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VIBRATION BEHVIOUR OF A STRESSED LAMINATED TIMBER DECK PEDESTRIAN BRIDGE

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ABSTRACT: Pedestrian bridges form an integral part of the transportation and infrastructure system of any society. Timber has gained popularity as an alternative construction material for pedestrian bridges. However, the lightweight and low mass of structural timber systems make them prone to high vibrations. Information for assessing pedestrian comfort on timber bridges is limited. Field experiments were carried out on a stress laminated timber pedestrian bridge using highly developed dynamic analysis methods to evaluate the vibration characteristics of the structure. Focus was on natural frequencies, mode shapes damping ratios and time history responses which are indicative parameters for assessing the vibration serviceability of structural systems.

KEYWORDS: bridges, modal analysis, pedestrian, timber, vibration

1 – INTRODUCTION

Pedestrian bridges provide means of crossing obstacles, such as water bodies, and canyons. Consequently, they create access for reaching previously inaccessible locations including communities and tourist attractions like waterfalls [1,2]. In high densely populated urban areas, pedestrian bridges are constructed to increase the safety of pedestrians and improve the efficiency of the transportation network. This is because pedestrian bridges are used to separate human and vehicular traffic as well as elevating crossings for pedestrians around at-grade crossings to reduce vehicular congestion [1].

The interest in using timber for the design and construction of bridges including those intended for human traffic has been enhanced due to various reasons [3]. Timber possesses high strength, low mass and lend itself to prefabrication and pre-cut, reflecting its economic viability as a construction material including foundation cost effectiveness [4]. Thus, timber is considered as an attractive alternative building material including the constriction of bridges. Other attributes that support the choice of timber in the built environment are its sustainability, renewability, aesthetics with natural colours that blend with the environment, and better green credentials compared to other mineral resourced based materials like concrete and steel [3-5]. Since late 1990's stress laminated timber (SLT) decks have become very popular for the development of pedestrian timber bridges [5,6]. The prestressing procedure in addition to preventing gaps between the various laminas forming the deck, also increase the loading bearing capacity of the deck system.

Various studies have been conducted on the performance of timber bridges involving the experimental and numerical investigations of the structural integrity of such structures made of various timber decks including SLT decks. Studies employing the principles of statics have focused on the influence of prestress force and joint butts on the stiffness of the decks as a basis for the overall system performance [6]. Attention has also been given to construction features such as connections which are crucial in putting whole timber structural systems together [5]. Other investigations considered the application of hygro-thermal model in which the prediction of moisture content distribution, relative humidity and temperature variations in wood may be used in monitoring the long-term durability of SLT deck bridges [7]. Investigations addressing both lateral and vertical vibration serviceability of timber pedestrian bridges have also been conducted. Most of these studies have been dedicated to comparing design guidelines provided in various design codes whilst assessing pedestrian comfort with regards to the usage of the structures [8,9]. Whereas dynamic analysis is considered as one of the successful non-destructive tools in evaluating both mechanical properties and conducting structural health monitoring of structures, its application to timber pedestrian bridges particularly those with SLT decks is limited to a few studies [10].

Structural timber systems are susceptible to high amplitudes of vibrations due to the high strength to low weight ratio of timber. Vibration serviceability may,

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therefore, be a crucial design issue with respect to stressed laminated timber deck pedestrian bridges. Human perception of vibrations depends on frequency components of the motions and responses such as acceleration. In this study field experimental campaign via operational modal analysis (OMA) is conducted to determine the vibration behaviour of a stressed laminated timber deck pedestrian bridge in Norway, (Fig. 1). The primary aim is to predict modal and time-history response parameters of the studied bridge, which are required as precursors for the appropriate performance assessment criteria. Dynamic data acquired enable the determination of modal parameters and acceleration responses under human footfalls. The secondary aim is contributing to SLT deck bridge vibration data for the long-term performance of timber pedestrian bridges under seasonal environmental changes. Moreover, the modal data may form the basis of calibrating numerical finite element (FE) models for pedestrian bridge vibration serviceability, and calibrated models employed for various parametric studies.

2 – FIELD TESTING PROGRAM

In this section a description of the case study bridge for which the experimental campaign was undertaken is provided in addition to a summary of the testing procedure.

