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VIBRATIONAL CHARACTERISTICS OF FAÇADE FRAME SCAFFOLDINGS

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The paper presents analysis of the vibrational environment on scaffoldings. It is based on the results obtained in the project considering workers safety on scaffoldings. The total number of 120 façade scaffoldings was analysed over a period of two years. One of the issues considered in this project was the vibrations influence on scaffoldings and workers safety. The values of natural frequencies were obtained based on in-situ measurements of free vibrations. Analysis of the tests results made it possible to verify the elaborated numerical models. Values of natural frequencies and displacements in mode shaped from numerical modal analyses were compared with test results. Measurements of forced vibrations were also made with various sources of vibrations active at scaffoldings. The detailed numerical dynamic analysis was performed considering excitation forces variable in time. The obtained results were compared with allowable values according to the appropriate Polish standards. Most influential sources of vibrations for human comfort were indicated in the conclusions.

Keywords: scaffoldings, vibrations, comfort, in-situ measurements, numerical analysis

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1. INTRODUCTION

Scaffoldings are temporary structures usually built-up near buildings during an erection stage and for finishing works. Due to the low natural frequencies of scaffoldings, they are susceptible to excitations caused by users' motion [9], mechanical devices action [1] or dynamic wind action [20]. Scaffoldings are also affected by accidental loads, e.g. impacts of vehicles or construction machines ([16], [26]), load rupture from cranes, vandalism, or fire. The standard PN-EN 12811-1 [7] names a violent impact on the security elements when the worker falls on the handrail, as an exceptional load, as well. The dynamic loads generated by nearby traffic, human motion, machinery and equipment, wind action, have been presented in detail in the following parts of this paper.

Fig. 1. Examples of the scaffoldings subjected to measurements

The effects of dynamic actions on scaffoldings were measured during the project lasting for two years. The total number of 120 façade scaffoldings all around Poland was considered. All these scaffoldings were typical façade frame scaffoldings with total widths varying from 2 m to 75 m and heights from 8.43 m to 57.33 m. Areas of the scaffoldings ranged from 40.4 m^2 to 1500 m^2. The histogram showing the numbers of scaffoldings in 100 m^2 ranges is shown in Fig. 2.

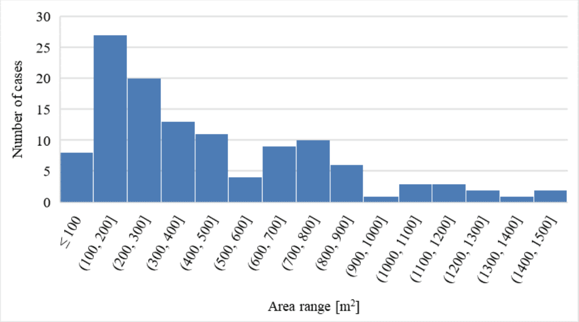

Fig. 2. Histogram of the analysed scaffoldings areas

Free vibrations were measured for each scaffolding. If the excitement of the selected type occurred at the scaffolding, the vibrations of the structure subjected to the dynamic loading were also measured. The tests were followed by the detailed numerical analysis.

The paper presents vibrational environment at scaffoldings. In the first part dynamic properties of scaffoldings are presented. Spectra of free vibrations have been obtained based on measurement and compared with results of calculations. Damping levels have been calculated based on measurement results. Various sources of forced vibrations are described, and the scaffolding vibrations generated with these sources are analysed considering if any of these sources can affect workers safety and generate disturbances in human comfort. The most influential sources of vibrations at scaffoldings are indicated.

2. VIBRATION EFFECTS ON WORKERS

The subject of vibration effects is widely analysed, published, and codified.

The effect of vibrations on human is depending on the parts of body exposed to vibrations. Griffin [10] and Mansfield [21], following the standard recommendations [11], [12], divided them into two groups: whole body vibrations and hand-transmitted vibrations. The vibrations which can be felt by the workers present at scaffolding can be in both groups. At scaffoldings, the hand transmitted vibrations are limited to the ones being generated by tools held in hands. These vibrations are transmitted through human bodies and as filtered ones can be felt by other scaffolding users as whole-body vibrations. Furthermore, whole-body vibrations can be generated by other workers walking on scaffolding decks or by machinery attached to the scaffolding.

