Dynamic research of dome structures

A Handruleva
USEA “Lyuben Karavelov” Bulgaria, Faculty of Construction, Department “Mechanics and Mathematics”, 1373 Sofia, 175 Suhodolska str.

E-mail: rector@vsu.bg

Abstract. In this paper the dynamic responses of discrete single-layer domes are discussed. As objects of the study, computational models of domes have been analysed. These models differ in the type of their boundary conditions, the grid configuration, and in the height of the spheres. The analysis was conducted in two stages: a modal and a spectral analysis. In the modal analysis, a coefficient of the effective modal mass and the type of natural forms of vibration have been observed. Comparison has been made between CQC and SRSS being two different methods for combining modal contributions, as well as between two other methods of combining modal responses in the direction of seismic effects, namely: SRSS method and the „Rule of 30%”. The purpose of the study is to work out the dynamic response of the discrete single-layer spherical domes.

1. Introduction
Thus far, the combination of coordinate directions following our norms is carried out by applying the SRSS method (square-root-of-the-sum-of-squares), which practically in two directions, it appears to be the Pythagorean theorem. It is written as follows:

\[ E_E = \sqrt{E_{E,x}^2 + E_{E,y}^2} \]  

(1)

where \( E_E \) is the force exerted in section \( E \), in turn used for dimensional purposes;

\( E_{E,x}^2 \) is a force exerted in section \( E \), generated from an activity of seismic forces along axis \( x \), i.e. having resulted from the application of a spectrum in this direction;

\( E_{E,y}^2 \) is a force exercised in section \( E \), generated from the action of seismic forces along axis \( y \), i.e. having resulted from the application of a spectrum in this direction;

Other ways of combining, called methods of coordinate combination, can be used, as well. One of them is based on expressions/equations (2) and (3) of Eurocode 8, Part I. [1]. It is a combination of the full effects obtained from the impact in one coordinate direction with those from the other, but multiplied by ± 0.3, i.e. 30% of their full dimension(value). The equation is as it follows:

\[ E_E = \pm E_{E,x} \pm 0.3E_{E,y} \]  

(2)

when calculating the horizontal forces only.

There is also a number of national norms for which the coefficient to be combined with is ± 0.4. It is most common within the range from ± 0.3 to ± 0.5. [3] Thence in two directions, the general expression of this method of coordinate combination can be written as
When $\alpha \in [0.3 \div 0.5]$, the most common method of combined effects in coordinate directions is expressed in the following equation:

$$E_E = \pm E_{E,x} \pm \alpha E_{E,y}$$

$$E_E = \pm \alpha E_{E,x} \pm E_{E,y}$$

(3)

The method with coefficient is recommended when rotating eigenforms dominate. However, in case of strong irregularity across plane, it is appropriate to compare the results by adopting other combination techniques for analysis. This is substantiated (validated) in detail in [4].

2. Description of the selected computing models

Eleven representative elements were considered as objects of research for studying the dome-like rod structures. Correspondingly, the domes are identified and marked as K1, K2, K3, K4, K5, K6, K7, K8, K9, K10 and K11, respectively, shown in Figure 1a (K1) and Figure 1.b (K11). The study is a parametric one, as diameter is subjected to change(s) in direction $y$ within a range of $30 \div 15$m. SAP 2000 was used to build and study the computational models.

The following fixed parameters have been adopted for the selected models of ribbed domes:

- diameter of base in x direction $D_x = 30$m;
- height of dome $h = 7$m
In generating computational models, the following:
• Boundary support conditions: supporting ring on radially movable supports
• Rigid connection of the elements with the support ring
• Rigid connection between the elements of the ribs and the inner rings of the lattice.

Tubular cross-sections and standard hot-rolled profiles were adopted for the structural elements. Table 1 shows the overall geometric characteristics of the selected domes.

|                | K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 | K9 | K10 | K11 |
|----------------|----|----|----|----|----|----|----|----|----|-----|-----|
| height of dome, h [m] | 7  | 7  | 7  | 7  | 7  | 7  | 7  | 7  | 7  | 7   | 7   |
| diameter of dome $D_x$ [m] | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30   | 30   |
| diameter of dome $D_y$ [m] | 30 | 30 | 29 | 29 | 28 | 28 | 25 | 23 | 20 | 18   | 15   |
| cover/span area [m$^2$]     | 707| 695| 683| 671| 660| 648| 589| 530| 471| 412  | 353  |

For the representative elements of the seven domes along the meridian and the rings, the same geometrical characteristics of the cross sections given in Table 2 were adopted.
The frame type beam-finite-element method of 6 degrees of freedom was used to build and simulate the computational models. [2] Based on the accepted parameters and the subsequent discretization, the following characteristics of the eleven computational models were obtained: number of elements - 224, number of nodes - 113, number of internal rings (without the support ring) - 6.

