Chapter 3
Structural Integrity Assessments of a Train Bridge Using SHM Data

Bjørn T. Svendsen, Niels Dollerup, and Eimantas Poskus

Abstract This paper presents the structural integrity assessment of a train bridge using data obtained from a comprehensive SHM system. The bridge, which consists of three similar bridge spans supported by two foundations, was repaired and re-installed in 2024 for normal operation after a collapse during a severe flooding. Overviews of the bridge damage condition and the SHM system are presented. Results from the structural integrity assessment are evaluated, with a particular focus on static inclination and the structural dynamic behaviour over time and for different temperatures, based on data obtained from one year of measurements. The effects of environmental conditions, i.e., the temperature, on the modal parameters of the bridge are mapped and the actual structural behaviour is validated by comparing the performance of all three bridge spans and assessing the performance over time to ensure increased bridge safety.

Keywords Structural health monitoring · Damage detection · Bridge · Operational and environmental variability · Temperature · Collapse · Modal tracking · Gaussian mixture modelling.

Introduction

Although bridges are essential parts of the infrastructure, an increasing trend of bridge collapses worldwide has been observed in recent years. Bridge collapses are, in many cases, caused by sudden changes in the operational and environmental loads affecting the structural behaviour. A fundamental challenge in structural health monitoring (SHM) is the process of separating changes caused by operational and environmental conditions from changes caused by damage. It is well known that variability in operational and environmental conditions affects the structural response and can mask changes caused by damage. An important part of the work towards solving this challenge is to understand the effects of environmental conditions on modal properties, such as natural frequencies, mode shapes and damping. Therefore, deploying long-term SHM systems on bridges are important to map such effects as well as performing structural integrity assessments. Automatic operational modal analysis (OMA) and modal tracking are examples of important tools that are used for such mapping [1], [2]. It is well known that SHM systems can result in enhanced decision support and structural diagnosis of the structure [3]–[6]. Consequently, the use of SHM systems for structural integrity evaluation of bridges has become increasingly important.

For bridges, variability in operational conditions is mainly caused by traffic, while variability in environmental conditions is mainly caused by humidity, wind and temperature effects. The most influential source of variability in the modal properties is due to temperature effects. In general, significant variations of the natural frequencies can be expected on a yearly (seasonal) basis for bridges [7]–[14], particularly for bridges located in cold climates such as Nordic and Scandinavian climates. A step-like variation in the natural frequencies of certain concrete and composite steel-concrete highway and railway bridges can be obtained during a yearly season, particularly around or below the freezing point. In the context of SHM, Gaussian mixture models (GMMs) have been used to characterize the effects of environmental variability, such as

Bjørn T. Svendsen
Department of Structural Engineering, Norwegian University of Science and Technology
e-mail: bjorn.t.svendsen@ntnu.no

Bjørn T. Svendsen · Niels Dollerup · Eimantas Poskus
Department of Marine Structures, Ramboll Energy
e-mail: bjorn.t.svendsen@ntnu.no; nsd@ramboll.com; eipo@ramboll.com

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temperature effects, on features such as natural frequencies [15]–[17]. There are, however, few such studies reported in the literature on full-scale bridges in operation. Understanding the temperature effects on the structural behaviour and bridge performance is crucial for performing reliable structural integrity evaluations.

This paper presents the structural integrity assessment of an operational train bridge using data obtained from a comprehensive SHM system. Results from the structural integrity assessment are evaluated, with a particular focus on static inclination and the structural dynamic behaviour over time and for different temperatures, based on data obtained from one year of measurements. The effects of environmental conditions, i.e., the temperature, on the modal parameters of the bridge are mapped and the actual structural behaviour is validated by comparing the bridge performance and assessing the performance over time to ensure increased bridge safety. The outline of this paper is as follows. Sections 2 and 3 provide overviews of the bridge damage condition and SHM system, respectively. Section 4 presents the static structural assessment. Section 5 presents the dynamic structural assessment, which includes modal tracking and the implementation of a GMM on the modal tracking data. Finally, section 6 summarizes and concludes the work.

Damage overview

The bridge considered in this study is a steel riveted truss train bridge consisting of three similar spans. The bridge was originally built in 1957 and is located in Norway. The structural system of each bridge span consists of two bridge walls, a bridge deck, and upper and lower lateral bracings. The total length of the bridge is approximately 180 m, where each bridge span is 57.5 m long and has a total width of 5 m and a height of 7.5 m. Figure 1 shows a schematic overview of the structural system of one bridge span. Figure 2 provides a damage overview and the state of the condition of the bridge spans after the collapse and prior to repair. During the collapse, bridge span 1 remained in its original position and thus experienced negligible structural damage. Bridge spans 2 and 3, however, collapsed into the river and experienced major structural damage. The damage was mostly local damage at the bridge ends. The typical damage types observed were tear (cracking), member separation, dents and overloading in terms of loss of rivets. The overall bridge damage situation was taken into consideration in the proposed alternatives and final design of the SHM system.

