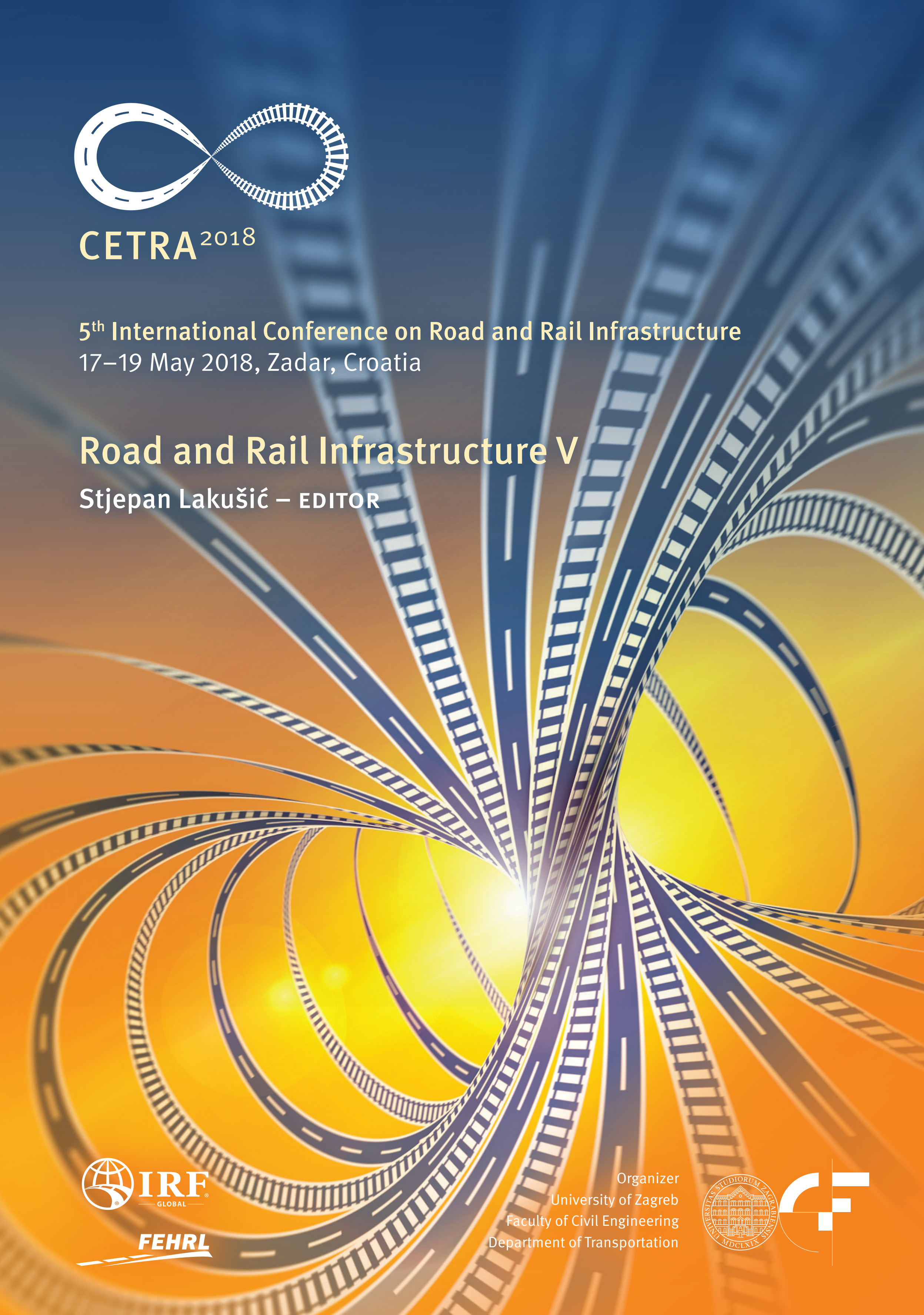

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

IRF GLOBAL

FEHRL

Organizer
University of Zagreb
Faculty of Civil Engineering
Department of Transportation

CETRA^{2018}
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

TITLE
Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

ISBN
978-953-8168-25-3

DOI
10.5592/CO/CETRA.2018

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
“Tiskara Zelina”, May 2018

COPIES
500

Zagreb, May 2018.

