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Research paper

Influence of the mesh structure of geodesic domes on their seismic response in applied directions

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Abstract: The paper presents the determination of the impact of earthquakes of varying intensity on the structure of geodesic domes. The structures of the analyzed domes were designed on the basis of the regular octahedron according to two different methods of creating their topology. The use of four seismic records of different intensity and duration of the record made it possible to subject 8 models to numerical analysis. The designed spatial structures are domes with a steel cross-section, thanks to which they are undoubtedly characterized by their lightness and the possibility of covering very large areas, without the need to use internal supports. Designing steel domes is currently a challenge for constructors, as well as architect, who take into account their aesthetic considerations. The paper presents the seismic response of geodesic domes in applied different directions (two horizontal "X" and "Y" and one vertical "Z"), using the Time History method. The values of forced vibrations and recording intensity were shown, and on this basis, an attempt was made to determine which seismic record may be more unfavorable for the designed geodesic domes created according to two different methods of shaping the topology of their structures. For this purpose, the FFT (Fast Fourier Transform) method was used. The maximum accelerations and displacements of the structures were also analyzed. The conducted analysis shows the influence of seismic excitations on geodetic dome structures, depending on the applied method (method 1 and 2) of shaping their topology. This paper will undoubtedly be useful in designing a geodesic dome structure in a seismic area. In addition, this analysis can be helpful in assessing the effects of an incidental earthquake.

Keywords: forced vibrations, geodesic dome, lightweight structures, numerical analysis, seismic analysis

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1. Introduction

Geodesic dome structures made of light construction material such as steel can be found in various parts of the world. It often happens that geodesic dome structures constitute a reference point for a given city. An example of such a structure is a dome located in Montreal, Canada (Fig. 1a). Sometimes, however, structures of this type can be found in typical buildings, e.g. in a residential building (in Milan, Italy – Fig. 1b). These constructions have numerous advantages: (i) the possibility of building structures covering large surfaces without the use of internal supports, (ii) reliability, (iii) good acoustics, (iv) exemplary ventilation of the interior of the structure, or (v) unique appearance thanks to a light load-bearing structure, often trying to deny the laws of physics.


(a) (b)

Fig. 1. Geodesic dome located in: a) Montreal, Canada (https://en.wikipedia.org/wiki/Montreal_Biosphere, by Ralf Roletchek: www.roletschek.at), b) Milan, Italy

Research on the construction of domes has been carried out for years. The main research area for these types of structures was their weight optimization [1–10].

The influence of the topology of geodesic dome structures was also investigated. In the papers [11–14] the influence of the topology of mesh shaping of geodesic domes was investigated with the use of two different methods. A regular octahedron was used as the basis for generating the analyzed geodesic domes, resulting in innovative, so far unexplored structures. It was found that the use of a particular method to create their mesh influences the weight of the structure by optimizing the cross-sections of strut elements in each specified group of struts. The conducted analyzes were guided by the fact that the use of steel struts was at a high level and amounted to about 90% according to Eurocode 3 [15]. In addition, these tests were carried out under the influence of a static load that was applied at individual nodes of the tested structures.

There is relatively little research on dynamic geodetic structures of strut domes. It has been assumed that such objects, despite their large size, are resistant to dynamic forces due to their unique structure. In fact, one may doubt this claim. Especially when these objects are located in seismic areas [16–22]. The seismic forcing aspect has also been investigated in other studies. The aforementioned theory may be true in the case of dynamic loads originating from wind, then thanks to its streamlined structure, the geodesic dome construction is able to ensure safety.

Therefore, the aim of this work is to determine the impact that an earthquake of varying intensity may have on the structure of geodesic domes, which were built according to two different methods of creating a mesh structure of steel elements, and the basis of their creation is a regular octahedron. The paper was forced into three directions simultaneously (horizontal X, Y and vertical Z). In addition, the study also analyzed the response of the structure in three different directions, both for displacements, accelerations and forced vibrations.