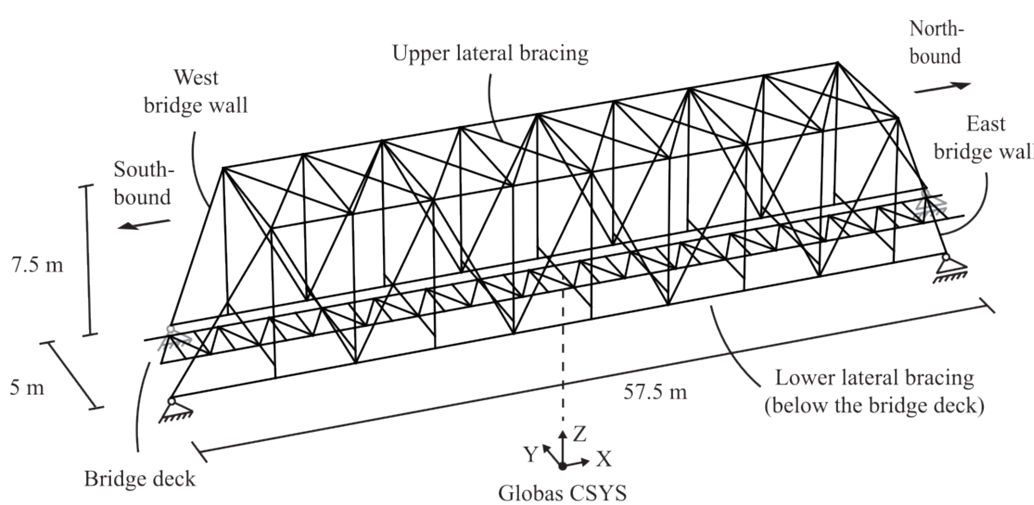

Fig. 1 Overview of the bridge span structural system

Structural health monitoring system

The SHM system of the bridge, shown in Figure 3, is a cabled system consisting of accelerometers, inclinometers, a weather station and a cabinet. The cabinet contains all relevant data acquisition units, an industrial computer, power supplies and a

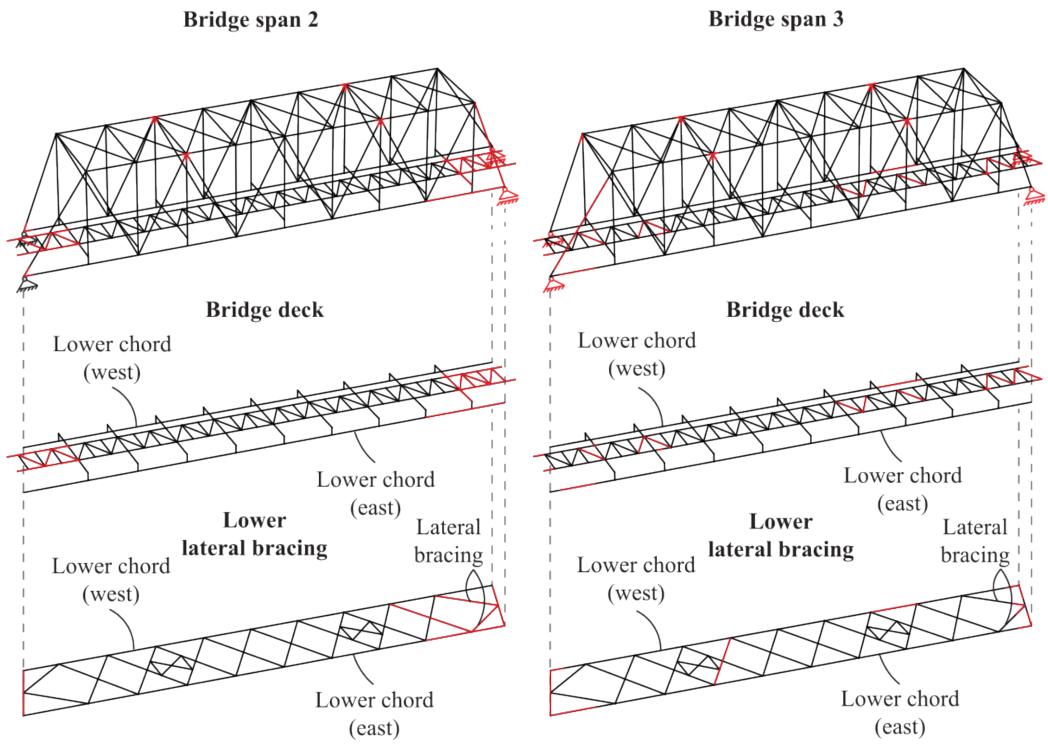

Fig. 2 Damage overview and bridge condition after the bridge collapse. Damaged areas of beam members and joints are highlighted in red

router for wireless data transfer. Altogether, the SHM system comprises 30 sensors in addition to the weather station and is designed as one system to provide fully synchronized data. Table 1 summarizes the sensors that are included in the SHM system and installed on each of the bridge spans. Apart from the weather station, the sensors consist of 1) accelerometers that measure acceleration and 2) biaxial static inclinometers (tiltmeters) that measure pitch and roll angles. All sensors, apart from the weather station, are micro-electro-mechanical system (MEMS) sensors. Data are collected and streamed continuously with a sampling rate of 100 Hz for the accelerometers and 1 Hz for the inclinometers and weather station.

The SHM system is designed to capture the global response of the bridge using accelerometers and inclinometers and the environmental load using the weather station. The SHM system was originally designed as a temporary system allowing short-term measurements for a period of approximately one full year. However, the original design of the system allows both an expansion of the system using additional sensors and an extension of the operating period, if needed. Data from the SHM system are streamed continuously to a Grafana dashboard using a Historian database service over the MQTT protocol.

Based on data obtained from the SHM system, two types of structural integrity assessments are performed. The first assessment considers the bridge static structural behaviour. The objective of this assessment is to compare and evaluate the static behaviour of all three bridge spans by considering inclination. The second assessment considers the bridge dynamic structural behaviour. The objective of this assessment is to compare and evaluate the behaviour of all three bridge spans by considering modal tracking. Common for both structural integrity assessments are the evaluation of the structural integrity over time and for different temperatures.

Table 1 Overview of the sensors included in the SHM system

Sensor type	Bridge span 1	Bridge span 2	Bridge span 3	Total
Accelerometer	8	8	8	24
Accelerometer and inclinometer	2	2	2	6
Weather station	-	-	1	1

