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Research paper

Influence of anchoring and bracing system on dynamic characteristics of façade scaffolding

Jarosław Bęc[1]

Abstract: The basic dynamic characteristics of façade scaffolding are natural frequencies of vibrations and corresponding mode shapes. These properties affect the scaffolding safety, as well as comfort and safety of its users. Many of the dynamic actions present at scaffolding are in the low frequency range, i.e. below 10–15 Hz. The first natural frequency of a structure is usually in the range of 0.7 to 4 Hz which corresponds to resonant frequencies of human body and it means that vibrations induced at scaffolding may strongly affect the human comfort. The easiest way of increasing the rigidity of the structure is by ensuring correct boundary conditions (support, anchorage) and bracing of the structure. The numerical analysis was performed for the real scaffolding structure of medium size. The analysis consisted of natural frequencies calculation for the original structure and for models with modified bracing and anchoring systems. The bracing modifications were introduced by reducing or increasing the number of vertical bracing shafts. The anchor system was modified by reduction of the 6 anchors in the top right corner of the scaffolding in three stages or by evenly removing nearly 1/3 of the total number of anchors. The modifications of bracing and anchor systems resulted in changing the natural frequencies. The increase of natural frequencies due to higher number of anchors and more bracing is not even for all mode shapes. Bracing is more effective in acting against longitudinal vibrations, while anchoring against vibrations perpendicular to the façade.

Keywords: façade scaffolding, dynamic characteristics, naturalfrequencies and mode shapes, anchoring and bracing system

[1]PhD., Eng., Lublin University of Technology, Faculty of Civil Engineering and Architecture, Nadbystrzycka 40 St, 20-618 Lublin, Poland, e-mail: j.bec@pollub.pl, ORCID: 0000-0002-5853-3710

1. Introduction

Façade scaffolding is an equipment most often used as temporary utility structures supporting construction and finishing works. A scaffolding structure should be checked by providing appropriate static and buckling analyses confirming that the safety of the structure is ensured. It is also necessary to provide appropriate working conditions for scaffolding users by reducing the levels of vibrations occurring during a scaffolding structure operation. An extremely important aspect that should be taken into account when designing scaffolding is the safety of the structure when it is exposed to dynamic actions. When such actions are considered it essential to avoid resonance, i.e. we should make sure that the excitation source frequencies are not in the ranges of natural frequencies, especially a few first ones. Many excitation sources generate vibrations with low frequencies, e.g. workers walking on a scaffolding deck. The easiest solution of avoiding the resonance is shifting first natural frequencies of the structure to the higher values. This can be achieved among other methods by increasing the structural rigidity. The designer of a single scaffolding structure choses the given scaffolding system and has no further influence on the stiffness of catalogue elements received from the producer of scaffolding system. However, it is possible to increase the rigidity of the scaffolding structure through a properly designed anchoring system and by the correct use of bracing, thus ensuring the dynamic safety of scaffolding structure and increasing vibrational comfort of its users. Influence of the anchoring and bracing systems on the dynamic characteristics of façade frame scaffolding is presented in this paper.

2. Vibrational characteristics of façade scaffolding

The basic dynamic characteristics of façade scaffoldings are described by the frequency of natural vibrations (circular frequency, vibration period) and the corresponding mode shapes. These values significantly affect the safety of scaffolding structure and their users, as well as vibrational comfort of workers at the scaffolding.

According to Jia [1] the human body is most sensitive to vibrations along the height of the body in the range of 4–8 Hz, transversely 1–2 Hz. The author of that book also lists the resonance frequencies referring to the specific parts of human body:

– Head 25 Hz (axial vibration);
– Shoulder/arm 4–5 Hz;
– Forearm 16–30 Hz;
– Hand 50–200 Hz;
– Chest 50–100 Hz;
– Abdomen 4–8 Hz;
– Spinal column 10–12 Hz (axially);
– Legs 2–20 Hz (depending on the body position).

The list of the most typical vibration sources present at scaffolding may be found in papers [2, 3] and these are:

– Environmental influences (mostly wind);

– Vibrations transmitted by the ground from nearby machinery and traffic (paraseismic actions) and seismic action;
– Vibrations caused by machines active on the scaffolding or human operated equipment (vibrations transmitted by the human body);
– People moving on scaffolding (horizontally or vertically).

