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# ANALIZA NOSIVOSTI I UPOTREBLJIVOSTI ČELIČNE PASARELE PREMA EVROKODU

***Rezime:***

Ovaj rad ukratko prikazuje analiizu nosivosti i upotrebljivosti čelične konstrukcije pešačke pasarele. Noseća konstrukcija, fomirana od hladno-oblikovanih profila, dimenzionisana je prema EN 1993-1-3. Analizirane su vibracije mosta i data komparatvna studija sa stanovišta različitih kriterijuma u pogledu komfora prema Evrokodu i prema SETRA/AFGC preporukama. Rad takođe poredi ponašanja čelične pešačke pasarele sa statički i konstruktivno ekvivalntnom pasarelom čiji je osnovni materijal Al legura.

*Ključne reči: pasarela, hladno oblikovani profili, Evrokod, vibracije, klase komfora*

# RESISTANCE AND SERVICEABILITY ANALYSIS OF STEEL FOOTBRIDGE STRUCTURE ACCORDING TO EUROCODE

***Summary:***

This paper briefly presents resistance and serviceability analysis of steel footbridge structure. The main structural system consists of cold-formed members, which were designed according to EN 1993-1-3. Analysis of vibration of the footbridge structure was performed, including comparative study from the aspect of different criteria regarding the comfort according to Eurocode and SETRA/AFGC recommendations. Additionally, the paper compares behavior of steel footbridge with static and structural equivalent footbridge whose base material is aluminum alloy.

*Key words: footbridge, cold-formed members, Eurocode, vibration, comfort classes*

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## 1. INTRODUCTION

Thin-walled cold-formed steel has growing base of application in civil engineering structures. The cold-formed steel members have been used for different building systems serving as purlins, wall girts, and the building covers. An essential feature of thin-walled elements is that cross-section local stability should be considered in their design, because it often contributes to their overall structural responses under load. Unlike the base part of European specification EN 1993-1-1 [1], where the design of structural element begins with the classification of cross sections, Eurocode for design of cold-formed structures EN 1993-1-3 [2] assumes that cross-section is slender and no full effective due to early elastic local buckling. For design of slender steel cold-formed structures, the effective-width concept is applied.

This paper presents structural analysis of steel footbridge. The lattice structural system was adopted for the main bearing structure including orthotropic steel decks for footpaths. The geometrical dimensions of the main pedestrian bridge structure are: span length is 30 m, width is 3,3 m and height is 3 m. All structural elements were designed as cold-formed members including open, press-braked sections and hollow cold-rolled sections. Figures 1-3 show adopted cross-sections of the man structural elements. The design resistance predictions for ultimate and serviceability limit states were calculate according to recommendations given in EN 1993-1-3 [2] and EN 1993-2 [3]. The base material is steel S355. Static and dynamic calculations were made using the Dlubal RFEM software program [4].

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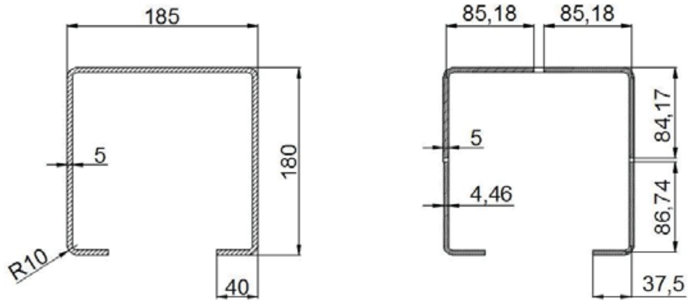

*Figure 1 – Main truss chords, gross cross-section on the left, effective cross-section on the right*

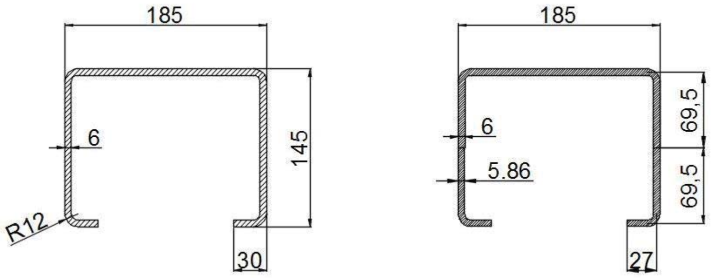

*Figure 2 – Main truss diagonal, gross cross-section on the left, effective cross-section on the right*