3. Comparative analysis of the results
In tables below from table 3 to table 5, in a sequential order the following are provided: periods of oscillation and seismic forces acting in a selected element; results on the different method of combined effects in coordinate directions; absolute difference between the maximum forces obtained with different methods of combination in the coordinate direction.

| Table 2. Geometric characteristics of the cross-sections of the elements |
|---------------------------|---------------------|----------------------|
|                          | K1, K2, K3, K4, K5, K6, K7, K8, K9, K10, K11 |
| cross-section surface [cm²] | supporting ring | meridian ribs | tension-and-compression ribs |
| cross-section surface [cm²] | 53.8          | 10.7            | 10.7                          |
| moment of inertia [cm⁴]    | 8356          | 96.3            | 96.3                          |
| modulus of inertia - E=206 000 MPa |

| Table 3. Periods of oscillation and seismic forces applied in a selected element |
|-----------------|------------------|-----------------|-----------------|------------------|------------------|
|                | T₁ [s] | T₂ [s] | ΔT [%] | Eₓ*1000 [kN] | Eᵧ*1000 [kN] | Eᵧ/Eₓ |
| K1 (30x30)     | 0.988  | 0.988  | 0.00   | 19.04          | 19.04          | 1.00            |
| K2 (30x29.5)   | 0.979  | 0.971  | 0.89   | 18.57          | 20.41          | 1.10            |
| K3 (30x29)     | 0.970  | 0.953  | 1.81   | 17.56          | 22.59          | 1.29            |
| K4 (30x28.5)   | 0.961  | 0.935  | 2.78   | 16.60          | 24.94          | 1.50            |
| K5 (30x28)     | 0.953  | 0.916  | 3.99   | 12.28          | 23.14          | 1.88            |
| K6 (30x27.5)   | 0.943  | 0.899  | 4.82   | 15.39          | 31.40          | 2.04            |
| K7 (30x25)     | 0.901  | 0.810  | 10.64  | 17.97          | 48.44          | 2.70            |
| K8 (30x22.5)   | 0.862  | 0.722  | 17.68  | 25.60          | 68.39          | 2.67            |
| K9 (30x20)     | 0.830  | 0.637  | 26.29  | 35.66          | 88.83          | 2.49            |
| K10 (30x17.5)  | 0.810  | 0.557  | 36.92  | 43.70          | 106.72         | 2.44            |
| K11 (30x15)    | 0.836  | 0.506  | 49.10  | 43.90          | 114.76         | 2.61            |

| Table 4. Results upon the various methods of combined effects in coordinate directions |
|-----------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Methods of combined effects in coordinate directions |
| SRSS | Eₓ+0.3Eᵧ | Eₓ-0.3Eᵧ | Eᵧ+0.3Eₓ | Eᵧ-0.3Eₓ | 0.3Eₓ+Eᵧ | 0.3Eᵧ-Eₓ | -0.3Eₓ+Eᵧ | -0.3Eᵧ-Eₓ |
| K1   | 26.92 | 24.75 | 13.33 | -13.33 | -24.75 | 24.75 | -13.33 | 13.33 | -24.75 |
| K2   | 27.59 | 24.70 | 12.45 | -12.45 | -24.70 | 25.98 | -14.83 | 14.83 | -25.98 |
| K3   | 28.61 | 24.34 | 10.79 | -10.79 | -24.34 | 27.85 | -17.32 | 17.32 | -27.85 |
| K4   | 29.96 | 24.08 | 9.12  | -9.12  | -24.08 | 29.92 | -19.96 | 19.96 | -29.92 |
| K5   | 26.20 | 19.22 | 5.34  | -5.34  | -19.22 | 26.83 | -19.46 | 19.46 | -26.83 |
| K6   | 34.97 | 24.81 | 5.97  | -5.97  | -24.81 | 36.02 | -26.78 | 26.78 | -36.02 |
| K7   | 51.67 | 32.50 | 3.44  | -3.44  | -32.50 | 53.83 | -43.05 | 43.05 | -53.83 |
| K8   | 73.02 | 46.12 | 5.08  | -5.08  | -46.12 | 76.07 | -60.71 | 60.71 | -76.07 |
| K9   | 95.72 | 62.31 | 9.01  | -9.01  | -62.31 | 99.53 | -78.13 | 78.13 | -99.53 |
| K10  | 115.32| 75.72 | 11.69 | -11.69 | -75.72 | 119.83 | -93.61 | 93.61 | -119.83 |
| K11  | 122.87| 78.33 | 9.47  | -9.47  | -78.33 | 127.93 | -101.59 | 101.59 | -127.93 |