Many of these dynamic actions are in the low frequency range, below the 10–15 Hz limit.

Wind action in most cases is not producing extreme values of forces and vibration amplitudes in façade scaffoldings. It is neither directly affecting the human comfort since during strong winds works at scaffolding are usually suspended. Nevertheless wind action should be carefully taken into account during the design of scaffolding structure [4–10], especially keeping in mind that these forces are highly increased in case of scaffolding structures with cladding or protective nets [11]. Seismic action is of great importance in design of scaffolding in regions with high seismic activity, while paraseismic action produced by nearby traffic [2,3] is usually of less importance. Vibrations caused by devices operating at the scaffolding or attached to the structure may be strongly affecting the scaffolding users comfort and safety, as well as the safety of the structure itself. The most important sources of vibrations are identified in the papers [2, 3] as chutes used for vertical transport of debris and shotcretes pumping grout. Strong vibrations are caused during working at scaffolding and by horizontal and vertical communication of scaffolding users. These vibrations are strongly affecting the workers' comfort and may endanger their safety [12, 13].

The total number of 120 real façade scaffolding structures in Poland have been analyzed during the scientific project considering general safety of façade scaffolding structures [14]. Based on the dynamic measurements and numerical analysis the histograms for the 3 first natural frequencies have been built and are shown in Fig. 1. The first natural frequency for this type of structure is usually in the range of 0.7 to 4 Hz [3]. As it can be seen, the natural frequencies correspond to many resonant frequencies of human body and it means that vibrations induced at scaffolding may strongly affect human comfort. The first mode shape is usually associated with vibrations along the scaffolding façade. The second mode shape is in most cases perpendicular to the scaffolding plane in horizontal direction. It has been observed during the research project by dynamic measurements of the façade scaffolding structures that during the standard operational life of such structures the values of the first natural frequencies may decrease even by 0.5 Hz due to anchor loosening generated by vibrations [3, 15]. This is the result of anchorage loosening due to detaching forces acting at the points of anchoring. It is necessary to control the quality of the anchorage during long-term use of the scaffolding, as it is strongly recommended by the authors of the paper [16]. It may still be safe enough to work on such scaffolding with the loosened anchors, but the decrease of the natural frequency may affect the comfort of its users.

Natural frequency values depend on the size of the scaffolding, its weight and additional weight accumulated on the scaffolding (building materials, protective nets and claddings, scaffolding users), as well as on the rigidity of the structure, which is determined by the stiffness of the scaffolding system elements, the way they are connected and by boundary conditions.

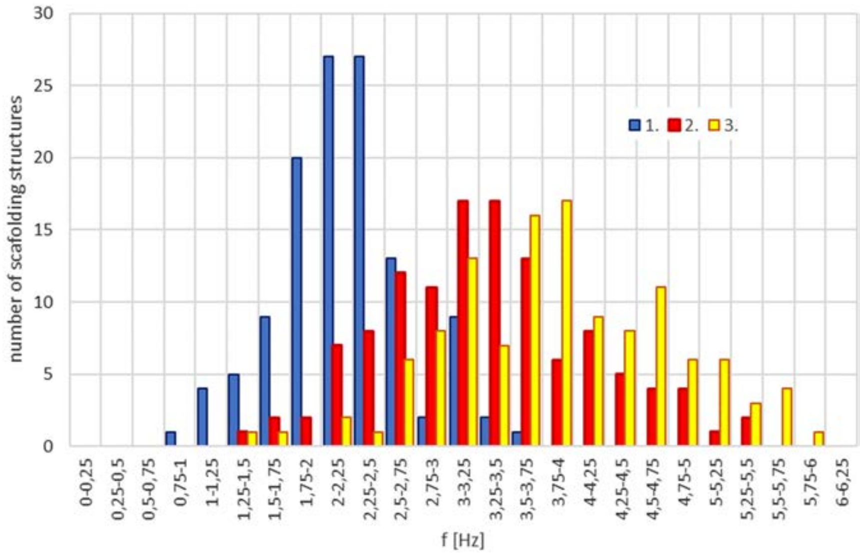

Fig. 1. Histogram of first 3 natural frequencies for 120 façade scaffolding structures

There may be distinguished the following ways to reduce displacement amplitudes of scaffolding vibrations:

– Reducing the amplitude of vibrations transmitted to the scaffolding or changing the excitation frequency;
– Damping increment;
– Modification of the natural frequencies and mode shapes of vibrations:
  • Reduction of structural weight and additional load;
  • Increasing scaffolding rigidity.

