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Tensegified Folded Glass Shells and Domes

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Abstract: Glass will not only be used as a transparent cladding but can be load-bearing part of the whole structure system. This paper will survey the structural capabilities of glass in Rhombus-Wing-Element folded plates system with high rate of transparency which provides the ability of covering wide spans by its moment resistant structure; but high tensile stresses increase height of folded plate sections to resist the imposed bending moment on the structure which causes decreasing of system field numbers and considerable loss of delicacy in the whole view of the structure. In this case reinforcing glass structure by cable and tensegrity systems will help to cover the weak point of glass which is in tension stresses. In this case, cables will help the section to bear bending moments and accept a considerable part of tension which decreases the tensile stress on glass structure and allow covering of wider spans by increasing the load bearing capacity and helps to have less height in sections and more fineness in the whole structure view. The structural concept and it's characteristics in different conditions is confirmed by Finite Element Analysis which puts the effect of supporting tensegrity system on structural capabilities of the whole system and it's fineness into focus that is an important architectural point, in comparison with the whole glass folded plates. So by using a combination of glass folded plates and tensegrity systems we will have structures with more load bearing capacity for covering of wide spans and acceptable transparency with considerable fineness and beauty.

Keywords: Glass Structures, Folded Plates, Tensegrity Structures, Structural Facades, Structural Glazing, Rhombus-Wing-Element

1. INTRODUCTION

Folded Plates have always been one of the most efficient structural systems which use materials such as glass as both structural and architectural elements of the system. Among all familiar forms of glass folded plates, Folded Triangulated Cylinder is type of structural glass, used in particular Rhombus Wing Elements that shape a cylinder can be used as cover or glazing facades.

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Figure 1. Some design samples of Folded Triangulated cylinders

As it is explored [4] this structural form leads the forces as barrel in addition to forming a shell by using Rhombus Wing elements. Height of the folding determines structural capacity of the shell to bear bending moments. Folding height, the most important structural factor in geometry of the cylinder, depends on N (system field number) and the relation H/S (H=height, S=span). [4] It means that for a definite height of the shell we have to reduce the number of folding for providing the required construction height for wide spans to have suitable structural performance.

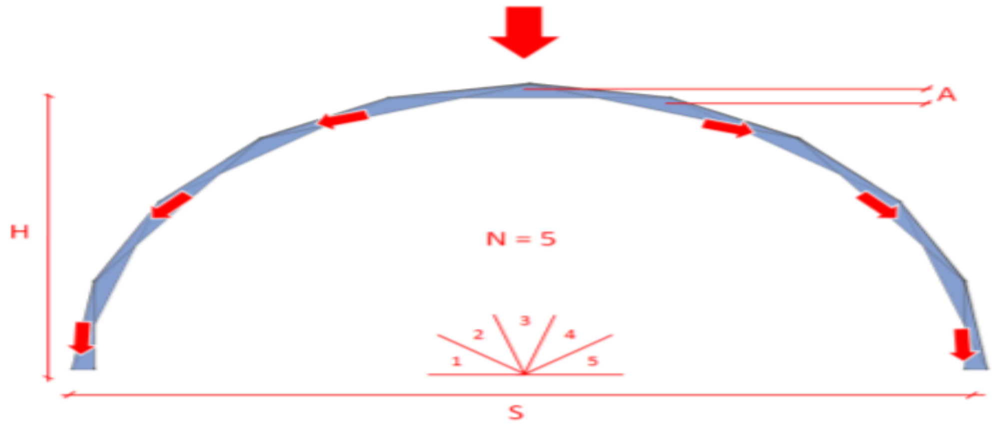


Figure 2. Geometric parameters

2. FOLDED GLASS

Folded triangulated cylinder shapes a structural form out thin, delicate plates of glass as structural material in addition to its decorative and architectural behaviors. This paper model glass structure can form different shapes according to its geometrical factors, such as span (S), height (H) and number of folds (N). Dependency of geometrical factors and required construction height as shown in table 1 impose some limitations to abilities of this system for covering wide spans.

Table 1. Dependency of parameters [4]

N		2	2	2	2	2	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
H	[m]	1	2	2,5	3,33	5	1	2	2,5	3,33	5	1	2	2,5	3,33	5	1	2	2,5	3,33	5
S/H	[-]	10	5	4	3	2	10	5	4	3	2	10	5	4	3	2	10	5	4	3	2
A	[m]	0,25	0,52	0,66	0,91	1,46	0,11	0,23	0,30	0,41	0,67	0,06	0,13	0,17	0,23	0,38	0,04	0,08	0,11	0,15	0,25
S/A	[-]	40	19	15	11	7	89	43	34	24	15	159	76	60	43	26	244	119	93	67	41

As we see in the picture reducing the number of folds ill cause an increase in construction height and more structural capacity but less folds will affect delicacy of the whole shape as a decorative and delicate architectural form and e know that reducing N is our only way for covering bigger spans in a definite height of the shell. The other negative effect of reducing N is bigger size of glass plates which should shape single part elements of system that can make some difficulties in assembling, maintaining the parts and whole structural behavior of the system as a shell. To sum up, we should avoid wide spans if we want to use Folded Triangulated Cylinder with acceptable structural behavior and delicate appearance of folds.

