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NUMERICAL ANALYSIS OF AN ALUMINUM GEODESIC DOME ROOF USING THE FINITE ELEMENT METHOD

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Abstract. *Geodesic domes are single layer spatial structures formed by a complex network of triangles which forms a roughly spherical surface and its behavior is like a continuum body. Due to both light weight and characteristics which make possible to cover large spans without intermediate supports, its application have been very useful mainly in industrial areas where they are used to cover storage tanks. In view of its growing demand, the present study has the purpose to analyze both the global and local behavior of a prototype subject to gravitational loads. The numerical analyses are based on the finite element method and take into account the linear buckling. The results demonstrate several buckling shapes of the structure and its respective critical buckling loads. Finally, the buckling shapes are reached first from individual members and not from the whole structure.*

Keywords: *Geodesic domes, Aluminum structures, Finite element method.*

1. INTRODUCTION

In the last years, engineers and architects have been looking for enlarge as much as possible the internal space of the buildings and due to that idea the use of structural systems able to overcome large spans without use of intermediate supports have been increasingly employed. Due to this, roofs shaped like dome have been a very interesting cost-effective solution, once they are capable to cover large spans using the minimal surface area (Çarbas and Saka, 2012).

Recently, it is possible to see a growing demand in the industrial areas for geodesic domes. In view of their low weight, easy erection and maintenance as well, these structures are used to cover atmospheric tanks (Fig. 1).

Figure 1. Samples of geodesic dome roofs for storage tanks

Geodesic domes are formed by a complex network of triangles which form a roughly spherical surface and his precursor it was Richard Buckminster Fuller (Diniz, 2006). According to Weingardt (2003), when compared to another kind of structures the geodesic dome presents the best rate between covered area and weight.

According Sujatha (2014), as the geodesic domes are formed from triangles, their shape makes possible to reach a quite good stability. Another advantage from geodesic domes is their very simple structural system, once they can be erected at site from parts prepared in modules, it can be replicated as much as needed. As disadvantage, the author gives special importance to the behavior regarding their stiffness, once that one is not fully known because there are still missing more researches to be developed in that area.

The purpose of this study is develop a numerical analysis of the prototype created by Rossot (2014) in order to evaluate its buckling modes when gravitational loads are acting. The study takes into account the linear analysis, considering the support conditions of the geodesic dome as simply supported as well as fixed supported. All the analyses will be performed by the finite element method.

2. LITERATURE REVIEW

The first studies about geodesic dome roofs have been started in 1940's (Shirley, 1984). In one of them, Shirley (1984) studied a wood geodesic dome and he attempts to provide an analysis procedure for any or all of the following causes of dome failure: the overstressing of individual members either axially or flexurally, buckling of individual members, local or "dimple" buckling of the overall shell and overall shell instability. However, only in the present century deeper studies about geodesic domes were found. By the way, Kato et al (2006) presented in their paper an effective evaluation method for elasto-plastic buckling loads of elliptic paraboloidal single layer lattice domes under vertical loads but, at same time, the authors highlight the lack of conclusive researches regarding the flexural stiffness of geodesic domes when it is compared to another single layer domes.

Then, the Brazilian architect Diniz (2006) presents a retrospective study about geodesic structures and also proposes, from a preliminary analysis, a spatial system that uses geodesic structures in order to highlight their potential.

In the following year, Saka (2007) presents a study using an algorithm that reaches the optimal geometry of geodesic domes. In addition, the author emphasizes models which considers domes as spatial structures rigidly connected leads to a more realistic results of their behavior. Finally, Saka (2007) considers the geodesic dome have members submitted to bending as well as axial loads and warns that the first one could affect the axial stiffness of the whole structure.

Two years later, Hasançebi et al (2009) present a study about optimized analysis of steel geodesic domes using metaheuristic search techniques, which applies randomized decisions while searching for solutions to structural optimization problems.

Next, Zamanzadeh et al (2010) investigate the buckling behavior of some geodesic and reticulated domes. The types of buckling concerned in that study are the general buckling of whole structure, the global and local buckling of a member. The authors affirm that buckling loads of domes can be estimated accurately without any need to time-consuming non-linear analysis and complicated mathematical calculations. In their studies, the geometrical non-linearity due to large displacements were included and the results of linear and non-linear buckling analyses were compared by finite element method. All the computational models were considered rigidly connected and the supports were considered as single supports. Based in the domes evaluated, the authors concluded that linear buckling load could be up to 1.7 times bigger than the non-linear buckling load.

