Product Research and Development

Smartphone Application for Structural Health Monitoring of Stay Cables

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Abstract: App4SHM is a mobile system for structural health monitoring (SHM) of bridges that aims to support routine inspections. It consists of a front-end smartphone application that is used to measure natural frequencies of vibration and to detect damage supported by a backstage server software, accessible through any internet browser. This paper focuses on the new module for stay cables, which directly converts natural frequencies into cable tension forces based on the cable's material and geometrical characteristics. The conversion uses an estimate of the forces from the taut-string theory. Regardless of the module, App4SHM works in two modes. The training mode is used to collect observations composed of natural frequencies under normal operational and environmental conditions. The observations are used to train an unsupervised machine learning algorithm to learn the structure's normal behavior. The damage detection mode collects unlabeled observations, which are tested against normal behavior to detect abnormal performance that may be indicative of damage or excessive tension. The Edgar Cardoso Bridge — a large cable-stayed bridge in Portugal, undergoing rehabilitation and stay cables replacement — is used as a case study for the measurement of cable tension forces.

1 Introduction

Since the early 1990s, structural health monitoring (SHM) has been proposed to support the bridge owners to find optimal life-cycle management, and ultimately to avoid structural failures, based on a damage identification strategy, which includes the detection, diagnosis, and prognosis of damage.

The combination of low-probability, high-impact risks of bridge failures has made SHM technology appealing to the scientific community. However, the full-field implementation of SHM has been challenged [1]. To overcome those challenges, researchers have collaborated with the bridge industry to identify applications where monitoring can have an impact, leveraging experience gained in bridge engineering through traditional periodic inspections – the routine inspections.

Since the collection and analysis of monitoring data remain highly specialized tasks, over the last decade, the rapid digital transformation of bridge management has fostered a diverse ecosystem of mobile applications and cloud platforms for SHM [2], as shown in Section 2.

Smartphones have been proposed as a pocket solution to make the SHM process more user-friendly. In 2022, the App4SHM was proposed as a smartphone-based application for long-term damage detection under ambient vibration conditions, leveraging the built-in accelerometer and a remote server [3]. The first Android version was tested on data sets from a laboratory steel beam and twin post-tensioned concrete bridges to demonstrate its sensing and damage-detection capabilities. In

both cases, the natural frequencies obtained from the application were compared with those estimated from data sets collected with a conventional data acquisition (DAQ) system [3].

As a step forward, this paper describes a new version of the App4SHM running in Android and iOS, and shows the basis of a new module for long-term damage detection in cables of cable-stayed bridges under ambient vibration conditions, making use of the built-in accelerometer and remote server.

In the field demonstration, the application is first tested to estimate the natural frequencies of the Edgar Cardoso Bridge deck and then on one of the longest cables supporting the bridge deck.

The manuscript is organized as follows. Section 2 discusses existing mobile-based solutions for SHM and presents the new version of the App4SHM as an SHM solution to support routine inspection for long-term damage detection in cables. Section 3 describes the Edgar Cardoso Bridge as a bridge case study under rehabilitation works along with its monitoring plans. Section 4 tests the applicability of the App4SHM for estimation of cable forces and compares the results to traditional DAQ systems in the context of long-term damage detection. Finally, Section 5 provides conclusions and recommendations based on the findings of this paper.

2   Smartphone-Based SHM of Bridges

2.1   Background

Existing smartphone-based SHM solutions can be broadly grouped into five partially overlapping categories [2]: (i) smartphone-based SHM applications, in which the mobile device itself acts as the primary vibration or imaging sensor; (ii) cloud- and IoT-based SHM platforms that integrate networks of dedicated sensors with web or mobile dashboards [4]; (iii) industrial SHM suites that provide turnkey "from sensor to cloud" solutions, often coupled with weigh-in-motion (WIM) systems [5]; (iv) bridge inspection apps that digitize visual inspections through checklists, photos, and georeferenced reports [6]; and (v) augmented-reality (AR) and image-based digital image correlation (DIC) systems where cameras on smartphones, tablets, or mixed-reality headsets are used to visualize or infer structural responses [7].

