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Stefan Kondić[1], *Jelena Dobrić*[2], *Nina Gluhović*[3]

PRORAČUN PEŠAČKE PASARELE PREMA EVROKODU 9

Rezime:

Primena aluminijumskih legura u građevinarstvu, zbog svojih brojnih prednosti, nalazi široku primenu za građenje različitih tipova konstrukcija. U ovom radu prikazan je proračun pešačke pasarele koja je izvedena od ekstrudiranih elemenata od aluminijumske legure EN-AW 6082 T6, sa posebno oblikovanim poprečnim presecima tako da omoguće primenu inovativnih spojnih sredstava. Prikazan je proračun i konstruisanje veza ekstrudiranih elemenata sa zavrtnjevima koristeći preporuke date u standardu CNR-DT 208/2011 za proračun konstrukcija od aluminijumskih legura. Takođe, u radu je dat proračun vibracija pešačke pasarele, kroz različite metode proračuna. Rezultati numeričke analize poređeni su sa preporukama iz različitih, trenutno dostupnih standarda i literature koji definišu kriterijume prihvatljivosti u pogledu vibracija pešačkih pasarela.

Ključne reči: pešačka pasarela, aluminijumske legure, vibracije, specijalne veze

DESIGN OF PEDESTRIAN BRIDGE ACCORDING TO EUROCODE 9

Summary:

Aluminum alloys, due to its numerous advantages, is widely used in the construction of various types of structures in civil engineering. Design of pedestrian bridge, entirely constructed of extruded elements made of aluminum alloy EN-AW 6082 T6 with cross sections designed to enable the use of innovative joints, is presented in this paper. The design and construction of special bolted joints is presented using the recommendations given in standard for design of aluminum structures CNR-DT 208/2011. Also, calculation of pedestrian bridge vibrations through different design methods is given here. Results of numerical analysis are compared with the recommendations from different currently available standards and literature referring to the comfort criteria of pedestrian bridge vibrations.

Key words: pedestrian bridge, aluminum alloys, vibrations, special joints

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1. INTRODUCTION

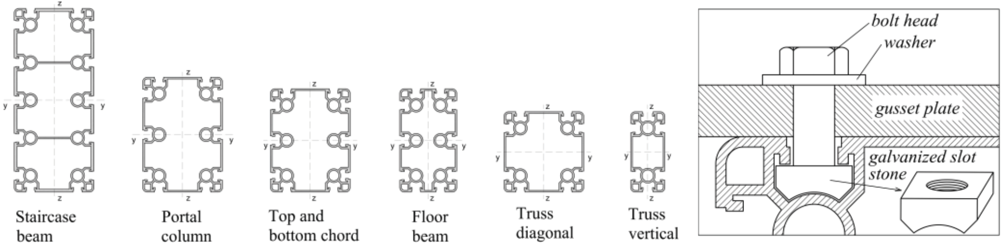
In addition to the well-known advantages of aluminum alloys such as corrosion resistance, lower weight and high strength-to-weight ratio in comparison to the carbon steel, one of the greatest advantages of aluminum alloys is the great flexibility of the cross-sectional design that the extrusion process provides. The most important advantages of the extruded profiles are the improvement of the cross-sectional properties, the optimization of the structural behavior and the weight reduction. Moreover, extruded aluminum profiles allow usage of special joints, which, unlike the traditional joints, can be completely accomplished without the cross-sectional weakening that occurs when drilling holes, for example. However, the lower modulus of elasticity of aluminum alloys and lower overall weight of the structure leads to higher susceptibility of these structures to the serviceability requirements, such as deflection and vibrations. The application of extruded aluminum alloy profiles and special joints for construction of a novel type of pedestrian bridge is presented in this paper. Moreover, vibrations of this pedestrian bridge due to human walking are analyzed through numerical model and the results are compared with different standards.

