Dynamic Characterization of a Real-Scale Prestressed Concrete Beam Tested Until Failure

Sierra, Pablo L.; Poliotti, Mauro; Yang, Yuguang; Martinez García, Xavier; Chacón, Rolando

DOI
10.1007/978-3-031-32511-3_92

Publication date
2023

Document Version
Final published version

Published in
Building for the Future: Durable, Sustainable, Resilient.

Citation (APA)
Sierra, P. L., Poliotti, M., Yang, Y., Martinez García, X., & Chacón, R. (2023). Dynamic Characterization of a Real-Scale Prestressed Concrete Beam Tested Until Failure. In A. Ilki, D. Çavunt, & Y. S. Çavunt (Eds.), *Building for the Future: Durable, Sustainable, Resilient.: Proceedings of the fib Symposium 2023 - Volume 2* (Vol. 350, pp. 896–906). (Lecture Notes in Civil Engineering; Vol. 350 LNCE). Springer. https://doi.org/10.1007/978-3-031-32511-3_92

Dynamic Characterization of a Real-Scale Prestressed Concrete Beam Tested Until Failure

Pablo L. Sierra[1](✉), Mauro Poliotti[2], Yuguang Yang[2], Xavier Martinez García[3], and Rolando Chacón[3]

[1] International Centre for Numerical Methods in Engineering, Barcelona, Spain
psierra@cimne.upc.edu
[2] Delft University of Technology, Delft, The Netherlands
[3] Polytechnic University of Catalonia, Barcelona, Spain

Abstract. In this work, dynamic characterization of a simply supported beam is carried out during different steps in a failure load test. The main goal of this work is to evaluate the evolution of the structural dynamic parameters of the beam with different status of damage. Real-scale prestressed concrete beams are tested to investigate its shear behaviour as a part of a large research program at TU Delft. Four dynamic tests are performed at different damage status of the beam: firstly in the initial or undamaged condition; secondly after the first flexural cracks; then, after shear cracking; and finally in the full damaged condition. The dynamic excitation is performed with an impact load at fixed location on the top of the beam and the vibration data is recorded by three different systems. The first one is a cost-effective and open source monitoring equipment, consisting of seven low-cost accelerometers. The second system is based on five trusted high performance accelerometers. The last one is a commercial alternative consisting of four high accuracy piezoelectric accelerometers. Acceleration data is analysed afterwards using Operational Modal Analysis techniques to obtain modal frequencies, modal shapes and damping of the structure in the different states. The obtained dynamic behaviour of the structure and its results are discussed and compared. It is concluded that a change in the frequency of the first flexural mode is only observed when the damage in the beam is very significant, while no changes are observed with the occurrence of flexural and shear cracks.

Keywords: Dynamic Characterization · Prestressed Concrete · Operational Modal Analysis · Cost-Effective Devices · Monitoring · Shear Failure

1 Introduction

Prestressed concrete girder bridges, usually prefabricated with in-situ concrete slabs, are a common typology in existing Dutch infrastructure. As part of a larger study seeking a better understanding of the failure mechanism and shear behaviour of this type of structures, dynamic characterisation tests with different damage levels are performed during static loading of a beam.

A. Ilki et al. (Eds.): *fib* Symposium 2023, LNCE 350, pp. 896–906, 2023.
https://doi.org/10.1007/978-3-031-32511-3_92

The objective of this work is to analyse the damage sensitivity of different dynamic parameters, such as eigenfrequencies, modal shapes and damping of this type of structure. Further, the applicability of monitoring these parameters in a damage inspection system is analyzed. For this purpose, it is proposed to perform dynamic tests on a beam with different damage levels generated by the load applied during static testing.

Dynamic testing of structures and bridges is a common practice and several cases can be cited since the middle of the twentieth century [1]. They are an important tool for civil engineers, allowing them to understand the dynamic behaviour of a structure and to identify potential problems that may not be detected during static testing. The results of dynamic tests can be used to improve the design, construction and maintenance of a structure and to assess the integrity of the structure. In this case, modal tests are performed using Operational Modal Analysis (OMA) techniques to analyse the response of the structure to environmental excitations. This allows the identification of natural frequencies and the corresponding modal shapes and associated damping. The OMA process consists of collecting data from sensors placed on the structure, performing signal processing and data analysis, using mathematical models to identify the modal parameters of the structure.