Recent reviews show that smartphones now appear across all these categories as sensors, edge devices, user interfaces or AR viewers, yet they also highlight fragmented workflows, dependence on dedicated hardware for long-term deployments, and a lack of bridge-owner-oriented tools specifically tailored to prestressed components such as stay cables [2,3,8]. Table 1 summarizes smartphone-based SHM configurations for bridges and their main limitations.

Within this broader landscape, Matarazzo et al. [9] exploited smartphone accelerometers carried inside vehicles crossing bridges to develop a drive-by and crowdsensing-based SHM paradigm, showing through numerical simulations, laboratory tests, and field deployments that large streams of smartphone data can be mined to extract bridge modal properties and track changes in global stiffness. Duan et al. [10] proposed a related smartphone-based, data-driven framework in which fundamental frequencies of in-service highway bridges, estimated from smartphone measurements, are coupled with survival-analysis models to predict the superstructure state condition and assist network-level maintenance planning. These studies clearly demonstrate that smartphones can support network-level SHM of road and highway bridges, but they also reveal important structural and operational limitations for the present application: measurements depend on uncontrolled traffic excitation and heterogeneous vehicle populations, the focus is on the global deck behavior of bridges rather than on individual prestressed members, and the

processing pipelines require substantial data volumes and expert post-processing, making them difficult to adopt as targeted tools for routinely stay-cable force assessment on specific cable-stayed bridges.

Table 1 Summary of smartphone-based SHM configurations for bridges and their main limitations

System type	Mechanism	Key limitations for bridge	Ref.
Phone fixed on deck (stationary)	Smartphones rigidly attached on the deck of a pedestrian bridge; ambient vibrations recorded by on-board accelerometers and processed via operational modal analysis (OMA) to extract the first natural frequency and compare with reference accelerometers.	Accurate mainly for the first mode under sufficient excitation; higher modes are difficult to identify due to low signal-to-noise; tests usually on a single footbridge; no damage indices, no cable-force estimation, no integration with owner workflows.	[8,11]
Phone on micromobility (scooter / bike)	Smartphones mounted on e-scooters or other micromobility devices crossing a footbridge; vertical accelerations converted into time–frequency maps and used together with deep-learning classifiers or OMA to detect and classify bridge damage or to estimate fundamental frequencies.	Indirect, vehicle–bridge interaction dominated; results are sensitive to speed, trajectory and riding style; mainly demonstrated on one or few footbridges; focused on damage classification rather than providing actionable cable-force or system-level SHM indicators for owners.	[11,12]
Phone in vehicles (drive-by / crowdsensing)	Smartphones carried in ordinary vehicles crossing highway or urban bridges; acceleration and GPS streams aggregated over many trips to identify modal frequencies and track changes over time in a crowdsensing framework.	Requires large data volumes and careful cleaning; strongly affected by vehicle type, suspension, road roughness and mounting position; mostly provides global deck-level indicators; current implementations are research-grade and do not output cable tensions or element-level condition metrics.	[9,13,14]
Phone-based campaigns on highway bridges	Smartphones used in planned, campaign-type measurements on in-service highway bridges; identified fundamental frequencies combined with survival-analysis / data-driven models to predict superstructure condition states at the network level.	Focus on overall superstructure ratings, not specific components; requires historical inspection databases and statistical expertise; sensing is intermittent (campaign-based) rather than continuous; no direct module for stay-cable force estimation or cable-specific diagnostics.	[10]
Phone fixed on deck	Acceleration-based crowdsensing	Small-scale case studies; limited guidance on standardized procedures, QA / QC and thresholds; whiteout an end-to-end workflow that bridge owners can adopt directly for stay-cable force monitoring or routine SHM at network scale.	[8]

Another category of smartphone-based solutions leverages the camera and graphics capabilities of mobile devices rather than the accelerometer. In this category, Awadallah et al. [15] developed an augmented-reality-based smart SHM system in which smartphones or mixed-reality headsets are used as non-contact sensors and AR viewers to overlay SHM data and numerical models on full-scale bridge demonstrators and other civil structures, integrating BIM models, video streams, and

wireless sensor data with 4G/5G connectivity for real-time visualization. Other authors have explored smartphone cameras as low-cost DIC sensors for measuring displacements and strains on bridge components [16,17]. While these systems are promising for enhancing situational awareness and supporting communication between stakeholders during bridge inspections, they primarily address visualization and qualitative condition assessment of bridges [18]; they do not provide a direct, field-practical procedure for estimating stay-cable forces, they often rely on controlled lighting and camera positioning, and they remain predominantly at the proof-of-concept stage in bridge applications [19].

