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STATIC AND DYNAMIC ANALYSIS OF THE STEEL VIEWING PLATFORM

ANALIZA STATYCZNO-DYNAMICZNA STALOWEJ PLATFORMY WIDOKOWEJ

A b s t r a c t

This article outlines static and dynamic analyses of the viewing platform in Trzęsacz. The steel construction consists of two parallel lattice girders placed on concrete columns. The elements of the girders are made of tubular profiles. Ultimate limit state and serviceability limit state criteria were fulfilled in accordance with algorithms from Eurocodes. This paper also presents an analysis of the platform's dynamic responses from rhythmical motion caused by human activity. The results of these calculations were checked with the comfort levels of people standing in the platform during the vibrations. Robot Structural Analysis Professional was used for the linear load case of static analysis and modal analysis.

Keywords: viewing platform, dynamic analysis, human body motion

S t r e s z c z e n i e

Artykuł przedstawia wyniki statycznej oraz dynamicznej analizy platformy widokowej w Trzęsaczu. Konstrukcja składa się z dwóch równoległych kratownic. Obiekt wykonany jest z rur stalowych o zmiennych przekrojach w zależności od wielkości sił przekrojowych. Na podstawie procedur zawartych w Eurokodach dokonano weryfikacji stanu granicznego nośności i użytkowalności wybranych elementów obiektu. Przeprowadzono ocenę wpływu intencjonalnego oddziaływania dynamicznego na konstrukcję. Sprawdzono czy nie dochodzi do przekroczenia dopuszczalnych wartości przyśpieszenia drgań z uwagi na komfort użytkowników. W programie Robot Structural Analysis Professional wykonano przestrzenny model konstrukcji, następnie przeprowadzono statyczną oraz modalną analizę.

Słowa kluczowe: platforma widokowa, analiza dynamiczna, oddziaływanie użytkowników

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1. Introduction: viewing platforms – characteristic and tasks

Viewing platforms are constructions designed for pedestrians, rather than for vehicular traffic, whose main purpose is to enable visitors to admire breathtaking views of the surrounding natural scenery. Observation decks can complement the landscape and visually link two distinct areas. Due to the fact that they are usually suspended over precipices or water obstacles, viewing terraces intensify the impressions and emotions of the people who use them. Platforms also enhance the attractiveness of tourist areas.

In many countries they are both functional objects and beautiful works of art and sculpture. Observation decks are characterized by unique shapes and forms. These constructions are one of a kind, which arouses people's interest in them.

Due to the nature of their location and function, terraces are under the influence of various kinds of loads (excitations). These are mainly atmospheric effects such as wind, rain, snow and temperature changes. A significant influence on observation decks is the pedestrian load, which determines the dynamic response. The increase of vibration problems in modern steel structures yields a significant amount of evidence that viewing platforms should be designed not only for static loads, but also for dynamics ones.

2. Viewing platform in Trzęsacz

The object of this article is the steel viewing platform (Fig. 1a, 1b), which is located near the ruins of a 12th century church situated high on the edge of a cliff in Trzęsacz (in the north of Poland). This spectacular observation deck was opened in 2009, thereby enabling tourists to admire the sea, the coast, beaches and the ruins of the historic church from an exceptional perspective.

a) b)

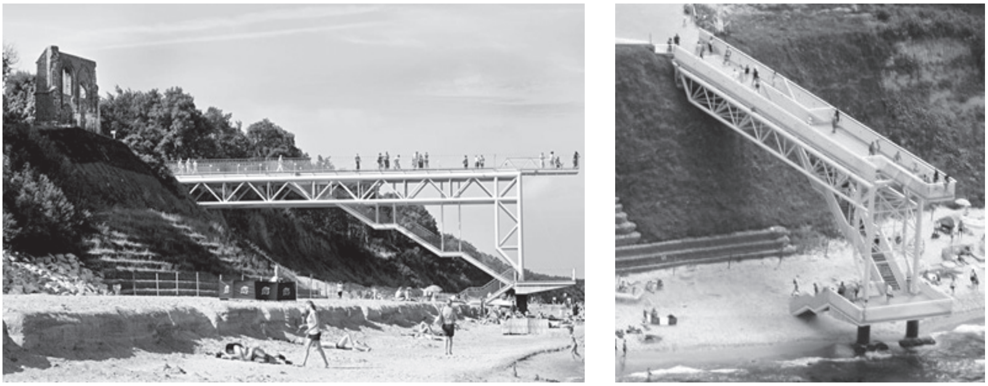

Fig. 1. The steel viewing platform in Trzęsacz: a) from the west, b) from the north

The steel construction reaches 15 meters high and consists of two parallel lattice girders, which are over 36 m long. The structure is located on two pillars placed 4.6 m from each other. The elements of the girders are made of tubular profiles and joined by welds.

