Vibration-based damage identification in railway concrete sleepers

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ABSTRACT: In this study, concrete sleepers, widely used in railway industry, are a subject to damage identification as mechanical failure of these components can lead to tragic consequences. Three-point bending tests are conducted on four concrete sleepers. Two sleepers are loaded until failure and are subjected to experimental modal analysis, while a multi-stage damage severity scheme is applied to other two sleepers. This scheme implies that sleepers are loaded until the appearance of the first crack. A subsequent experimental modal analysis is performed. Then these sleepers are loaded until load equal to 1.5 times of the load corresponding to the first crack. Experimental modal analysis procedure is repeated and dynamic structural parameters, namely, natural frequencies, damping and mode shapes are extracted and compared among sleepers at healthy and damaged conditions.

1 INTRODUCTION

Trends of increasing population worldwide have a direct impact in railway industry. First and foremost, this means increasing haul freight axle loads and train speeds which accelerates track degradation during service life. This aspect highlights the immediate necessity for advanced Non-Destructive Testing (NDT) techniques to assess the quality of critical railway components and ideally predict their remaining lifetime. The later goal is mostly tackled by sophisticated Structural Health Monitoring (SHM) methods where sensors are permanently installed on components of interest and used for continuous monitoring.

One of the main components of a railway track is a sleeper that lies perpendicular to the track on a ballast formation and sub-structure of the rail. The main functions of sleepers are to support the rail foot, distribute loads from the rail foot to the ballast, maintain the rail gauge and shape, resist wearing, loading and endure extreme weather conditions as stated by Remennikov et al. (2006). Nowadays, commercially available sleepers are mostly produced from concrete in two configurations – either in mono-block or twin-block.

Dynamic loads are transmitted from rail to sleepers from various sources. The analysis of free vibration characteristics of railway sleepers is essential in understanding the nature of vibration-induced damage, such as one inflicted by a passing rolling stock in a prolonged exploitation of a railway track. According to Parvez et al. (2014), sleeper may be subjected to about 80 million dynamic loading cycles through its service life. The cracking of sleepers may lead to tragic consequences if not addressed properly. Domingo et al. (2014) reported that concrete sleeper cracks at the rail seat introduced more pronounced deflections and stresses than the ones at the centre of the sleeper span. One of the tools used to evaluate health condition of sleepers is modal analysis which exploits the effect that cracking causes local decrease of stiffness of the structure and thus natural frequencies experience a shift to smaller values. This shift can be clearly seen in frequency response function (FRF) plot by comparing structure at healthy and damaged states. An experimental modal analysis study of pre-stressed concrete sleepers done by Kaewunruen et al. (2008) highlights this fact. FRF signatures were compared between sleepers at healthy state and after receiving one to several impact blows. It was found that natural frequencies for first modes decreased as much as 16 %, whereas damping ratio increased by about 50 % for the first mode and on average by 10-40 % for other modes. Kaewunruen et al. (2009) performed a series of modal analysis tests on concrete sleepers with voids and pockets on ballast support and studied the effect of proportion of sleeper/ballast interaction on vibration characteristics of the sleepers. Experimental work was complemented by finite element modelling. It was found that fundamental vibration mode experienced the most significant natural frequency shift as compared to other modes when void proportion was increased. Prado et al. (2016) conducted an experimental work of pre-loading reinforced concrete beams to loads of 40 % and 70 % of their strength and a subsequent experimental modal analysis to detect and locate the damage based on dynamic response. They concluded that the failed beams showed an average of 20 % reduction of natural frequency values with respect to a healthy reference beam. A study of reinforced concrete beams reinforced with CFRP circular rods and subjected to static and dynamic loads conducted by Capozucca et al. (2016) shows that modal analysis is a reliable tool of damage detection – natural frequency of fundamental mode decreased by 30 % after notches appeared in CFRP rods.

In present work, the feasibility to detect damage in prestressed reinforced concrete sleepers using experimental modal analysis is evaluated. A total of four sleepers are tested in three-point bending. Two of them are put in negative bending moment configuration, while other two – in positive configuration. Also, two sleepers are loaded till failure and a multi-stage loading is applied to other two sleepers. First, these sleepers are loaded until first crack with a subsequent modal analysis procedure. Then, these sleepers are loaded until load equal to 1.5 times the load at first crack and modal analysis is performed again. Natural frequencies, damping ratios and mode shapes are extracted from frequency response functions and these values are compared between sleepers at healthy reference state and at various severities of damage, including failure. Finally, the location of cracks is assessed by comparing normalized mode shapes of healthy and cracked beams.