Synthesizing the above, the comprehensive reviews by Ozer and Kromanis [8] and by Sarmadi et al. [20] on smartphone sensing for SHM emphasize that, despite rapid progress in bridge-related case studies, most smartphone-based solutions still take the form of fragmented prototypes rather than owner-oriented products for bridge management.

Common limitations identified across the bridge literature include: (i) dependence on manual configuration and expert interpretation of spectra or images, with limited support for non-specialist bridge inspectors; (ii) a predominant focus on global deck behavior or generic damage indices, with no explicit integration of prestressed components such as stay cables into the monitoring workflow; (iii) weak coupling between one-off smartphone measurements on bridges and long-term SHM or cable-inspection plans, with scarce guidance on thresholds, re-measurement intervals or decision rules; and (iv) inherent constraints of smartphone sensors themselves, such as limited sensitivity and irregular sampling at low vibration amplitudes, which complicate the identification of higher-order bridge modes and subtle stiffness changes [3,21,22].

Overall, the existing literature confirms that smartphones are mature enough to support vibration- and vision-based SHM of bridges, but also reveals a clear gap in dedicated, cable-oriented smartphone tools that deliver an integrated workflow—from data acquisition and stay-cable force estimation to statistical damage detection and database management—aligned with the practical needs of cable-stayed bridge owners in the context of routine inspections.

2.2 App4SHM – A New SHM Solution for Stay Cables

App4SHM is a smartphone application designed for SHM of bridges and other flexible civil engineering structures. The application interrogates the internal accelerometer to measure structural vibrations, extracts dynamic characteristics (natural frequencies) over time, and performs damage detection automatically using a machine learning algorithm. With the new module, these quantities are subsequently used for cable force estimation and structural condition assessment.

2.2.1 Advantages and Drawbacks

The use of App4SHM offers several practical advantages over traditional monitoring systems based on dedicated sensors and mobile data acquisition units.

The first advantage is cost efficiency. Modern smartphones incorporate accelerometers, storage, and wireless communication, enabling vibration measurements without specialized equipment. This makes the App4SHM particularly attractive to bridge owners and infrastructure managers who require rapid and inexpensive assessments.

A second advantage is the integration of sensing, processing, data logging, and visualization within a single device. The smartphone accelerometer is used to acquire vibration data, while App4SHM performs signal processing and visualization directly on the device. Results are immediately available to the user, and the measurements can be automatically transmitted and stored in a centralized database for further analysis.

A third advantage is the ease of use in field conditions. The application was designed with a simple graphical interface, so that field engineers and bridge inspectors can perform measurements without requiring specialized training in vibration analysis or signal processing.

Despite these advantages, some limitations must be acknowledged. First, the accelerometers embedded in smartphones are less sensitive than professional accelerometers, which may reduce measurement accuracy under very low vibration amplitudes. Second, the sampling frequency of smartphone accelerometers may be irregular, depending on the operating system and hardware constraints. In App4SHM, this issue is mitigated through software-based interpolation and resampling techniques applied during signal processing. Finally, the maximum reliable sampling frequency of typical smartphone accelerometers is around 50 Hz, which limits the highest recoverable vibration frequency to approximately 25 Hz according to the Nyquist criterion. However, this range is typically sufficient for the vibration frequencies of stay cables in cable-stayed bridges, which usually fall well below this threshold.

2.2.2 Software Architecture and Details

App4SHM's software architecture is composed of two main components: a mobile application and a remote, back-office, computational platform.

The mobile application is developed in Flutter, allowing compatibility with both Android and iOS devices. The application performs the acquisition of acceleration signals, signal processing, visualization of the results, and interaction with the user through an intuitive graphical interface. Smartphones running Android 5 or later or iOS 11 or later are supported.

