Analysis of scaffolding harmonic excitation

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Abstract. Scaffolding is equipment usually used at construction sites. A scaffolding structure is lightweight and made of elements used many times. The characteristics of scaffolding make it susceptible to dynamic actions present at the structure or occurring nearby. A scaffolding structure of medium size was subjected to analysis in this paper. The structure FEM model was loaded with single force harmonic excitation with various frequencies ranging from 1 Hz to 12 Hz applied in one of many selected points on the scaffolding façade. In the first step, natural frequencies and mode shapes of the analyzed structure were calculated. Then the full dynamic analysis was carried out to obtain maximum displacements of selected control points. The relation of excitation force frequency and location to the amplitudes of generated displacement was observed. It was found that low excitation frequencies close to the natural frequencies of the structure produced vibrations ranging to large areas of the scaffolding surface. Higher excitation frequencies are usually less propagated at the scaffolding but still may produce some discomfort to the structure users in the vicinity of the excitation force location. Scaffolding is equipment usually used at construction sites. A scaffolding structure is lightweight and made of elements used many times. The characteristics of scaffolding make it susceptible to dynamic actions present at the structure or occurring nearby. A scaffolding structure of medium size was subjected to analysis in this paper. The structure FEM model was loaded with single force harmonic excitation with various frequencies ranging from 1 Hz to 12 Hz applied in one of many selected points on the scaffolding façade. In the first step, natural frequencies and mode shapes of the analyzed structure were calculated. Then the full dynamic analysis was carried out to obtain maximum displacements of selected control points. The relation of excitation force frequency and location to the amplitudes of generated displacement was observed. It was found that low excitation frequencies close to the natural frequencies of the structure produced vibrations ranging to large areas of the scaffolding surface. Higher excitation frequencies are usually less propagated at the scaffolding but still may produce some discomfort to the structure users in the vicinity of the excitation force location.

Key words: scaffolding; harmonic excitation; dynamic analysis; direct integration.

1. INTRODUCTION

Scaffolding is a lightweight structure made of slender elements used many times, i.e., assembled and disassembled. The dynamic characteristics of such a structure are represented by low natural frequencies (see [1, 2]). Scaffoldings are mainly used at construction sites as temporary support structures and therefore are influenced by all dynamic actions present at the place (cf. [3]). These actions include the impact of workers during vertical communication at the structure and walking along scaffolding decks, among others. Other important dynamic actions that may be observed are wind action, vertical debris transport with the use of chutes, shotcrete machines transporting grout, man-operated and machine lifts, other equipment operated by workers, e.g., drillers, nearby traffic and other seismic or paraseismic actions. The frequency range of dynamic actions affecting scaffolding structure and its users mainly spreads from 1 Hz to 10 Hz or even 15 Hz. These vibrations excited with various frequencies and amplitudes can increase the structural element effort and cause human discomfort.

In this paper, the harmonic excitation of scaffolding structures was analyzed. Such a simplified dynamic load was selected in order to avoid the influence of other factors. The selected numerical scaffolding model was loaded with the use of a single point load with sinusoidal amplitude variation and with various frequencies, directions and points of application. The purpose of this study is to find out which dynamic force parameters make the excited vibrations dangerous to the scaffolding structure and its users.

2. THE IMPACT OF VIBRATIONS ON HUMANS

Vibrations acting on scaffoldings may have a negative influence on the scaffolding structure, especially when considering the vibrations generated by wind action on scaffolding with sheet cover. However, it is the workers' comfort which is mostly affected by the vibrations of the broad spectrum.

Vibrations in various ranges of frequencies influence the human body in different ways. Jia [4] lists the frequencies of response for individual elements of human bodies. The following are exemplary values: head – 25 Hz (axial vibrations), shoulder 4–5 Hz, forearm – 16–30 Hz, hand – 50–200 Hz, chest – 50–100 Hz, abdomen – 4–8 Hz, spinal column – 10–12 Hz (axial), legs – 2–20 Hz (depending on the position). The author summarizes that the human body is most sensitive to vibrations along the body height in the range of 4–8 Hz, while in the transverse direction, it is 1–2 Hz.

The perception of vibrations largely depends on the human position. Two groups of perception positions are usually subdivided: seating and non-seating (e.g. by Mansfield [5]). The in-

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fluence of human posture on human response to vibrations is presented by Matsumoto and Griffin [6]. The human body is more sensitive to accelerations in the horizontal direction than in the vertical one. According to Jia [4] the effective amplitude a_e commonly used in analysis of vibration effects on human body can be calculated as a combination of accelerations in all three directions, horizontal (a_X and a_Y) and vertical (a_Z) ones in the following way:

$$a_e = \sqrt{2\left(a_X^2 + a_Y^2\right) + a_Z^2}. \tag{1}$$

3. VIBRATION SOURCES ACTING ON SCAFFOLDING

There may be found many sources of vibrations active on scaffolding or nearby. The following sources may be listed with some examples of the expected range of frequencies:

- Workers walking (passage) on scaffolding decks (1–2 Hz);
- Drillers (7–8 Hz) and other hand equipment;
- Rope cranes;
- Lifts;
- Chutes;
- Shotcretes (1–2 Hz);
- Wind action (up to 2 Hz);
- Earthquakes;
- Nearby traffic and other paraseismic actions.

The vibrations of 120 scaffolding structures during their operation were measured in the research project [3]. The measured data was subjected to frequency analysis and the spectra are presented in Fig. 1. The peak values for the respective sources of forced vibrations were marked. Only horizontal vibrations are presented here since they have much larger amplitudes than the vertical components of accelerations. The first graph shows the auto power spectrum of accelerations for horizontal vibrations along the scaffolding façade, while the second one represents vibrations perpendicular to the façade.

