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SYSTEM SAFETY OF FAÇADE SCAFFOLDING: ACHIEVING ACCEPTABLE DYNAMIC PERFORMANCE THROUGH ANCHORAGE AND BRACING DESIGN

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Abstract: Facade scaffolding is an auxiliary structure used in construction, which is exposed to dynamic actions related to construction works. In this paper, dynamic actions have been characterized and methods of reducing their impact on scaffolding structures have been presented. The perception of vibrations by humans is particularly strong in the range of 1÷2 Hz, which coincides with the frequency of vibrations caused by people walking on scaffolding decks. Attention was paid to creation of the correct system of braces and anchorages, which is the main way to increase the stiffness of scaffolds, and thus to increase the first natural frequency and, if possible, go beyond the resonance area. In the computational example, a scaffold was analyzed, in which the system of braces and anchorages was modified to illustrate their impact on the dynamic characteristics of the scaffolding. The conclusions also noted the problem of the uneven distribution of anchors on the surface of the scaffolding. It has been found that leaving a large area without anchors can cause dangerous situations and affect the comfort of scaffolding users. The results provide practical guidance for safety-oriented design and on-site quality control of anchorage and bracing to reduce resonance-related discomfort and hazardous operating conditions.
Keywords: façade frame scaffolding, dynamic properties, anchorage and bracing systems, human vibration comfort

1. INTRODUCTION

Façade frame scaffolding is a temporary building structure typically connected to a building under construction or renovation. In addition to guaranteeing the stability of the scaffolding, another important task for the designer is to ensure appropriate dynamic properties that affect the safety of the scaffolding structure itself and the people performing work with the use of scaffolding. The basic dynamic parameters of building structures are frequencies and mode shapes of natural vibrations, the level of damping, the characteristics of the sources forcing vibrations. Of these parameters, the scaffolding designer has a real impact on the frequencies and mode shapes of vibrations. In the case of façade scaffolding, the first natural vibration frequency is usually in the range of 0.7 to 4 Hz (Bęc et al., 2020), which coincides with the frequency range of many of the vibration

sources that occur during scaffolding construction work. Human body is most sensitive to vibrations along the height of the body in the range of 4÷8 Hz, transversely – 1÷2 Hz (Jia, 2014). For human comfort, i.e. to ensure the safe and comfortable work on scaffolding and to perform this work for a long time, it is important that vibrations take place with the lowest possible amplitudes in the indicated ranges.
The vibration frequencies of the scaffolding depend on its size, total weight (including materials accumulated on it and its users) and the rigidity of the structure. Stiffness is determined by the cross-sections and material properties of the scaffolding system elements, which is not influenced by the designer of a single scaffolding structure, as they result from the adopted scaffolding system. However, it can be increased by using an appropriate anchoring and bracing system. Information on the required braces and anchor spacing for typical façade scaffolding is available in the respective standards (PKN, 1996) and manufacturers' catalogues (ALTRAD-MOSTOSTAL, 2020).
This paper presents the characteristics of various sources of dynamic influences on building scaffolding and ways to reduce their impact on the safety of the structure and the comfort of users. In the calculation example, attention was drawn to the need for proper implementation of anchorage and brace systems.

2. SOURCES OF DYNAMIC ACTIONS ON FAÇADE SCAFFOLDING

The most common sources of dynamic interactions are presented below, along with a brief characterization.

- Workers on scaffolding

Workers' movement has a big impact on scaffolding. With normal walking, the speed of movement ranges from 1.1 m/s to 1.5 m/s, and the step length ranges from 0.6 m to 0.75 m, respectively. Moving around the structure, people force vibrations with low frequencies of 1.0 ÷ 2.0 Hz. This loading range is consistent with human-induced vibration studies, where typical walking excitation frequencies and comfort assessment are explicitly discussed in relation to structural response and damping (Jiang et al., 2022). In the case of slender structures with low natural vibration frequencies, such forcing is a significant dynamic load, causing an increase in stress in the structural elements and discomfort for people. In addition to the vertical component, the moving person also induces horizontal forces: along the direction of movement and in the transverse direction. Especially the horizontal forces generated by workers walking on scaffolding platforms excite vibrations in the horizontal direction parallel to the scaffolding façade with low frequencies strongly transmitted to the entire structure.

