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# Dynamic Analysis of Suspension Footbridges Using an Actual Pedestrian Load Model Compared with EUR23984 EN Requirements

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*ABSTRACT*

The suspension footbridges are very flexible due to their geometrical structure; hence they may face severe vibration problems induced mainly by natural forces and pedestrians crossing. By exceeding a certain limit, these vibrations can disturb the serviceability of the bridge as well as health and safety of the structure and pedestrians. Therefore, standard design guidelines are sets of recommendations to control the vibrations by applying restrictive design criteria. Because of the complexity of the exact simulation of the human-induced loads, these guidelines provide simplified methods to cover the frequency ranges of the human motion types in order to estimate the response of the structure without modeling the actual motion. As current paper, the simplified loading method proposed by EUR23984 EN code-as the main footbridge design standard was investigated. Its compliance with pedestrian's synchronization phenomenon was evaluated using the analysis results of a discontinuous type loading model proposed by authors. It was shown that the response of the footbridge strictly depends on the type and the speed of the pedestrian motion applied to the bridge, which is not included in the design parameters of the code. In this research work, a series of analysis is conducted on a suspension footbridge as a case study under both actual human loads and the simplified loads suggested by the code and the results were compared. It was found out that in the same crowd loading, the actual human loading creates greater vertical accelerations compare to EUR 23984 EN method results.

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## 1. INTRODUCTION

Suspension footbridges are very flexible due to their light weight and geometrical slender structure, which makes them vibrate quickly under loadings such as pedestrian crossing. The human-induced vibrations can affect the performance and the operation of suspension footbridges. By increasing the amplitudes of the vibrations, the comfort of the pedestrians is lost and then it can cause concern and anxiety to them.

At higher levels of vibrations, the health and safety of the structure can be affected and may even lead to structural failure. The Broughton and Angers bridges collapsed under extreme vibrations applied by marching groups. Also, the Montrose and Yarmouth bridges collapsed due to crowds rushed on it in order to watch the events passing below and the Millennium bridge was severely excited on the day of opening [1].

Studies explain the famous "jump phenomenon" in the Millennium bridge -when it began to vibrate laterally with a large amplitude once the number of pedestrians became greater than the critical one- that was mostly due to the synchronization of the crowd in both lateral and vertical directions [2, 3].

Based on literature review, the research works conducted by researchers can be categorized into two main fields of investigation: (a) Interaction mechanisms between the pedestrians and the bridges (b) Characterizing the human body motions during passing the bridges

As the first field, some significant studies and their results are as follows. A plane pendulum model was

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proposed in order to characterize the lateral lock-in phenomenon of the suspension footbridges under the crowd excitation, where the hangers are assumed as the rope and the bridge deck as the rigid body [4]. Also, as a result of a study, it is found out that the dynamic excitations induced by people walking together are not periodic but are narrow-band random phenomena and varies significantly not only among different people but also for a single person who cannot repeat two identical steps [5]. Another study has been proposed a nonlinear stochastic model approach for modeling lateral vibration of footbridges taking into account for narrowband randomness caused by the variability between two subsequent walking steps [6]. These studies indicate that the determination of the dynamic interaction mechanisms between the pedestrians and the bridges has been of special concern in the past few years and have been studied a lot [7].

The difficulties concerning the modeling of the human motions make it practically impossible to simulate the exact motion of people's flow. The resultant lack of insight into these complicated and nonlinear stochastic systems has influenced the quality of structural models used in oscillation evaluation of pedestrian structures such as footbridges and floors [8]. As the second research category, simulation of the human's body motion and the crowd flow behavior have been studied by some researches as follows.

Racic et al. [8] have presented the characteristics of human's time-dependent step forces and amplitudes and kinematics of human body motion. Nakamura and Kawasaki [9] have introduced a method for estimating the lateral response of the footbridge girder for practical purposes. Ingólfsson et al. [10] presented a stochastic load model with an equivalent lateral static force for simulating the lateral response of pedestrian-induced footbridges. Carroll et al. [11] published their studies on modeling the people-bridge dynamic interaction with a separate definition of people's walking motions. Bocian et al. [12] have investigated the interaction between the pedestrians and the vibrating ground. It is shown that the pedestrians have the capacity to interact with the vibrating structures, which can lead to the amplification of the structure's responses.