2. NUMERICAL MODEL OF PEDESTRIAN BRIDGE

The numerical model of the analyzed pedestrian bridge was developed in 3D FEA software Dlubal RFEM 5 [1]. Analyzed pedestrian bridge is a lattice girder, spanning 30 m, with a 3.0 m structural height of lattice girder. Overall width of the pedestrian bridge is 3.3 m and height is approximately 6.50 m. Vertical lattice girders are supported by the vertical portal frames. Access of the pedestrians to the bridge is enabled with the stairs, pin connected to the vertical portal frames, on the both sides of the bridge.

Figure 1 – Numerical model of pedestrian bridge

Pedestrian bridge deck consists of a deckplate and longitudinal stiffeners and is supported by the cross beams. Cross beams are pin connected to the vertical lattice structure, except at the position of vertical portal frames. Vertical portal frames are constructed from simply supported columns, vertical bracing and cross beams connected to the columns as moment resisting joint. Overall stability of the structure is accomplished using vertical and horizontal bracings, as shown in Figure 1. Cross-sections of extruded aluminum alloy EN-AW 6082 T6 profiles which are used for construction of pedestrian bridge are shown in Figure 2a, and design resistance of cross-sections and structural members are defined according to recommendations given in EN 1999-1-1 [2]. Class of cross sections of all extruded profiles is three, except for the cross beams, which are the second class.



a) extruded cross sections b) bolt-channel joint

Figure 2 – Member cross-sections and a connection detail of aluminum alloy profiles

Most commonly used special joints are: snap-fit joints, screw port joints, and bolt-channel joints. Cross section of every single member of the pedestrian bridge is specifically designed to enable the use of bolt-channel joints, which are shown in Figure 2b. Bolt-channel joints are composed of galvanized slot stone, with thread which is positioned in the channels of the extruded profiles, and bolt with the washer, as shown in Figure 2b. Construction and design of this type of joint according to CNR-DT 208/2011 [3] is in detail explained in this paper.

3. DESIGN OF BOLT-CHANNEL JOINTS

Design resistance of bolt-channel joints, which is used for connection of extruded profiles of pedestrian bridge, shown in Figure 2a, was determined according to Italian Recommendations for aluminum structures CNR-DT 208/2011 [3]. CNR-DT 208/2011, Section IV [3] defines design recommendation for this type of joint. Design resistance is determined relative to the direction of the channel/slot axis. Instead of using partial safety factor for slip resistance γ_{M3}=1.25, which is used for the design of carbon steel joints, according to EN 1993-1-8 [4], CNR DT 208/2011 [3] defines partial safety factor γ_{M3}=1.5. The main symbols which represent the dimensions of different parts of bolt-channel joint, which are used in Eq. (1) to (3), are given in Figure 3.

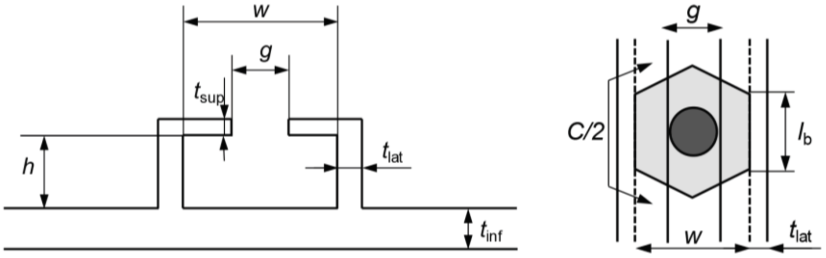


Figure 3 – Channel geometry and symbols used for design [3]

Slip resistance (bolt resistance for force acting parallel to the channel axis) should be calculated according to the Eq. (1):

$$F_{s,Rd} = \frac{n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} \tag{1}$$

where:

$F_{p,C}$ is bolt preloading force $F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s$;

μ is friction coefficient;

n is the number of friction surfaces;

A_s is nominal stress area.

