FACTA UNIVERSITATIS
Series: **Architecture and Civil Engineering** Vol. 14, N^o 2, 2016, pp. 141 - 166
DOI: 10.2298/FUACE1602141W

CONDITION ASSESSMENT OF STEEL TRUSS BRIDGE USING TIME FREQUENCY DOMAIN ANALYSIS

UDC 624.21.014.2

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Abstract. *In the present article the work is carried out on scaled modeled bridge for condition assessment due to seeded damage. The objective is to find the location of damage in the steel bridge using vibration signal. For the differentiation between damage and intact condition, time, frequency domain analysis has been used. Power spectral density has been applied to the vibration signal to extract the mode shapes and compare between healthy and damage state of the modeled. Further, Short Time Fourier Transform gives the 3D visualization of amplification in different mode of vibration which helps to identify the damage location. Using nodal energy approach, Wavelet Packet Transform has been used to determine the location of damage, which is superior than the frequency and time domain analysis parameters.*

Key words: *Steel truss bridge, Time domain analysis, power spectral density, Short Time Fourier Transform, Wavelet Packet Transform*

1. INTRODUCTION

Damage is often observed in many engineering structures during their service life. Among various engineering structures bridges are among the most expensive investment asset of any country's civil infrastructure and have a long service life compared with most commercial products and are rarely replaceable once erected [1]. Damages in most of the bridges may be caused due to various factors such as excessive loading, fatigue and wear-tear due to dynamic vehicular loads, environmental factors constructional defects and cumulative crack growth [2]. SHM has emerged as a reliable, efficient, and economical approach to monitor the system performance, detect damage, assess/ diagnose the structural health condition, and make corresponding maintenance decisions [3].

Received November 28, 2015 / Accepted April 4, 2016
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In the present work a single span steel truss bridge model fabricated in the lab is studied through the modal parameter extraction methods, considering vibration signals either stationary or nonstationary. The signal is often transformed to different domains in order to better interpret the physical characteristics inherent in the original signal [8]. Traditional Fourier transform are obtained generally for obtaining the modal properties. FT is a data reduction process and structural health might be lost during process [9]. The modal parameter identification can be divided into two categories, namely frequency domain identification and time domain identification [10]. It transforms measured time domain data to frequency domain with FFT and is identified with power spectral density (PSD) [11]. The fast Fourier transform (FFT) is a perfect tool for finding the frequency components in a signal [12]. The FFT is being used for the last two decades and is suitable for stationary signals only [13]. The time domain identification uses comparison statistical data of different state of structure. For small and simple structure, both time domain and frequency domain analysis methods can achieve satisfactory result, In case of nonstationary signal, the extracted modal parameters and their derivatives is always in question if FFT is used for modal parameter extraction [14]–[16]. Moreover in case of FFT the frequency components can only be extracted from the complete duration of the signal [17]. Thus any variation in the frequency content during period of vibration cannot be worked out by FFT. The structural elements also exhibit geometrical nonlinearity during vibration [18] due to which the structural frequencies are non uniform during the vibration time span. The time frequency based method such as Short Time Fourier Transform (STFT) and Wavelet based methods are best suited for such applications [19].

Wavelet analysis, as a promising tool for damage detection, may be viewed as an extension of the traditional Fourier transform with adjustable window location and size. The wavelet transform is used for the determination of modal parameters such as natural frequencies, damping ratios and mode shapes of a vibrating system [20]. The wavelet packet transform is an extension of WT that provides complete level by level decomposition and can be used for damage detection. The results illustrate a great promise of wavelet analysis for detecting damage, identifying the moment when a sudden damage occurred, and localizing the damage regions, particularly for an online health monitoring of bridges.

2. DESCRIPTION OF STEEL TRUSS BRIDGE MODEL

Through type steel bridge model was constructed in the Highway laboratory. The span of the bridge is 6 m and is divided into 10 equidistant zones (Fig. 1). The deck of the bridge consists of 10 mm thick steel plate This Bridge model is a simply supported bridge with a hinge support at one end and the roller support at other. The vertical and diagonal members of the bridge model are made up of 20 mm x 3 mm steel plate member. The top and bottom horizontal members are made of angle section 30 x 30 x 3 mm.

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Fig. 1 Lab Model for through type Steel Bridge

The analytical model of the bridge was generated in SAP 2000 [21]. The members are assigned specifically as built cross-section to achieve the analytical model as accurate as close to the actual bridge (Fig. 2).

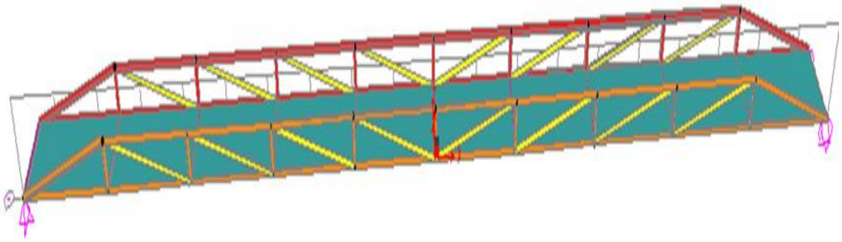
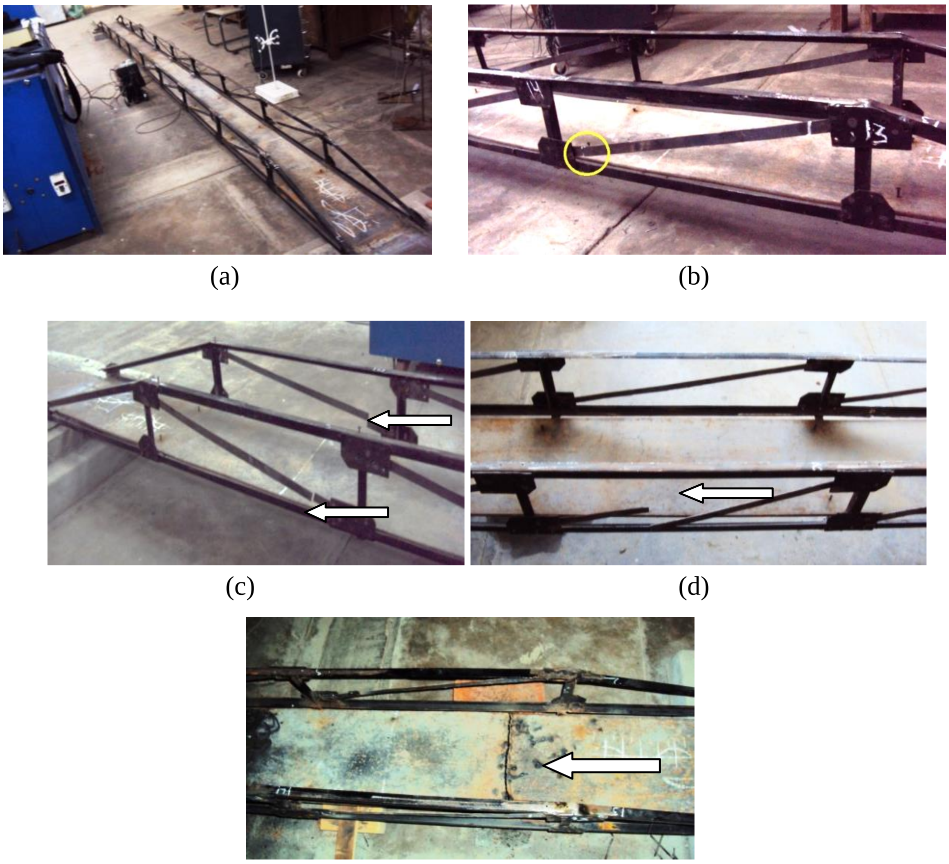


Fig. 2 Analytical Model on SAP 2000 of the Bridge

3. EXPERIMENTATION

The experiment on the steel truss bridge was carried out to detect the damage by sequentially cutting the truss members. As any variation in the expected behavior of the trusses can be due to a particular steel member being ineffective in taking the stress and is transferring the load to other members with partial rigidity. Impact testing utilizes a sudden power by an object such as hammer to excite the bridge model[22]. The weights of the impact hammer can be adjusted to produce different forcing levels to be applied to the structure. In the present work the forced and ambient vibrations were measured with hammering with hammer of 5 kg. In the present study the bridge is a single lane and the hammer was struck at three points at 2/3, 1/2 and 1/3 one-third of the span. In the present study the mass of the hammer has been kept same and bridge was excited by hammering with same intensity so that the comparative values will not be affected. Different cases have been considered for the damage detection in the members and damage in deck of the bridge. Different cases of damages for which experimentation carried out are as below

- Case 1 No Damage in the Bridge Structure
- Case 2 Inclined Member 13-14 Damaged
- Case 3 Inclined Member 13-14 and 2-3 Damaged
- Case 4 Deck damaged between Nodes 2/3 and 13/14



(a) (b) (c) (d) (e)

Fig. 3 Damages in the model bridge (a) No Damage (b) Single member Damage (c) Double Member Damaged (d) Triple members Damaged (e) Damage in Deck

Following are the parameters such as sensor location, input motion, sampling frequency, which are considered in order to perform the experiment under the same setup before and after retrofitting. The details of the test model are as follows.