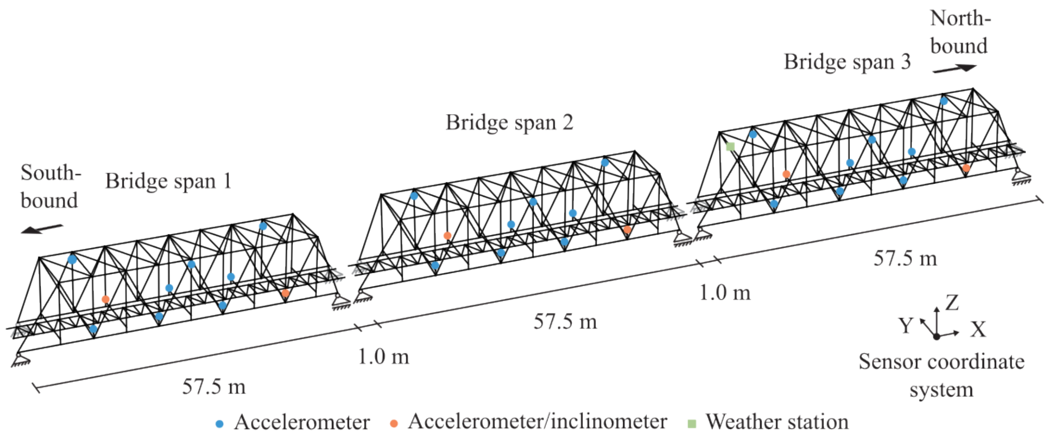

Fig. 3 The bridge SHM system

Static structural assessment

The static behaviour of all three bridge spans is compared and evaluated by considering inclination. The assessment is performed by comparing and evaluating the static inclination over time, including considerations of temperature variations. Figure 4 shows an overview of the inclinometers and inclination angles, i.e., roll and pitch, that are evaluated. A clockwise tilt provides positive inclination values.

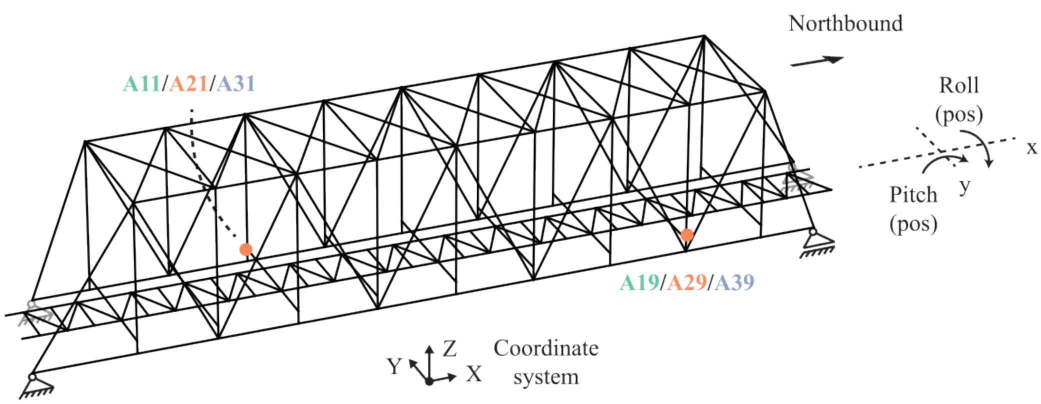

Fig. 4 Inclinometers and the corresponding angles evaluated

One dataset per day is chosen as a basis for performing analyses. Each dataset provided from the SHM system between 12.00-13.00 local time is chosen. If the dataset at the chosen time of a specific day is incomplete, data from the nearest complete hour has been chosen. Each dataset contains a time series of 60 min. The average value of the inclination for each channel of each sensor is computed for the time series in addition to the average value of the temperature. The daily average static inclination of the bridge spans throughout one year are summarized in Figure 5 and Figure 6 for roll and pitch motions, respectively.

From the results presented in Figure 5 and Figure 6, two important observations are made. First, the variation in the roll motion for all sensors is low in the period October 2024 to March 2025. The low variation appears to be related to the low temperature in this period, which is around and below the freezing point. As such, these results indicate a more stable static inclination behaviour during low temperatures than high temperatures. This variation is more distinct for the sensors located on the upstream side of the bridge, i.e., sensors A11, A21 and A31, than the sensors located on the downstream side of the bridge, i.e., sensors A19, A29 and A39. The variation is assumed to be related to different exposure of sun affecting the structural behaviour. Second, the curves generally follow each other well and the inclination values for roll and pitch

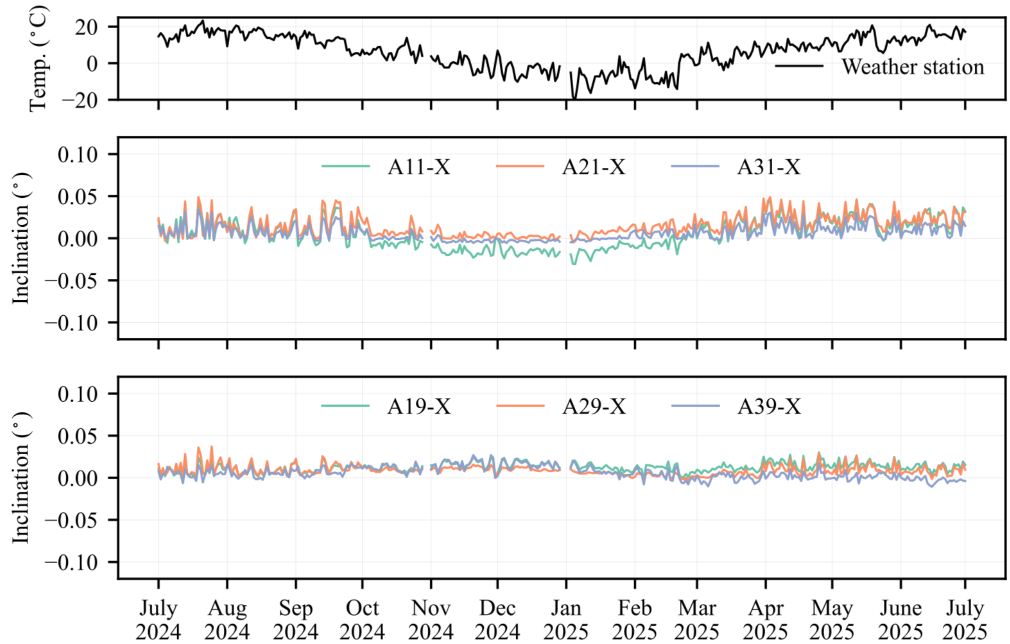

Fig. 5 The daily average static inclination about the bridge (sensor) x-axis (roll motion) of all three bridge spans, including the temperature, throughout one year

