A Proposal for the Classification of Structural Systems of Large Domes

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Abstract- **During the ages, architects and engineers have tried to cover the wide spans without using the columns. To access this objective, they have used the different kinds of domes. The materials used in these structural systems include the weighty materials like stone and brick. Since The Industrial Revolution, the rapid progress in technology and finding new materials has caused to devise more kinds of structural systems, which were used for constructing the domes with wider spans.**

The goal of this article is to provide a proposal for the classification of structural systems of large domes, based on the Case Studies, and to specify the abilities of these systems. In order to this purpose, 50 Large Domes, which have been constructed between the years 1964-2009, are selected as Case Studies, in beginning. The criteria for selection are: First, Structures must have a clear span of 100m or greater. Second, the size of a clear span is taken to refer to the diameter of the largest horizontal circle that will completely fit inside the structure. Third, Structures must be fully covered, or capable of being fully covered. A few Small holes in the roof are permitted. Fourth, Structures must be multi curvature. Thereafter, the data of the domes inserted in a table and 17 structural systems have been specified. In this paper the methodology of the classification for this kind of structures has been presented and the results have been discussed and concluded in the end of the article.

Keywords- Large dome; Structural systems; Clear span

I. INTRODUCTION

Dome, is one of the most important building elements which has been used to cover the wide spans, during the ages. Either the Static stability or the symbolic forms are important for the domes. After the Industrial Revolution the construction methods are changed, the new domes are designed [1] and the different structural systems are used for Building domes. The dome is a surface that generated from rotation of a curve line around an axis. The sphere is the best known geometry for the dome. [2]

This article, aims to study and categorize the structural systems of Large Domes, not based on this classic definition of the dome, but based on a special methodology in selection the wide curved surfaces. Data are accumulated from internet references and literature review. We can specify the structural systems, have been used for Large Domes construction and analyse different information about structural systems Such as Abundance and capability of each structural system. When the number of cases is increasing, the classification seems to be necessary. Also this research contributes to designers for selecting an appropriate structural system, when they commence to design a place that will be covered by a large dome.

II. METHODOLOGY

The criteria for selecting the case studies include four items. The first three items, are the method of the website, "*largedomes.com*" for listing an index of the Large Domes. First, Structures must have a clear span of 100 meters or greater. Second, the size of a clear span is taken to refer to the diameter of the largest horizontal circle that will completely fit inside the structure. Third, Structures must be fully covered, or capable of being fully covered (A few Small holes in the roof are permitted – but large holes - or large numbers of holes that let in wind and rain - are not). Fourth, Structures must be multi curvature and have convex form.

Based on this selection method, 50 domes constructed between the years 1964-2009, are selected from internet and literature review resources. After scientific analysis and recognition of the structural systems, the accumulated data are inserted in Table 1. The classification is based on Fuller *Moore*'s known categorization for structural systems [2]. This categorization provided primary structural types (General types) three of which are capable of including all structural systems of large domes. Thus, 17 structural systems are extracted from three primary structural types: Truss Systems, Form–Active Systems and Shell Systems (Diagram 1). In this classification, the Tensegrity Cable System, in the Space Frame category, is categorized in a separate class, because of the plurality of use and radial shape feature. Also, the Arch Truss System and Arch-Suspended Cable Net System are classed in Synthetic System category. Tables 1 to 3, present Case Studies, Classifications and abilities of Structural Systems.

TABLE 1 CASE STUDIES (DATA, FROM REFERENCES: 2 AND 4 TO 16.
STRUCTURAL SYSTEMS HAVE BEEN RECOGNIZED FROM REFERENCES: 2 AND 4 TO 16 AND SCIENTIFIC ANALYSIS BY AUTHORS)

No	Name	Date	Country	Usage	Span	Structural System	Retract ability
1	Akita Skydome	1990	Japan	Stadium/Arena	109 m	Frame-Supported Membrane	no
2	Alamodome	1993	USA	Multipurpose hall	185 m	Cable-Suspended Truss	no
3	Amsterdam arena	1996	Nederland	Stadium/Arena	180 m	Arch Truss	yes