The dynamic characterisation of a simply supported beam is presented in this paper. The beam is instrumented with a total of 16 accelerometers distributed on the bottom of the beam, with 3 different systems. By analysing the behaviour of the beam with different levels of damage, the values of frequencies, modal shapes and damping are compared, looking for relationships between the level of damage and these parameters.

2 Specimen Geometry and Materials

This study is carried out on an 11.25 m long, simply supported beam. The section consists of a prestressed inverted T-beam with a height of 900 mm and a web thickness of 300 mm. It then has a top flange, casted in situ separately of the T-beam, with a height of 160 mm and a width of 1200 mm. This specimen is half the length of real-scale bridge girders with the same section. The compressive strength of the concrete used is 65 and 40 MPa for the precast beam and top flange respectively, see Figs. 1 and 2.

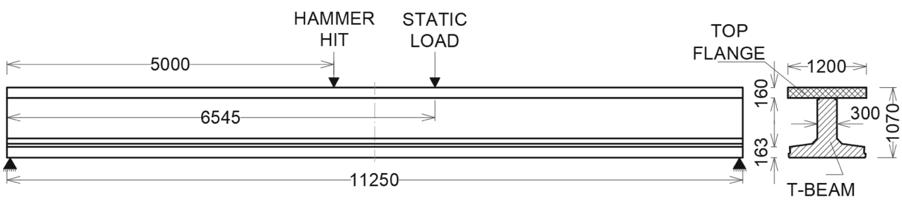

Fig. 1. Beam geometry, lateral view and cross section. Dimensions in mm

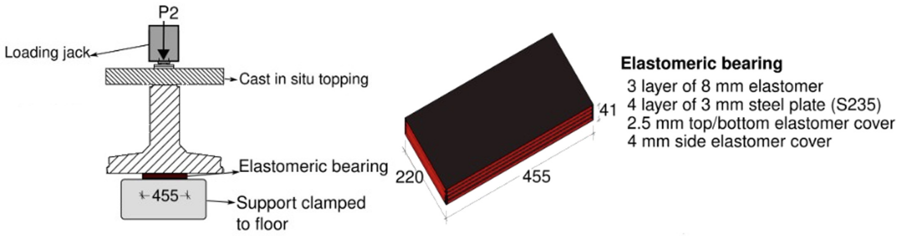

Fig. 2. Support scheme and bearing description

3 Measurement Equipment

For the dynamic characterisation of the structure, accelerometers distributed throughout the structure are deployed. Three different systems are used in this test and are described below.

3.1 UPC Low-Cost Equipment

This measurement equipment was developed at UPC with the idea of obtaining a functional prototype with the lowest possible cost and simplicity of installation, based on low cost and open-source sensors and microcontrollers. This equipment includes digital accelerometers based on Micro-Electro-Mechanical Systems (MEMS) technology, with two different sensors.

- 4 units are equipped with an MMA8451 (referred as Acc001 to Acc004).
- 3 units are equipped with an MPU6050 (Acc101 to Acc103).

The main characteristics of these 3-axis and digital sensors are shown in Table 1. In addition to the advantage of low cost, they have low power consumption and compact size.

NodeMCU v3 boards based on ESP8266 microprocessors are chosen to control these sensors and send data wirelessly. These processors use the I^2C protocol for bidirectional communication with the sensors and able Wi-Fi connections with their integrated antenna. Accelerometer and microcontroller board form a measurement unit powered by a power bank.

Finally, a Raspberry Pi 3B + board acts as a Wi-Fi access point for the measurement units and manages communication with them. It also collects and stores the data received from the sensors.

3.2 NetPlus

Prototype developed at Shenju University [2]. Equipped with a 3-axis MEMS-based accelerometer, ADXL355, whose main features are listed in Table 1. Five of these units (designated C1 to C5) are used in the test.

This prototype is optimised for vibration measurement in historic buildings. Each unit includes measurement, control and data storage. It should be configured previously using a computer, where certain operating parameters are defined, such as the mode (continuous measurement or automatic start from threshold values), sampling frequency, resolution, etc. The devices are powered with batteries and the data is internally stored. This data can be accessed later by connecting to a computer.

3.3 PCB Accelerometer 356B18

Manufactured by PCB Piezotronics of ICP Gamma, these devices are high performance tri-axial accelerometers. These sensors are piezoelectric, offering wide frequency ranges and high sampling rates. The main characteristics are listed in Table 1. Four units are available for testing (designated RP1 to RP4).