Low natural frequencies make scaffolding susceptible to wind-induced vibrations [7, 8] and vibrations generated by the movement of users on the scaffolding [2]. The movement of the structure is perceptible to users when walking on the scaffolding. An increase in the strain of scaffolding structures caused by dynamic interactions is observed [9].

4. NATURAL VIBRATIONS OF FAÇADE FRAME SCAFFOLDINGS

A total number of 120 façade frame scaffolding structures in Poland were subjected to investigation. Vibrations of scaffolding structures were measured to find out the natural frequencies of structures. Vibrations were excited by the human body oscillations and damped free vibrations were registered with the use of accelerometers. These time series of accelerations were subjected to Fast Fourier Transform analysis which led to spectra of free vibrations of scaffolding structures. This facilitated assessing the natural frequencies of structures. For each of the measured scaffolding, the numerical model was built, and modal analysis was performed. These models were carefully tuned to reflect the static and dynamic parameters of the structures.

Based on the experimental and numerical research, it can be stated that the first natural frequencies of the scaffolding (structure without additional load) ranged from 0.7 Hz to 4 Hz depending not only on the size of the scaffolding but on the quality of anchoring, as well. The results for all 120 structures are presented in Fig. 2 as the histogram for the three first natural frequencies.

Regarding mode shapes, the following conclusions may be drawn:

- The first mode shape is usually associated with horizontal vibrations along the plane of the scaffolding (for 100 of the analyzed scaffoldings).
- The second mode shape is in most cases perpendicular to the plane of the scaffolding in the horizontal direction. However, for 40 of the analyzed scaffoldings, the second mode was also longitudinal.

The results are presented in the graphs grouping 24 scaffolding structures located in a specific Polish voivodship. Each scaffolding is represented by a series of bars showing the spectrum of 20 first natural vibrations. The bar for each frequency was built based on the effective mass in each horizontal direction (X – along the façade, Y – perpendicular to the façade) showing the prevailing direction of vibrations in each mode shape. The exemplary figure (Fig. 3) shows the results for the Lódzkie voivodship.
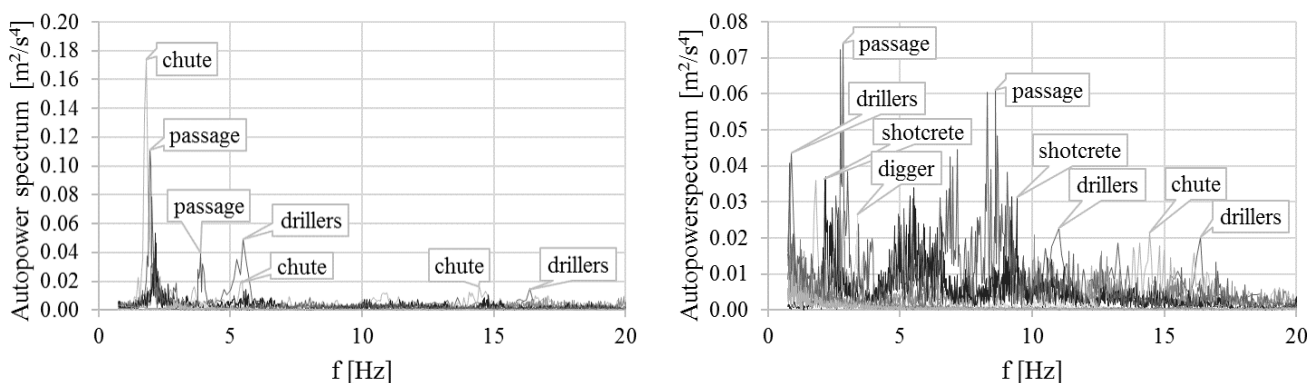

Fig. 1. Exemplary spectra of forced vibrations of scaffoldings in two horizontal directions: X – along the scaffolding façade (left), Y – perpendicular to the façade (right)

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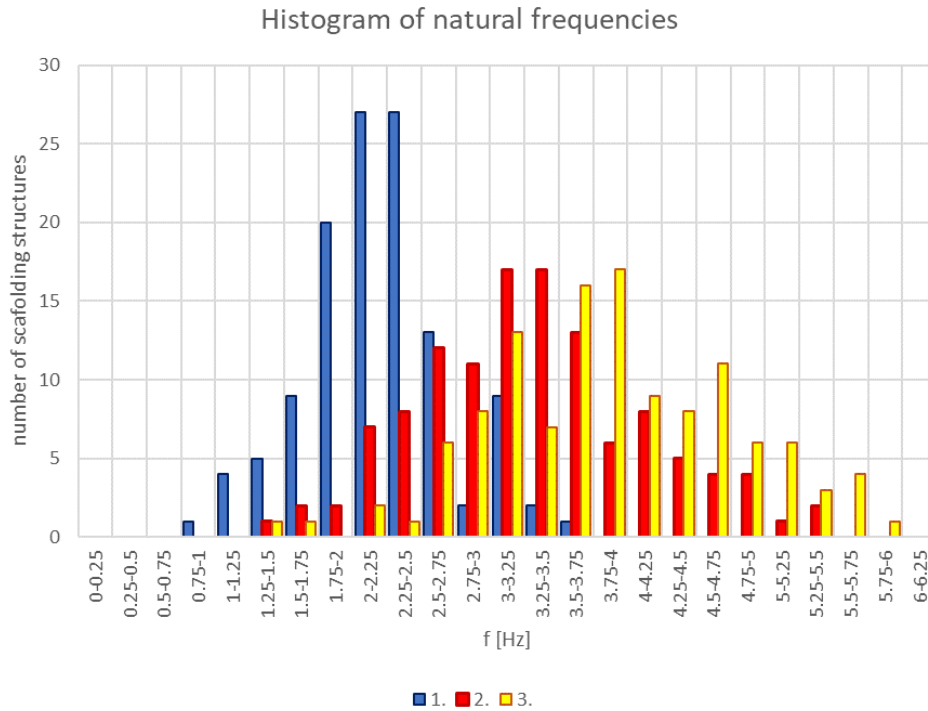
Histogram of natural frequencies