On the smartphone, the operational workflow of App4SHM follows a sequence of steps implemented through the application interface. The respective interfaces are presented in Figure 1 and briefly explained as follows:

- Structure identification (Figure 1a). The user selects the structure to be monitored from a structural database. New structures can be defined through the web administration interface, where relevant structural properties such as cable length and mass per unit length can also be stored.
- Data acquisition (Figure 1b). The smartphone is attached to the structure, typically with its screen parallel to the cable axis, and the internal accelerometer records an acceleration time series in the direction orthogonal to the screen. The duration of the acquisition can be controlled by the user. Conversely, the acquisition frequency is set at 50 Hz because of the limitations of the in-built accelerometer.
- Feature extraction (Figure 1c). The recorded acceleration signal is sent to the back-office server and processed to construct the power spectral density (PSD) of the signal. The standard Welch method is used. The peaks corresponding to the first three natural frequencies are identified by the user and provisionally listed in an interface table, along with the average of the historical readings of each frequency and the difference between the currently registered frequencies and their average values. Zoom and snap capabilities are implemented to support precision reading. The selected frequencies are stored as a feature vector representing the new observation of the reference data set.
- Cable force estimation and reporting (Figure 1d). In the cable module, the identified natural frequencies are converted into cable tension forces using the taut-string theory. The forces obtained from the first three vibration modes are listed on screen and averaged to obtain a robust estimate of the cable tension. A probability density function of the estimated cable forces is constructed and displayed in the mobile interface together with the force estimate from the

current observation. For instance, for the case presented in Figure 1d, the current observation follows a large load increment applied to the cable. This causes the observation of the monitored cable to fall considerably below the bulk of the observations, leading to large values of the cable tension force.

- Damage detection (Figure 1e). In a broader SHM framework, every new observation can be compared against a reference data set representing the undamaged condition of the structure. A machine learning algorithm based on the Mahalanobis squared distance is trained. A damage indicator is computed using the Mahalanobis squared distance between the current observation and the baseline distribution defined upon the reference data set of observations. The resulting indicator is displayed graphically alongside the reference data to assess whether the structural state remains within the expected range. For illustration purposes, in the case shown in Figure 1e, the damage indicator is well above the threshold due to an abnormal operational and environmental condition. It is therefore highlighted with a red dot, and a damage indication message is given. This example is important to highlight that the Mahalanobis squared distance does *not* actually detect damage, but structural state conditions that are statistically different from the ones measured in the past (outliers). Such outliers may or may not be indicative of structural damage – proper engineering interpretation is fundamental.
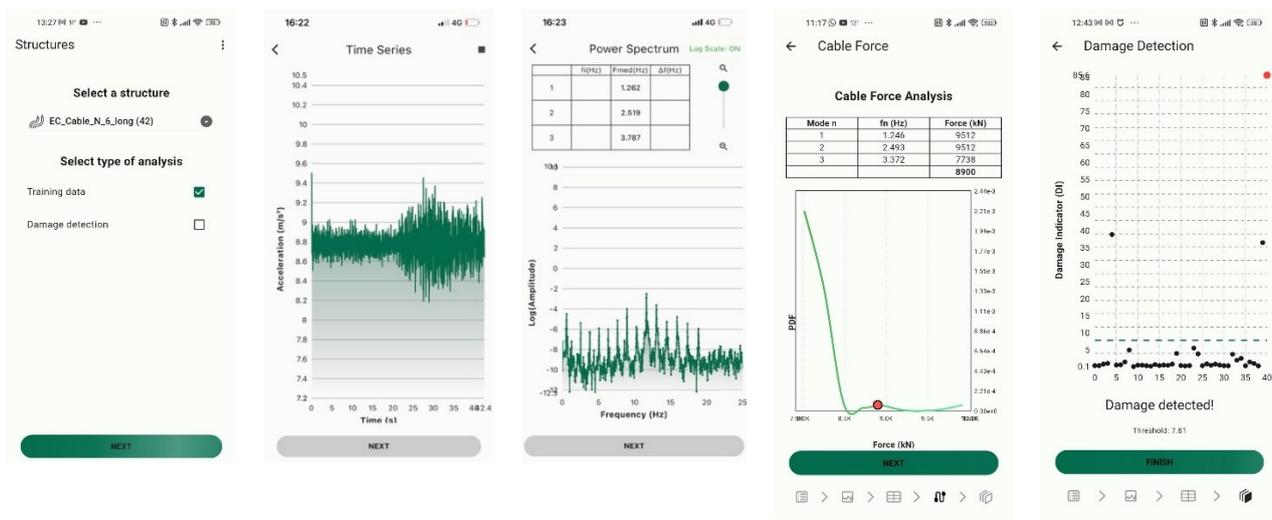
| a) Structure selection | b) Measurement of an acceleration time series | c) Power spectrum with average values of the natural frequencies | d) Cable force analysis and probability distribution function | e) Damage detection result |