4. Sensor and Data Acquisition System

The data acquisition system and laptop was installed at one end of the model bridge. The sensors used were dual channel MEMS accelerometers having natural frequency of 150 Hz. The results obtained from cabled sensors are comparable with wireless sensors and thus cabled sensors were used in the present study [23]. Accelerometers provide voltage output, which is proportional to the acceleration of the points of placement. This analog acceleration time history is then fed to data acquisition system. The data acquisition system first conditions the analog signal to its requirement through signal conditioning amplifier and then the conditioned analog signal is fed to 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 achieved with the in built interactive software and hardware system. These systems can be standalone 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 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 data acquisition system DAQ used for this study is KI-4100-A-8-500 of KAPTL instrumentation make is an advanced Micro controller Based system which is designed for high speed precision simultaneous measurement of physical parameters. This 12V battery operated DAQ of eight channel with analog to digital converter of 16 bit, precision of 2.5 to 5 volts, with short circuit protection, zero balancing and simultaneous sampling up to 500sps is suitable for MEMS based accelerometers. The Data acquisition system has programmable filter of up to 500 hz, Drift - 2μV/°C, Accuracy - 0.05%, Signal Conditioner Skew rate - 2.4 x 10-6 V/sec, resolution - 0.001 g, noise level on high speed - ± 0.002 g. The accelerometer and data acquisition system interface is through RS – 232C/ USB port. The self-calibrated MEMS technology based accelerometer used is of make Freescale, Type – Triaixial, Frequency response upto 150 hz, sensitivity - 1volt/g.

5. Sensor Location

To obtain the distributed response of the structure, sensors were placed at the intersection points of the vertical and diagonal members in the vertical direction of motion on both the trusses of the bridge.

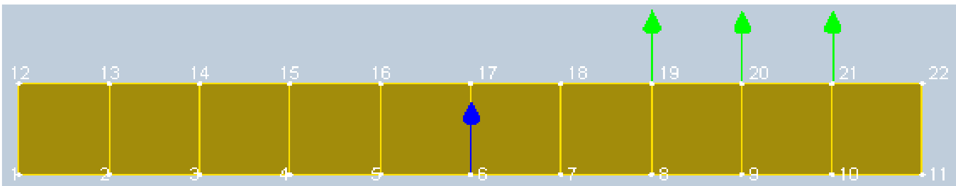


Fig. 4 Typical sensor location of one of setup on the bridge

In a single set, four sensors were used for measurement. Thus, vertical acceleration time histories at 18 locations were measured in six sets. The sensors were not placed at supports (four nodal points) as complete fixity is considered at the supports. Each sensor location has been identified with unique nodal coordinate number. Fig.3 shows the placement of the sensors position 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 designated as 1,2…11 of one truss and 12, 13, ...22 of the other truss with ,12,13…,22 on the other truss of the model bridge. The accelerometer at node 6 has been used as reference sensor. The vibration measurements of the nodes in the model 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.

6. Processing of Recorded Data

Power Spectral Density using Welch's method, Short Time Fourier Transform and wavelet packet transform was determined using MAT LAB environment [24] from the recorded data before and after damage. The digitized output signal recorded by the data acquisition system was used for the conditional diagnosis of steel bridge. The sampling rate for acquiring the signal was kept as 200 samples per second (sps) during whole of the experiment. The vibration was recorded at high sampling rate and DC offset was carried out before analyzing the signal. The vibration signal was down sampled to 50 sps to concentrate on modal frequencies because our model frequencies are in lower range. This down sampled signal is sufficient to provide information regarding modal frequencies up to 25 Hz and three modes can be covered in this range.

7. Parametric Studies

The variation under the applied dynamic forces leads to different amplitude of vibration in the structure. In the present study these different applied forces are generated through the moving vehicle. The results obtained are compared in terms of time domain analysis (Variance), frequency domain analysis (Power spectral density using welch method), and time frequency domain analysis (Short Time Fourier Transform and Wavelet packet Transform).

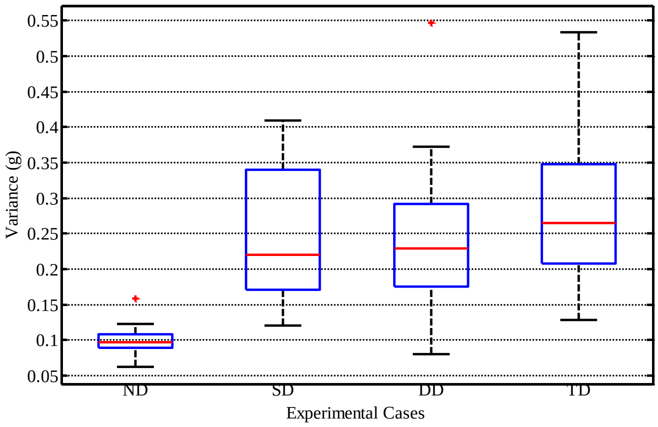
7.1. Variance

In health monitoring of structures, time-based analysis of signals is well established in industrial practice. Intermittency, trend monitoring, threshold monitoring of statistical characteristics like mean, peak, standard derivation, and root mean square are common methods for qualitative fault analysis [25]. As a variation, Caesarendra et al. done experimentation on their condition monitoring approach on circular domain features and claim superiority to time-frequency analysis methods [26]. Serido et al. [27] use Autoregressive Moving Average-based methods (ARMA), a more elaborated time-based analysis. Variance and Euclidean length are derived from vibration signal and the statistical inference is further extended by boxplot and cumulative distribution function plot respectively.

The statistical process control technique is implemented to monitor the occurrence of damage in the test structure [28]. When a structural system experiences unusual conditions, the mean and variance of the extracted features are expected to vary. The control chart measures the variability of the structure over the independent variable (such as time or acceleration), and this is employed to monitor the changes of the selected features by identifying particular samples that are outliers from an autoregressive estimation based on the different extracted data sets [29]

In probability theory and statistics, variance measures how far a set of numbers is spread out. A variance of zero indicates that all the values are identical. Variance is always non-negative: a small variance indicates that the data points tend to be very close to the mean (expected value) and hence to each other, while a high variance indicates that the data points are very spread out around the mean and from each other.

Fig.3.10 shows the boxplot of variance calculated from different cases of observation of bridge model in the lab. The figure indicates that as the level of fault increases the variance increases and box spread up. The variance of no damage case is very narrow in range and as the damage occurs the variance becomes wider. A boxplot provides a graphical summary of the distribution of a sample. The boxplot shows the shape, central tendency, and variability of the data



ND-No damage, SD-Single Damage, DD-Double Damage, TD- Triple Damage

Fig. 5 Box plot of Variance for different cases of damage in Members

Fig.3.11 shows the boxplot of variance calculated from observation of data for the Damaged and undamaged deck data of the tested bridge model in the lab. The variance of no damage case is very narrow in range and as the damage occurs the variance becomes wider.

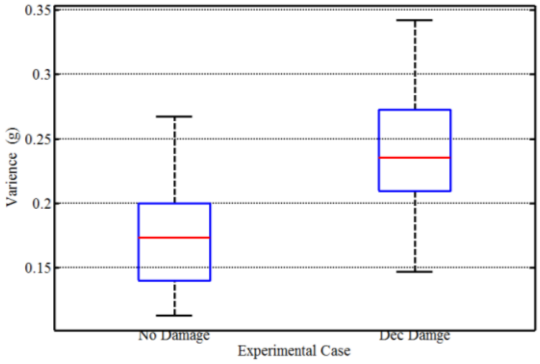


Fig. 6 Box plot of Variance for damage in Deck of Bridge Model

7.2. Cumulative distribution

In probability theory and statistics, the cumulative distribution function (CDF), describes the probability that a real-valued random variable X with a given probability distribution will be found to have a value less than or equal to x. In the case of a continuous distribution, it gives the area under the probability density function from minus infinity to x. Cumulative distribution functions are also used to specify the distribution of multivariate random variables. For a continuous distribution, this can be expressed mathematically as:

$$F(x) = \int_{-\infty}^{x} f(\mu) d\mu$$

Where, $F(x)$ is the cumulative distribution function

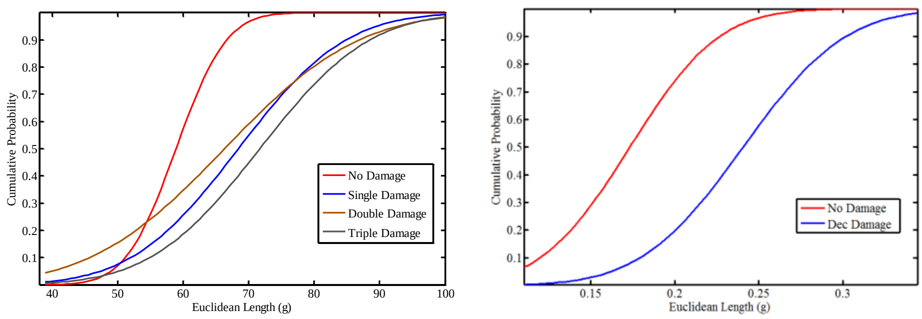


Fig. 7 CDF of Euclidean Length for (a) Damage in Members (b) Damage in Deck

By calculating the cumulative distribution function of the vibration signals variations in the data before and after damage can be studied. In the present work, Euclidean length of statistical parameters is found, for a given operating condition, to arrive at various condition of steel bridge structure. The conditions are case1: no damage, case 2: single damage, case 3: double damage and case 4: triple damage has been taken in figure 3.12. Similarly damage and undamaged case for damage in deck case has been presented in Total 18 Euclidean lengths are calculated from 18 nodes of the bridge and plotted its cumulative distribution. The acceleration levels shown by calculated Euclidean length value are vary between 40g to 100g., Case 1 gives a sharp curve with least range; case 2, case 3 and case 4 gives higher slope in increasing order with higher range indicating spread in the curve of CDF. At no damage, a sharp curve is found. As the damage increases not only does the range increase, but the shape of the CDF expands indicative of large variation.

7.3. Power spectral density

Although steel is a homogenous material but various component of the structure i.e. structural member, connection plates, bolts, connecting beam and column all made of steel undergo different mode of failure when subjected to forces beyond their capacity. In case of structural members, cracks develop at a particular location when either tensile, bending or shear failure occurs. All these different types of failure lead to different stiffness reductions in the structure. While for the analysis purpose it is immaterial whether the joint or member has failed so long as the vibrational parameters are able to depict that the particular structural member is not being utilized to its full capacity for carrying load. Hence it is so necessary that the vibration based techniques should be able to pin point the damage in the structure due to a particular component failure of the element as the indication of the failure of the element would be sufficient to approach at the address of the damage in the structure. Taking these aspects into consideration the work was directed in the direction such that significance of the stiffness reduction is studied through the induced damage in the structure by evaluating various modal parameters[30]. The Power Spectral Density is a Frequency Domain Analysis which describes distribution of power of signal with frequency, which changes with joint flexibility[33]. In the present study the PSD of vibration signal recorded after hammering on the bridge corresponding to damage and intact is extracted using Welch method. Welch method is nonparametric method that include the periodogram that have the advantage of possible implementation using the Fast Fourier Transform [34].

Damage in Bridge Members

The frequency peaks of power spectral density at different nodes before and after retrofitting are as shown in Table 4.1 and Table 4.2. The analytical values of frequencies is 8.80, 16.55, 22.95 and 38.46 for 1st, 2nd, 3rd and 4th modes respectively

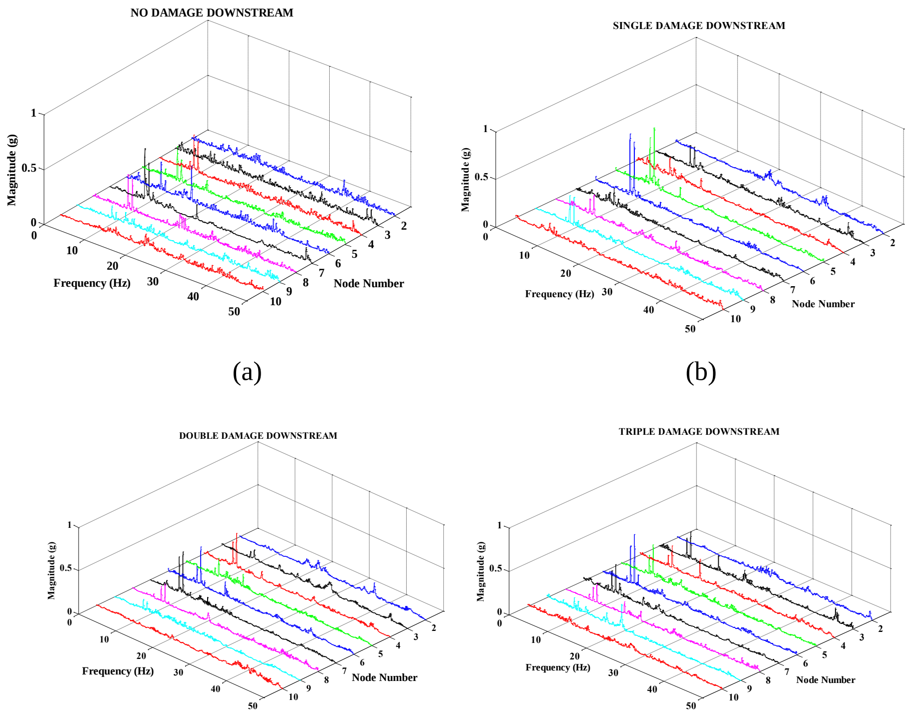
Table 1 Peak Frequency along span on downstream truss

	Span Condition	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11
1st Mode	C1	NP	7.69	8.69	8.73	8.66	8.72	8.75	8.67	8.70	NP	NP
	C2	NP	NP	8.34	8.26	8.28	8.30	8.33	8.26	8.31	8.23	NP
	C3	NP	7.75	7.72	7.83	7.8	7.83	7.83	7.84	7.81	7.79	NP
	C4	NP	6.9	7.25	7.28	7.239	7.214	7.227	7.11	7.12	7.12	NP
2nd Mode	C1	NP	NP	16.2	NP	16.00	16.26	16.21	16.18	16.1	13.72	NP
	C2	NP	NP	15.73	15.78	15.59	15.54	15.61	15.67	15.54	15.64	NP
	C3	NP	18.07	15.59	15.58	15.39	15.38	15.48	15.32	NP	NP	NP
	C4	NP	NP	15.38	15.42	15.42	15.31	15.33	15.15	NP	15.52	NP
3rd Mode	C1	NP	NP	21.47	NP	NP	NP	21.48	21.46	NP	21.14	NP
	C2	NP	22.72	20.55	NP	20.88	NP	NP	20.8	20.96	NP	NP
	C3	NP	21.13	20.37	20.25	NP	NP	19.54	20.46	NP	20.38	NP
	C4	NP	NP	22.12	19.45	NP	21.16	19.34	19.25	19.31	19.45	NP
4th Mode`	C1	NP	36.7	32.7	37.62	34.7	36.4	37.7	37.5	36.5	37.5	NP
	C2	NP	36.23	39.40	46.51	NP	38.18	38.49	36.63	35.02	38.45	NP
	C3	NP	36.21	45.47	44.97	NP	38.38	40.9	40.4	34.08	38.12	NP
	C4	NP	33.3	38.25	40.11	NP	36.99	36.72	35.23	NP	38.37	NP

NP - Not Present;

From the table 1 it has been observed that in the damaged nodal points for downstream truss either the nodal frequency obtained is least as compared to other nodes or no frequency values have been observed. For single damage and double damage when the inclined members 2/3 and 13/14 damaged, the value obtained at nodes 2 and 3 is either least or no frequency values have been observed.

In case of triple damage the value obtained at nodes 8 and 9 for mode 1st to 3rd the nodal frequency observed is either least as compared to other nodes or no nodal frequency observed, However the nodal frequency for higher node ie 4th mode nodal frequency even for damaged nodal points were observed indicating that damaged nodal points participated in modal vibrations in the higher modes in spite of fact that value obtained is least as compared to other nodes.



(a) (b)

(c) (d)

Fig. 8 PSD for (a) No Damage (b) Single Damage
(c) Double Damage (d) Triple Damage of D/S Truss

The frequency for the intact bridge for different nodes is more as compared to damaged states. The average values of the nodal frequency observed for 1st mode is 8.589, 8.289, 7.79 and 7.18 for no damage, single damage, double damage and triple damage respectively indicating increasing level of damages in the bridge. Almost Similar trend observed for other modes also. The frequencies of the bridge model in intact state vary from 8.68 to 8.79 Hz at different nodes for downstream truss with average value of 8.73 and 8.61 to 8.81 for the upstream truss with average value of 8.73 for the first mode. The value of frequency decreases as damage is increased.

