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INFLUENCE OF THE NUMBER OF SENSORS IN THE MODAL PARAMETER ESTIMATION AND DAMAGE DETECTION USING OPERATIONAL MODAL ANALYSIS

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Abstract. *Structural Health Monitoring (SHM) based on dynamic techniques relies on accurate identification of modal parameters to assess structural integrity. This study investigates the impact of the number of sensors on the estimation of natural frequencies, damping ratios and mode shapes, as well as on the ability to detect damage. The experimental work is conducted on a four-story laboratory-scale shear building model. Damage is introduced in a controlled manner by varying the mass of each floor slab, simulating changes in service conditions. Operational Modal Analysis (OMA) under ambient excitation is employed to identify modal parameters across different scenarios and sensor configurations. Several layouts are considered to evaluate how reducing the number of sensors affects both modal identification accuracy and sensitivity to structural changes. Results indicate that natural frequencies remain relatively robust under sparse instrumentation, whereas mode shapes and damping ratio estimations degrade significantly, impacting the effectiveness of damage indices based on modal correlation. This work provides practical guidelines for optimizing structural monitoring systems, balancing cost and reliability. The results are promising for real-world applications where full instrumentation is often impractical, such as bridges, buildings and wind towers. Furthermore, implications for predictive maintenance strategies and the deployment of SHM systems in constrained environments are discussed.*

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1 INTRODUCTION

Vibration-based Structural Health Monitoring (SHM) has become a key tool for assessing the condition of civil engineering structures and supporting maintenance decisions. Among the available approaches, Operational Modal Analysis (OMA) is particularly attractive because it enables modal identification under ambient excitation [1]. Other techniques such as Experimental Modal Analysis (EMA) require input forces to be monitored. OMA is therefore suitable for real structures in service conditions, where modal testing is often a difficult task.

An additional practical limitation of SHM systems is that full instrumentation is rarely possible. Budget restrictions, accessibility issues and the need to minimize installation effort usually force engineers to work with a limited number of sensors. As a result, it is necessary to understand how both their count and spatial distribution affect the reliability of modal parameter estimation and subsequent Structural Damage Detection (SDD). While natural frequencies (ω_i) are often expected to be relatively stable to different layouts, damping ratios (ζ_i) and mode shapes ($\vec{\phi}_i$) may be more sensitive to incomplete observation.

This work addresses these issues through an experimental case study on a laboratory-scale shear building demonstrator. The main goal is to evaluate the effect of different accelerometer layouts on the identification of modal parameters and on the detection of controlled structural changes. Rather than assuming a single optimal configuration, the study compares several layouts in order to characterize the impact of sparse sensing under realistic OMA conditions.

2 METHODOLOGY

The structure under study is a four-story laboratory-scale shear building demonstrator, representative of a multi-story civil structure with lumped mass behavior [2]. Accelerometers are placed on each floor slab to record the system's shear motion. The building is excited by means of a fan which simulates wind loads, which allows the use of response-only identification techniques like OMA. This setup is well suited to studying monitoring strategies intended for real structures under service conditions. Damage is introduced in a controlled and repeatable manner by modifying the mass distribution of the floor slabs adding M45 steel nuts (190.5 g each). This produces changes in the dynamic characteristics of the structure without requiring irreversible intervention. The induced damage provides a set of scenarios that can be compared in terms of their modal response and the specific sensor layout employed. Figure 1 describes the structure and its 4-degree-of-freedom model. The mode shapes corresponding to the 4 modes of vibration of the undamaged scenario (no steel nuts) are also represented.