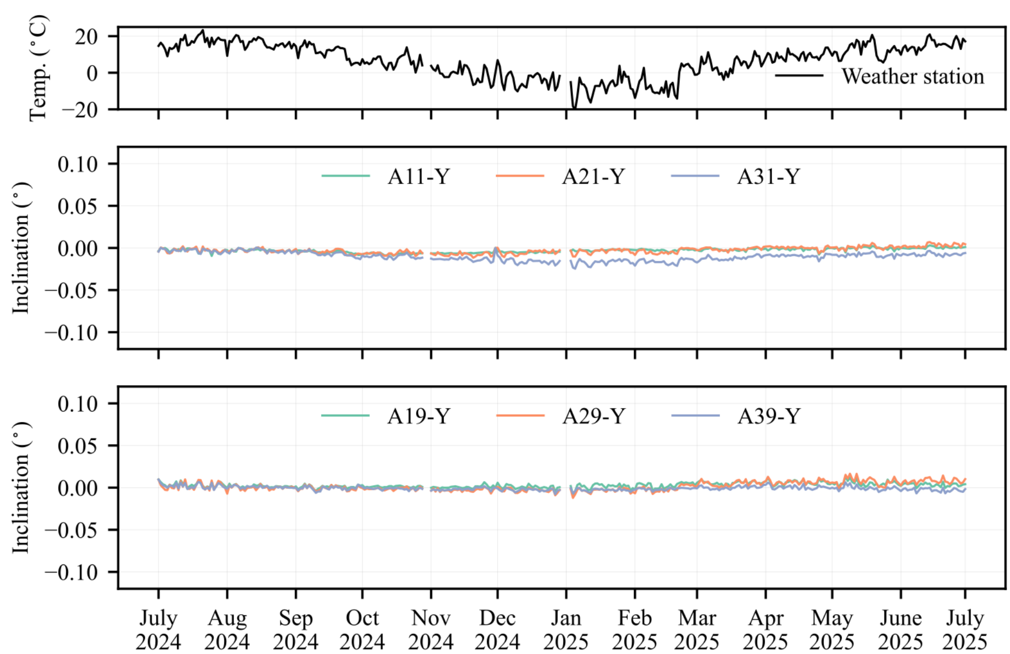

Fig. 6 The daily average static inclination about the bridge (sensor) y-axis (pitch motion) of all three bridge spans, including the temperature, throughout one year

motions are stable, low and with low variations. As such, the bridge spans compare well considering static inclinations over time.

No changes in the structural integrity of the bridge occurred during the period. Consequently, the variations in the static inclination of the bridge spans are mainly caused by environmental variability, such as the temperature. From the results presented, it is concluded that the effect of temperature on the static inclination is low. Some variation is observed; however, this variation is the level of variation to be expected for such bridges in typical Nordic and Scandinavian climates.

Dynamic structural assessment

Modal tracking

The dynamic behaviour of all three bridge spans is compared and evaluated by considering modal tracking. The assessment is performed by comparing and evaluating the modal properties over time, including considerations of temperature variations. The modal tracking is implemented as an automatic procedure to detect modes from multiple datasets. The modal tracking procedure, shown in Figure 7, consists of two parts. In the first part, a reference analysis is performed to establish the modes to be tracked. The reference analysis is based on data representing the yearly average temperature at the bridge location (4.0°C). In the second part, modes are automatically extracted from each dataset in a defined time period and identified.

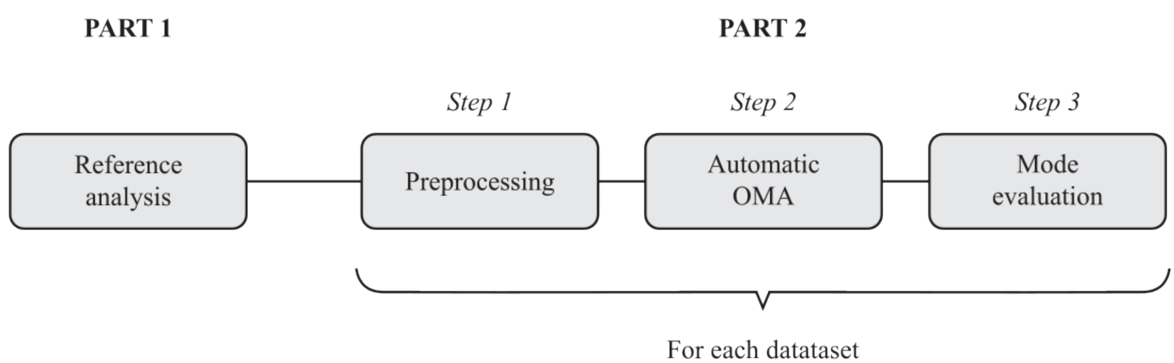

Fig. 7 The modal tracking procedure

Modes in a particular dataset are identified using a mode match index (MMI) based on the modes established in the reference dataset. The MMI is defined as [18], [19]:

$$MMI = (1-\gamma)\, MAC_{r,i} - \gamma \frac{|f_r - f_i|}{f_r} \tag{1}$$

where γ is a value between 0 and 1 that provides the weighting to be considered between the modal assurance criterion (MAC) numbers and natural frequencies, f. The subscripts r and i are denoted for the reference mode and dataset mode being evaluated, respectively. The cov-SSI method is used as an automatic OMA method with a range of order between 20-120 and a minimum of 15 poles as a general requirement, with some deviations, to determine stable modes. Examples of other applications of the considered OMA method is given in [20].

Modal tracking of the first 11 modes of each bridge span throughout one year is performed. The tracked modes are considered the most relevant modes that excites the bridge globally. One dataset per day is chosen as a basis for the modal tracking, where each dataset between 12.00-13.00 local time is used. If the chosen time of a specific day is incomplete, data from the nearest complete hour has been chosen. A 20 min time series is chosen from each dataset with no restrictions regarding traffic in terms of regular train passings. Consequently, time series with and without traffic are used as a basis for analysis in the modal tracking.