The perception of vibrations largely depends on the human position. Two groups of perception positions are usually subdivided: seating and non-seating [21]. The influence of human posture on human response to vibrations has been presented by Matsumoto and Griffin [22]. Human body is more sensitive to accelerations in the horizontal direction than in the vertical plane. According to Jia [15] the effective amplitude a_e commonly used in analysis of vibration effects on human body can be calculated as combination of accelerations in all three directions, horizontal (a_X and a_Y) and vertical (a_Z) ones in the following way:

$$a_e = \sqrt{2(a_X^2 + a_Y^2) + a_Z^2} \tag{2.1}$$

Since the horizontal vibrations are more strongly sensed by human, the limiting values in horizontal directions are lower, than the ones for vertical direction, when analysis of vibrational human comfort is analysed in separate directions. The works at the scaffolding are predominantly performed in vertical and non-seating positions.

Vibrations in various ranges of frequencies are affecting human body in different ways. Jia [15] has listed 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 summarized that human body is most sensitive to vibrations along the body height in the range 4-8 Hz, while in transverse direction it is 1-2 Hz.

This diversion in vibration frequency perception leads to the analysis of the vibrations effect on human body in bands. In standards usually 1/3 octave filters are used to obtain vibrations acceleration or velocity series in each bandwidth. The comparison of RMS values with the allowable ones in each range leads to the determination of human vibrational comfort. This method, already introduced by the Polish standard [23] in 1988, is also present in its updated version from 2017 [24]. The time of RMS value calculation for non-stationary vibrations according to Polish standards is limited to the range, where the amplitudes of vibrations are bigger than 0.2 of the maximum amplitude.

The modification proposed by Stypuła [17], [18] is based on the human vibration perceptivity ratio – HVPR (WODL in Polish) – the measure of human vibration perception. It consists in calculation, in each of the 1/3 octave band, of the ratio of the RMS value of vibrations amplitude to the allowable value in this band and finding the maximum value. The result is a pair consisting of the ratio and the band where the maximum ratio occurs. This measure gives clear information if the comfort criteria were exceeded and in which band is the exceedance occurring.

Alternative method more sensitive to peak values [18], useful if workers or residents are exposed to shocks rather than constant vibration, has been recently introduced in Polish standard [24]. It is based on comparison of the VDV (vibration dose value) [m/s$^{3/4}$]:

$$VDV = \left[\int_0^T a_w(t)^4 \,\mathrm{d}t\right]^{\frac{1}{4}} \tag{2.2}$$

(a_w is frequency-weighted acceleration and T is the duration of measurements) with threshold values. It gives an information, based on the entire period of human exposure to vibration, if these vibrations will be bothersome to the residents of buildings and if administrators should expect complaints.

The effect of background leads to the division in standards for two different terms of vibrations perception: day and night. The limiting values of allowable acceleration amplitudes are diversified in terms of time of day. Similar reasons are for the variations in limits for different intended use of the building.

Scaffoldings as temporary structures are usually of minor interest of structural engineers. But since the workers are spending almost whole of their workday at the scaffoldings, the influence of nearby vibration sources on human at the scaffolding should not be neglected. The subject has been analysed in this paper and the description of vibrational environment at scaffolding is also presented.

3. DYNAMIC PROPERTIES OF SCAFFOLDING STRUCTURES

Discussion on the importance of operational dynamic loads requires introductory information about the dynamic properties of the scaffolding. The construction of scaffoldings, as in any other structure, has a big influence on its dynamic parameters such as free vibrations and damping. In the Rayleigh material and stiffness damping model, most commonly used in civil engineering, damping is the sum of material damping effects that arise as a result of internal interactions in the material and construction damping that arises as a result of the individual structural elements interaction. A more detailed discussion of the model can be found, among others, in the work of Wielgos [29].

