EURODYN 2020
XI International Conference on Structural Dynamics
M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (eds.)
Athens, Greece, 23–26 November 2020

EVALUATION OF HUMAN INDUCED VIBRATIONS IN KJÆRRA BRIDGE

Thomas T. Tenev[1], **Ole A. Kristiansen**[1] **and Emrah Erduran**[2]

[1] Dept. of Civil Engineering, Technical University of Denmark - DTU
Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark
e-mail: tenev.thomas@gmail.com / olekri95@gmail.com

[2] Dept. of Civil Eng. and Building Technology, Oslo, Norway Metropolitan University
Pilestredet 35, 0166 Oslo
e-mail: emrah.erduran@oslomet.no

Keywords: Human induced vibrations, Modal analysis, Lock-in effects, Footbridge, Field Measurements

Abstract. *The users of the 132-meter-long Kjærra Bridge in Larvik, Norway, noticed severe lateral vibrations due to pedestrian loading on the opening day in 2001. During the period that the bridge was designed, there were no clear guidelines to minimize pedestrian induced vibrations in footbridges. This article aims to explain severe vibrations induced by pedestrians on the Kjærra Bridge, and to highlight the importance of clear guidelines to prevent similar cases in the future. To this end, a series of vibration measurements, both free and forced, are conducted on the Kjærra Bridge. The free- and forced-vibration tests are supplemented by numerical analysis for several different loading scenarios. Field measurements and numerical analysis results are compared with the current guidelines to evaluate the design of the bridge. The analyses results show vibration levels in the unacceptable range put forth by current design guidelines for several loading scenarios indicating that these guidelines can successfully predict human-induced vibrations on footbridges.*

1 INTRODUCTION

The Kjærra Bridge is a 132m long timber footbridge with a free span of 92 metres across the Numedalslågen river in Larvik, Norway. The structure is based on two concrete bridgeheads, each supporting a triangular console. The consoles support a double, undertensioned structural system with laminated timber compression members and steel wires taking the tensional forces. The lateral load carrying system consists of a horizontal steel truss between the laminated timber arches and was designed for wind loads. The width of the bridge is 2.4m and, architecturally, it was designed to fit in its environment which is surrounded by woods and waterfalls leading to a very slender structure; see Figure 1. The bridge was opened to the public on the 5th of July 2001 [1] and the users of the bridge noticed severe lateral vibrations due to pedestrian loading on the opening day of the bridge. The slender structure and the lateral vibrations observed in the bridge were similar to those observed in the London Millenium Bridge, which had been designed in the same period as the Kjærra Bridge.

During the design and construction of the Kjærra Bridge, there were no standards or guidelines available in Norway to minimize human-induced vibrations. Although some dynamic analysis had been conducted during the design stage, these analysis had no effect on the final design mainly due to lack of such guidelines.

The aim of this article is two-folds: (1) to investigate the reasons of the human-induced vibrations observed in the Kjærra Bridge and (2) to investigate whether the current design guidelines such as HIVOSS [2] and Sétra [3] can successfully predict the excessive vibrations observed. To achieve these goals, free- and forced-vibration tests were carried out on the bridge and dynamic analyses were conducted using a detailed numerical model in Autodesk Robot.

Figure 1: The Kjærra Bridge has a total span of 132m and a free span of 92m across the Numedalslågen River in Lardal, Norway. Photo: Lisbeth Michelsen

2 DESIGN LAYOUT

The bridge was designed as part of a municipal effort to improve access to the public riverbanks. The bridge structure consists of two triangular consoles supported by concrete foundations on each riverbank. These consoles are made of three main components: Two 13 metre long side spans with an elaborate truss brackets made of glulam, and a 92 metre long mid-span with a lower span cable construction system.

The main span is constructed as a truss, consisting of arched glulam girders, compression members made of glulam cigar beams and steel cables to absorb tensile forces. The truss system is jointed at the middle as a variant of the Polonceau system first designed by French railway engineer Jean-Barthélémy Camille Polonceau (1813 - 1859) [4].

The distance between the extremes of the console beams carrying the main span is 66 metres resulting in a maximum free span of 92 meters. The cantilever console-structure is made of beams and compression members in glulam timber, as well as diagonal steel cross-bracing in the transverse direction leading the forces from the main span to triangular concrete foundations. Furthermore, the two console-structures are anchored at reinforced concrete abutments on each riverbank. Figure 2 shows the elevation view of the bridge.

