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SHM approach for cable-stayed bridges based on stay load cell measurements

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ABSTRACT: This study proposes a novel methodology for monitoring cable-stayed bridges by using measurements of load cells installed on bridge stays to capture both static and dynamic responses of the structure. The reconstruction of mode shapes based on force measurements aims to reduce the number of sensors while maintaining full diagnostic capabilities. In this work, the differences between force-based and displacement-based modal profiles have been investigated with a parametric analysis highlighting differences between force and displacement mode shapes across various bridge configurations, providing reference guidelines for harp and fan layouts. Moreover, to optimize both the number and position of instrumented stays, an advanced sensor placement strategy is introduced. The full methodology is validated on a real cable-stayed bridge in central Italy, supported by experimental tests and finite element modelling. Results demonstrate that this load-cell-based monitoring framework offers a comprehensive solution for structural health assessment of cable-stayed bridges with a limited number and typology of sensors.

1 INTRODUCTION

Cable-stayed bridges are widely used for medium and long-span crossings due to their efficiency and aesthetic appeal, but their complex structural behaviour requires continuous monitoring, particularly of stay cables, which play a key role in load transfer and global stability (Li et al, 2021; Zhou et al, 2017). Cable tension monitoring is traditionally performed using load cells operating at low sampling rates for quasi-static applications, while dynamic identification of global bridge behaviour is commonly based on high-frequency vibration measurements acquired with accelerometers (Machelski et al, 2025).

This study investigates the use of high-frequency load cell measurements installed on stay cables near the deck connection for combined static and dynamic Structural Health Monitoring (SHM). Dynamically sampled force data are exploited for Operational Modal Analysis (OMA), allowing the identification of modal force profiles and, when required, the reconstruction of displacement-based mode shapes. The conditions under which force-based and displacement-based mode shapes differ are analysed through a parametric study on cable-stayed bridge configurations.

In addition, the paper addresses the problem of Optimal Sensor Placement (OSP) for cable-stayed bridges, proposing a strategy that integrates both static and dynamic information to reduce the number of monitored stays while preserving monitoring effectiveness. The proposed methodology is validated through numerical analyses and application to a real cable-stayed bridge, demonstrating its potential for efficient and cost-effective SHM.

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2 DISPLACEMENT-BASED RECONSTRUCTION OF MODE SHAPES USING LOAD CELL MEASUREMENTS

When bridge responses are measured in terms of deck accelerations or velocities, OMA provides mode shapes proportional to displacements. Conversely, when forces are measured, the identified quantities are modal force profiles. These profiles are proportional to displacement mode shapes only if the stiffness activated by deck displacements is uniform along the bridge; otherwise, significant discrepancies may arise and displacement mode shapes must be properly reconstructed. Moreover, the flexural dynamics of the stays can affect force measurements, which should therefore be taken as close as possible to the stay-deck connections. Reconstructing displacement mode shapes from load cell data allows physical interpretation of the experimentally identified modes, consistent comparison with numerical modal analyses, support for model updating procedures, and the development of damage localization techniques.

The modal force profiles can be converted into modal displacement shapes by computing the dynamic compliance matrix $\mathbf{D}(\omega)$ of the structure at the identified resonant frequencies (Quarchioni et al, 2025). The compliance matrix can be evaluated either experimentally, through forced vibration tests, or numerically, by means of a calibrated Finite Element (FE) model. In the experimental approach, a shaker applies harmonic forces to the deck at frequencies corresponding to the resonant ones and is positioned at one of the monitored stays. By measuring the responses at all monitored stay locations, standard identification procedures can be used to estimate the compliance matrix associated with the monitored Degrees of Freedom (DOFs). Alternatively, when $\mathbf{D}(\omega)$ is obtained numerically, the FE model must accurately represent the actual structural behaviour. The dynamic compliance matrix is computed in the frequency domain by performing multiple steady-state analyses on the calibrated model. Unit-amplitude forces are sequentially applied at the deck-stay connection nodes of the monitored stays, along the global reference system directions. The resulting displacements are numerically evaluated at all monitored stays in the same directions. By collecting the numerical displacements in the vector $\mathbf{U}(\omega)$ and the applied forces in the vector $\mathbf{F}(\omega)$, both referred to the global reference system, the following equilibrium relation holds:

$$\mathbf{U}(\omega) = \mathbf{D}(\omega)\mathbf{F}(\omega) \tag{1}$$

Once the compliance matrix $\mathbf{D}(\omega_i)$ is obtained for the i-th resonant frequency, the experimental modal displacement vector φ_i, expressed in the global reference system, can be reconstructed from the corresponding experimental modal force profile vector ϕ_i as:

$$\varphi_i = \mathbf{D}(\omega_i)\mathbf{R}\phi_i \tag{2}$$

where ϕ_i contains the experimental modal forces identified by OMA from load-cell ambient vibration data. The matrix $\mathbf{R}$ is a rotation matrix that transforms the modal force components from the local stay reference system to the global one, depending on the orientation of each cable. A schematic flowchart of the proposed procedure is shown in Figure 1.