4	Assembly Hall of University of Illinois	1964	USA	Lecture hall	122.7 m	Shell-Folded Plate	no
5	BC Place Stadium	1983	Canada	Stadium/Arena	190 m	Air-Supported Membrane	no
6	Big eye	2001	Japan	Stadium/Arena	245 m	Arch Truss	yes
7	Burswood Dome	1988	Australia	Stadium/Arena	133 m	Air-Supported Membrane	no
8	Cardinals stadium	2006	USA	Stadium/Arena	200 m	Truss	yes
9	Crown Coliseum	1997	USA	Stadium/Arena	100 m	Tensegrity Cable	no
10	Dallas Cowboys New Stadium	2009	USA	Stadium/Arena	226 m	Arch Truss	yes
11	Eden Project	2000	UK	Glasshouse	110 m	Geodesic Dome	no
12	Fukuoka dome	1993	Japan	Stadium/Arena	212 m	Truss Dome	yes
13	Georgia Dome	1992	USA	Stadium/Arena	185 m	Tensegrity Cable	no
14	Izumo Dome	1992	Japan	Stadium/Arena	143 m	Arch-Supported Membrane	no
15	King dome	1976	USA	Stadium/Arena	202 m	Arch-Supported Shell	no
16	Komatsu Dome	1997	Japan	Stadium/Arena	145 m	Arch Truss	no
17	Kumagaya Dome	2003	Japan	Sports and Leisure	150 m	Truss	no
18	Kumamoto Park Dome	1997	Japan	Stadium/Arena	128 m	Air-Inflated Membrane	no
19	Long Beach Cruise Terminal	1983	USA	Aircraft hangar	126 m	Geodesic Dome	no
20	Louisiana Superdome	1975	USA	Stadium/Arena	207 m	Truss Dome	no
21	Metrodome	1982	USA	Stadium/Arena	180 m	Air-Supported Membrane	no
22	Miller Park Stadium	2001	USA	Stadium/Arena	183 m	Arch Truss	yes
23	Nagoya Dome	1997	Japan	Stadium/Arena	187 m	Truss Dome	no
24	Namihaya Dome	1996	Japan	Stadium/Arena	106 m	Space Frame	no
25	Nantong sports center	2006	China	Stadium/Arena	240 m	Arch Truss	yes
26	Ocean Dome	1993	Japan	Swimming pool	100 m	Arch-Supported Membrane	yes
27	Odate Jukai Dome	1997	Japan	Stadium/Arena	157 m	Frame-Supported Membrane	no
28	Olympic Gymnastics Arena	1986	South Korea	Stadium/Arena	120 m	Tensegrity Cable	no
29	Pontiac Silverdome	1975	USA	Stadium/Arena	177 m	Air-Supported Membrane	no
30	RCA Dome	1983	USA	Stadium/Arena	175 m	Air-Supported Membrane	no
31	Reliant Astrodome	1965	USA	Stadium/Arena	196 m	Truss Dome	no
32	Roof of the Montreal Olympic Stadium	1987	Canada	Stadium/Arena	140 m	Cable-Suspended Membrane	yes
33	Sant Jordi Sports Palace	1994	Spain	Stadium/Arena	108 m	Space Frame	no
34	Sapporo dome	2001	Japan	Stadium/Arena	218 m	Shell	no
35	Seibu dome	1999	Japan	Stadium/Arena	220 m	Frame-Supported Membrane	no
36	SoccerFive-Arena	1983	Germany	Ice skating rink	100 m	Arch-Suspended Cable net	no
37	Sun Dome	1995	Japan	Stadium/Arena	114 m	Space Frame	no
38	Suncoast dome	1989	USA	Stadium/Arena	209 m	Tensegrity Cable	no
39	Sydney SuperDome	2000	Australia	Stadium/Arena	109 m	Cable-Suspended Truss	no
40	Tacoma Dome	1983	USA	Stadium/Arena	161 m	Lamella Vault	no
41	Tao-Yuan County Arena	1993	Taiwan	Multipurpose hall	136 m	Tensegrity Cable	no
42	Telstra dome	1997	Australia	Stadium/Arena	198 m	Truss	yes
43	The O2 millennium dome	2000	UK	Congress center	206 m	Cable-Suspended Membrane	no
44	Tokyo Dome	1988	Japan	Stadium/Arena	176 m	Air-Supported Membrane	no
45	Tropical islands dome	2000	Germany	Dirigible hanger	210 m	Arch-Supported Membrane	no
46	Tsugaru Dome	2002	Japan	Multipurpose hall	112.6 m	Arch-Supported Membrane	yes
47	Uni Dome (old roof)	1975	USA	multi-purpose stadium	129 m	Air-Supported Membrane	no
48	Veltins Arena	2002	Germany	Stadium/Arena	187 m	Truss	no
49	Walkup Sky dome	1977	USA	Gymnasium	153 m	Lamella Vault	no
50	Yamaguchi Dome	2001	Japan	Multipurpose hall	157 m	Space Frame - Tensegrit	no

