Damage localization using controllable inputs: an experimental study

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Abstract

The recently proposed Shaped Damage Locating Input Distribution (SDLID) method locates structural damage by active interrogation with controllable inputs. The methodological premise is to shape these inputs such that certain steady-state vibration features (depending on the type of damage to be located) are rendered dormant in one subdomain at a time. As such, damage is localized when the vibration response induced by the shaped inputs in the damaged state corresponds to that stored for the reference state. Previously, the SDLID method, which operates free of system identification, has been tested through numerical simulations and, in this context, demonstrated its merits; namely, a low demand on output sensors, robustness towards noise, and conceptual simplicity. This paper presents an experimental application study, in which the SDLID method is used to locate different mass perturbations in a frame structure investigated using two actuators delivering harmonic excitation. Based on steady-state acceleration measurements, it is shown how the method succeeds in locating all the added mass perturbations.

Keywords: Structural Health Monitoring, Damage localization, Input shaping, Experimental study.

1 Introduction

Structural damage localization is conventionally handled by mapping shifts in vibration features, such as transfer functions or modal parameters, from the reference and damaged states to the structural domain [1]. This mapping can be conducted either directly, in which case we refer to the approach as *data-driven*, or by use of a theoretical model of the structure in question, implying that the approach is *model-based* [2]. Here, the theoretical model is typically established on the basis of a finite element (FE) formulation.

Numerous studies document successful model-based damage localization under both laboratory conditions [3, 4, 5] and in-situ settings [6, 7, 8], but it is evident that damage localization has yet to find the applicability level required for industrial use. One of the major issues is that the sensitivity to structural damage of the employed vibration features is typically lower than the features' sensitivity to noise and other variabilities [9].

Two approaches to (attempt to) resolve the noted sensitivity issue is 1) reducing the impact of noise and other variabilities [4, 10, 11] and 2) designing closed-loop systems with enhanced sensitivity to damage [12, 13, 14]. In the present study, we focus on the former path and investigate the Shaped Damage Locating Input Distribution (SDLID) scheme proposed by Ulriksen et al. [11]. The SDLID scheme employs inputs that are shaped by use of a theoretical model to "deactivate" the damage for determining its location. The idea is to operate with the shaped inputs in a forward interrogation for damage of one structural subdomains at a time; with damage revealing itself when, under ideal conditions, the vibration signatures prior and posterior to damage coincide. In this way, the impact of noise is reduced since the SDLID scheme operates without calling for system identification to extract the damage features.

Besides circumventing system identification, the merits of the SDLID scheme include a user-defined spatial localization resolution (as postulated damage areas are selected), a low demand on output sensors (in principle, one may suffice), and conceptual simplicity. These merits have been highligted through numerical application examples with simple structural systems [11] and an offshore jacket structure [2]. The scope of the present paper is therefore to further test the applicability of the SDLID scheme by applying it in an experimental context with a frame structure, which is analyzed in its reference state and "damaged" states with different mass perturbations.

The rest of the paper is organized as follows: in section 2, the SDLID method is reviewed, section 3 outlines the experimental setup, and section 4 presents the obtained damage localization results. A brief conclusion in section 5 closes the paper.

2 The SDLID method

The SDLID method interrogates for damage in a structural subdomain by applying a set of controllable inputs, $u(t)$, which, for each structural subdomain, is shaped to render dormant certain kinematic quantities [11]. If the subdomain containing the damage is suppressed, the steady-state vibration output will, under ideal circumstances, be the same in the damaged state and in the healthy one; given, of course, that the set of inputs is identical in the two states. The task of shaping the inputs can be resolved by numerous approaches; of which two are proposed in [11]. One of these two takes its outset in the Laplace domain and is, as such, useful when shaping harmonic inputs, while the second one operates in the time domain. Since the experimental study in the present paper employs harmonic excitation, we focus on the Laplace domain-based approach and refer the reader to [11] for a tutorial on the time domain-based approach.