Shear resistance (bolt resistance for force acting transverse to the channel axis) should be calculated according to the Eq. (2):

$$F_{v,Rd} = \frac{1.2 \cdot l_b \cdot t_{lat} \cdot f_u}{\gamma_{M3}} \tag{2}$$

where:

l_b is contact length between the web of the channel and the bolt head;

t_{lat} is web thickness of the channel;

f_u is ultimate strength of the aluminum alloy.

Pull-out resistance of bolt should be calculated according to Eq. (3):

$$F_{o,Rd} = 1.2 \cdot \frac{g \cdot t_{sup} \cdot f_u}{\gamma_{M3}} \tag{3}$$

where:

g is width of channel opening;

t_{sup} is thickness of upper flanges;

f_u is ultimate strength of the aluminum alloy.

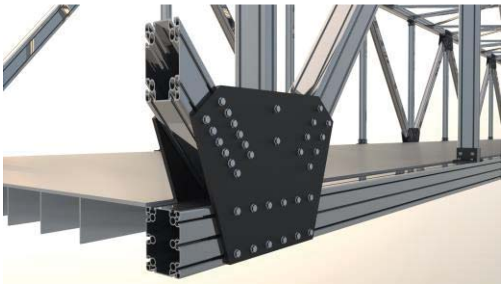


Figure 4 – Bottom chord and truss members connected using gusset plates

Figure 5 – Staircase beam and bottom chord connected to portal frame using angle plates

The bolt-channel joints of the analyzed pedestrian bridge used for the connections of different structural members are presented in Figure 4 and Figure 5. The main conclusions which are drawn from construction of this type of the joint is that relevant design resistance was always the slip resistance (design resistance in the channel axis direction), calculated according to Eq. (1). This particular resistance can be increased with the increase of bolt diameter and material properties of bolt. The shear resistance in perpendicular direction to that of the channel, according to Eq. (2) and pull out resistance according to Eq. (3) depends on the geometry of the channel and can be significantly increased by the appropriate geometric modeling of the cross-section channel.

4. PEDESTRIAN INDUCED VIBRATIONS

4.1. DESIGN METHODS

Numerical analysis of natural frequencies and accelerations of a pedestrian bridge due to human walking was performed using a 3D FEA software Dlubal RFEM 5 [1], with add-on module RF-DYNAM Pro, which is used to model different types of dynamic loads, and is capable of time-history analysis [5].

Vertical forces due to human walking, applied to the numerical model of a pedestrian bridge, are divided into different sinusoidal oscillations by a Fourier transformation [6] and should be determined according to Eq. (4):

$$F(t) = \sqrt{N} \cdot G \cdot \left(1 + \sum_{j=1}^{3} a_j \cdot sin(2\pi \cdot j \cdot f_s \cdot t - \varphi_j)\right) \tag{4}$$

and horizontal component in transverse direction [7] according to Eq. (5):

$$F(t) = \sqrt{N} \cdot G \cdot \sum_{j=1/2}^{2} a_j \cdot sin(2\pi \cdot j \cdot f_s \cdot t) \tag{5}$$

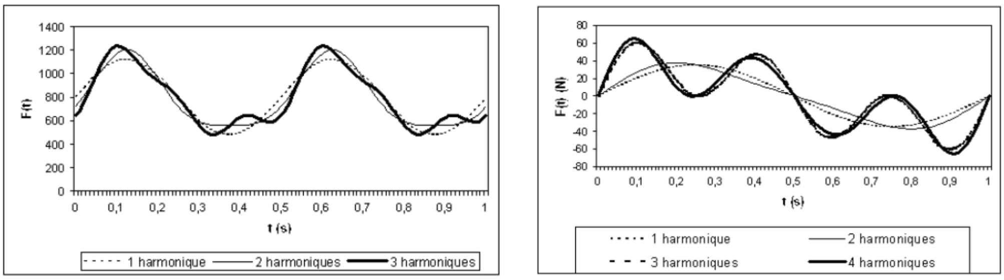
where:

N	is the number of pedestrians;
G	is the self-weight of a single pedestrian, 0.80 kN;
f_s=2 Hz	is the step frequency;
a_j	is a factor for j^{th} harmonic fraction;
φ_j	is a shift of each harmonic function.