- Vibrations caused by machines on scaffolding

Wire rope winches can be manual or machined, they are usually attached to the scaffolding structure, which makes them strongly affect the vibration environment on the scaffolding. Vibrations can be felt over large areas of the structure, but this equipment is usually used for a short time, and while it does cause some discomfort to scaffolding workers, it does not strongly affect the all-day working experience.
Mechanized lifts used in high-rise buildings to transport workers and materials are usually separated from the scaffolding and attached to the building structure and therefore do not affect the vibration of the scaffolding. However, there exist solutions in which it is proposed to anchor the crane to the scaffolding itself causes vibrations to be transmitted to their structures, which significantly affects the vibration comfort of scaffolding users.

Chutes are used to transport debris vertically (downwards). They produce a large amount of momentary vibrations, which can be a strong disruption to the comfort of workers on the scaffolding, especially when the transport of debris is repeated frequently.
The last group of machines often present on construction sites and affecting scaffolding are shotcretes used to pump grout. They generate a low frequency vibration of about 1-2 Hz, the grout transport pipes are usually attached to the scaffolding components and work for a long time, making them the equipment that has the strongest impact on the vibration environment on scaffolding.
Workers working on scaffolding are often equipped with heavy drills or hammers. Such accessories in their hands usually cause temporary disturbances on the scaffolding. The frequencies of drills are in the range of 7 to 8 Hz, and the vibrations produced by them are strongly filtered and damped by human bodies.

- Environmental actions (wind)

Wind action does not significantly affect scaffolding. The forces generated by the wind are usually small, unless a net or cladding is applied to the structure. When the scaffolding is cladded, the forces can increase significantly, and if there are errors in the anchoring, the wind action can even lead to the collapse of the scaffolding structure. Recent full-scale field measurements on façade scaffolds confirmed strong spatial variability of wind action and highlighted limitations of simplified normative assumptions, especially for edge/corner zones and netted scaffolds (Jamińska-Gadomska & Sumorek, 2025). This risk is consistent with studies showing that aerodynamic effects can markedly amplify wind-induced actions on supporting structures, depending on flow conditions and geometric features, which may become critical when additional surfaces (e.g., cladding/netting) are introduced (Gąćkowski & Verbakel, 2024). The wind does not have a direct effect on the vibration environment on the scaffolding, because in the event of strong winds, all work on the scaffolding is usually suspended.

- Seismic and paraseismic influences

Seismic impacts (earthquakes) are rare in Poland or only low-intensity earthquakes occur, so their impact on scaffolding structures is negligible. Paraseismic actions are vibrations transmitted through the ground to structures (buildings and scaffolding) from road traffic or caused by machinery working nearby. The impact of nearby traffic is usually small. The scaffolding is usually located at a certain distance from the edge of the road, and vibrations are dampened in the ground and by supports of the scaffolding on the ground. In the vibration measurements of the façade scaffolding, no large vibrations of the scaffolding produced by cars or even passing trams or trains were observed. The acceleration levels observed on scaffolding almost never reached the values permissible for workplaces according to the Polish Standard (PKN, 2017). The impact of machines working near the scaffolding can be significant due to the possibility of locating them at a short distance from the scaffolding. In addition, the scaffolding designer should pay attention to the possibility of collision of machines and vehicles working nearby with the scaffolding structure, which may generate huge impact not only on the vibration environment, but can pose a threat to the safety of the entire structure and workers. It is imperative to avoid such situations, among other things, by properly organizing the construction site. Another type of paraseismic impacts are events caused by mining exploitation (rockfalls, blasting works). Such impacts are limited to the areas where such works are carried out, and their short-term, incidental nature significantly reduces the impact on scaffolding structures and the comfort of people working on scaffolding.

