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ANALYSIS OF THE HARMONIC EXCITATION OF SCAFFOLDING STRUCTURES

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ABSTRACT: Scaffoldings are lightweight temporary structures used mostly at construction sites. Due to their dynamic characteristics they are prone to dynamic excitation occurring at the structures or in the nearby at the construction site. A medium size scaffolding FEM model was subjected to harmonic excitation with frequencies ranging from 2 Hz to 12 Hz as a single harmonic force located in one of the selected nodal points. Full dynamic analysis of structure subjected to the load varying in time was provided by direct integration. Maximum displacement during forced vibrations and fading free vibrations after the source of excitation became inactive were watched in relation to the force parameters and its location. It has been observed that frequencies close to the first natural frequencies propagate to the entire structure, while higher frequencies cause discomfort for scaffolding users, but have a smaller range of action.

Keywords: scaffolding, harmonic excitation, dynamic analysis, direct integration.

1. INTRODUCTION

Scaffoldings are structures made of elements that can be used many times. The elements are shaped to make the assembly quick and easy. Because of these two features of scaffoldings, such structures are characterized by low frequencies of free vibrations (Bęc and Błazik-Borowa 2019, Błazik-Borowa and Bęc 2021). The fact that the scaffoldings are used for construction works means that they are subjected to dynamic influences caused by (Bęc et al. 2020): workers walking on the scaffolding, wind action, vibrations of chutes, transport of the grout by shotcretes, small equipment operation, e.g. drilling, paraseismic vibrations caused by road traffic. These sources of vibration induce vibrations in the range from 1 Hz to mainly 10 Hz or even up to 15 Hz. Depending on the frequency of the induced vibrations and the acceleration values, these vibrations may increase the effort of the structure or produce workers' discomfort.

The purpose of this work is to determine the range of vibration frequencies that are dangerous to the safety of the structure and its users. To obtain this, a selected scaffolding with typical dynamic parameters was subjected to harmonic forces of different frequencies. This type of load is an idealized model, but because of its simplicity you can study the effect of excitation, avoiding the effects coming from other factors.

2. NUMERICAL ANALYSIS

The numerical analysis was provided for an exemplary façade scaffolding of middle size. Length of the structure is 25.73 m and its height is 24.15 m. The calculations were made using Autodesk Simulation Multiphysics 2013, based on the Finite Element Method. A number of points (121) on the structure were selected for analysis. These were the points in the scaffolding main frame, i.e. the connection point of outer stand pipe and the lover transverse beam.