A wind bracing made of steel L-beams are bolted to the primary beams along the bridge main axis. Horizontal forces are obtained by the wind bracing and transferred down to the foundations through cross bracing.

3 CHARACTERISTICS OF DYNAMIC PEDESTRIAN LOADING

The severe vibrations on the Kjærra Bridge normally occurs when relatively dense flows of people cross the bridge simultaneously. Pedestrian loadings are complex loadings that are challenging to carefully define. This dynamic loading is affected and modified by many parameters. However, studies show that the average frequency of the loading, i.e. the number of steps per second, for normal walking is somewhere between 1.6 and 2.4 Hz. For the same walk, the transverse loading frequency is equal to half of the vertical loading, i.e. the transverse loading frequency for normal walking is somewhere between 0.8 and 1.2 Hz [3].

The phenomenon of ***lock-in*** of a pedestrian crowd is defined as "a pedestrian crowd, with frequencies randomly distributed around an average value and with random phase shifts, will gradually coordinate at a common frequency (that of the footbridge) and enters in phase with the footbridge motion". [3]. To compensate for the imbalance from the vibrational behaviour in the structure, crowds tend to instinctively follow the footbridge motion frequency. As soon as the amplitude of the movements are perceptible, crowd behaviour is no longer random and a motion synchronized with the vibrations of the bridge is developed. Thus, the vibrations tend to amplify as crowd-motion synchronizes with the transverse vibrations in the footbridge, ultimately leading to resonance to the accelerations. These vibrations may reach a critical acceleration if a critical number of pedestrians provoke the vibrations [3].

4 GUIDELINES FOR HUMAN INDUCED VIBRATIONS IN FOOTBRIDGES

At the time of construction, there were no clear guidelines in Norway concerning design for human-induced vibrations in footbridges. Currently, EN-1990:2002 [5] is the relevant standard in Norway that sets the criteria for comfort of the pedestrians on footbridges. According to EN-1990:2002, all footbridges that has a frequency lower than 5 Hz in the vertical direction and 2.5 Hz in the horizontal should be verified for comfort criteria. The comfort criteria is further defined in terms of the maximum acceleration created by groups of 8 to 15 walking normally (persistent design situation). The maximum allowed accelerations are 0.7 m/s^2 in the vertical direction and 0.2 m/s^2 in the horizontal direction. For exceptional crowd conditions, i.e. when the number of pedestrians is significantly over 15, the maximum allowed horizontal acceleration is 0.4 m/s^2. Further, EN-1990:2002 also suggests that, due to uncertainty and complexity of the calculations, it may be necessary to make provisions in the design such as use of dampers unless the comfort criteria is cleared by a substantial margin.

Although EN-1990:2002 [5] provides guidelines and criteria to avoid severe vibrations in footbridges, these guidelines are not very detailed and can be regarded as imprecise. On the other hand, two guidelines, Sétra [3] and HIVOSS (Human-Induced Vibrations of Steel Structures) [2] provide more detailed and precise requirements to minimize human-induced vibrations in footbridges. According to Sétra [3], the critical eigenfrequencies are 0.3-2.5 Hz and 1-5 Hz in horizontal and vertical directions, respectively. HIVOSS [2] sets these critical eigenfrequencies at 0.5-1.2 Hz and 1.25-2.3 Hz, respectively. According to these two documents, the structures whose predominant vibration frequencies fall into these ranges must undergo a more detailed evaluation. This evaluation requires the evaluation of the comfort level based on the maximum expected acceleration in both vertical and horizontal directions computed via dynamic analysis under pedestrial loading [2, 3]. Table 1 presents the range of accelerations in vertical and horizontal directions for different comfort classes. It should be noted that the range of accelerations given in Table 1 are valid for both Sétra and HIVOSS guidelines [2, 3].

