

Vibration Serviceability Evaluation of a Footbridge Using Finite Elements

Diar F. A. Al-Askari¹, Hiwa F. Hamid², Zandy O. Muhammad³

¹Sulaimani Polytechnic University, Technical College of Engineering, Wrme Street, Sulaimani, Kurdistan Region, Iraq

²University of Sulaimani, Faculty of Engineering, Rapareen Road, Sulaimani, Kurdistan Region, Iraq

³ University of Sulaimani, Faculty of Engineering, Rapareen Road, Sulaimani, Kurdistan Region, Iraq

Abstract: *Vibration serviceability of pedestrian bridges is a vital part in designing and construction of footbridges. In this study a concrete footbridge is investigated which is located inside the campus of the Sulaimani Polytechnic University (SPU). ABAQUS 6.12 is used for FE modelling and analysing the SPU Footbridge. Several international codes of practice renowned for vibration serviceability of footbridges are considered. Mode shapes and natural frequencies are obtained from ABAQUS and are compared to the recommended criteria for comfort level. It is found that by comparing the limit acceleration and comfort level with the codes of practice, the SPU Footbridge provided minimum comfort level for pedestrians.*

Keywords: Vibration serviceability, Finite Elements, Footbridge, Codes of Practice, Comfort Criteria

1. Introduction

Vibration of footbridges is an important consideration in designing and constructions of such walkways; since it is categorised under serviceability limit state and verification of comfort criteria is essential for pedestrians [1]. Vibration of structures when excited to their natural frequencies are in some mode shapes. A combination of mode shapes is possible under normal operating conditions due to the geometry of footbridges and pedestrian induced excitation. Hence, prediction of mode shapes is a crucial part in understanding footbridge vibrations. Therefore, modal analysis is required at design and construction stage to envisage the mode shapes and their corresponding frequencies of a structure [2].

Modelling footbridges using advanced Finite Element (FE) models have played a major role in simulating static and dynamic behaviours of footbridges; although some uncertainties may arise in the modelling due to discrepancies with the real structure [2]. Such uncertainties can be tackled by dynamic tests on some bridges and engineering judgement in order to improve FE modelling in future studies. In addition, codes of practice that stipulate regulation on vibration serviceability can be used in this aspect.

This paper considers the vibration serviceability of a concrete footbridge in which modal analysis using FE modelling is employed. The first part of this study covers a detailed literature review on common codes with vibration requirement and some study on numerical investigation of footbridges. Then, a detailed model of the footbridge is considered in ABAQUS programme with all dynamic characteristics to assess its vibration serviceability. Finally, a comparison between the FE model and the requirement of codes on comfort criteria is made and key results is discussed.

2. Research Significance

This study provides analytical data of a footbridge using FE modelling in order to assess the vibration serviceability under self-weight with the as-built drawings and material properties. In addition, comparison of FE modelling of the footbridge with some codes of practice is made. The authors have considered the case study so as to find the critical mode shapes and the fundamental frequency of the footbridge.

3. Literature Review

Analysis and design of vibration serviceable pedestrian bridges has gained popularity in the recent years because of the incident of Millennium Bridge which made engineers try to comprehend the negative effects of vibrations produced by pedestrians. Research in this area fall into three main categories: (i) testing of full-scale existing bridges subject to crowd loading, (ii) laboratory studies of bridges subject to miscellaneous crowd loading and (iii) mathematical modelling of the pedestrian induced loading [3].

At the design stage, it is difficult to deal with information related to the as-built structure such as boundary conditions, properties of materials and non-structural element effects. Thus, the uncertain nature of vibrations in civil engineering structures has made researchers use FE modelling with caution. To overcome this issue, testing of structures for vibration after construction is carried out. Nevertheless, this procedure does not help the design very much. However, combining testing and analysis reduces design uncertainties of such structures and will help with the design of similar structures in the future [2].