The modal tracking results for bridge spans 1, 2 and 3 based on one year of monitoring are summarized in Figure 8. The statistical distributions of the modal tracking results for each bridge span are shown in Figure 9. Table 2 summarizes the basic statistics from the modal tracking, such as the mean frequency value and standard deviation, whereas Table 3 summarizes statistics such as the detection rate and correlation with temperature. The statistics in Table 2 and Table 3 are provided for all modes of each bridge span.

From the results presented in Figure 8, Figure 9, Table 2 and Table 3, four important observations valid for all the bridge spans are made. First, when considering the modes separately, there is a low variation of the modes with varying temperature, i.e., the tracked modes appear stable. Second, some outliers of natural frequencies in terms of low minimum and high maximum values of each mode of each bridge span are observed. Third, there is a higher uncertainty, i.e., a large

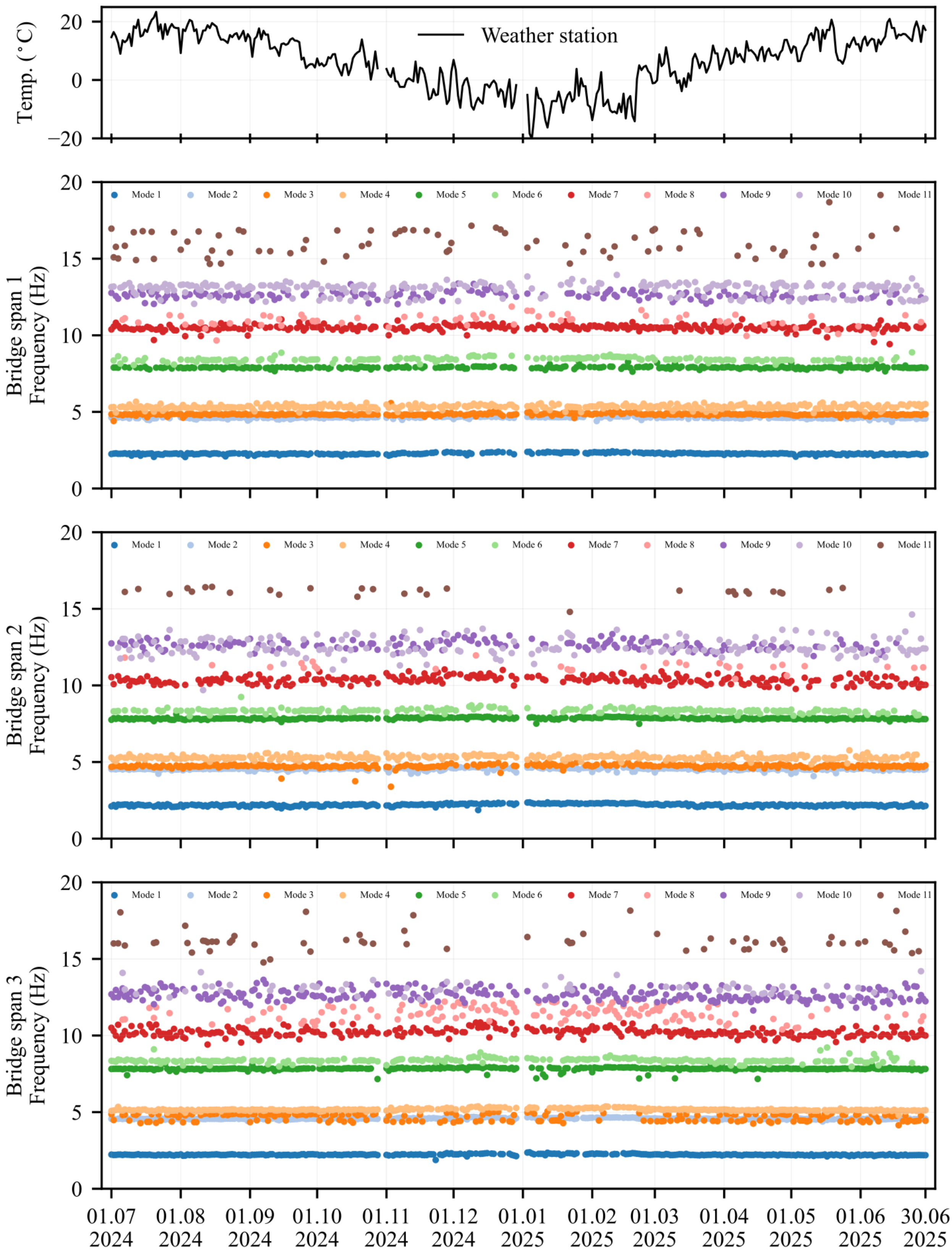

Fig. 8 One year of modal tracking results for bridge spans 1, 2 and 3

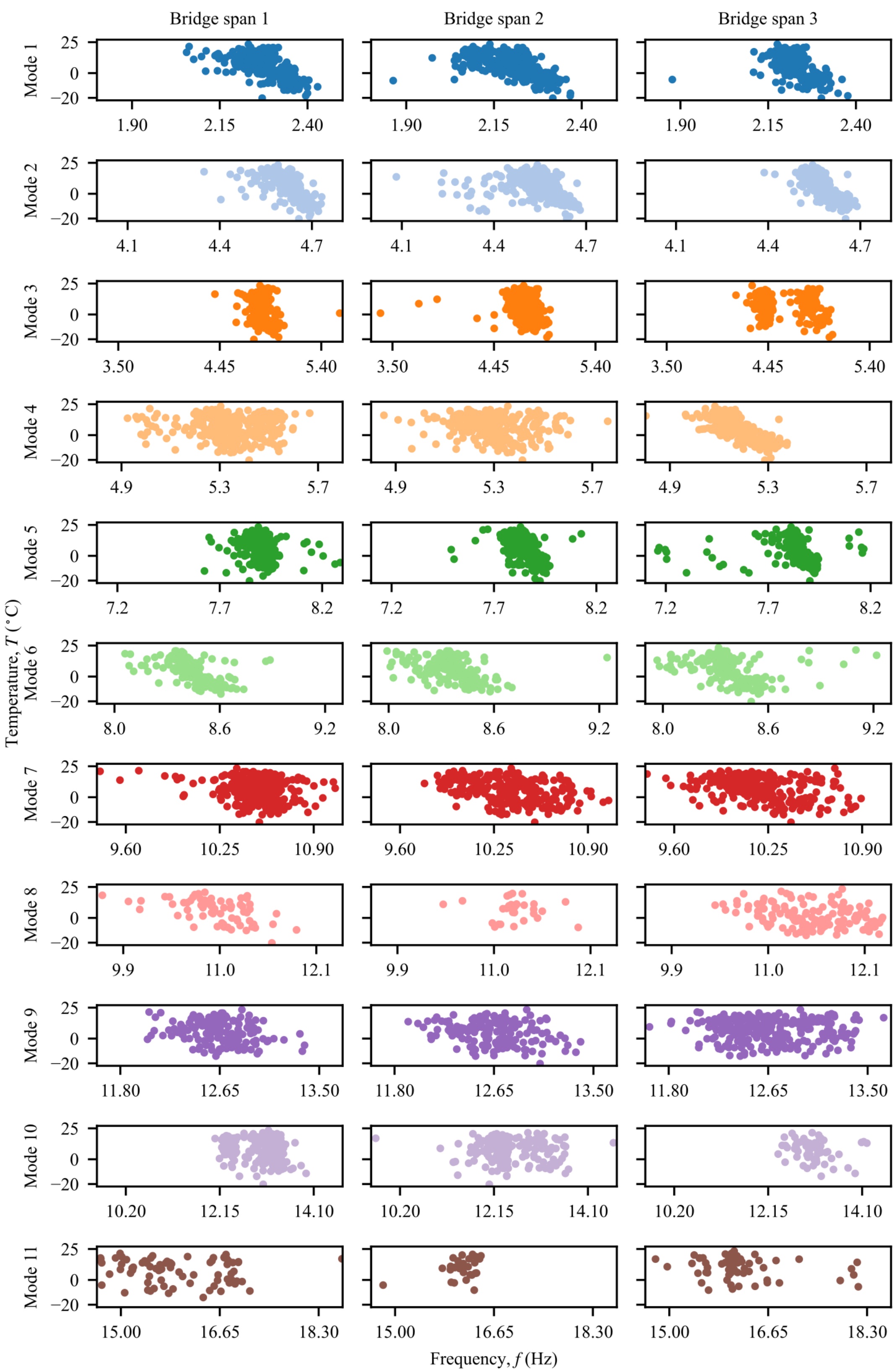

Fig. 9 Statistical distributions of the modal tracking results.

Table 2 Mean frequency values and standard deviation for all modes of bridge spans (BS) 1, 2 and 3

	Mean (Hz)			Standard deviation (Hz)		
Mode	BS1	BS2	BS3	BS1	BS2	BS3
1	2.273	2.199	2.224	0.058	0.076	0.044
2	4.621	4.542	4.576	0.053	0.080	0.040
3	4.842	4.729	4.672	0.074	0.137	0.228
4	5.334	5.302	5.163	0.129	0.125	0.077
5	7.899	7.848	7.827	0.074	0.063	0.116
6	8.442	8.351	8.380	0.127	0.142	0.157
7	10.497	10.361	10.206	0.192	0.244	0.255
8	10.964	11.239	11.507	0.399	0.285	0.449
9	12.643	12.656	12.660	0.240	0.287	0.367
10	13.021	12.502	13.093	0.391	0.598	0.394
11	15.992	16.107	16.180	0.800	0.292	0.676

Table 3 Detection rate and correlation with temperature for all modes of bridge spans (BS) 1, 2 and 3

	Detection rate* (%)			Correlation coefficient		
Mode	BS1	BS2	BS3	BS1	BS2	BS3
1	86.3	95.6	91.8	-0.55	-0.61	-0.48
2	75.3	90.1	91.8	-0.54	-0.24	-0.71
3	94.0	82.7	62.7	-0.21	-0.14	0.04
4	85.2	74.0	83.0	-0.09	-0.19	-0.71