Although all care was taken to ensure the integrity and quality of the publication and the information herein, no responsibility is assumed by the publisher, the editor and authors for any damages to property or persons as a result of operation or use of this publication or use the information’s, instructions or ideas contained in the material herein.
The papers published in the Proceedings express the opinion of the authors, who also are responsible for their content. Reproduction or transmission of full papers is allowed only with written permission of the Publisher. Short parts may be reproduced only with proper quotation of the source.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

EDITOR
Stjepan Lakušić
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Zagreb, Croatia

CETRA^{2018}
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

ORGANISATION

CHAIRMEN

Prof. **Stjepan Lakušić**, University of Zagreb, Faculty of Civil Engineering
Prof. emer. **Željko Korlaet**, University of Zagreb, Faculty of Civil Engineering

ORGANIZING COMMITTEE

Prof. **Stjepan Lakušić**
Prof. emer. **Željko Korlaet**
Prof. **Vesna Dragčević**
Prof. **Tatjana Rukavina**
Assist. Prof. **Ivica Stančerić**
Assist. Prof. **Maja Ahac**
Assist. Prof. **Saša Ahac**
Assist. Prof. **Ivo Haladin**
Assist. Prof. **Josipa Domitrović**
Tamara Džambas
Viktorija Grgić
Šime Bezina
Katarina Vranešić
Željko Stepan
Prof. **Rudolf Eger**
Prof. **Kenneth Gavin**
Prof. **Janusz Madejski**
Prof. **Nencho Nenov**
Prof. **Andrei Petriaev**
Prof. **Otto Plašek**
Assist. Prof. **Andreas Schoebel**
Prof. **Adam Szeląg**
Brendan Halleman

INTERNATIONAL ACADEMIC SCIENTIFIC COMMITTEE

Stjepan Lakušić, University of Zagreb, president
Borna Abramović, University of Zagreb
Maja Ahac, University of Zagreb
Saša Ahac, University of Zagreb
Darko Babić, University of Zagreb
Danijela Barić, University of Zagreb
Davor Brčić, University of Zagreb
Domagoj Damjanović, University of Zagreb
Sanja Dimter, J. J. Strossmayer University of Osijek
Aleksandra Deluka Tibljaš, University of Rijeka
Josipa Domitrović, University of Zagreb
Vesna Dragčević, University of Zagreb
Rudolf Eger, RheinMain Univ. of App. Sciences, Wiesbaden
Adelino Ferreira, University of Coimbra
Makoto Fujiu, Kanazawa University
Laszlo Gaspar, Széchenyi István University in Győr
Kenneth Gavin, Delft University of Technology
Nenad Gucunski, Rutgers University
Ivo Haladin, University of Zagreb
Staša Jovanović, University of Novi Sad
Lajos Kisgyörgy, Budapest Univ. of Tech. and Economics
Anastasia Konon, St. Petersburg State Transport Univ.
Željko Korlaet, University of Zagreb
Meho Saša Kovačević, University of Zagreb
Zoran Krakutovski, Ss. Cyril and Methodius Univ. in Skopje
Dirk Lauwers, Ghent University
Janusz Madejski, Silesian University of Technology
Goran Mladenović, University of Belgrade
Tomislav Josip Mlinarić, University of Zagreb
Nencho Nenov, University of Transport in Sofia
Mladen Nikšić, University of Zagreb
Andrei Petriaev, St. Petersburg State Transport University
Otto Plašek, Brno University of Technology
Mauricio Pradena, University of Concepcion
Carmen Racanel, Tech. Univ. of Civil Eng. Bucharest
Tatjana Rukavina, University of Zagreb
Andreas Schoebel, Vienna University of Technology
Ivica Stančerić, University of Zagreb
Adam Szeląg, Warsaw University of Technology
Marjan Tušar, National Institute of Chemistry, Ljubljana
Audrius Vaitkus, Vilnius Gediminas Technical University
Andrei Zaitsev, Russian University of transport, Moscow