When FE modelling is implemented, the model should be tuned based on technical data from the design and engineering judgement; which is needed when modelling stiffness of supports and non-structural elements, material properties, difference between the design and the as-built structure properties and so on. Because of these issues, these

FE models cannot precisely predict natural frequencies and mode shapes. It is best practice for the structure to be tested and the model to be tuned accordingly. However, the fundamental frequency differs from one structure to another and therefore it should be experimentally determined after the particular structure is built [2]. However, in case the experimental data is too laborious to obtain, there are simplified methods for calculating maximum vertical and horizontal accelerations for footbridges given in standards and guides such as [4, 5, 6, 7, and 8]

Although the usage of the formulae available from standards of practice help with identifying fundamental frequencies, they are not well established yet. For example, the span, material properties, loading and damping of the bridge affect certain parameters in the calculations. This leads to some discrepancy in the results obtained using different codes of practice. However, nearly all codes of practice provide frequencies of about 3Hz while others provide higher frequencies at 5Hz. Nevertheless, codes of practice in the current form could be used to obtain tuned FE models which have dynamic properties similar to the structure; in order to pass vibration serviceability checks [9].

Ref. [6] Describes in detail vertical and horizontal frequency components of walking, running and jumping. It is shown that horizontal oscillations (swaying) tend to bring pedestrians to imbalance more than vertical oscillations, therefore pedestrians are more sensitive to horizontal vibrations.

According to [6] comfort requirements in international standards fall into two main categories:

- Structural frequencies limit values: pedestrian loading induces certain frequencies as shown in Table (3.1). When natural frequencies of a structure are greater than pedestrian loading frequencies, they are generally not at risk. Therefore, many international codes provide frequencies for which dynamic calculations are not required.
- Acceleration frequencies limit values: if structural frequencies fall within the range of pedestrian induced frequencies then it is required to calculate dynamic calculations and then those accelerations are limited to ensure pedestrian comfort (See Table 3.2).

4. Footbridge Analysis

4.1 Sulaimani Polytechnic University (SPU) Footbridge

The SPU footbridge is a continuous three span concrete structure with a total length of the 21.1 m, maximum middle span length of 9.9 m, and the total bridge width of 2m. The deck has two concrete barriers on each side and is supported by a continuous rectangular beam placed under the middle of

Table 3.1: Summary of critical frequencies in international codes [6]

Code / Standard	Limit values	
	Vertical	Horizontal
American Guide Spec.	< 3 Hz	
Eurocode 2 (ENV 1992-2)	1.6 Hz – 2.4 Hz	0.8 Hz – 1.2 Hz
DIN-Fachbericht 102	1.6 Hz – 2.4 Hz,	

	3.5 Hz – 4.5 Hz	
Eurocode 5 (ENV 1995-2)	< 5 Hz	< 2.5 Hz
SBA (former East Germany)	1.0 Hz – 3 Hz	
SIA 260 (Switzerland)	1.6 Hz – 4.5 Hz	< 1.3 Hz transverse < 2.5 Hz longitudinal
BS 5400 (Great Britain)	< 5 Hz	
Austroroads (Australia)	1.5 Hz – 3 Hz	
Japanese Footbridge Design Code (1979)	1.5 Hz – 2.3 Hz	

Table 3.2: Summary of acceleration as comfort criteria [6]