2. Methodology

2.1. Description of geodesic domes

To create the structures of the analyzed geodesic domes, two different methods of dividing a spherical triangle, which is the initial face of a regular octahedron, were used. By interpolating a flat, triangular face of the octahedron, the division points were obtained, which were projected by radial rays onto the surface of the sphere concentric with the polyhedron. In method 1 a mesh of steel struts of the dome was created by dividing each triangular side into *n* parts and drawing three families of lines parallel to the sides of the initial face of the regular octahedron. However, in method 2, three families of parallel lines were drawn to the height line. In the first method, after dividing the initial triangle of the regular octahedron into 19 frequencies, 2888-hedron was obtained, i.e. a structure consisting of 761 nodes and 2204 struts (Figure 2a). The analysed dome is 49.97 m wide and 25.0 m high and weighs 58 tons. Using the second method, after dividing the initial triangle of the regular octahedron into 22 frequencies, 2904-hedron was modelled. This dome consists of 749 nodes and 2156 struts (Figure 2b), with a width of 50.0 m and a height of 25.0 m. It weighs 43 tons. A detailed analysis of the topology of geodesic domes is presented in [11–14, 16].

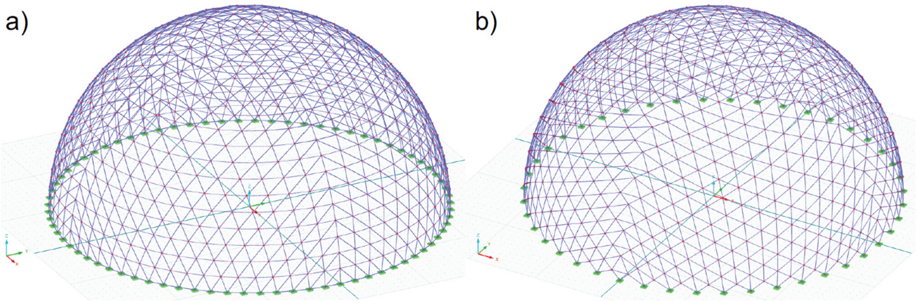


Fig. 2. Geodesic dome made of: a) method 1 and b) method 2

Fig. 2 shows the meshes of the domes analyzed in this paper, taken from the numerical program Dlubal RFEM.

Two geodesic domes with the same parameters were used in the paper: (i) span 50 m and (ii) height 25 m. Steel struts were modelled from S235 steel in accordance with Eurocode 3. The properties of this type of steel are following:

(i) Poisson's ratio (ν) 0.3,

(ii) Kirchhoff module (G) 80.76 GPa,

(iii) Young's modulus (E) 210 GPa,

(iv) thermal expansion coefficient (α) 1.2×10^{-5},

(v) volumetric weight (γ) 7850 kg/m^3, and

(vi) partial safety factor (γ_M) 1.0 [16].

