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Joint discrepancy evaluation of an existing steel bridge using time-frequency and wavelet-based approach

Suresh Kumar Walia^{*}, Raj Kumar Patel, Hemant Kumar Vinayak and Raman Parti

Abstract

The objective of this study is to bring out the errors introduced during construction which are overlooked during the physical verification of the bridge. Such errors can be pointed out if the symmetry of the structure is challenged. This paper thus presents the study of downstream and upstream truss of newly constructed steel bridge using time-frequency and wavelet-based approach. The variation in the behavior of truss joints of bridge with variation in the vehicle speed has been worked out to determine their flexibility. The testing on the steel bridge was carried out with the same instrument setup on both the upstream and downstream trusses of the bridge at two different speeds with the same moving vehicle. The nodal flexibility investigation is carried out using power spectral density, short-time Fourier transform, and wavelet packet transform with respect to both the trusses and speed. The results obtained have shown that the joints of both upstream and downstream trusses of the bridge behave in a different manner even if designed for the same loading due to constructional variations and vehicle movement, in spite of the fact that the analytical models present a simplistic model for analysis and design. The difficulty of modal parameter extraction of the particular bridge under study increased with the increase in speed due to decreased excitation time.

Keywords: Steel truss bridge; Frequency; Power spectral density; Short-time fourier transform; Wavelet packet transform

Introduction

The development of infrastructures such as bridges in a remote region apart from the mainstream infrastructure is an inevitable aspect to be dealt by the state road organization. The speed of the vehicles gets reduced at entry and exit points of the bridges which are constructed at the locations where there are sharp curves. These bridges are not subjected to a very high vehicle speed and lead to decreased dynamic loading over the bridge and exhibit linear system behavior irrespective of the speed.

However, heavy vehicles even with low speed produce enough vibration in the medium-size bridges for evaluation (Guan and Karbhari 2008). The signals of the nodal locations can further be utilized to determine the relative flexibilities through the modal parameter extraction methods, considering signals which are either stationary or nonstationary. The conventional

method, i.e., fast Fourier transform (FFT), is being used for the last two decades and is suitable for stationary signals only. In the present study, since the recorded signal is nonstationary as excitation is nonstationary, the extracted modal parameters and their derivatives are always in question if FFT is used for modal parameter extraction (Qiao 2009; Gu 2010; Yu and Giurgiutiu 2005). The structural elements exhibit geometrical nonlinearity during vibration (Staszewski and Robertson 2007). The time-frequency-based methods such as short-time Fourier transform (STFT) and wavelet-based method are best suited for such applications (Hamtaei et al. 2008). It is the rationality of these methods that time-frequency-based methods justify its adoption. The time-frequency-based method would involve an external source of excitation. However, the short bridges require an initial impetuous so that the bridge is set into vibration for recording. The initiation of vibration with vehicle has been carried out by various researchers (Feng et al. 2008). Further, the vehicle weight does affect the frequency of the structure but with error less than 5.5% (Kim et al. 2003). The bridge

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frequency additionally gets affected with the speed of the vehicle. In case of concrete bridges, the vehicle speed turns out to be less important than the vehicle mass (Broquet et al. 2004). However, it needs to be checked whether the similar structural behavior is presented by the other material as well. The accuracy of extraction of frequency and mode shape also depends on the signal-to-noise ratio (Alampalli et al. 1997). Hence, the excitation of the structure to appreciable amplitude becomes important for an accurate and complete extraction of modal parameters (Yuen 2011). Moreover, the improper measurements lead to incomplete extraction. With the already established studies on the full scale bridge testing, the present study on a single span steel truss bridge was carried out with: (a) variable speed loading of vehicle at 10 and 30 km/h to compare the modal parameters of the bridge at different speeds; although the two different speeds may not be enough to draw the conclusion in case of the determination of absolute values of modal parameters, however, the trend in the variation of the results for both the speeds is enough to determine the flexibility of the portion of the bridge. (b) Uneven placement of sensors on both trusses of bridge to generate the mode shape and mode shape curvature with missing nodes and uneven interval to understand the variation. (c) Reference sensor node on downstream truss and moving sensors on both upstream and downstream nodes to find the disparity between nodes if any. The reference sensor node is that node for which recording will be obtained for all the sets of vibration while the moving sensor nodes are those nodes on which only one recording have been taken for the particular set of vibration record.