Vertical acceleration $a_{v,max}$ [m/s^2]		
ISO 2631	$1.9 * \sqrt{f_1}$	f_1 =fundamental natural frequency of the bridge
AISC Guide 11	0.5	
Eurocode 1	Min $\begin{cases} 0.50 * \sqrt{f_n} \\ 0.70 \end{cases}$	for $f=1$ to 3 Hz for $f=3-5$ Hz: check dependant on case from $f=5$ Hz: no check necessary
DIN-Fachbericht 102	$0.5 * \sqrt{f_{1,vert}}$	for $f_1 \leq 5$ Hz: f_1 =fundamental natural frequency of the unloaded bridge
VDI 2057	$0.6 * \sqrt{f_{1,vert}}$ 0.214. hor.	f_1 =fundamental natural frequency of the bridge
SBA	0.39	
BS 5400	$0.5 * \sqrt{f_1}$	f_1 =fundamental natural frequency of the bridge
Ontario Bridge Code ONT83	$0.25 * f_1^{0.75}$	f_1 =fundamental natural frequency of the bridge
Eurocode 5 (ENV 1995-2)	0.7	
Bachmann [40]	0.5 – 1.0	
Japanese Footbridge Design Code(1979)	1.0	
Lateral acceleration $a_{L,max}$ [m/s^2]		
Eurocode 1	Min $\begin{cases} 0.14 * \sqrt{f_n} \\ 0.15 \end{cases}$	for $f=0.5$ to 1.5 Hz for $f=1.5-25$ Hz: check dependant on case from $f=2.5$ Hz: no check necessary
Eurocode 5 (ENV 1995-2)	0.2	for $f < 3$ Hz (for standing individuals)

the deck. The beam is supported by three concrete columns and a masonry wall. The deck, barriers, beam, and the columns are monolithic, while the end of the beam on the far right side is simply supported on the masonry wall (Figure 4.1). The material properties of the concrete bridge are as follows: density: 24 kN/m³, modulus of elasticity: 192,640,000 kN/m², poisson ratio: 0.2.



Figure 4.1.1: Front view **Figure 4.1.2:** Side view
Figure 4.1: Views of the SPU Footbridge

4.2 FEM Modelling

ABAQUS 6.12 was used as FE analysis software to establish 3D FE full-scale model of the pedestrian bridge as shown in Figure 4.2. The bridge was simulated based on the drawings given by the Engineering Division at the Technical College of Engineering at SPU. Modal analysis was performed on the bridge in ABAQUS and the mode shapes of the bridge were obtained. The first mode shapes of the bridge, i.e. the fundamental mode shape is torsional with fundamental frequency of 5.022Hz. The rest of the mode shapes and natural frequencies can be seen in Figure 4.3.

It is to be noted that some parametric studies were carried out in order to reach to a reasonable FE model as it is stated in [10].

Also because of the lack of experimental data, the critical damping for SPU Footbridge is assumed to be 5%. According to [6], damping is problematic because it depends on several parameters such as materials properties, surfacing, loading pattern and non-structural elements such as hand railing.

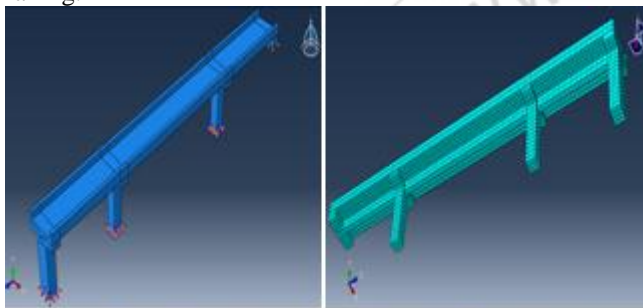


Figure 4.2.1: with boundary **Figure 4.2.2:** with mesh
Figure 4.2: 3D model of the bridge in ABAQUS