4
Table 5. Absolute difference between the maximum forces as obtained upon different methods of combined effects in coordinate directions

|     | SRSS | $0.3E_x+E_y$ | $|\Delta| [kN]$ |
|-----|------|--------------|----------------|
| K1  | 26.92| 24.75        | 2.17           |
| K2  | 27.59| 25.98        | 1.62           |
| K3  | 28.61| 27.85        | 0.76           |
| K4  | 29.96| 29.92        | 0.04           |
| K5  | 26.20| 26.83        | 0.63           |
| K6  | 34.97| 36.02        | 1.05           |
| K7  | 51.67| 53.83        | 2.17           |
| K8  | 73.02| 76.07        | 3.05           |
| K9  | 95.72| 99.53        | 3.81           |
| K10 | 115.32| 119.83   | 4.51           |
| K11 | 122.87| 127.93   | 5.06           |

From Figure 2 to Figure 8, accordingly are shown the following: periods of oscillation; $\Delta T$ chart; seismic forces $E_x$ and $E_y$; the $E_y/E_x$ ratio; comparison between the methods of combined effects in coordinate directions; alteration(s) of $|\Delta|$; $|\Delta|$ as a function of $E_y/E_x$.
Figure 4. Seismic forces $E_x$ and $E_y$

Figure 5. The $E_y/E_x$ Ratio

Figure 6. Comparison between the methods of combined effects in coordinate directions
The consideration of the real interaction of the structure and the ground base are of special importance both for achieving optimality and economy of the design solution, as well as for the management and minimization of the generated waste. More information can be found in [5], [6] and [7].

4. Conclusions

In the present study, three methods of combined effects in coordinate directions, as well as the acting forces in a particular single case obtained upon independent seismic impact in these same directions have been theoretically compared. These are the three possible technologies provided by the Unified European Building Standards concerning the design of structures in seismic areas, i.e. Eurocode 8. Based on a numerical experiment, two of these methods were practically compared, namely SRSS and the Rule of 30%. This was performed through the computational models of rod domes.

From the obtained results, the following more important conclusions may be drawn:

- for effects relatively close in value in/along the two horizontal coordinate directions, the SRSS method gives higher (more optimal) results, i.e. resulting in higher consistency;
- in cases where the effects differ significantly (by more than 80% for the specific models), the Rule of 30% yields higher (optimal) end-values;
- the CQC combination method, i.e. method based on correlation (4), it can be considered as the most general one and when an appropriate choice of coefficient $\beta$ is made, it will always develop results in the direction of the safety of the structure.
It is rather advisable, especially for geometrically complex space-frame systems, that separate comparisons of the results attained by the SRSS and the Rule of 30 methods be made. This is especially true for some particular areas or certain elements that are rather fundamental for the load-bearing capacity of the structure, i.e. elements that mainly predetermine its capacity. Studies of a similar nature provide further clarity on dispositive regulations of Eurocode 8. It is absolutely desirable that studies of such nature may continue to be conducted further, while using different structural configurations, as it is quite vital to look for a reference value of coefficient $\beta$ that leads to a higher overall safety of the structure.

5. References

[1] European standard Eurocode 8 – BDS EN 1998-1-1;
[2] Stoynova I 2012 Dynamic response of reinforced concrete members and connections, VSU Publishing house, Sofia, ISBN: 978-954-331-116-3, p.32-33;
[3] Georgiev and St Tsvetkov, Guide for Design of special Reinforced Concrete Structures According to Eurocodes, Part 1, Chapter 1, General Information for Analysis and Construction of Special Reinforced Concrete Structures, USEA (VSU), Sofia, Bulgaria;
[4] Tsvetkov St 2019 Design of steel arched roofs and implementation of the connection "steel-concrete (reinforced concrete)" at the foundations, In Proc. IX International Scientific Conference on Architecture and Construction ArCivE 2019, section II, paper № 9 ISSN: 2535-078;
[5] Stoyanov V A, Petkova V, Andonova V 2020 Analysis of the construction site waste management plans in Bulgaria, adopted in the period 2015-2017, IOP Conf. Ser.: Mater. Sci. Eng., 951, (2020), 012007, http://doi.org/10.1088/1757-899X/951/1/012027 SJR=0.2 for 2019 r.
[6] Frangov G, Zayakova H, Frangov S 2017 Destructive influence of technogenic factors and precipitations on the landslide support structure. Proceedings of the 4th WLF, Ljubljana, Slovenia, published in Advancing Culture of Living with Landslides, Volume 3: Advances in Landslide Technology, ISBN 978-3-319-53487-9, pp. 529-536.
[7] Hamova M, Zayakova H, Frangov G 2015 Passive grouted anchors for emergency reinforcement of retaining structures”, 6th ACES Conference GEOTECHNICS IN CIVIL ENGINEERING, 2-6 November 2015, Vrsac, Serbia.