Class	Degree of Comfort	a_{limit}-vertical	a_{limit}-lateral
CL1	Maximum	$<$ 0.50 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	$>$ 2.50 m/s^2	$>$ 0.80 m/s^2

Table 1: Defined comfort class with common acceleration ranges for Sétra and HIVOSS

5 FIELD MEASUREMENTS

Free-vibration and forced-vibration measurements were conducted on the bridge in the spring of 2019 in order to understand the vibration characteristics of the bridge. The measurements were done using a one triaxial accelerometer, Diciducer Model 333D01, at a rate of 800 Hz, on various locations on the bridge. Figure 2 presents the elevation view of the bridge and the five points where the measurements were taken. Point 3 in Figure 2 is the mid-point of the bridge and points 1 and 5, and 2 and 4 are symmetric with respect to the mid-point. As expected, the measurements at the symmetrical points gave very similar response. Therefore, results are only presented for points 1 and 2 for brevity.

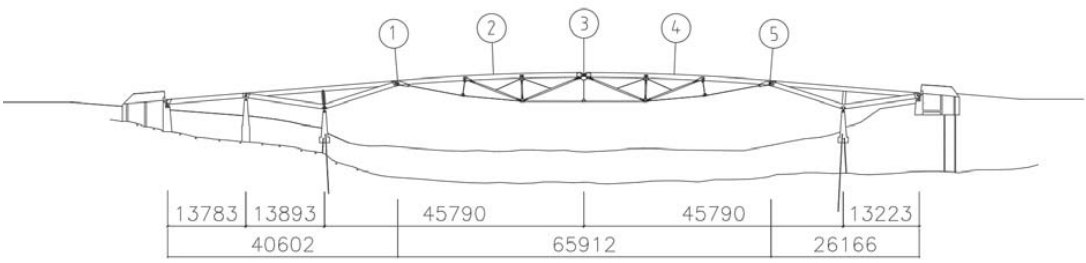
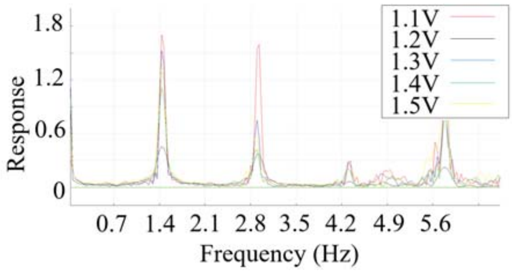
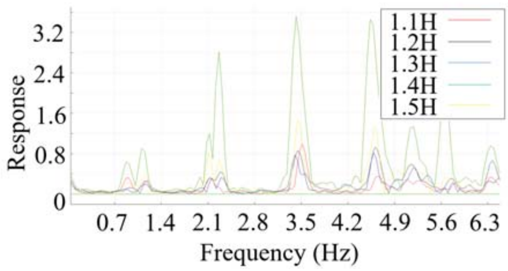


Figure 2: Elevation view: Kjærra Bridge with points of measurements (all dimensions in mm)

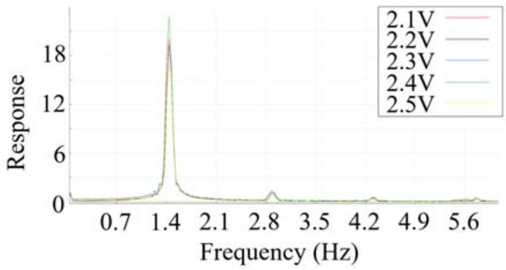
The measured acceleration time histories from the free-vibration analyses were converted to frequency domain using Fast Fourier Transformation (FFT) for the measurements at points 1, 2 and 3. The results plotted in Figure 3 shows that the predominant frequencies in the horizontal and vertical directions are 0.88 Hz and 1.43 Hz, respectively. Measurements at points 1 and 2 also show the frequencies of the higher modes that are suppressed at point number 3. The predominant frequencies fall into the critical range in EN-1990:2002 [5], Sétra and HIVOSS [2, 3] guidelines.