Two terraces are designed within the structure: the upper one is situated 15 m above sea level and the lower one is placed 4 m above sea level. Both terraces are connected by steel stairs. A special lift for disabled tourists is also planned. Because of harsh maritime atmospheric conditions, all surfaces are covered with special protective layers.

The truss structure is a stable prop for the pedestrian deck. The bridge is designed as a grid supported by a framework of gusset plates and slides.

3. The numerical model of the platform

The three-dimensional model of the viewing platform was created in Robot Structural Analysis Professional (Fig. 2). It consists of 525 elements, mainly tubular profiles, which are connected by vertical and horizontal welds.

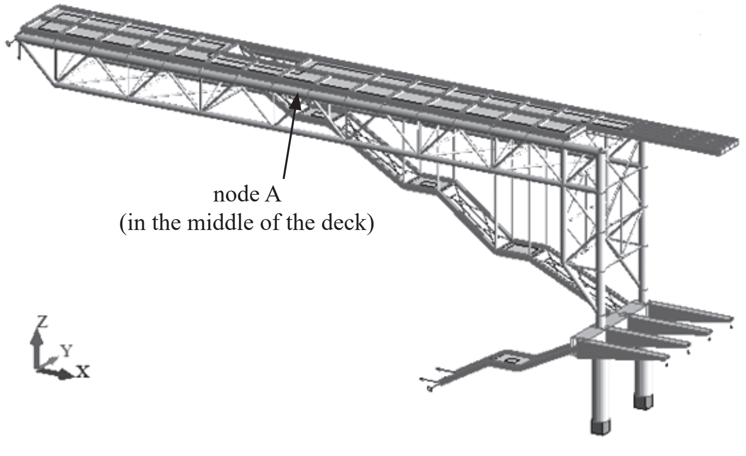

Fig. 2. The numerical three-dimensional model of the viewing platform in Trzęsacz

The construction was propped up in three places. The pillar on the land side was designed as a cross tilting support roller with the possibility of horizontal movement (in the direction of the x-axis). The concrete pillars were created as brackets. The prop on the stair side was designed as a cross tilting support roller with the possibility of vertical movement (in the direction of the z-axis).

After finishing the three-dimensional model of the structure, applying loads, and creating combinations of loads, a series of static, modal and time history analyses were made. The results were used for the calculations carried out in this work.

The structure was tested by various kinds of influences: the weight of the structure itself, environmental effects (like snow, frost, wind, and temperature changes) and a crowd occupying the upper deck of viewing platform. The largest values of internal forces were generated by structure's weight and crowd load. Maximum displacement caused by these influences occurred in the middle node of the upper deck (Fig. 2).

4. Static analysis of steel the viewing platform

There are two essential conditions which have to be considered at the design stage: the ultimate limit state (ULS) at failure and the serviceability limit state (SLS) under working loads. The ultimate limit state and serviceability limit state criteria are used to verify that the structure remains stable and can withstand multiple loads. It is important to check that the structure satisfies these criteria in order to ensure the safety of people or objects inside the structure.

The automatic calculation results of steel member verification and design were made in Robot Structural Analysis Professional to carry out the static analysis of the structure. This procedure analyzes an individual element and its nodes according to a theoretical algorithm from Eurocodes. The element verification gives a positive result, ensuring that he structure satisfies ULS and SLS criteria. The bearing capacities of every element of the steel viewing platform are enough to carry the loads. Occurred deflections do not exceed acceptable deformation.

5. Analysis of the dynamic response of rhythmical motion caused by human activity

Different types of rhythmical motion caused by human activity (walking, running, jumping, dancing, lateral body swaying etc.) can cause variable steady-state vibrations in structures. Table 1 defines the different types of activity and gives the estimated ranges of their vibration rates in structures.