Following the same research line regarding the buckling behavior of domes, Fan et al (2010) have evaluated more than 2000 domes, including the geodesic one. In their study, the authors make an investigation of elasto-plastic stability of those structures using finite elements BEAM189 in the Ansys® software. Only gravitational loads were considered, in both symmetrical and asymmetrical positions, and the analyses were performed considering single supports as well as fix supports. With respect to the connections between members at the joint, all of them were assumed to be rigid. In fact, the authors emphasize the condition is always the case with analysis of single layer reticulated shells due to their tridimensional behavior. The results highlighted by Fan et al (2010) are the first buckling mode of the geodesic domes, which occurs at members closely to the supports (Fig. 2), and the small difference between the geodesic dome behavior simply supported to the geodesic dome behavior fixed supported, once the difference between the critical buckling load was less than 5%.

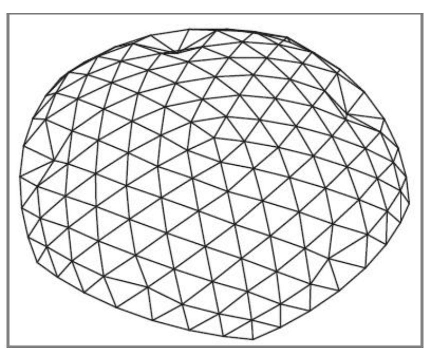


Figure 2. First buckling mode of geodesic dome

More recently were performed analyses related to the structural optimization which consist of finding optimal sections for elements (size optimization), optimal height for the crown (geometry optimization) and the optimum numbers of elements (topology optimization) under determined loading conditions, for instance, the studies from Kaveh and Talatahari (2011) and Çarbas and Saka (2012).

There are some authors which define as poor the elastic stability of a reasonable span dome (Han and Liu, 2002), where a quite small perturbation introduced can lead to a large additional strain. In other words, it has been understood the buckling analysis of geodesic domes is a key point to investigate the maximum load carrying capacities and their respective mode shapes.

Another relevant study was done by Zhu et al (2012), where the authors state the reticulated shells may undergo three types of buckling: the general buckling, the local snap-through buckling and member buckling between joints depending on their design, so it means a similar concept with other authors (Shirley, 1984; Kashani and Croll, 1994; Zamanzadeh, et al., 2010).

Finally, it can be mentioned the study done in the last year by the Brazilian's engineer Rossot (2014), where the author does an embracing description about geodesic domes, highlighting since their concepts and criteria up to their structural behavior, and presenting the results of a numerical and experimental analyses done in a physical model constructed by himself (Fig. 3).

a. Outside view b. Inside view

Figure 3. Prototype from Rossot (2014)

In his study, Rossot (2014) develops a finite element numerical model and determine the critical buckling loads considering some static loads introduced in the model. Moreover, the author also evaluates the resonant frequencies as well as vibration modes from the numerical model and, after that, he compares them with the results got from the physical model (prototype). In a third analysis, Rossot (2014) makes the stiffness examination of the numerical and physical model as well as presents a comparison between them. The reached results in the numerical model analyses were dissonant from those from the physical model. Although, the author emphasizes the highest stiffness found in the numerical model.

Another highlight done by Rossot (2014) was the adjustments in the numerical model in order to reduce the divergence between those results referred above. These adjustments were performed considering the reduction in Young's modulus of the material and, therefore, in some load cases the stiffness of the numerical model was a little bit closer to the physical model. According to the author, it means that the elastic modulus could justify those divergences found.

3. NUMERICAL ANALYSES

The numerical analyses were performed based on the physical model from Rossot (2014). That model has a diameter equal to 2.000 mm and it is 250 mm high. It is formed by aluminum cold-formed angles, whose geometry and properties are detailed in Fig. 4 and Tab. 1, respectively.