Table 1 - The values of the Fourier transformation coefficients [6], [7]

	Vertical component		Transverse component
j	α_j	φ_j	α_j
1	$0.4+0.1\cdot(f_s-2)/0.4$	0	0.05
2	0.1	$\pi/2$	0.01
3	0.1	$\pi/2$	0.05
4	/	/	0.05

Values for different harmonics of Fourier transformation coefficients for vertical and transverse component of human walking force are given in Table 1. Pedestrian load which is applied to the numerical model of pedestrian bridge is given in Figure 6. For vibration analysis three design methods were used, two numerical FEA software based methods, and a response spectra method. Numerical methods are used for modeling of pedestrian load with or without the change of position over time (which we named *accurate* or the *simplified method*), while the *response spectra method* is based on the determination of the characteristic acceleration, which is the 95 % fractile of the maximum acceleration, for different pedestrian densities, according to recommendations from literature [7], [8].

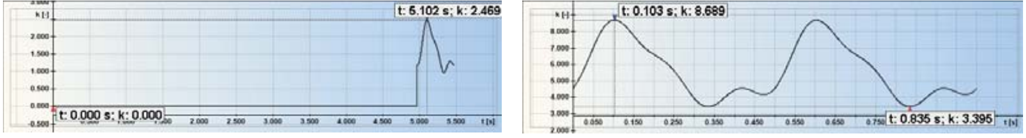


a) vertical component [7] *b) transverse component [7]*

Figure 6 –Pedestrian load applied on the numerical model of a pedestrian bridge (f_s*=2* Hz)

4.1.1. Accurate and simplified method for numerical modeling of pedestrain load

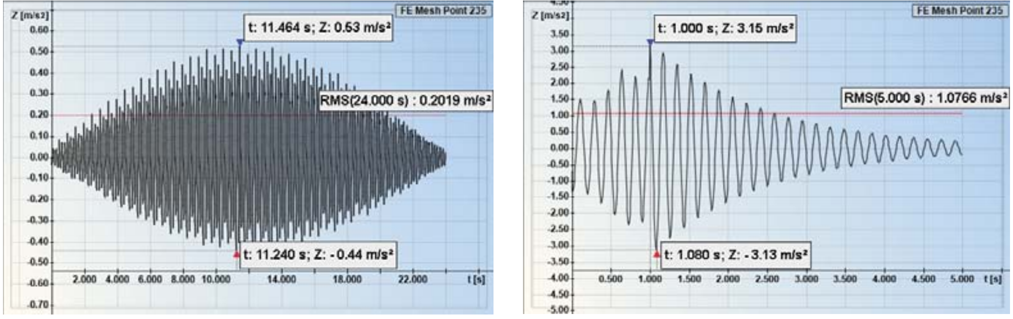
Numerical models of pedestrian walking are analyzed by two methods: accurate and simplified method. In accurate method, pedestrian walking is simulated by generating separate load cases and applying nodal loads for each position of the foot over the entire length of the bridge deck, followed by generating the corresponding time diagrams presented in Figure 7a. The step length of l_s=62.5 cm was selected so that the load was applied at the certain time interval at the middle of the bridge span.



a) accurate method *b) simplified method*

Figure 7 –Pedestrian load applied on the numerical model of a pedestrian bridge

According to simplified method, pedestrian load is applied only in nodes where greatest displacement or acceleration is expected, and corresponding time diagram is given in Figure 7b. Assuming the pedestrian bridge is a simply supported beam, with 30 m span, accelerations are analyzed only in the middle of the span.



a) accurate method *b) simplified method*

Figure 8 – Accelerations of the pedestrian bridge deck at the middle of the span

Acclerations of the pedestrian bridge deck in the middle of the bridge span according to the two diffrenet methods of analysis are presented in Figure 8. As presented in Figure 8, simplified method gives higher values of maximal peak accelerations and root mean square acclerations, which are often used for comparison with the design recomendations.