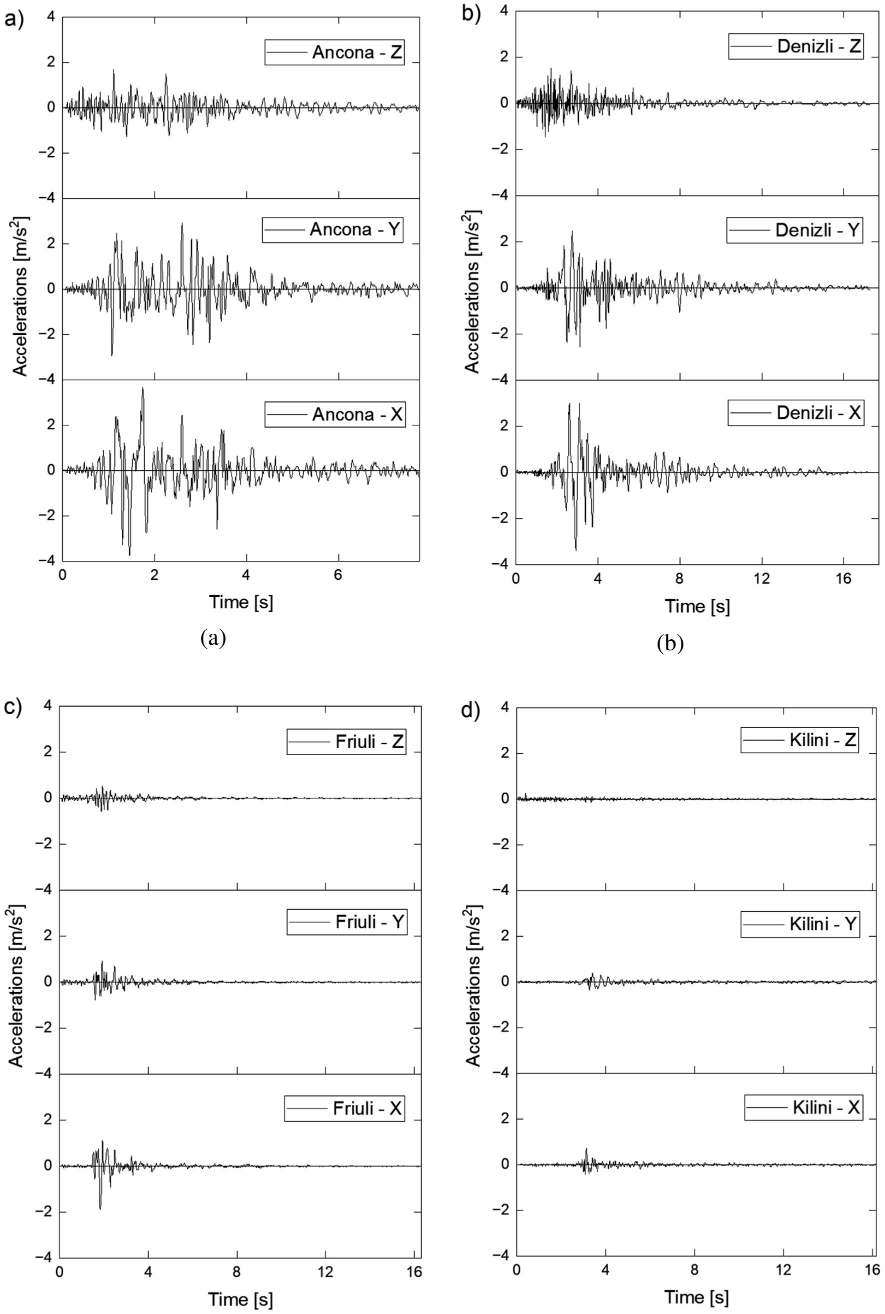
Taking into account the above assumptions and the number of seismic records, 8 numerical models were created (models I–VIII). The struts in numerical models were modelled as pinned joints.

2.2. Numerical analysis

In order to determine the seismic response of the domes to the given load in different directions, an analysis was performed over time. In this respect, the Time History method was used, where the time step for each of the applied excitation was 0.02 s. As a result, about 1000 time steps were obtained depending on the given record (Ancona, Denizli, Friuli, Kilini). The FFT (Fast Fourier Transform) method was used to determine the value of forced vibrations and the intensity of the record as well as its harmfulness for the structure. This method is known and widely used in the analysis of structures [23–26]. In addition, the maximal length of finite element was 0.5 m.

2.3. Seismic excitations

In order to find out about the seismic response of the studied domes, four seismic records of different intensity and recording duration were selected. In addition, the records were selected in such a way as to check, based on the forced vibration, whether a recording with a lower intensity is more harmful than a recording with a higher intensity. Therefore, for this seismic analysis, records from Italy, Turkey and Greece were used. The weakest one from Greece (Kilini) was characterized by ground acceleration equal to 0.714 m/s^2 (Fig. 3d) and duration of 16.18 seconds. The two records from Italy had different parameters. The Ancona record was characterized by an acceleration of –3.740 m/s^2 and a duration of 7.76 seconds (Fig. 3a). In turn, the second recording (Friuli) from Italy lasted 16.30 seconds and was characterized by an acceleration of –1.870 m/s^2 (Fig. 3c). On the other hand, the Denizli (Turkey) record had an acceleration equal to –3.387 m/s^2 (Fig. 3b) and lasted 17.31 seconds.