The method of assembling scaffolding components, and thus structural damping, is much more important than the materials used to make these constructions. The foundation should be analysed as the first component, affecting the frequencies of natural vibrations and mode shapes. Scaffoldings are based on sleepers. Such a foundation mainly protects against sinking of bases into the ground. If the scaffolding is high and heavy, then the friction between the ground and the sleeper, as well as between the sleeper and the base, disables the horizontal movement. This arrangement also works well in case of lower scaffoldings when they are subjected to static actions only. However, during dynamic actions which cause vibrations, the friction can be overpowered, i.e. the horizontal force can exceed the static friction force, and the horizontal movement of the standards can occur. Light scaffoldings can also move in a vertical direction. Such problem also applies to higher, underloaded scaffolding levels. During vibrations, at the connections between the standards, the higher standards slide out of the bolts and simultaneously rotate. Therefore, apart from vertical movement, additional horizontal vibrations of the frames are added. On the other hand, the clearances occurring in the connections of individual components increase the structural damping significantly and reduce the area of vibrations. It seems that the biggest impact on the damping have decks, which are arranged so that between the brackets and the bolt on which they are stacked, a few millimetres clearance is created. High frequency horizontal vibrations with small amplitudes in the direction along the scaffolding are damped due to friction between individual decks or between decks and handles. Unfortunately, this does not apply to vibrations with low frequencies and correspondingly large amplitudes greater than the clearance on the platform handles. These vibrations are transmitted to through the structure and cause vibrations of the entire scaffolding, but due to high damping, they quickly disappear when excitation source becomes inactive. During such an excitation, the vibrations have an unfavourable effect both on the stress level in the structure elements and on the comfort of people on the scaffolding. The reduction of dynamic effects is possible through the bracing of the structure and mostly by the correct anchorage [4].

To improve safety of scaffolding, the natural frequencies should be increased. In the case of longitudinal vibrations, this can be done by adding more bracing and reducing lengths of anchors. Increasing the number of anchors is also especially important, because it increases the frequencies of free vibrations associated with the mode shapes, both along the facade and in the perpendicular direction. For high scaffoldings, these actions may not be enough to increase the first natural frequency. In such cases, you can increase safety by increasing the level of damping, which can be hard to achieve.

4. IN-SITU MEASUREMENTS

Two kinds of vibrations were measured at scaffoldings: free and forced ones. Firstly, each of scaffoldings was excited with human induced oscillations. The measurements were made with use of

Brüel & Kjær system: three triaxial (type 4506-B-003, 500mV/g sensitivity) and two uniaxial (type 4508, 100 mV/g sensitivity) accelerometers connected to the 12-channel input module (type 3053) attached to a portable computer with time data recorder software installed. The sampling frequency was set to 8192 Hz. The vibration accelerations of the structure were measured at minimum three points located beneath the highest level of decks. Three points of excitation were also introduced. The frequency analysis of the obtained time series allowed identification of natural frequencies and verification of the numerical model.

4.1. NATURAL FREQUENCIES AND MODE SHAPES

The measured values of the first natural frequencies ranged from 0.85 Hz to 3.85 Hz. These values highly depended on the size of the scaffolding, but on the quality of the anchorage, as well. It was been found that during the scaffolding usage first natural frequency might get lower even of 0.5 Hz as the result of ease in anchorage.

4.2. DAMPING PARAMETERS

Damping parameters of some of the analysed scaffoldings were also determined. Filtering-regressive method was used to obtain logarithmic decrements of damping. Butterworth digital filter of the 8th order was applied to several time series of accelerations for each of the analysed scaffolding. Local extreme values were used to build the envelopes of the filtered time series. Only damped fragment of time series was extracted from the filtered time series to find local extremes. Then the extreme points were approximated by a curve with the equation:

$$y_a = Ae^{-\gamma t} \tag{4.1}$$

where: γ – damping coefficient.

Logarithmic decrement of damping was calculated using the formula:

$$\Delta = \frac{\gamma}{\omega_s} \tag{4.2}$$

where: $\omega_s=2\pi f_s$ – circular frequency of free vibrations, γ – damping coefficient.

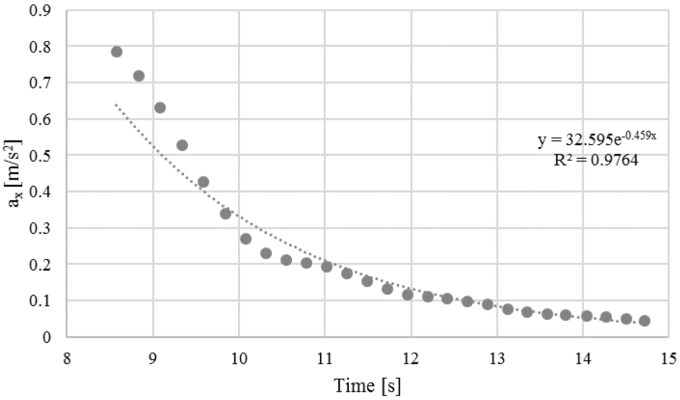

Fig. 3. Determination of the damping coefficient curve fitted to the maxima of accelerations

Fig. 3 presents local extreme values in the damped fragment of the accelerations time series and the curve fitted to these local extremes. A filter with the bandwidth of 1.5 Hz to 2.5 Hz was used and it was selected based on the frequency analysis of the time series with the peak representing the natural frequency at $f_s = 2$ Hz.