Data acquisition is performed using a National Instrument NI USB-4431, which provides up to 4 differential analogue input channels, a maximum sampling rate of 102,400 samples/s and 24-bit accuracy. Due to the limited number of inputs, data acquisition in this test is limited to one axis per accelerometer. Only vertical axis data of the accelerometers is acquired.

Table 1. Sensors main characteristics

Parameter	Sensors				Unit
	MMA8451	MPU6050	ADXL355	3556B18	
Range	± 2, ± 4, ± 8	± 2, ± 4, ± 8, ± 16	± 2, ± 4, ± 8	± 5	g
Analog to Digital Converter	14	16	20	24	Bits
Sensitivity	4096	16,384	256,000	–	LSB/g
Max. Output Data Rate	200	250	4000	4000	Hz
Frequency bandwidth	0–66	0–44	0–1500	0.5–3000	Hz
PSD Noise	99	400	25	4	$\mu g/\sqrt{Hz}$
Dimension	40 × 30x20	60 × 40x20	69 × 64x16	26 × 20x20	Mm
Cost	15	15	70	1300	€

4 Test Description

The static test consists of applying the load in steps of 50 kN. The first bending cracks are expected to appear at 650 kN. The load steps are then reduced to 25 kN until failure is reached. The load is applied in displacement controlled at a constant rate of 0.02 mm/s. Dynamic tests are performed in the following cases:

1. Damage level 0: Undamaged, see Fig. 3.
2. Damage level 1: Appearance of the first bending cracks (650 kN), see Fig. 4.
3. Damage level 2: Appearance of the first shear cracks (750 kN), see Fig. 5.
4. Damage level 3: After failure, see Fig. 6.

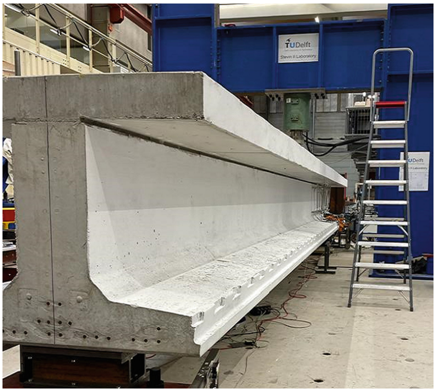

Fig. 3. Damage level 0. Test setup

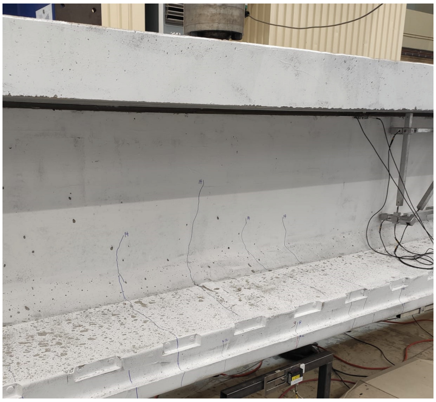

Fig. 4. Damage level 1. Crack pattern

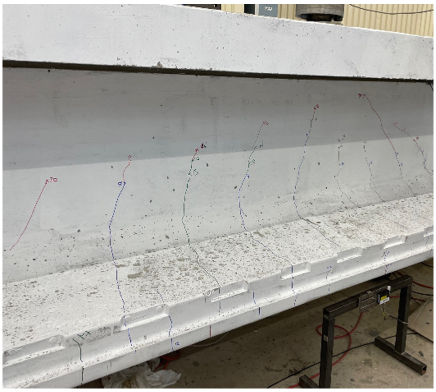

Fig. 5. Damage level 2. Crack pattern

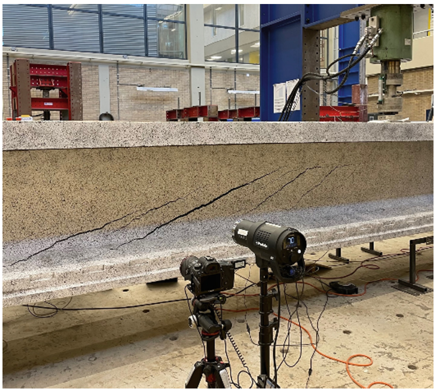

Fig. 6. Damage level 3. Failure

In the last three cases, once the beam has reached the indicated load, it is completely unloaded, releasing the jacks from the structure. The dynamic test is then executed.