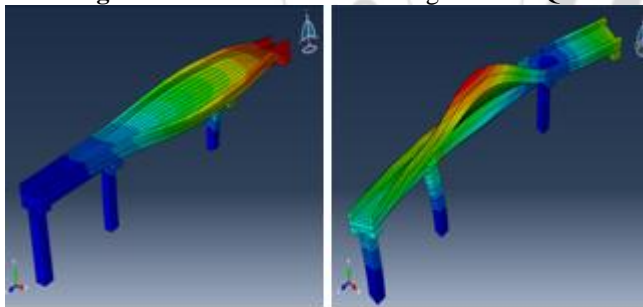


Figure 4.3.1: Model 1
 Freq.: 5.022Hz

Figure 4.3.2: Mode 2
 Freq.: 8.434Hz

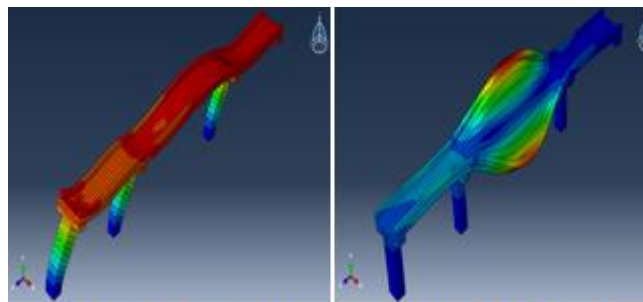


Figure 4.3.3: Mode 3
 Freq.: 11.036Hz

Figure 4.3.4: Mode 4
 Freq.: 11.417Hz

Figure 4.3: Natural frequencies and mode shapes of the SPU Footbridge

4.3 Comfort Criteria and Evaluation

According to [8], there are four classes of pedestrian footbridges based on the crowd traffic it can bear. The SPU Footbridge falls in the third class (Class III) – standard or very light footbridges. In addition, the complex configuration of the SPU Footbridge seems to be inappropriate to determine the natural frequencies using the standard formulae. Therefore, FE is used to obtain the first four natural frequencies of the SPU Footbridge.

Although [8] gives details of calculating critical frequencies, international codes of practice such as [11] and [4] give the highest critical frequencies which should be less than 5Hz for vertical component and less than 2.5Hz for horizontal component (Table 3.1). Hence, in terms of critical frequencies the SPU Footbridge falls within the acceptable range.

In order to further investigate the dynamic behaviour, the acceleration as comfort criteria is being considered. From Table 3.2, the critical accelerations are limited to 0.7 m/s² for [11]; and 1.12 m/s² as calculated for [4]. The limit of acceleration proposed by [4] is more critical than the one from [11]. Therefore according to the comfort criteria proposed by [8], the SPU Footbridge satisfies the minimum comfort level for vertical acceleration (Table 4.1).

Table 4.1: Acceleration ranges (in m/s²) for vertical acceleration [8]

Acceleration ranges	0	0.5	1	2.5
Range 1	Max			
Range 2		Mean		
Range 3			Min	
Range 4				

5. Results and Discussion

The standard codes of practice give equations to estimate fundamental frequencies for bending and torsion for structures which can easily be modelled as simply supported. However due to the complex nature of the SPU Footbridge, FE modelling seems to be more reliable as recommended by [8]. The obtained fundamental frequency from ABAQUS is 5.022Hz which is greater than the limit values given by the standard codes for footbridges [4, 5, 6, 7, and 8].

As from Figure 4.3, the fundamental (predominant) mode shape is torsion which is mostly due to the presence of a stiff beam placed under the middle of the deck. Such torsional mode shape has occurred in the long middle span and in the span close to the end of the bridge sitting on the wall due to its simply supported behaviour.

As far as the comfort criteria is concerned, the limit acceleration (1.12 m/s² from [4]) of the SPU Footbridge falls within Range 3; i.e. the minimum acceleration range criteria for comfort (Table 4.1). This limit should not be exceeded at any time during service life of the footbridge.

Although this study considers some of the major international codes of practice and FE modelling, experimental data can play a major role in determining the actual conditions of the footbridge, such as boundary conditions, material properties, loading patterns and intensity. Inevitably, differences between designed and as-built structures occur, therefore verification of the FE model and the actual structure with experimental data can give better understanding of the behaviour of the structure under self-weight and human loading.

6. Conclusion

A detailed FE model of the SPU footbridge is developed based on the available design data and best engineering judgement, the obtained natural frequencies of the structure is 5.022Hz for the fundamental mode shape. The FE model is analysed using different types of elements, the results vary with the type of the element used. This points out the significance of experimental data in enhancing the FE modelling and verifying the results. However, in this study it was not possible to undertake experiments due to the lack of instruments and technical expertise.