Description of steel truss bridge model

The bridge under study is a newly constructed (in 2009) 40-m single lane through steel-type truss bridge. This bridge is situated on Nagta Khad on Jandpur Trehal Nagta Bharwan Battan road, in Kangra district of the state of Himachal Pradesh, India.

The motivation of taking up this bridge for study was that the bridge was not constructed by a single agency. It is to be noted that whenever such administrative problems come up at the construction site, the integrity of structure gets affected and structures may not be constructed as designed. Hence, even though the traffic volume over this bridge is only 50 commercial vehicles per day, this bridge was selected for the study. The vehicular speed is limited to 30 km/h due to the small radius of curvature of the approach road at one end of the bridge. The maximum speed limit was the main consideration for testing in the present study. The bridge is a simply supported bridge with hinge at one end and

roller support at the other end. The vertical members of the bridge span are placed at an equal distance of 4 m interval (Figure 1). The detail of bridge components is given in Figure 2. The vertical and diagonal members are built-up sections consisting of four angles with the set of two angles attached toe to toe. The top and bottom horizontal members are made of two channel sections fabricated back to back. The longitudinal and crossbeams consist of ISMB 450 and ISMB 550, respectively. The members of the trusses have been joined with the gusset plates and rivet connections. The bridge deck is a reinforced concrete slab of 175 mm thickness with the 75-mm wearing coat. The carriageway is 5 m with side curb of 225 mm \times 225 mm. The deck is supported by a grid of longitudinal and crossbeams at a spacing of 1.4 m \times 4 m.

The structural modal frequencies were determined through the analytical model of the bridge generated in SAP2000, Berkeley, MA, USA, (SAP2000 2006) as per the built-up drawing of the bridge to achieve the maximum possible accuracy in the analytical model (Figure 3). The analytical frequencies of the bridge obtained were 4.61, 11.53, and 16.58 Hz for the first, second, and third mode, respectively, in the vertical plane of the bridge. The joints have been considered as rigid joint.

Methods

Experimentation

The experimentation on the steel bridge was carried out to study the disparity in the joint behavior of the downstream and upstream trusses of the steel bridge. Any variation in the expected behavior of the trusses can be due to a particular steel member being ineffective in taking the stress or the joint has lost its full rigidity and is transferring the load to other members with partial rigidity or the bearings are ineffective in transferring the load to the substructure. The experiment consists of measuring the forced and ambient vibrations generated with to-and-fro movement of the vehicle. For each setup, the acceleration response at the vehicle passage with 10 and 30 km/h has been measured. The basis of the speed selection for the experiments was the possibility of minimum and maximum speed required on a particular bridge to see whether all the modes of the structure get excited or not. In the present study, it has been considered that the various factors such as speed of the vehicle, temperature, surface roughness, etc. have similar effect on the whole bridge and not specific to any particular node, though these factors will have an effect on the individual values of the results but get nullified when the relative variations are considered.

The parameters such as sensor location, input motion, and sampling frequency are considered in performing



Figure 1 Side view of 40-m steel truss bridge.

the experiment under the same instrument setup with change in the speed of the vehicle. The details of the test model are as follows.

Sensor and data acquisition system

The data acquisition system (DAQ) and laptop were installed at one end of the bridge. The sensors used were dual channel microelectromechanical systems (MEMS) accelerometers having natural frequency of 150 Hz. Accelerometers provide voltage output, which is proportional to the acceleration of the points of placement. This analog acceleration time history is then fed to the data acquisition system. The data acquisition system first conditions the analog signal to its requirement through signal conditioning amplifier, and then, this conditioned analog signal is fed to an AD converter where digitization at prescribed sampling rate takes place. This digital data is then stored in hard disks of the laptop in ASCII format. The basic functions of data acquisition system are obtained through a vendor who has supplied interactive software and hardware system. These systems can stand alone or coupled to a computer and have the facility of acquiring simultaneously multiple channels of data from various sensors. The data acquisition system acquired for this particular case study for generating the output of the response of the structure had the desired specification to generate the