2 MATERIALS AND METHODS

2.1 Concrete sleepers

Four concrete sleepers of type G44 manufactured by CEMEX are considered in this study.
According to CEMEX brochure, G44 sleepers are designed for all types of track, except where 3rd rail electrification is used for axle loads of 25 tons. The physical dimensions of sleepers are as follows: length = 2500 mm, depth at rail seat = 200 mm, nominal maximum weight = 309 kg + 3 kg for loose fastening components. The photo the sleepers is shown in Figure 1.

Figure 1. G44 concrete sleepers.

2.2 Experimental modal analysis

In order to simulate real ballast conditions in terms of vibration damping, rubber conveyor matting is placed between the rail seats of sleepers. It is found that 5 layers of matting is enough to avoid excessive vibrations from the floor. These free support conditions are shown in Figure 2 (left). Experimental modal analysis with impact hammer excitation is performed on concrete sleepers in their healthy and damaged condition to extract the global dynamic parameters. Modal testing equipment is shown in Figure 2 (right).
The equipment contains PROSIG P8004 acquisition box with 4 channels. The modal impact hammer is connected to the first channel, while accelerometer – to the second channel. Plastic vinyl tip is used for the impact hammer.

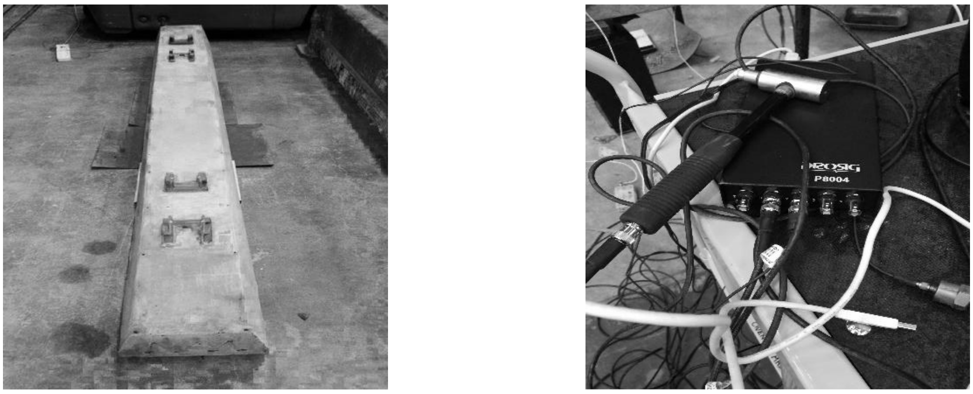


Figure 2. Modal analysis test setup. Left: concrete sleeper on a rubber mat, right: testing equipment.

Roving impact excitation is performed in 26 points along the perimeter of the top surface of the sleepers. Locations of excitation points are chosen to lie where slope of the surface relief experiences changes. Dynamic response of the sleepers is measured via uniaxial accelerometer that is mounted at one of the corners of the sleepers and remains in a fixed position. Setup information is passed to DATS software (PROSIG) where the following parameters are edited – frequency bandwidth = 0:2048 Hz, resolution = 1 Hz, number of averaging for each impact: 10 times, window functions: exponential window for response and force window for excitation. Frequency Response Functions (FRFs) and Coherence plots are recorded for every excitation point. Curve fitting of collected raw FRFs employing Half-Power method is performed in DATS Modal Analysis package in order to extract resonance frequencies, corresponding damping ratios and mode shapes. Overall, 5 to 6 first mode shapes, which are of interest, are extracted
The experimental procedure is shown in Figure 3. At first, experimental modal analysis is performed on all 4 sleepers at their healthy state. Afterwards, sleepers are subjected to 3-point bending where 2 sleepers are set for positive bending moment configuration and remaining 2 sleepers – for negative. Two sleepers (one from each of 2 bending configurations) are loaded until failure and tested for modal analysis, whilst for other two sleepers a 2-stage procedure with the following steps is employed:

- sleepers are loaded till first crack and then a modal analysis is performed;
- sleepers are set for bending test where the load is increased from 0 kN to load corresponding to 1.5 times the load of first crack and modal analysis is conducted again.