2.1 DESCRIPTION OF CASE STUDY BRIDGE

The field experimental tests were carried out on the 3-span Nodre Finstad pedestrian bridge located in Northern Follo Municipality in Viken county, Norway. The width of the structure is 3 metres, with a total length of 38 metres on plan, made up of a 18 metre main span and two end spans each of length 10 metres. The superstructure is built from 0.4 metre thick stress laminated timber deck fitted with lightweight steel guardrails. The decks span longitudinally from the two abutments unto two interior I-steel beams with a 0.04 metre asphalt overlay. In elevation the footprint of the bridge is curved, and the height of the crown is estimated to be approximately 6.4 meters from the top of the asphalt of the underpass highway as shown in Fig. 1. The substructure consists of the two abutments and two interior piers with both supporting systems anchored on reinforced concrete (RC) footings. The abutments are built in RC whilst the I-steel beams also serve as the pier caps supported on a pair of oval shaped glulam columns.

2.2 TESTING PROCEDURE

Under the operating conditions of the bridge modal analysis [11] was conducted to procure the vibration behaviour of the bridge in terms of characterizing the modal natural frequencies, modal shapes, and modal effective damping ratios as well capturing acceleration time-history responses. The bridge deck plan was divided into three across the width and nineteen along the span creating a grid system, with the points of intersections considered as points of degrees of freedom (DOF). Accelerometers were placed at the points of DOF to capture the bridge motion responses in the vertical direction. Two other nodal locations were selected for reference accelerometers (R1 & R2) with careful consideration of all nodal locations to enable the discovery of all significant modes as shown in Fig. 2.

Ten number accelerometers/sensors were used: two as reference and eight as roving accelerometers, reflecting a total of ten test setups. In Fig. 2 the shaded circles indicate test set up 2 (consisting of the eight roving sensors and the two reference sensors R1 and R2), and the unshaded circles mark the DOF positions for other test setups. Disturbances on deck surfaces of bridges causing annoyance to pedestrians are often caused by human activities [8,9], and vehicular traffic. Therefore, to achieve a broadband excitation, each test setup involved a person of about 80 kg weight walking from end of the bridge to the other. The test setups were repeated for the person running across the bridge span to assess the vibration performance of the structure under different human activities. Each round of test lasted for 120 seconds for both walking and running scenarios. The motion responses were recorded using a state-of-the-art data acquisition system equipped with the LabVIEW commercial software with sampling rate of 100 Hertz.

Figure 1: Case study bridge – Nodre Finstad Footbridge, Norway

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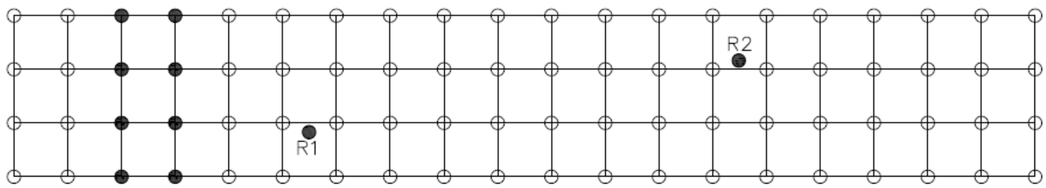

Figure 2: Illustration of accelerometer placement on plan for various test setups

3 – DYNAMIC PARAMETER IDENTIFICATION

Modal parameters and time-history responses are normally used to assess the dynamic performance of various systems. For large civil engineering structures such as timber pedestrian bridges, the relative high stiffness to mass ratios usually leads to closely spaced modes. Thus, appropriate modal analysis of such structures requires a multi-degree of freedom (MDOF) approach to identify as many modes as possible contributing to motions likely to cause pedestrian discomfort. Various methods for MDOF modal analysis in both frequency and time domain have been developed including the singular value decomposition (SVD) method [12,13].