output which has sufficient information to extract the modal frequencies after processing accurately. The DAQ used for this study is KI-4100-A-8-500 of Kaptl instrumentation (Dehradun, Uttarakhand, India) that makes an advanced microcontroller-based system which is designed for high speed precision simultaneous measurement of physical parameters. This 12-V battery-operated DAQ of eight channels with analog to digital converter of 16 bits, precision of 2.5 to 5 V, and with short circuit protection, zero balancing, and simultaneous sampling up to 500 samples per second (sps) is suitable for MEMS-based accelerometers. The data acquisition system has programmable filter of up to 500 Hz, drift of $2 \mu\text{V}/^\circ\text{C}$, accuracy of 0.05%, signal conditioner skew rate of $2.4 \times 10^{-6} \text{ V/s}$, resolution of 0.001 g, and noise level on high speed of $\pm 0.002 \text{ g}$. The accelerometer and data acquisition system interface is through RS-232C/USB port. The self-calibrated MEMS technology-based accelerometer used, Freescale, Triaxial type, Austin, TX, USA, makes frequency response up to 150 Hz and sensitivity of 1 V/g.

Sensor location

To obtain the distributed response of the structure, sensors were placed on bottom nodes at the intersection points of the vertical and diagonal members in the direction of motion on both the trusses of the bridge. In a single set, four sensors were used for the measurement. Thus, vertical acceleration time histories at 18 locations were measured in 6 sets. The sensors were not placed at supports (four nodal points) as there were no vibrations at the supports. Each sensor location has been identified with unique nodal coordinate number. Figure 4 shows the placement of the sensor positions on the bridge with the typical green-colored arrows indicating movable sensor location and blue-colored arrow as reference sensor location. The nodes have been named as 1, 2, ..., 11 on downstream and 12, 13, ..., 22 on upstream with 1, 2, 11, and 22 as nodal points at supports. One accelerometer has been used as reference sensor at node 6. The vibration measurements of the nodes in the bridge were carried out along the vertical direction. The direction of the installed acceleration pick up was accounted for during the analysis of the data.



Figure 2 Truss arrangement detail.

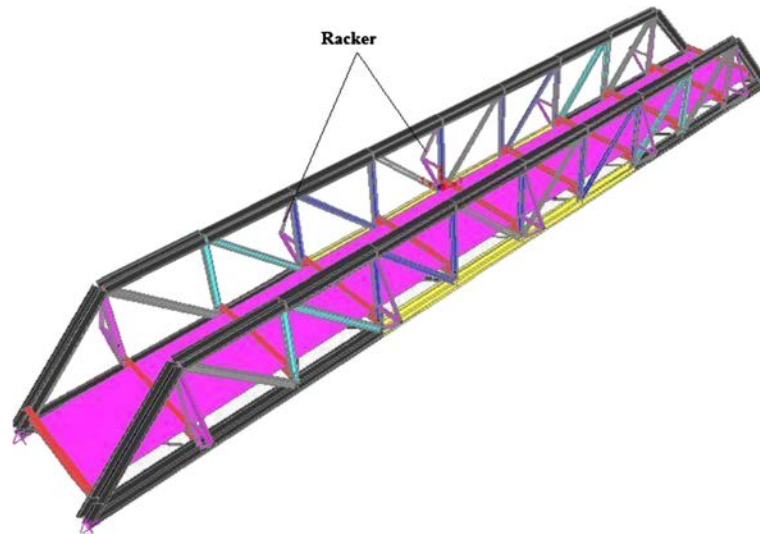


Figure 3 As-built analytical model of 40 m steel truss bridge.

Processing of recorded data

MATLAB environment, Natick, MA, USA, (MATLAB 2006) was used for the determination of power spectral density (PSD) using Welch's method, short-time Fourier transform, and wavelet packet transform from the recorded data at various speed. The digitized output signal recorded by the data acquisition system was used for the conditional diagnosis of steel bridge. Throughout the experiment, the sampling rate for acquiring the signal was kept as 200 sps. The vibration was recorded at a high sampling rate, and DC offset was carried out before analyzing the signal. Since our modal frequencies are in lower range, the vibration signal was downsampled to 50 sps to concentrate on modal frequencies. The downsampling of the data from 200 to 50 sps was done by picking the fourth sample from the signal. This downsampled signal is sufficient to provide information regarding modal frequencies up to 25 Hz, and three modes can be covered in this range. To obtain the comparative variation in the studied parameter, no filters were used for the vibration records. A typical record of one of the setups obtained on the bridge is given in Figure 5.