Therefore in order to reach at a sound judgement, the results of FE modelling were compared to different formulae provided by various codes of practice. The following conclusions can be made:

1. FE modelling cannot predict natural frequencies and accelerations precisely, if used alone, therefore experimental investigation or comparison with standard codes of practice will help enhance FE results. Nevertheless, codes of practice, such as [8], recommend using FE modelling for the determination of natural frequencies of footbridges.
2. The fundamental mode shape in this study is torsion, which is due to the positioning of a stiff beam under the deck. Torsional mode shape is a rather rare case and not many literature can be found discussing such an issue. However, [8] provides a brief description of torsional mode shapes which is not comprehensive.
3. The SPU footbridge provides minimum comfort criteria for pedestrians and is thus safe for daily use for pedestrians using it.
4. Current codes of practice in the current form could not be used independently to assess vibration serviceability of footbridges.

References

- [1] Caprani, C.C., 2014. Application of the pseudo-excitation method to assessment of walking variability on footbridge vibration. *Computers & Structures*, 132, pp.43–54.
- [2] Živanović, S., Pavic, A. & Reynolds, P., 2006. Modal testing and FE model tuning of a lively footbridge structure. *Engineering Structures*, 28(6), pp.857–868.
- [3] Ingólfsson, E.T., Georgakis, C.T. & Jönsson, J., 2012. Pedestrian-induced lateral vibrations of footbridges: A literature review. *Engineering Structures*, 45, pp.21–52.

- Evolutionary Computation (CEC), pp. 1951-1957, 1999. (conference style)
- [4] British Standards Institute (1978). *Steel, Concrete and Composite Bridges Part 2: specification for Loads*: British Standards Institution.
 - [5] Ethiopian Standards Agency (2012). *Bases for design of structures - Serviceability of buildings and walkways against vibrations*: Ethiopian Standards Agency.
 - [6] fib Fédération internationale du béton (2005). *Guidelines for the Design of Footbridges: Guide to Good Practice*: fib Fédération internationale du béton.
 - [7] International Standard (2007). *Bases for design of structures - Serviceability of buildings and walkways against vibrations, Second edn.*, Switzerland: International Standard.
 - [8] Sétra service d'Études techniques des routes et autoroutes (2006). *Assessment of vibrational behaviour of footbridges under pedestrian loading*, Paris: Sétra service d'Études techniques des routes et autoroutes.
 - [9] Van Nimmen, K. et al., 2014. Vibration serviceability of footbridges: Evaluation of the current codes of practice. *Engineering Structures*, 59, pp.448–461.
 - [10] Živanović, S., Pavic, A. & Reynolds, P., 2007. Finite element modelling and updating of a lively footbridge: The complete process. *Journal of Sound and Vibration*, 301(1-2), pp.126–145.
 - [11] ENV 1995-2, Eurocode 5 - Design of timber structures – bridges. European Committee for Standardization, 1997.

Authors Profile



Diar F. A. Al-Askari received the B.S. in Building and Construction from University of Sulaimani in 2009 and MSc. degree in Structural Engineering with Materials from Nottingham Trent University in 2012. During 2009-2011 he worked in construction industry and since 2012 he is employed at the Sulaimani Polytechnic University as Assistant Lecturer in the Technical College of Engineering.



Zandy O. Muhammad received the BSc degree in building construction engineering at University of Sulaimani in 2009 and MSc degree in Structural Engineering from the University of Sheffield, UK in 2013. During 2009-2011, he worked at University of Sulaimani as graduate assistant. He is appointed assistant lecturer and he is delivering lectures at Civil Engineering Department, University of Sulaimani.



Hiwa F. Hamid received the BSc degree in building construction engineering at University of Sulaimani in 2009 and MSc degree in Civil Engineering majoring in structures from the Youngstown State University, USA in 2013. During 2009-2011, he worked at University of Sulaimani as graduate assistant. He is appointed assistant lecturer and he is delivering lectures at Civil Engineering Department, University of Sulaimani.