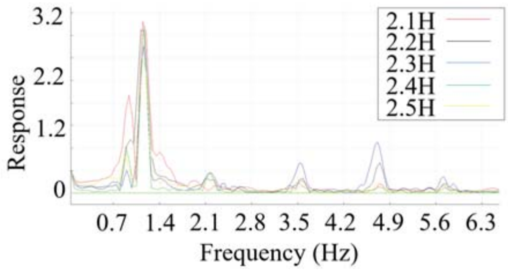
(a) Point 1 - Vertical direction



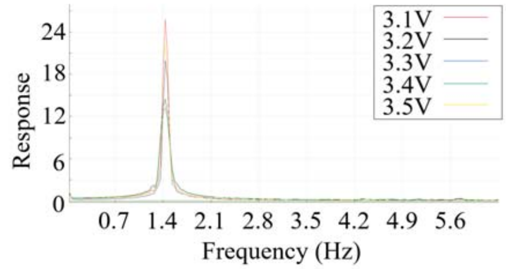
(b) Point 1 - Horizontal direction



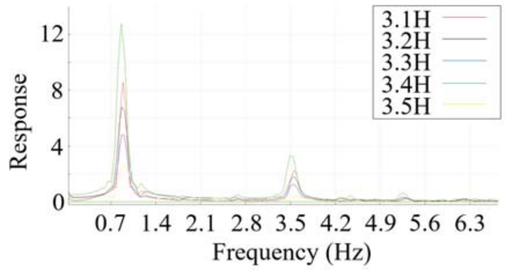
(c) Point 2 - Vertical direction



(d) Point 2 - Horizontal direction



(e) Point 3 - Vertical direction



(f) Point 3 - Horizontal direction

Figure 3: Frequency response function at the mid-span measured from free vibration analyses

In addition to the free vibration measurements, forced-vibration measurements induced by up to three people were conducted to measure the level of accelerations. Around hundred measurements were made on different locations on the bridge to understand the characteristics of the vibrations. However, in this article, we will only focus on the critical results, which are the measurements made at the middle of the main span (point 3 in Figure 2). This area on the bridge shows the highest response to the lowest vibration frequencies on the structure for both horizontal- and vertical vibrations.

The forced-vibration tests conducted on the bridge show that, as expected, the accelerations increase linearly by the number of people inducing the vibrations. By first introducing vibrations induced by one, and then two and three people to amplify the vibrations on the bridge, it is measured that the accelerations (associated to the dominating frequencies) increase by approximately 0.11 m/s^2 for vertical vibrations and 0.28 m/s^2 for horizontal vibrations per person. As a result, maximum horizontal and vertical accelerations were recorded as 0.34 m/s^2 and 0.80 m/s^2 in the vertical and horizontal directions, respectively when the forced-vibrations are introduced by three people; Figure 4 and 5. This shows that, even for a load of three persons, the maximum accelerations recorded on the bridge get fairly close to the *Medium* degree of comfort set forth by Sétra and HIVOSS guidelines; Table 1.