CETRA^{2018} 17–19 May 2018, Zadar, Croatia
5th International Conference on Road and Rail Infrastructure

SIMPLIFIED PROCEDURE FOR MAXIMUM ACCELERATION DETERMINATION ON SIMPLE BRIDGE STRUCTURES

Ivana Štimac Grandić, Davor Grandić, Nina Čepić
University of Rijeka, Faculty of Civil Engineering, Croatia

Abstract

A verification of the comfort criteria for serviceability limit state due to pedestrians should be done if the fundamental frequencies of the bridge deck are below values determined in bridge design codes. Nowadays, the comfort criteria is usually defined as maximum acceptable acceleration of any part of the bridge deck. Dynamic load models of single pedestrian and group of pedestrians are determined as single pulsating force moving along the bridge. Though the model of moving pulsating force is similar to real character of pedestrian loading (walking along the bridge) acceleration assessment is not simple because the lack of easily available software able to conduct dynamic analysis due to moving loads. The process of bridge designing can be significantly accelerated if a simplified procedure for maximum acceleration determination is established. In this paper an improved simplified procedure based on response of single degree of freedom oscillator i.e. response of a structure due to pulsating stationary force of unlimited duration is proposed.

Keywords: SLS, pedestrian bridge, acceleration, beam structures

1 Introduction

Formulation of footbridge vibration serviceability design procedures has been in focus of researchers and engineers for many years. To satisfy the serviceability limit state in relation to vibration due to pedestrians the maximum value of dynamic response of the bridge deck should be smaller than the value of comfort criteria defined through the corresponding value of bridge deck dynamic response.

Nowadays, the comfort criteria are given in terms of maximum acceptable accelerations of any part of the bridge deck [1] as recommended maximum values. For example the limit value for acceleration in vertical direction according to HRN EN 1990 [1] is 0,7 m/s^2.

The aim of most of the design procedures is to determine the peak response of a footbridge in order to assess its vibration serviceability. The process of bridge designing can be significantly accelerated if a simplified procedure for maximum acceleration determination is established.

The dynamic load model of single pedestrian or group of pedestrians in vertical direction F(t) is usually defined as pulsating harmonic force presented in Eq. (1)

$$F(t) = F \cdot \sin(2 \cdot \pi \cdot f \cdot t) \tag{1}$$

which moves along the bridge with speed of $v = l_s \cdot f$ where F is amplitude of the pulsating force, l_s is the step length, f is the fundamental bridge and t is the time [2-6].

DOI: https://doi.org/10.5592/CO/CETRA.2018.835

The simplified procedures for determination of maximum acceleration are based on analytical formulae for response of single degree of freedom (SDOF) oscillator due to pulsating stationary force of unlimited (Eq. 2) or limited duration (Eq. 3).

$$a_{max,stat} = \frac{F}{M_{gen}} \cdot \frac{\pi}{\delta} \tag{2}$$

$$a_{max,stat} = \frac{F}{M_{gen}} \cdot \frac{\pi}{\delta}\left(1 - e^{-n\delta}\right) \tag{3}$$

Where F is the amplitude of stationary pulsating force, M_{gen} is the modal mass of equivalent SDOF oscillator, n is the number of steps needed to cross the span (number of cycles per span) and δ is the logarithmic decrement, which is equal to $2\pi\zeta$ (ζ is the structural damping) [7]. The maximum response of structure due to stationary pulsating force, $a_{max,stat}$, is different from response due to moving pulsating force, $a_{max,mov}$. The reason of mentioned difference is the variation of the mode shape amplitude along the walking path and force duration. Therefore the factor R should be introduced in analytical formulae for response of single degree of freedom oscillator due to pulsating stationary force (Eq. 4).

$$a_{max,mov} = R \cdot a_{max,stat} \tag{4}$$

Procedures given in some codes and guides [2,3,5,6,8] which are based on stationary pulsating force define different constant values of factor R even though it is known that constant factor could not involve all possible situations produced by different bridge structures.
In this paper an improved simplified procedure for maximum acceleration determination on simple beam structures is proposed by introducing a novel approach based on response of single degree of freedom oscillator i.e. response of a structure due to pulsating stationary force of unlimited duration. The main goal of the proposed procedure is to make the formulation easy to use.