4.1.2. Response spectra method

The aim of a spectral design method is to find a simple way to describe the stochastic loading and system response that provide design values with a specific confidence level [8]. This analysis method is developed as relatively simple order-of-magnitude calculation, which can be used in common engineering practice. However, considering that this design method should incorporate various types of bridge structures and stochastic nature of pedestrian walking, the results which are given by this design method should be on the safe side of the prediction. The maximum structure acceleration should be defined according to Eq. (6):

$$a_{\mathrm{max}} = k_{\mathrm{a,95\%}} \cdot \sqrt{\frac{C \cdot \sigma_F^2}{m_{\mathrm{e,i}}} \cdot k_1 \cdot \xi^{k_2}} \qquad (6)$$

where:

$k_{\mathrm{a,95\%}}$	is the peak factor to transform the standard deviation of the response σ_{a} to the characteristic value $a_{\mathrm{max,95\%}}$;
C	is constant describing the maximum of the load spectrum;
ξ	is damping ratio;
a_1, a_2, a_3	are constants which depends on the pedestrian loading density;
b_1, b_2, b_3	are constants which depends on the pedestrian loading density;
f_{i}	is natural frequency that coincides with the mean step frequency of the pedestrian stream;
σ_{F}^2	is variance of the acceleration response;
$m_{\mathrm{e,i}}$	is modal mass of the considered mode *i*.

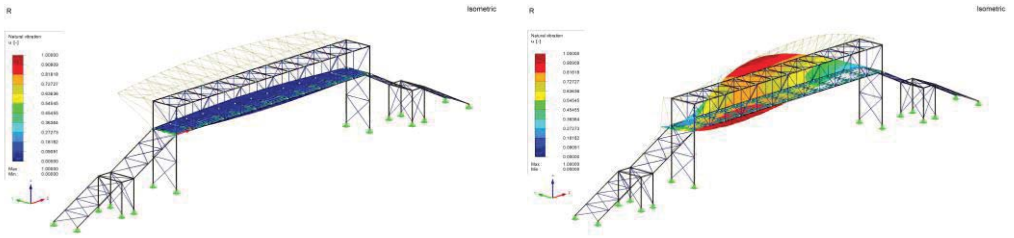
Variables k_1 and k_2 should be calculated as a function of constants a and b and considered natural frequency of the structure, as presented in Eq. (7):

$$k_1 = a_1 \cdot f_i^2 + a_2 \cdot f_i + a_3 \qquad k_2 = b_1 \cdot f_i^2 + b_2 \cdot f_i + b_3 \qquad (7)$$

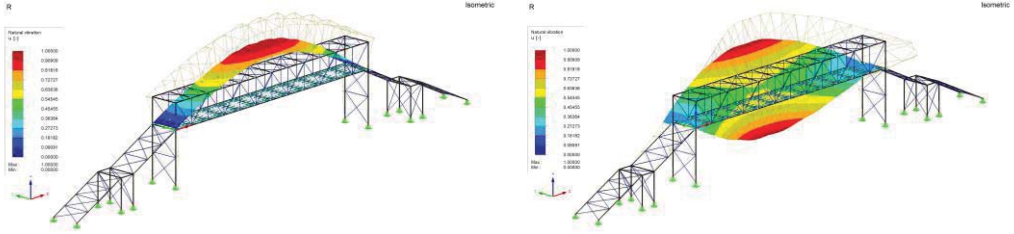
Calculation procedure using Response spectra method is explained in detail in [7] and [8], with definition of all constants used in Eq, (6) and (7). Numerical analysis of pedestrian bridge accelerations is conducted using three presented analysis methods and the results of the numerical analysis are compared with design recommendations.