(a) (b)

(c) (d)

Fig. 3. The particular component (directions) of seismic excitations: a) Ancona (Italia), b) Denizli (Turkey), c) Friuli (Italia), d) Kilini (Greece)

2.4. Validation of numerical model

The numerical model of the domes was built on the basis of assumptions known from the buildings mechanics and steel structures. The domes were designed as skeletal structures using a steel cross-section under a static load of 90% (as in the papers [11–14]). It should be added that conducting a real-scale experiment on this type of domes is impossible due to the size of the analyzed structures and their topology. Hence, in order to determine the impact of seismic excitations, it was decided to make numerical models in DLUBAL RFEM using the dynamic analysis module. Experimental tests could be made to reduced scale modes, but other problems would be associated. It could be a next subject to study, though.

Table 1. Maximum values from numerical analysis

	Seismic record							
Directions	Ancona (Italia)		Denizli (Turkey)		Friuli (Italia)		Kilini (Greecce)	
	Method							
	1	2	1	2	1	2	1	2
	Model							
	I	II	III	IV	V	VI	VII	VIII
	Accelerations [m/s^2]							
X	64.14	29.34	33.77	26.48	10.67	5.88	8.90	4.78
Y	81.71	30.19	55.78	27.44	13.50	6.66	4.89	3.49
Z	39.21	32.42	28.06	–34.35	6.26	6.01	4.51	3.79
	Displacements [mm]							
X	17.4	6.8	8.3	6.6	3.9	2.3	–1.9	1.1
Y	23.4	–7.6	13.3	–6.9	3.6	2.1	1.1	0.9
Z	10.2	4.5	6.7	5.6	1.7	0.9	1.0	0.6

3. Results and discussion

3.1. General remarks

The paper analyzes the effect of seismic excitations on the structure of geodesic domes built according to two different methods of dividing the initial octahedron mesh (method 1 and 2). In addition, the study considers the maximum values that were recorded in individual directions (horizontal X and Y, vertical Z) for accelerations and displacements. Additionally, forced vibrations based on acceleration data were taken into account. It should be added that the load was applied to the structure supports simultaneously in all directions, i.e. horizontal (X and Y) and vertical (Z), as well as the self-weight was set at the same time. Table 1 summarizes the results obtained from the numerical analysis for maximum accelerations and displacements.

3.2. Accelerations

When analyzing the maximum accelerations (Fig. 4 and 5), it can be observed that the maximum value was recorded in the horizontal direction Y (81.71 m/s^2 – Fig. 4a) in model I, and therefore in the model whose dome was constructed on the basis of method 1. This value was obtained in the model that was subjected to the strongest excitation, but at the same time the shortest (Ancona). In method 2 (model II), for the same excitation, the obtained value was much lower and it amounted to 32.42 m/s^2 (Fig. 5a), therefore it was lower by 60% compared to model I. It can therefore be observed how important the value of the ground acceleration of the seismic record during an earthquake is.