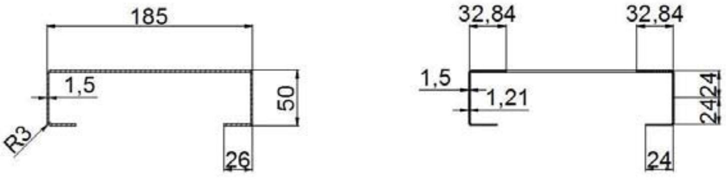

*Figure 3 – Main truss vertical, gross section on the left, effective cross-section on the right*

## 2. VIBRATIONS

### 2.1 EUROCODE PEDESTRIAN COMFORT CRITERIA (FOR SERVICEABILITY)

Eurocode 1990 [5] gives recommendations for Serviceability Limit States, which is, inter alia, related to vibration pedestrian bridges:

(1) The comfort criteria should be defined in terms of maximum acceptable acceleration of any part of the deck.

The following accelerations are the recommended maximum values for any part of the deck:

- 0,7 m/s$^2$ for vertical vibrations,
- 0,2 m/s$^2$ for horizontal vibrations due to normal use,
- 0,4 m/s$^2$ for exceptional crowd conditions.

(2) A verification of the comfort criteria should be performed if the fundamental frequency of the deck is less than:

- 5 Hz for vertical vibrations,
- 2,5 Hz for horizontal (lateral) and torsional vibrations.

### 2.2 COMFORT CLASSES AND ACCELERATION RANGES

The comfort classes for different acceleration ranges of the bridge recommended by this guideline are presented in the Table 1. In general, four comfort classes are distinguished. The given comfort classes and acceleration levels are values given by Charles and Hoorpah with reference to the SETRA/AFGC guidelines [9].

*Table 1 – Definition of comfort classes and related acceleration ranges* [6]

| *Comfort level* | *Degree of comfort* | *Acceleration level vertical* | *Acceleration level horizontal* $a_{limit}$ |
|---|---|---|---|
| *CL1* | *maximum* | $<0{,}5\ m/s^2$ | $<0{,}10\ m/s^2$ |
| *CL2* | *medium* | $0{,}50 - 1{,}00\ m/s^2$ | $0{,}10 – 0{,}30\ m/s^2$ |
| *CL3* | *minimum* | $1{,}00 – 2{,}50\ m/s^2$ | $0{,}30 – 0{,}80\ m/s^2$ |
| *CL4* | *unacceptable discomfort* | $>2{,}50\ m/s^2$ | $>0{,}80\ m/s^2$ |

## 2.3 MODAL ANALYSIS

Modal analysis is done to check if Eurocode 1990 [5] requirements, which refer to the fundamental frequency, are satisfied. As results, modal analysis gives the characteristic mode shapes and corresponding frequency values necessary for vibration analysis.

Results obtained by modeling in the RFEM program are shown in Figures 4-6 [4]:

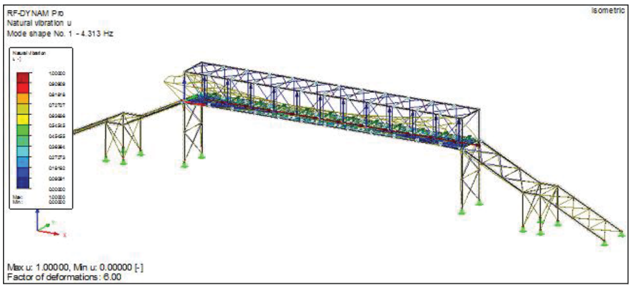

*Figure 4 – First mode shape, horizontal* $f_1$*=4,313Hz*

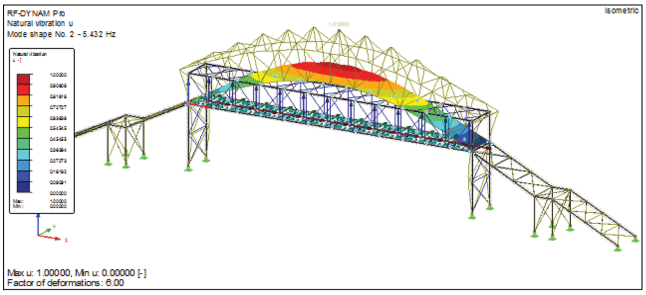

*Figure 5 – Second mode shape, vertical* $f_2$*=5,432Hz*

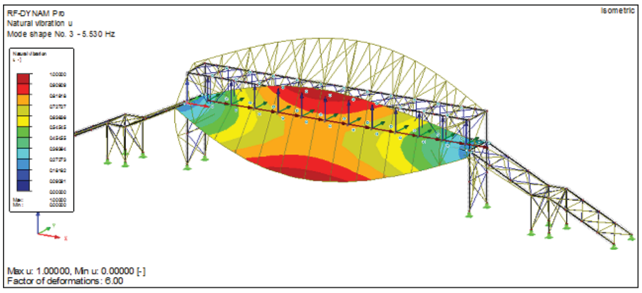

*Figure 6 – Third mode shape, torsion $f_3$=5,530Hz*

Authoritative node for the analysis of vertical vibration (Figure 7) was selected based on the maximum amplitude of the second mode shape (Figure 5), which is provided in the appropriate vertical direction. The first mode shape (Figure 4), in the horizontal direction, shows that no node in the zone of the lower belt of the bridge, i.e. the board on which the pedestrians are walking, has pointed out. So in the analysis of horizontal vibrations, the same node (Figure 7) is observed.

Since the research goal is to compare the vibration results of the steel bridge made from cold-formed members with an analog bridge made of aluminum, it was necessary to analyze the results of the node emphasized on Figure 8.

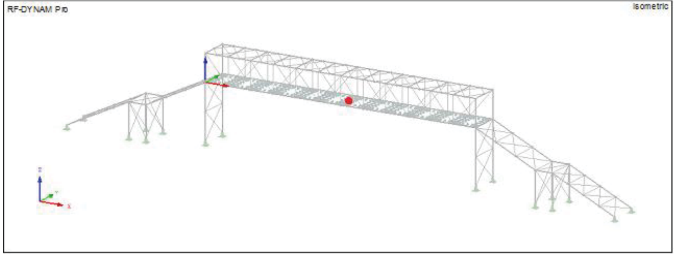

*Figure 7 – Node 1 position in the mid of a span*

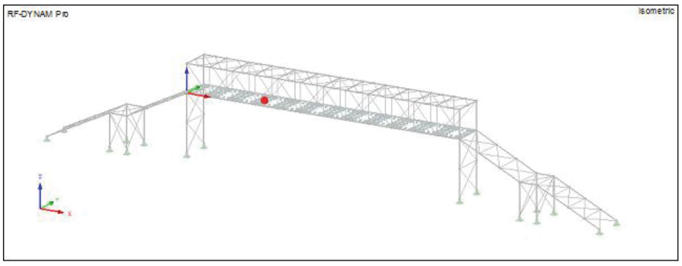

*Figure 8 – Node 2 position in the quarter of a span*

## 2.4 DESIGN – VIBRATIONS INDUCED BY PEDESTRIAN TRAFFIC

By observing the pedestrians while walking, it can be noted that each step represents a single impulse, while the steps during movement are a series of impulses moved along the path and time. Assuming that the load of both feet is the same, and that it takes time for the foot to be fixed on a surface constant for a particular walk mode, the load induced by the stroke is periodic and can be divided into different sinusoidal oscillations using the Fourier transform [7]. Time history analysis has common use in dynamic analysis of the structures by software. A full and simplified Time history analysis in RFEM is considered.

Accurate – RFEM Time history analysis [8] covers simulation of the human movement to gain the response of the construction as the maximum acceleration.

For the vertical vibrations, Bachmann [8] represents the load of the human walk at a normal pace of 2 Hz (taking into account the first three harmonics) as:

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

where:

| | |
|---|---|
| $G=0{,}8$ kN | self-weight of one pedestrian |
| $N=4$ | number of pedestrians (adopted 4 for natural frequencies $f > 2{,}4\ Hz$) |
| $\alpha_j$ | load component for $j$-th harmonic (Table 2) |
| $\varphi_j$ | phase angle of the $j$ -th harmonic (Table 2) |
| $f_s=2$ Hz | adopted frequency of walking |

*Table 2 – Fourier terms for the process of walking* [8]

| *j* | $\alpha_j$ | $\varphi_j$ |
|---|---|---|
| *1* | $0{,}4+0{,}1\ (f_s\text{-}0{,}2)/4$ | *0,0* |
| *2* | *0,1* | $\pi/2$ |
| *3* | *0,1* | $\pi/2$ |