Results and discussion

Parametric studies

Although steel is a homogenous material but with various components of the structure, i.e., structural members, connection plates, rivets, connecting beams, and columns, all made of steel, it undergoes different modes of vibration when subjected to dynamic excitation. The variation under the applied dynamic forces leads to different amplitudes of vibration in the structure. The comparison between the modal frequency parameters determined through site measurements and the built-up drawing has been published by the author in his earlier work (Walia et al. 2012). In the present study, the distribution of energy across the spectra of frequency for the different applied forces generated through the different speed of the moving vehicle has been compared.

Power spectral density using Welch's method

The behavior of the structure changes with the variation in the joint flexibility, considering mass and stiffness of the member as constant. The PSD describes the distribution of power of signal with frequency, which changes with joint flexibility (Anton 2008). In the present study,

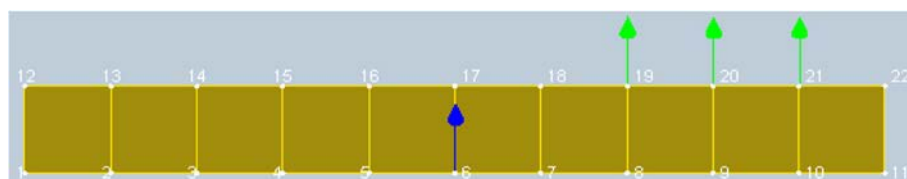
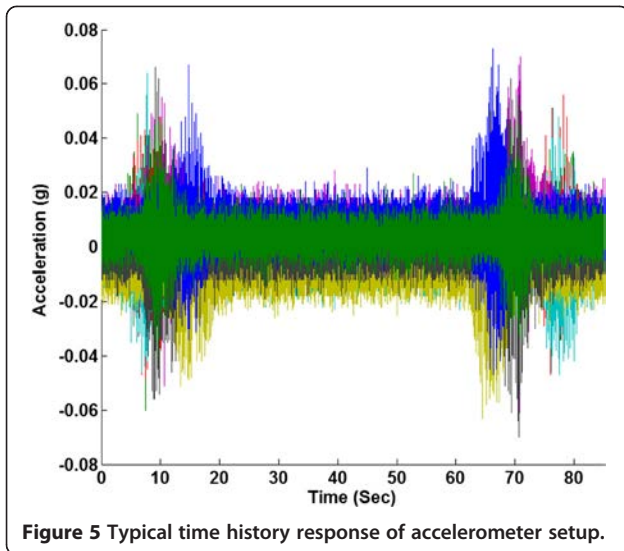
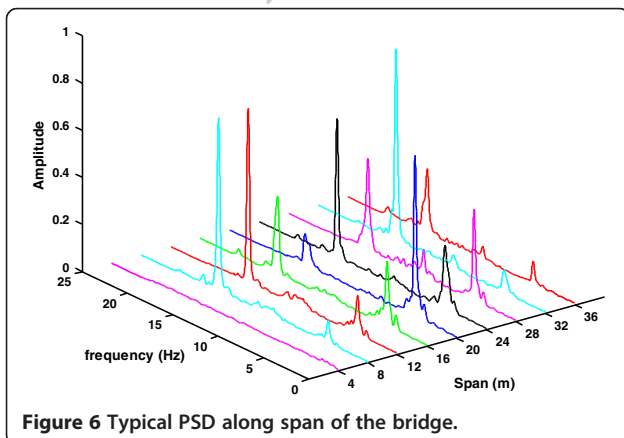


Figure 4 Typical sensor location of one of the setups on the bridge.