2 Improved simplified procedure for maximum acceleration determination

If we introduce Eq. (2) into Eq. (4) then:

$$a_{max,mov} = R \cdot \frac{F}{M_{gen}} \cdot \frac{\pi}{\delta} \tag{5}$$

With some transformation Eq. (5) can be written as follows:

$$a_{max,mov} = \Phi \cdot \frac{F}{M \cdot \zeta} \tag{6}$$

where Φ is the the amplification factor and M is the mass of the bridge deck at length of span L. To determine the maximum acceleration of the bridge deck under pulsating force which moves over the bridge with constant speed v by using Eq. (6) engineer must know only the total mass M of the bridge deck structure over the span L, the amplitude of the pulsating force F, the structural damping ζ and the amplification factor Φ which depends of bridge structural system.

3 Determination of amplification factor Φ

The aim of this chapter is established the amplification factor Φ which can be used in procedure for maximum acceleration determination (described in Chapter 2) for simple beam structures. As it is shown in paper [9] the factor R varies in dependence on changes in structural system, structural damping and span length while structural frequency changes do not affect the reduction factor. The factor R does not depend on construction material (concrete, wood, steel, etc.) [8]. The same conclusion can be applied to amplification factor Φ. Therefore the amplification factor Φ will be determined for different simple structural systems of different span length L and different structural damping ζ. The amplification factor Φ is defined as:

$$\Phi = \frac{a_{max,mov}}{\frac{F}{M \cdot \zeta}} \tag{7}$$

In this paper, $a_{max,mov}$, maximum acceleration of the bridge deck structure, is determined using software DARK [10], suitable for dynamic analysis of 2D beam structures due to moving pulsating force.

3.1 Description of structural systems

The amplification factor is determined for non-hollow plate bridge decks with following structural parameters:

a) bridge structural system:
   - · simply supported beam with span length ($L_{tot} = L$);
   - · fixed beam with span length ($L_{tot} = L$);
   - · continuous beam with two spans ($L_{tot} = 2L$);
   - · continuous beam with three spans ($L_{tot} = 3L$);

b) span length L: 9 m, 18 m, 27 m, 36 m, 45 m and 54 m;

c) structural damping ζ: 0,25%, 0,5%, 0,75%, 1%, 1,25%, 1,5%, 1,75%, 2%;

d) first vertical frequency of structure f_v = 2 Hz;

e) deck cross sectional properties: rectangle cross section; width b = 2 m, height h depending of L and structural system (Table 1); h_1 for structural systems of simply supported beam and continuous beams; h_2 for structural system of fixed beam.

Table 1 Plate height h_1 and h_2 in relation to L

L [m]	9	18	27	36	45	54
h_1 [m]	0,10	0,40	0,89	1,57	2,46	3,54
h_2 [m]	0,43	0,17	0,39	0,69	1,1	1,56

Each deck structure is modelled using 50 beam finite elements over the span L. Each finite element is defined by the following geometrical, material, and cross-sectional properties: element length $\Delta L = L/50$, dynamic modulus of elasticity E_d, moment of inertia I, specific weight γ, and cross-sectional area A of the bridge deck. The bridge deck structure in all analysed structural variants has the same dynamic modulus of elasticity $E_d = 3.36 \cdot 10^7$ kN/m^4 and specific weight γ = 25 kN/m^3. The moment of inertia I and cross-sectional area A for different structural systems and span length can be found in [11]. The dynamic analyses are conducted using m = 5000 time steps, each in duration of Δt = T/5000 where the total time T of the force acting equals the time needed for the pedestrian to cross the bridge length L_{tot} ($T = L_{tot}/v$). The force speed is taken as $v = 0.9 \cdot f$ (l_s = 0,9 m) as it is defined in [2, 3, 5, 12]. The amplitude of pulsating force for load model of one pedestrian is taken as F = 280 N [2-5]. Number of steps needed to cross the span (number of cycles per span) is $n = L/l_s$.