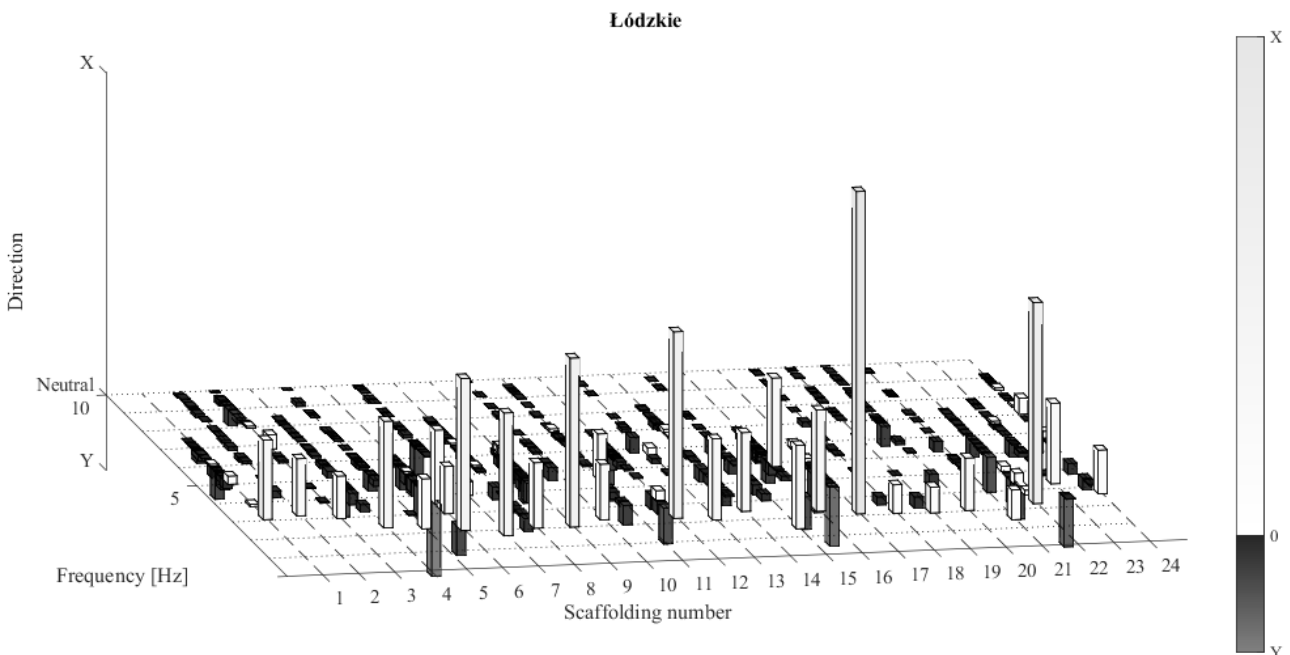**Fig. 2.** Histogram of first 3 natural frequencies for 120 structures

Fig. 3. Spectra of the natural frequencies for 24 analyzed scaffoldings in Łódzkie voivodship showing the prevailing direction of vibrations

5. NUMERICAL ANALYSIS

An exemplary scaffolding structure of medium size was subjected to numerical analysis. The dimensions of the structure are 25.73 m (length) and 24.15 m (height).

The numerical FEM model consisting of frame and shell elements was built with the use of Autodesk Simulation Multiphysics 2013. The model of the structure was verified based on the measurements made in situ. The process of model verification is described in detail by Cyniak *et al.* [10] and Jamińska-Gadomska *et al.* [11].

There were 121 points selected on the façade of the scaffolding in the connection of the outer standard pipe and the lower transverse beam (Fig. 4). These locations were used as points of force application and the results readout points.
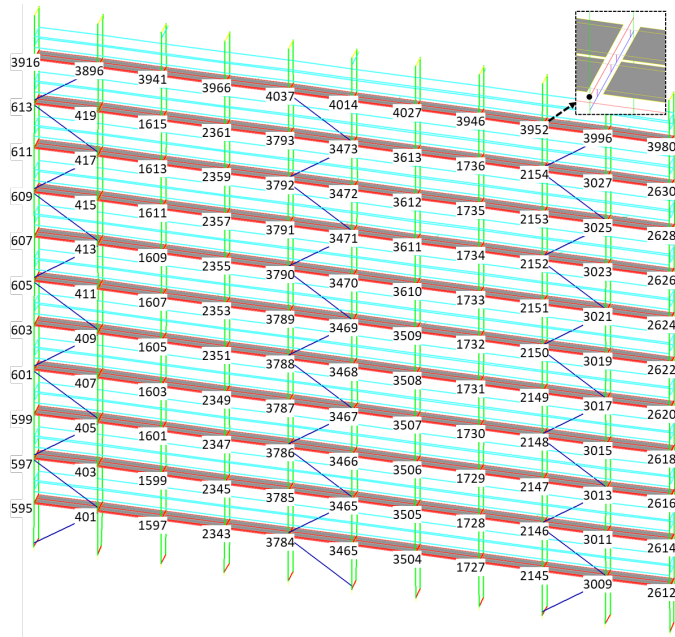
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Fig. 4. Scaffolding with numbered selected nodes and detailed location of these nodes (upper right corner)

6. RESULTS

The first part of the dynamic analysis consists of the modal analysis, i.e., the calculation of the natural frequencies and mode shapes for the scaffolding structure. In the next step, a series of full dynamic analyses with harmonic excitation force were carried out. A single excitation force was applied at a selected point on the scaffolding façade in each analysis.