4.2. RESULTS OF ANALYSIS OF PEDESTRIAN BRIDGE VIBRATIONS

The criteria regarding pedestrian comfort and design recommendations are usually expressed by limits placed on the accelerations of the pedestrian bridge deck. The acceleration of the pedestrian bridge deck in the middle of the bridge span obtained by numerical analysis in Dlubal RFEM 5 software [1] and using the response spectra method are compared with design recommendations given in EN 1990 [9] and comfort criteria given in [7]. Although the effects of horizontal vibrations are also analyzed through numerical analysis, more interesting results, from the design point of view, were the ones due to vertical vibrations in the middle of the bridge span, which are presented in this paper.



a) *First mode shape-horizontal f*=2.92 Hz   b) *Second mode shape-torsional f*=5.53 Hz



c) *Third mode shape-vertical f*=5.65 Hz   d) *Fourth mode shape-torsional f*=8.90 Hz

Figure 9 – Mode shapes and natural frequencies of pedestrian bridge

EN 1990 [9], defines limit values for accelerations in the vertical and horizontal direction, of 0.7 m/s^2 and 0.2 m/s^2, respectively, which should not be exceeded. Also, this standard defines conditions when it is necessary to perform a dynamic analysis depending on the range of natural frequencies for relevant modes. Dynamic analysis of structure should be performed when natural frequency of vertical mode shapes is less than 5 Hz and of horizontal mode shapes less than 2.5 Hz. Relevant mode shapes and natural frequencies of analyzed pedestrian bridge are shown in the Figure 9. As shown in Figure 9, natural frequencies of vertical and horizontal mode shapes are slightly higher than limiting values defined in EN 1990 [9].

Table 2 – Comfort classes of pedestrian bridge vibrations induced by human walking [7]

Comfort class	Degree of comfort	Acceleration level vertical	Acceleration level horizontal
CL1	Maximum	<0.5 m/s^2	<0.10 m/s^2
CL2	Medium	0.5 - 1.0 m/s^2	0.1 - 0.3 m/s^2
CL3	Minimum	1.0 - 2.5 m/s^2	0.3 - 0.8 m/s^2
CL4	Unacceptable discomfort	>2.5 m/s^2	>0.8 m/s^2

Comfort classes defined in [7] give a direct relation between horizontal and vertical accelerations of pedestrian bridge structure, as shown in Table 2. Comfort class should be defined based on the pedestrian bridge purpose and level of traffic over the bridge, and are classified form class 1 to class 4, which represent maximum comfort to unacceptable discomfort, respectively. Analysis which is presented in this paper includes different levels of pedestrian traffic density (from 0.15 to 1.50 pedestrians over one square meter) as given in Table 3.

Table 3 – Comparison of vertical accelerations of analyzed pedestrian bridge with design recommendations

		Bridge deck acceleration		Comparison with comfort classes [7]	Comparison with EN 1990 [9]
Design methods	Density [P/m^2]	$a_{\max}$ [m/s^2]	a_{RMS} [m/s^2]	$a_{\max}$ [m/s^2]	$a_{\max}$ [m/s^2]
RFEM Accurate	/	0.53	0.20	CL2	✓
RFEM Simplified	0.15	1.72	0.59	CL3	✗
	0.20	1.99	0.68	CL3	✗
	0.50	3.15	1.08	CL4	✗
	1.00	4.45	1.52	CL4	✗
	1.50	5.45	1.86	CL4	✗
Response spectra	0.15	$a_{d,vert}$=1.64 m/s^2		CL3	✗
	0.20	$a_{d,vert}$=1.90 m/s^2		CL3	✗
	0.50	$a_{d,vert}$=3.00 m/s^2		CL4	✗
	1.00	$a_{d,vert}$=3.17 m/s^2		CL4	✗
	1.50	$a_{d,vert}$=2.05 m/s^2		CL4	✗