3.2 Simply supported beam

The values of $a_{max,mov}$ M, L and ζ for simply supported beam are listed in Table 1. The amplification factors Φ , for simply supported beam constructed using Eq (7) and values presented in Table 1, are shown in Figure 1.

Table 2 The values of $a_{max,mov}$ M, L and ζ for simply supported beam

Span length L [m]	Structural damping ζ [%]	a max.mov [m/s2]	M [t]	Span length L [m]	Structural damping ζ [%]	a max.mov [m/s2]	M [t]
9	0.25	2.336	4.512	18	0.25	0.538	36.097
	0.50	2.166	4.512		0.50	0.471	36.097
	0.75	2.014	4.512		0.75	0.421	36.097
	1.00	1.895	4.512		1.00	0.380	36.097
	1.25	1.784	4.512		1.25	0.347	36.097
	1.50	1.688	4.512		1.50	0.317	36.097
	1.75	1.607	4.512		1.75	0.291	36.097
	2.00	1.533	4.512		2.00	0.269	36.097
27	0.25	0.224	121.828	36	0.25	0.118	288.777
	0.50	0.187	121.828		0.50	0.095	288.777
	0.75	0.161	121.828		0.75	0.079	288.777
	1.00	0.140	121.828		1.00	0.067	288.777
	1.25	0.125	121.828		1.25	0.059	288.777
	1.50	0.112	121.828		1.50	0.052	288.777
	1.75	0.101	121.828		1.75	0.047	288.777
	2.00	0.092	121.828		2.00	0.042	288.777
45	0.25	0.071	564.017	54	0.25	0.047	974.622
	0.50	0.055	564.017		0.50	0.035	974.622
	0.75	0.045	564.017		0.75	0.028	974.622
	1.00	0.038	564.017		1.00	0.023	974.622
	1.25	0.032	564.017		1.25	0.020	974.622
	1.50	0.028	564.017		1.50	0.017	974.622
	1.75	0.025	564.017		1.75	0.015	974.622
	2.00	0.022	564.017		2.00	0.013	974.622

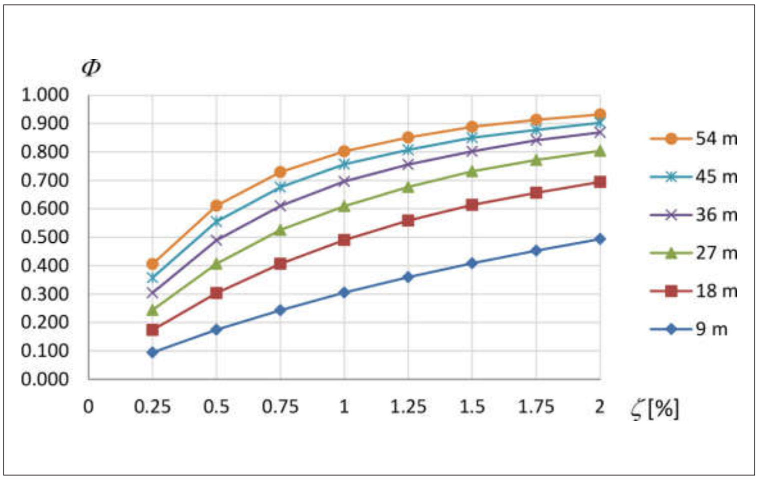

Figure 1 The amplification factor Φ for simply supported beam

A well as for simple supported beam, the amplification factor Φ is determined for all other structural systems analyzed in this paper. For reason of simplicity, only the charts with amplification factors Φ in relation to structural damping and span length are shown in Figures 2 to 4.