The detailed analysis of damping was performed for 6 selected scaffoldings. Most of the results of the logarithmic decrement of damping were in the range 0.05 to 0.06, however for the sixth scaffolding a smaller value of 0.03 was found. This shows that the scaffoldings are not a homogenous group of structures and further detailed analysis of the damping of scaffoldings is planned. More of the results obtained so far can be found in the authors' paper [2] and in the book by Błazik-Borowa [4].

4.3. SOURCES OF FORCED VIBRATIONS

The next part of in-situ research was focused on forced vibrations of the scaffolding structure. Depending on the situation observed at the construction site, the time series of accelerations were measured during active nearby road traffic, workers' activities at the scaffolding, machinery working near or at the scaffolding.

The effect of nearby traffic was generally small, and no large scaffolding vibrations produced by cars, and even trams or trains passing by, were observed. The reason of such an effect was due to the location of the scaffolding usually in some distance from the road edge. The vibrations were damped in the surrounding ground, but even more by the foundation of the scaffolding at the ground. The levels of accelerations observed at the scaffoldings never reached the limit values for workplaces.

Horizontal (walking along the deck) or vertical (climbing the ladders) movements of workers were observed to be very influential to the scaffolding vibrational environment. Especially the vibrations generated by workers walking along the scaffolding decks gave disturbances in the horizontal direction, in the plane of the scaffolding, with low frequencies strongly transmitted to the whole structure [9].

The workers operating at scaffoldings were usually equipped with heavy drillers or hammers. These accessories in hands of workers produced temporary disturbances at scaffoldings. The frequencies of the drillers are in the range of 7 to 8 Hz and the vibrations produced by them were highly filtered and damped by human bodies.

The next group of equipment often present at the scaffoldings are rope cranes, lifts and chutes. Cranes may be man-powered or equipped with an engine, and in both cases are usually attached to the scaffolding structure. This fact makes them highly affecting the vibrational environment at scaffoldings. They produce vibrations that can be felt at large parts of the structure, but since they are used for transportation of grout in buckets or other building materials, they are in use only for several seconds at one go. Although they produce some discomfort for workers at scaffolding, they do not affect the whole workday strongly. External lifts used at high buildings to transport workers and materials are usually separated from the scaffolding and attached to the building structure, and therefore do not affect the vibrations of scaffoldings. Chutes are used to transport debris in vertical direction (downwards). They often produce temporary vibrations which can be a strong disturbance for workers comfort at the scaffolding, especially when the debris transportation is repeated frequently.

The last group of machines often present at building sites and affecting scaffolding vibrations are shotcrete machines used for pumping grout. They generate low frequency vibrations (1-2 Hz), the pipes transporting the grout are usually attached to the scaffolding elements and they are active for the long time. This makes them the most dangerous equipment for the scaffolding vibrational environment.

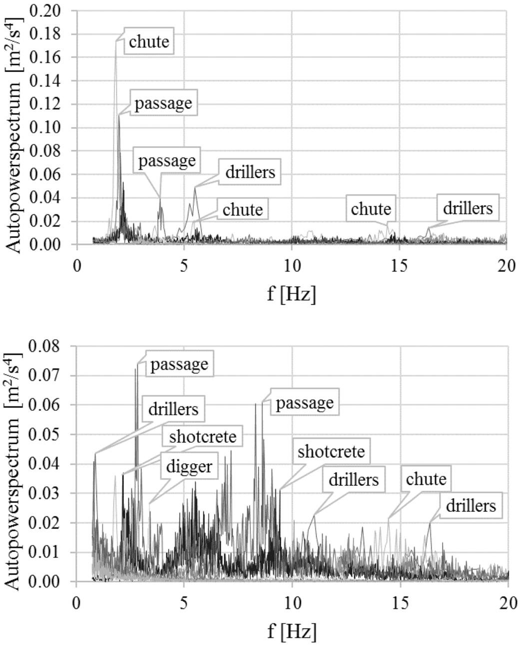

Fig. 4. Exemplary spectra of forced vibrations of scaffoldings in two horizontal directions: X – along scaffolding façade (left), Y – perpendicular to the façade (right)

Wind action does not significantly affect scaffoldings. The forces generated by wind are generally small, unless the cladding of the structure is in use [28]. When the scaffolding is cladded, the forces can increase significantly and if there are errors in anchorage the wind action can even lead to the structure collapse. This is not directly affecting the vibrational environment at scaffoldings since in case of strong winds all works at scaffoldings are usually suspended. Detailed analysis of the wind action on scaffolding and on building-scaffolding system was presented in previous papers ([13], [19], [20]).