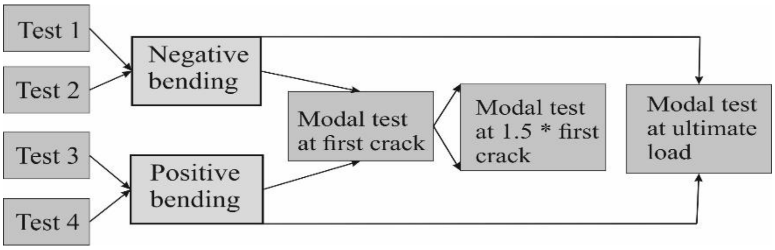


Figure 3. Modal analysis testing flowchart.

3 RESULTS AND DISCUSSION

Fitted FRFs of all sleeper responses averaged over all points of excitation along with corresponding coherence at healthy and failed state are shown in Figures 4-7. As can be seen from FRF spectra, the magnitude of resonance peaks has decreased with the presence of damage. This effect is especially pronounced for higher damage severity (failed sleepers no. 1 and 3). Also, not all peaks are present in spectra of failed specimens as opposed to healthy ones. Instead of two close-spaced peaks in the FRF for 3rd sleeper at healthy state, there is only one peak at failed state with a substantial increase in damping and frequency shift.

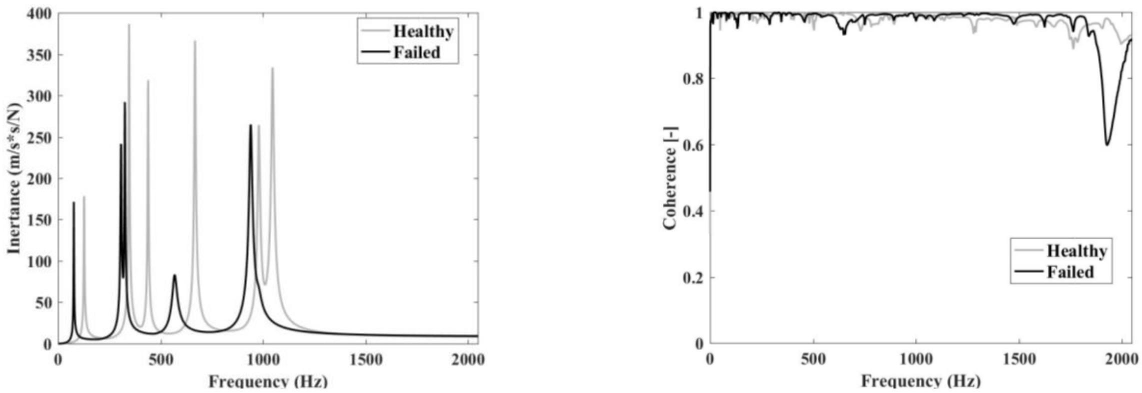


Figure 4. Modal analysis results for sleeper 1 at healthy and failed states. Left: FRF, right: coherence.

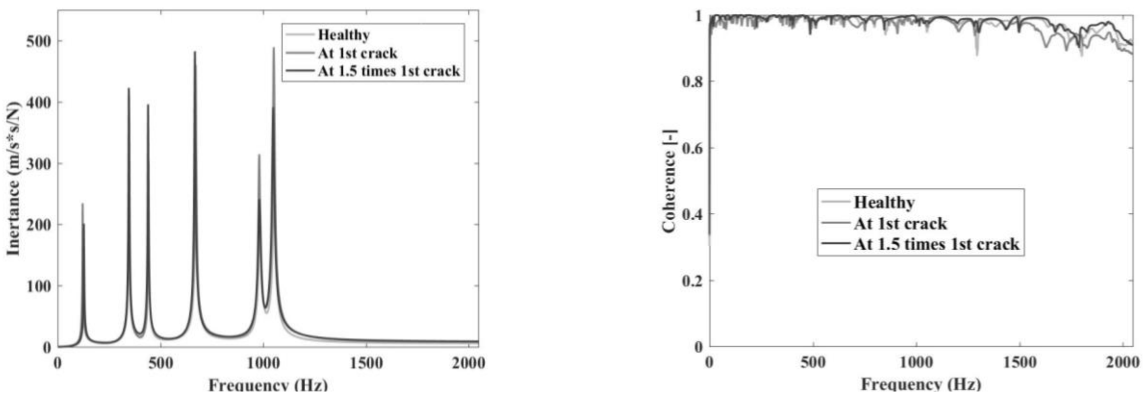


Figure 5. Modal analysis results for sleeper 2 at healthy, first crack and cracked at load of 1.5 times the load for the first crack states. Left: FRF, right: coherence.