the PSD corresponding to different speeds of the moving vehicle on the bridge is extracted using Welch's method. Although in analytical model, the modal parameters are independent of applied dynamic force as a computational parameter and depend on stiffness, mass, and damping. Taking these features into consideration, joint flexibility variations have been determined at different speeds of the vehicle. The modal parameters determined through the analytical model have been considered as reference for comparison. The frequency peaks of power spectral density at different nodes with speed of 10 km/h are compared to those obtained with speed of 30 km/h. A typical PSD at different nodes is shown in Figure 6. The peak in PSD diagram is of the bridge and not of picked up forced vibration of the vehicle since dynamic load applied by the heavy vehicles is in the frequency range of 1.5 to 4.5 Hz. However, the first fundamental analytical frequency of the bridge was determined to be 4.61 Hz. The difference between the frequencies obtained for two speeds 10 and 30 km/h for three modes



of vibration at different nodes is shown in Table 1. All the nodes of both the trusses of the bridge got excited with the vehicle speed of 10 km/h. However, the excitation at nodal locations 24, 28, and 32 m in the downstream truss for the vehicle at 30 km/h is less than those at 10 km/h. This clearly indicates an unexpected behavior at these locations (Figure 7a). However, the variation in the modal frequencies for upstream truss for different speeds was not appreciable. Further, the variation in the frequencies at these locations is much higher than the variation in frequencies at other nodes which reflect speed dependency of the downstream truss of bridge. The variation in frequencies at various nodes of upstream truss of the bridge was found to be much less than that in downstream truss of the bridge (Figure 7b). Thus, without comparing the base model with the existing status of the bridge, the flexibility along the span of the bridge truss was obtained.

Short-time Fourier transform

The deficiencies in the downstream and upstream trusses along the span were further substantiated with the short-time Fourier Transform. Time-dependent variation of joints can further be studied through the determination of frequency content of the random process (Figueiredo et al. 2009). The variation in the frequency content with time at different nodes of the structural member reflects undesired flexibility at the nodes due to nonexcitation at a particular structural frequency. Since the nodes at 24, 28, and 32 m span of the downstream truss bridge were found to be flexible, hence, the study was concentrated on this portion only. The short-time Fourier transform of the nodal response was compared with that of the response at 12 m span which was found to be in good condition as discussed in PSD. The moving vehicle passed over the bridge twice at approximately 10 and 70 s (Figure 8). Although the structural frequencies at above nodal span due to the response at 10 km/h was extracted through STFT but the structural frequencies at 24, 28, and 32 m span for 30 km/h vehicle speed, the response could not be extracted contrary to the response at 12 m span. At a specified passage of the moving vehicle, the target node of the bridge got excited, but clear distinct resonating excitation to a particular frequency was not obtained. This nonextraction of the structural frequency bridge response obtained from 30 km/h vehicle speed excitation at the target span nodes revealed the insensitivity of the node towards the vibration along with the other nodes of the bridge.

Wavelet packet transform

The differences in PSD and STFT of both downstream and upstream trusses of the bridge indicated some variations for different speeds of the moving vehicle but did

Table 1 Frequency along span on D/S and U/S truss at different vehicle speeds

	Speed (km/h)	Span (m)									Analytical
		4	8	12	16	20	24	28	32	36	
D/S truss	10	4.09	4.43	4.46	4.44	4.54	4.45	4.54	4.47	4.53	4.61
First mode	30	4.64	4.47	4.54	4.52	4.62	3.93	3.91	3.87	4.62	
U/S truss	10	4.55	4.78	4.84	4.51	4.64	4.63	4.45	4.66	4.64	
First mode	30	3.60	4.70	4.69	4.64	4.52	4.46	4.80	4.60	4.61	

D/S downstream: U/S upstream.

not present the relative differences quantitatively. Since wavelet transform (WT) is a mathematical tool that can decompose a temporal signal into a summation of time-domain basis functions of various frequency resolutions and hence worked upon for the present study, this simultaneous time-frequency decomposition gives the WT a special advantage over the traditional Fourier transform in analyzing nonstationary signal. The WT decomposes the signal only on the low pass filter, and the frequency resolution becomes quite poor in the high frequency region. Since structural damage is typically a local phenomenon captured most likely by high frequency modes, this potential drawback can affect the application of the wavelet-based damage assessment techniques. Also, the continuous WT is a similar form of STFT with advanced resolution capabilities due to variable window length, hence not adopted for further interpretation (Yaghin and Kooohdaragh 2011), since WPT decomposes both low and high pass filters and adopts redundant basis functions and hence can provide an arbitrary time-frequency resolution. Therefore, WPT-based method is proposed for the damage assessment of structures in the present study. Dynamic signals measured from a structure are first decomposed into wavelet packet components. The Daubechies family db10 is used as a mother wavelet for wavelet packet analysis. In WPT, the recorded signal is decomposed up to three levels because

the frequency of interest was achieved up to this level. At level three, eight components of the original signal are obtained (Figure 9).