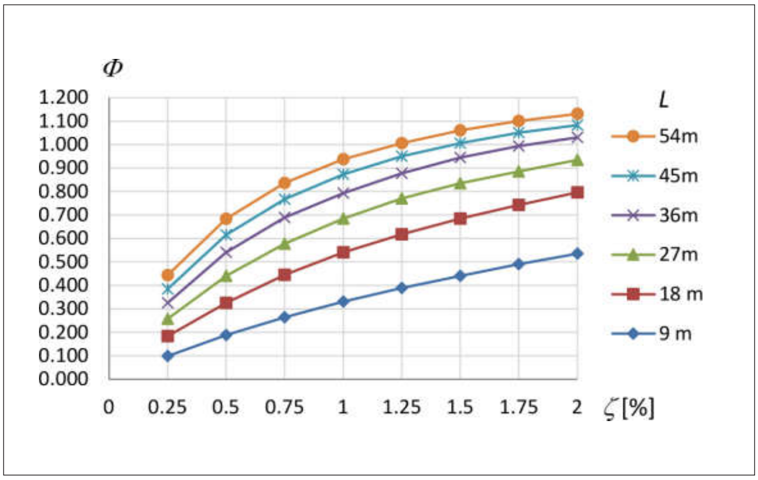

Figure 2 The amplification factor Φ for fixed beam

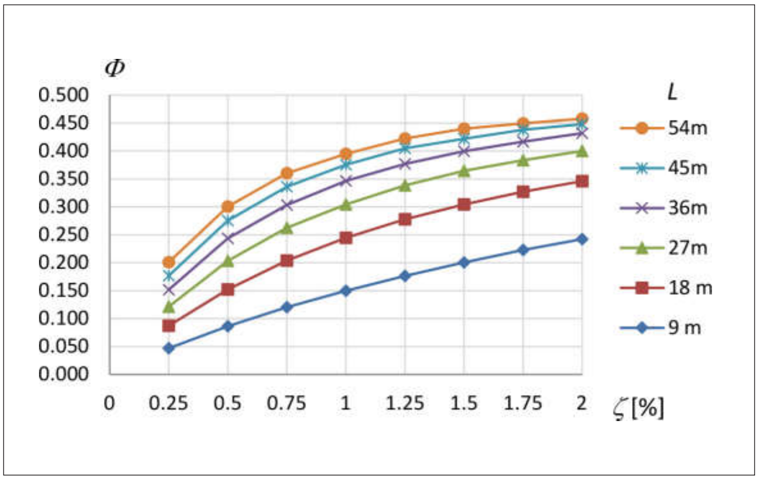

Figure 3 The amplification factor Φ for two-span continuous beam

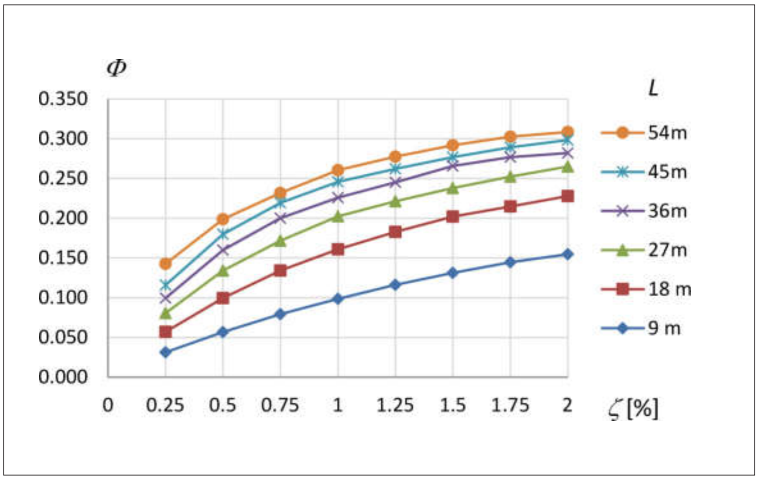

Figure 4 The amplification factor Φ for three-span continuous beam

4 Generalization of amplification factor Φ

The main shortages of determination of amplification factor Φ using charts in Figures 1-4 are:

- insecurity of determination of Φ for span length which are not shown in Figures 1-4 (9 m, 18 m, 27 m, 36 m, 45 m and 54 m);
- applicable only in cases when $v = l_s \cdot f$ (where $l_s = 0{,}9$ m).

To overcome shortages listed above the modified presentation of amplification factor Φ in given Figure 5. The values of amplification factors Φ are shown in relation to structural system and product of number of steps per span n and structural damping ζ.