5	72.3	93.4	90.7	-0.16	-0.46	-0.07
6	47.7	54.0	63.8	-0.55	-0.38	-0.29
7	79.2	71.8	76.7	-0.24	-0.37	-0.35
8	18.4	8.2	38.6	-0.49	-0.11	-0.32
9	45.2	43.3	75.6	-0.26	-0.25	-0.05
10	66.6	49.6	16.4	-0.10	-0.01	-0.18
11	21.6	8.2	17.5	-0.16	0.36	-0.23

* The detection rate is based on the total number of days throughout the defined period (365 days), including maintenance and downtime of the SHM system (7 days).

scatter, in the tracking of higher modes (modes 7-11) compared to lower modes (modes 1-6). This uncertainty can also be clearly seen from the standard deviations presented in Table 2. Furthermore, from Table 3, it is also observed that the mode detection rate is lower for the higher modes compared to the lower modes. It should be noted, however, that the mode detection rate depends, to a certain degree, on the quality of the identified modes in the reference analysis. Fourth, and lastly, a similar behaviour of the bridge spans is observed, indicating that all three bridge spans generally compare well.

The correlation coefficients between the tracked modes and the temperature are presented in Table 3. From the results presented in Table 3, it is observed that the correlation coefficients are consistently negative, with two exceptions. These results indicate that the natural frequencies increase when the temperature decreases. Increasing natural frequencies imply a stiffer structural behaviour. Consequently, the bridge spans become stiffer for lower temperatures.

The temperature effects and their subsequent influence on the bridge structural behaviour are important for structural integrity evaluations. Table 4 summarizes the details of the frequency values, whereas Table 5 summarizes the variations of the mean frequencies of all modes for each bridge span. By considering the total difference as presented in Table 5, i.e., the difference between the maximum and minimum values over the mean of the natural frequencies, variations of approximately 8-25%, 8-40% and 7-23% for bridge spans 1, 2 and 3, respectively, of the natural frequencies can be expected on a yearly (seasonal) basis.