Further, the energy of each component is calculated using Parseval's theorem, and the component in which mode shape exists is worked upon. The energy difference at different excitations and nodes are used to investigate the flexibility of the joints. In the present study, the comparison of variations of energy at vehicle speed of 10 and 30 km/h gives uneven energy distribution along the downstream truss of the steel bridge, since the comparison of the energy level is being used to determine the structural deficiency; hence, the accuracy of the obtained values are not the governing factor. The energy difference for first and third mode shapes is shown in Figure 10. It has been observed that the bridge at the 28 and 32 m span of downstream truss showed lower energy difference, in comparison to energy difference at other nodes as shown in Figure 10. The low energy difference clearly indicates nonvariation in the excitation due to different vehicle speeds, although increased speed should result in increased excitation.

Conclusions

- It is observed that the flexible joints showed large variation in the frequency of signal with increased

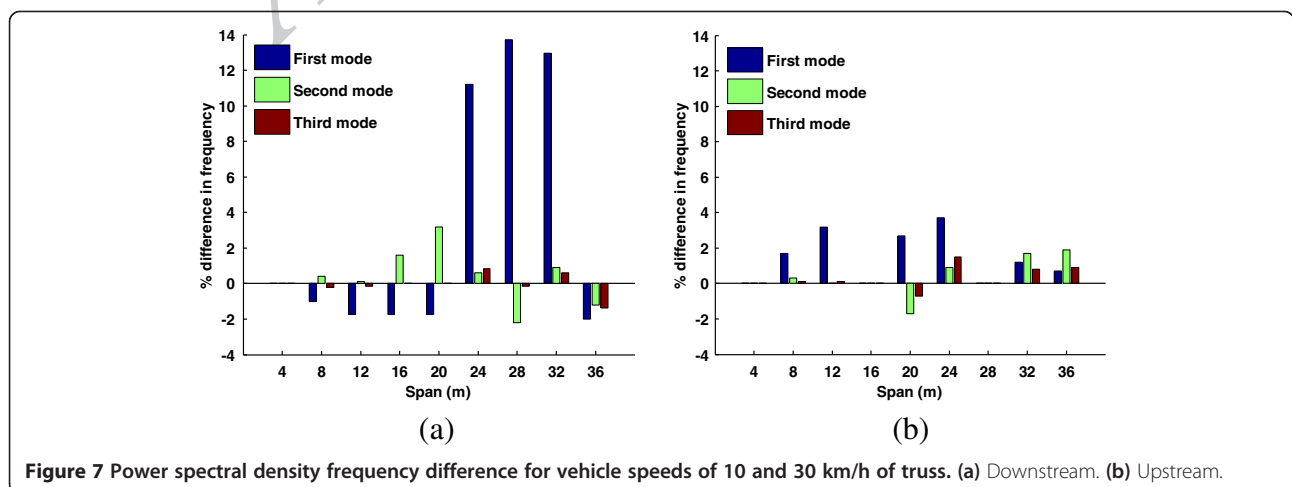


Figure 7 Power spectral density frequency difference for vehicle speeds of 10 and 30 km/h of truss. (a) Downstream. (b) Upstream.