Table 2 shows the frequency at different nodes of upstream truss of the bridge

	Span Condition	Node 12	Node 13	Node 14	Node 15	Node 16	Node1 7	Node1 8	Node 19	Node 20	Node 21	Node 22
1st Mode	C1	NP	8.63	8.734	8.786	8.60	8.69	8.72	8.79	8.73	8.71	NP
	C2	NP	8.13	8.21	8.337	8.26	8.32	8.29	8.39	8.28	8.31	NP
	C3	NP	7.6	7.758	7.751	7.79	7.843	7.81	7.84	7.813	NP	NP
	C4	NP	7.18	7.19	7.21	7.22	7.239	7.13	7.12	7.208	7.214	NP
2nd Mode	C1	NP	NP	16.29	16.28	16.04	16.07	NP	16.21	NP	15.92	NP
	C2	NP	NP	15.72	15.83	15.55	15.71	15.72	15.53	15.74	15.55	NP
	C3	NP	NP	15.23	15.64	15.43	NP	15.47	15.32	NP	NP	NP
	C4	NP	NP	15.45	15.38	15.11	15.41	15.31	15.21	15.30	15.4	NP
3rd Mode	C1	NP	20.81	NP	21.54	21.13	23.77	21.02	NP	21.44	18.84	NP
	C2	NP	16.08	20.37	20.96	20.67	NP	NP	NP	NP	19.12	NP
	C3	NP	18.74	NP	20.39	20.12	NP	NP	NP	20.61	20.54	NP
	C4	NP	NP	19.46	19.12	19.45	NP	NP	NP	19.17	NP	NP
4th Mode	C1	NP	38.70	37.76	38.84	35.52	38.74	38.97	36.90	38.64	NP	NP
	C2	NP	36.42	42.72	37.80	37.75	37.23	38.23	37.61	37.03	NP	NP
	C3	NP	36.27	NP	40.47	41.46	42.80	NP	42.23	45.45	39.70	NP
	C4	NP	38.65	38.56	37.3	36.93	NP	38.62	41.02	45.43	37.09	NP

NP- Not Present

In case of single damage for the downstream truss the value of frequency vary from 8.26 to 8.37with average value of 8.31. For the single damage in upstream truss the value of the frequency vary from 8.26 to 8.34 with average value of 8.30.

For the double damage the value of frequency further decreases to average value of 7.86 for upstream truss and 7.84 for downstream truss. The value of frequency at nodes 13 and 2 could not be extracted as these nodes could not vibrate as the members joining these members have been damaged. For the triple damage when the inclined member 8-9 damaged the frequency further decreased with average value of 7.21 in both upstream and downstream trusses. The frequency for the intact bridge for different nodes is more as compared to damaged states. The average values of the nodal frequency observed for 1st mode is 8.71, 8.28, 7.77 and 7.19 for no damage, single damage, double damage and triple damage respectively indicating increasing level of damages in the bridge. Almost Similar trend observed for other modes also.

From the table 2 it has been observed that in the damaged nodal points for downstream truss either the nodal frequency obtained is least as compared to other nodes or no frequency values have been observed. For single damage when the inclined members 13/14 damaged, the value obtained at nodes 13 and 14 is either least or no frequency values have been observed for different nodes.

In case of triple damage when the inclined member joining 13 and 14 damaged the value obtained at nodes 19 and 20 opposite to the damaged members for mode 1st to 3rd the nodal frequency observed is either least as compared to other nodes or no nodal frequency observed, However the nodal frequency for higher node ie 4th mode nodal frequency even for damaged nodal points were observed indicating that damaged nodal points participated in modal vibrations in the higher modes with minimum nodal frequency value as compared to other nodes in same mode.

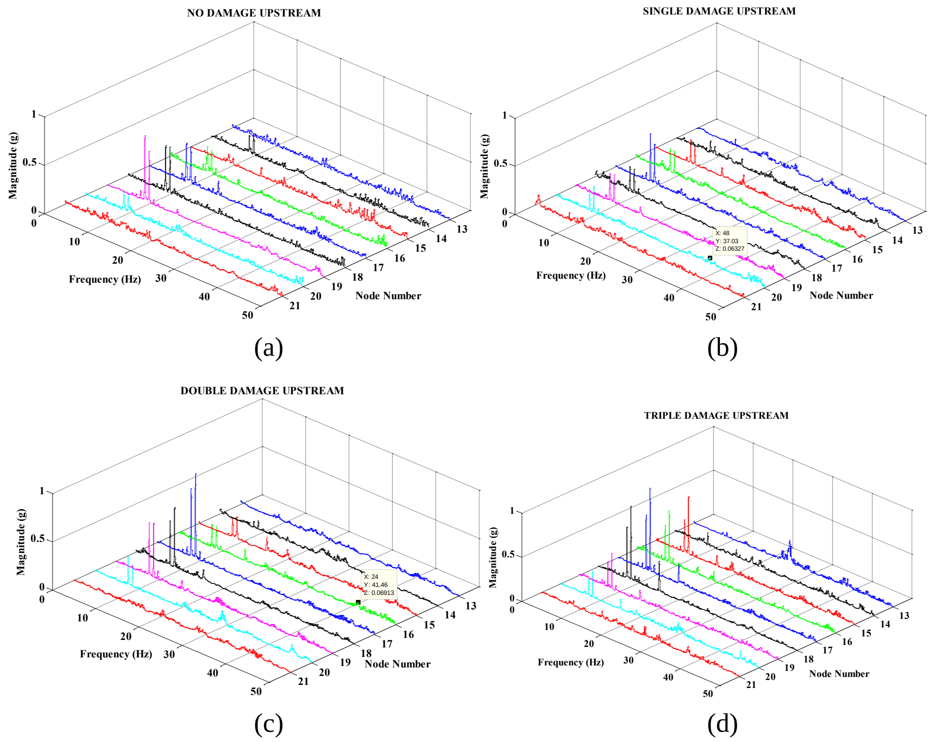


Fig. 9 PSD for (a) No Damage (b) Single Damage (c) Double Damage (d) Triple Damage of U/S Truss

Damage in Bridge Deck

From Table 3 after the damage in deck the nodal frequencies of most of the nodes decreased as compared to the nodal frequency in the intact sate. The nodal frequency adjoining the damaged portion at node 2 after damage could not be extracted for first mode

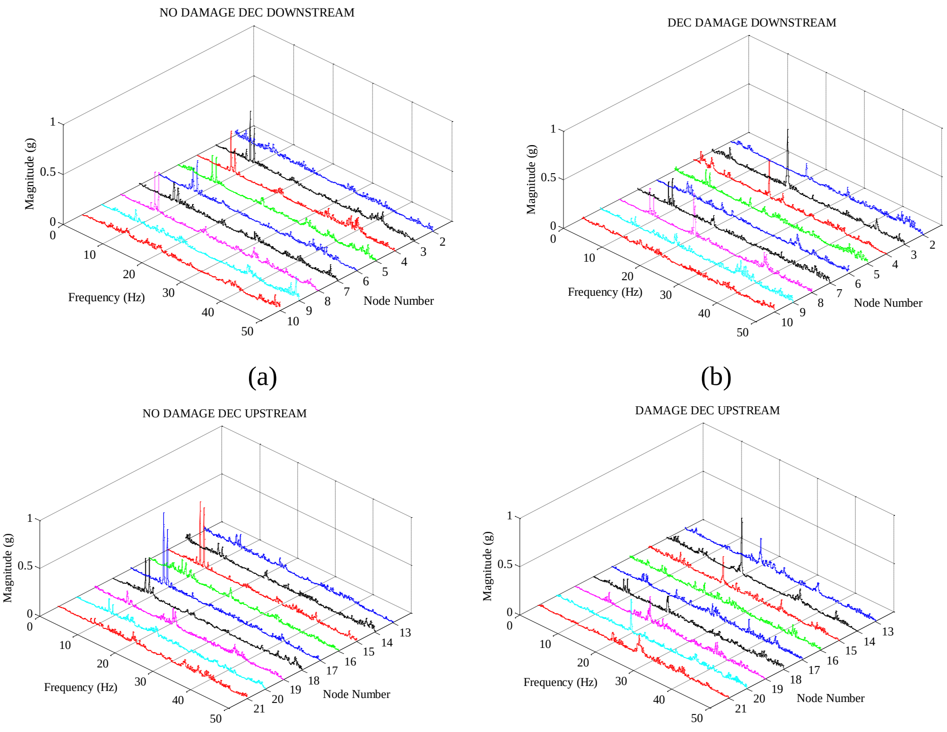
Table 3 shows the frequency at different nodes of downstream truss of the bridge for damage in Deck

Mode	Span Condition	Node 1	Node 2	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11
1st	C1	NP	8.85	8.72	8.67	8.71	8.71	8.67	8.70	8.64	8.5	NP
	C2	NP	NP	4.59	4.68	8.10	8.20	8.10	8.0	8.0	NP	NP
2nd	C1	NP	19.73	19.68	19.78	19.58	17.14	19.82	19.48	19.28	20.04	NP
	C2	NP	17.41	15.75	16.26	16.12	16.21	16.19	16.33	15.36	16.53	NP
3rd	C1	NP	28.7	27.54	26.03	24.46	27.86	29.47	29.20	26.32	27.42	NP
	C2	NP	30.42	26.17	23.09	23.39	25.0	24.71	23.12	23.05	28.0	NP
4th	C1	NP	38.04	36.01	39.11	37.92	39.11	37.43	37.4	37.7	38.6	NP
	C2	NP	35.16	34.10	34.96	35.91	36.57	37.35	37.14	36.47	35.21	NP

and for node 3 and 4 the value is minimum indicating decreased in stiffness of the nodal points. The value of nodal frequencies near the damaged portion the value is less as compared to other nodes. Similarly in case of downstream truss as per table 4 the nodal frequency decreased appreciably near the damaged portion after the damage induced in the Deck. The decrease in the value of nodal frequency indicates the damage portion of the bridge deck. The value of nodal frequencies in general decreases after the damage in the deck.