The ARTeMIS Modal software [14] was employed for signal processing and modal parameters extraction. The software is a state-of-the-art commercial tool equipped with various algorithms such as the Enhanced Frequency Domain Decomposition (EFDD), the Curve-fit Frequency Domain Decomposition and the Stochastic Subspace Identification (SSI) [14]. These algorithms leverage on the SVD approach for modal parameter extraction. The application of these three methods in ARTeMIS Modal for extracting the modal parameters enables the comparison and verification of the modes already identified and to identify modes not already identified [12,13]. The in-built Modal Assurance Criterion (MAC) algorithm calculates MAC matrix between mode shapes from the different techniques adding value to the results validation. Besides, since the SSI approach does not depend on DFT, it has been found to limit challenges associated with leakage [15].

In the EFDD, the Discrete Fourier transform (DFT) converts the test data into spectra densities in the frequency domain. A singular value decomposition (SVD) of the spectral density matrix is performed from which the modal parameters may be obtained. This reflects that the singular values represent peaks along the frequency spectrum, with the vicinity of each peak being considered as the dominate corresponding single degree of freedom (SDOF) mode [13,16]. The CFDD technique is like the EFFD with an addition of curves fitted to the frequency content of the signal as shown in Fig. 3. The curves from which modal parameters may be obtained, represent the identified dominate SDOF spectral density functions [17].

The SSI which works completely in the time domain requires the description of structure by a stochastic space model [12,13]. The dynamic data resulting in the state space matrix is taken through various matrix operations including SVD, least squares and eigenvalue decomposition for the development of a stabilisation diagram (Fig. 4) to extract the modal parameters. Details of the various algorithms employed in ARTeMIS Modal are explained by various researchers [12-13; 16-17].

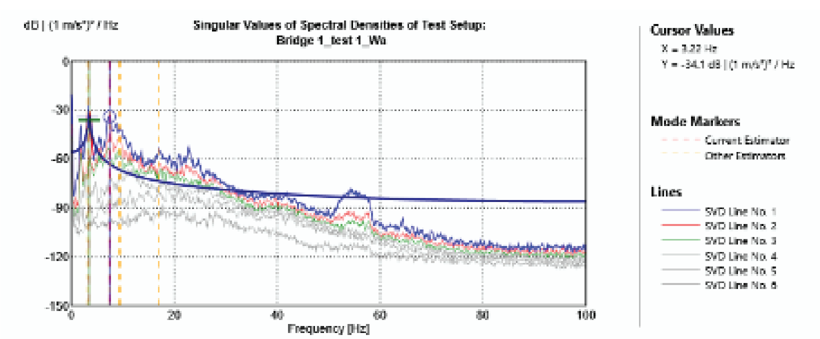

Figure 3: Illustration of the application of the CFDD technique for modal parameter estimation for mode 1 of the walking test in test setup 1

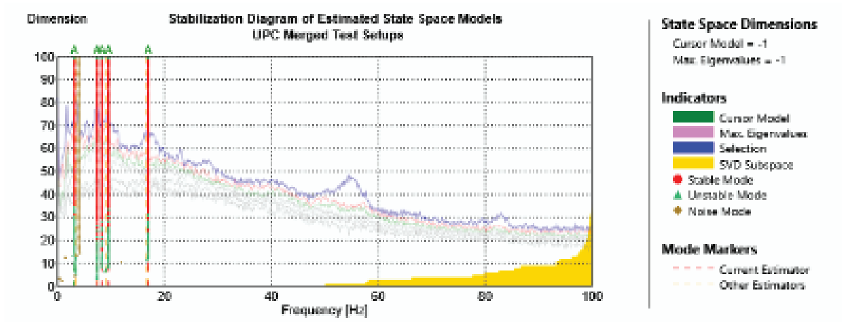

Figure 4: Stabilization diagram for merged selected models in SSI for all test setups for the identification of modal parameters – walking test

4 – FIELD CAMPAIGN RESULTS

Dynamic forces which lead to oscillations of pedestrian bridges in various directions include human activities such as walking and running/jogging. The impact of such activities may be due to single persons engaged or group of persons often called crowd induced vibration. Results presented in this study are based on field work carried out with a single person either walking or running along the bridge span. The expectation was to generate a broadband excitation, whilst considering the bridge in its operating conditions, to identify as many modes as possible likely to provide enough data for assessing the future condition of the bridge. In addition to modal parameters, acceleration responses on the bridge deck surfaces are also provided contributing to data base for evaluating vibration serviceability performance of timber pedestrian bridges. Using three analysis methods in ARTeMIS Modal enables the comparison and validation of the estimated modal parameters. Comparing the various mode shapes for any mode from the various techniques is essential in verifying the accuracy of the results. Furthermore, the use of multiple techniques allows for the determination of the averages of the modal natural frequencies and damping ratios which may be very useful for finite element simulations.