Yamamoto et al. [13] have studied the pedestrian's body rotating motion for collision avoidance while passing the bridge. They showed that this aspect can be critical and should be reflected in the design procedure, particularly when the passage is narrow and two pedestrians passing each other have to rotate their bodies for collision avoidance. Most of the studies have been done so far are aimed at characterizing the human's body motion during passing the bridges. However, for practical applications, it is not possible to use mathematical models because of the complexity and difficulty in the modeling process.

The EUR 23984 EN [14], as the most reliable and important standard source for designing the lightweight footbridges, proposes a method for loading in order to simplify the process and take the different aspects of human motions into effect. However, in some cases, it cannot cover all aspects of human motions and models. Accordingly, an extensive literature review has been conducted by Živanović et al. [15] on the vibration serviceability of footbridges subjected to human-induced loads. They concluded that current design guidelines do not cover all aspects of the problem.

By investigating the literature review, it can be seen that numerous researchers are working in both human motion characterization and human structure interaction but little studies have been carried out on the evaluation of the current design guidelines based on the recent theoretical advances. In other words, the capability of these guidelines for estimation of bridge behavior, pedestrian safety and comfort and their interaction to comply with rapid advancing study results in this field is under question.

In this paper, the compliance of the EUR 23984 EN loading method with the lock-in effect of the synchronized pedestrians has been studied. A discontinuous motion was used to model the walking of pedestrians, which is close to actual human loading. Because of the importance of the correct prediction of the footbridge's structural behavior, a suspension footbridge as a case study has been modeled and subjected to two different types of loadings: First, the simplified loading proposed by EUR 23984 EN, and second, a discontinuous type loading proposed by the authors for actual pedestrian motions. Then the results were compared and discussed.

## 2. EUR 23984 EN LOADING MODEL

The EUR 23984 EN guidelines for dynamic loading of footbridges provide a harmonic load induced by the present population on the bridge. In addition, after loading and analyzing the structure, to control the amplitudes of vibrations, it considers restrictive criteria for acceleration. These criteria are related to the comfort level of pedestrians using the bridge. The only parameter used in this method for loading is the density of the crowd and is used to create a dynamic load of a harmonic function. It was found that human walking forces are not periodic but, are narrow-band random phenomena [8]. Therefore, the various types of pedestrian activities and motions cannot be modeled using only a harmonic load. The procedure of loading the footbridge according to the EUR 23984 EN guidelines will be as follows:

**Step 1.** Determination of the traffic class: This step determines the number of pedestrians crossing the bridge, which can be determined from Table 1.

**Step 2.** Calculation of the inherent characteristics of the structure (natural frequencies, Shape modes, damping, etc.).

**Step 3.** Loading the structure: The critical natural frequency ranges of pedestrian bridges under human loading are [14] as follows:

- For vertical and longitudinal oscillations: $1.25\ H_Z \le f_i \le 2.3\ H_Z$
- For lateral oscillations: $0.5\ H_Z \le f_i \le 1.2\ H_Z$
- Footbridges with frequencies for vertical or longitudinal vibrations in the range: $2.5\ H_Z \le f_i \le 4.6\ H_Z$
- maybe reached to resonance by the 2nd harmonic of human loading. In such condition, the critical frequency for vertical and longitudinal oscillations up to: $1.25\ H_Z \le f_i \le 4.6\ H_Z$
- Lateral oscillations are not influenced by the 2nd harmonic of human loading.

The structure must be checked for these frequency ranges, and for each of the frequency modes in these ranges, the loading according to Equation (1) and based on the shape mode shown in Figure 1 should be applied.

$$P(t)=P\times COS(\ 2\pi\ f_s\ t)\times n'\times\psi \quad [N/m^2] \qquad (1)$$

where;

$P\times COS\ (\ 2\pi\ f_s\ t\ )$ is the harmonic load applied by one person,

$P$ is the load applied by one person with a walking frequency $f_s$ ,

$f_s$ is the step frequency, equal to the natural frequency of the bridge,

$n'$ is the number of people on the loading zone of S,

S is the area of loading,

$\psi$ is the reduction coefficient due to the probability of the coincidence of the step frequency and the natural frequencies of the bridge.

These parameters are defined in Figure 2.

$\xi$ is the damping ratio and, n is the number of people on the loading zone S (n=S×d).

**Step 4.** Determination of the comfort class

Loading and analyzing of the structure and determining the acceleration response in the vertical, longitudinal and lateral directions should be compared with the limiting criteria provided in the guidelines and is shown in Table 2.