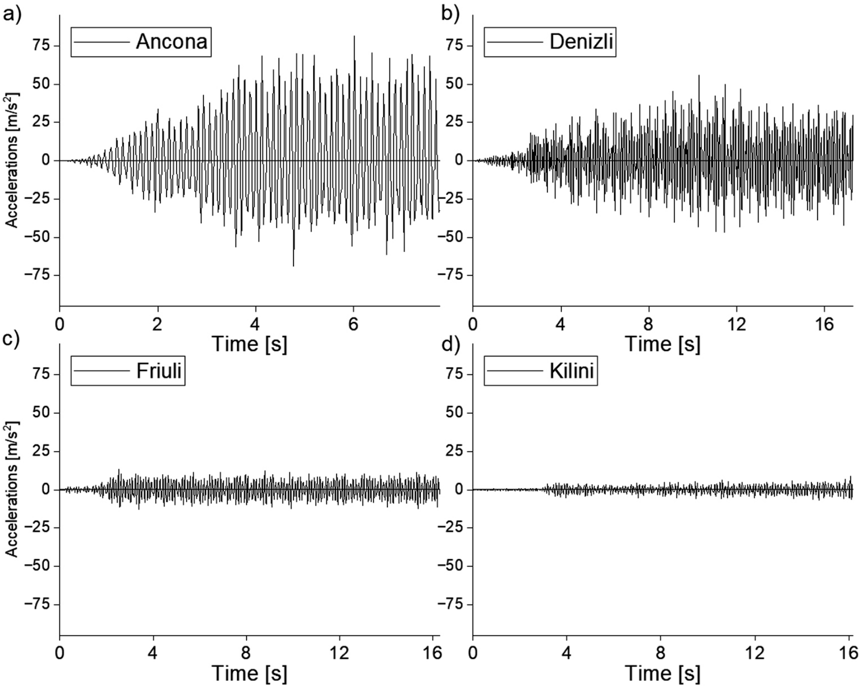


Fig. 4. Accelerations for method 1: a) Ancona (Italia), b) Denizli (Turkey), c) Friuli (Italia), d) Kilini (Greece)

It can also be noticed that in method 1 (models I, III, V, VII) the highest acceleration values were obtained in the horizontal directions (X and Y), so the vertical direction was not the dominant one. In the case of method 2, there was no such clear trend. In the II and IV models, the maximum acceleration values were recorded in the vertical direction, i.e. in the models where the input with higher acceleration was applied (Ancona, Denizli). In VI and VIII models, where the forcing was lower, the maximum acceleration was recorded in the horizontal directions (X and Y). The maximum accelerations were observed around half the height of the tested domes for both methods 1 and 2.

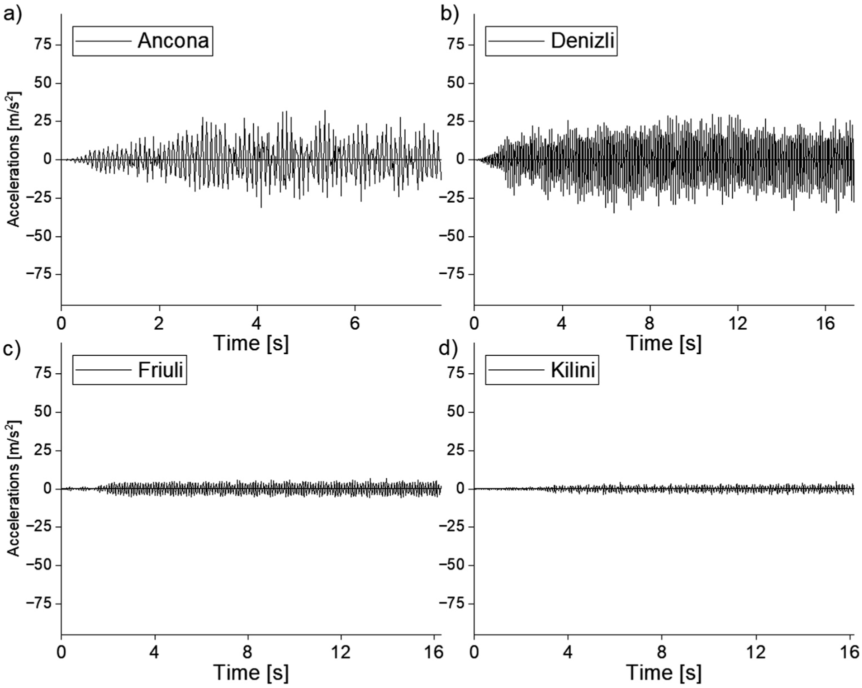


Fig. 5. Accelerations for method 2: a) Ancona (Italia), b) Denizli (Turkey), c) Friuli (Italia), d) Kilini (Greece)

With regard to other papers [17–23] relating to dynamic analyzes, the influence of the excitation on the maximum acceleration values depending on the direction of their occurrence has not been investigated. Efforts were only made to assess the impact of the forcing on structures. This analysis shows that the geodesic dome structure behaves a bit differently than typical skeleton structures.

3.3. Forced vibrations based on acceleration

As mentioned earlier, the paper also attempts to determine which seismic record may be more unfavorable for the surveyed geodesic domes built according to two methods (1 and 2) of creating their structure. This aspect is extremely important from the point of view of the mechanics of the structure, because the engineer designing the structure must know the conditions under which the structure will work, and therefore what type of load is the worst. Moreover, the fact that the seismic load is unlikely to repeat 100% increases the importance of determining the most unfavorable seismic record.