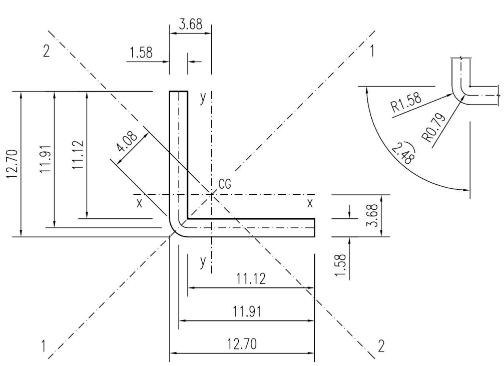


Figure 4. Angle geometry

Table 1. Angle properties

Material	1060	Moment of inertia, axis x and y, mm4	564.09
Density, kg/m3 (γ)	2710	Radius of gyration, axis x and y, mm	3.80
Modulus of elasticity, MPa	70000	Moment of inertia, axis 1, mm4	889.00
Yield stress, MPa	21	Radius of gyration, axis 1, mm	4.77
Ultimate stress, MPa	82	Moment of inertia, axis 2, mm4	239.19
Cross sectional area, mm2	39.06	Radius of gyration, axis 2, mm	2.47

Figure 5 and Tab. 2 show both the dimensions and quantities from each one of the 130 members used in the physical model designed by Rossot (2014).

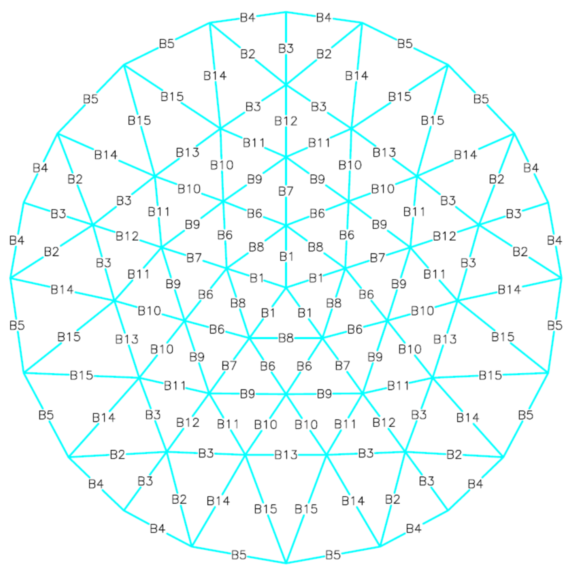


Figure 5. Angle types

Table 2. Members' dimensions and quantities

Angle	L (mm)	Qty.
B1	227.93	5
B2	377.80	10
B3	290.75	15
B4	281.14	10
B5	349.40	10
B6	246.44	10
B7	253.51	5
B8	267.58	5
B9	281.40	10
B10	272.90	10
B11	264.30	10
B12	275.58	5
B13	296.19	5
B14	418.80	10
B15	450.82	10
	Total	130

The present numerical model not considers B4 and B5 members once they are located between supports and, thereby, they have no internal forces as well as they do not contribute to the structure stability. Figure 6 shows the final geometry of the numerical model which will allow the analyses.

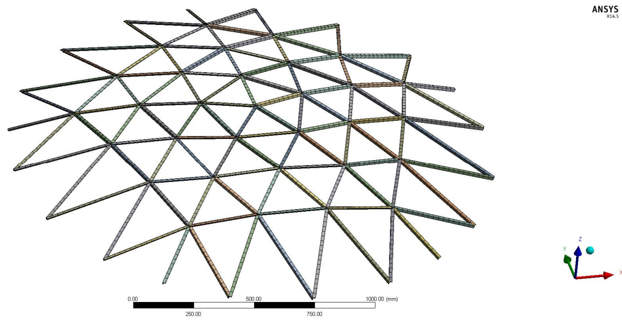


Figure 6. 3D view of the numerical model

The numerical analyses were performed in ANSYS® release 14.5, using finite elements BEAM188 with their biggest dimension limited in 25 mm long. In this way, the numerical model presents a total number of 1420 elements, which were originated from 2871 nodes. The self-weight of elements was not considered.

Based on the both boundary conditions, it was performed a linear analysis with the purpose to predict the buckling behavior as well as its associated critical loads. The two types of analyses were performed considering first the geodesic dome as simply supported and, in a second moment, as fixed supported.

The first five buckling modes are found from the global buckling of a member. That kind of behavior is common to both support conditions of the structure (Fig. 8 and 9). Table 3 shows the five gravitational buckling loads according to notation presented in Fig. 5 and 7.