The transverse component, corresponding to changing from one foot to the other when walking, occurs, therefore, at a frequency of half that of the frequency of walking (1 Hz for $f_s$= 2 Hz). Taking into account the first three harmonics, Fourier coefficients of lateral force components can be described as [9]:

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

where:

*Table 3 – Components of load for j-th harmonics*

| *j* | $\alpha_j$ |
|---|---|
| *1/2* | *0,05* |
| *1* | *0,05* |
| *3/2* | *0,05* |
| *2* | *0,05* |

For the application simplified analysis (RFEM No position dependency) [8], the same functions (1) and (2) are used to describe the human walk as in the RFEM Time history analysis, but with different numbers of pedestrians (3) and without changing the position. The relevant nodes (Figures 7-8) and their reaction for different traffic densities are examined.

$$N=b \cdot L \cdot d \tag{3}$$

where:

b=3,3 m is bridge width
L=30 m is span length
d is traffic density (Table 4)

*Table 4 – Pedestrian traffic classes and densities* [6]

| *Traffic class* | *Density d (P=person)* | *Description* | *Characteristics* |
|---|---|---|---|
| *TC1* | *group of 15P*<br>*d=15 P/bl* | *Very weak traffic* | *(b=width of deck; l =length of deck)* |
| *TC2* | *d=0,2 P/m$^2$* | *Weak traffic* | *Comfortable and free walking,*<br>*Overtaking is possible,*<br>*Single pedestrians can freely choose pace.* |
| *TC3* | *d=0,5 P/m$^2$* | *Dense traffic* | *Significantly dense traffic,*<br>*Unrestricted walking,*<br>*Overtaking can be intermittently inhibited.* |
| *TC4* | *d= 1,0 P/m$^2$* | *Very dense traffic* | *Freedom of movement is restricted,*<br>*Uncomfortable situation,*<br>*obstructed walking,*<br>*Overtaking is no longer possible.* |
| *TC5* | *d=1,5 P/m$^2$* | *Exceptional dense traffic* | *Very dense traffic and unpleasant walking,*<br>*Crowding begins,*<br>*One can no longer freely choose pace.* |

## 2.5 COMPARISON OF RESULTS

This section presents the comparative dynamic analysis between footbridge structural systems made from cold-formed sections presented in this paper, and aluminum alloy presented in study of Kondić [10-11]. Table 5 and 6 compare their vertical and horizontal fundamental frequency in accordance with EN 1990 [5] and SETRA guidelines [9], respectively.

It can be seen from Table 5 that, regarding to values of the vertical and horizontal fundamental frequency of both bridges, a verification of the comfort criteria is not needed according to EN 1990 [5].

Given used methods, there are quite big margins in obtained results - from the fact that, according to the first method, the steel bridge meets the comfort conditions according to the requirements of EN 1990 [5] and provides maximum comfort according to the classification by SETRA guidelines [9], to the extent that, according to the third method nothing is fulfilled.

The vertical acceleration (Table 5) of the Aluminum Bridge (mass 12.6 t) is several times higher than the acceleration of the steel bridge (mass 27.9 t). The horizontal acceleration (Table 6) of the two bridges is approximately the same except for the Spectra response method.

*Table 5 – Vertical acceleration results compared with EN 1990 comfort demand and Comfort level*