For this purpose, the values of forced vibrations from the acceleration of the structure were determined, and the FFT (Fast Fourier Fransform) method was used as a tool. This method is known and widely used in the analysis of building structures, where it is important to know about the significant intensities for structures originating from dynamic excitations. In addition, one of the ways to determine the stiffness of a structure under seismic excitation is to determine the significant frequencies. These frequencies can be determined from the nodal data coming from acceleration. In order to determine the significant frequencies, the acceleration data was obtained for the eight models analysed under a given seismic excitation. SeismoSignal software was used, which allows for proper signal processing (from accelerations) and the determination of significant frequencies in the tested models.

From Fig. 6, it can be seen that the significant frequency range is influenced by the method (method 1 or 2) of shaping the strut dome structure. In models II, IV, VI and VIII, where method 2 was used to generate the structures (Fig. 6b), the range of significant frequencies was greater and ranged from 8.87 Hz to 22.02 Hz. For comparison, in the models based on method 1 (models I, III, V and VII), the range was from 8.40 Hz to 16.89 Hz (Fig. 6a). When analysing the obtained values of significant frequencies in the domes, it can be seen that, for high-intensity excitations (model I, II, and IV) the range of these frequencies was greater than in the models III, V–VIII, where the intensity of the excitation was lower. Moreover, it is worth paying attention to the fact that the dominant

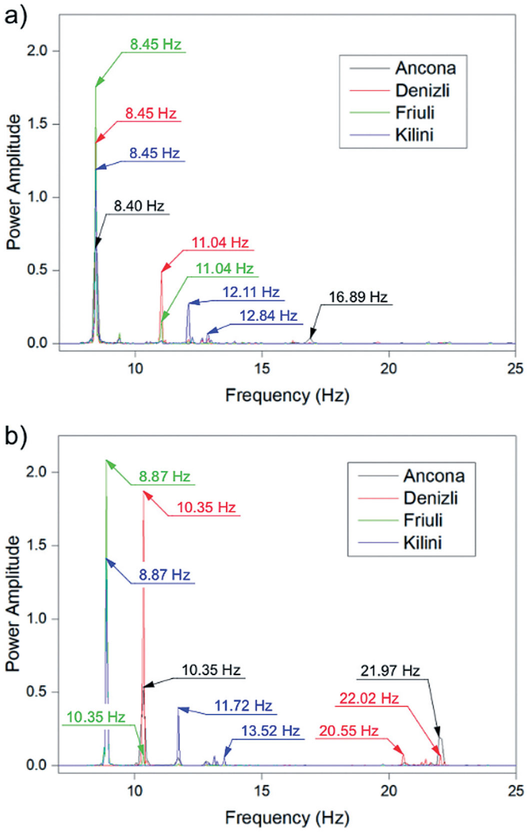


Fig. 6. Forced vibrations of: a) method 1, b) method 2

frequencies in the analysed models were 8.45 Hz (method 1), 11.04 Hz (method 1), 8.87 Hz (method 2) and 10.35 Hz (method 2).

On the basis of Fig. 6, it can first of all be noticed which notation is the most unfavorable for the analyzed geodesic dome structures. The analyzes show that the most important record is the Friuli record (Italy), i.e. the record with a relatively low ground acceleration in relation to the Ancona (Italy) and Denizli (Turkey) record. However, if you look at its characteristics, you can see that if you repeat this notation with an increased force, e.g. with a force similar to that of El Centro (Benchmark in the seismic analysis of a structure), then we can see that its intense zone may be more destructive than in the other studied seismic records (Ancona, Denizli, Kilini).

3.4. Displacements

In the case of displacements (Fig. 7 and 8), the situation is similar to that of accelerations. The largest displacements were recorded for model I (23.4 mm – Fig. 7a), built according to method 1 (Ancona record). For the same record (Ancona) according to method 2 (model II), the obtained value was much lower, i.e. 7.6 mm (68% lower than in model I – Fig. 8a). In the other models, the displacement values were lower, so it can be concluded that only the force of the maximum ground acceleration during an earthquake has a significant impact on the displacement value.