**TABLE 1.** Determination of the traffic class [14]

| Traffic Class | Density, d (P=pedestrian) | Description | Characteristics |
|---|---|---|---|
| TC 1 | group of 15 P d=15 P / (B L) | Very weak traffic | (L =length of deck) B=width of deck |
| TC 2 | d = 0,2 P/m² | Weak traffic | Comfortable and free walking, Overtaking is possible. Single pedestrians can freely choose the pace |
| TC 3 | d = 0,5 P/m² | Dense traffic | Still, unrestricted walking. Overtaking can intermittently be inhibited |
| TC 4 | d = 1,0 P/m² | Very dense traffic | Freedom of movement is restricted. Obstructed walking. Overtaking is no longer possible |
| TC 5 | d = 1,5 P/m² | Exceptionally dense traffic | Unpleasant walking. Crowding begins. One can no longer freely choose the pace |

## 3. PROPOSED LOADING MODEL

To model human walking steps, two approaches can be adopted: the first is a continuous motion, and the second, is a discontinuous motion.

### 3. 1. Continuous Motion

Continuous motion can be modeled using the Fourier series of Equation (2).

$$F_P(\ t)= G + \sum_{i=1}^{n} G\ \alpha_i\ Sin\ (\ 2\ \pi\ i\ f_P\ t- \varnothing_i\ ) \qquad (2)$$

where G is the weight (n people), i is the order of the harmonic, n is the number of contributing harmonics, $\alpha_i$ is the Fourier coefficient of the i-th harmonic, $f_P$ the activity rate (Hz) and $\varnothing_i$ is the phase shift of the i-th harmonic (rad). In existing sources, G = 700 N is

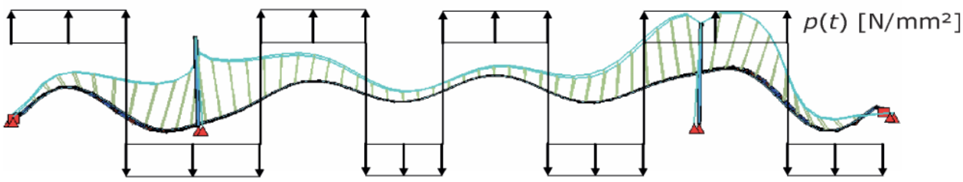


**Figure 1.** Application of harmonic load according to shape mode [14]

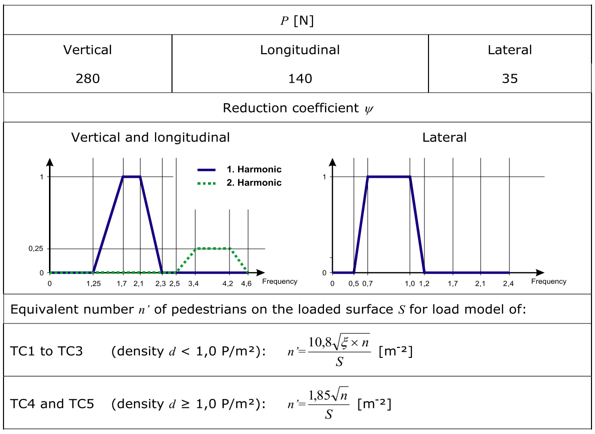


**Figure 2.** Parameters for the load model of TC1 to TC5 [16]

**TABLE 2.** Structural comfort class [16]

| Comfort class | Degree of comfort | Vertical *a* limit | Lateral *a* limit |
|---|---|---|---|
| CL 1 | Maximum | < 0.50 m/s² | < 0.10 m/s² |
| CL 2 | Medium | 0.50 – 1.00 m/s² | 0.10 – 0.30 m/s² |
| CL 3 | Minimum | 1.00 – 2.50 m/s² | 0.30 – 0.80 m/s² |
| CL 4 | Unacceptable discomfort | > 2.50 m/s² | > 0.80 m/s² |

commonly considered, and various values are also reported by researchers in numerous publications [8].

**3. 2. Discontinuous Motion** Walking parameters, including pace length, footstep length, footstep width, walking velocity, and step frequencies are shown in Figure 3 [3]. Each time the human's foot reaches the surface, it creates contact forces between the feet and the surface, which is referred to as GRF [3]. Many attempts have been made by researchers to measure these forces and generate patterns of forces for various human activities. An example of these patterns is shown in Figure 4.

