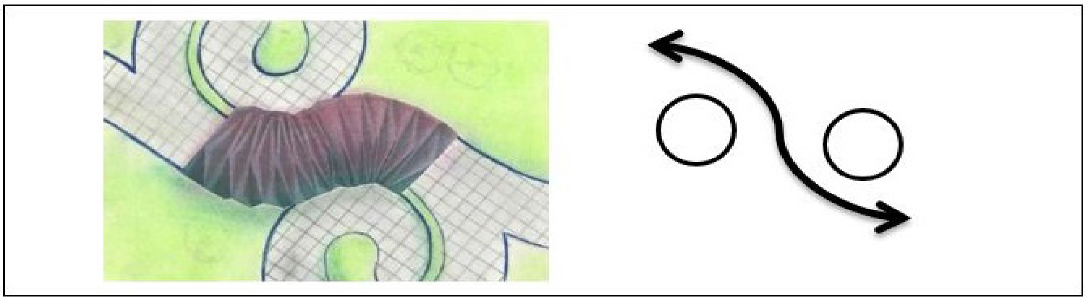

Fig. 12. Spiral Form in Line with Environmental Adaptation

C) Adaptability in the Siting of Architectural Elements:

By the assistance of cutting or omitting some constituent members of the pattern, the architectural elements such as the entrance and exit can be arranged in proportion to the environmental conditions.

Fig. 13. An Example of Patterns' Arrangement for Shaping the Architectural Elements

D) Adaptability in Diversity and Variegation: Diamond pattern created by metal plates features diversity in various colors. In terms of the general dimensions of the spatial context, as well, it is adaptable to the various environments.

Fig. 14. Diversity and Adaptation in the physical body by the Use of Diamond Pattern

REFERENCES

- Ahmed, E., Wan Badaruzzaman, W.H., & Wright, H.D. (2000). Experimental and Finite Element Study of Profiled Steel Sheet Dry Board Folded Plate Structures. *Thin-walled Structures*, 38(2), 125-143. https://doi.org/10.1016/S0263-8231(00)00039-2.
- Albotan, D. (2009). Flexibility in multi- Residential Housing projects: Three innovative cases from Turkey. 1-74.
- Baghaei, A. (2009). The Role of Structure in Aesthetic of Contemporary Architecture, *Hoviat Shahr*, 8(2), 5-14.
- Bemanian, M.R., Amirkhani, A., & Leilian, M.R. (2010). Order and Disorder in Architecture. Tehran: Tehran Press, 91.
- Bentley, I. (1985). Responsive Environments: A Manual for Designers. New York: Routledge.
- Buri, H., & Weinand, Y. (2008). ORIGAMI-folded Plate Structures, Architecture (No. CONF).
- Buri, H. U., & Weinand, Y. (2010). Origami aus Brettsperrholz. DETAIL Zeitschrift f¸ r Architektur+ Baudetail, (ARTICLE), 1066-1068.
- Cambridge Advanced Learner's Dictionary (2013), Fourth Edition
- Charleson, A. (2014). Structure as Architecture: A Source Book for Architects and Structural Engineers. New York: Routledge.
- Ching, F.D. (2014). Architecture: Form, Space, and Order. John Wiley & Sons. 201.
- Ching, F.D., Onouye, B.S., & Zuberbuhler, D. (2013). Building Structures Illustrated: Patterns, Systems, and Design. John Wiley & Sons. 134.
- Dehkhoda, A.A. (1998). Dehkhoda Dictionary Encyclopedia. Tehran: Tehran University Press.
- Einifar, A.R. (2003). A Model to Analyze Residential Spaces: Based on Flexibility Criteria of Traditional Housing. *HONAR-HA-YE-ZIBA (FA)*, 13(461), 64-77. https://jhz.ut.ac.ir/article_10660.html
- Einifar, A.R., Shayan, H.R., & Garipour, M. (1989). Investigation and Comparison of Flexibility in Residence Architecture between Iran and Japan. *ABADI Journal*, 55, 12-19.
- Erabi, J. (2011). Form Creation, 6ed. Mashhad: Kasra Publishing, Mashhad, 14- 138.
- Felbrich, B., Nönnig, J.R., & Wiesenhütter, S. (2014). Rigid Folding in Robotic Multi-agent Systems. Procedia Computer Science, 35, 1342-1351. https://doi.org/10.1016/j.procs.2014.08.174.
- LaFosse, M.G., & Alexander, R.L. (2008). Origami Art: 15 Exquisite Folded Paper Designs from the Origamido Studio: Intermediate and Advanced Projects: Origami Book with 15 Projects. Tuttle Publishing.
- Lang, J. (1987). Creating Architectural Theory. The Role of the Behavioral Sciences in Environmental Design.
- Mahdavi-nejad, M.J., Farajolahi-rad, A., & Karam, A. (2011). Flexible Architecture, an Approach toward Architecture and Structure Harmony. Published by Art and Architecture, Tarbiat Modares University, Tehran, Iran. 1.
- Matcha, H., & Ljubas, A. (2011). Parametric Origami. New Design Concepts and Strategies_ eCAADe 28. 326
- Moore, F. (1999). Understanding Structures. McGraw-Hill Science Engineering.
- Musavi, S.S. (2013). Analysis of Seismic Behavior and Impact of Opening on Composite Shear Wall Incorporating Flat and Corrugated Plates [MSc Thesis], Department of Civil Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.
- Salvadori, M.G., Heller, R., & Oakley, D.J. (2017). Salvadori's Structure in Architecture: The Building of Buildings.
- Schenk, M., & Guest, S.D. (2011). Origami Folding: A Structural Engineering Approach. In Origami 5: Fifth International Meeting of Origami Science, Mathematics, and Education. 291-304. CRC Press, Boca Raton, FL.
- Schneider, T., & Till, J. (2005). Flexible Housing: Opportunities and Limits. *Arq: Architectural Research Quarterly*, 9(2), 157-166.
- Sheppard, D., & Town, P. (1974). Housing Flexibility? *Architectural Design*, 43(11), 698-727.
- Venturi, R., & Scully, V. (1977). Complexity and Contradiction in Architecture. *The Museum of Modern Art*.1, 12-49.

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