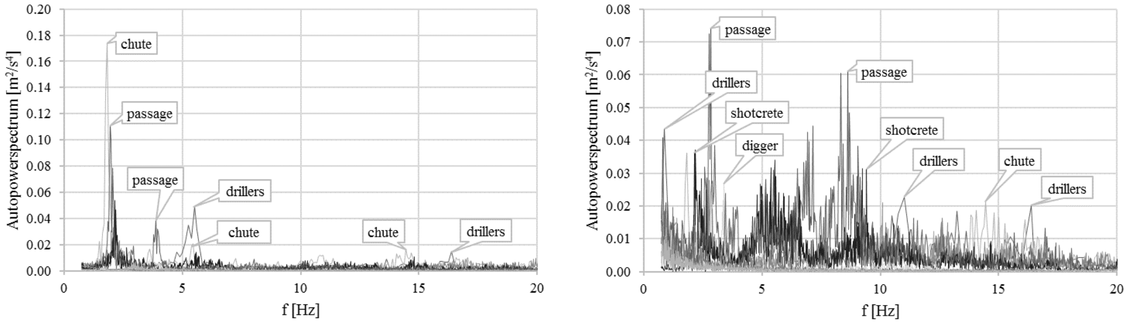

Fig. 1. Spectrum of forced vibrations in horizontal direction parallel and perpendicular to the façade

Based on dynamic measurements on 120 façade scaffolding, which were carried out as part of a research project in 2016-2018 (Bęc, 2023), the spectra of forced vibrations in two horizontal directions were obtained, which are shown in Fig. 1. Such vibration-based measurements are consistent with diagnostic approaches used to assess the technical condition of operating machinery and devices (Biały, 2024).

3. WAYS TO REDUCE SCAFFOLDING VIBRATIONS

There are several ways to reduce the impact of vibrations on the scaffolding structure and the comfort of its users. However, it should be remembered that not all methods are equally available to the scaffolding designer.

Reducing the amplitude of vibrations transmitted to the scaffolding, i.e. reducing the sources of vibrations, although it is possible, is usually not influenced by the scaffolding designer. Scaffolding is not built so as not to work on it. However, it is possible to imagine a situation where devices, such as freight and passenger lifts, are attached to the scaffolding structure, and then it is definitely worth considering their construction in such a way that the impacts are not transmitted to the scaffolding. In the case of traffic, it is not possible to change the location of the scaffolding in relation to the road axis, but the elimination of obstacles on the road (unevenness) that can increase the transmitted vibrations allows to minimize the amplitudes of vibrations transmitted through the ground.

Another way to reduce dynamic influences on structures is to increase vibration damping. This phenomenon occurs due to the flow of mechanical energy (resonance phenomenon – mechanical dampers) from the structure to the additional mass or its dissipation in the damping constraints (e.g. liquid flow – liquid dampers, or in the joints of structural elements and at anchor points – friction dampers) (Jurczyńska, 2025). Due to the temporary nature of scaffolding structures, such solutions are not found, and the use of friction dampers should be considered in the case of scaffolding of large dimensions and exposed to strong dynamic influences, e.g. located near constantly operating machines causing strong vibrations.

The greatest possibilities for reducing dynamic influences on façade scaffolding are provided by modifying the frequencies and mode shapes of the scaffolding. Increasing the natural vibration frequency above 2 Hz allows significant increase of the comfort of scaffolding users by eliminating the phenomenon of resonance during the movement of employees on the scaffolding structure. This is possible by increasing the stiffness of the scaffolding or by reducing the weight of the scaffolding itself and the additional load. The cross-sections of the scaffolding elements are independent of the designer of the specific scaffolding structure. It is particularly important to be able to ensure the rigidity of the structure by taking care of the correct boundary conditions (support, anchoring) and bracing of the structure, which is presented in detail in the further part of this paper. This is consistent with measurement-based FEM calibration reported for façade scaffolding, where reproducing low measured natural frequencies required modelling the anchors' connection to the wall as a hinged support (Błazik-Borowa et al., 2020). For planned scaffolding work using equipment that causes significant dynamic actions, consideration should be given to adjusting the anchoring system and braces to the dynamic loads on the scaffolding. During dynamic measurements of scaffolding, it was noticed that during operation on the scaffolding, the values of the natural vibration frequencies can decrease by up to 0.5 Hz as a result of loosening the anchorage. Therefore, it is necessary to control the quality of the anchorage during long-term use. Such control can be supported by vibration-based monitoring using high-sensitivity (including wireless) accelerometers capable of capturing low-level structural responses relevant for modal parameter tracking (Zhu et al., 2018).