6.1. Natural vibrations

Fifty natural frequencies and respective mode shapes were obtained for the analyzed structure. The first 10 natural frequencies are presented in Table 1, and 8 first exemplary mode shapes are presented in Fig. 5.

Table 1
Natural frequencies

Freq. 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
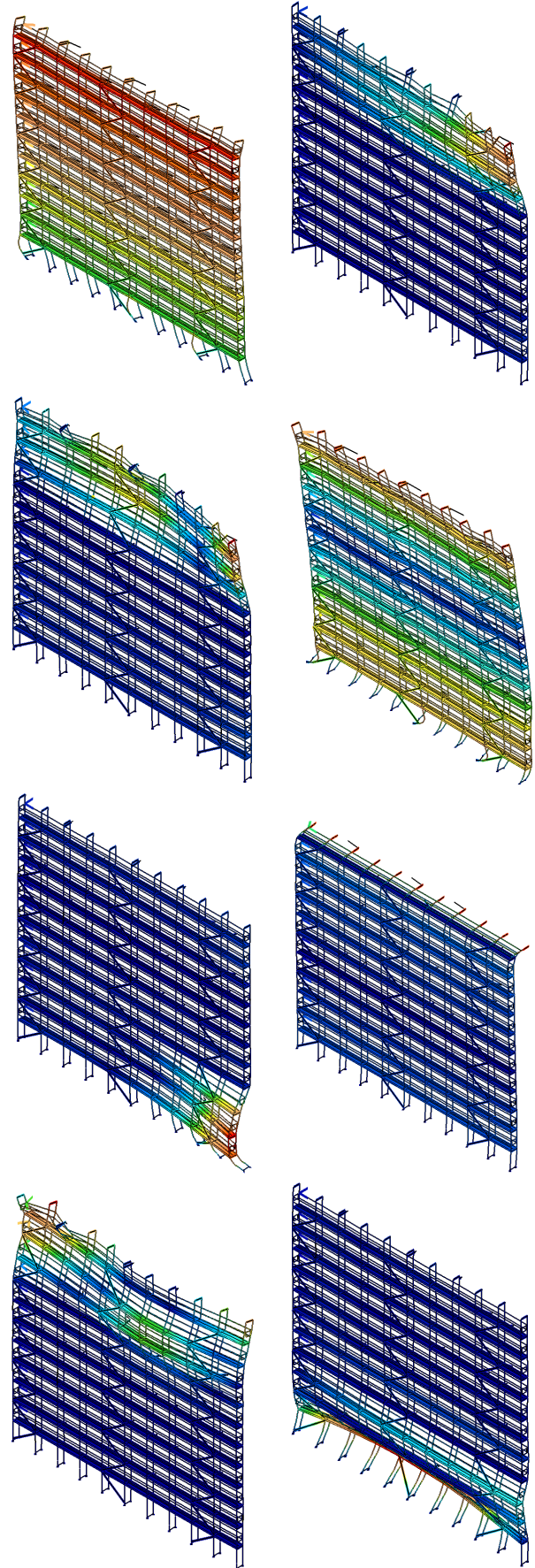
Fig. 5. Exemplary first 8 natural mode shapes

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A very compact frequency spectrum was observed for such a complex structure as the analyzed façade scaffolding. There are many natural frequencies observed in the range of excitation frequencies which can be typically found at the construction site. Out of the 50 calculated frequencies almost all fit below the planned limit frequency for this analysis (12 Hz) and the highest frequency just slightly exceeds this limit.

6.2. Forced vibrations

The dynamic analysis (forced vibrations) was carried out with the use of the direct integration method. A series of such dynamic calculations for the scaffolding model was performed with excitation in the form of single harmonic force of various frequencies ranging from 1 Hz to 12 Hz with the step of 1 Hz to reproduce the possible sources of vibrations present at the scaffolding. The force was successively applied in one of the several points out of the 121 selected points on the scaffolding façade with various directions: horizontal – (X) along the façade and (Y) perpendicular to the façade, vertical (Z).

The analysis time was set to 10 seconds with the excitation force active in the first 5 seconds, while the second half of the total analysis time was used for the observation of fading free vibrations.

The following parameters were used in each dynamic analysis:

- Time step length: 0.01 s.
- Total number of time steps: 1000.
- Harmonic force excitation time steps number: 500.
- Force amplitude: 1 kN.
- Logarithmic decrement of damping: 0.06.

The readout of the results was made in the selected 121 points on the scaffolding façade as time series of vibration displacement and respective graphs. Figure 6 presents exemplary graphs with the obtained series of horizontal displacements along the façade (X) in selected three points (1615, 1609 and 2612). The vibrations presented in these graphs were generated by the horizontal harmonic force with the same direction as the presented displacement component (X) located in node 1615 and the excitation frequency here is 3 Hz. There are given additional annotations in the graphs with the information on the readout node location in relation to the excitation point. The annotation in the first line gives the relative location in the grid of selected points in horizontal (*col*) and vertical (*row*) directions. There is also given the distance in three directions, i.e., two horizontal ones: along the façade (X) and perpendicular to the facade (Y), and vertical (Z). The total distance D from the excitation point given in meters is shown in the second line of the annotation, as well. Various levels of excited amplitudes may be observed in these graphs depending on the distance from the excitation point.