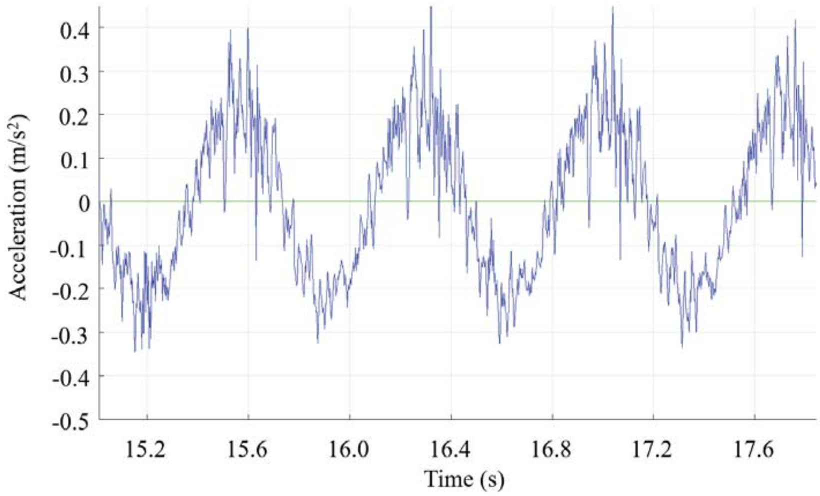


Figure 4: Acceleration measurements for induced vibrations in vertical direction

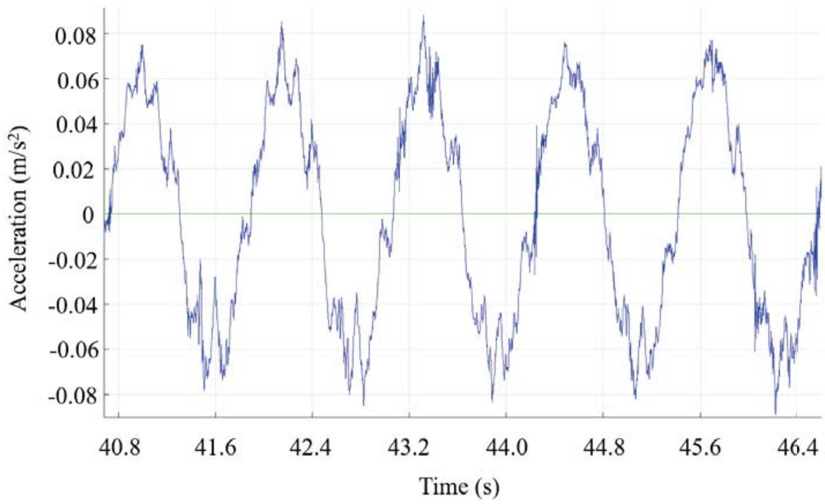


Figure 5: Acceleration measurements for induced vibrations in horizontal direction

6 NUMERICAL ANALYSIS

A detailed finite element model of the bridge was created in the Autodesk® Robot™ Structural Analysis environment to conduct a dynamic analysis of the bridge structure. Both modal analysis and *Footfall Harmonic Analysis (FHA)* of the structure was performed to investigate the free-vibration and forced-vibration behaviour of the bridge. When establishing the dynamic model, the nodal stiffnesses were carefully assessed and modelled, among other things by defining rigid links, master nodes and slave nodes. Furthermore, the hand railing was modelled as imposed load, converted to structural mass prior to the modal analysis, assuming negligable contribution to the overall stiffness of the structure.

A modal analysis of the structure was performed to investigate the dynamic behaviour. The results from the modal analysis show low natural frequencies both in the vertical- and lateral directions. Table 2 presents these frequencies together with the percentage of total mass vibrating in each mode in lateral (UY) and vertical (UZ) directions.

Mode shape [-]	Frequency [Hz]	Period [Sec]	Cur.mas.UY [%]	Cur.mas.UZ [%]
1	1.06	0.94	31.4	0.0
2	1.33	0.75	24.9	0.0
3	1.80	0.56	0.0	42.4

Table 2: Results of the modal analysis for the first five modes

The results of the modal analysis (Table 2) are in quite a good agreement with the free-vibration tests (Figure 3) although the numerical model seems to slightly overestimate the frequencies of the structure. Figure 6 and 7 depict the mode shapes of the predominant lateral and vertical modes obtained from modal analysis. The vibration frequencies in both the horizontal and vertical directions (1.06 Hz and 1.80 Hz, respectively), similar to the frequencies from the free-vibration measurements, fall into the critical range according to all three documents considered. As such, evaluation of maximum expected accelerations is necessary to assess the level of human-induced vibrations in the bridge.