Table 4 Frequency at different nodes of upstream truss of the bridge for damage in Deck

Mode	Span Condition	Node 12	Node 13	Node 14	Node 15	Node 16	Node 1 7	Node 1 8	Node 19	Node 20	Node 21	Node 22
1st	C1	NP	8.60	8.72	8.72	8.77	8.70	8.72	8.74	8.67	8.74	NP
	C2	NP	2.86	8.40	8.47	8.37	8.2	8.10	9.0	NP	NP	NP
2nd	C1	NP	19.17	19.73	19.05	17.02	12.15	19.7	19.82	19.63	19.82	NP
	C2	NP	15.8	16.48	16.41	16.36	16.33	19.75	18.29	14.94	16.48	NP
3rd	C1	NP	26	NP	23.02	26.2	26.4	26.12	23.1	28.14	26.54	NP
	C2	NP	20.7	21.48	21.22	21.56	20.87	21.58	20.8	21.04	20.02	NP
4th	C1	NP	35.03	35.16	35.06	42.8	36.08	33.15	37.01	36.55	37.82	NP
	C2	NP	32.64	27.17	39.33	33.96	40.04	39.05	37.16	37.33	33.72	NP



(a) (b)

(c) (d)

Fig. 10 PSD for (a) No Damage in Deck D/S Truss (b) No Damage in Deck U/S Truss (c) Damage in Deck D/S Truss (d) Damage in Deck U/S Truss

7.4. Short Time Fourier Transform

The Fourier analysis performed on the signals to determine the content of frequency spectrum has some serious drawbacks. In transformation of the signal to frequency domain, information related to time is lost. If the signal is a stationary signal i.e. properties do not change much over time - this drawback is not significant. However, for the present study of hammering with hammer over the bridge, the signals are expected to contain numerous non-stationary or transitory characteristics: drift, trends, and abrupt changes. Such characteristics are important from sensitivity analysis aspect of the signal, and Fourier analysis is not sufficiently capable to detect such irregularities. Short time Fourier Transform is an effort to correct this deficiency, in which only a small section of the signal is Fourier transformed at a time with windowing technique. STFT, maps the signal in two-dimensional function of time and frequency. The STFT is one of the most popular methods in practical applications. The representation of the results in the time-frequency plane or a spectrogram is easily understood

Damage in Bridge Members

The STFT of the nodal responses before damage were compared with responses after damage. The increased excitation of the structural frequency bridge response after damage of

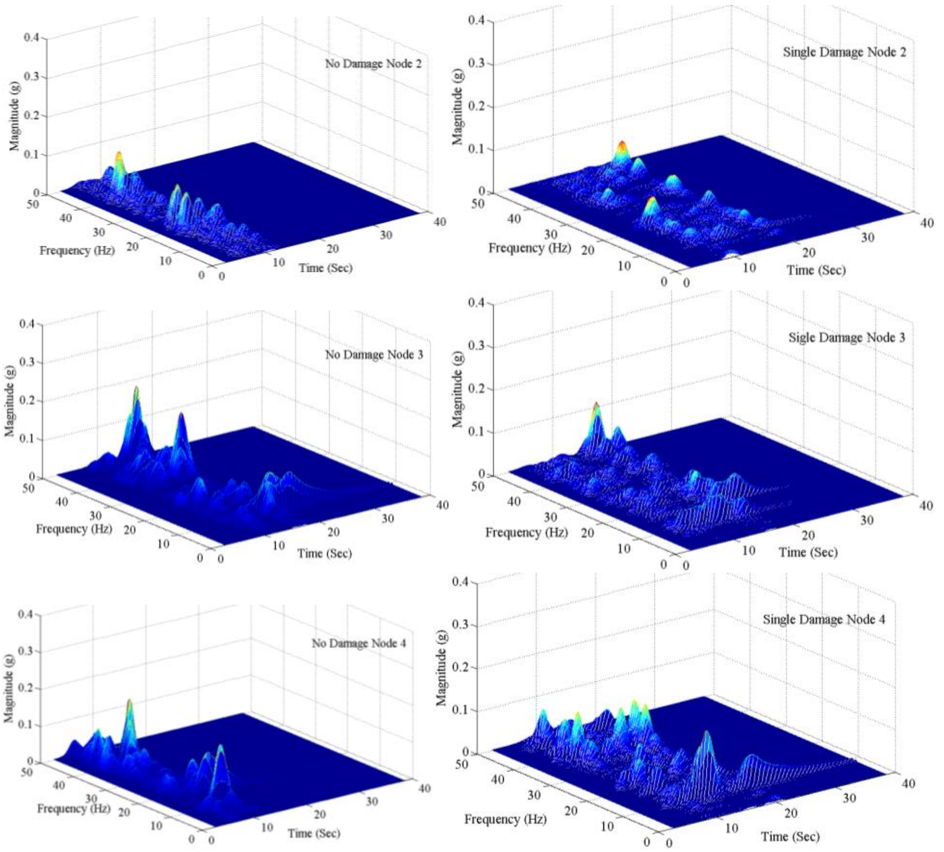


Fig. 11 STFT of Node number 2 to 4 for Downstream Truss for Case I&II

the nodal joints revealed the damage of the bridge. Further distributed extraction of the bridge response at the target nodes revealed the nodal sensitivity before damage. In case of single damage in downstream truss, all the modes have been observed for node 2 and 3 in the intact state but some modes have not been observed after damage, as the these nodes did not generated modal response of a flexible joints, which showed that after damage nodal points were defective which is also evident in PSD.

In upstream truss for single damage Node 13 and 14 modal responses obtained have been changed after the damage as some of modes could not be extracted for nodes 14 indicating that these nodes participating in the vibration is less as compared to other nodes. In general the proper mode shapes have not been generated after damage as the joints are not intact and did not generated proper mode shapes.

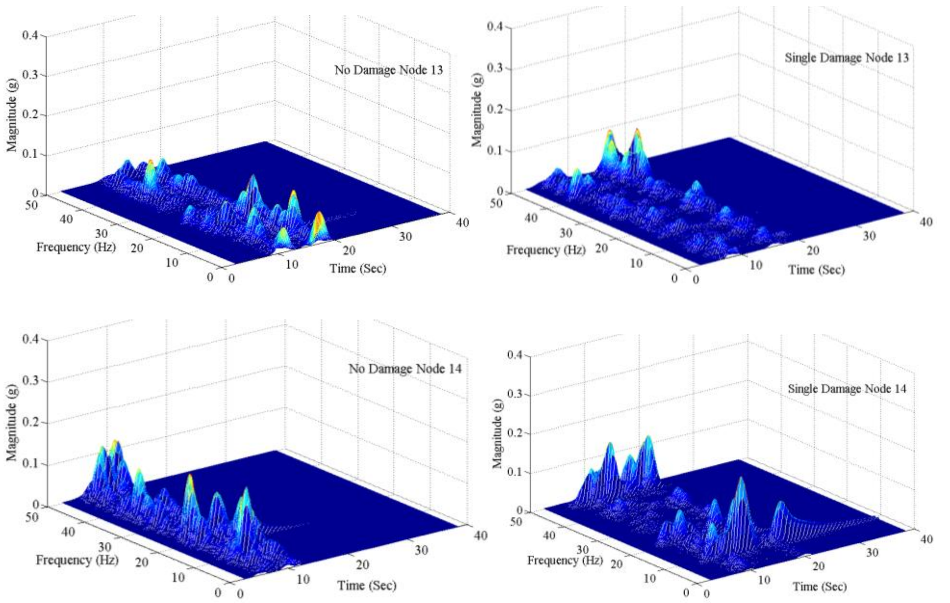


Fig. 12 STFT of Node number 13 and 14 for Upstream Truss for Case I &II

For double and triple damage the STFT showed in the Fig. 11 and Fig. 12. the amplitude of vibrations in the damaged nodes have also more indicating more flexibility of the joints. For triple damage the 2nd mode could not be extracted and for nodal points 19 just opposite to the damaged node 8 and 9 the 3rd mode could not be extracted due to the damage in the region. In general, the graphical representation of time and magnitude increases after the damage due to more flexibility of the joints.