The human motions continuously create harmonic like forces. To simplify the modeling, these forces can be transformed into sinusoidal pulses, as shown in Equation (3) and Figure 5 [16]. By converting the walking forces to the sinusoidal pulses, in fact, the patterns are shown in Figure 4 converted to the sinusoidal pulses shown in Figure 5.

$$f(t) = \begin{cases} K_P \, P \, Sin(\pi \, f_P \, t) & t < t_P \\ 0 & t_P < t < T_P \end{cases} \tag{3}$$

where $t_p$ is the human step interval, $T_p$ is the step period equal to $\frac{1}{f_p}$ and the variable $K_p$ is equal to the ratio $\frac{F(t)_{max}}{P}$ and $F(t)_{max}$ is the maximum amplitude of the sinusoidal function, and P is the person's weight [16].

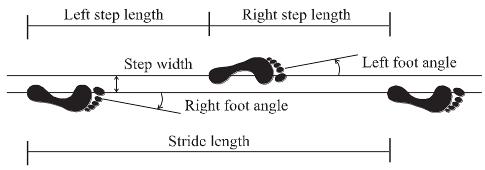


**Figure 3.** Spatial parameters of walk [3]

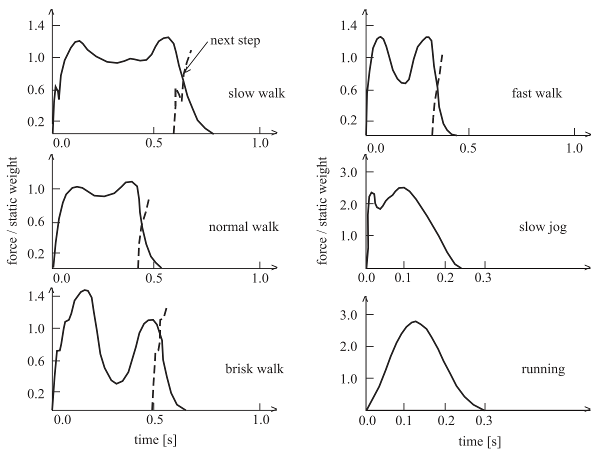


**Figure 4.** Vertical load patterns for different forms of human motion [8, 15]

**3. 3. Idealization of Vertical Force Patterns** The main idea for modeling human loading in this study is to model the human motion as a discontinuous type using the idealization of vertical force patterns of Figure 4 and then are ideally transformed to discontinuous contact dynamic excitation as shown in Figures 5 and 6.

**3. 4. Loading Model Information** The load models provided in this section are the synchronized motion of dual-pedestrian groups moving along the bridge at different speeds, as shown in Figure 7. It is assumed that three classes of groups pass the bridge at three different speeds, so there will be nine load models totally as presented in Tables 3 and 4.

## 4. ANALYTICAL MODEL

**4. 1. Structural Geometry** Soti Ghat suspension footbridge in Nepal was chosen as a case study [17]. The side view and the main dimensions are shown in Figure 8. The width of the deck is 2 m, the distance between the hangers is 1.25m and the distance between the transverse beams, (X-braced) is 1.25 m. The sections used for longitudinal beams- transverse beams, braces, and towers are tubular steel.

The diameter of the sections used for transverse beams and braces are 15 cm and for the longitudinal beams are 30 cm. The main cables' diameter is 12 cm and the hangers' is 2.6 cm. The connection between the transverse beams and braces and the connection between longitudinal beams and towers are considered as simply supported. For all materials, the following values were assumed: Young's module = $2\times10^{11}$Pa , the density of steel is $7850\frac{kg}{m^3}$ , for the main cables and hangers, $F_u=1.57\times10^9$Pa where $F_y$ and $F_u$ are yield stress and tensile strength, respectively.

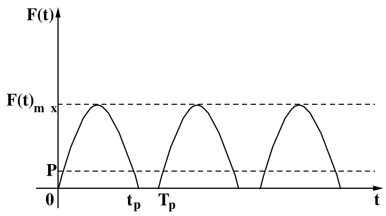


**Figure 5.** Discontinuous contact dynamic excitation [16]

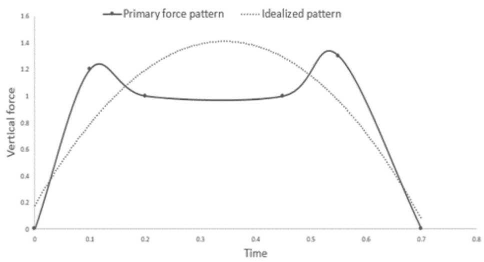


**Figure 6.** Initial vertical and ideal forces for slow walk

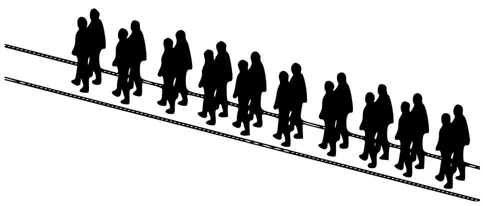

**Figure 7.** Synchronized motion of 10 groups of people

**TABLE 3.** Number of people in each group for loading

| Model Number | 1 | 2 | 3 |
|---|---|---|---|
| Number of dual pedestrian groups | 10 | 30 | 60 |
| Total number of pedestrians | 20 | 60 | 120 |