The scaffolding designer has few possibilities to influence the sources of vibrations at scaffolding. The works have to be done, there is not much possibility of changing the surrounding at the construction site. Damping levels can be increased by using additional vibration dampers. This equipment is used for many advanced and high-rise engineering structures, but it is not expected to be applied in case of temporary structures like scaffolding. The easiest ways of reduction excessive vibrations are given in the last point of the list. Though reduction of the structural weight of the scaffolding structure is rather out of a single scaffolding structure designer's competence since it is decided by the selection of the scaffolding system, there is still some designer's or construction site manager's influence on the additional load. It has been shown in the paper [15] that additional permissible dead load present at the scaffolding may make even 75% of the structural weight. This would clearly lead to decrement of the values of natural frequencies moving them to the ranges more influencing scaffolding users. The stiffness of the structural elements depends on their cross-sections which is independent of the scaffolding designer's decisions. The easiest way of increasing the rigidity of the structure is by ensuring the correct boundary conditions (support [17], anchorage) and the bracing of the structure [16].

3. Standards demands and other recommendations

The scaffolding structure must be firm and its rigidity and stability should be checked by static and buckling analyses, especially for non-typical scaffolding structures [16, 18]. In case of typical façade scaffolding the system producers analyze safety of such structures and give recommendations published in assembly manuals [19] to promote construction of correct structures considering structural rigidity and safety. These instructions should be based on the test demands given in standards [20].

There are no direct requirements considering anchoring and bracing systems of façade scaffolding in the respective European standard [21]. More tips on how the structure should be anchored and braced are given in the older Polish standard from 1996 [22]. According to this publication the outer standards of façade scaffolding structures should be connected with bracing elements at the whole height of the structure. Vertical bracing should be distributed symmetrically and the number of the braced fields should not be less than 2 per each scaffolding level. The distance between braced vertical shafts must not exceed 10 m. The scaffoldings with the height greater than 4 times the smaller dimension of its base should be anchored independently of the results of static analysis. A scaffolding should be anchored to the adjacent building's walls to ensure its stability and rigidity and to enable bearing external forces acting on the scaffolding such as wind action, eccentric static load, dynamic action generated by workers, forces generated by uneven ground subsidence. The number of anchors per section of structure should be obtained based on the static analysis taking into account the condition that the detaching force in any anchor should not exceed 250 daN (2.5 kN). Anchors should be distributed symmetrically across all of the scaffolding surface. The distances between anchor points in horizontal direction should not exceed 4–5 m, while in the vertical direction it is 4–6 m. One anchor point should be designed per each 16–30 m^2 of the scaffolding façade area.

The authors of paper [23] following the study of 105 scaffolding structures recommend that at least one of five of the scaffold modules at the same scaffolding level should have diagonal bracing. As for anchoring the recommendation is given here that an anchor is needed for every 24 m^2 of the scaffolding area or even for 12 m^2 when there is any cladding or netting mounted at the scaffolding façade.

4. Methods of analysis and analysed cases

The analysis was performed for the real scaffolding structure of medium size with the dimensions: 25.73 m (length) and 24.15 m (height). The numerical FEM model consisting of frame and shell elements has been built with use Autodesk Simulation Multiphysics 2013. The model was verified based on the dynamic measurements of the structure and the model parameters were adjusted, by adding e.g. spring supports, to reflect its dynamic characteristics. The process of the model verification is described in detail in papers [24,25]. The analysis presented in this paper consists of calculation of the natural frequencies for the original structure and for the models with modified bracing and anchoring systems.

Static and buckling analyses of the scaffolding structure are not presented here in this paper. The focus is set only on dynamic properties of scaffolding on the users' vibrational comfort. However, it should be noticed that at least some of the subsequently presented cases, though similar to the ones which are met in reality, can be leading to structure failure due to standard loads. A structure without proper anchor or bracing systems can be faced with extreme stresses generated by e.g. wind action when large area of the scaffolding is left without anchoring points or experience buckling, even if the allowable load on the scaffolding decks is not exceeded.