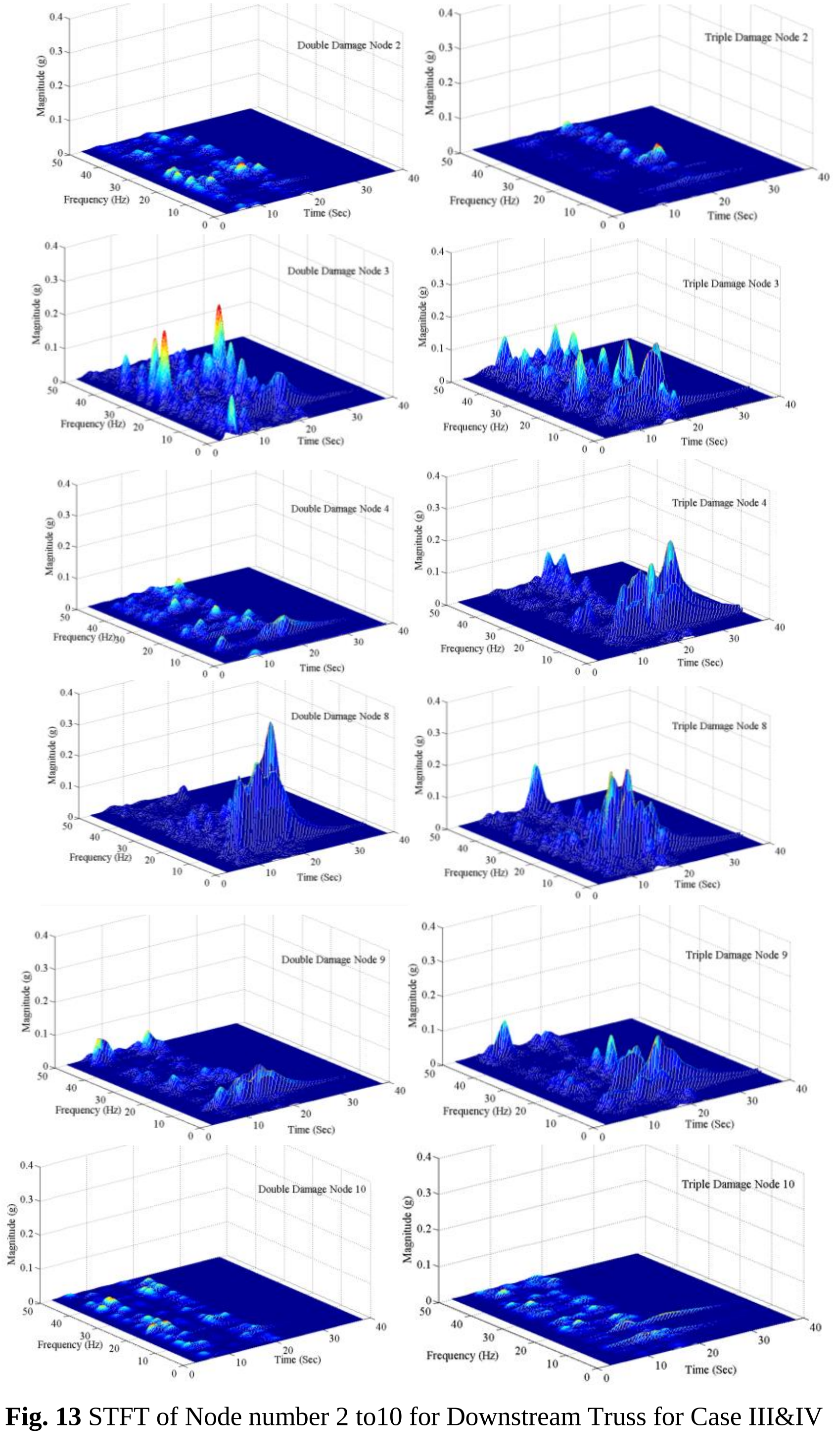


Fig. 13 STFT of Node number 2 to10 for Downstream Truss for Case III&IV

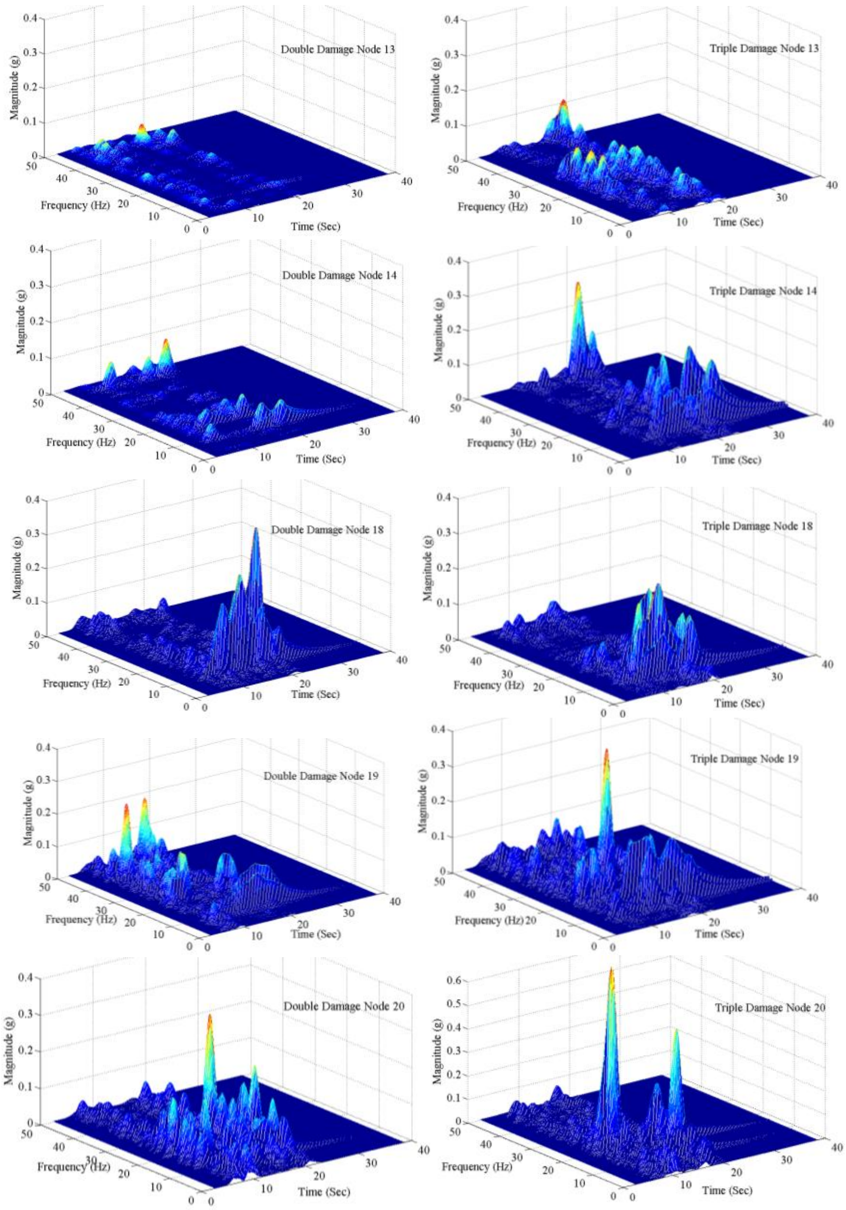


Fig. 14 STFT of Nodes for Upstream Truss for Case III&IV

The nodal frequencies indicated that the nodes did not behaved identically. The variation in the amplitude of extracted nodal frequency indicated the degree of flexibility in the nodes. The nodal frequencies both for upstream truss and downstream truss before and after damage changed.

Damage in Bridge Deck

After the damage is induced in the bridge deck the nodal frequency in first mode not extracted and time frequency plot changed. Time taken to achieve frequency for different nodes increased.