The spectra of the exemplary recorded time series of accelerations of scaffoldings subjected to various sources of excitation are presented in Fig. 4. The results for the following sources are shown in the graph: drilling workers operating from scaffolding decks, chutes during debris dropping, rope cranes used to lift building materials, shotcrete pipes attached to a scaffolding and pumping grout, diggers operating near a scaffolding, nearby road traffic, lifts used to transport workers and materials, human passage along a scaffolding deck, wind action.

It is worth mention that the measurements referring to different sources of excitation were recorded at different scaffoldings and distances between excitation and measurement points. The results are presented here to give rough orientation of the importance level for sources of vibrations present at scaffoldings. Moreover, relatively high values of spectra for drillers may rather come from the movement of the workers during driller usage than the equipment vibrations themselves. The spectrum for wind action generated accelerations presented in

Fig. 4 was obtained at wind speeds measured at five 2D anemometers located at penultimate working level of scaffolding with values of 1.5 m/s to 2 m/s (mean) and 6 m/s to 7 m/s (gusts). Additional 3D anemometer located 2.5 m above the building roof showed wind speeds of up to 3 m/s (mean) and 7.5 m/s (gusts).

5. NUMERICAL ANALYSIS

The numerical model for each of scaffoldings was built with use Autodesk Simulation Multiphysics 2013. Fig. 5 presents one of the scaffolding models. The structure of the scaffolding was modelled with beam elements, while the decks – with shell elements. Connections between handrails and stands, braces and stands are modelled as hinge joints. The other connections are stiff. Supports, modelling the foundation on the ground and anchors in the wall, are modelled using hinged supports. Modal analysis resulted with natural frequencies and mode shapes. They served for verification of the numerical model accuracy and consistency with the measurements results, i.e. the numerical model was calibrated based on measurements of the free vibrations' frequencies. The calculated values of natural frequencies were close to the measured free vibrations frequencies (within 10% range of differences). Not only the first natural frequency and mode shape, but also higher frequencies and respective mode shapes were considered in the comparison of the measurements and calculations results. The process of the numerical model creation based e.g. on the geodetic inventory [3], [5] and verification of the model based on free vibrations measurements was presented in detail in the papers [8], [14].