It is important to highlight that these variations are not solely caused by temperature effects, since some of the outliers of the natural frequencies in terms of low minimum and high maximum values of each mode of each bridge span are found from datasets containing traffic, i.e., passing trains. An improved modal tracking can be obtained by filtering, i.e., replacing time series that contain traffic with time series that contain no traffic. Such a filtering may significantly improve the results in terms of lower variations of the natural frequencies considering only temperature effects. As such, the actual variability

Table 4 Details of frequency values for all modes of bridge spans 1, 2 and 3

	Bridge span 1			Bridge span 2			Bridge span 3		
Mode	Min (Hz)	Max (Hz)	Mean (Hz)	Min (Hz)	Max (Hz)	Mean (Hz)	Min (Hz)	Max (Hz)	Mean (Hz)
1	2.056	2.429	2.273	1.863	2.368	2.199	1.877	2.377	2.224
2	4.349	4.732	4.621	4.082	4.680	4.542	4.387	4.689	4.576
3	4.405	5.573	4.842	3.388	4.975	4.729	4.149	5.052	4.672
4	4.925	5.666	5.334	4.852	5.763	5.302	4.802	5.377	5.163
5	7.625	8.288	7.899	7.491	8.126	7.848	7.161	8.167	7.827
6	8.060	8.887	8.442	7.991	9.245	8.351	7.967	9.218	8.380
7	9.422	11.049	10.497	9.769	11.043	10.361	9.412	10.893	10.206
8	9.662	11.875	10.964	10.422	11.960	11.239	10.395	12.304	11.507
9	12.032	13.375	12.643	11.917	13.390	12.656	11.636	13.637	12.660
10	12.053	13.942	13.021	9.696	14.629	12.502	12.357	14.198	13.093
11	14.650	18.688	15.992	14.800	16.433	16.107	14.770	18.154	16.180

Table 5 Variations of the mean frequencies for all modes of bridge spans 1, 2 and 3

	Bridge span 1			Bridge span 2			Bridge span 3		
Mode	Min (%)	Max (%)	Total (%)	Min (%)	Max (%)	Total (%)	Min (%)	Max (%)	Total (%)
1	-9.6	6.9	16.4	-15.3	7.7	23.0	-15.6	6.9	22.5
2	-5.9	2.4	8.3	-10.1	3.1	13.2	-4.1	2.5	6.6
3	-9.0	15.1	24.1	-28.4	5.2	33.6	-11.2	8.1	19.3
4	-7.7	6.2	13.9	-8.5	8.7	17.2	-7.0	4.1	11.1
5	-3.5	4.9	8.4	-4.5	3.6	8.1	-8.5	4.3	12.8
6	-4.5	5.3	9.8	-4.3	10.7	15.0	-4.9	10.0	14.9
7	-10.2	5.3	15.5	-5.7	6.6	12.3	-7.8	6.7	14.5
8	-11.9	8.3	20.2	-7.3	6.4	13.7	-9.7	6.9	16.6
9	-4.8	5.8	10.6	-5.8	5.8	11.6	-8.1	7.7	15.8
10	-7.4	7.1	14.5	-22.4	17.0	39.5	-5.6	8.4	14.1
11	-8.4	16.9	25.3	-8.1	2.0	10.1	-8.7	12.2	20.9

caused by only temperature effects are somewhat lower than reported here. Nevertheless, the results indicate the expected yearly (seasonal) variability caused by operational and environmental variability for modal properties of such bridges.

Modal tracking allows, to a certain extent, to monitor the development, including potentially unwanted changes, in the modal properties within a defined time period. Here, modal tracking has provided an overview of the modal properties of each bridge span over time. From the results obtained, it is concluded that the bridge spans compare well to each other over time when considering the dynamic structural behaviour and performance. No changes in the structural integrity of the bridge occurred during the period. Consequently, the observations made are mainly caused by operational and environmental variability.

Gaussian mixture modelling

Understanding the temperature effects on the structural behaviour and bridge performance is crucial for structural integrity evaluations. A two-component GMM is implemented on the modal tracking data [21]. The GMM is implemented with the constraints of using only two mixture components with all components sharing the same general covariance matrix. In general, a GMM is a probabilistic model that works under the assumption that all data points in a data set are generated from a mixture of a finite number of Gaussian (normal) distributions, where each Gaussian distribution has a set of unknown parameters. As such, the assumption is based on the data points representing a finite number of subpopulations, or components (clusters), which are Gaussian. The expectation-maximization (EM) algorithm is commonly used for estimating the parameters of the mixture of Gaussian models. The statistical distributions obtained by the GMM of the modal tracking data are shown in Figure 10. The dashed horizontal line indicates the freezing point (0°C).