4.1 MODAL PARAMETERS

Table 1 and Table 2 present the results from the field tests which capture the modal parameters involving walking and running respectively. The identified modes captured are within a frequency range of up to about 23 Hertz for both excitation scenarios. Modal natural frequencies and effective damping ratios are listed for all the three techniques employed in ARTeMIS modal, with the averages providing a basis for discussions. Various footbridge vibration serviceability design guidelines focus on predicting the fundamental frequency (f_1) [18,19], with the assumption that the other higher-order modes participate at energy levels that account for relatively insignificant masses compared to f_1. However, as many modes as may be identified are of importance due to the reason that motion response component likely to disturb pedestrians depend on the aggregation of all participating modes with frequencies up to a certain threshold [13,15]. Moreover, such information is required in establishing a database for systems for which modal parameters are indicators for assessing their long-term performance.

Comparing Table 1 and Table 2, various observations may be made between when the bridge is under operating conditions of a pedestrian walking and running/jogging. Firstly, four modes were identified from walking excitation compared to five modes from running, suggesting impact from footfall forces under a pedestrian running is associated with relatively higher energy than walking. This is to be expected as during running the feet is lifted off the deck surface relatively higher thus creating a much larger impact than when walking.

Secondly, it may be observed that similar mode shapes in the same mode order up to the fourth mode are identified for both walking and running/jogging impact on the bridge deck surfaces. This reflects the effectiveness of both walking and running as sources of excitation for the dynamic testing of flexible slender pedestrian bridges, particularly, running across the bridge span to engage extra higher-order modes. Thirdly, it may be noticed that overall, the modal natural frequencies compare very well between the two footfall forces. Nevertheless, the average fundamental frequency for walking is about 12% higher than that for running, whilst the average frequency for the third mode under walking is about 8% less than its correspondent for running. However, there appears to be insignificant differences between the natural frequencies for the second and fourth modes. These observations may be attributed to redistribution of the modal stiffness to mass ratios under the different excitation scenarios, especially for the fundamental mode. Fourthly, as may be seen from Table 2, the fifth mode identified under running has a similar mode shape to mode 1. This is a phenomenon that is often associated with structural systems in which intermediary supports turn to mirror dynamic deformations in ways that create repeated mode shapes [20]. The average recorded fundamental frequencies from both walking and running seem to be in the range of proposed design values from various design rules.

Last but not the least, the average effective damping ratio for the fundamental mode estimated under the walking excitation is about 26% higher than that found under the

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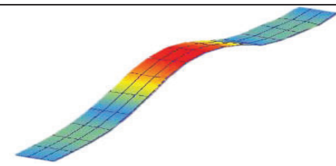
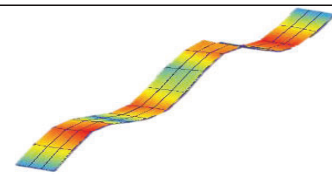
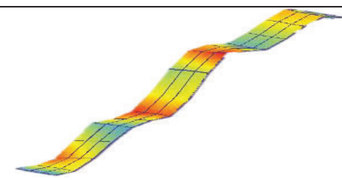
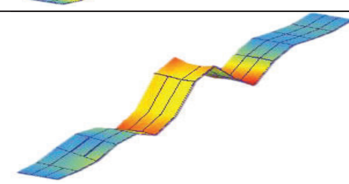
running excitation. Minor discrepancies are observed for the effective damping ratios between walking and running footfalls for the other higher-order modes ranging from 6.2% for mode 1 to about -0.4% for mode 4. Considering design guidelines formulated based on the fundamental frequency and its corresponding damping ratio, it appears that the almost constant contact between the feet and the deck surfaces during walking have more influence on the damping ratio compared to running/jogging. Also, the damping ratios reported here are relatively higher than what is recommended in most design guidelines [18,19].