Figure 1 Interfaces of the App4SHM during acquisition

The remote computational platform for structure creation, data access, and administration is implemented using the Python/Django framework and is hosted on a remote server. This platform (see Figure 2) manages the database of structures, stores the collected measurements, and provides a web-based administration interface protected by user authentication mechanisms. The backend also enables the retrieval and export of measurement data for further processing, and allows authorized users to review and change frequency readings, computed cable forces, and historical measurements for each monitored structure or cable.

All raw acceleration signals, extracted frequencies, and computed cable forces are automatically stored in a MySQL database hosted on the remote server. These data can later be accessed through the web administration interface and exported in spreadsheet format for further analysis.
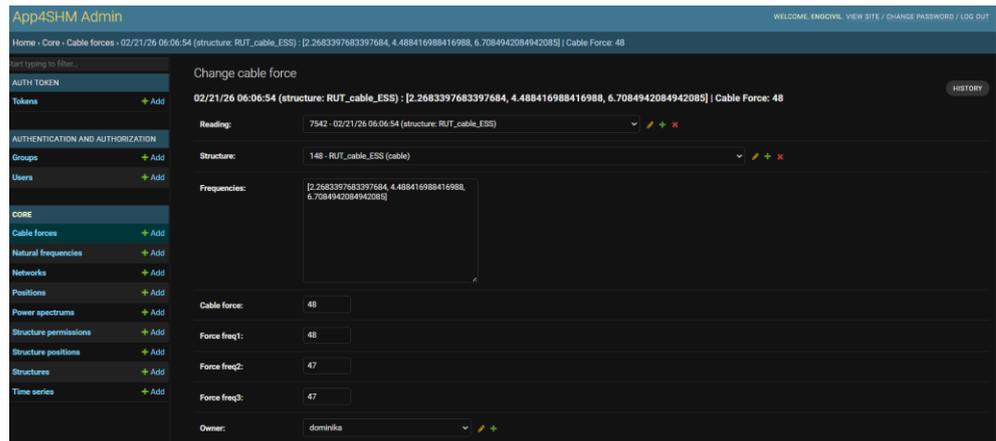
Figure 2   App4SHM's back-office platform

3   Edgar Cardoso Bridge and Monitoring Plan

3.1   Structural Description

The Edgar Cardoso Bridge (Figure 3) over the Mondego River was the first cable-stayed bridge in Portugal, opening to traffic in 1982. It was designed by one of the most famous Portuguese bridge designers, Edgar Cardoso. The bridge has two lateral spans, 90 m long, and a central span of 225 m. Its steel-concrete deck is supported by two towers, two transition piers, and six pairs of cables that diverge from the top of the towers and connect to the deck at intervals of 30 m. Table 2 summarizes the physical and mechanical properties of the medium and long stay cables of the bridge [23].

The historical importance and distinctive design, in the context of Portuguese structural engineering, justify concerns about its preservation and operational maintenance, as evidenced by the various interventions to which the bridge has been subjected over the last 20 years. Of note are the rehabilitation studies conducted between 1998 and 2001, which culminated in the rehabilitation completed in 2006, and the additional intervention on the towers' foundations carried out in 2013 [24].