4.1. Bracing system

The original structure contained three vertical shafts containing bracing. The scheme showing the designed bracing system is presented in Fig. 2 with each anchor point shown as a red circle on the scaffolding façade. Circles at the bottom of the structure mark the ground supports and springs at the left are modelling the adjacent scaffolding structure.

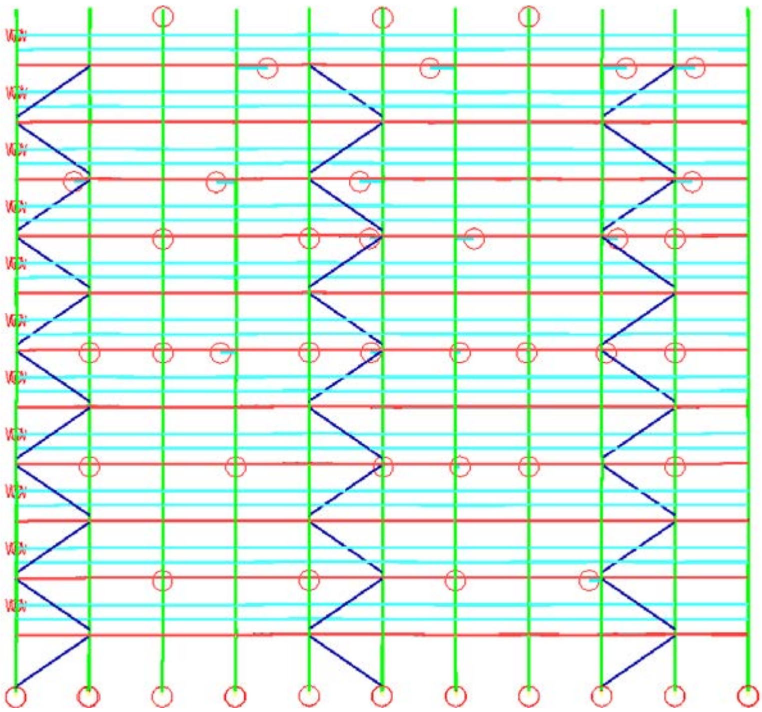

Fig. 2. Original bracing and anchor system

The bracing system has been modified by reducing the number of vertical bracing shafts, i.e. eliminating the middle one (2 bracing shafts). The second modification was by introduction of two additional bracing shafts to the original structure to obtain the over stiffened structure (5 bracing shafts). The modified bracing systems are presented in Fig. 3.

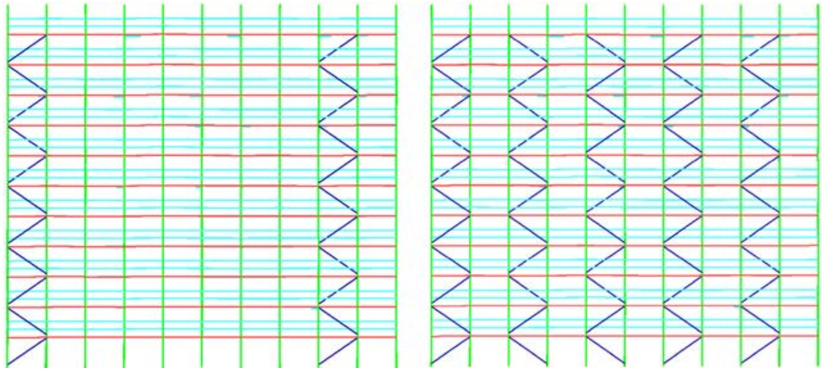

Fig. 3. Modified bracing systems

4.2. Anchor system

The original anchor system was designed according to the demands and following the available locations of the adjacent building that the scaffolding structure was attached to.