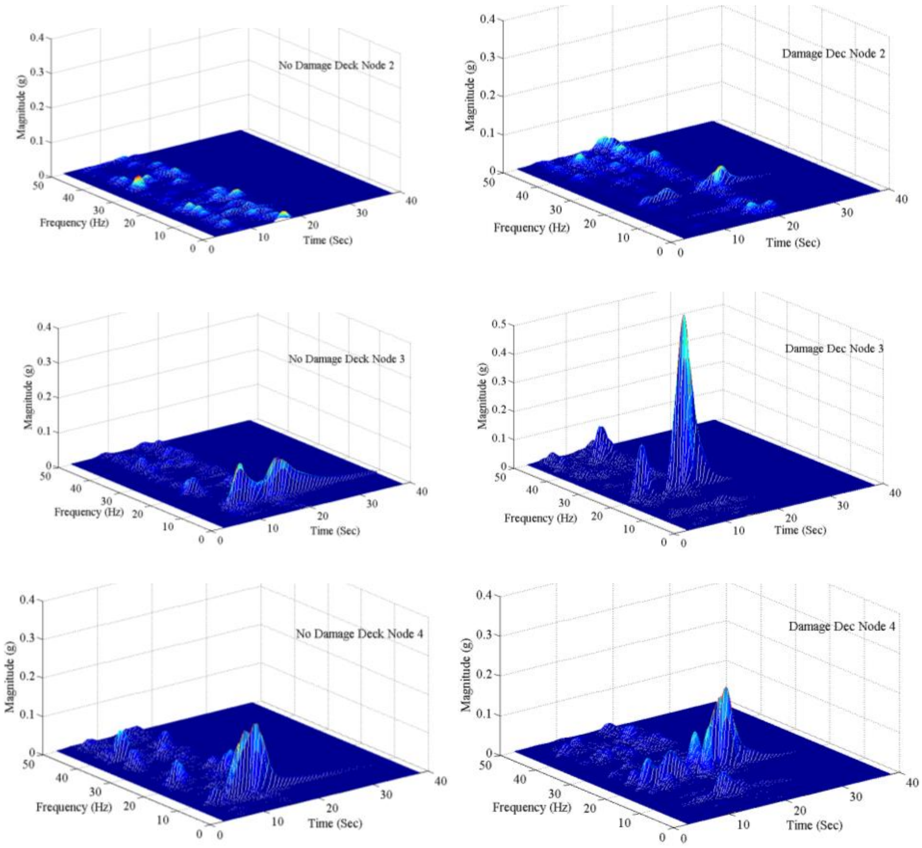


Fig. 15 STFT of Node number 2 to 4 for Downstream Truss for Damage in Deck

After the damage amplitude of vibration also increases indicating more flexibility of the damage affected nodal points. The nodal points 2,3 in downstream truss and 13, and 14 in upstream truss shows behavioral change in the time frequency plot indicating more flexibility of the nodal points.

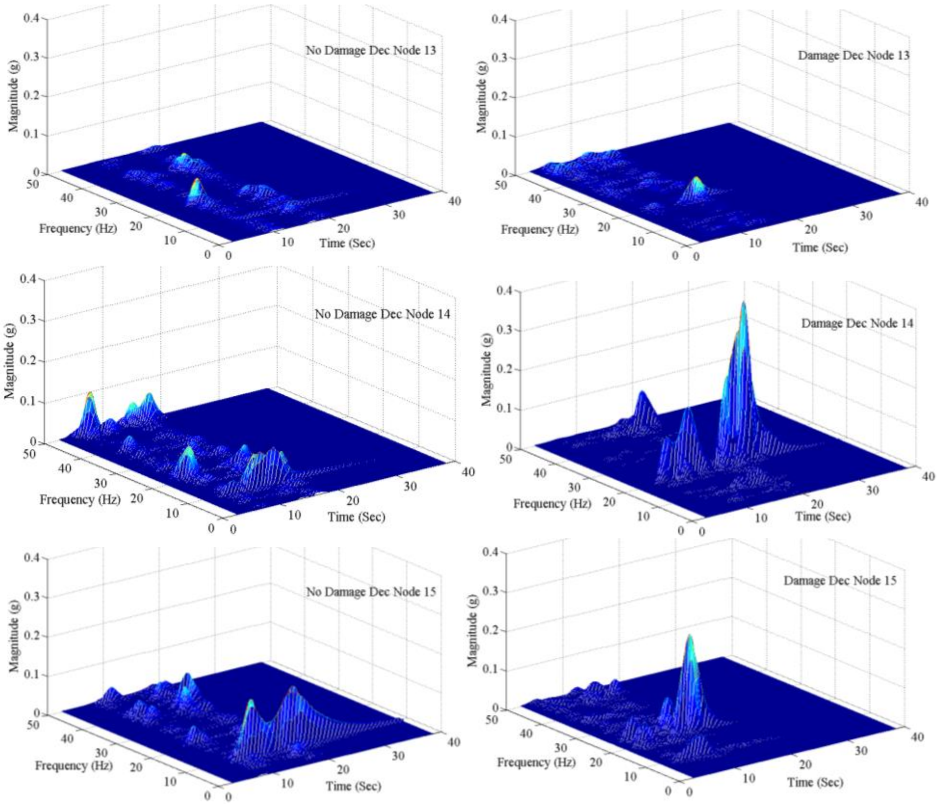


Fig. 16 STFT of Node number 13 to 15 for Upstream Truss for Damage in Deck

7.5. Wavelet Packet Transform

The difference in PSD and STFT of both downstream and upstream trusses of the bridge model indicated damage in model after the damage was introduced in the structure, but did not present the relative differences quantitatively. STFT analyses the transient signal by assuming stationary within short interval and thus is employed to extract the localized transient feature in certain cases. STFT provides some information about both when and at what frequencies a signal event occurs with limited precision, depending upon the window size. However, the fixed windowing used in the STFT implies fixed time-frequency resolution. The drawback of this method is that the accuracy of extracting frequency information is limited by the length of the window relative to the duration of the analyzed signal [25]. Many signals require a more flexible approach where we can vary the window size to determine more accurately either time or frequency. For this, wavelet analysis can be used. Thus, Wavelet analysis represents the next logical step: a windowing technique with variable-sized regions. Wavelet analysis allows the use of long time intervals where more precise low-frequency information is required and shorter regions where high-frequency information is required.

Wavelet transforms have advantages when the signal is non-stationary as signal analysis both in frequency and time domains is allowed [42]. The Wavelet packet transform (WPT) is a technique to decompose a signal repeatedly into successive low and high frequency components. Wavelet transforms have advantages when the signal is non-stationary since it allows signal analysis both in frequency and time domains. The only difference between WPT and DWT is that WPT decompose not only the approximation but also the details at a given level of decomposition. Therefore it is more flexible and have wider base for the analysis of signals. WPT also enables multi resolution damage detection since it can localize multi-frequency bands in time domain. Wavelet transform and wavelet packets based damage detection is widely used in many vibration-based structural health monitoring and damage detection [43].

Continuous wavelet transform (CWT) is similar form of STFT with advanced resolution capabilities due to variable window length hence not adopted for further interpretation [44]. The Daubechies family db10 is used as a mother wavelet for wavelet packet analysis. The level of decomposition should be determined so that fundamental natural frequencies are separated into each wavelet packet. It is suggested to choose the wavelet packet of the frequency band that includes natural frequencies corresponding to fundamental modes. It is postulated that fundamental modes are more influenced by component damage than higher modes. Hence, in WPT the recorded signal is decomposed up to two levels and reconstructed because the frequency of interest was achieved upto this level. At level two, four components of original signal are obtained with different frequency band (Fig. 17). Figure 17 schematically illustrates a WPT- based decomposition process, where a two level WPT produces a total 4 sub bands. The enhanced signal decomposition capability makes WPT an attractive tool for detecting and differentiating transient elements with high frequency characteristics.

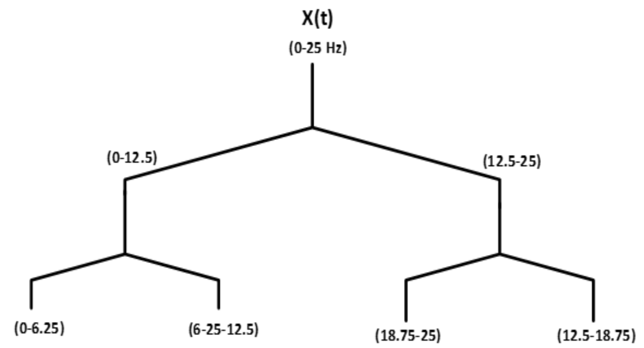


Fig. 17 Two level Wavelet packet decomposition tree

Further energy of each component is calculated using Parsvel's theorem, in intact and in damage states. 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 diagram of 1st mode shape (Fig. 3.29) depicts that downstream truss has significant difference in Energy for the damaged nodes. Energy levels at various nodes have increased at the damaged nodes.

For Damage in Members

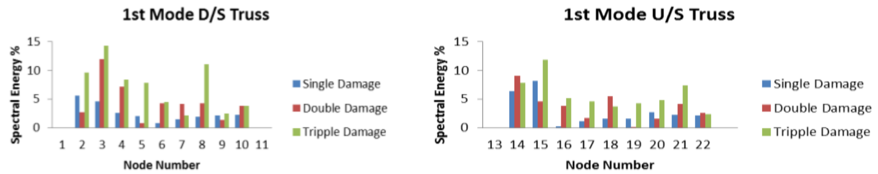


Fig. 18 WPT node energy difference for different damage cases for 1st mode

The difference in energy for 1st Mode in upstream and downstream truss is higher for the damaged nodes. As the damage increases from single damage to triple damage the difference in energy of the nodal points in general increases for the damaged nodes. In case of single damage in D/s truss the energy difference for node 2 and 3 is maximum as the node 13 and 14 of upstream truss have been damaged which are opposite to the nodes 2 and 3. For double damage the energy difference is maximum for nodes 2 and 3 as the in double damage the inclined members joining these nodes have been removed. Similarly in triple damage the energy difference in nodes 2, 3, 8 and 9 are more as compared to other nodes. Similarly in U/S truss the energy levels for the damaged nodes 13 and 14 for single damage and double damage, 20 and 21 for triple damage are higher than other nodes. The nodes damaged on U/S truss have similar effect on the opposite nodes of D/S truss and vice a versa.