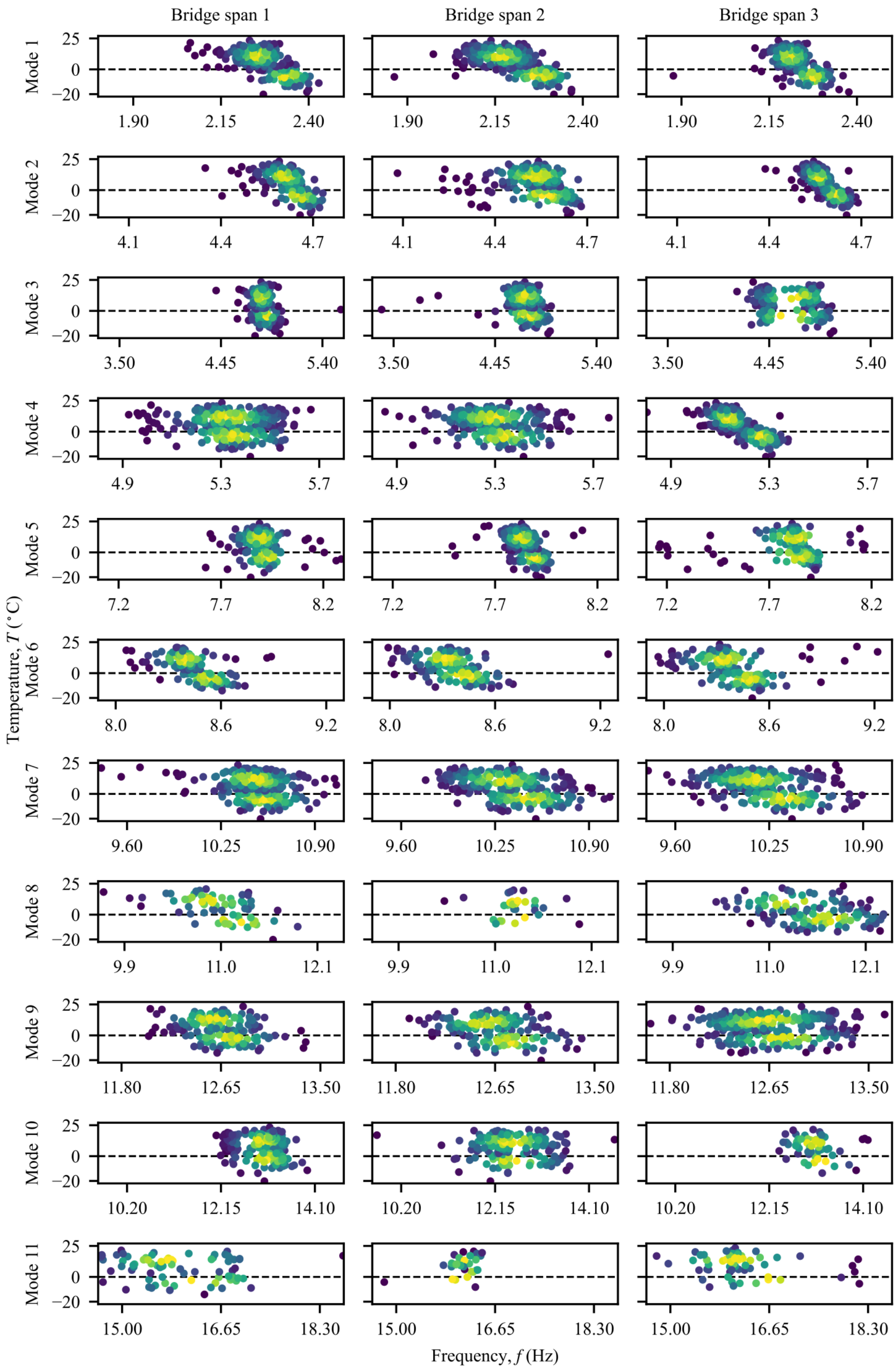

Fig. 10 Statistical distributions by GMM of the modal tracking results

From the results presented in Figure 10, it is clearly observed that the GMM separates the statistical distributions of the modal tracking data based on temperatures above and below the freezing point. This separation is consistent across all modes for all three bridge spans. The separation is less distinct for certain modes, such as modes 8 and 11, where the statistical representation is low. It is noteworthy, however, that despite the low detection rate for certain modes, the GMM still separates the data into two distributions based on the temperature, i.e., above and below the freezing point, under the predetermined constraints.

In the context of damage detection and SHM, the results obtained are important because they clearly show that the bridge has a distinct behaviour around the freezing point. The results clearly confirm a step-like variation in the natural frequencies of the bridge for many of the modes. Such a behaviour is explained by a contribution to the global stiffness of the structure, most likely from the timber sleepers in the bridge deck.

Summary and conclusion

This paper presented the structural integrity assessment of a train bridge using data obtained from a comprehensive SHM system. The structural integrity assessment focused on static inclination and the structural dynamic behavior over time for different temperatures, based on data obtained from one year of measurements. The effect of environmental conditions, i.e., the temperature, on the modal parameters of the bridge were investigated based on modal tracking and the implementation of a GMM on the modal tracking data. Lastly, the actual structural behavior was validated by comparing the performance of all three bridge spans and assessing the performance over time.

From the static structural assessment, it was shown that the effect of temperature is low. From the dynamic structural assessment, several important findings were established from the modal tracking. First, the correlation between temperature and natural frequencies showed that the bridge spans become consistently stiffer for lower temperatures. Second, significant variations in the natural frequencies can be expected on a yearly (seasonal) basis, typically in the range of 7-40%, of modes that excite the bridge globally. It should be noted, however, that this variation is caused by both operational and environmental variability and not only environmental variability, such as temperature effects. Third, through the implementation of the GMM on the modal tracking data, it was demonstrated that the bridge has a different behavior above the freezing point compared to below the freezing point. A step-like variation in the natural frequencies of the bridge was confirmed, most likely explained by a contribution to the global stiffness of the structure from the timber sleepers in the bridge deck for temperatures below the freezing point. Since the bridge has such a distinct behavior with respect to temperature, any damage detection and structural integrity evaluations, in the context of SHM, should be considered using separate data from above and below the freezing point.

In conclusion, the effects of operational and environmental variability, particularly the temperature effects and their subsequent influence on the structural behavior of the bridge, are important for structural integrity evaluations. Furthermore, it is concluded that the results presented represent the level of variation to be expected for similar steel truss bridges in typical Nordic and Scandinavian climates.

It is important to highlight that, since no known changes in the structural integrity of the bridge occurred during the period, the results obtained are attributed to variability in the operational and environmental conditions. Furthermore, the datasets used as a basis for the structural integrity assessments of static inclination and the structural dynamic behavior had no restrictions regarding operational variability, such as traffic in terms of train passings. Consequently, although the main source of variability in the results presented is mostly believed to be caused by the effect of environmental conditions, i.e., the temperature, some variability may also be attributed to operational conditions, i.e., train passings, particularly for the modal tracking results. The potential variability caused by operational conditions is believed, however, to be low compared to the variability caused by the environmental conditions, such as the temperature effects.

The main limitations of this study include (1) the low, or limited, statistical representation of the data, and (2) the consideration of both operational and environmental variability in the assessment. For the latter, operational variability should be excluded to establish only the environmental variability in terms of the temperature effect, since the temperature effect is the most influential source of variability in modal properties. Further work includes addressing the limitations and evaluating the basic statistics of the GMM for each component of each mode for all bridge spans.

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