7. ANALYSIS OF THE RESULTS

The maximum values of excited vibrations for each case of dynamic excitation were collected in tables and put in graphs. Readings of maximum values were made for each of the 121 control points (see Fig. 4). Each graph presents amplitudes of displacements in forced vibrations shown on the façade
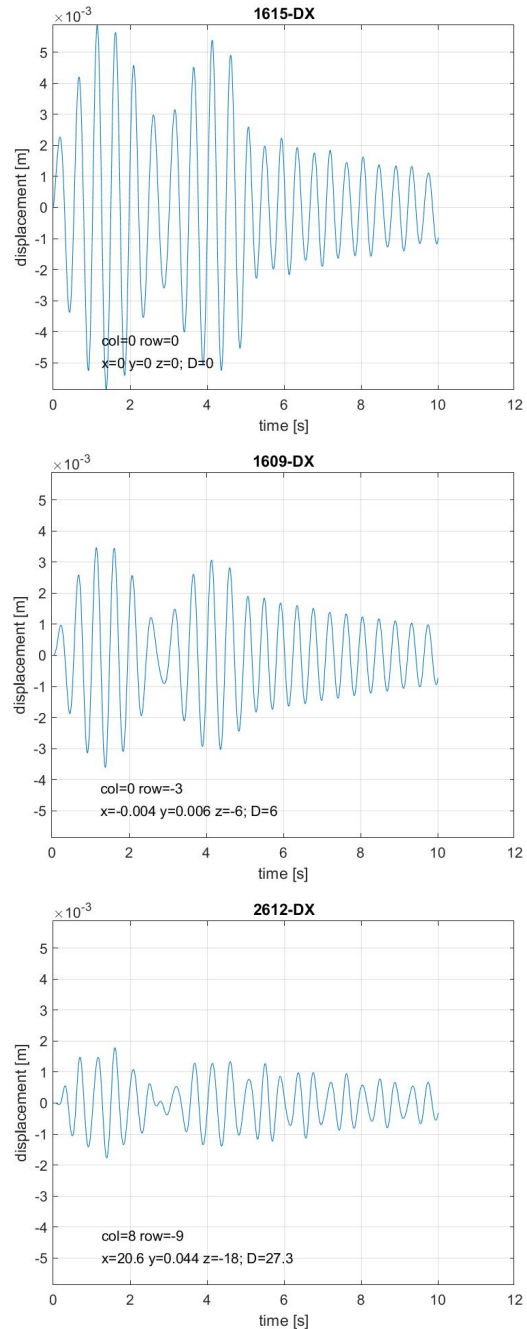

Fig. 6. Displacement series in three exemplary points of the structure

(plane XZ) with the third axis representing the values of vibration displacement amplitudes. Values given along the Y axis may show components of displacements in any of three directions. The displacements component of vibrations shown in the graph is marked in the heading along with the loaded node number and excitation frequency and the force direction. For example, the heading "1615-DX; $fy = 10$ Hz" stands for vibrations excited in the point 1615 in the direction horizontally perpendicular to the façade ("fy") with frequency 10 Hz and the component of displacement shown in the graph is horizontal along the façade ("DX"). The axis associated with the excitation was additionally marked with bold red in graphs. The point where

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the excitation force is applied was also marked with a red dot at the plane of the graph (scaffolding façade). The values at the X axis represent the numbers referring to the columns of the scaffolding scheme (frames) and at the Z axis – to the rows (deck levels).

7.1. Excitation in the horizontal direction along the façade (X)

When vibrations were excited in the horizontal direction along the façade (X), the components of vibrations excited in the same direction resulted in the biggest amplitudes. Exemplary results are shown below (Fig. 7). For the excitation frequency equal to 2 Hz, the whole scaffolding obtained significant values of amplitudes of vibrations in the X direction with values rising with the scaffolding height. For the frequency of 3 Hz, larger amplitudes were observed at the bottom of the scaffolding. These amplitudes in some cases were even larger than the ones observed at the point of excitation.