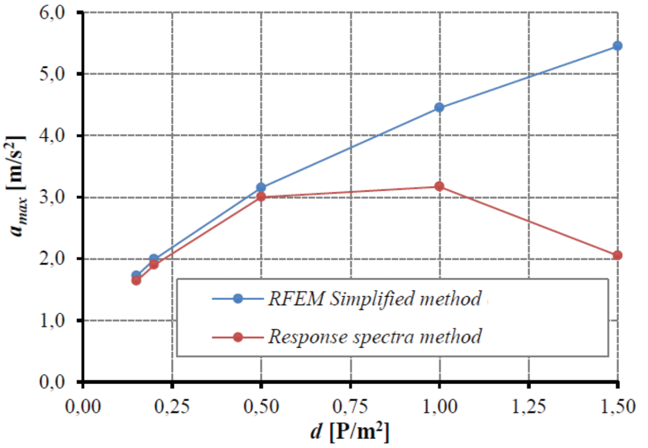


Figure 10 – Comparison of maximum vertical accelerations for different pedestrian traffic

As shown in Table 3, design recommendations which are given in EN 1990 [9] are satisfied only using the accurate numerical modeling of pedestrian loading in numerical analysis. Also, the accurate method of pedestrian load modeling resulted in fulfillment of the comfort criteria for the comfort class 2, which represent the medium comfort class. The simplified approach of pedestrian load modeling or calculation of vertical accelerations according to response spectra leads to fulfillment of the comfort class 3 for the lower values of pedestrian traffic density (0.15 P/m^2 and 0.2 P/m^2). The higher values of pedestrian traffic density over the bridge span, leads to comfort class 4, which represent unacceptable discomfort.

Comparison of the maximal accelerations obtained from the numerical analysis using the simplified method with the results obtained from the response spectra method, is given in Figure 10. Note that the difference between the maximum acceleration values obtained from the two methods is small for densities of pedestrian traffic up to 0.5 P/m^2. However, the difference significantly increases for higher densities. This is due to the static nature of the pedestrian load for the high traffic densities, which the response spectra method takes into account.

Based on the comparison with the corresponding pedestrian bridge model made of the cold-formed steel profiles, it is obvious that the aluminum pedestrian bridge is much more sensitive to the pedestrian-induced vibrations. The acceleration that occurs is up to five times higher than that of similar carbon steel bridge **Error! Reference source not found.**, [11]. This is particular to the material used - the low damping, and the low weight of the pedestrian bridge made of aluminum which makes up only 45% of the total weight of the steel bridge.

5. CONCLUSION

The main objective of this paper was to investigate vibrations induced by pedestrian traffic in a novel aluminum pedestrian bridge, as well as to investigate the possibility of application of extruded profiles and special bolt-channel joints.

The implementation of extruded profiles and special joints appears to be a good solution in terms of optimizing the cross-sectional properties and avoiding the cross-sectional weakening at the joint location. Bearing capacity of a single bolt in special joints, although smaller than of the traditional joints of carbon steel, can be significantly increased by using a larger bolt diameter and by adjusting the geometry of the cross-section of the extruded profiles. Also, the lower weight of the aluminum alloy structure and the relatively simple assembly of the presented joints, results in a significantly easier and faster installation in comparison to the similar carbon steel structure.

EN 1990 [9] does not define precise recommendations for fulfillment of pedestrian bridge vibrations criteria. The upper bounds of the maximal accelerations, prescribed by the standard, can be satisfied only by a detailed numerical analysis and the accurate method of pedestrian load modeling, of the analyzed pedestrian bridge. The simplified method for pedestrian load modeling or calculation according to response spectra method leads to the higher values of vertical accelerations and medium or minimal comfort classes depending on pedestrian traffic density.

Response spectra method, considered to be relatively simple calculation procedure, can often lead to higher values of vertical accelerations or even unacceptable discomfort for pedestrians, especially in the case of structures made form light materials such as aluminum. Therefore, detailed numerical analysis is sometimes necessary in order to satisfy high comfort criteria and serviceability of the structure.

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