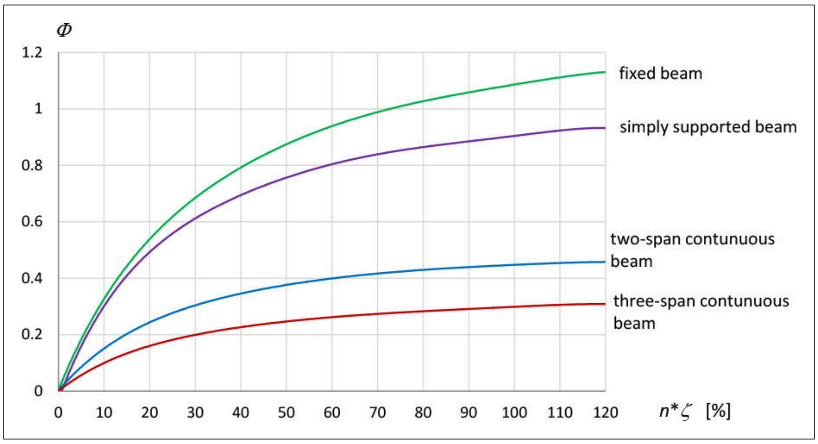

Figure 5 The amplification factor Φ for different simple beam structures

5 Conclusion

In the paper, an improved simplified procedure for determination of maximum acceleration based on response of a structure due to pulsating stationary force of unlimited duration is proposed. The procedure is very simple to use: only the total mass M of the bridge deck structure over the span L, the amplitude of the pulsating force F, the structural damping ζ and the amplification factor Φ have to be known. The amplification factor Φ given in Figure 5 cover simple beam structures subjected to moving pulsating force of different constant speed and it can be used no matter of natural frequency of structure or construction material.

Acknowledgment

This paper is a part of research supported by University of Rijeka through Grant No. 13.05.1.1.01. The authors are grateful for this support.

References

[1] HRN EN 1990:2011, Eurocode: Basis of structural design (EN 1990:2002+A1:2005+A1:2005/AC:2010), (2011) Zagreb: Croatian Standard Institute

[2] Guide to basis of bridge design related to Eurocodes supplemented by practical design – Handbook 4, (2004) Edited by Luca Sanpaolesi and Pietro Croce, Leonardo da Vinci pilot project, Pisa

[3] FIB Bulletin 32: Guidelines for the design of footbridges, (2005) Stuttgart: CEB

[4] NA to BS EN 1991-2:2003, UK National Annex to Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges, (2008) BSI

[5] ENV 1995-2: 1997, Eurocode 5: Design of Timber Structures–Part 2: Bridges, (1997) Brussels: European Committee for Standardization

[6] HRN EN 1995-2:2013, Eurocode 5: Design of timber structures – Part 2: Bridges (EN 1995-2:2004), (2013) Zagreb: Croatian Standard Institute

[7] Bachnamm, H., et al.: Vibration problems in structures: practical guidelines, Basel: Birkhauser Verlag, 1995.

[8] Rainer, J. H., Pernica, G. Allen, D.E.: Dynamic loading and response of footbridges, Canadian Journal of Civil Engineering, 15(1988) 1, pp. 66-71.

[9] Štimac Grandić, I., Grandić, D., Berić, N.: Parameters affecting the reduction factor in pedestrian load models based on pulsating stationary force, Journal of Applied Engineering Science, 13 (2015), 3, pp. 178-184. doi:10.5937/jaes13-7750

[10] Štimac, I., Meštrović, D., Kožar, I.: Analiza mostovnih konstrukcija pobuđenih pokretnim opterećenjem, Građevinar, 56 (2004) 6, pp. 347–353.

[11] Štimac Grandić, I.: Serviceability Verification of Pedestrian Bridges under Pedestrian Loading, Technical Gazette, 22 (2015) 2, pp. 527-537.

[12] HRN ENV 1992-2:2004, Eurocode 2 – Design of concrete structures – Part 2: Concrete bridges (ENV 1992-2:1996), (2004) Zagreb: Croatian Standard Institute