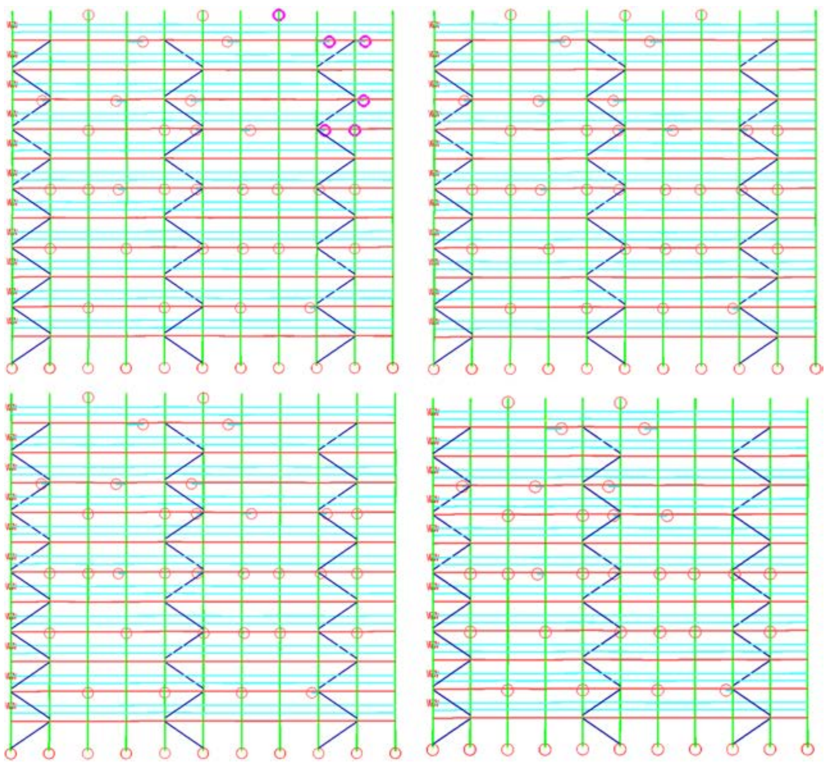

Fig. 4. Modified anchor systems: original anchor system with highlighted anchors to be dropped out (top-left); stage I (top-right), stage II (bottom-left) and stage III (bottom-right)

In the first part of the analysis the anchor system was modified by reduction of the 6 anchors in the top right corner of the scaffolding in three stages. Initially, three anchors were removed, then one more anchor was dropped-out (stage II), and at the stage III two more anchor points were removed. The modified layouts of anchor systems are presented in Fig. 5. In the top-left corner of this figure there is presented the original anchor system with the highlighted points of anchoring to be removed in the following stages. Then the three stages of removing anchor points are shown.

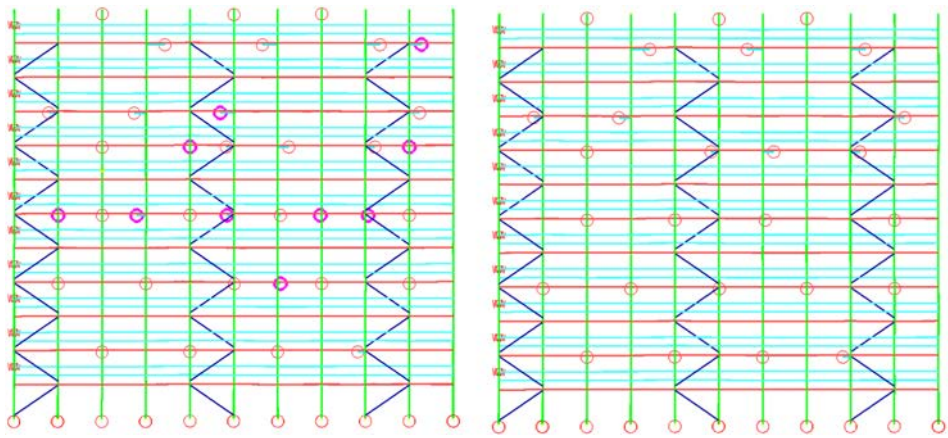

Fig. 5. Evenly spread modification of the anchor system: original anchor system with highlighted anchors to be removed (left); modified anchor system (right)

The other modification of the original system was introduced by removing 10 of 36 anchors evenly across the scaffolding façade. In Fig. 5 there is presented the evenly modified anchor system.

5. Results

The results of the analyzes are natural frequencies and mode shapes of the structures. The original values of quantities describing natural vibrations are presented in Table 1. Mode shapes of the original structure in 3D view are presented in Fig. 6.

The natural frequencies after introduction of modifications, both in bracing and anchor systems have been compared in Table 2. Ten values of natural frequencies in each analytical cases have been presented in columns. In the "Original" column there are put the values of the natural frequencies for the original structure from Table 1. The next two columns show values of the natural frequencies of the structure with the modified bracing system. Four last columns are presenting the frequencies for the scaffolding structure with modified anchor system. Columns "Stage I-III" show values for the structure with anchors removed in its upper-right corner. In the column "Evenly" there are given values for the structure with evenly removed 10 anchors out of the total number of 36.