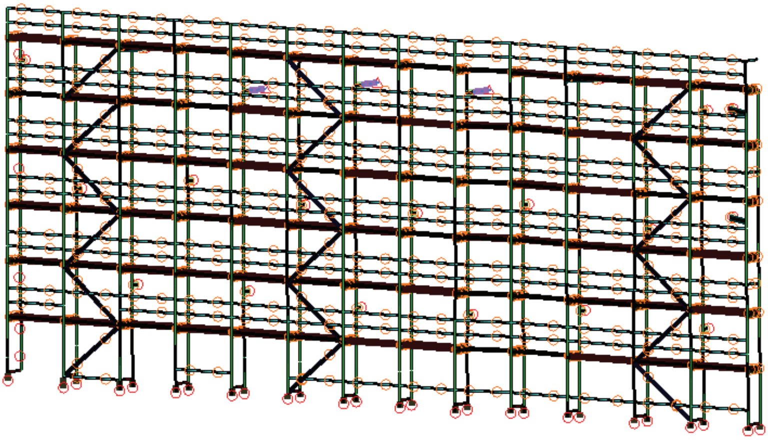

Fig. 5. Exemplary scaffolding numerical model

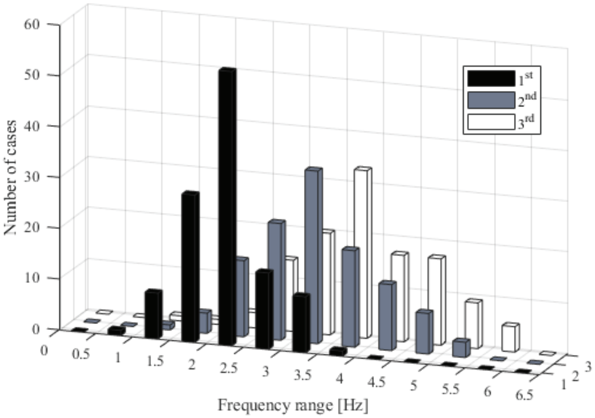

Fig. 6. The distribution of the values of the first three natural frequencies

For each of 120 analyzed scaffoldings a wide spectrum of first 20 natural frequencies and mode shapes was obtained in numerical modal analyses. In Fig. 6 the histogram for the first three natural frequencies for all analyzed scaffolding is presented. As it can be seen, the first natural frequency for all scaffoldings is below 4 Hz. There was only one case of the calculated first frequency below 1 Hz (0.77 Hz in calculations and 0.85 Hz measured).

The values of the modal participation factor for each mode shape in the directions *X*, *Y* and *Z* were obtained during the numerical modal analysis of each scaffolding. Since the ones for the vertical direction (*Z*) were always almost equal to zero, this direction was skipped in the further analysis. In order to distinguish the prevailing direction of vibrations in each mode shape, the *XY* factor was proposed. It was calculated for each mode shape by dividing the modal participation factors of *X* and *Y* directions (bigger value of the factor by the lower one) and application to this ratio plus sign if the bigger value of modal participation factor was found for the *X* direction (along the scaffolding façade) and minus sign for the *Y* direction (perpendicular to the scaffolding plane). This led to the graph presented in Fig. 7.

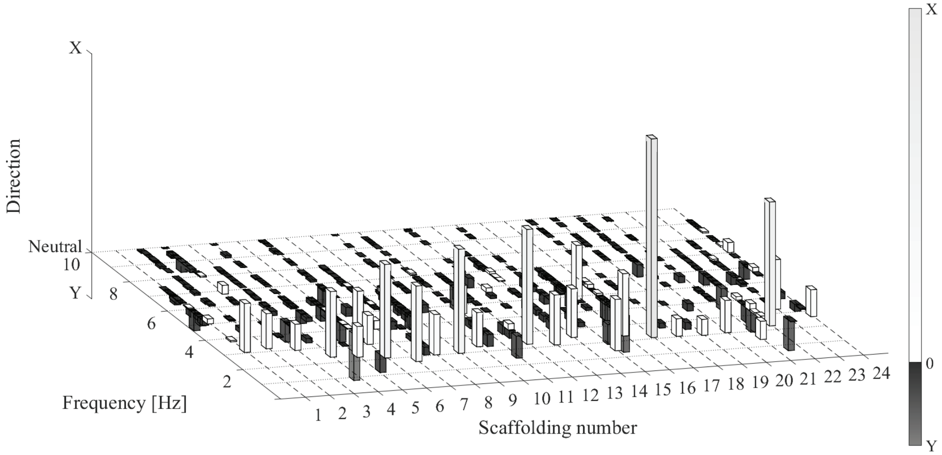

Fig. 7. Spectra of the natural frequencies for 24 analysed scaffoldings from "Łódzkie" voivodship with indication of the prevailing direction of vibrations

The horizontal plane is spread on two axes: the one representing the scaffolding number and the other for the presentation of the values of the natural frequencies. For each of 24 scaffoldings (from "Łódzkie" voivodship of Poland – one of 5 analysed regions) presented on this graph, there is a dotted line parallel to the frequency axis. Along such a line the spectrum of natural frequencies for each scaffolding is presented. The light columns represent mode shapes with vibrations along the scaffolding façade (*X*), while the dark ones (below the plane) are for the perpendicular (*Y*) horizontal direction. Similar pictures, as the one seen in Fig. 7, can be obtained for scaffoldings in other four regions of Poland and the total number of 120 analysed scaffoldings.

For most of the scaffoldings – 100 out of the total number of 120 analysed – the first natural frequency was associated with the mode shape in horizontal direction along the scaffolding plane (*X*) and for 40 scaffoldings the second mode shape was found also longitudinal (comp. [2]). Only a few of the first mode shapes were related to the horizontal direction perpendicular to the façade (*Y*). The vertical vibrations were neglectable.

In the second part of the numerical analysis, forced vibrations of the structures were calculated. The obtained results were compared with the ones coming from in-situ measurements.