3 PARAMETRIC ANALYSIS OF THE DIVERGENCE BETWEEN MODAL FORCE AND MODAL DISPLACEMENT SHAPES

This section investigates the conditions under which force-based mode shapes differ from displacement-based ones and assesses their suitability SHM of cable-stayed bridges. A parametric study is performed on two different families of cable-stayed bridges. The analysis is based on numerical simulations of simplified models representative of real cable-stayed bridges. Since force-based mode shapes are not directly available from standard modal analysis, they are reconstructed from displacement mode shapes using the compliance matrix. Displacement-based modes are obtained through numerical modal analysis, while the

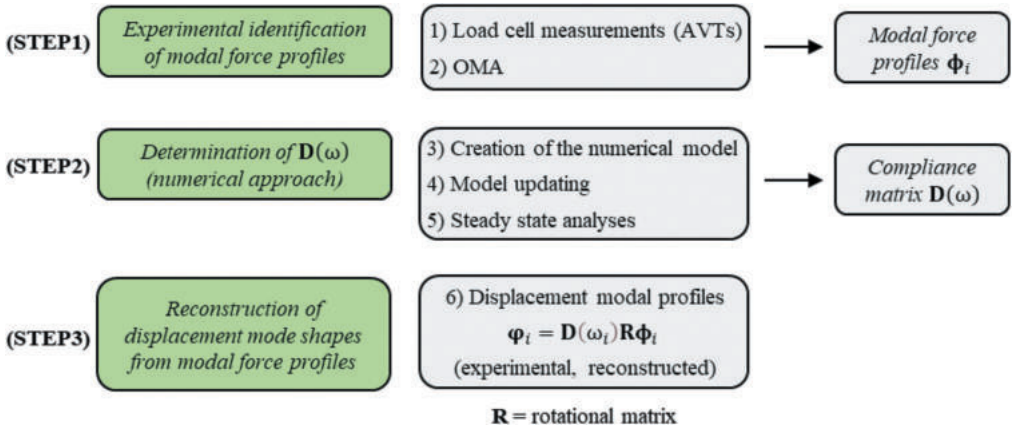


Figure 1. Procedure to reconstruct modal displacement profiles from modal force profiles measured by load cells.

compliance matrix is computed via steady-state analyses by applying unit forces at the stay-deck connections. Force-based mode shapes are then derived by inverting the displacement-force relationship and are compared with displacement-based ones using the Modal Assurance Criterion (MAC). The parametric study considers a three-span cable-stayed bridge with two pylons, analysing both harp and fan cable systems. The simplified models consist of three-span Euler-Bernoulli beams with fixed vertical supports at the pylons and abutments, while the effect of stay cables is modelled through elastic supports aligned with the cable directions. The first ten vibration modes are examined. Although the reference configuration is a three-span bridge, the results are generally applicable to cable-stayed bridges with multiple piers due to their repetitive and symmetric layouts. The system response depends on the ratio between the axial stiffness of the stays and the flexural stiffness of the deck k_R, and the number of stays per side of the pylon p. A non-dimensional formulation is adopted using the Buckingham theorem (Sedov, 2018). The parametric results are presented in terms of the average MAC value of the first ten modes, which quantifies the difference between force-based and displacement-based mode shapes (Figure 2). The results show that, for the harp system, the two mode shape representations are practically equivalent over the entire parameter range. For the fan system, equivalence is observed for sufficiently high values of the stay-to-deck stiffness ratio, while for lower values the differences slightly increase but remain limited, with MAC values not lower than about 0.85. These results provide a practical tool for evaluating the reliability of force-based mode shapes in real bridge applications based on simple geometric and mechanical parameters.