Vibration amplitudes in horizontal direction perpendicular to the façade (Y) are significantly smaller with the same excitation force (Fig. 8). Exemplary graph for excitation frequency 3 Hz shows maximum amplitudes of vibration displacement in "weak" parts of the scaffolding, i.e., where there are large ranges of poorly anchored structure. For higher frequencies a similar pattern is observed; however, we can clearly recognize the deck levels with a different number of anchors.
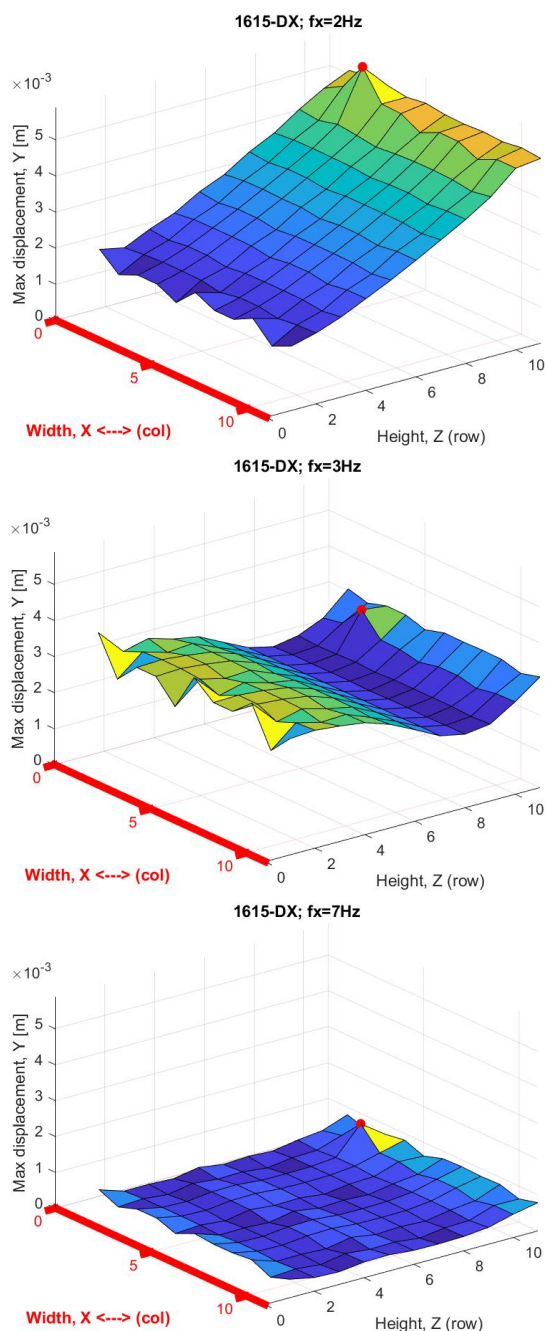

Fig. 7. Amplitudes of vibration displacements in X direction, excitation force in X direction
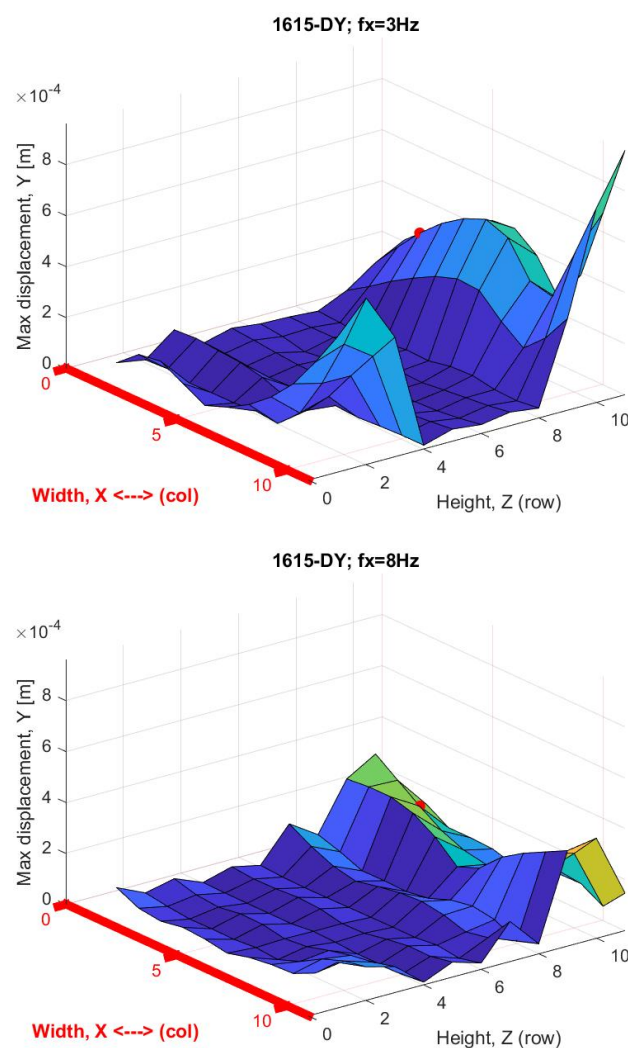

Fig. 8. Amplitudes of vibration displacements in Y direction, excitation force in X direction

Vertical components of displacement (Z) in vibrations generated with a horizontal force along the façade shows quite a different pattern, but repetition for all frequencies (Fig. 9). The highest values of amplitudes can be found for excitation frequency 3 Hz.
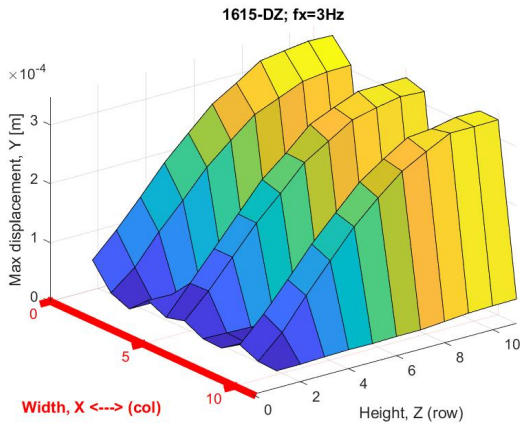
Fig. 9. Amplitudes of vibration displacements in the Z direction, excitation force in the X direction

7.2. Excitation in the horizontal direction perpendicular to the façade (Y)

Excitation force with a direction perpendicular to the façade (Y) produces small amplitudes of vibration displacements in the direction along the façade (X) (Fig. 10). The highest values are obtained for frequencies 3–5 Hz and the areas of scaffolding affected by vibrations are at the top (decks level of the excitation point) and at the bottom of the structure.