Table 1

Activity rate for different types of motion

Type of motion	Activity rate [Hz]
Walking	1.6–2.4
Running	2.0–3.5
Jumping	1.8–3.4
Dancing	1.5–3.0

The natural frequencies of the construction were evaluated in Robot Structural Analysis Professional. The first frequency f_u = 2.68 Hz is associated with vertical vibrations. The typical frequency of jumping equals 1.8 Hz÷3.4 Hz, f_u = 2.68 Hz lies within this range.

The structure was tested by the force of one person jumping in the middle of the upper deck of viewing platform. The largest vertical displacements caused by structure's weight and crowd load occurred in this area of the structure. The force was divided into equal halves and applied to each of two lattice girders.

The dynamic characteristics of the steel viewing platform derived from the modal analysis made in Robot Structural Analysis Professional are presented in Table 2.

The first natural frequency exceeded the value of 1 Hz. It can be concluded that the viewing platform is characterized by high rigidity. The dynamic analysis of the structure does not take into account the dynamic influence of wind because it would not affect the results of analysis.

Table 2

The dynamic characteristics of the steel viewing platform

No. of mode shape	Frequency [Hz]	Pulsation [1/s]	Period [s]	Description
1	2.68	16.87	0.37	vibrations in the vertical (dominant) and horizontal direction
2	3.70	23.26	0.27	torsional vibrations
3	3.81	23.95	0.26	vertical vibrations (occurring only on the cantilever of the upper deck)
4	5.09	31.95	0.20	vertical vibrations
5	7.03	44.19	0.14	vertical, horizontal and torsional vibrations

The forcing function due to a person's rhythmical body motion can be mathematically described by a Fourier series of the form:

$$F_z(t) = G + \sum_{i=1}^{n} G\alpha_i \sin(2\pi i f_u t - \varphi_i)$$

where:

G – human's weight (average pedestrian weight: G = 800 N),

α_i – Fourier coefficient of the i-th harmonic (estimated values for f_u = 2.68 Hz)
$\alpha_1 = 1.732$,
$\alpha_2 = 1.164$,
$\alpha_3 = 0.564$,

i – number of the i-th harmonic (i = 1, 2, 3),
n – total number of harmonic components,
f_u – activity rate,
t_c – the contact time of the user's feet to the structure (t_c = 0.187 s),
φ – phase lag of i-th harmonic relative to the 1st harmonic $\varphi_2 = \varphi_3 = \pi(1 - f_u t_c) =$ = 1.571.

For the parameters above, the forcing function $F_z(t)$ of the dynamic interaction caused by a person jumping was created. The graph below (Fig. 3) shows that the function is periodic.

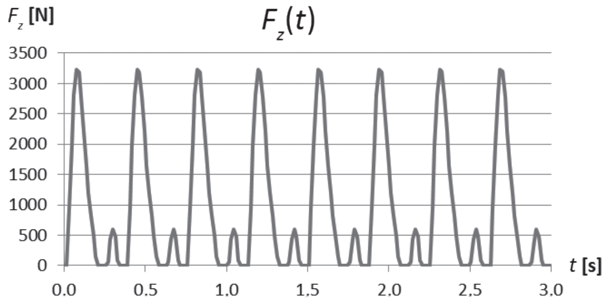

Fig. 3. Forcing function from jumping one person during 3 seconds

The time history analysis was carried out using the Newmark method to define the dynamic load of the structure. The Rayleigh model of damping was introduced in analysis. The damping coefficient (α) equal 0.34. Calculations obtained the maximum vibration acceleration, which equals 0.3 m/s². Fig. 4a and 4b present vertical displacement and vibration acceleration measured in the middle node of structure in 15 s.

The quantity of maximum vibration acceleration measured in the middle node of the structure (0.3 m/s²) does not exceed the range at which people on the platform express discomfort over the movement of the structure, which is given in various sources (see Table 3).