4 AN OSP-BASED STRATEGY FOR MONITORING CABLE-STAYED BRIDGES

A key challenge in the implementation of combined static-dynamic SHM systems for cable-stayed bridges is the optimal selection of monitored stays, since full instrumentation is economically inefficient and leads to excessive data volumes. To overcome this limitation, an OSP strategy is adopted to maximize the effectiveness of the SHM system. The proposed approach combines static information (axial forces measured by load cells) with dynamic information (modal force profiles obtained from OMA of high-frequency load-cell data) (Nicoletti et al, 2025).

The OSP problem is formulated as an optimization task and solved using a Particle Swarm Optimization (PSO) algorithm (Sengupta et al, 2019). The objective is to identify the subset of stays that maximizes the information content of the SHM system for a predefined number of sensors and vibration modes. For each candidate sensor configuration, an Objective Function (OF) is evaluated and minimized.

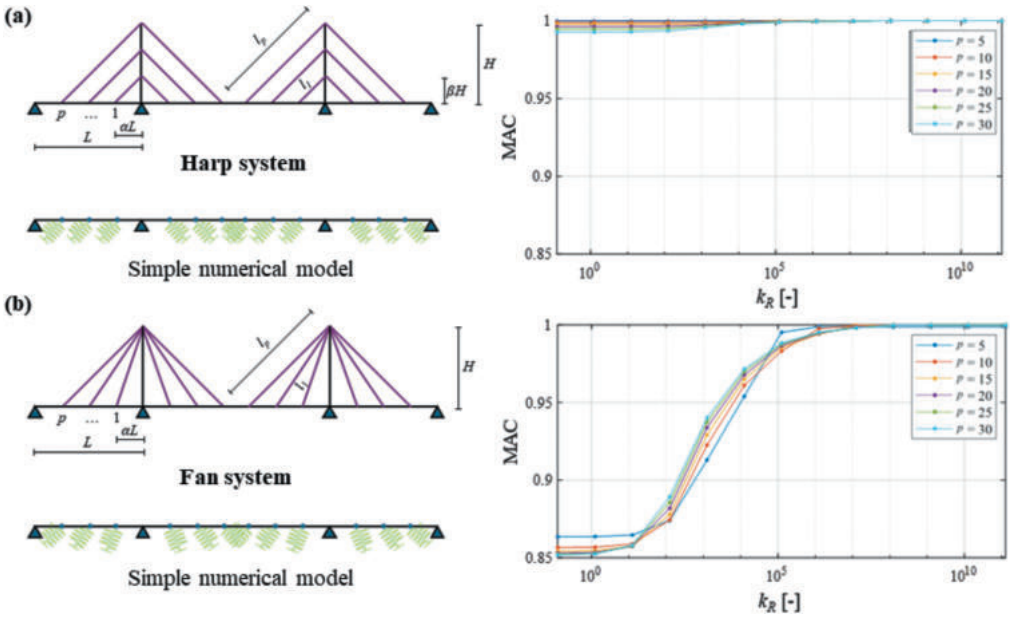


Figure 2. Parametric analysis: (a) schematization hypothesis for the harp systems, (b) schematization hypothesis for the fan systems.

The OF is defined as:

$$\mathrm{OF} = w_1 c_1 + w_2 c_2 + w_3 c_3 \tag{3}$$

where the coefficients $c_i \in [0, 1]$, with $i = 1, 2, 3$, quantify different aspects of the quality of the selected stay configuration:

- c_1 is the force-based damage sensitivity coefficient, which evaluates the sensitivity of axial forces in the monitored stays to localized damage in other stays;
- c_2 is the force modal shape damage sensitivity coefficient, which measures the ability of the selected layout to discriminate between damaged and undamaged conditions using the MAC computed from modal force profiles;
- c_3 is the modal force profile orthogonality coefficient, which evaluates the correlation among the selected modal force profiles independently of damage, with the aim of minimizing redundancy and ensuring clear identification of the M considered modes (AutoMAC).

The weighting factors w_i satisfy $\sum w_i = 1$ and allow the user to prioritize specific contributions. In this study, equal weights are adopted ($w_1 = 0.33$, $w_2 = 0.33$, $w_3 = 0.34$).

All coefficients c_i are computed through numerical analyses performed on a finite element model that accurately reproduces the static and dynamic behaviour of the bridge.

The number of monitored stays N and the number of considered modes M are predefined by the user. The optimal sensor configuration is identified by iterating over all admissible combinations of N stays and minimizing the OF through the PSO algorithm, implemented via a custom MATLAB routine (Figure 3). During the optimization process, the coefficients c_i are updated at each iteration by recalculating sensitivity, MAC, and AutoMAC metrics using only the selected stays. Convergence is achieved when successive iterations yield negligible variations in the minimum OF value. The optimal configuration identified at each PSO step is used to initialize the subsequent one. Finally, the minimum number of sensors ensuring satisfactory SHM performance can be determined by repeating the procedure for different values of N and selecting the configuration that provides an adequate OF minimization.