Due to the low weight of the scaffolding structure, the natural vibration frequencies of the scaffolding with the weight of the users are even lower than for the scaffolding structure itself. The weight of one of the tested scaffolds was 5.9 tons. The permissible load according to EN 12811-1 (CEN, 2003) (class 3) is 200 kg/m^2 on one level of the platforms. The total additional weight of this scaffolding is 4.6 tons, which is 75% of the weight of the scaffolding. It has been shown that the natural vibration frequencies of the scaffold decrease significantly with the increase in the mass located on the scaffold (Bęc and Błazik-Borowa, 2019).

4. INFLUENCE OF THE BRACING AND ANCHORAGE SYSTEMS ON THE DYNAMIC PARAMETERS OF THE SCAFFOLDING

Computer calculations of an example of a medium-sized façade scaffolding were performed in order to analyze the impact of modification of the brace and anchorage system on its dynamic parameters. The spatial model of the finite element method of the structure was created in Autodesk Simulation Multiphysics 2013 and is presented with dimensions in Fig. 2. The process of building and verifying the model based on the research of the actual scaffolding structure was presented earlier in the paper (Jamińska-Gadomska et al., 2018). The original model contained braces (3 braced vertical shafts with diagonal braces in the outer plane of the scaffolding) and anchorages (36 anchor points in total) proposed by the designer of the scaffolding structure on the basis of standard regulations.

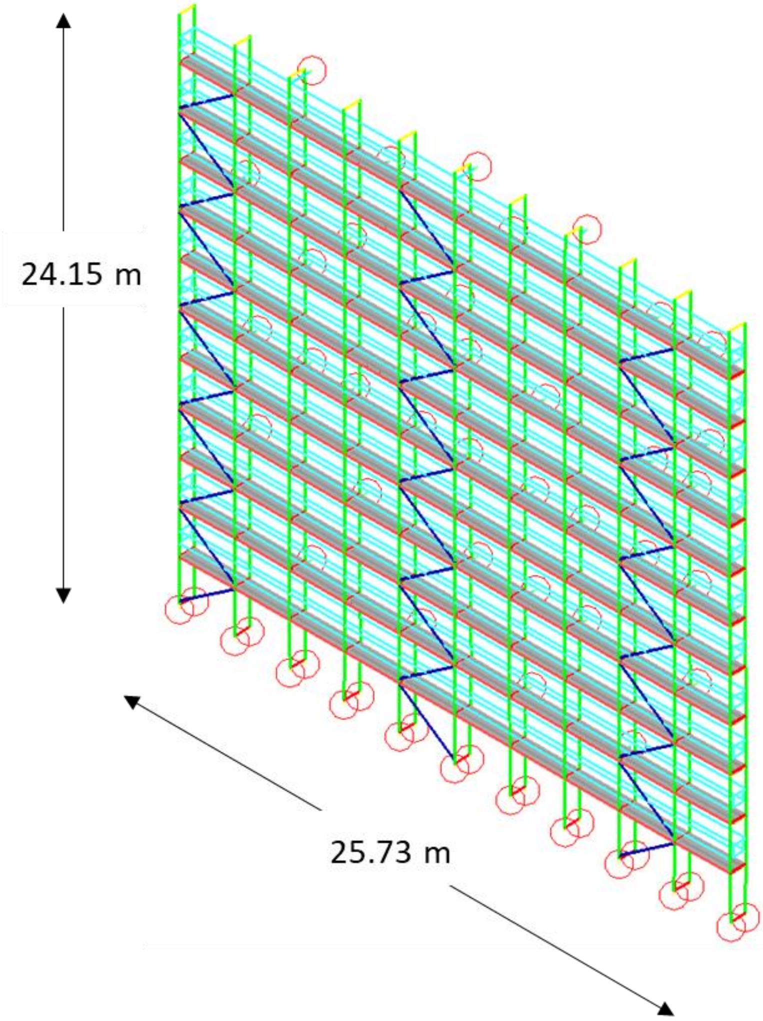

Fig. 2. Scheme of the analyzed scaffolding

In subsequent variants, the number of brace vertical shafts was modified, i.e. from the original number of brace verticals (3) 2 were left (poorly braced scaffolding), and then the number of brace vertical shafts was increased to 5 (stiffened scaffolding) (Fig. 3).