Table 1. Natural vibrations parameters for the original scaffolding structure

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

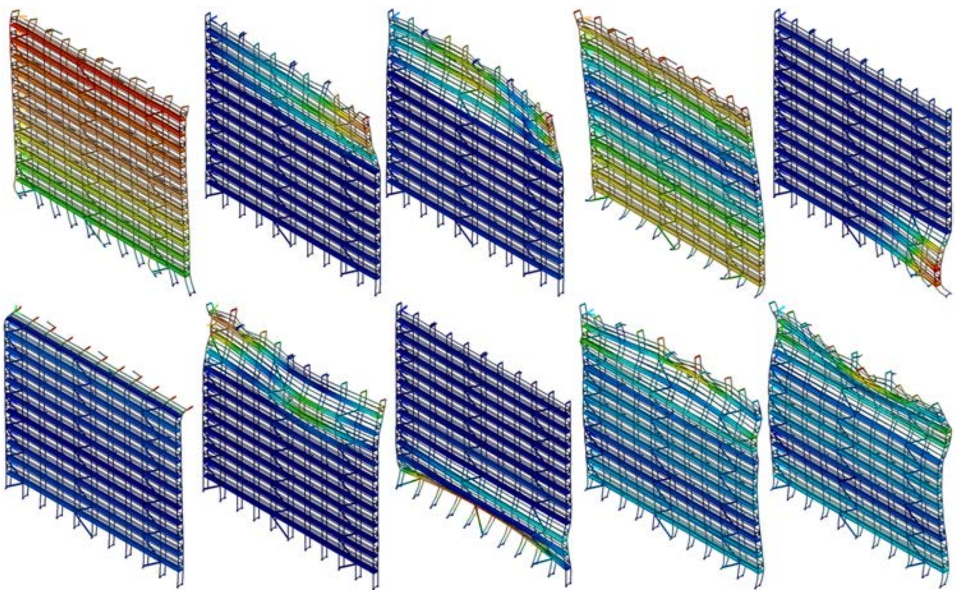

Fig. 6. Mode shapes of the original scaffolding structure (3D view)

As it can be observed, the modification of bracing and anchor systems results in changing the natural frequencies. Of course the general conclusion may be drawn at once, that more bracing and more anchors make the scaffolding structure stiffer and produces higher values of natural frequencies. However, it is not a simple shift of values. The introduced modification of anchor system as removing anchors in the upper-right corner in three stages results with basically lowering of the first natural frequency with each removed

Table 2. Natural frequencies comparison

No.	*f* [Hz]						
	Original	Modified bracing system		Modified anchor system			
		2 shafts	5 shafts	Stage I	Stage II	Stage III	Evenly
1	**2.36**	2.32	2.44	1.87	1.62	1.23	2.30
2	**2.92**	2.92	2.90	2.37	2.37	2.37	2.37
3	**3.28**	3.05	3.26	3.21	3.16	3.16	3.07
4	**3.35**	3.31	3.64	3.35	3.35	3.22	3.35
5	**3.65**	3.64	3.81	3.65	3.65	3.35	3.65
6	**4.55**	4.36	4.73	4.55	4.55	3.65	4.10
7	**5.07**	5.04	5.03	4.88	4.80	4.56	4.55
8	**5.48**	5.08	5.41	5.24	5.16	5.09	4.91
9	**5.65**	5.53	5.64	5.48	5.48	5.28	5.37
10	**5.69**	5.68	5.73	5.66	5.59	5.48	5.48

anchor. Higher natural frequency values are not changing significantly. This result is due to the large area of the scaffolding being unattached to the adjacent building. This situation should be obviously avoided to make the scaffolding structure safe and comfortable to use. In other cases of modification of anchor and bracing systems we can observe more or less even changes of natural frequencies values. Closer observation shows that bracing influences the mode shapes with displacements mostly along the façade of the scaffolding, while modification of anchors number affects rather those mode shapes in which displacements are in the direction vertical to the façade. This may generate interchanging of the natural frequencies numbers and modification of their order.