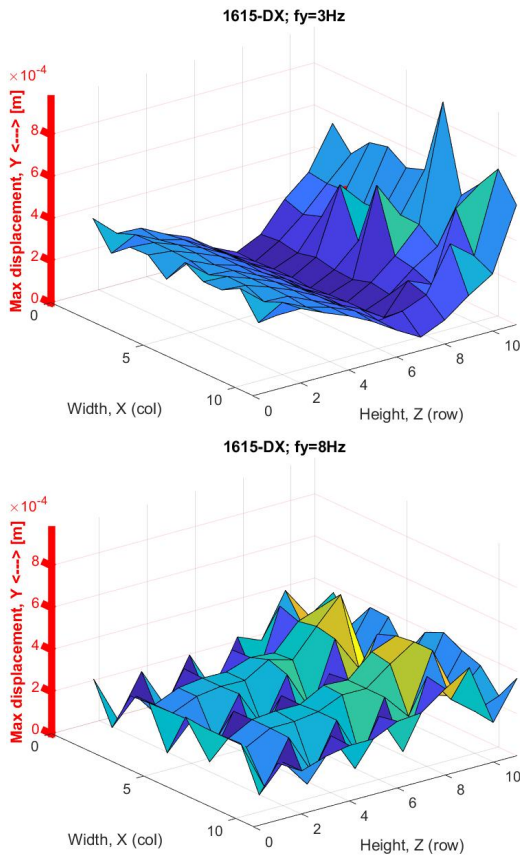Frequencies of 6 to 8 Hz result in significant amplitudes at the whole plane of the scaffolding. For frequencies higher than 9 Hz, the amplitudes are very small at the whole of the scaffolding.

The highest amplitudes of vibration displacements are observed in the direction perpendicular to the façade (Y) with the excitation force in the same direction (Fig. 11). For all examined frequencies, the affected area is limited to the level containing the excitation point and the extreme values are observed for excitation frequencies of 3 Hz and 5 Hz.
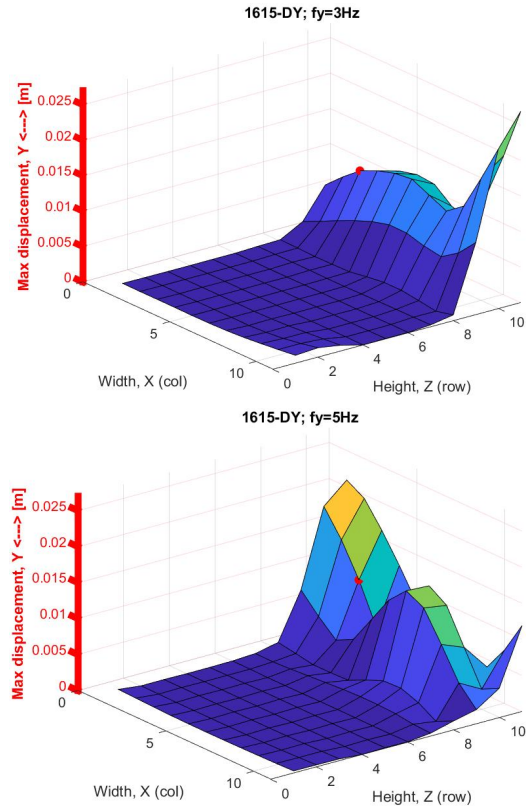

Fig. 11. Amplitudes of vibration displacements in the Y direction, excitation force in the Y direction

The patterns in the graphs for vertical components of vibrations are similar to the ones obtained for X direction of excitation (Fig. 12). The extreme values are obtained for frequencies

Fig. 10. Amplitudes of vibration displacements in the X direction, excitation force in the Y direction
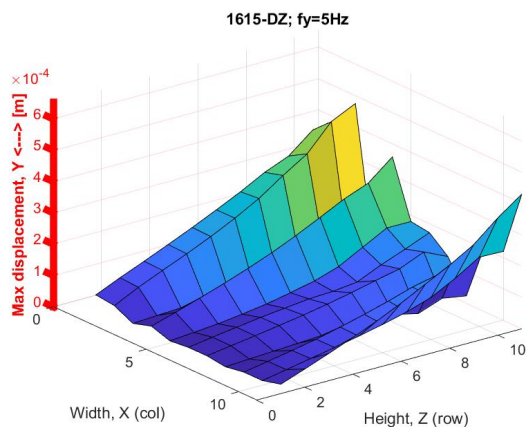

Fig. 12. Amplitudes of vibration displacements in the Z direction, excitation force in the Y direction

of 3 Hz and 5 Hz, and they are much higher than for other frequencies.