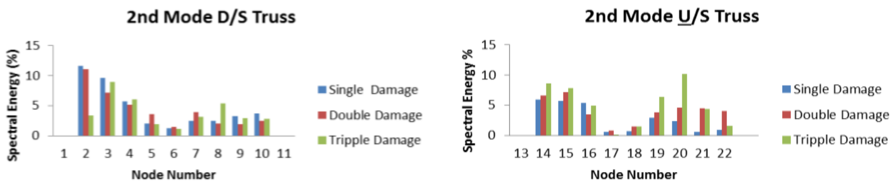


Fig. 19 WPT node energy difference for different damage cases for 2nd mode

In 2nd mode and third mode the energy difference shows the similar trend for the damaged nodes in u/s and D/S truss. For increased level of damage in higher mode the adjoining nodes also shows increased energy level indicating that distribution of energy is more non uniform for different nodes. Upstream and downstream truss behaves differently at different levels of damage in each mode.

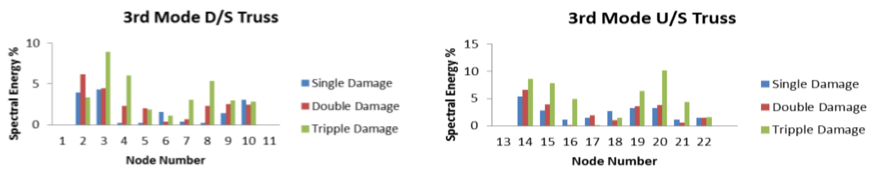


Fig. 20 WPT node energy difference for different damage cases for 3rd mode

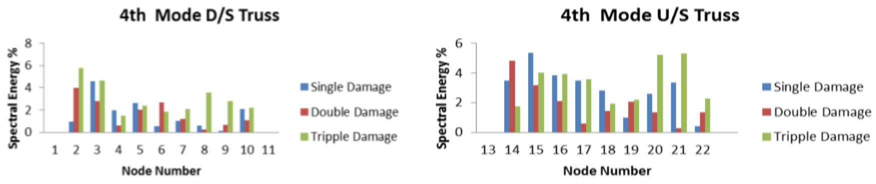


Fig. 21 WPT node energy difference for different damage cases for 4th mode

WPT for Damage in Deck between Nodes 2/13 and 3/14

The damage in the deck induced between nodes 2/13 and 3/14 clearly visible in the figure. The energy difference for nodes 2 and 3 and 4 are more as compared to other nodes for downstream truss and in case of upstream truss energy difference for nodes 13 and 14 are predominant than other nodes. Similar trend observed for the other modes.

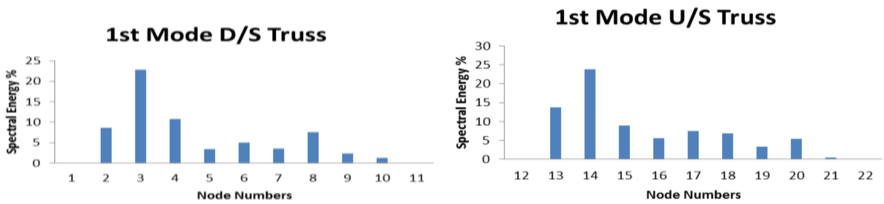


Fig. 22 WPT node energy difference for damage in deck 1st mode

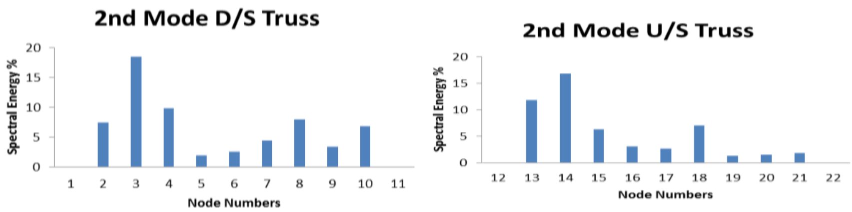


Fig. 23 WPT node energy difference for damage in deck 2nd mode

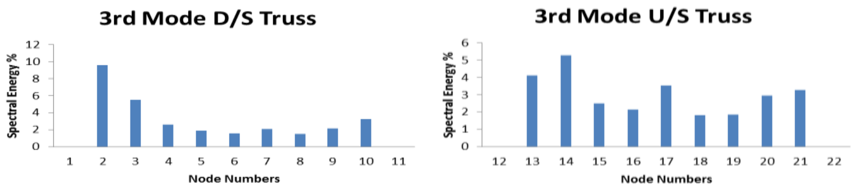


Fig. 24 WPT node energy diference for damage in deck 3rd mode

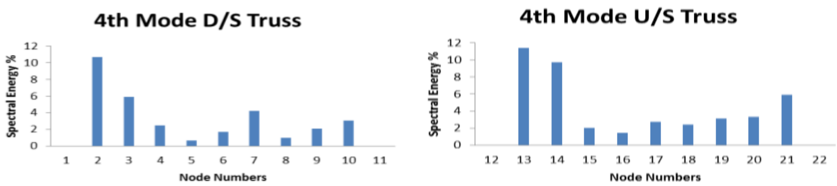


Fig. 25 WPT node energy difference for damage in deck 4th mode

8. INTERIM CONCLUSIONS

- In time domain analysis boxplot of variance calculated from vibrational data obtained for different damage cases of bridge provides a graphical summary of the distribution of a sample and indicates that as the level of fault increases the variance increases and box spreads up. The variance of no damage case is very narrow in range and as the damage occurs the variance becomes more and wider. The variance as statistical parameter gives the indication of existence of damage in the bridge
- In case of CDF of the vibration signal Euclidean length of statistical parameters gives idea to arrive at condition of steel bridge structure. No damage case gives a sharp curve with least range and damaged case gives higher slope in increasing order with higher range indicating spread in the curve of CDF. As the damage increases range increases, but the shape of the CDF expands because of large variation in data from intact state of bridge indicative of damage in the bridge.
- The experimentally obtained decreased frequency for different cases is an indication of the reduction of the stiffness offered by the structure and this is only possible incase either number of structural members are removed or damaged.
- The frequency obtained by PSD for the intact bridge for different nodes is more as compared to damaged states. As the level of damage in the bridge increases the average frequency obtained decreases. In the damaged nodal points for downstream truss either the nodal frequency obtained is least as compared to other nodes or no frequency values have been observed. However the nodal frequency for higher node i.e. 4^{th} mode nodal frequency even for damaged nodal points were observed indicating that damaged nodal points participated in modal vibrations in the higher modes in spite of fact that value obtained is least as compared to other nodes.
- It is observed that the frequency of the bridge model decreases consistently with increase in the damage introduced in the structure. The decrease in the frequency indicates the damage in the structure but does not indicate the location of the damage induced.
- The difference in wavelet packet energy for 1^{st} Mode in upstream and downstream truss is higher for the damaged nodes than the intact state. As the damage increases from single damage to triple damage the difference in energy of the nodal points in general increases for the damaged nodes. The nodes damaged on U/S truss have similar effect on the opposite nodes of D/S truss and vice a versa. For increased level of damage in higher mode the adjoining nodes also shows increased energy level indicating that distribution of energy is more nonuniform for different nodes. Upstream and downstream truss behaves differently at different levels of damage in each mode.
- In case of the damage in deck the energy difference for nodes 2 and 3 and 4 are more as compared to other nodes for downstream truss and in case of upstream truss energy difference for nodes 13 and 14 are predominant than other nodes. For other modes also the energy difference obtained by wavelet packet transform is predominant for the nodes pertaining to the damaged portion.

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PROCENA STANJA ČELIČNIH REŠETKASTIH MOSTOVA KORIŠĆENJEM ANALIZE VREMENSKOG I FREKVENTNOG OPSEGA

U ovo članku, izloženo je istraživanje na umanjenom modelu mostu na kome je vršene procena stanja oštećenja. Cilj je naći mesto oštećenja na mostu korišćenjem vibracionog signala. Za diferencijaciju oštećenja i zdravog stanja, korišćena je analiza vremenskog i frekventnog opsega. Primenjena je spektralna gustina snage vibrirajućeg signala da bi se izvukli oblici modova i uporedila zdrava i oštećena stanja modela. Dalje, kratkotrajna Furijeova transfromacija je dala 3d visuelizaciju pojačanja u različitim modovima vibracije, što pomaže da se pronađe mesto oštećenaj. Korišćenem pristupa energije čvorova, upotrebljen je Wavelet Packet Transformacija da se odredi mesto oštećenja što je bolje nego parameter analize vremenskog i frekventnog opsega..

Ključne reči: *Čelični rešetkasti mostiovi, analiza vremenskog i frequentnog opsega, spektralna gustina snage, kratkotrajna Furijeova transformacija, , Wavelet Packet transformacija*