Table 1: Extracted modal parameters from tets based on walking footfall forces

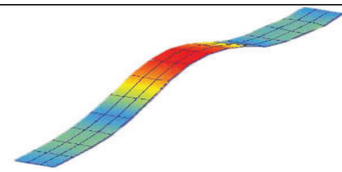
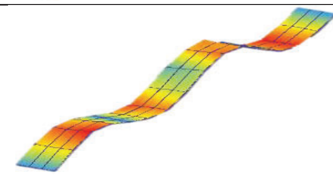
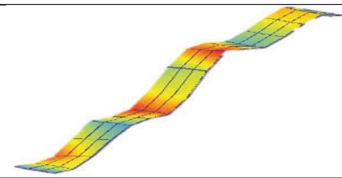
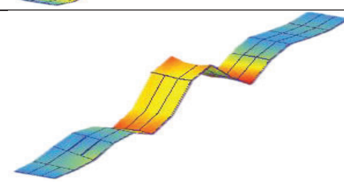
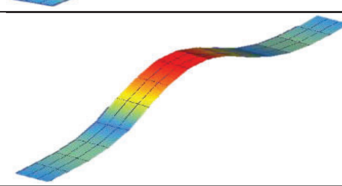
Mode	**Technique**	**Frequency [Hz]**	**Damping [%]**	**Mode shape**
*1	EFDD	3.43	4.85	
	CFDD	3.46	5.63	
	SSI	3.17	5.26	
	AVERAGE	3.35	5.25	
2	EFDD	7.45	3.61	
	CFDD	7.45	1.88	
	SSI	7.44	2.21	
	AVERAGE	7.45	2.57	
3	EFDD	9.19	2.60	
	CFDD	9.20	1.40	
	SSI	9.58	3.30	
	AVERAGE	9.32	2.43	
4	EFDD	16.9	2.82	
	CFDD	17.1	2.01	
	SSI	17.0	3.65	
	AVERAGE	17.0	2.83	

* Mode order as extracted from field test

4.2 BRIDGE MOTION RESPONSES

Fig. 5 illustrates motion responses on the bridge deck surfaces in terms of the accelerations recorded during test setup 5 and scaled down to 20 seconds. Fig. 5(a) compares the responses between walking and running under reference accelerometer R1 whilst Fig. 5(b) compares the motion responses for both excitation sources under reference sensor R2. As may be seen, in both situations relatively high peak responses are observed for the running footfalls than for the walking excitations. For instance, from the time-history recordings from reference sensor 1, the peak accelerations for walking and running are 0.153m/s2 and 0.552m/s2 respectively. Considering that very little variations are estimated for the effective average damping ratios except for mode 1, between the walking and running footfall impacts, the recorded motion responses buttress the high energy contents related to the running excitations. For practical applications during modal testing, impact forces with energy levels capable of exciting other higher-order modes may be recommended to provide enough data for long term monitoring of structures. Besides modal data with enough information including extra modes of vibration may be preferred for FE modal model updating for parametric studies.

Table 2: Extracted modal parametersfrom test under running footfall forces

Mode	Technique	Frequency [Hz]	Damping [%]	Mode shape
1	EFDD	2.98	4.28	
	CFDD	2.98	3.11	
	SSI	2.99	5.08	
	AVERAGE	2.98	4.16	
2	EFDD	7.60	2.11	
	CFDD	7.65	1.62	
	SSI	7.46	3.53	
	AVERAGE	7.57	2.42	
3	EFDD	10.1	1.97	
	CFDD	10.1	1.96	
	SSI	10.0	4.23	
	AVERAGE	10.1	2.72	
4	EFDD	16.9	2.18	
	CFDD	17.1	2.07	
	SSI	17.2	4.28	
	AVERAGE	17.1	2.84	
5	EFDD	22.2	2.01	
	CFDD	22.4	2.13	
	SSI	22.4	4.77	
	AVERAGE	22.3	2.97	

5 – CONCLUSION

Experimental campaign with regards to obtaining modal parameters and time history responses were conducted on a pedestrian bridge designed and built with timber components including stress laminated deck and piers made of glulam. Tests were carried out under the operating conditions of the bridge during which vibration data under walking and running footfall impacts of a pedestrian on the structure were procured.