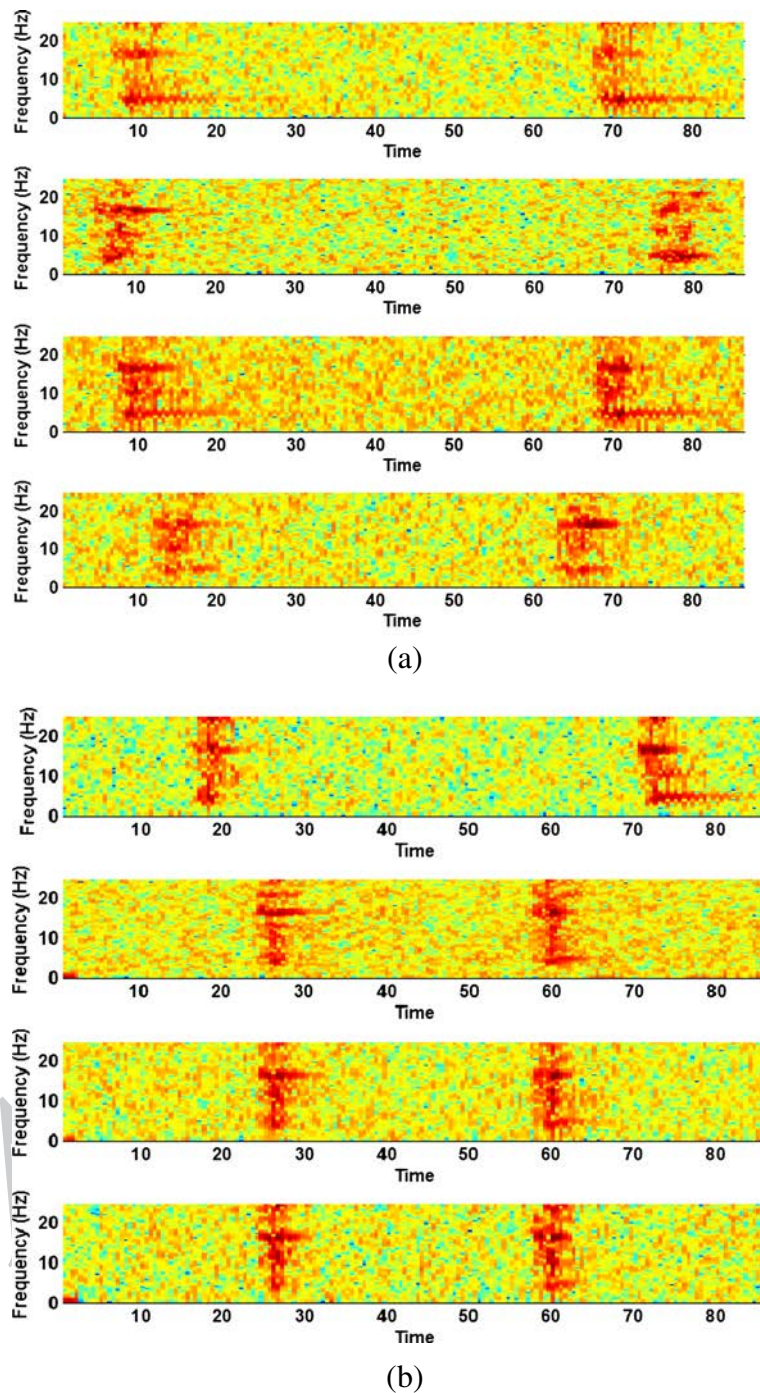


Figure 8 STFT of 12, 24, 28, and 32 m span of downstream truss of bridge. At (a) 10 km/h and (b) 30 km/h.

- vehicular speed due to excessive excitation. Thus, the poorly constructed portion of the bridge would behave differently at different vehicular speeds, reflecting nonhomogeneity along the bridge span.
- The variations of power spectral density in the first mode of the upstream and downstream trusses clearly revealed error induced in the constructed

bridge due to the improper riveting at the joints signifying the importance of generating bridge signature after construction.