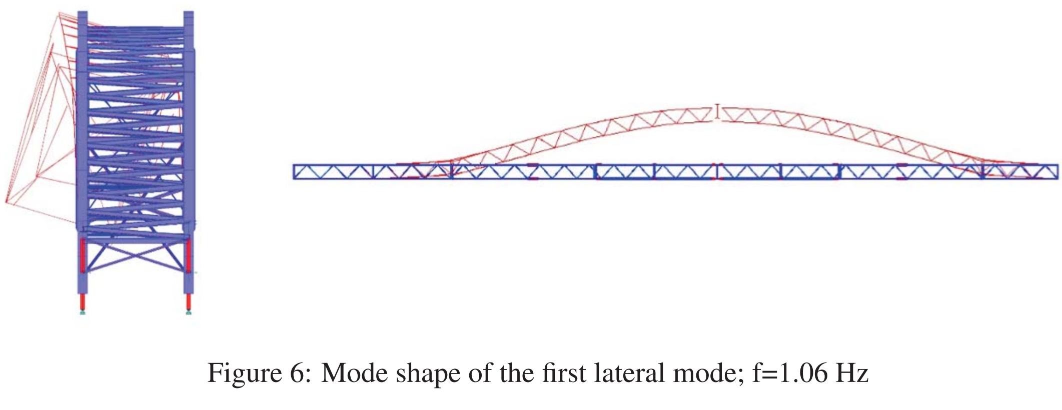


Figure 6: Mode shape of the first lateral mode; f=1.06 Hz

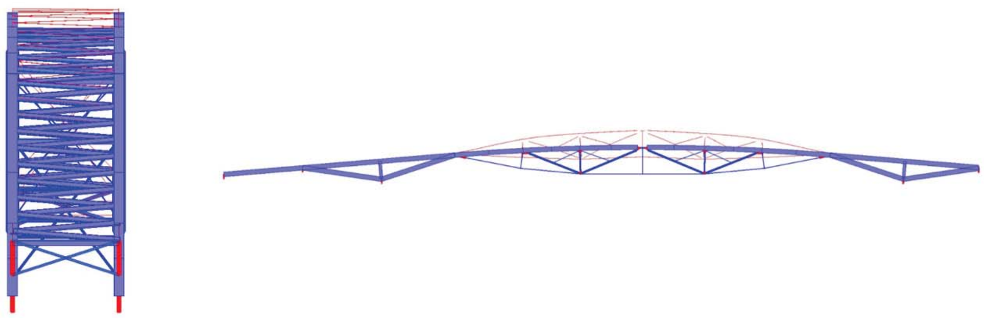


Figure 7: Mode shape of the first vertical mode; f=1.80 Hz

For this, a *footfall harmonic analysis* (FHA) was performed, examining the effect of human footsteps interpreted as a harmonic load at a specific range of frequency on the structure. Due to the limitation of the software used, only vertical direction response was investigated through the FHA. The frequency of movement of the harmonic load was set to be between 0.5 Hz - 5.0 Hz and the number of steps was set to 100. Furthermore, the damping ratio was modelled as 5% of the critical damping and the harmonic load was set to 70 kg based on the average weight of a person.

The FHA has been repeated to simulate different number of people crossing the bridge simultaneously. Figure 8 shows the response of the bridge when the number of people crossing the bridge is set to ten. As expected, the most severe response is observed at 1.80 Hz, which is the predominant frequency in the vertical direction. The footfall analysis show that the maximum acceleration levels in the vertical direction can reach 1.6 m/s^2, which is much higher than the comfort criteria set forth by EN-1990:2002 [5] for groups of 8 to 15 people; 0.7 m/s^2. This level of acceleration also places the comfort level of the bridge at *Minimum* according to Sétra and HIVOSS guidelines.

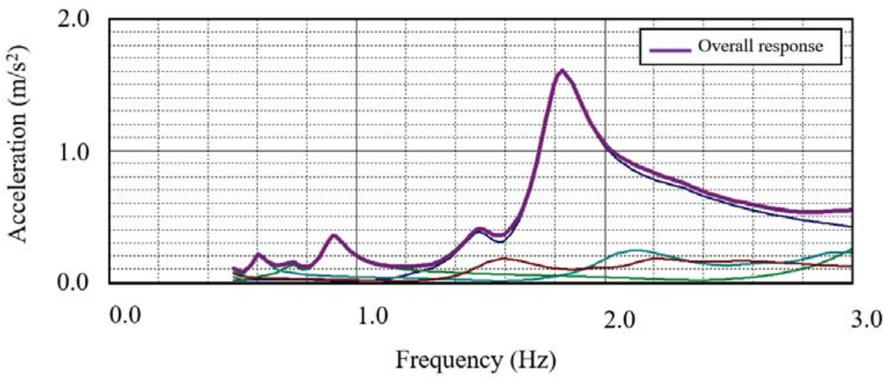


Figure 8: Results of Footfall Harmonic Analysis

Table 3 summarizes the results of the FHA for different number of pedestrians crossing the bridge including the estimated maximum acceleration for all cases. The variation of maximum acceleration with the number of pedestrians computed using FHA is also depicted in Figure 9 together with the maximum accelerations obtained from forced-vibration measurements. Also plotted in Figure 9 is the linear extrapolation of the maximum observed accelerations in the forced-vibration tests. Although the measurements are limited to three people, linear extrapolation of the observed maximum accelerations up to 15 people can be regarded as realistic considering that the behaviour of the bridge most likely remain elastic for a pedestrial load of up to 15 persons.

The maximum acceleration levels presented in Table 3 and Figure 9 show that the human-induced vibrations in the Kjærra Bridge exceeds the comfort criteria of EN-1990:2002 [5] already for five pedestrians. According to the Sétra and HIVOSS guidelines, the comfort level of the bridge reduces from *Maximum* to *Medium* at four pedestrians and further down to *Minimum* at seven pedestrians. Extrapolating the results of the FHA suggests that the threshold of *Unacceptable* vibrations will be exceeded when a group of 16 people cross the Kjærra Bridge at the same time.