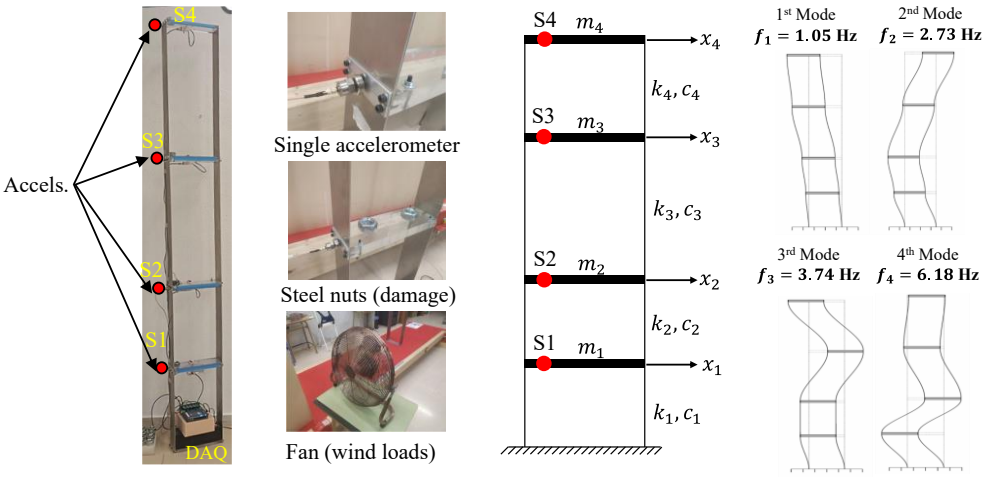


Figure 1: 4-story laboratory-scale shear building demonstrator under study.

Regarding the instrumentation layout, several accelerometers are considered to evaluate the influence of the number and position of sensors. In this communication, the scenarios range from a full configuration of one sensor per floor (base scenario) to the situation in which a single accelerometer is ignored when performing OMA. On the other hand, damage scenarios correspond to those in which a single nut is added to a slab, locally increasing the mass of the system and changing the modal properties to be identified. When combining both—sensors and damage—cases, a total of 25 scenarios arise. Natural frequencies, damping ratios and mode shapes are subsequently sought by means of OMA and compared to the base scenarios (all sensors without damage). Figure 2 depicts the whole set of scenarios considered when combining sensor usage with induced damage. Specifically, a 0 is assigned to a particular floor when no additional mass (steel nut) is added and 1 when it is, while X means that the corresponding accelerometer has been ignored when performing OMA (S otherwise). Eventually, several error metrics and indicators are used to compare the whole set of scenarios. Modal Assurance Criterion (MAC) is employed to check for consistency of mode shapes across sensor layouts for each damage case. It is important to note that in some scenarios a loss in the total number of modes identified might be present due to employing 3 instead of 4 sensors, meaning that comparisons with the fully instrumented case (SSSS) are not directly possible.

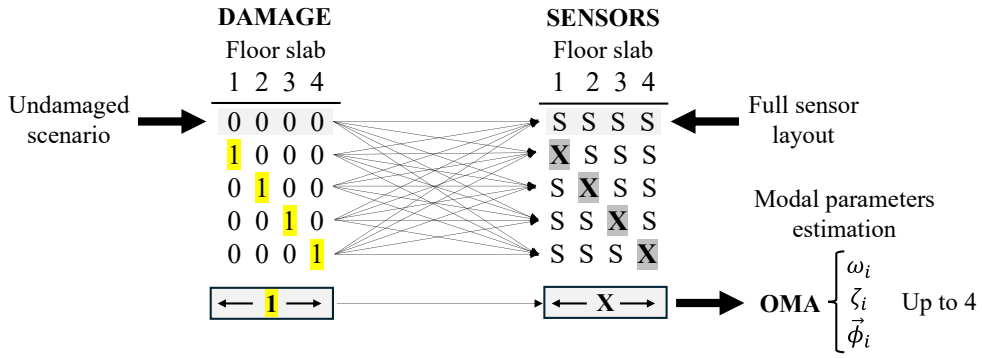


Figure 2: 4-story laboratory-scale shear building demonstrator under study.

3 EXPECTED RESULTS AND DISCUSSION

The study is expected to show that natural frequencies remain robust under reduced instrumentation, while mode shapes and damping estimates are more sensitive to a decreasing sensor count. This would confirm that frequency-based indicators may remain usable in sparse configurations, whereas shape-based metrics require better spatial coverage to preserve reliability.

A second expected outcome is that damage detection performance will strongly depend on the chosen sensor layout. Configurations with more complete spatial information are likely to provide better mode-shape reconstruction and, therefore, stronger sensitivity damage indicators. By contrast, sparse layouts may still capture global dynamic changes, but they may lose detail in the identification of local or subtle modifications.

From a monitoring design perspective, the results are expected to support the idea that reduced but strategically placed sensors may be sufficient for basic tracking of structural state, while more demanding diagnostic tasks may require denser coverage. This distinction is important for real-world SHM applications with much larger instrumentation, where sensor economy must be balanced against the level of diagnostic detail required.

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