5 APPLICATION TO A REAL CABLE-STAYED BRIDGE

The case study focuses on the "Filomena Delli Castelli" bridge, recently constructed over the Saline River in Central Italy (Figure 4). The structure is a 188.6 m long steel-concrete composite cable-stayed bridge with three spans measuring 42.6 m, 103.4 m, and 42.6 m. The deck, varying in width from 19.2 to 22.8 m. It consists of two 1.2 m deep I-shaped main girders, crossbeams with depths between 0.8 and 1.2 m, and a 25 cm concrete slab partially lightened with polystyrene. The pylons are formed by four inclined steel tubular elements (1.9 m diameter, up to 36.4 m high), partially filled with concrete at the base and transversely connected under the deck by a steel box girder. The stay cable system consists of 40 cables, with 36 connected to the deck and 4 to the abutments, arranged in two longitudinal planes on the upstream and downstream sides. The stays are anchored to the pylons in a semi-fan layout and are inclined both longitudinally and transversely due to the inclination of the pylons.

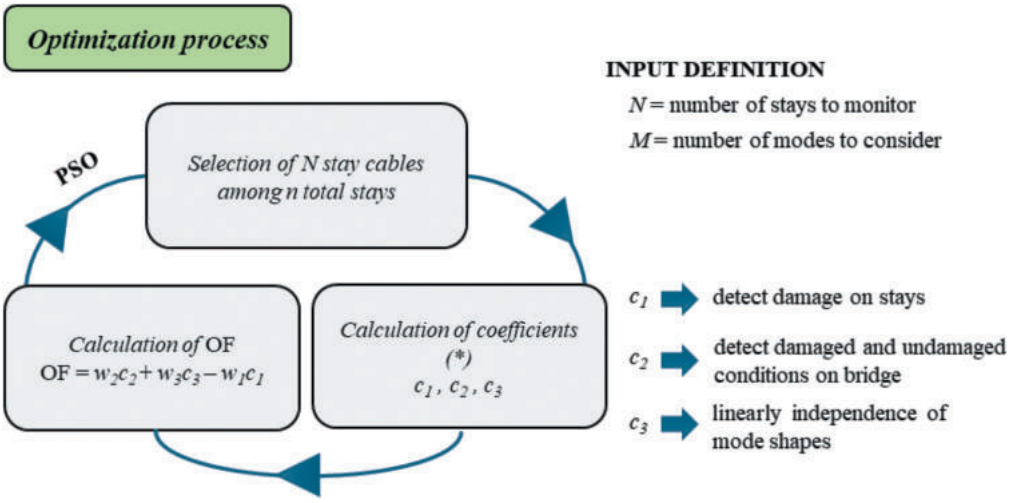


Figure 3. Optimal sensor placement procedure for cable-stayed bridges.

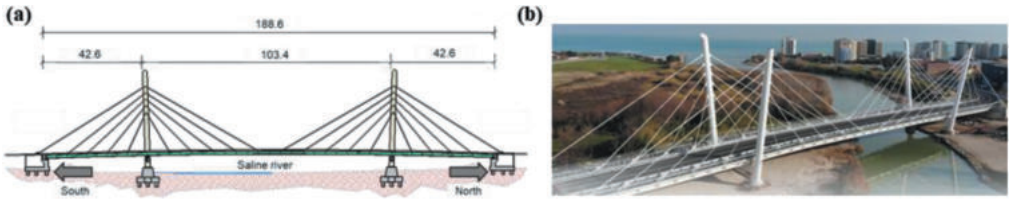


Figure 4. Real cable-stayed bridge case study: (a) schematic view with main geometric features; (b) aerial photo.