TABLE 2 PRIMARY STRUCTURAL TYPES, STRUCTURAL SYSTEMS, ABUNDANCE, PERCENT, USAGE PERIOD, AVERAGE SPAN, MINIMUM SPAN AND MAXIMUM SPAN.

General Type	Structural System	No	Percent %	Year		Avg. Span	Min. Span	Max. Span
				From	To			
Truss Systems	Cable-Suspended Membrane	2	4%	1987	2000	173 m	140 m	206 m
	Cable-Suspended Truss	2	4%	1993	2000	147 m	109 m	185 m
	Geodesic Dome	2	4%	1983	2000	118 m	110 m	126 m
	Space Frame	3	6%	1994	2001	126.3 m	108 m	157 m
	Tensegrity Cable	5	10%	1986	1997	150 m	100 m	209 m
	Truss	4	8%	1997	2006	183.75 m	150 m	200 m

	Truss Dome	4	8%	1965	1997	200.5 m	187 m	212 m
Active Form Systems	Air-Inflated Membrane	1	2%	1997	-	128 m	128 m	128 m
	Air-Supported Membrane	7	14%	1975	1988	165.7 m	129 m	190 m
	Arch-Supported Membrane	4	8%	1992	2002	141.4 m	100 m	210 m
	Arch-Supported Shell	1	2%	1976	-	202 m	202 m	202 m
	Arch-Suspended Cable net	1	2%	1983	-	100 m	100 m	100 m
	Frame-Supported Membrane	3	6%	1990	1999	162 m	109 m	220 m
	Lamella Vault	2	4%	1977	1983	157 m	153 m	161 m
Sell Systems	Shell	1	2%	2001	-	218 m	218 m	218 m
	Folded Plate	1	2%	1964	-	122.7 m	122.7 m	122.7 m
Combination of Active Form and Truss Systems	Arch Truss	6	12%	1996	2009	203 m	145 m	245 m

TABLE 3 NUMBER OF RETRACTABLE CASES IN STRUCTURAL SYSTEMS

Retractable Structures	**Number of Case Studies**
Arch Truss	5
Arch-Supported Membrane	2
Cable-Suspended Membrane	1
Truss	2
Truss Dome	1

III. RESULTS

The results, generated from the tables, are presented in Figures 1 to 5. These results include the- Classification of Structural Systems of the Large Domes, Abundance of primary Structural Types and each Structural System in Case Studies, Clear Spans and Retractable cases.