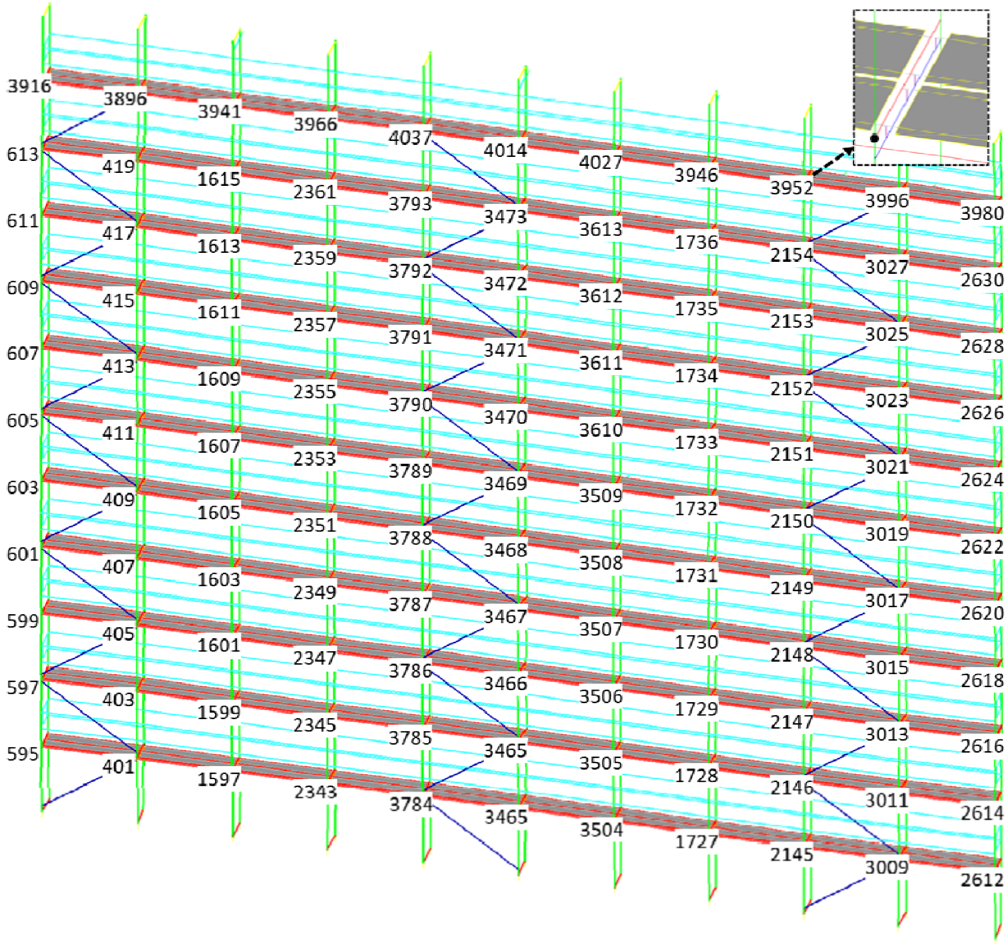

Fig. 1. Scaffolding with numbered selected nodes and detailed location of these nodes (upper right corner).

The numerical model of the scaffolding structure consists of frame and shell elements. The scaffolding model has been verified on the basis of free vibrations measurements of the actual structure. The verification methods have been described by Cyniak et al. (2018) and Jamińska-Gadomska et al. (2018).

3. RESULTS

Dynamic analysis was performed in two parts. First the scaffoldings natural frequencies and mode shapes were calculated by modal analysis. The second part of the analysis consisted of series of dynamic calculations (forced vibrations) with excitation in sinusoidal form located in a single point on the façade scaffolding structure.

3.1. Natural vibrations

As the result, 50 natural frequencies and respective mode shapes were calculated. First 10 natural frequencies are presented in Table 1.

Table 1. Natural frequencies.

Freq.	Natural vibrations parameters		
No.	ω [rad/s]	*f* [Hz]	*T* [s]
1	14,85	2,36	0,423
2	18,34	2,92	0,343
3	20,64	3,28	0,304
4	21,05	3,35	0,298
5	22,92	3,65	0,274
6	28,61	4,55	0,220
7	31,85	5,07	0,197
8	34,42	5,48	0,183
9	35,48	5,65	0,177
10	35,75	5,69	0,176

As it can be seen the analyzed scaffolding structure is quite complex and the natural frequency spectrum is very compact. A lot of natural frequencies can be found for such a structure in the range characteristic for typical equipment generating vibrations at construction sites. The 50^{th} of the calculated natural frequencies is just slightly exceeding the 12 Hz value.

3.2. Forced vibrations

Direct integration method was used to solve the equations of motion. On the basis of the probable occurrence of vibration excitation sources and the natural frequency spectrum of the analyzed scaffolding structure, it was decided to take into account harmonic excitation forces with frequencies from 2 Hz to 12 Hz every 1 Hz. Each of performed analyzes consisted of dynamic calculations of the scaffolding model subjected to action of a single harmonic force set at one of the selected points. Calculations for several selected points being loaded, one at the time were performed. In each loaded point excitation force was applied successively in each of perpendicular directions: horizontal along the façade (*X*), perpendicular to the façade (*Y*) and in vertical direction (*Z*). The total time of the single analysis was set to 10 s, and the source of vibrations was active in the first half of the calculations.