Dynamic tests consisted of applying a point and instantaneous load with a heavy iron hammer manufactured by Lixie, model 300H-MH-35, weighing 0.05 kN, see Fig. 7. Accelerations are obtained for several minutes, while hits of different intensities are applied manually. The hammer is raised to a certain height and dropped onto the beam. The point of impact is made on the top face, see Fig. 8.

After the dynamic test, the beam is continuously reloaded to the step where it stopped. It is then reloaded in steps to the next case where the process is repeated.

The Fig. 9 shows the position of the accelerometers on the bottom face of the beam. This distribution was chosen to maximise the spatial information of the modal shapes.

Fig. 7. Lixie hammer

Fig. 8. Hammer hit

Both, the UPC system and NetPlus sensors, were configured with a 200 Hz of sampling rate, while the PCB accelerometers were set to 5000 Hz. Therefore, for the modal analysis, the signal obtained with the first two systems are analysed together, labelled as UPC-Netplus, and the signal obtained with the remaining system is analysed separately as they have different analysis frequency ranges.

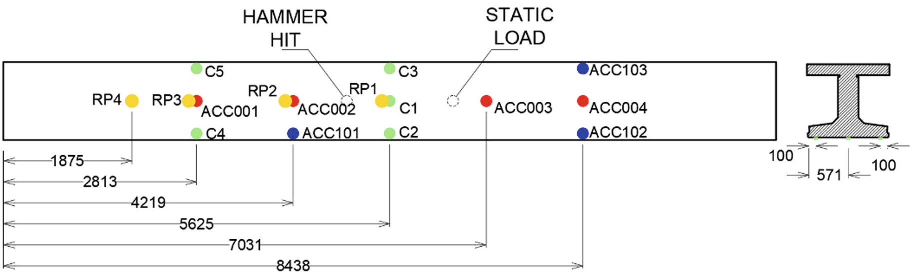

Fig. 9. Layout of accelerometers, bottom view and section of the beam. Dimensions in mm

5 Dynamic Analysis

The series of acceleration data obtained during the dynamic tests are pre-treated and processed in order to obtain the main vibration frequencies of the structure, as well as the modal shapes and the associated dynamic damping. For this, Multiple Operational Modal Analysis Platform (MOMAP) is developed, a Python software for signal analysis. The application performs the following tasks.

5.1 Data Pre-Treatment

In this task, the signals are processed to reduce noise and eliminate frequency content outside the range of interest of the signal, to avoid misinterpretation of the analysis results and to increase the accuracy of the structural values obtained. This includes the option of applying a digital high-pass filter, selecting the cut-off frequency, applying a down-sampling technique with a selectable factor, and applying a noise reduction algorithm based on decomposing the signal into singular values.

5.2 Data Analysis

To obtain the dynamic parameters of the structure, various OMA techniques are available, which have the advantage of not needing to control or know the load applied during the test. These algorithms only require as input the response of the structure, in this case accelerations, to dynamic disturbances.

In this work the following methods are used for the analysis, for details see references:

- Enhanced version of the Frequency Domain Decomposition [3, 4].
- Covariance-driven Stochastic sub-Space Identification [5].

In both cases, the result of the analysis is the identification of the structure's eigenfrequencies, modal shapes and associated damping.

6 Results

The signals obtained from the different dynamic tests are processed with OMA techniques as explained above. Figures 10, 11, 12, 13, 14, 15 and 16 show the Power Spectrum Density (PSD) function (blue line), the Singular Value Decomposition (SVD) (green line) and the Stabilisation Diagram (points, colours represent different ranks) for the different cases, with both UPC-Netplus and PCB equipment.

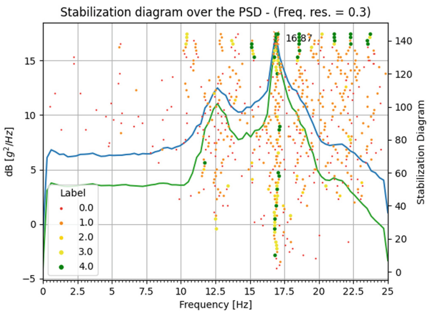

Fig. 10. Damage level 0 UPC-Netplus equipment, results in frequency spectrum

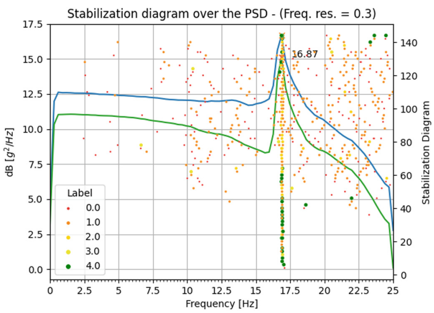

Fig. 11. Damage level 1 UPC-Netplus equipment, results in frequency spectrum

As a consequence of the higher sampling rate of the PCB accelerometers, the frequency range of analysis is greater with this equipment than with the UPC-Netplus based. This range is also affected by the downsampling factor used in decimation. However, frequencies and its respective damping for the first flexural mode are obtained with both and listed in Table 2 and shown in Fig. 17.