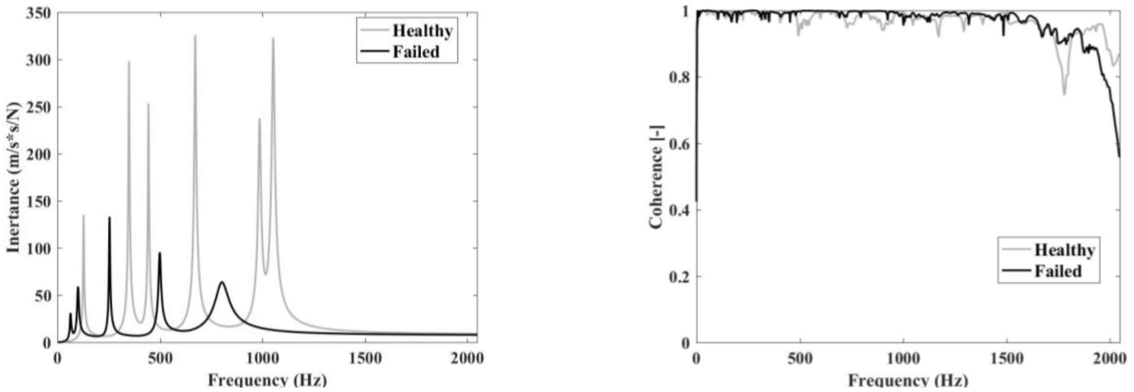


Figure 6. Modal analysis results for sleeper 3 at healthy and failed states. Left: FRF, right: coherence.

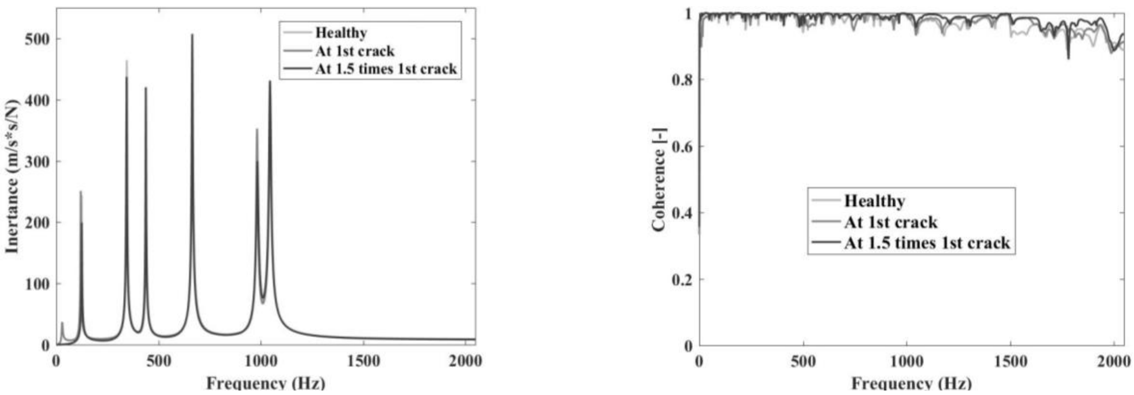


Figure 7. Modal analysis results for sleeper 4 at healthy, first crack and cracked at load of 1.5 times the load for the first crack states. Left: FRF, right: coherence.

Coherence plots indicate a good correlation between input and output over all frequency range of interest, except for the highest frequencies, where coherence decrease reaches as much as about 40 % (failed specimens) with respect to its highest value. There are no considerable deviations in coherence for light damage with respect to healthy state, whereas this difference is magnified for failed sleepers at the end of the spectrum.

The photos of sleepers showing progressing damage are shown in Figure 8.