The following analysis parameters were used:

- Time step length: 0.01 s;
- Number of time steps: 1000;
- Number of time steps with active harmonic load: 500;
- Logarithmic decrement of damping: 0.06.

The analysis results were the series of vibration displacements in each of the selected 121 points. These results were put in graphs and additional table with extreme values of displacements in three perpendicular directions obtained during vibrations in each of selected nodes was produced for further analysis during each of calculations.

In Figure 2 exemplary graphs presenting the obtained series of displacements in three points are shown. These vibrations were excited with horizontal harmonic force in the plane of the façade with the amplitude of 1 kN and frequency of 3 Hz. The load was set in the node 1615. At each of presented graphs, there are applied annotations giving information on the relative node location for easier analysis of the distance influence on the obtained results. The first line of the annotation presents relative location in the grid of selected points: *col* in horizontal and *row* in vertical direction. The second line presents the distance in three directions: *X*, *Y* and *Z*, and the total distance *D* given in meters.

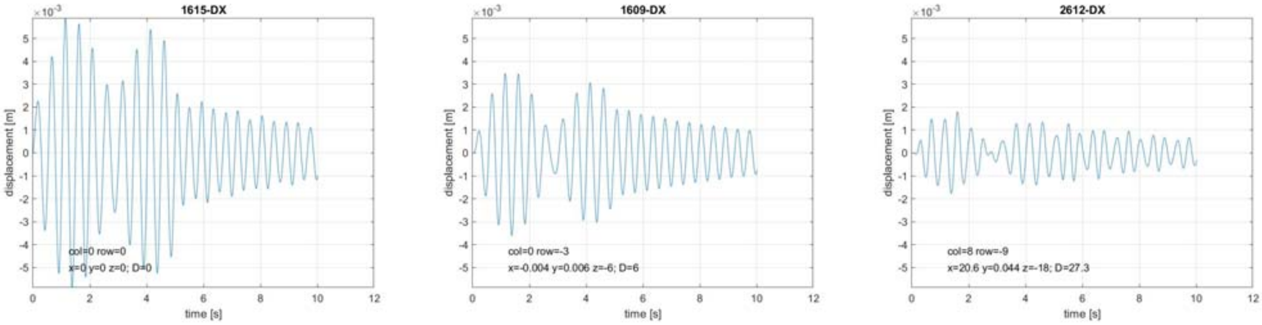

Fig. 2. Displacement series in three exemplary points of the structure.

As the result, the action of the excitation force was analyzed in relation to the previously described force parameters and the location of the force.

4. CONCLUSIONS

Horizontal vibrations along the façade are the most propagated through the structure. Frequencies close to the first natural frequencies increase nodal displacements and internal forces in the elements of the entire structure. Such vibrations may last longer, even after the source of vibrations becomes inactive. Higher natural frequencies (10 Hz and above) cause discomfort for scaffolding users, but these vibrations have a smaller spatial range of action. A very important factor of a scaffolding susceptibility to induced vibrations is quality of anchorage. If a scaffolding is well anchored, then the amount of damping is bigger and vibrations are harder to induce and propagate. It is also important to take into account geometry of anchorage locations. If the source of vibrations is in the point which is well anchored the vibrations cannot be excited. If the point is not anchored then vibrations may be observed not only close to the excitation point, but they sometimes occur in a far-away part of scaffolding structure which is not properly tied. This was observed mainly for horizontal vibrations, i.e. in *X* and *Y* directions. The direction of the resulting maxima of vibrations may be different than the direction of excitation force.

Further calculations will be made for scaffoldings of various sizes and sources of excitation with various character and amplitudes. Since during operation of the scaffolding its condition can change over time and anchors can be weakened, other damping levels will be analyzed. As it has been found on the basis of existing scaffoldings measurements (Bęc and Błazik-Borowa 2019) typical range of logarithmic decrement of damping values is 0.05-0.06, but for some scaffoldings can be as low as 0.03.

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