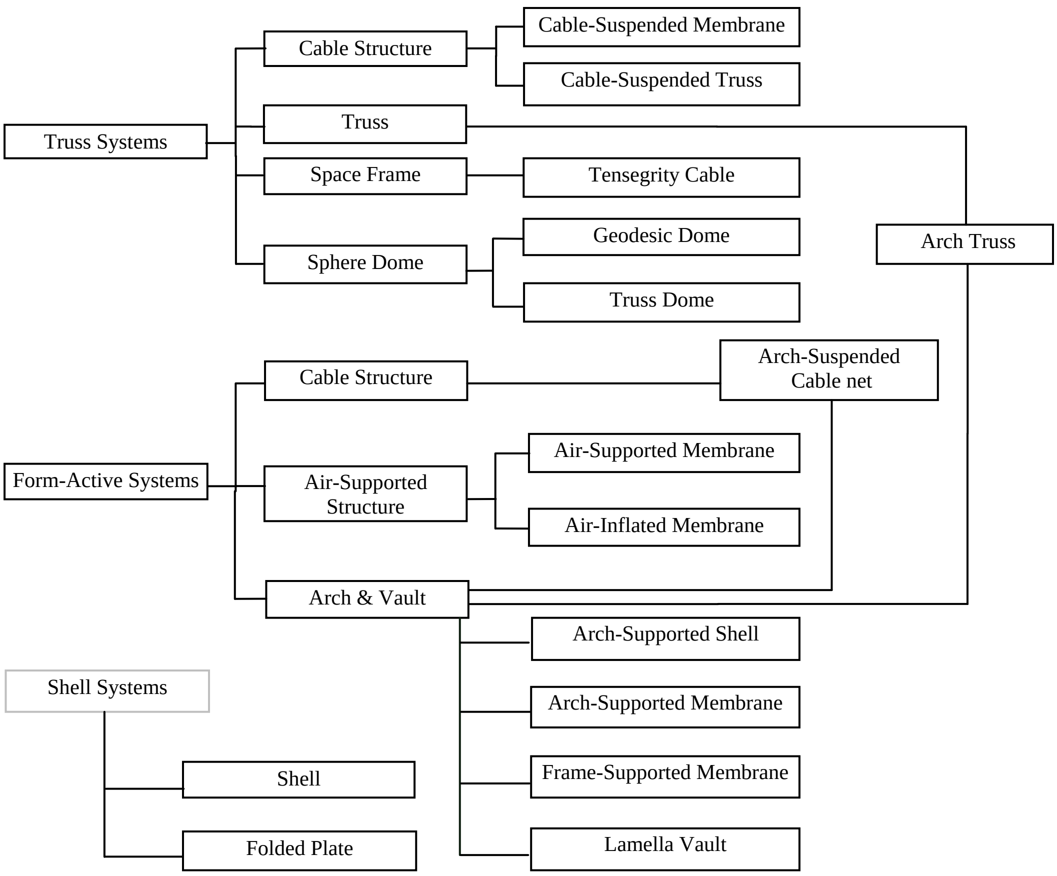

Fig. 1 Classification for Structural Systems of Large Domes

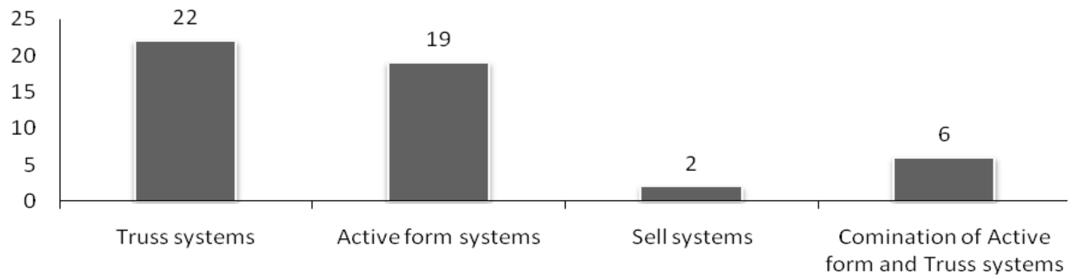

Fig. 2 Abundance of primary Structural Types in Case Studies

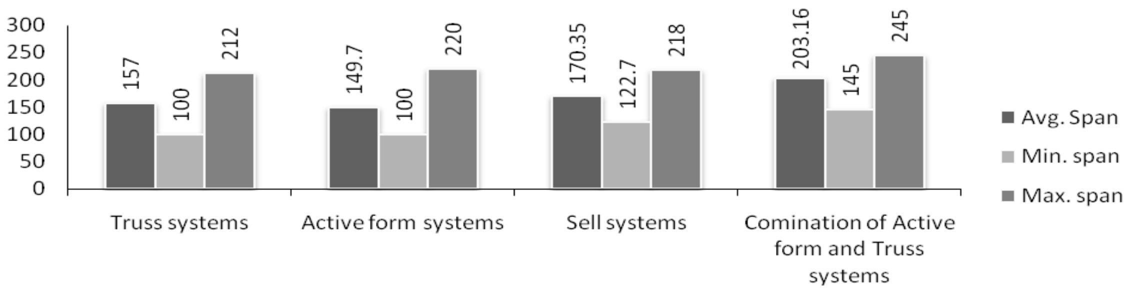

Fig. 3 Minimum, Maximum and Average of Clear Span, covered by the primary Structural Types