The method for reconstructing displacement mode shapes from force-based modal results is applied to the bridge. Load-cell measurements from a full-scale field test conducted on October 7, 2022, which also included deck acceleration recordings, enable a direct comparison between displacement shapes derived from load cells and modal shapes identified from accelerometers. By using N = 4 instrumented stays along the deck and targeting M = 7 vibration modes, displacement mode shapes $\boldsymbol{\phi}_i$ are calculated from the experimentally measured modal

forces φ_i, which are aligned with the primary directions of the stays. To match the global coordinate system of the accelerometers, the modal forces are rotated via a transformation matrix. The accuracy of the reconstructed mode shapes is evaluated through the MAC matrix, which shows a very high correlation (MAC > 0.98) (Figure 5b) with accelerometer-based modes, confirming the effectiveness of the load-cell-based reconstruction. Comparing mode shapes obtained directly from force-based data with those from accelerometers indicates overall agreement as well; although less precise than the proposed reconstruction approach, the bridge's nearly uniform stiffness results in an average MAC of 0.87 (Figure 5a) for the first seven modes, which is considered highly satisfactory. These findings demonstrate that the proposed approach is reliable for reconstructing displacement mode shapes from modal forces. They also indicate that acceptable results can be obtained by using force-based modal data alone, bypassing the need for full displacement reconstruction. This alternative reduces data processing time and lowers monitoring costs, as load cells can simultaneously track both the stay forces and the global structural behaviour of the bridge.

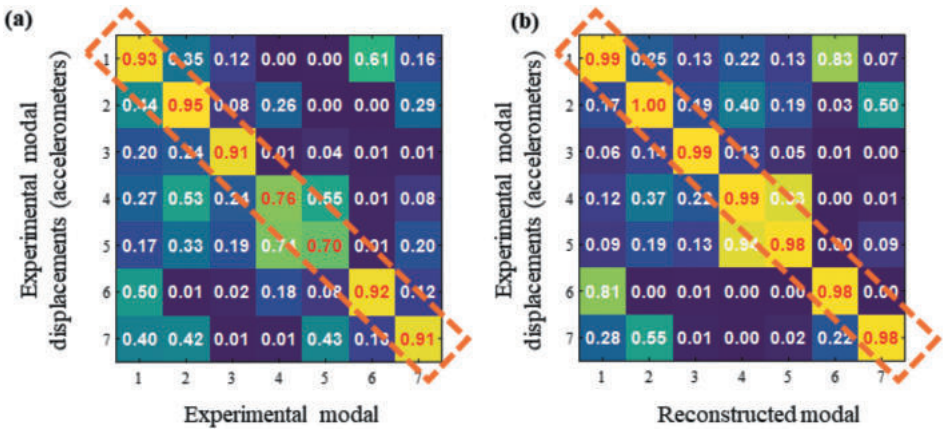


Figure 5. (a) comparison between modal force profiles identified from load cell recordings and OMA and modal displacements from accelerometer recordings and OMA; (b) comparison between reconstructed modal displacements from load cells and identified ones from accelerometric recordings.

Finally, the proposed OSP strategy is applied to identify the optimal number and configuration of monitored stays. The PSO algorithm is executed with a high iteration count and stringent convergence criteria to ensure accurate results, while computational demands remain low by leveraging precomputed finite element model outputs. As noted earlier, all coefficients in the objective function are assigned equal weighting.

After setting the number of target modes to M = 7, a preliminary study is conducted to determine the optimal number of sensors by gradually reducing the monitored stays from 40 down to 1. The evolution of the objective function and its components (Figure 6a) indicates that increasing the number of sensors improves performance, but gains are minimal beyond eight stays. Consequently, N = 8 is chosen as the optimal sensor count.

The OSP procedure is then carried out using N = 8 and M = 7, reaching convergence after several PSO iterations (Figure 6b), demonstrating the method's computational efficiency. The resulting sensor layout (Figure 6c) is almost symmetrical and well distributed along the bridge, providing complete structural coverage. Compared to the original configuration (Figure 6d), which was primarily designed for static force monitoring and considered only the c_1 coefficient, the optimized arrangement achieves a more uniform sensor distribution and improves the identification of the bridge's dynamic response.