$n_{pedestrians}$ [-]	$F_{harmonic}$ [kg]	Accel. [m/s^2]
1	70	0.16
2	140	0.31
3	210	0.47
4	280	0.63
5	350	0.79
10	700	1.60
15	1050	2.40

Table 3: Dynamic response of Kjærra Bridge obtained from FHA

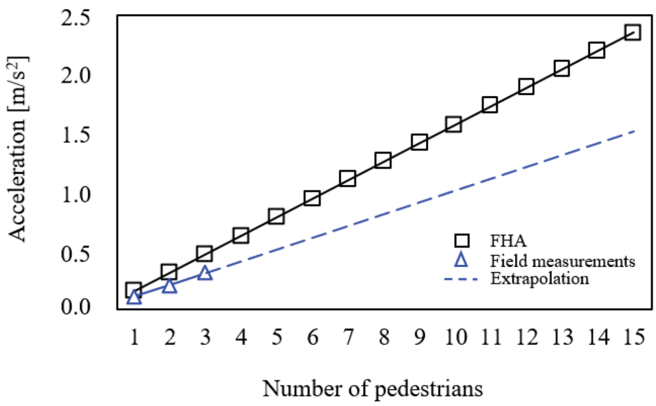


Figure 9: Measured and computed maximum accelerations for Kjærra Bridge

7 CONCLUSION

Kjærra Bridge had been designed and constructed at the beginning of the 21st century, when there were no clear guidelines or standards that has focused on human-induced vibrations on footbridges. As a result of the slender geometry of the bridge, the pedestrians crossing the bridge in groups have been experiencing severe vibrations. This paper has investigated the dynamic behavior of the bridge through field measurements and numerical analysis. The conclusions drawn from the results of free- and forced-vibration measurements conducted on the Kjærra Bridge and the numerical analysis performed can be summarized as follows:

- The free-vibration measurements indicate that the predominant frequencies in both horizontal and vertical directions are in the critical range according to all three prominent documents that focus on comfort criteria for vibrations in footbridges [2, 3, 5] .
- The forced-vibration measurements show that, even for three persons, the acceleration levels get close to the comfort level *Medium* according to Sétra and HIVOSS guidelines.
- The modal analysis results can be deemed to be in good agreement with free-vibration measurements although the former seems to slightly overestimate the vibration frequencies in both horizontal and vertical directions.
- The footfall harmonic analysis conducted for different number of pedestrians show that the comfort level of the Kjærra Bridge is not acceptable according to EN-1990:2002 [5] for pedestrian groups five or more people. The acceleration level falls into *Minimum* comfort level when the number of pedestrians exceed seven and becomes *Unacceptable* for 16 people according to Sétra and HIVOSS [3, 2] guidelines.
- The results of this study suggest that both EN-1990:2002 [5] and HIVOSS [2] and Sétra [3] guidelines can effectively predict that the human-induced vibrations in Kjærra Bridge can exceed acceptable levels for a relatively small group of pedestrians. As such, it can be argued that any future design that follow the aforementioned guidelines can be expected to have a satisfactory behavior as far as human-induced vibrations are concerned.
- On the other hand, the problems associated with human-induced vibrations for Kjærra Bridge demonstrate the need for a theroetically-sound and precise standard to avoid such problems in future designs.

ACKNOWLEDGEMENT

The work presented herein was supported by Dr. Techn. Kristoffer Apeland A/S (K. Apeland) and Oslo Metropolitan University. The authors gratefully acknowledge their generous support.

REFERENCES

[1] Kjærra Fossepark *Official Website*, Reached on the 13th of February 2020 from: https://www.kjaerra.no/kjrrabrua.

[2] Directorate General for Research and Innovation. Design of Footbridges - Guidelines: *Human-Induced Vibrations of Steel Structures (HIVOSS)*, EU publications, 2010.

[3] The Technical Department of Transportation, Sétra, Techincal guide: *Footbridges: Assessment of vibrational behaviour of footbridges under pedestrian loading*, 2006.

[4] B. N. Sandaker, *The Structural Basis of Architecture*, page 20, ISBN-13: 978-0415415477, 2011.

[5] European Committee for Standadization. NS-EN 1990:2002+A1:2005+NA:2016: *Basis of Structural Design*, 2016.