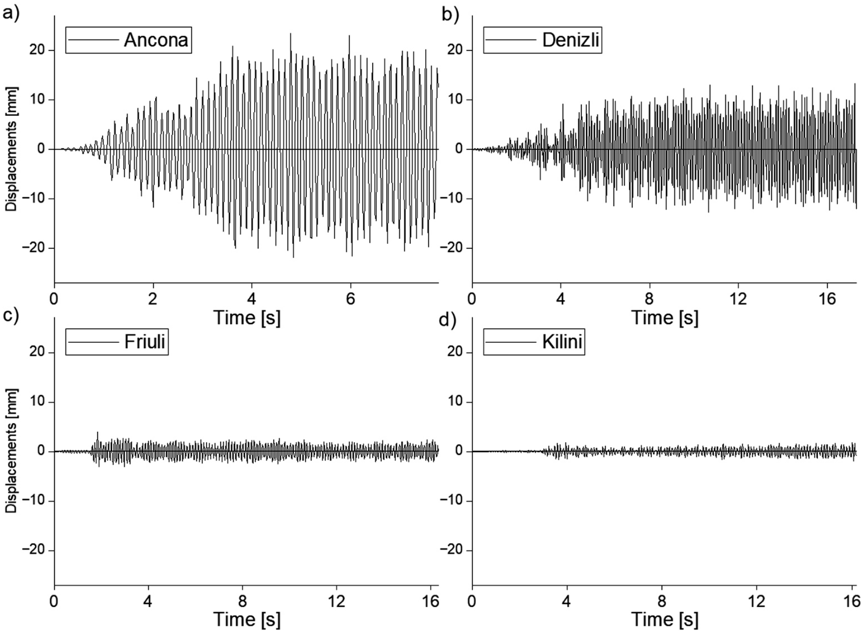


Fig. 7. Displacements for method 1: a) Ancona (Italia), b) Denizli (Turkey), c) Friuli (Italia), d) Kilini (Greece)

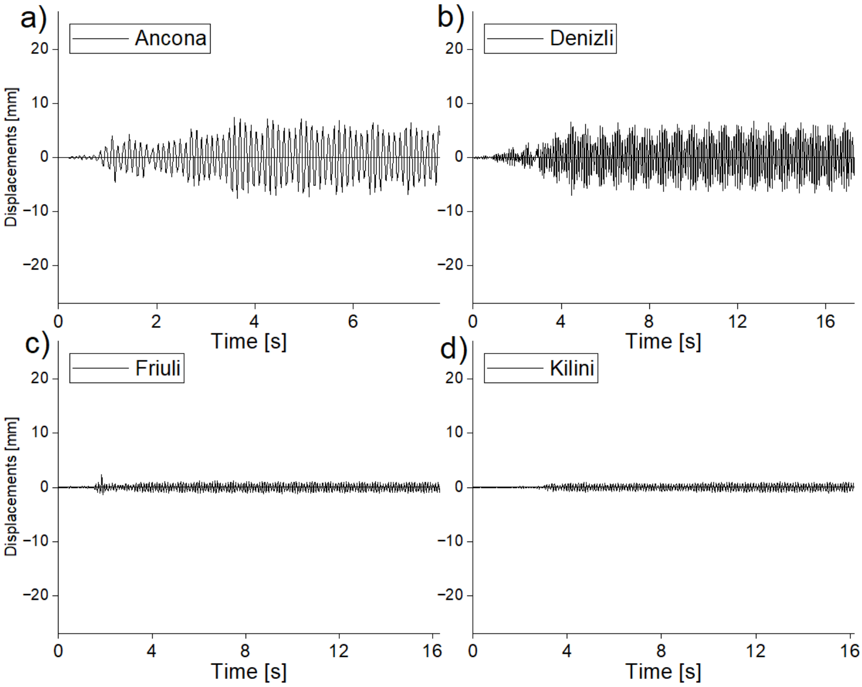


Fig. 8. Displacements for method 2: a) Ancona (Italia), b) Denizli (Turkey), c) Friuli (Italia), d) Kilini (Greece)

It should also be emphasized that for all analyzed models of geodesic domes (models I–VIII), the maximum displacements were recorded in the horizontal directions (X and Y).