The dynamic wind action was presented in detail in the paper [20]. The authors conducted dynamic numerical simulation of the scaffolding subjected to the time varying wind field simulated with use of own computer software based on WAWS (Weighted Amplitude Wave Superposition method) [27]. The results of the analysis were compared with the ones obtained with use of equivalent static wind loads calculated following procedures found in respective codes [6], [7], [25]. The analysed scaffolding structure consisted of 6 rows of frames and 6 levels of decks. The first natural frequency of the structure was $f_1 = 3.03$ Hz. Particularly, the following calculations were made and the results were compared: in-situ measurements; Eurocode procedure, perpendicular load; Eurocode procedure, parallel load; Eurocode procedure, perpendicular load, coefficients like for scaffoldings systems; Eurocode procedure, parallel load, coefficients like for scaffoldings systems; dynamic load.

Dynamic analysis of the structure indicated that displacements of nodes were relatively low, with maximum less than 2 cm, and normal stresses in beam elements are much lower than allowed limits. The results from the dynamic analyses of scaffolding structures subjected to the wind load varying in time and simulated with WAWS method are much higher than most of the results obtained when equivalent quasi-static load based on codes or load based on in-situ measurements is used.

Numerical dynamic analyses were also made for other sources of excitations. They not only confirmed the results obtained from measurements but gave a wider image of scaffolding vibrations generated by different sources of excitation. Readout of the accelerations in many points of scaffolding became possible. The obtained results were compared with appropriate Polish standards for estimation of the vibrations effect on people inside the buildings PN B 02171:2017-06 [24] based on the comparison of RMS acceleration values with threshold in 1/3 octave bands. The maximum values in most cases were not exceeding the allowable limits for heavy industry workshops (highest of the limits). The most dangerous of the dynamic actions were caused by workers moving along the scaffolding decks or by the shotcrete pipes attached to the structure of the scaffolding.

6. CONCLUSIONS

The natural frequencies analysis shows that for all 120 analysed scaffoldings first natural frequency is below 4 Hz. The prevailing direction of vibrations in first mode shape is along the scaffolding façade. The stiffness of the scaffolding usually depends on the correctness of the anchorage scheme. The values of logarithmic decrement of damping for the analysed scaffoldings seems to be various. For 5 out of 6 scaffoldings where damping parameters where calculated the average value of logarithmic decrement of damping is at the level of 0.05-0.06, however at the 6th scaffolding lower value of 0.03 was obtained. Further analysis is required with consideration of the dependence on shapes and frequencies of vibrations.

The nearby traffic, machines working near scaffolding or workers using drillers at scaffoldings are not affecting strongly the scaffoldings vibrations, however higher values may be observed when the drilling workers are moving during operation of equipment. Wind action does not produce strong vibrations however it can be potentially a source of structural disaster.

Most significant vibrations of scaffoldings are generated by horizontal motion of workers, rope cranes and chutes operation, and most of all by shotcretes pumping the grout. These vibrations can strongly affect the vibrational environment at scaffoldings, make working at scaffolding difficult and they usually last for a long time. Even more these significant actions are affecting large parts of scaffolding structures. However, these actions are in almost all cases harmless to the scaffolding structures. If any failures occur, they are usually associated with errors in the design or in anchorage.

7. ACKNOWLEDGMENTS

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LIST OF FIGURES AND TABLES:

CHARAKTERYSTYKA WIBRACYJNA RAMOWYCH RUSZTOWAŃ FASADOWYCH

*słowa kluczowe***:** rusztowania, drgania, komfort, pomiary in-situ, analiza komputerowa

STRESZCZENIE:

W pracy przedstawiona została analiza środowiska wibracyjnego na rusztowaniach budowlanych. Opracowanie opiera się na wynikach projektu, w którym brano pod uwagę bezpieczeństwo pracowników na rusztowaniach. Łączna liczba 120 rusztowań fasadowych została przeanalizowana w ciągu dwóch lat. Jedną z kwestii branych pod uwagę w tym projekcie był wpływ drgań na konstrukcje rusztowań i bezpieczeństwo pracowników przebywających na nich.

Wartości częstotliwości własnych uzyskano na podstawie pomiarów in-situ drgań swobodnych. Pomierzone przebiegi przyspieszeń poddano analizie częstotliwościowej, a następnie odczytano wartości częstotliwości odpowiadających maksymalnym amplitudom. Następnie przebiegi przyspieszeń filtrowano w celu separacji drgań swobodnych związanych z wybraną częstotliwością własną. Z tak przefiltrowanych przebiegów wybrane zostały lokalne ekstrema przyspieszeń, do których dopasowane zostały krzywe (obwiednie). Z równań obwiedni odczytane zostały parametry tłumienia drgań.