**TABLE 4.** Motion type and speed of people

| Walk type | Slow walk | Normal walk | Fast walk |
|---|---|---|---|
| Walking speed (m/s) | 1.25 | 1.5 | 2 |

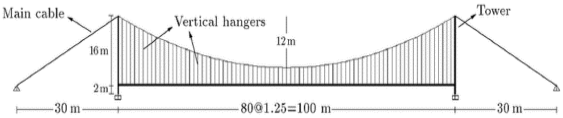


**Figure 8.** Side view of Soti Ghat footbridge [17]

**4. 2. Modeling and Analysis** Modeling and analysis of the bridge are done by using the finite element software SAP2000. This structural analysis is of a linear dynamic type including direct integration option and is done using Hilber - Hughes – Taylor method [18].

## 5. RESULTS

**5. 1. Results of EUR-23984-EN Loading Analysis** In order to compare the two loading types discussed previously, the number of people on the bridge deck will be assumed to be of three groups. To apply the loads in accordance with the guideline, for each group, the crowd density has been calculated and then loaded based on this calculated value. The more the crowd density is, the higher the loading intensity gets.

Based on the studies presented in references [3] and [10], as the density of pedestrians increases their tendency to amplify the vibrating ground also intensifies. Therefore, as a critical comparison to simulate the intense loading and compare it with the actual human loading, it is rational to select group 3 of Table 3 and then calculate the crowd density. By then, the load characteristics can be obtained following Figure 1 procedure.

In this case, the vertical and lateral responses (acceleration and displacements) of the bridge is obtained and presented in Figures 9 and 10. The vertical acceleration response of the structure in Figure 9 is composed of several pulses along the span.

The comfort class obtained for the structure by this case is in the minimum comfort class range (CL3 in Table 2). The lateral displacement of the structure in Figure 10 has only one pulse with a maximum value at the center of the span. The comfort class with respect to the lateral acceleration limit is in the range of medium comfort class (CL2 in Table 2).

## 5. 2. Results of Actual Human Loading Analysis

### 5. 2. 1. Vertical Acceleration Response

The loading presented in this study includes nine load groups, in which each three has three different speeds. The analysis results will be categorized for each group and three speeds.

The results of these loadings will be compared to Table 2. The vertical acceleration response for the first loading group of 20 people (group 1 of Table 3) is shown in Figure 11. The vertical acceleration responses of the bridge along the bridge span obtained for group 1 with slow and fast walking rates are in minimum comfort class range (CL3). For normal walking rate, the response exceeds the minimum comfort class and the acceleration is in the unacceptable range (CL4). The vertical acceleration response for a group of 60 people (group 2**)** is shown in Figure 12. For slow walking rate, the acceleration response is almost in the minimum comfort class range.

For normal walking rate, is in the unacceptable range (CL4) and for fast walking rate is in the boundary of the minimum comfort class range (CL3). For groups comprising 120 people (group 3**)**, the acceleration responses for all three speeds are in the unacceptable range (CL4), as shown in Figure 13. It is evident that in all vertical acceleration responses, the shape of these responses is composed of several pulses along the span of the structure, and these responses, in general, have a pattern similar to the acceleration response of loading presented by EUR 23984 EN.