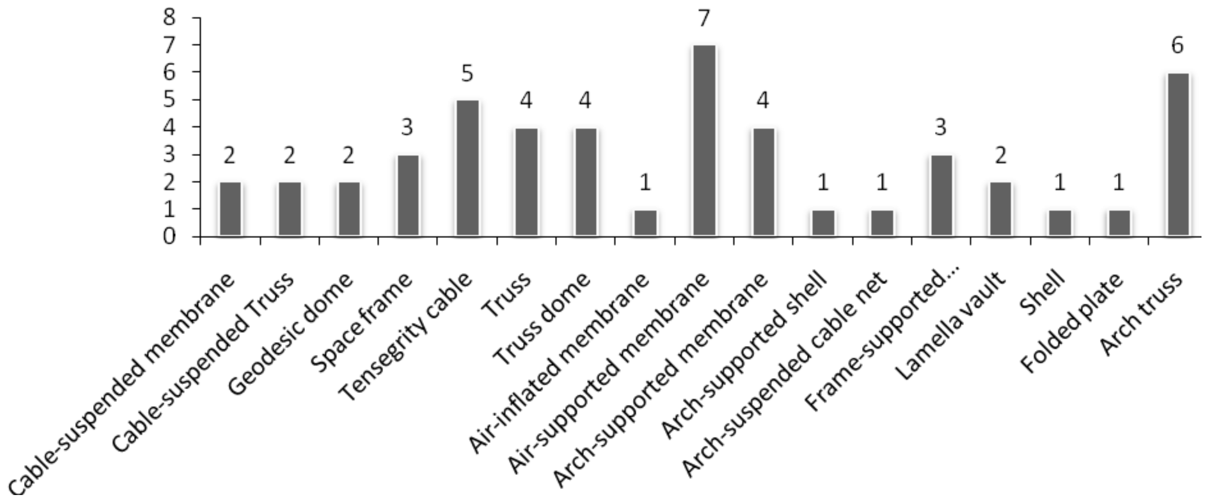

Fig. 4 Abundance of each Structural System in the Case Studies

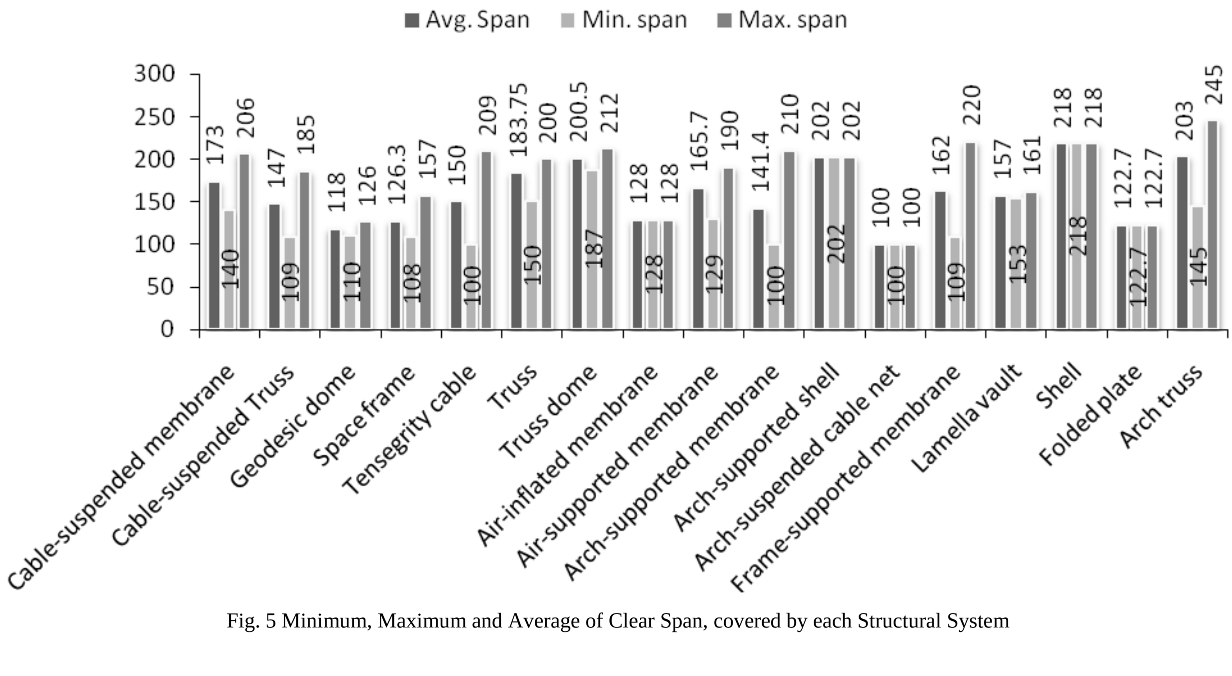

Fig. 5 Minimum, Maximum and Average of Clear Span, covered by each Structural System

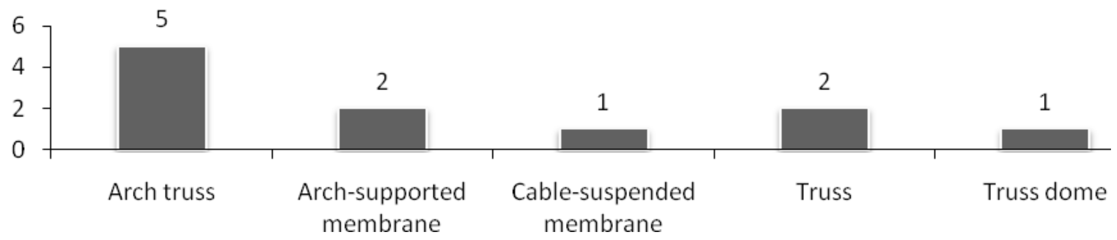

Fig. 6 Abundance of Retractable cases in Structural Systems

IV. DISCUSSION

The results obtained from the tables and the diagram, are presented below:

1. Among the primary Structural Types, *Truss Systems* are mostly used (22 numbers and %44). Thereafter, *Form-Active Systems* (19 numbers and %38) are in the second. The *Combination of Active-Form and Truss Systems* (*Arch Truss*) (6 numbers and %12) and *Shell Systems* (2 numbers and %4) are located respectively.

2. The *Combination of Active-Form and Truss System* have the highest Clear Span average (203 meters). Thereafter, *Shell System* (170 meters), *Truss System* (157) and *Form-Active System* (149.7 meters) are located respectively.

3. *Air-Supported Membrane System* (7 numbers and%14) has the most usage among the 17 Structural Systems. This is a suitable Structural System for the domes, because: all Air-Supported Structures are tending to hemisphere form and their curvature must have convexity in one direction or more [2]. In this Structural System the membrane weight is negligible in comparison to other loads. [2] Also, the cost of each square meter of the air-supported membrane roof is inexpensive in comparison to other wide span roof systems. Against the fire, this system is more confident than what was predicted. [3]

4. *Arch Truss System* rate of use, is in the second level (6 numbers and %12). Then, there is *Tensegrity Cable System* (5 numbers and %10).

5. *Air-Inflated Membrane*, *Arch-Supported Shell*, *Folded Plate* and *Shell* Systems have the least rate of use (1 number and %2) among the 17 Structural Systems. Apparently, technical limits and executive difficulties are the reasons for low rate of use.

6. The largest Clear Span is 245 meters, constructed by synthetic *Arch Truss* System.

7. In attention to selection methodology, the smallest clear span is 100 meters, covered by *Tensegrity Cable*, *Arch-Suspended Cable net* and *Arch-Supported Membrane*.