Figure 3   Edgar Cardoso Bridge

Table 2   Physical and mechanical properties of medium and long stay cables

Cable	Length /m	Number of wires (5 mm)	Cross section /cm²	Mass (kg/m)	Cover mass estimation (kg/m)	Total mass (kg/m)
M-S	75.00	540	106.03	83.2	8.2	91.4
L-S	100.62	900	176.72	138.7	9.4	148.1

3.2   Periodic Inspections and Need for Maintenance

As a result of the periodic inspections to which the bridge has been subjected over the past 20 years, an increasing number of loose and broken tie wires have been

noted in areas near the anchorages on the deck. Although these deficiencies still affect only a relatively small number of wires in each cable, this situation will tend to worsen over time, potentially putting operational safety at risk.

The solution adopted in the original project, given the knowledge and existing technology at the time, led to certain areas of the cables being highly exposed to aggressive environments, particularly dust and water, triggering accelerated corrosion. Moreover, the type of anchorages used, unlike those currently used, does not allow the repair or replacement of the anchorages or the wires, requiring the complete replacement of the stay system.

This circumstance dictated the decision made by the bridge owner – Infraestruturas de Portugal (IP) – to completely replace the cables. This will provide the bridge with increased safety and facilitate both maintenance and future repairs to the stay system.

3.3 Monitoring Plan

Figure 4 represents the structural measurement points at the central span on the east side (upstream), namely on cables M-S and L-S as well as on the deck.

The installation conditions of the smartphone on the structure play a critical role in the quality and reliability of the measured signals. Figure 5 illustrates the smartphone's position on one of the cables during the acquisition of acceleration time series and natural vibration frequencies. Tape was used as a practical and low-cost means of installation in field conditions to ensure a rigid connection between the device and the structural surface.
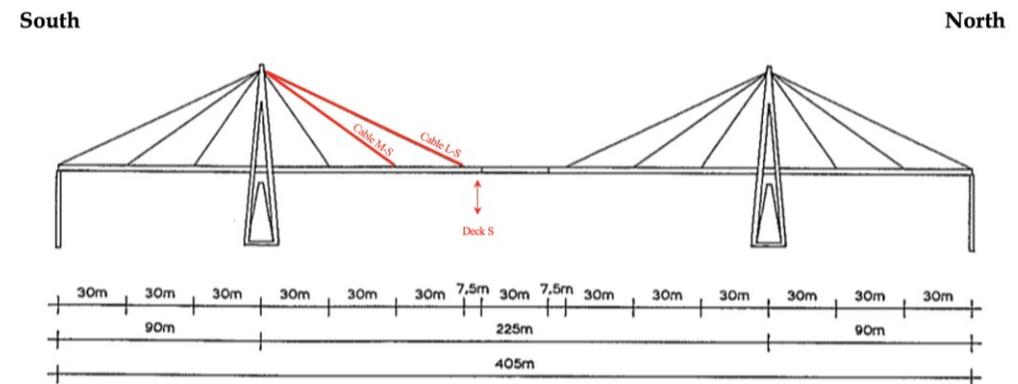

Figure 4 Location of frequency measurements on the Edgar Cardoso Bridge
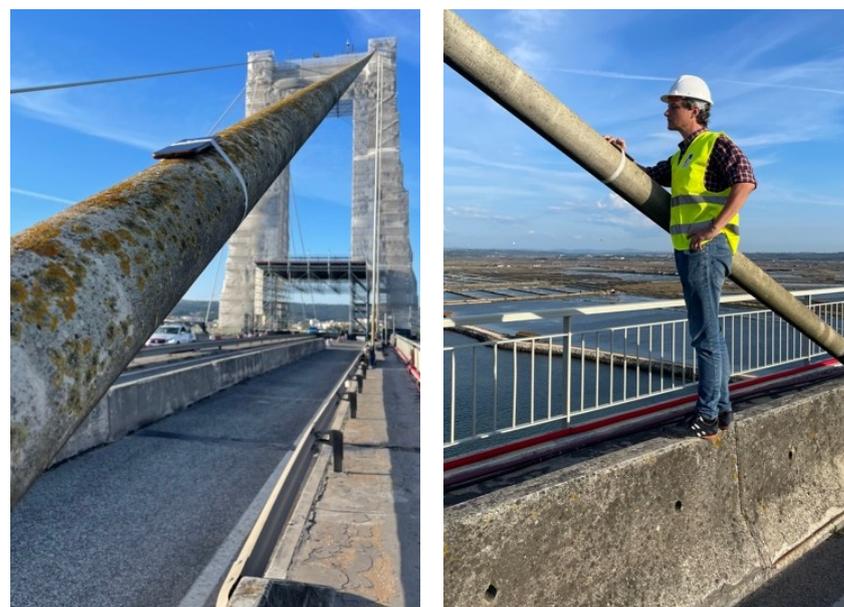