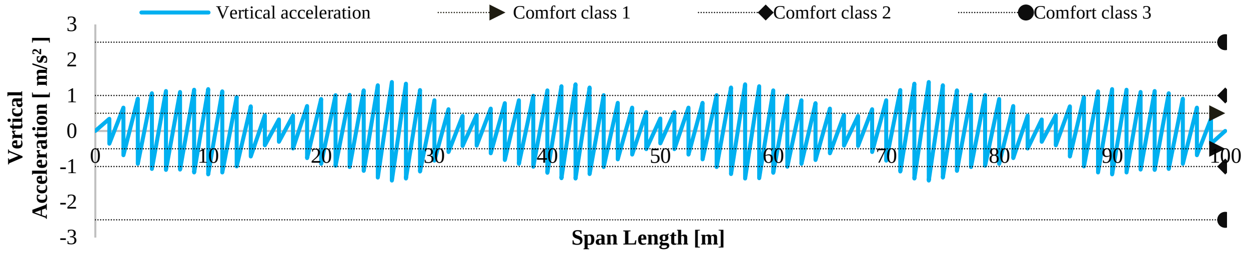


**Figure 9.** Vertical acceleration response of the bridge in the loading presented by Euro code

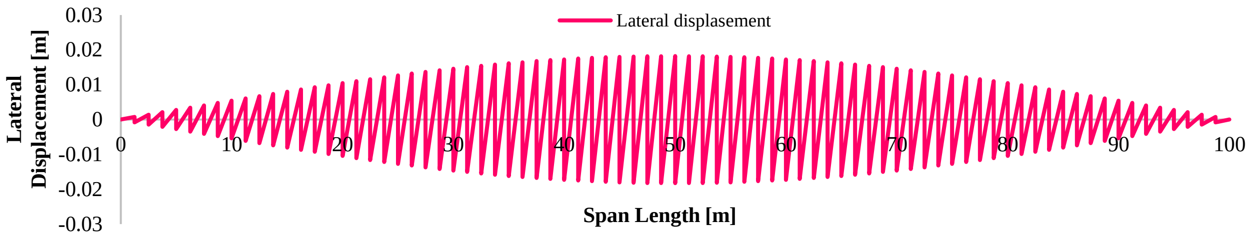


**Figure 10.** Lateral displacements response of the bridge in the loading presented by Euro code

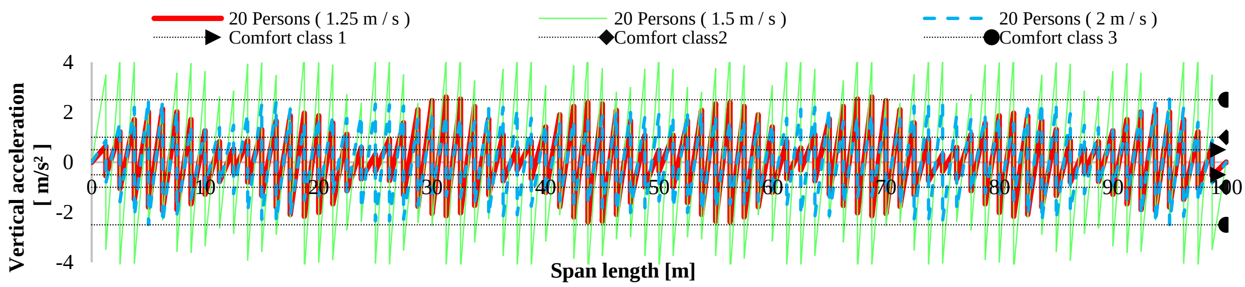


**Figure 11.** Vertical acceleration response of the bridge for a group of 20 people

In addition, vertical acceleration response pulses have different bandwidths for different speeds, and the largest bandwidths occur for slow walking, fast walking, and normal walking rates, respectively.

**5. 2. 2. Lateral Acceleration Response** The lateral acceleration responses of the footbridge under the actual human loading, for all walking speeds and crowd groups, are in the maximum comfort class range (CL1). In all models, the highest responses occur at slow, normal, and fast walking rates, respectively.

The shape of the lateral acceleration responses for slow, normal and fast walking rates are different from the verticals, e.g. the acceleration response for slow walking rate is composed of two pulses for all crowd groups, as shown in Figure 14. The highest acceleration responses occur for groups comprising 20 people (group 1), 120 people (group 3) and 60 people (group 2), respectively.The general shape of the acceleration response for normal walking rate is composed of five pulses. The highest acceleration responses are similar to the previous diagram, that is shown in Figure 15.

The general shape of acceleration response for fast walking rate is composed of three pulses and is shown in Figure 16.