8. Apparently, the largest average of clear span is 218 meters constructed by *Shell* System. But Shell System has been used just once in the Case Studies. Therefore, the largest average is 203 meters, covered by synthetic *Arch Truss* System. Also, the smallest average of Clear Span is 118 meters, constructed by *Geodesic Dome*. Obviously, the *Arch Truss* System, obtained from combination of Arch and Truss, is a capable system for covering the wider span. In theory, the *Geodesic Dome* has more structural capability for covering the wide spans, but has been used less. Because it has executive difficulties such as: water proofing, creating the openings, [2] complexity of designing and reactions against the tensions [1].

9. Respectively, following Systems are used for covering the clear spans, larger than 200 meters: *Arch Truss, Frame-Supported Membrane, Shell, Truss Dome, Arch-Supported Membrane, Cable-Suspended Membrane and Arch-Supported Shell.*

10. Regardless of the Systems that are used only once, the largest size of Minimum Clear Span is 187 meters, constructed by *Truss Dome* System. Also the Maximum size of Clear Span, covered by this system is 212 meters.

11. Some Structural Systems have a distance more than 100 meters form the Minimum size of Clear Span to Maximum. These Systems include: *Arch Truss, Frame-Supported Membrane, Arch-Supported Membrane*, and *Tensegrity Cable*.

12. Following Systems are Retractable: *Arch Truss* (5 numbers), *Arch-Supported Membrane* and *Truss* (2 numbers), *Cable-Suspended Membrane* and *Truss Dome* (1 number).

13. Among the Case Studies, *Folded Plate* System is the oldest System (constructed in 1964). Afterward, *Truss Dome* (1965 - 1977) is in the next level.

14. The most recent system is *Arch Truss* (1996 – 2009).

15. *Air-Supported Membrane* System has just been used in the period of time (1975-1988). The main reason for this matter is collapsing some of the structures and decreasing the confidence to these systems. This system has other problems such as, providing the access and openings while retaining the internal air balance, and the costs of the utilization period. [2]

16. 35 cases are from Japan and USA. (17 cases from Japan and 18 cases from USA). It may create this hypothesis that, the plurality of constructing these large domes, is under the influence of Economic power and Technological progress.

V. CONCLUSION

The Structural Systems have been applied for construction the Large Domes, which are selected, based on the special methodology of this article, include 17 Structural Systems. These Systems are extracted from three Primary Structural Types (Truss Systems, Form–Active Systems and Shell Systems). The classification is presented below:

A) Truss Systems: 1.Truss, 2.Space Frame, 3.Cable-Suspended Membrane, 4.Cable-Suspended Truss, 5.Tensegrity Cable, 6.Geodesic Dome, 7.Truss Dome.

B) Form-Active Systems: 1.Air-Supported Membrane, 2.Air-Inflated Membrane, 3.Arch-Supported Shell, 4.Arch-Supported Membrane, 5.Frame-Supported Membrane, 6.Lamella Vault, 7.Arch-Suspended Cable net.

C) Shell systems: 1.Shell, 2.Folded plate.

D) Combination of Form-Active and Truss: 1.Arch Truss.

Among the primary Structural Types, the Truss Systems are mostly used. The Arch Truss System results from combination of Form-Active System and Truss System, is a capable System for construction the Large Domes. The largest Clear Span (245 meters), the largest Average of Clear Span (263 meters) and Maximum Number of Retractable Structure (5 numbers) are constructed by Arch Truss System.

The Truss Dome System has been used only for wide spans (187 meters to 212 meters). It seems that this System is suitable for large Clear Spans. But, the Arch Truss, Frame-Supported Membrane, Arch-Supported Membrane and Tensegrity Cable System are appropriate for different span distances. The Structural Systems that are built with reinforced concrete like Shell, Folded Plate, and Arch-Supported Shell, or the Systems that have technical difficulties for internal air balance like Air-Inflated Membrane, are less used. The Air-Supported Membrane System is outdated, because of the technical difficulties, high costs of the utilization period and lack of assurance of stability. Today, the Arch Truss and Tensegrity cable system have been replaced.

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