Moreover, it can be seen that in method 1 (models I, III, V, VII) the maximum values were significantly higher than in the case of method 2 (models II, IV, VI, VIII). Additionally, it can be observed that the displacement values increased with the increase in the value of the maximum acceleration of a given recording. Thus, the trend is as linear as possible.

In addition, it should be added that the maximum values for both domes were recorded in the side sectors of the domes as a result of the maximum horizontal seismic excitation. It was a place located around mid-height for the domes constructed according to both methods of shaping their sphere.

4. Conclusions

After the numerical analysis, it can be concluded that the effect of seismic excitations on the geodesic domes is visible. In addition, it depends on the method of topological structure shaping that was used to design the geodesic dome. In method 1, higher values of displacements and accelerations were obtained than in the case of method 2. Additionally, it was noticed that:

- displacement values increased with an increase in the value of the maximum acceleration of a given recording. Therefore, the length of the record is not important, but the maximum value of the record,
- higher values of displacements and accelerations were recorded in the horizontal direction than in the vertical direction,
- based on the FFT analysis, it can be concluded that the most destructive record for the structure of the geodesic dome is the one from Fruila (Italy),
- The forced vibration frequency range ranged from 8.45 Hz to 22.02 Hz, with a greater frequency range reported for method 2.

The conducted assessment of the impact of seismic excitations on geodesic dome in the individual directions will be helpful for designers during the constructing of a geodesic dome in a seismic area. In addition, this analysis can be helpful in assessing the effects of an incidental earthquake. In the future, it is still planned to seek the answer to the question "what is the impact of seismic excitations on the structure of geodesic domes". The aspect of locating the additional masses seems interesting. The mentioned masses can disrupt the apparently ideal structure of the domes and lead to completely different responses.

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Wpływ siatki struktur kopuł geodezyjnych na ich odpowiedź sejsmiczną na zadanych kierunkach

Słowa kluczowe: analiza numeryczna, analiza sejsmiczna, drgania wymuszone, konstrukcje lekkie, kopuła geodezyjna

Streszczenie:

Praca dotyczy określenia wpływu trzęsienia ziemi o różnej intensywności na konstrukcję kopuł geodezyjnych. Struktury analizowanych kopuł, których podstawą kształtowania był ośmiościan foremny, zaprojektowane zostały według dwóch różnych metod tworzenia topologii tego typu konstrukcji. Wykorzystanie czterech zapisów sejsmicznych o różnej intensywności i o zróżnicowanym czasie trwania zapisu umożliwiło poddanie analizie numerycznej 8 modeli. Zaprojektowane przestrzenne struktury to kopuły o przekroju stalowym, dzięki czemu niewątpliwie odznaczają się swoją lekkością i możliwością przekrycia bardzo dużych powierzchni, bez konieczności zastosowania podpór wewnętrznych. Zaprojektowanie stalowych kopuł jest obecnie wyzwaniem zarówno dla konstruktorów, jak i architektów, którzy kierują się również względami estetycznymi. W pracy przedstawiono odpowiedź sejsmiczną kopuł geodezyjnych w zastosowanych różnych kierunkach (dwa poziome “X” i “Y” oraz jeden pionowy “Z”) przy użyciu metody Time History. Wykazano wartości drgań wymuszonych i intensywności zapisu i na tej podstawie podjęto próbę określenia, który zapis sejsmiczny może być bardziej niekorzystny dla badanych kopuł geodezyjnych utworzonych według dwóch różnych metod kształtowania topologii ich struktur. W tym celu posłużono się metodą FFT (Fast Fourier Transform). Przeanalizowano również maksymalne przyspieszenia i przemieszczenia konstrukcji. Przeprowadzona analiza pokazuje wpływ wstrząsów sejsmicznych na konstrukcje kopuł geodezyjnych, w zależności od zastosowanej metody (metoda 1 i 2) kształtowania ich topologii. Praca ta będzie niewątpliwie przydatna przy projektowaniu struktury kopuły geodezyjnej na obszarze sejsmicznym. Ponadto analiza ta może być pomocna przy ocenie skutków spowodowanych przypadkowym trzęsieniem ziemi.

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