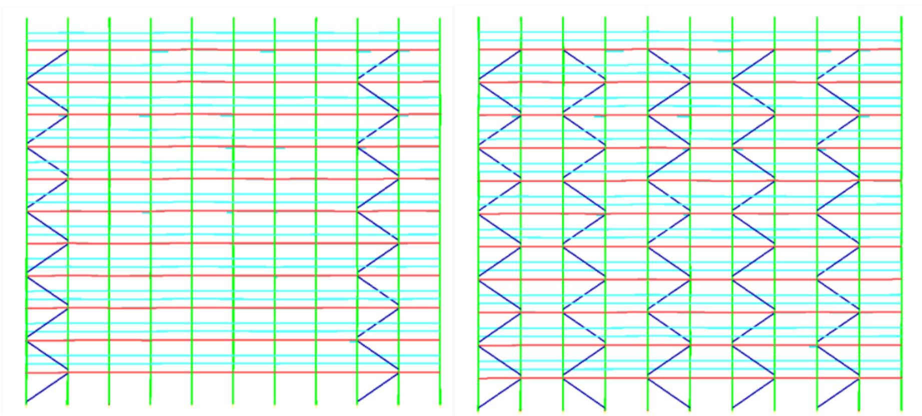

Fig. 3. Modified bracing: poorly braced scaffolding (left) and stiffened (right)

The influence of the number of anchors while maintaining the original bracing system was also analyzed. It was assumed that the fragment of the structure remained unanchored, which was introduced into the model by eliminating the 6 anchors in the upper right corner of the scaffolding in three stages. In the figure, the eliminated anchor points are shown as circles drawn with a bold line, while the next three diagrams show the scaffolding after eliminating 3 anchor points, another 2 and additionally one anchorage (6 in total), which ultimately created a static scheme of the scaffolding with a significant area without anchorages (Fig. 4).

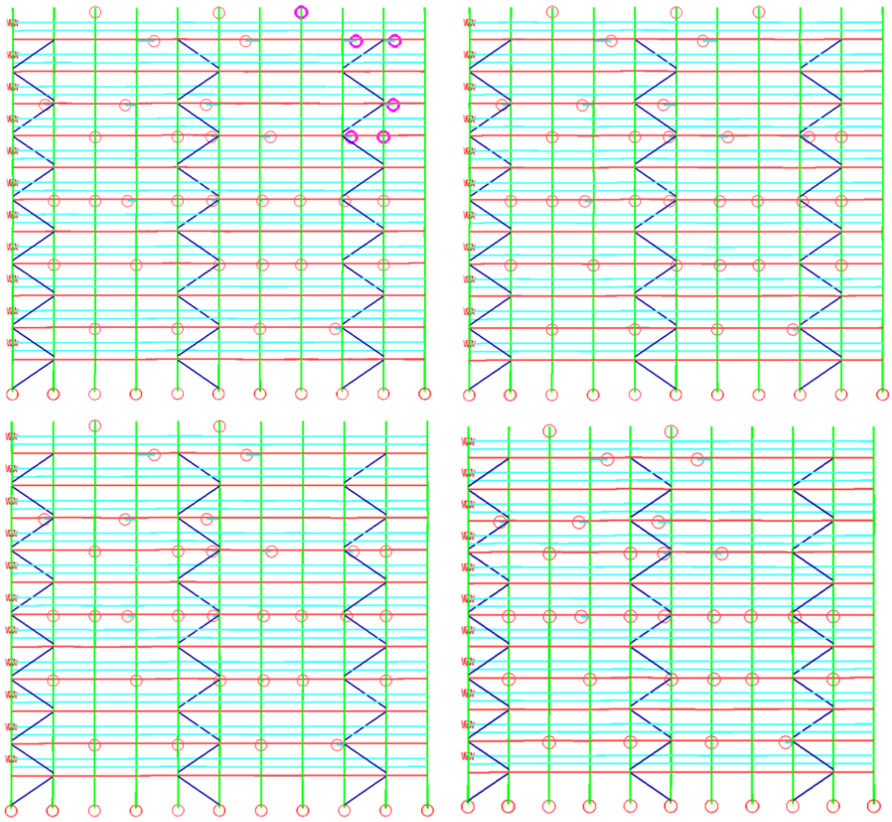

Fig. 4. Modified anchor systems: original anchor system with highlighted anchors to be dropped out (top-left); stage I (top-right), stage II (bottom-left) and stage III (bottom-right)