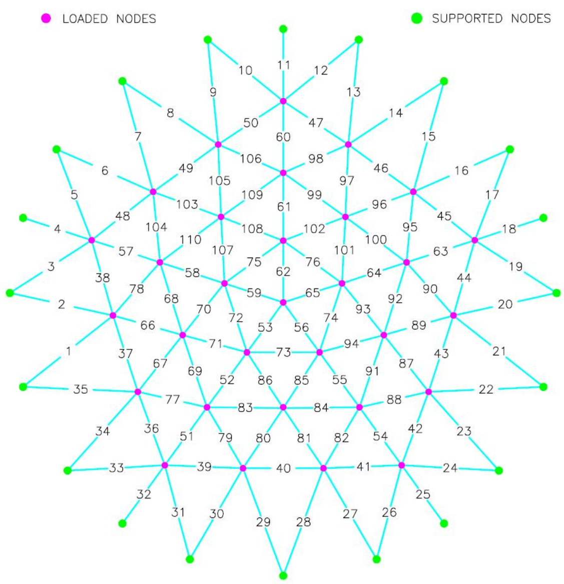
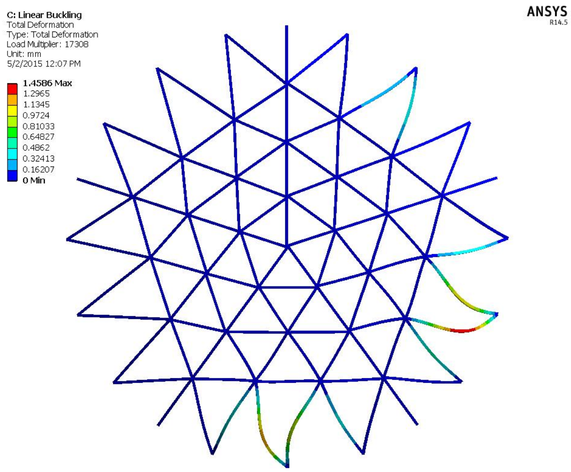


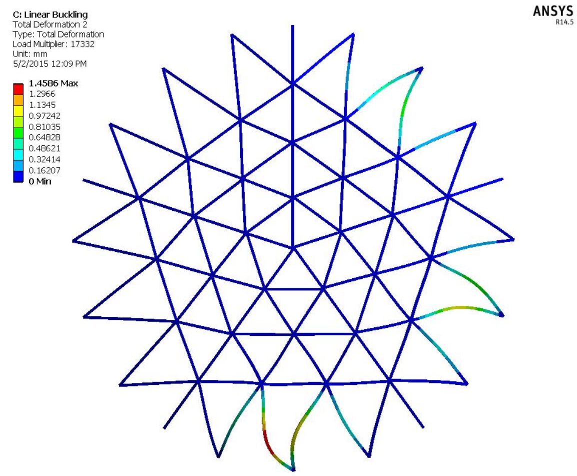
Figure 7. Notation and boundary conditions

Table 3. Critical gravitational loads (N)

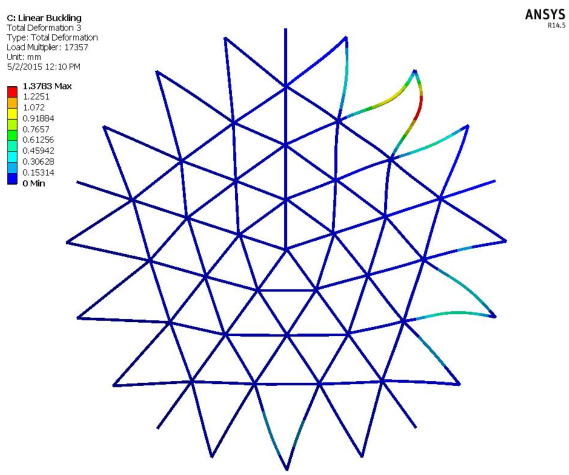
	Single Supports		Fixed Supports	
Buckling mode	Gravitational load	Element - Angle	Gravitational load	Element - Angle
1º	17308	22 - B15	29763	22 - B15
2º	17332	29 - B15	29829	29 - B15
3º	17357	15 - B15	29888	15 - B15
4º	17607	1 - B15	30729	1 - B15
5º	17625	8 - B15	30835	8 - B15
6º	20478	34 - B14	30858	28 - B15
7º	20500	6 - B14	30897	21 - B15
8º	20755	20 - B14	31050	14 - B15
9º	20819	27 - B14	31424	8 - B15
10º	20891	13 - B14	31459	1 - B15