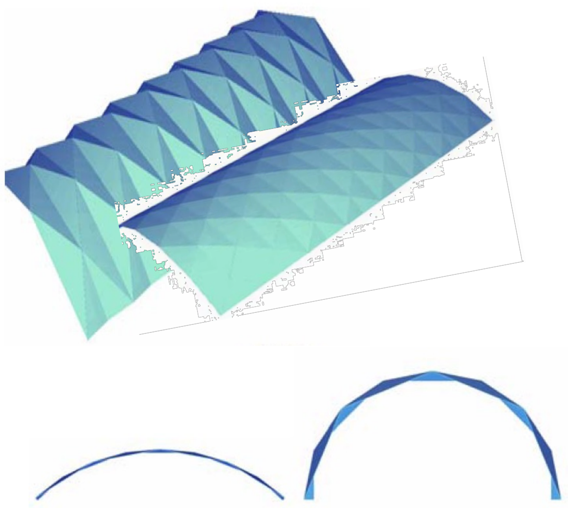


Figure 2. Dependency of construction height (A) on N and H/S [4]

3. TENSEGRIFIED FOLDED GLASS SHELL

Using tensegrity as a support for structural glasses will help the structural system to act as a composite section of glass and cables. Glass is a material with high ability of bearing pressure but weak in tensile stresses and is a brittle material too. Utilizing steel fine cables as ductile material with high tension bearing capacity in combination with glass to form a composite section will improve glass behavior in tension and ductile performance of whole structural system.

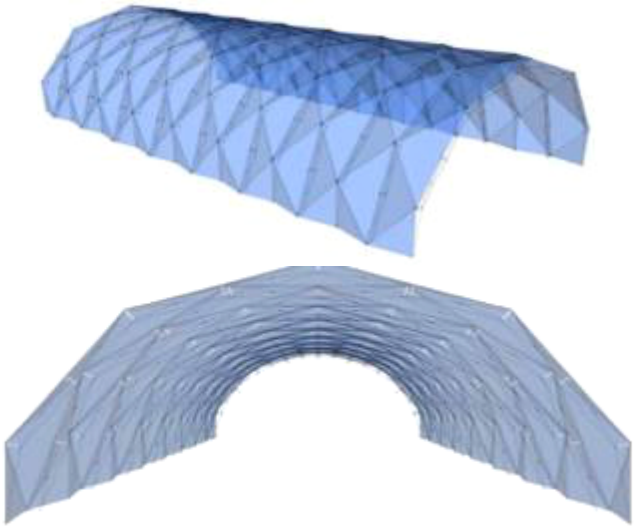


Figure 3. Two typical Tensegrified Folded Glass

Cables will take most part of tension in structural composite section and glass will be held in compressive part of it which will result in more efficient use of materials.

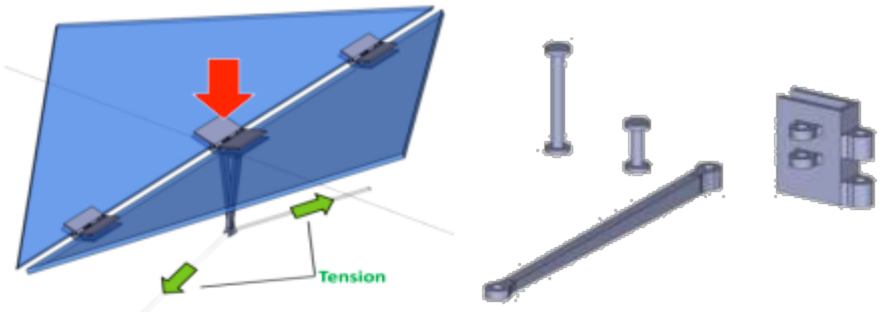


Figure 4. Typical hinged connection and force path in elements

To confirm effects of using tensegrity as tensile support for Folded Triangulated cylinder system we verified the model in Abaqus 6.9.1, using finite elements methods.