In Table 3 there is presented a comparison of mode shapes for model with different bracing systems. The first column shows the picture of the mode shape in frontal view for the original scaffolding structure with three vertical shafts of bracing. Only the last row shows mode shape for the modified bracing system with 2 shafts. For each of the first 9 natural frequencies of the original structure there have been identified respective similar mode shapes for modified models. In the subsequent three columns there are given values of the respective natural frequencies with the index showing the order of mode shape for the given bracing system. For two first mode shapes there is no variation in the order of mode shapes. The third mode shape of the original structure has been identified as the 4th for the scaffolding with one shaft removed. Similar differences can be observed for the next mode shapes. However for the 9th mode shape similar mode has been found as 7th in the 2 shaft model and yet 16th for the over stiffened 5 shaft model. There is no mode shape found which is similar to the 10th mode shape of the original structure among the 20 mode shapes calculated for each structure. This is why in the last row of the table there is shown 10th mode shape for the 2 shaft model and 9th one for the 5 shaft structure, which are similar and

Table 3. Identification of mode shapes in structures with various bracing systems

No.	2 shafts	Original (3 shafts)	5 shafts
1	f_1 = 2.32 Hz	$\boldsymbol{f_1}$ = **2.36** Hz	f_1 = 2.44 Hz
2	f_2 = 2.92 Hz	$\boldsymbol{f_2}$ = **2.92** Hz	f_2 = 2.90 Hz
3	f_4 = 3.31 Hz	$\boldsymbol{f_3}$ = **3.28** Hz	f_3 = 3.26 Hz
4	f_3 = 3.05 Hz	$\boldsymbol{f_4}$ = **3.35** Hz	f_5 = 3.81 Hz
5	f_5 = 3.64 Hz	$\boldsymbol{f_5}$ = **3.65** Hz	f_4 = 3.64 Hz
6	f_6 = 4.36 Hz	$\boldsymbol{f_6}$ = **4.55** Hz	f_6 = 4.73 Hz
7	f_8 = 5.08 Hz	$\boldsymbol{f_7}$ = **5.07** Hz	f_7 = 5.03 Hz
8	f_9 = 5.53 Hz	$\boldsymbol{f_8}$ = **5.48** Hz	f_8 = 5.41 Hz
9	f_7 = 5.04 Hz	$\boldsymbol{f_9}$ = **5.65** Hz	f_{16} = 6.45 Hz
10	f_{10} = 5.68 Hz	**–**	f_9 = 5.64 Hz

the "original" column is left empty. Similar observations can be made when comparing mode shapes of the original model and models with modified anchor systems.

6. Conclusions

It has been shown in the paper that the correct bracing and anchor systems directly influence a façade scaffolding stiffness and ensures the higher values of natural frequencies. This gives scaffolding structures less prone to dynamic actions which may occur at the construction site near scaffolding or at the scaffolding structure itself. This way a safer structure is obtained and the users of the scaffolding can work in more comfortable environment.

It has been observed that the increase of natural frequencies due to larger number of bracing elements or anchoring points is not even for all mode shapes. Bracing is more effective in working against longitudinal vibrations, while anchoring – against vibrations perpendicular to the façade. Leaving a large part of scaffolding unanchored may result with very significant drop in the value of the first natural frequency which may strongly affect the comfort of the scaffolding users or even lead to endangering the structure and workers safety. Though the anchoring system must be adjusted to the structure of the adjacent building that it is anchored to, large areas of the scaffolding must not be left without anchoring points. Such a recommendation may also be found in standards, as well as in the scaffolding systems manufacturers catalogues.

The behavior of a structure under dynamic action is also highly dependent on the sources of vibration. If a designer of a single scaffolding structure can forecast the dynamic actions that could occur at the scaffolding, it would be reasonable to adjust the bracing and the anchor systems to counteract these expected sources of the vibrations. It should be made in such a way that there is produced the natural frequencies shift to the higher values range. A designer can also influence mode shapes of the scaffolding structure by keeping the locations of anchors evenly spread across the façade. It is also possible to locate anchors in the predicted locations of sources of a dynamic action. If there is an expected location of the equipment attachment point to the scaffolding façade, e.g. of a lift or a shotcrete, then it would be a good idea to anchor this point or even to consider putting some additional anchors along the scaffolding standard that shotcrete would be attached to. A source of vibrations acting at the point of structure which is deprived of the movement will not propagate to the rest of the scaffolding.