Figure 5 Smartphone running App4SHM attached to one of the cables of the Edgar Cardoso Bridge

Each observation is defined by a set of the first three natural frequencies of the cable obtained at a given instant. Figure 1 illustrates several app interfaces for acquiring acceleration time series and estimating natural frequencies to create the reference database of observations. The natural frequencies of the cables are estimated using the peak-picking method based on prior knowledge.

4   Analysis and Discussion of Results

4.1   Bridge Deck

Table 3 summarizes the natural frequencies of the bridge deck, estimated in three different periods (1997, 13-Sep-2023, and 22-Jan-2024), and the differences recorded between consecutive periods. Significant reductions of the natural frequencies of vibration are observed from 1997 to 13-Sep-2023 (e.g., -4.5% for f_1). This change may be associated with the result of added mass on the bridge deck caused by the installation of temporary Jersey barriers used to separate traffic lanes during the cable-replacement intervention. The additional frequency reductions observed between 13-Sep-2023 and 22-Jan-2024 are also due to a mass addition: two under-bridge inspection platforms.

Table 3   Estimation of the first three natural frequencies of the bridge deck

Mode n	1997 Traditional DAQ (Reference)	13-Sep-2023 App4SHM		22-Jan-2024 App4SHM	
	f_n (Hz)	f_n (Hz)	Δf_n	f_n (Hz)	Δf_n
1	0.510	0.487	-4.5%	0.482	-1.0%
2	0.600	0.568	-5.3%	0.562	-1.1%
3	0.730	0.712	-2.5%	0.696	-2.2%

4.2   Cables

Cable-tension assessment is essential for cable-stayed bridges during construction and/or for SHM. Methods of cable tension estimation can be generally divided into two groups, direct and indirect [25]. Direct methods focus on measuring the cable force itself, while indirect methods estimate the force from other quantities, such as the vibration method. The vibration method is widely used for this purpose due to its simplicity and accuracy. An estimation of the cable force is given by the taut-string theory:

$$F = 4mL^2 \left(\frac{f_n}{n}\right)^2 \tag{1}$$

where:

m = mass (kg/m)

L = cable length (m)

f_n = natural frequency associated with mode n

F = tension force (N)

This formula has limitations for long cables, so it does not account for cable sag or bending stiffness. To increase the experimental accuracy, the cable force can be estimated through the means of n frequencies:

$$F = 4mL^2 \left(\frac{1}{k}\sum_{n=1}^{k}\frac{f_n}{n}\right)^2 \tag{2}$$

Table and Table summarize the first three natural frequencies and estimation of the forces in cables M-S and L-S, respectively, in 2021; September 13, 2023; and January 22, 2024. On average, a significant increase of 5.5% of the cable forces is observed in 13-Sep-2023, compared to 2021, which validates the results observed previously at the bridge deck.

As the cable tension estimation uses the taut-string theory, which neglects cable sag, bending stiffness, and boundary conditions, the observed consistency between medium and long cables suggests an unbiased force.

Note that the discrepancy in the force increase from 13-Sep-2023 to 22-Jan-2024 for the medium and long cables (5.5% and 1.7%, respectively) may be related to the non-linear redistribution of forces caused by moving local loads, such as the under-bridge inspection platforms.

Finally, although the paper mentions smartphone limitations (sensor sensitivity and sampling frequency), the measurement uncertainty was not quantified. Despite the limited sensitivity of the accelerometers embedded in smartphones, this study shows that the frequency content of the accelerograms obtained with the App4SHM is consistent with that produced by professional accelerometers. However, frequencies above 25 Hz cannot be reliably recovered due to the limited sampling frequency of smartphones' accelerometers (<50 Hz in this case).