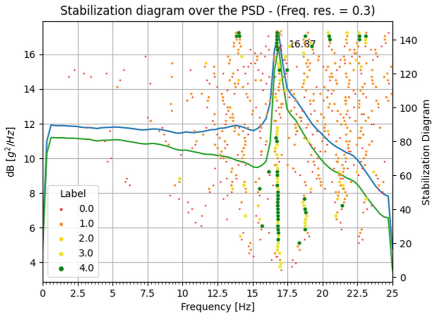

Fig. 12. Damage level 2 UPC-Netplus equipment, results in frequency spectrum

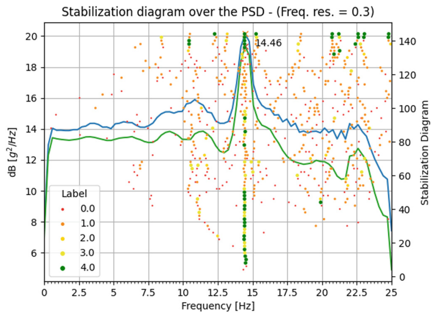

Fig. 13. Damage level 3 UPC-Netplus equipment, results in frequency spectrum

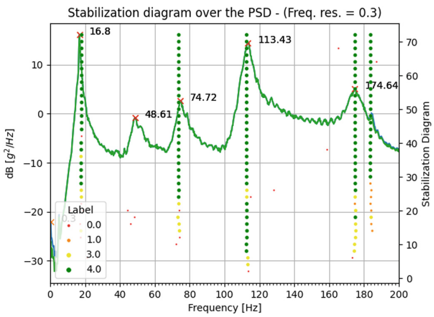

Fig. 14. Damage level 1 PCB equipment, results in frequency spectrum

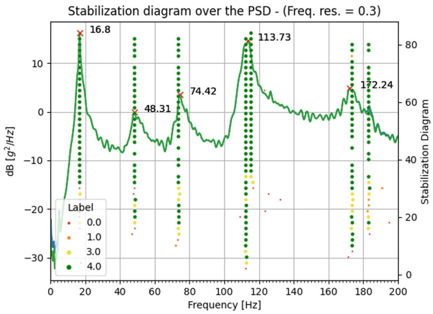

Fig. 15. Damage level 2 PCB equipment, results in frequency spectrum

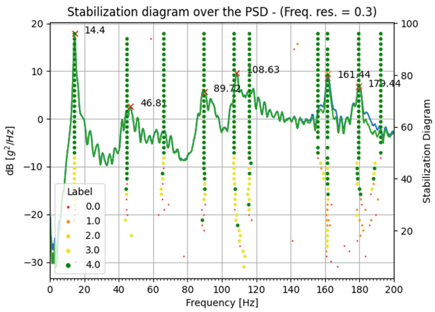

Fig. 16. Damage level 3 PCB equipment, results in frequency spectrum

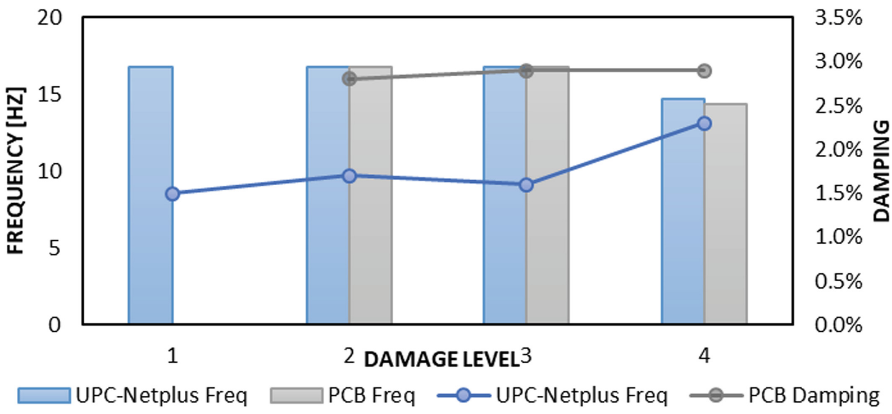

Fig. 17. Frequency and damping with different damage levels

The modal shape obtained in the analysis of the Damage level 3 with the UPC-Netplus equipment is shown in Fig. 18. This confirms that the detected mode is the first flexural mode of the beam.