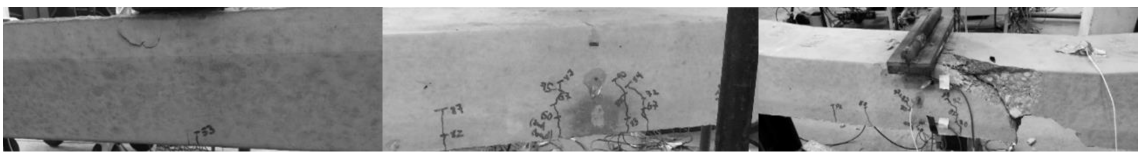


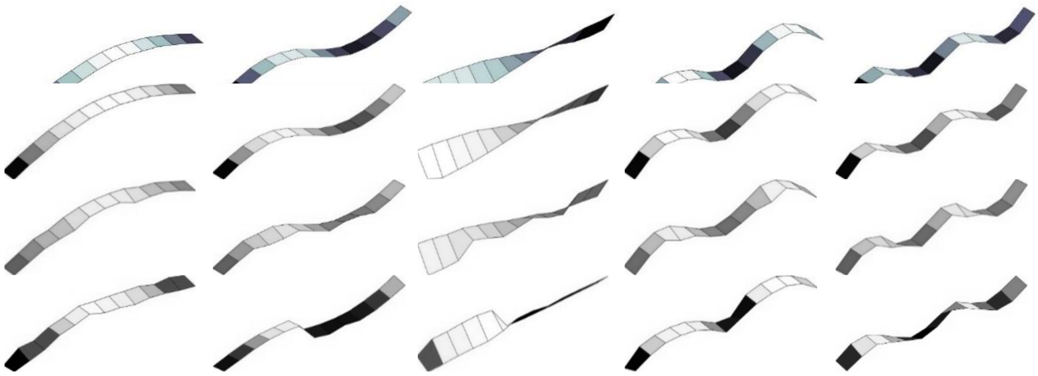
Figure 8. Photographs of sleepers at different health states. Left: first crack appeared at 53 kN, middle: 1.5 load of first crack load, right: failed sleeper.

Only three pictures highlighting the damage severity of sleepers are shown. The first picture shows a sleeper in negative bending configuration and loaded until first crack. The location of crack is marked at load of 53 kN. The middle picture shows crack evolution after loading up to

1.5 load of first crack load (80 kN). More cracks have appeared and crack growth is marked with respective load values. The last picture shows that sleeper has failed in shear.
Extracted mode shapes are shown in Table 1. Only five modes that correspond to all cases of damage are shown, although for some cases the 6th mode is also present (the 2nd torsional mode). Visual comparison of the mode shapes reveals how structural integrity is affected with the evolution of cracks. The correlation between mode shapes decreases as the severity of damage increases which can be the most readily assessed by computing Modal Assurance Criterion (MAC) between all mode shapes of healthy and damaged structure. The elements of main diagonal of MAC matrix which have the most deviations from unity indicate the modes that are the most affected by damage (Ndambi et al. (2002), An et al. (2013)).

Table 1. Extracted mode shapes for sleepers at different health states.

	2nd bending	3rd bending	1st torsional	4th bending	5th bending
Healthy					
First crack					
1.5 first crack					
Failed					



Natural frequencies and respective damping ratios for each mode shape are depicted in Tables 2-5. For healthy sleepers, there is no considerable differences in natural frequencies with the exception of last mode – 5th bending for which the frequency difference reaches 6.8 % between sleepers 3 and 4. At the lightest severity of damage (the first crack), the largest natural frequency shift is attributed to the 2nd bending mode with 5.5 % decrease, while the largest increase of damping ratio (over 76 %) is experienced by 4th bending mode. For the intermediate damage severity (1.5 load of the first crack load), the most considerable frequency shift is only less than 0.8 % for the 4th bending mode of sleeper 2. The largest increase of damping is 17.5 % for 2nd bending mode of sleeper 4. It is worth mentioning that no consistent frequency and damping shifts are observed with the increasing damage severity for any particular mode. As expected, the most significant changes in modal parameters are caused by the failure. The most drastic shifts in modal parameters are associated with sleeper 3 with a decrease of natural frequency of 71.5 % for 3rd bending mode and increase of damping by 429 % for 5th bending mode.

Table 2. Modal parameters for healthy sleepers. Left: natural frequency (Hz), right: damping ratio (%).

Sleeper	2nd bending		3rd bending		1st torsional		4th bending		5th bending	
1.	126.5	2.20	345.9	1.11	438.4	0.74	667.6	1.01	1046.1	1.02
2.	128.4	2.13	348.5	0.94	442.0	0.74	673.3	0.69	985.5	1.13
3.	127.0	3.21	348.7	1.47	443.4	1.20	672.0	1.35	1053.3	1.10
4.	123.9	1.83	344.9	0.98	438.9	0.64	665.5	0.88	981.4	0.99

Table 3. Modal parameters for sleepers at first crack. Left: natural frequency (Hz), right: damping ratio (%).

Sleeper	2nd bending		3rd bending		1st torsional		4th bending		5th bending	
2.	121.4	1.81	346.2	1.04	440.9	0.94	670.2	1.22	981.2	0.70
4.	120.1	1.90	343.6	1.03	439.5	1.12	666.2	1.26	981.9	0.75

Table 4. Modal parameters for sleepers at load equal to 1.5 of first crack load. Left: natural frequency (Hz), right: damping ratio (%).