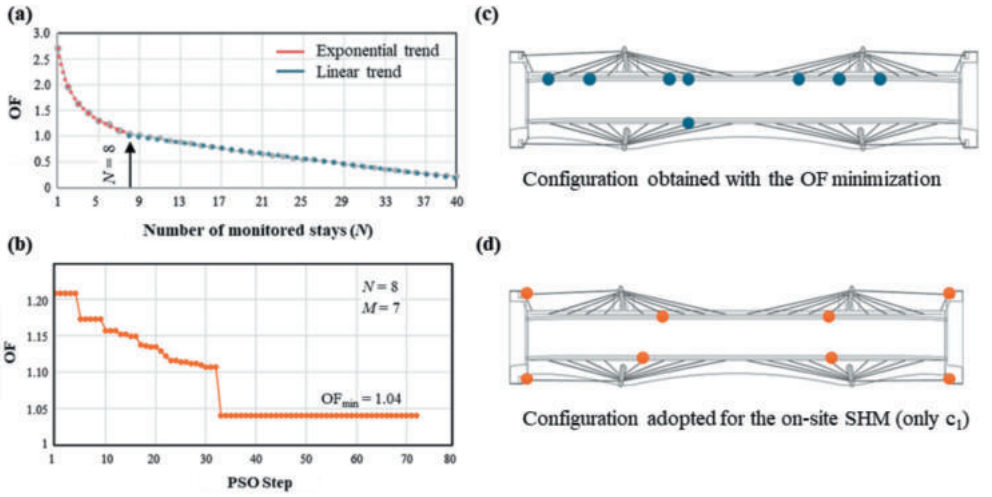


Figure 6. Results of the proposed OSP procedure: (a) choice of the number of monitored stays; (b) OF evolution; (c) optimal position of load cells obtained by the method; (d) position of load cells installed on the bridge for the SHM.

The bridge is equipped with a permanent SHM system, installed in 2022, which supports static, dynamic, and seismic monitoring, with over three years of continuous data now available. A detailed overview of the monitoring setup and procedures is provided by Nicoletti et al. (2023). In this study, the focus is on data from four deck accelerometers (providing seven measurement directions) and four load cells installed on the stay cables near the deck connections. Continuous 30-minute AVT recordings are archived on the server and processed using standard pre-processing routines, followed by AutoOMA for automated identification of the structure's modal parameters, aided by clustering analysis. Load-cell data are further post-processed to compute the average axial force of each stay over the recording interval.

Analysis of the monitoring records reveals clear seasonal and daily fluctuations of the stay cable forces around their mean values, consistent with the design forces (Figure 7a). No significant variations are detected, indicating the absence of damage throughout the monitoring period. Global bridge frequencies derived from both load-cell and accelerometer data are compared (Figure 7b, Figure 7c). Modes detected by both sensor types are matched, while modes identified by only one sensor are highlighted (grey lines). Frequency estimates from load cells exhibit slightly higher variability but closely correspond to results from high-sensitivity, low-noise accelerometers, confirming the suitability of load cells for dynamic monitoring of cable-stayed bridges. Observed frequency patterns show both seasonal and daily variations across modes, without sudden drops, further supporting that the structure remained undamaged during the monitoring period.

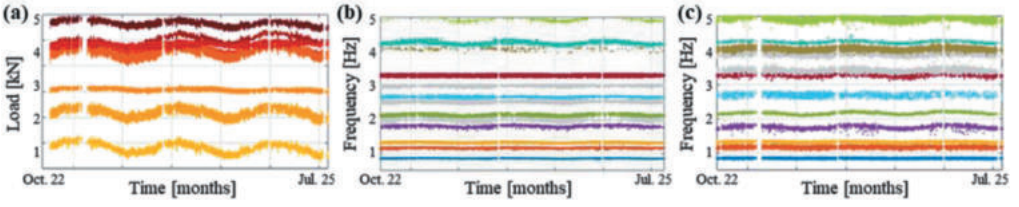


Figure 7. Results of the first three years of monitoring: (a) load on stays; (b) frequencies identified from accelerometer measurements; (c) frequencies identified from load cell measurements.

6 CONCLUSIONS

This study presented an integrated and efficient SHM strategy for cable-stayed bridges based on the use of load cells installed near the stay-deck connections. Since load cells are commonly already available for construction control, their use for SHM enables both static and dynamic monitoring while optimizing instrumentation and resources. High-frequency force measurements are exploited for modal identification, and a procedure to reconstruct displacement-based mode shapes from force-based ones is proposed using either experimental or, more practically, numerical compliance matrices derived from calibrated models. A non-dimensional parametric study was carried out to assess when the reconstruction of displacement-based mode shapes is necessary for SHM and damage localization. Generalized results for both harp and fan cable layouts show that, in many practical cases, force-based and displacement-based mode shapes are sufficiently similar, making reconstruction unnecessary. In addition, a novel optimal sensor placement strategy was developed, integrating static and dynamic criteria to determine the optimal number and layout of monitored stays. The proposed approach was validated through extensive numerical analyses and experimental data from a real cable-stayed bridge, demonstrating the feasibility, effectiveness, and cost-efficiency of load-cell-based SHM for long-term monitoring of cable-stayed bridges.

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