Although the presented results from the signal processing represent the initial stage of evaluating the vibration performance of the bridge and its long-term health monitoring, various conclusions can be drawn. Using different techniques for signal processing enables comparison of extracted modal parameters whilst averages can be determined for further discussions. Also, it may be quite feasible to induce more vibration modes when a pedestrian is running across a footbridge than engaging in walking. Furthermore, within a particular frequency range, modal natural frequencies and damping ratios identified from human induced vibrations due to walking and running compare very well with each other. Finally, peak acceleration responses support the fact that footfall impacts due to running have relatively high energy which may lead to the recovery of more modes than walking footfall impacts.

Ongoing work will assess the vibration performance of the studied bridge using various design rules from various design codes and guidelines. Periodic field tests are also planned to capture more data including those under seasonal variations to support the long-term performance assessment of timber pedestrian bridges.

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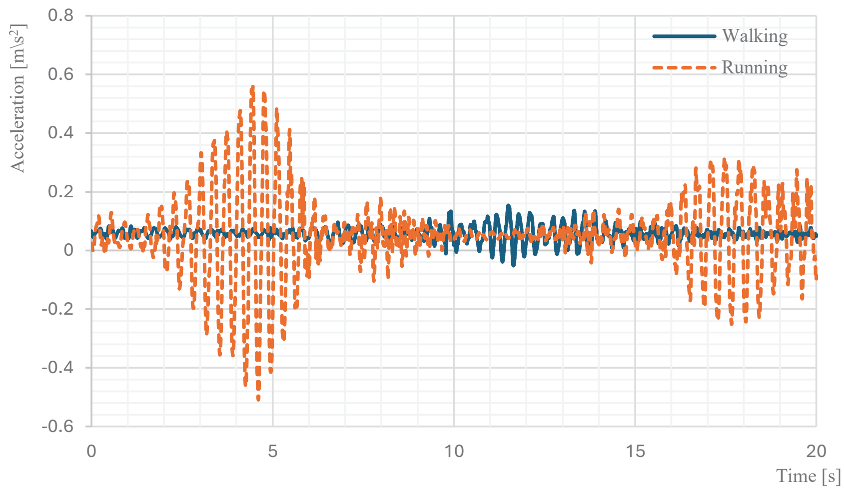
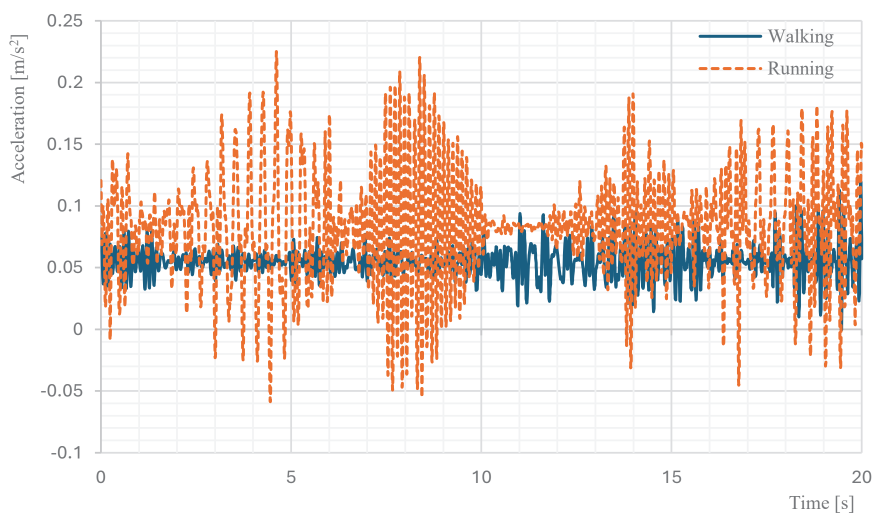


(a) Acceleration responses for walking and running under reference sensor 1



(b) Acceleration responses for walking and running under reference sensor 2

Figure 5: Vertical motion responses of bridge under walking and running footfalls recorded from reference sensors 1 & 2

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