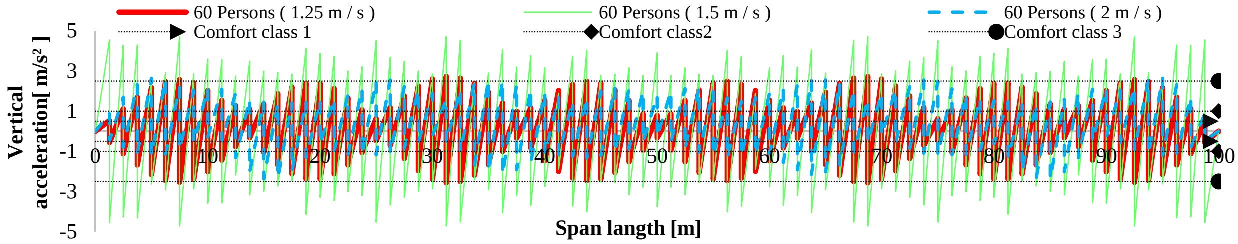


**Figure 12.** Vertical acceleration response of the bridge for a group of 60 people

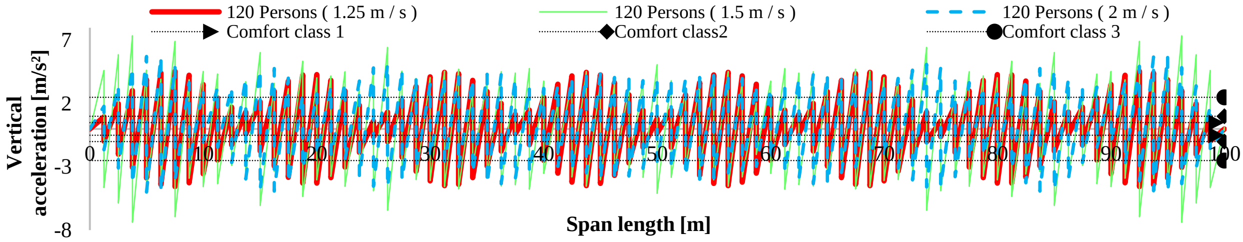


**Figure 13.** Vertical acceleration response of the bridge for a group of 120 people

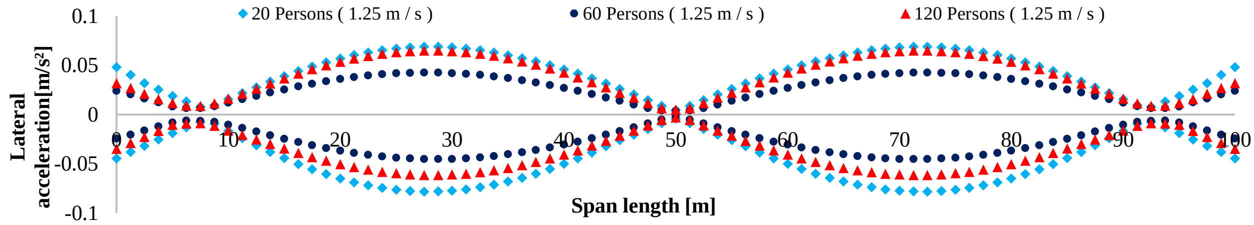


**Figure 14.** Lateral acceleration response of the bridge to slow walking for crowd groups (V=1.25 m/s)

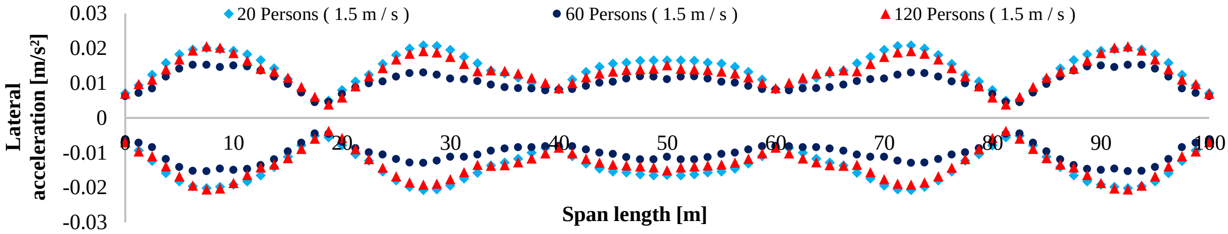


**Figure 15.** Lateral acceleration response of the bridge to normal walking for crowd groups (V=1.5 m/s)

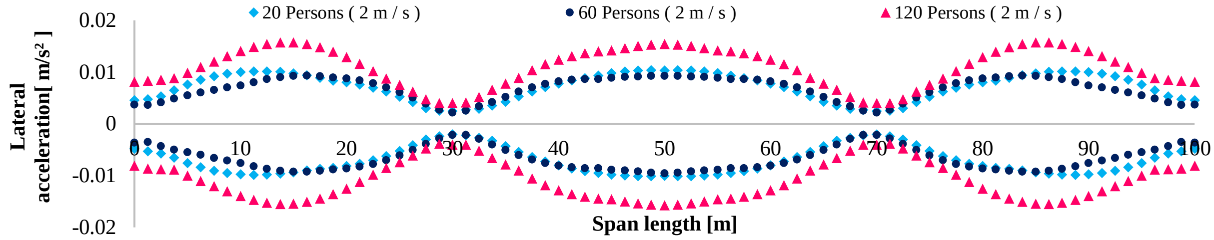


**Figure 16.** Lateral acceleration response of the bridge in fast walking for crowd groups (V=2 m/s)

## 6. CONCLUSION

In this paper, the compliance of the loading method proposed by Eurocode standard has been studied considering the lock-in effect of the synchronized pedestrians. Based on numerous studies, as the density of pedestrians increases, their tendency to amplify the vibrating ground also rises. A discontinuous motion model used to model the walking, which is close to actual human-induced loading. The vibration response of the footbridge was evaluated using the code's loading method and the proposed motion model. It was shown that the response of the footbridge strictly depends on the type and the rate of the pedestrian motions on the bridge, which is not included in the EUR23984 EN method's parameters. Also, it has been observed that applying the code criteria in high crowd conditions does not comply with the actual responses and needs more attention. In addition, it has been demonstrated that the walking rate can make the responses exceed the acceptable ranges. Thus, the following conclusions can be made:

(1) The general shape of the vertical acceleration response for both loadings are similar and are composed of several pulses, but maximum values of the actual human loading are greater than of the code method. Therefore, the code may not be able to properly simulate the effect of the synchronization phenomenon of pedestrians, as well as the effect of different walking speeds.

(2) By increasing the crowd density, the tendency of pedestrians to synchronize their motion and structure increases, thus groups comprising 120 people (group 3) have the highest levels of acceleration responses, which is in agreement with previous research works.