The last variant of modification of the original anchor system is the uniform removal of 10 out of 36 total anchor points (Fig. 5).

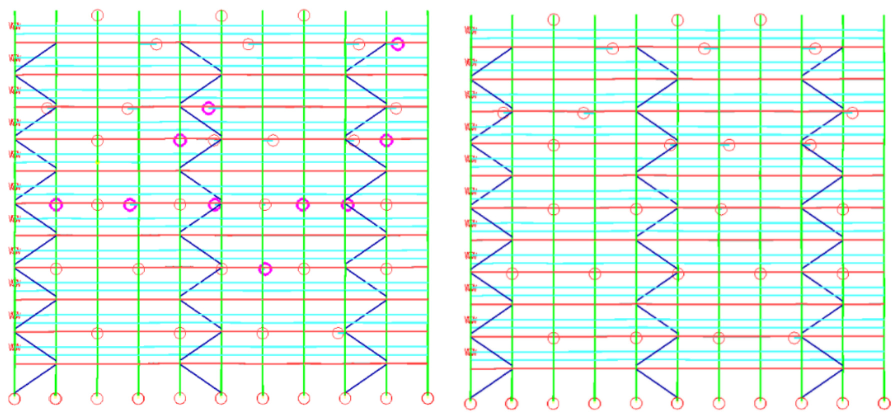

Fig. 5. Uniform modification of the anchor system: original anchor layout with marking of the eliminated anchor points (left) and elimination of 10 anchor points on the entire scaffolding (right)

5. RESULTS

In Tab. 1 the results of the calculations are presented, i.e. the first ten natural vibration frequencies while maintaining the designed anchoring system (the "Original" column), as well as after the modification of the bracing system (the next two columns) and after the elimination of selected anchor points (the last 4 columns).

Table 1
Natural frequencies of the scaffolding structure

Frequency No.	f [Hz]						
	Original	Bracing modification		Anchorage modification			
		2 shafts	5 shafts	Stage I	Stage II	Stage III	Uniform
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

Modification of the anchor and brace system significantly affects the natural vibration frequencies. An increase in the number of braces and a greater number of anchorages results in an increase in the frequency of natural vibrations. This is not the same change for all frequencies and mode shapes. The braces have a greater effect on the mode shapes associated with horizontal vibrations along the façade, while the number of anchorages has a significant effect on the values associated with modes with displacements perpendicular to the façade. Leaving a large area without anchors results in a significant reduction in the first natural vibration frequency, while the higher frequencies remain unchanged. A detailed analysis of the natural mode shapes was carried out, which shows that the arrangement of individual modes changes when the anchorage and bracing systems are modified, and the individual modes and their corresponding frequencies change their order (Bęc, 2023).

6. CONCLUSIONS

Correct placement of braces and anchorages is crucial to ensure stiffness of the scaffolding. This directly translates into a reduction in the susceptibility of the structure to dynamic loads, which in turn significantly increases the level of safety and comfort of its users. Such technical measures are crucial components of effective occupational risk management strategies aimed at accident prevention (Kuzior & Kopij, 2024). Negligence in this area, especially leaving large sections of scaffolding without proper anchorages, poses a serious threat to the structure and can lead to discomfort and even danger for people working at height. Unfortunately, such situations occur, especially when working on existing buildings, where technological specifics may make it difficult to anchor properly. It should be emphasized that insufficient concentration and anchoring of façade scaffolding adversely affects not only their dynamic properties, but also the load on individual structural elements. This can result in emergency conditions even if the loads do not exceed the permissible.

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