Table 4 Natural frequencies and force estimations for cable M-S

Mode n	2021, Traditional DAQ		13-Sep-2023, App4SHM				22-Jan-2024, App4SHM			
	f_n (Hz)	Force (kN)	f_n (Hz)	Δf_n	Force (kN)	ΔF	f_n (Hz)	Δf_n	Force (kN)	ΔF
1	1.581	5,140	1.619	2.4%	5,390	4.9%	1.663	5.2%	5,687	5.5%
2	3.150	5,101	3.243	3.0%	5,407	6.0%	3.330	5.7%	5,701	5.4%
3	4.744	5,143	4.874	2.7%	5,428	5.6%	5.005	5.5%	5,724	5.4%
		5,128			**5,409**	**5.5%**			**5,704**	**5.5%**

Table 5 Natural frequencies and force estimations for cable L-S

Mode n	2021 Traditional DAQ		13-Sep-2023 App4SHM				22-Jan-2024 App4SHM			
	f_n (Hz)	Force (kN)	f_n (Hz)	Δf_n	Force (kN)	ΔF	f_n (Hz)	Δf_n	Force (kN)	ΔF
1	1.256	9,462	1.292	2.9%	10,012	5.8%	1.302	3.7%	10,167	1.6%
2	2.513	9,469	2.580	2.7%	9,981	5.4%	2.606	3.7%	10,183	2.0%
3	3.781	9,527	3.880	2.6%	10,032	5.3%	3.909	3.4%	10,183	1.5%
		9,486			**10,008**	**5.5%**			**10,178**	**1.7%**

5 Conclusions and Future Developments

This study presented App4SHM as an innovative, practical smartphone-based system designed to support SHM of bridges during routine inspections. The

application integrates a bridge database, vibration measurement, frequency identification, cable-force estimation, and statistical anomaly detection into a single mobile platform, providing a low-cost, practical tool for bridge engineering. Overall, the results suggest that smartphone-based sensing can provide a practical, scalable approach to extending SHM capabilities for routine bridge inspections, thereby supporting more data-informed decisions in bridge management.

The App4SHM was validated using data sets from the Edgar Cardoso Bridge, including measurements of the bridge deck and cable stays. As a novelty, the results have highlighted the usefulness of the app for estimating forces in stay cables for long-term damage detection.

The comparison between measurements obtained with App4SHM and historical data collected with professional DAQ systems indicates that the natural frequencies, identified using the smartphone accelerometer, are consistent with those obtained from conventional monitoring equipment.

The observed variations in natural frequencies and cable forces are consistent with temporary mass changes on the bridge deck during the rehabilitation works, including the installation of Jersey barriers and inspection platforms. The results from the bridge deck show a significant reduction of the natural frequencies from 1997 to 2023 (e.g., a reduction of 4.5% was observed in the first natural frequency because of added mass on the bridge deck caused by the installation of temporary Jersey barriers, employed to separate the traffic lanes during the ongoing rehabilitation works). These results demonstrate that smartphone-based measurements are sufficiently sensitive to capture operational changes in bridge structural behavior.

Regarding the results from both medium and long cable forces, compared to 2021, an increase of 5.5% was observed in September 2023. The increase in change from 13-Sep-2023 to 22-Jan-2024 for the medium and long cables (5.5% and 1.7%, respectively) may be related to the non-linear redistribution of forces caused by moving local loads, such as under-bridge inspection platforms.

As this paper focused primarily on the use of the App4SHM to estimate stay-cable forces, future work should demonstrate the app's use for detecting damage in stay cables over time by comparing the current state with a reference state.

To overcome some of the scientific limitations of this study, future work should also consider the following: (i) herein, the app's validation relied essentially on a single case study and compared results with only a few historical measurements; the robustness of the app across different bridge types, cable lengths, boundary conditions, or environmental conditions must be demonstrated in future publications; (ii) the frequencies were identified by the user through peak picking, which introduces user subjectivity and reduces reproducibility; to overcome it, implementing automated peak detection or operational modal analysis algorithms should be pursued.

In the long term, integrating automated modal identification, improved uncertainty quantification, and multi-bridge validation campaigns will be essential steps toward transforming smartphone-based sensing from experimental demonstrations into reliable tools for bridge management and SHM.

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