(3) Various speeds of human walking can affect the overall response shape and cause changes in the bandwidth of the pulse responses.

(4) The higher the vertical acceleration responses, the lower is the pulse bandwidths.

(5) The overall acceleration response shapes of the Eurocode loading has only one pulse, but in the actual human loading, this shape can be comprised of multi-pulse depending on the pedestrian speeds; Slow walking has two pulses, normal walking has five pulses and fast walking has three pulses.

(6) The lateral accelerations of the bridge under the loading presented by the Eurocode are greater than the actual human loading.

(7) The greatest amounts of acceleration responses to the actual human loadings are related to slow, normal and fast walking rates respectively. Thus, slow walking rate exhibits the critical case -which can be the reason for caused problems in the Millennium Bridge at the day of opening.

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# Dynamic Analysis of Suspension Footbridges Using an Actual Pedestrian Load Model Compared with EUR23984 EN Requirements

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**چکیده**

پل‌های معلق عابرپیاده با توجه به ساختار هندسی خود و انعطاف‌پذیری بالا، در اثر حرکت عابران پیاده می‌توانند به سرعت مرتعش شوند، که علت این موضوع نزدیک بودن محدوده فرکانس طبیعی این سازه‌ها با محدوه فرکانس گام‌برداری انسان است. از سویی دیگر ارتعاشات بیش از حد این سازه‌ها بر روی بهره‌برداری از آن‌ها اثرگذار بوده و سبب اخلال در سلامت عملکرد آن‌ها می‌گردد. بنابراین دستورالعمل‌های طراحی با استفاده از شرایط محدودکننده سعی در کنترل این ارتعاشات دارند. مدل‌سازی حرکات انسان دشوار است و بر این اساس بارگذاری‌های ارائه شده توسط آیین‌نامه‌ها ساده‌سازی شده می‌باشند. در این آئین‌نامه‌ها، فرکانس حرکات مختلف انسانی مبنای آنالیز سازه قرار می‌گیرد و این در حالی است که رفتار واقعی سازه علاوه بر فرکانس حرکت به نوع حرکت و سرعت آن نیز بستگی دارد. در این مطالعه، پل معلق عابر پیاده تحت بارگذاری واقعی انسانی و بارگذاری ارائه شده توسط آیین‌نامه EN EUR23984 مورد تحلیل و مقایسه قرار گرفته است. بر اساس نتایج بدست آمده مشاهده گردید که بارگذاری واقعی حرکات انسان موجب ایجاد شتاب قائم بزرگتری نسبت به بارگذاری پیشنهادی آئین‌نامه می‌گردد.

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