Table 3

Acceptable vibration acceleration given in different sources

Acceptable vibration acceleration	Source	Check
$0.5f_u^{0.5} = 0.82$ [m/s²]	BS 5400 (1978)	✓
0.7 [m/s²]	PN-EN 1990/A1 (2004)	✓
10% g = 0.98 [m/s²]	Bachmann, Ammann (1987)	✓
$1.0f_u^{0.5} = 1.64$ [m/s²]	Tilly, et al.	✓

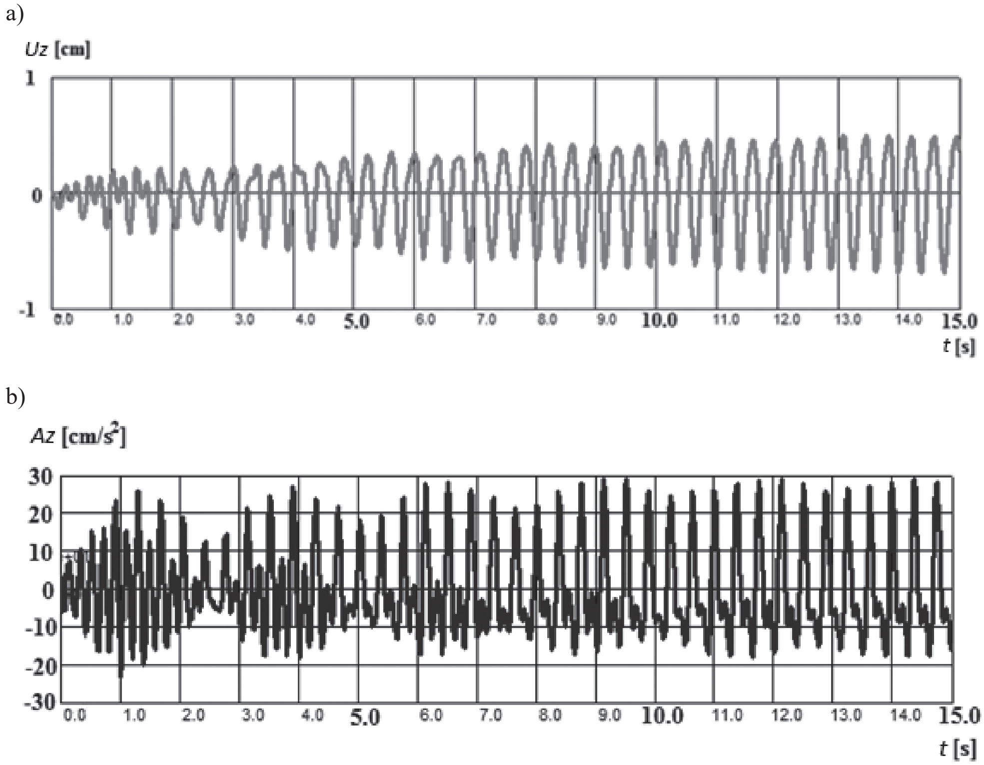

Fig. 4. Graph of: a) vertical displacement measured in node A of structure (Fig. 2) within 15 s, b) vibration acceleration measured in node A of structure (Fig. 2) within 15 s

6. Conclusions

The results of the analyses which were carried out in this article allow for the following conclusions:

– The steel viewing platform in Trzęsacz fulfills the ultimate limit state and serviceability limit state criteria in accordance with algorithms provided by Eurocodes. The observation deck satisfies the criteria for the safety of people and objects inside the structure.
– Based on the measurement of the structure's natural frequency, it can be concluded that the viewing platform is characterized by high rigidity. The platform is not susceptible to the impacts of the dynamic interaction of wind.
– The numerical dynamic analysis proved that vibrations caused by the rhythmical motion of human activity do not disturb the comfort of those on the platform.
– The vibrations are discernable to pedestrians on the viewing platform, but they are not uncomfortable nor inconvenient.
– If several people (a maximum of three, according to the research) are involved in an activity, their motion will be practically synchronized. The dynamic forces increase almost linearly with the rise of number of people on the platform.

– If three people jump in a synchronized manner, they generate vibrations, which accelerate to 0.9 m/s^2. This quantity exceeds the values allowed by British [5] and Polish engineering standards [6]. Rhythmical motions caused by human activity are classified as unusual loads. Exceeding the criteria for the comfort levels of people on the platform is acceptable because these structures are designed only for usual and habitual loads.

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