Table 2. Materials properties

Material	Material properties			
	E (N/m2)	ν	y (N/m2)σ	ρ (kg/m3)
Steel	2.1×10^{11}	0.3	2.7×10^{8}	7.89×10^{3}
Glass	7.6×10^{10}	0.3	1.38×10^{8}	2.5×10^{3}

Plates are modeled as shell, with tie connections which connect the surfaces on shear resistant edges. Boundary conditions are defined as pinned joints of end edges in barrel which restrain movements but not the rotations. We have two major loadings: vertical and combination of vertical & horizontal (wind) as can be seen in table 3.

Table 3. Load combinations

Load Combination 1	Wind+Dead+Live+Asymmetric Snow
Load Combination 2	Dead+Live+symmetric Snow

Table 4. Loads properties

Load Name	(N/m2) Rate	Explanations
Weight	Due to ρ	g =9,8(m/s2)
Snow	1500	------
	357	More than 60 Degree slope
Wind	1400	Suction
	800	Slope of 15 to 30 degree
	1400	Slope of 30 to 45 degree
	1200	Slope of 45 to 90 degree

Geometry of the barrel is defined as: span(S) =10 m, height (H) =2,5 m, width of each RW element=3 m. maximum size of finite elements in the model is 0,38 m in big plates and 0,23 m in smaller ones. Models are analyzed under all described conditions for two models of simple glass folded plates and the result of analysis for mises stress and deflections (U) is shown in Table 5 and Table 6.

Table 5. Analysis results of models under load combination 2

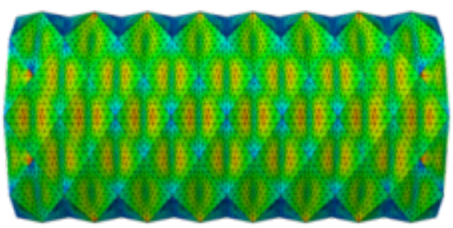
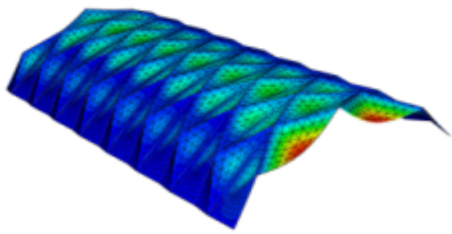
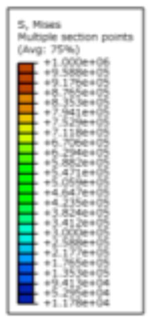
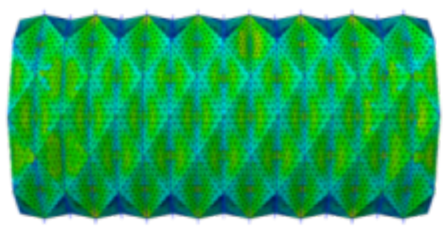
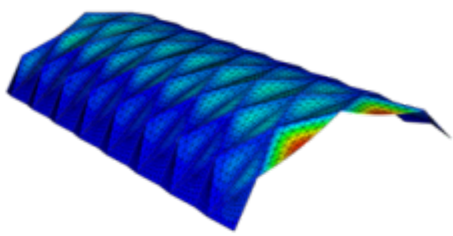
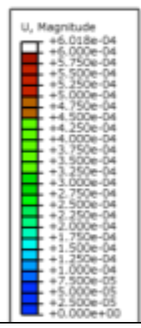
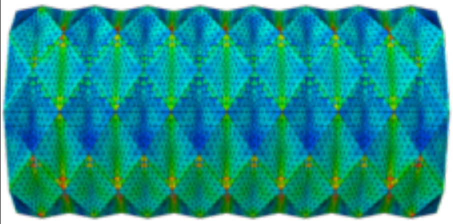
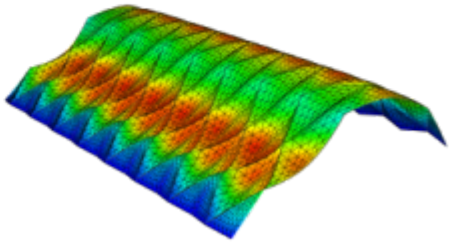
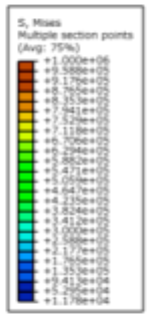
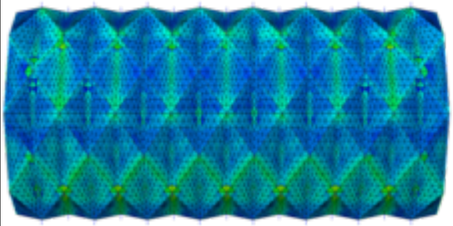
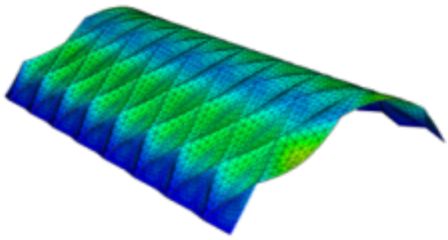
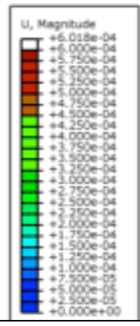
	Stress	Deflection	Guide
Simple Folded Glass			
Tensegrified			