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Wpływ układu zakotwień i stężeń na charakterystyki dynamiczne rusztowań fasadowych

Słowa kluczowe: rusztowania fasadowe, charakterystyki dynamiczne, częstości i postacie drgań własnych, układ zakotwień i stężeń

Streszczenie:

Rusztowania fasadowe to tymczasowe konstrukcje użytkowe wspomagające prace budowlane. Istotne jest zapewnienie bezpieczeństwa konstrukcji i pracowników, a także komfortowych warunków pracy ich użytkownikom poprzez zmniejszenie poziomów drgań docierających do nich. Podstawowe charakterystyki dynamiczne rusztowań fasadowych to częstotliwości drgań własnych oraz odpowiadające im postacie drgań. Pierwsza częstość drgań własnych w przypadku konstrukcji tego typu zazwyczaj mieści się w zakresie od 0,7 do 4 Hz, a więc są to wielkości zgodne z częstościami generowanymi przez wiele urządzeń działających na rusztowaniu, a także są one zbliżone do częstości rezonansowych części ciała ludzkiego. Częstotliwość drgań własnych uzależniona jest od rozmiarów rusztowania, jego masy oraz masy dodatkowej zgromadzonej na rusztowaniu (materiały budowlane, siatki ochronne i plandeki, użytkownicy rusztowania), a także od sztywności konstrukcji. Projektant pojedynczego rusztowania nie ma wpływu na elementy katalogowe systemu rusztowaniowego. Możliwe jest jednak zwiększenie sztywności rusztowania poprzez odpowiednio zaprojektowany system kotwienia konstrukcji rusztowania i przez prawidłowe stosowanie stężeń. Wymagany układ stężeń oraz rozstawy zakotwień w typowych rusztowaniach fasadowych można znaleźć w przepisach normowych lub katalogach producentów systemów rusztowań.

Przeprowadzono obliczenia komputerowe przykładowego rusztowania fasadowego o średniej wielkości. Model metody elementów skończonych został stworzony w programie Autodesk Simu-

lation Multiphysics 2013. Oryginalny model zawierał stężenia i zakotwienia zaproponowane przez projektanta konstrukcji rusztowania na podstawie wymagań producenta systemu. W kolejnych wariantach modyfikacji ulegała liczba pionów ze stężeniami, tj. z oryginalnej liczby pionów stężeń (3) pozostawiono 2 (rusztowanie słabo stężone), a następnie liczbę pionów stężeń zwiększono do 5 (rusztowanie przesztywnione). Podobnie, analizie poddano wpływ liczby zakotwień. Założono, że fragment konstrukcji pozostaje niezakotwiony, co wprowadzono do modelu przez eliminację 6 kotew w trzech etapach. Ostatni wariant modyfikacji oryginalnego sytemu zakotwień to równomierne usunięcie 10 spośród 36 ogółem punktów zakotwień.

Wyniki obliczeń zostały zebrane w postaci pierwszych dziesięciu częstości drgań własnych. Analizowano także postacie drgań własnych, odpowiadające zbliżonym częstościom drgań.

Zwiększenie liczby stężonych pól i większa liczba zakotwień powoduje zwiększenie częstotliwości drgań własnych. Nie jest to jednakowa zmiana dla wszystkich częstości i postaci. Stężenia mają większy wpływ na postaci związane z drganiami poziomymi wzdłuż fasady, podczas gdy liczba zakotwień wpływa istotnie na wartości związane z postaciami z przemieszczeniami prostopadle do fasady. Pozostawienie dużego obszaru pozbawionego zakotwień powoduje znaczne zmniejszenie przede wszystkim pierwszej częstości drgań własnych. Taka sytuacja jest niedopuszczalna, a mimo to spotykana w przypadku rusztowań zlokalizowanych przy istniejących budynkach, gdzie z powodów technologicznych kotwienie części konstrukcji jest utrudnione i czasem przez projektantów zaniedbywane. Należy również mieć na uwadze, że niedostateczne kotwienie i stężenie rusztowań fasadowych ma wpływ nie tylko na ich charakterystyki dynamiczne, ale także na wytężenie elementów konstrukcji. Może to prowadzić do stanów awaryjnych, mimo nieprzekroczenia dopuszczalnych wielkości obciążeń.

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