7.3. Excitation in the vertical direction (Z)

Vibrations generated in a horizontal direction along the façade (X) and produced with the vertical excitation force (Z) are very small (Fig. 13). Due to a poor anchorage at the bottom in the column below the excitation point, a weakness of the structure may be observed.
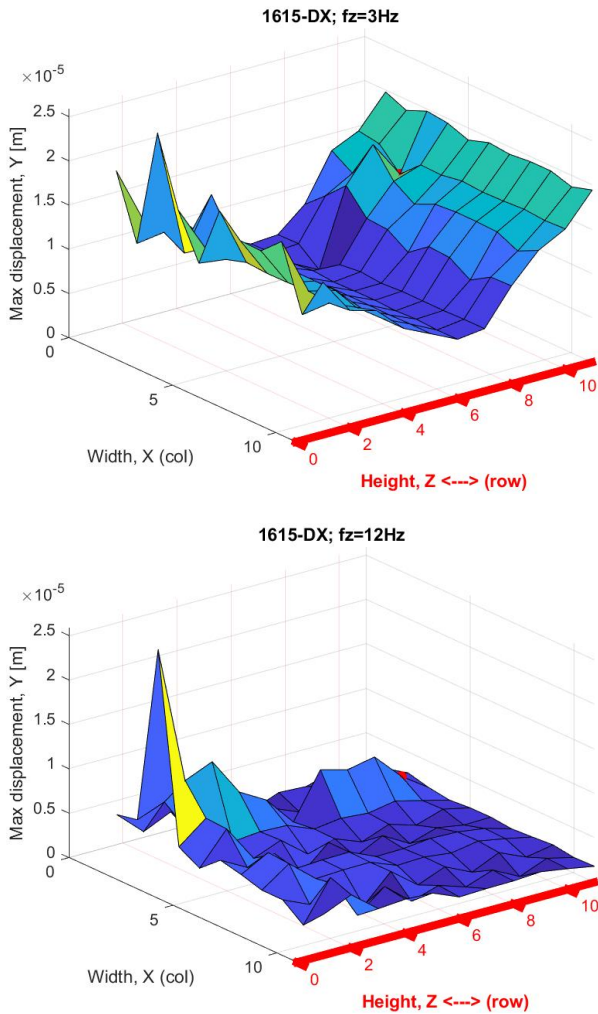

Fig. 13. Amplitudes of vibration displacements in the X direction, excitation force in the Z direction

Though the excitation point is located near the top of the scaffolding, the biggest amplitudes of vibrations generated in a horizontal direction perpendicular to the façade (Y) are also observed at the bottom for vertical excitation force (Z) (Fig. 14). The maxima occur for frequencies 5–6 Hz.

For the whole range of examined frequencies, the pattern in the graphs for the vertical component of vibration displacements excited with vertical force is almost identical and the vibrations are limited to the column below the excitation point (Fig. 15). The values for all frequencies are very similar with a very small increase for the highest analyzed frequencies.
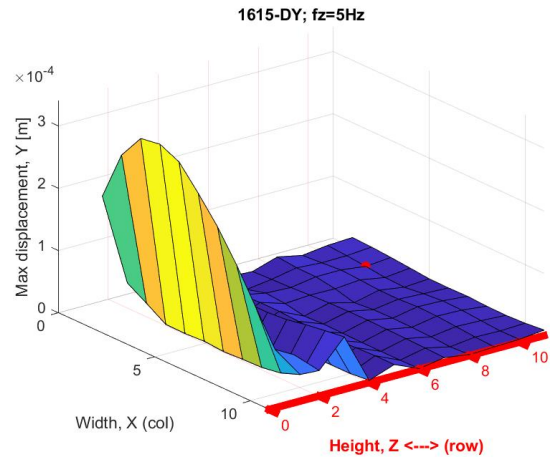

Fig. 14. Amplitudes of vibration displacements in the Y direction, excitation force in the Z direction
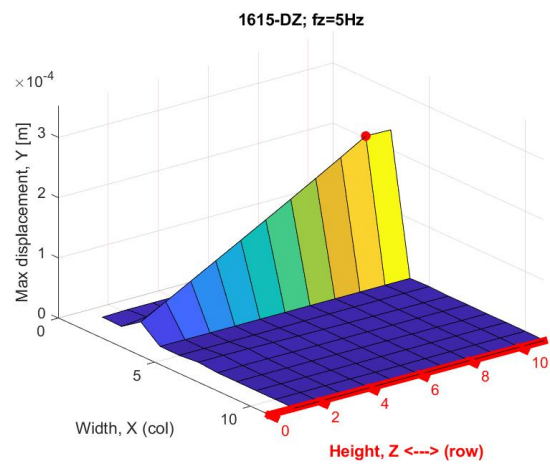

Fig. 15. Amplitudes of vibration displacements in the Z direction, excitation force in the Z direction

8. CONCLUSIONS

The biggest amplitudes of vibrations displacements occurred in a horizontal direction perpendicular to the façade when the sinusoidal force in the same direction was applied. However, these vibrations are limited to the same deck level as for the excitation force location. The most propagated vibrations are the ones produced with the horizontal force along the façade and the component of displacements in the same direction is also visible at the large areas of the scaffolding façade. When the excitation frequency is close to the natural frequency of the structure, an increase in amplitudes of vibration displacements and internal forces of the whole structure may be observed. The vibrations produced with such excitation frequencies usually last longer and are not fading instantly after the source of excitation becomes inactive. For the frequencies of 10 Hz and above, even if close to one of the natural frequencies, it may be stated that they produce disturbances of only local character. This is due to the much smaller spatial range of vibrations for the higher natural mode shapes associated with higher natural frequencies. Of course, such local vibrations still can cause discomfort for scaffolding users near the excitation force.

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The quality of the anchorage is a very important factor affecting scaffolding susceptibility to vibrations. A well-anchored structure, i.e., with a sufficient number of anchors and the proper geometry of the anchorage scheme, cannot be easily forced to vibrate and the spatial range of such vibrations is usually limited. The relative location of the excitation and the anchors is also important. If the source of vibrations is located at the anchored point of the façade, the vibrations do not propagate to the whole structure or even they cannot be excited. In the case of poor-quality anchorage, the resulting vibrations may be observed in improperly tied points distant from the excitation. Such vibrations were observed mainly for both horizontal directions of excitation and produced vibration displacement. The directions of both the source and the result may sometimes interchange.

Further calculations are planned in the future for scaffoldings of various sizes and sources of excitation and with various character and amplitudes. The level of the applied damping parameters can also be the subject of a more thorough analysis. The typical range of logarithmic decrement of damping values for the analyzed façade scaffoldings is 0.05–0.06, but for some structures, it can be as low as 0.03 (see [1]).

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