Table 6. Analysis results of models under load combination 1

	Stress	Deflection	Guide
Simple Folded Glass			
Tensegrified			

The results show the maximum reduction of 45% in stresses and deflections in tensegrified model, comparing to simple folded glass under load combination 2 and 35-40% reduction in critical parts of the barrel under load combination 1 which means the noticeable improvement in structural capacity of the whole structural system that can make it possible to cover bigger spans without reducing delicacy of system's appearance.

4. TENSEGRIFIED FOLDED GLASS DOME

For the first time we have used Rhombus Wing elements to form a structural glazing in shape of a dome.

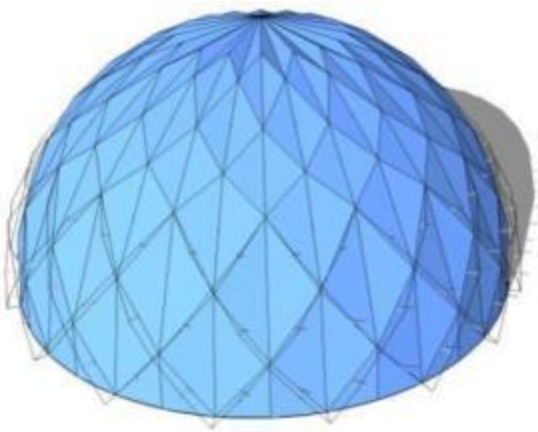


Figure 5. Fourfold typical Tensegrified Folded Glass Dome

In this form structural glass is providing construction height of the moment resistant section in dome's shell. In addition, tensegrities make up lack of structural capacity to the glass in the same way as described in previous section. Tensegrities support the structure on both sides of dome's surface, where ever we need more bending capacity. Besides, inside ring cables help the stability of dome as tensile rings.

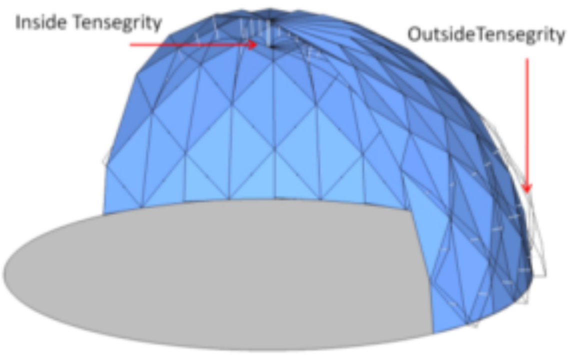


Figure 6. Structure of Tensegrified Folded Glass Dome

Pattern of changing the length and rotation degree of elements over the height of dome leads to various shapes of domes and different construction heights of shell. Required tensegrities will be designed due to bending moment of each point over the shell.

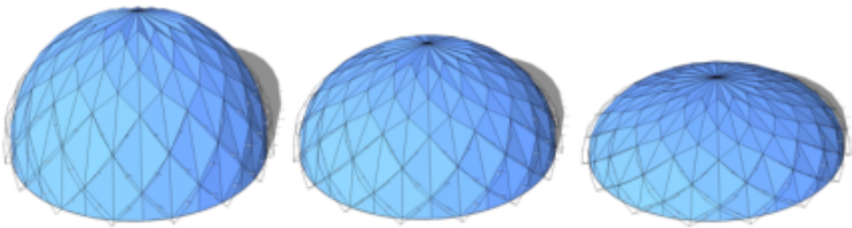


Figure 7. Different shapes made by changing parameters

In this dome, structural glass plates in form of woven rhombus wing elements beside tensegrities and ring cables make a structural statue of glass and cables which has decorative, structural and architectural performances together and can be used where ever we need transparent structural glazing.

Figure 8. Design of Tehran Botanic Garden glass house using Tensegrified Folded Glass Shells and Dome

5. CONCLUSION

Folded Triangulated Glass system is a structural use of glass which makes load bearing structural system out of separate thin glass plates with noticeable structural performance and eye-catching appearance. However, brittle nature of glass and its weak tensional performance make it difficult to be used in wide spans. Utilizing tensegrity as support to cover vulnerability of glass in glass in tension and improving bending moment capacity of the shell in a composite form of glass-cable section causes up to 45% reduction of stresses which makes it practical to be used for covering wide spans without disturbing delicacy of folding structure. Besides, Better structural behaviour leads to innovative designs of domes, using new system of Tensegrified Folded Glass for different purposes.

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