| | *Cold-formed steel footbridge* | | | | *Aluminum alloy footbridge* [10] | | | |
|---|---|---|---|---|---|---|---|---|
| | *Node 2* $a_{max,vert}$ $[m/s^2]$ | *Node 1* $a_{max,vert}$ $[m/s^2]$ | *Comfort level* | *EN 1990* | *Node 2* $a_{max,vert}$ $[m/s^2]$ | *Node 1* $a_{max,vert}$ $[m/s^2]$ | *Comfort level* | *EN 1990* |
| *RFEM Time history analysis* | *0,07* | *0,10* | *CL1* | √ | *0,82* | *0,53* | *CL2* | *x* |
| *RFEM No position dependency* | - | - | | | - | - | | |
| *d=0,15* | *0,36* | *0,60* | *CL2* | √ | *1,71* | *1,72* | *CL3* | *x* |
| *d=0,2* | *0,42* | *0,69* | *CL2* | √ | *1,97* | *1,99* | *CL3* | *x* |
| *d=0,5* | *0,66* | *1,10* | *CL3* | *x* | *3,12* | *3,15* | *CL4* | *x* |
| *d=1,0* | *0,93* | *1,55* | *CL3* | *x* | *4,42* | *4,45* | *CL4* | *x* |
| *d=1,5* | *1,14* | *1,90* | *CL3* | *x* | *5,41* | *5,45* | *CL4* | *x* |
| *Response spectra method* [6] | $a_{d,vert}[m/s^2]$ | | | | $a_{d,vert}[m/s^2]$ | | | |
| *d=0,15* | *0,73* | | *CL2* | *x* | *1,64* | | *CL3* | *x* |
| *d=0,2* | *0,83* | | *CL2* | *x* | *1,90* | | *CL3* | *x* |
| *d=0,5* | *1,32* | | *CL3* | *x* | *3,00* | | *CL4* | *x* |
| *d=1,0* | *1,41* | | *CL3* | *x* | *3,17* | | *CL4* | *x* |
| *d=1,5* | *0,99* | | *CL2* | *x* | *2,05* | | *CL4* | *x* |
| *Mass* | *27,9 t* | | | | *12,6 t* | | | |
| *Vert. frequency* | *5,43 Hz* | | | | *5,65 Hz* | | | |
| *Lat. frequency* | *4,31 Hz* | | | | *2,92 Hz* | | | |

*Table 6 – Horizontal acceleration results compared with EN 1990 comfort demand and Comfort level*

| | *Cold-formed steel footbridge* | | | | *Aluminum alloy footbridge* [10] | | | |
|---|---|---|---|---|---|---|---|---|
| | *Node 2* $a_{max,lat}$ *[m/s$^2$]* | *Node 1* $a_{max,lat}$ *[m/s$^2$]* | *Comfort level* | *EN 1990* | *Node 2* $a_{max,lat}$ *[m/s$^2$]* | *Node 1* $a_{max,lat}$ *[m/s$^2$]* | *Comfort level* | *EN 1990* |
| *RFEM Time history analysis* | *0.01* | *0.01* | *CL1* | √ | *0,02* | *0,03* | *CL1* | √ |
| *RFEM No position dependency* | - | - | | | - | - | | |
| *d=0,15* | *0,03* | *0,04* | *CL1* | √ | *0,03* | *0,05* | *CL1* | √ |
| *d=0,2* | *0,03* | *0,05* | *CL1* | √ | *0,04* | *0,05* | *CL1* | √ |
| *d=0,5* | *0,05* | *0,08* | *CL1* | √ | *0,06* | *0,09* | *CL1* | √ |
| *d=1,0* | *0,07* | *0,11* | *CL2* | √ | *0,08* | *0,12* | *CL2* | √ |
| *d=1,5* | *0,09* | *0,14* | *CL2* | √ | *0,10* | *0,15* | *CL2* | √ |
| *Response spectra method* [6] | $a_{max,lat}$*[m/s$^2$]* | | | | $a_{max,lat}$*[m/s$^2$]* | | | |
| *d=0,15* | *0,77* | | *CL3* | *x* | *1,94* | | *CL4* | *x* |
| *d=0,2* | *0,89* | | *CL4* | *x* | *2,23* | | *CL4* | *x* |
| *d=0,5* | *1,40* | | *CL4* | *x* | *3,53* | | *CL4* | *x* |
| *d=1,0* | *1,75* | | *CL4* | *x* | *4,88* | | *CL4* | *x* |
| *d=1,5* | *1,71* | | *CL4* | *x* | *6,57* | | *CL4* | *x* |

## 3. CONCLUSION

EN 1990 [5] is stiff with only one limit of the required comfort. Classification of comfort in four levels is more practical.

According to the EN 1990 [5], no comfort check is necessary when the required limits demands of the bridge's fundamental frequencies are satisfied. In the case of a steel bridge, the validity of this condition is confirmed by the first most precise method, while in the case of Al bridge is not.

Response spectra method calculations are on the safe side and engineers should apply them to small objects, while for larger structures a more accurate software calculation should be used.

When comparing the result of vibrations of the pedestrian bridge from cold-formed steel members and aluminum, the results were less favorable for aluminum due to less weight.

### ACKNOWLEDGMENT

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