Sleeper	2nd bending		3rd bending		1st torsional		4th bending		5th bending	
2.	127.1	2.07	346.3	1.02	439.4	0.68	668.0	0.81	982.0	1.12
4.	125.0	2.15	344.7	0.90	438.1	0.63	665.0	0.76	983.4	1.00

Table 5. Modal parameters for failed sleepers. Left: natural frequency (Hz), right: damping ratio (%).

Sleeper	2nd bending		3rd bending		1st torsional		4th bending		5th bending	
1.	76.3	2.36	305.9	1.23	325.7	0.95	568.9	3.82	937.1	1.45
3.	63.9	6.32	99.5	5.89	254.0	1.63	499.4	2.00	806.0	5.82

The location of damage is assessed by comparing the normalized modal amplitudes for sleepers 2 and 4 at the lightest and intermediate severity of damage with the corresponding modes of healthy sleepers. The difference in normalized amplitude is summed up for all of the modes and plotted with respect to longitudinal coordinate of the sleeper in Figure 9. Only one half of each mode is considered as bending mode shapes are symmetric with respect to the central axis passing in the longitudinal direction of sleepers. Thus, instead of 26 nodes modal amplitude difference for only 13 nodes is shown. It can be seen that the largest modal deviations for the lightest damage severity are located at the 1st node of sleeper 2 and the 2nd node of sleeper 4. This result should be ignored as the first crack occurred near midspan. At intermediate damage severity the largest differences are at 4th and 10th nodes for sleeper 2 and 2nd and 11th nodes of sleeper 4 which does not precisely correlate with the actual locations of cracks. More advanced damage localisation techniques, such as the ones based on mode shape curvature or wavelet transform (Janeliukstis et al. (2017)) are desired to locate the damage, and this is the problem for future studies.

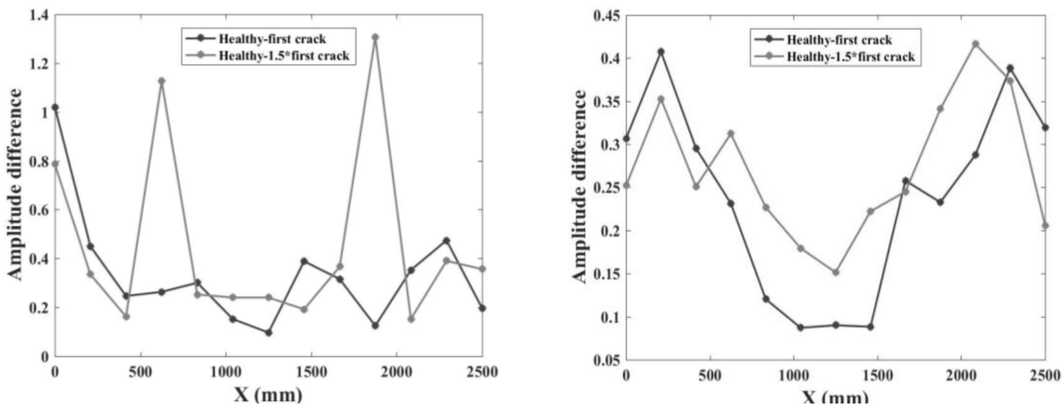


Figure 9. Difference of normalized modal amplitude distribution summed over all modes. Left: sleeper 2, right: sleeper 4.

4 CONCLUSIONS

The present study is aimed at underlying the feasibility of experimental modal analysis to detect the damage in prestressed concrete sleepers subjected to flexural loading. Three stages of damage severity are studied – light damage (first crack), moderate damage (1.5 load of first crack load) and failed specimens. Modal parameters, such as natural frequencies, damping ratios and mode shapes are extracted and compared to the ones for sleepers at healthy baseline condition. Overall, there is a correlation with the magnitude of shift of natural frequencies and damping ratios with the severity of damage, although it is not consistent through the progression of damage for any particular mode. Normalized mode shapes themselves are not a plausible means to localize the damage, thus more sophisticated techniques, for example, mode shape curvature and wavelet transform are preferred.

ACKNOWLEDGEMENTS

The research leading to these results has partially received the funding from Latvia State Research Programme under grant agreement "Innovative Materials and Smart Technologies for Environmental Safety, IMATEH".

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