Table 2. First flexural mode, frequency and damping

Case	Cost-effective equipment		PCB	
	Frequency	Damping	Frequency	Damping
1	16.82 Hz	1.5%	–	–
2	16.82 Hz	1.7%	16.80 Hz	2.8%
3	16.82 Hz	1.6%	16.80 Hz	2.9%
4	14.71 Hz	2.3%	14.40 Hz	2.9%

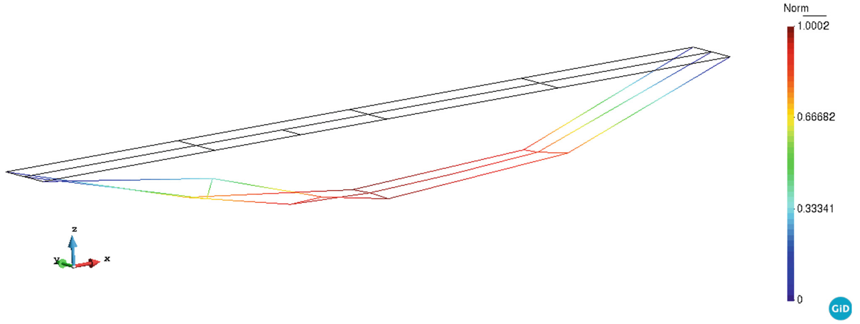

Fig. 18. Damage level 3 low – cost equipment, modal shape

7 Conclusions

In this work, the dynamic characterization of a prestressed concrete beam with 4 levels of damage has been performed. The analysis was performed with two acceleration measurement equipment, one based on two low-cost different accelerometers and the other is a higher-performance market reference equipment. The following conclusions are drawn from the study:

- Comparing the results of the first 3 damages levels in Table 2, it can be concluded that the appearance of the flexural cracks and the first shear cracks does not alter the frequency of the first mode of vibration of the structure. It can be observed that the values obtained for both systems show no change. This may be due to the fact that in prestressed structures, once the load that caused the cracks to open has been removed, the cracks close thanks to the tension of the active reinforcement and the stiffness of the structure is restored. However, in damage level 3, where the damage in the beam is very significant, there is a reduction in the frequency of the first mode of approximately 13%.
- Comparing the mode shapes and damping obtained with the different levels of damage, no direct correlation could be found. Both dynamic variables are sensitive to analysis parameters and measurement errors. This leads to uncertainties in the results and makes it more complex to find relationships between changes in the results and the occurrence of damage in the beam.

- Regarding the comparison of measurement equipment, satisfactory results are obtained with UPC-Netplus equipment in terms of frequency estimation and obtaining modal shapes. The range of analysis of the response in the frequency spectrum is limited by a more limited sampling frequency. More modes of the structure can be detected with a higher sampling frequency. In addition, the structure analysed in this work is considerably stiffer than full-scale structures, which raises the vibration frequencies of the different modes outside the analysis range.
- From the results, it can be concluded that the UPC-Netplus system can be applicable to this type and scale of structures. Monitoring only the frequency of the first mode has important limitations, so other dynamic features or the analysis of more vibration modes should be added to the study.

References

1. Salawu OS, Williams C (1995) Review of full-scale dynamic testing of bridge structures. Eng Struct 17(2):113–121
2. Endo Y, Niitsu Y (2020) Health Monitoring Tests of Heritage Structures: Application of MEMS Accelerometers to Two Multi Tier Pagodas. In: Roca P, Pelà L, Molins C (eds) 12th International Conference on Structural Analysis of Historical Constructions. Scipedia
3. Brincker R, Zhang L, Andersen P (2001) Modal identification of output-only systems using frequency domain decomposition. Smart Mater Struct 10:441–445
4. Gade S, Moller N, Herlufsen H, et al (2005) Frequency domain techniques for operational modal analysis. International Operational Modal Analysis Conference. Scopus, Copenhagen
5. Ho B, Kálmán R (1966) Effective construction of linear state-variable models from input/output functions. at – Automatisierungstechnik 12:545–592