- Short-time Fourier transform also showed the flexibility in the joints of the downstream truss with respect to excitation. The nodes did not respond in resonance with the structural frequency, thus

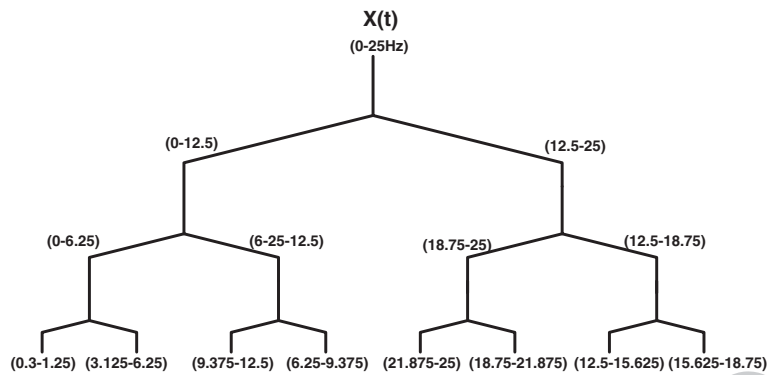


Figure 9 Three-level wavelet packet decomposition tree.

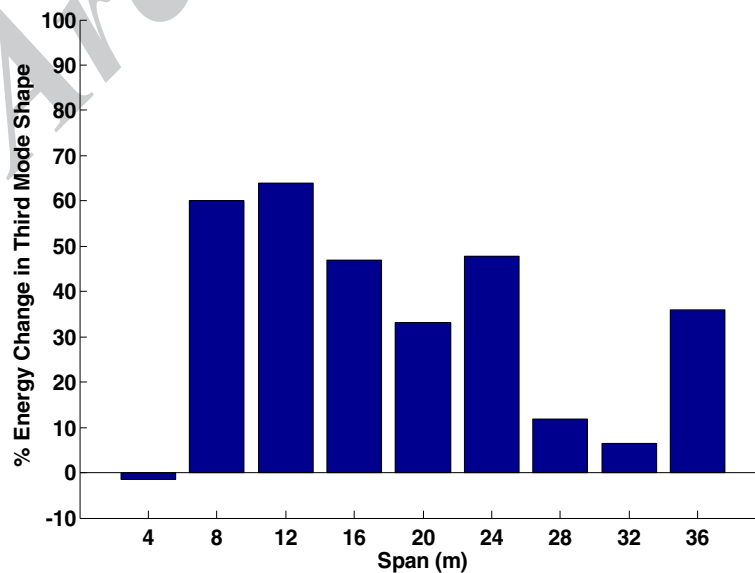
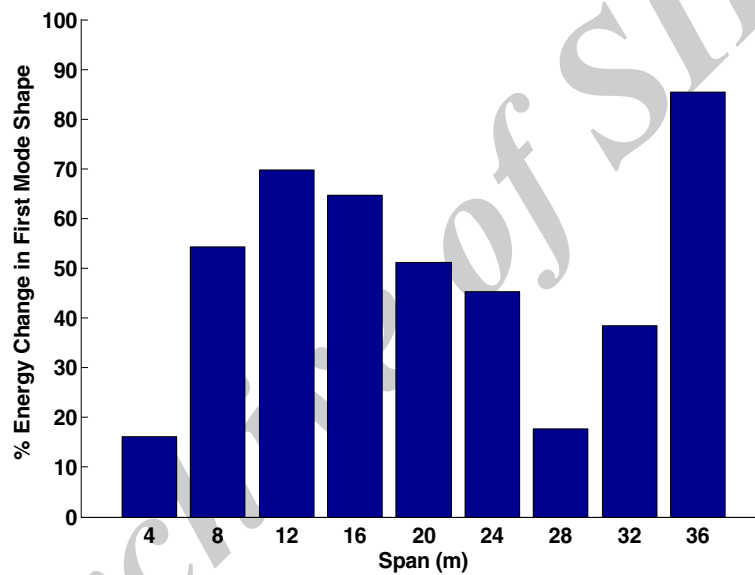


Figure 10 WPT change in downstream truss for 10 and 30 km/h.

implicating nonuniform behavior among various elements of the bridge.

- The nodal response in distinct frequency of vibration varied with time of excitation. The higher the excitation time, the higher is the nodal response.
- The wavelet packet transform technique reflected nondependency on particular modal response for flexibility identification contrary to power spectral density technique.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Suresh Kumar Walia got experiment conducted at birdge site, analysed the bridge model, drafted the manuscript Raj Kumar Patel, involved in formulation of programs and data analysis Hemant Kumar Vinayak conceived the study and coordinated the analytical and experimental results. Raman Parti checking of manuscript and coordinated the work. All authors read and approved the final manuscript.

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