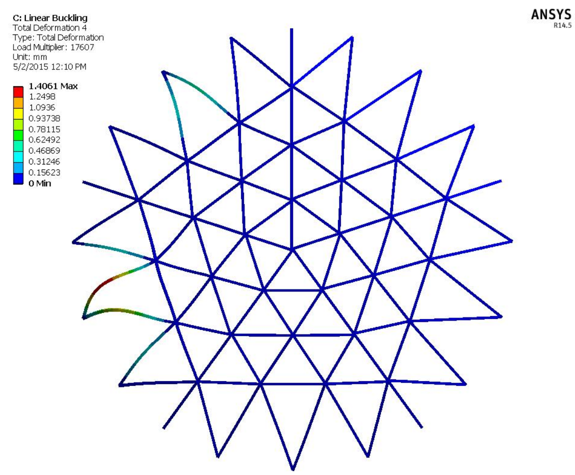
a. 1º buckling mode



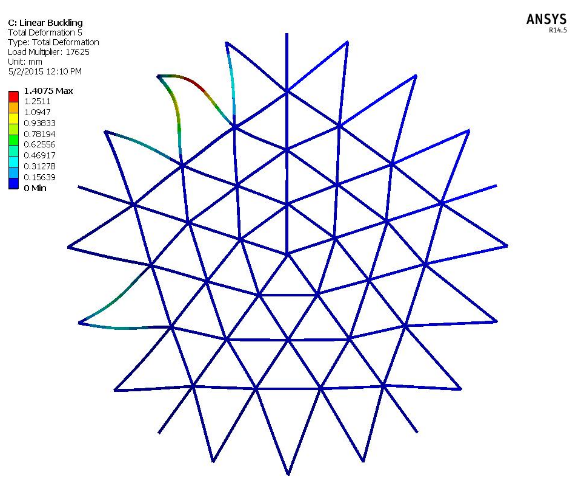
b. 2º buckling mode



c. 3º buckling mode

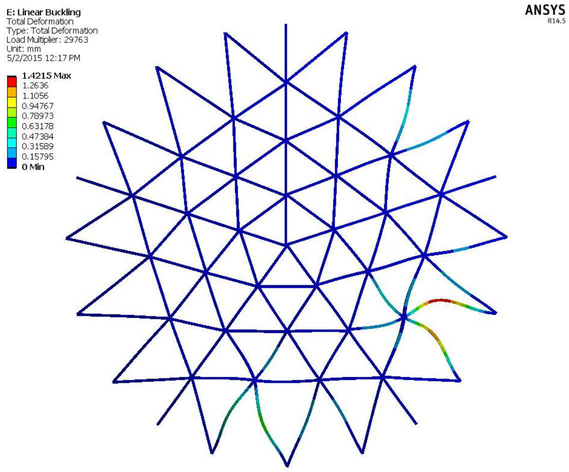


d. 4º buckling mode

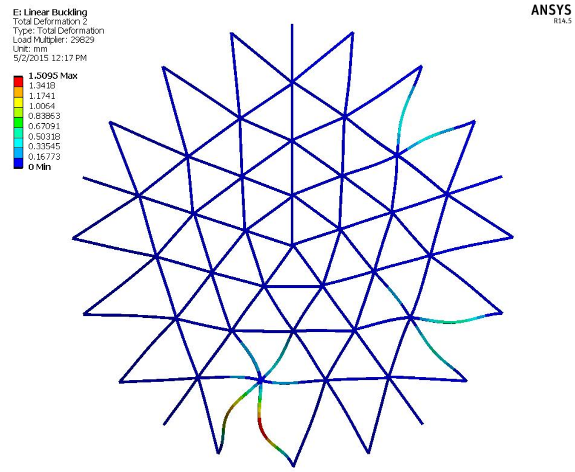


e. 5º buckling mode

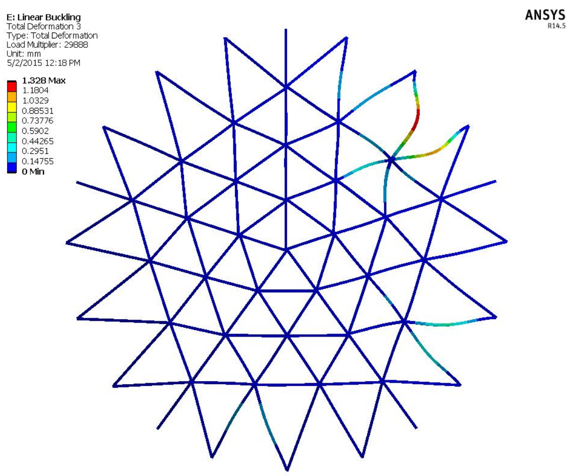
Figure 8. Buckling modes to the simply supported geodesic dome



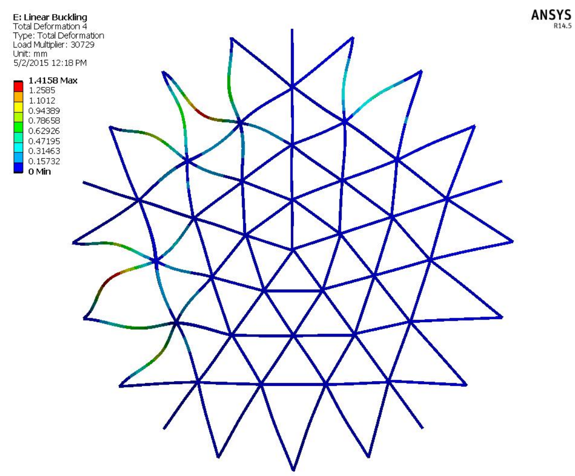
a. 1º buckling mode



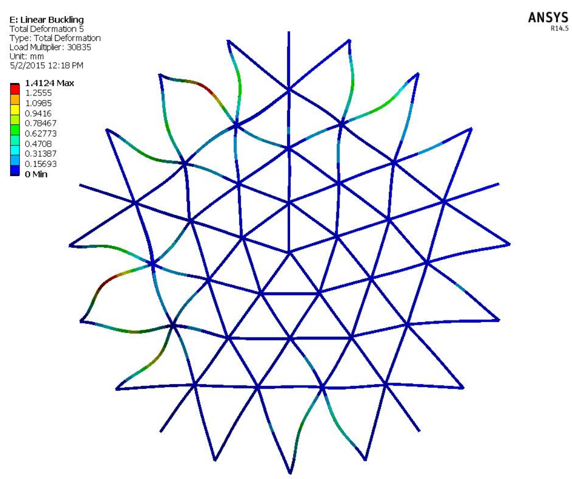
b. 2º buckling mode



c. 3º buckling mode



d. 4º buckling mode



e. 5º buckling mode

Figure 9. Buckling modes to the fixed supported geodesic dome

A significant point to highlight is the first five buckling modes almost happen with the same load, in order words, the gravitational load variation between the first and the fifth loads is 1,83% considering the geodesic dome as simply supported and 3,60% considering it as fixed supported. That behavior was already expected once the geodesic dome has a repeatability standard. In addition, the five buckling modes in both support conditions are presented in Figs. 8 and 9, where is apparent the buckling of members which have one end as the support of the whole structure (members B15).

The five subsequent buckling modes for each support condition show a very similar behavior, where the buckling also occurs only in those members where one of their ends are responsible to support the whole structure. That analysis was performed up to the fiftieth buckling mode and up to here there is no mode that would reach a global collapse of the whole structure, considering both support conditions of the geodesic dome.

4. CONCLUSIONS

It is important to lay emphasis to present study which was performed in a physical model designed from several simplifying assumptions, making use of both material and physical resources to enable the prototype construction. Thereafter, a new concept for geodesic domes which fully differs from the standard models that have been found in the literature review was created.

The buckling analyses of the geodesic dome show that till to fiftieth buckling modes only failure in individual members occurs and there is no collapse of the whole structure. That statement applies to both support conditions of the structure.

Regarding the first five buckling modes where was possible to identify a quite small deviation in the gravitational loads that produce the respective modes, considering the repeatability standard of the geodesic dome it was expected these loads with the same value. However, one of the reasons that could justify those deviations it is the structure modeling, once the members were defined from the spatial coordinates of each node, which was accurately of hundredth of millimeter. It means also some small differences in the members lengths of the same type can exist.

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