Przeprowadzono również pomiary drgań wymuszonych wywołanych przez różne źródła drgań działające na rusztowaniach i w ich pobliżu. Pod uwagę wzięto drgania powodowane przez robotników używających wiertarek, zsypy budowlane, wciągarki ręczne i napędzane mechanicznie używane do transportu pionowego materiałów budowlanych, tymczasowe dźwigi towarowo-osobowe zlokalizowane w pobliżu rusztowań, maszyny torkretujące transportujące masę

betonową przez rury powiązane z elementami rusztowania, maszyny budowlane (koparki, ładowarki) operujące w pobliżu rusztowań, pobliski ruch uliczny, przejście pracownika po pomoście rusztowania, komunikację w pionie, oddziaływanie wiatru. Wyniki zestawiono na wykresach spektrum częstotliwościowego. Na podstawie takiego porównania stwierdzono, że największy wpływ na drgania rusztowań mają wzbudzenia spowodowane poruszaniem się pracowników po rusztowaniu oraz wywołane transportem mieszanki betonowej za pomocą maszyn torkretujących, zaś silne drgania generowane podczas zrzutów odpadów przez zsypy, mimo że mocno odczuwalne na rusztowaniu, mają jedynie charakter chwilowy.

Analiza wyników pomiarów umożliwiła weryfikację opracowanych modeli numerycznych rusztowań. Porównane zostały częstotliwości drgań swobodnych otrzymane na podstawie analizy pomiarów z częstotliwościami drgań własnych wyznaczonymi w wyniku komputerowych analiz modalnych. Dokonano również sprawdzenia pomierzonych przemieszczeń drgań swobodnych i porównano je z przemieszczeniami występującymi w poszczególnych postaciach drgań własnych. W celu otrzymania jak największej możliwej zgodności modeli komputerowych z rzeczywistymi konstrukcjami wprowadzano między innymi sprężyste podpory odwzorowujące nieidealne zakotwienia rusztowań. Dzięki przeprowadzeniu analiz modalnych rusztowań stwierdzono, że większość spośród analizowanych konstrukcji charakteryzuje się pierwszą częstotliwością poniżej 4 Hz i postacią drgań własnych o kierunku poziomym wzdłuż fasady rusztowania (100 ze 120 przeanalizowanych przypadków), zaś w przypadku 40 spośród tych rusztowań także druga postać jest wzdłużna.

Przeprowadzono szczegółowe numeryczne analizy dynamiczne. Przeprowadzono szczegółowe symulacje z uwzględnieniem oddziaływania wiatru, co pozwoliło stwierdzić, że działanie wiatru na rusztowania ramowe nie ma znaczącego wpływu, jeśli rusztowanie nie jest pokryte siatką. Analizowano także oddziaływania komunikacyjne, których wpływ na drgania rusztowań okazał się znikomy. Podobnie jak w badaniach stwierdzono, że najbardziej istotny wpływ mają drgania wywołane przez przemieszczanie się robotników (w pionie, a szczególnie w poziomie) oraz podczas podawania mieszanki betonowej przez maszyny torkretujące. Uzyskane wyniki porównano z dopuszczalnymi wartościami zgodnie z odpowiednimi normami polskimi. Dzięki zbudowanym modelom komputerowym wiernie odwzorowującym rzeczywiste konstrukcje rusztowań, umożliwiona została dokładna analiza komputerowa, co pozwaliło na odczyt wyników w licznych punktach rusztowań, w przeciwieństwie do badań, gdzie analiza wyników ograniczona jest do wybranych punktów pomiarowych określonych przed wykonaniem pomiarów.

We wnioskach wskazano najbardziej znaczące źródła drgań wpływające na komfort pracowników na rusztowaniach. Zwrócono uwagę, że drgania w większości przypadków nie powodują istotnego zagrożenia dla konstrukcji rusztowań. Jedyne zagrożenie odnośnie do potencjalnej katastrofy budowlanej możliwe jest w przypadku rusztowania pokrytego siatką lub innymi powłokami mało przepuszczalnymi, jednak nie jest to bezpośrednio związane ze środowiskiem wibracyjnym, a raczej stanowi efekt powstawania w takich przypadkach znacznych sił statycznych pochodzących od wiatru. Możliwe awarie związane z drganiami rusztowań są zazwyczaj związane z nieprawidłowościami w realizacji zakotwień lub błędami projektowymi.

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