Consider a structural domain that is discretized to n degrees of freedom (DOF) and subjected to p inputs that are collected in $u(t) \in \mathbb{R}^p$ and distributed spatially through $B_2 \in \mathbb{R}^{n\times p}$. The governing temporal equation reads

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = B_2u(t), \tag{1}$$

where M, C and $K \in \mathbb{R}^{n\times n}$ are the mass, damping and stiffness matrices, while, $x(t)$, $\dot{x}(t)$ and $\ddot{x}(t) \in \mathbb{R}^n$ are the nodal displacement, velocity and acceleration vectors. Assuming steady state and zero initial conditions, equation (1), with p shaped inputs acting solely in the DOF indexed by τ, can be expressed in the Laplace domain as

$$X(s) = (Ms^2 + Cs + K)^{-1}B_2U(s) = G(s)B_2U(s) = G_{\bullet,\tau}(s)U(s), \tag{2}$$

where $G_{\bullet,\tau}(s)$ is the transfer matrix containing the columns in which the shaped inputs are applied and $X(s) = \mathcal{L}(x(t))$ and $U(s) = \mathcal{L}(u(t))$ are the Laplace transforms of the output and the input.

For simplicity we assume that the structure is only affected by the p shaped inputs, hence implying that any other exogenous loading is neglected. The task therefore becomes to shape the amplitude and the phase angle of the harmonic inputs, such that some linear transformation of $X(s) \in \mathbb{C}^n$, denoted $\Gamma(s) \in \mathbb{C}^q$, is suppressed. That is,

$$\Gamma(s) = LG_{\bullet,\tau}(s)U(s) = 0, \tag{3}$$

where $LG_{\bullet,\tau}(s) \in \mathbb{C}^{q\times p}$ and with L being the transformation matrix. Provided that $p > q$ (that is, the number of shaped inputs is greater than the number of suppressed kinematic quantities), there exists a null space

$$U(s) = \text{null}(LG\bullet, \tau(s)), \tag{4}$$

from where relative values of the amplitudes and phase angles are directly computed as the moduli and arguments of the chosen vector within the span of $\text{null}(LG\bullet, \tau(s)) \in \mathbb{C}^{p\times(p-q)}$.

One gathers that the inputs are most conveniently shaped using a model of the healthy structure. By applying the inputs to the structure prior and posterior to damage, we capture the steady-state response, $y(t)$ and $\tilde{y}(t)$, where $(\tilde{\bullet})$ denotes a quantity from the damaged state. On the premise that $y(t)$ can contain displacements, velocities, accelerations, and so forth, the Euclidean distance of the steady-state response shift in frequency domain, that is,

$$\Xi_i = \sqrt{\sum_j (|Y_j(\omega)| - |\tilde{Y}_j(\omega)|)^2}, \tag{5}$$

is used as damage metric with the index i indicating the ith subdomain being interrogated. In this way, damage is located in the subdomain that yields the lowest metric.

In the present study, we focus on locating mass perturbations, thus, as proved in [11], steady-state accelerations must be suppressed. If, on the other hand, stiffness-related damage was to be located, one would suppress the steady-state strains. A further elaboration on this can be found in [11].

3 Experimental setup

A frame structure with 5 floors is assembled and used as a damage localization test bed in a controlled laboratory environment, see figure 1. The structure is assembled using aluminium beam elements, all connected by corner cubes, screws and threaded rods, see table (1) for the structural properties of a single aluminum beam element.

The structure is instrumented with two actuators that generate a horizontal load. Two load cells are attached to the structure that measure the input force from the actuators. The structural response is captured by 9 piezo-electric accelerometers, distributed on the frame structure. The structure is mounted on a HEB260 profile, which is reinforced with steel braces and bolted to the ground.

Table 1: Material properties of a single aluminum beam element.

Description	Symbol	Value	Unit
Cross-sectional area	A	$49 \cdot 10^{-6}$	[m^2]
Density	ρ	2900	[kg/m^3]
Modulus of elasticity	E	$68 \cdot 10^{9}$	[Pa]
Poisson's ratio	υ	0.33	[-]
Shear modulus	G	$25 \cdot 10^{9}$	[Pa]
Second moment of inertia	I_y/I_z	$495 \cdot 10^{-12}$	[m^4]
Polar moment of inertia	I_x	$991 \cdot 10^{-12}$	[m^4]

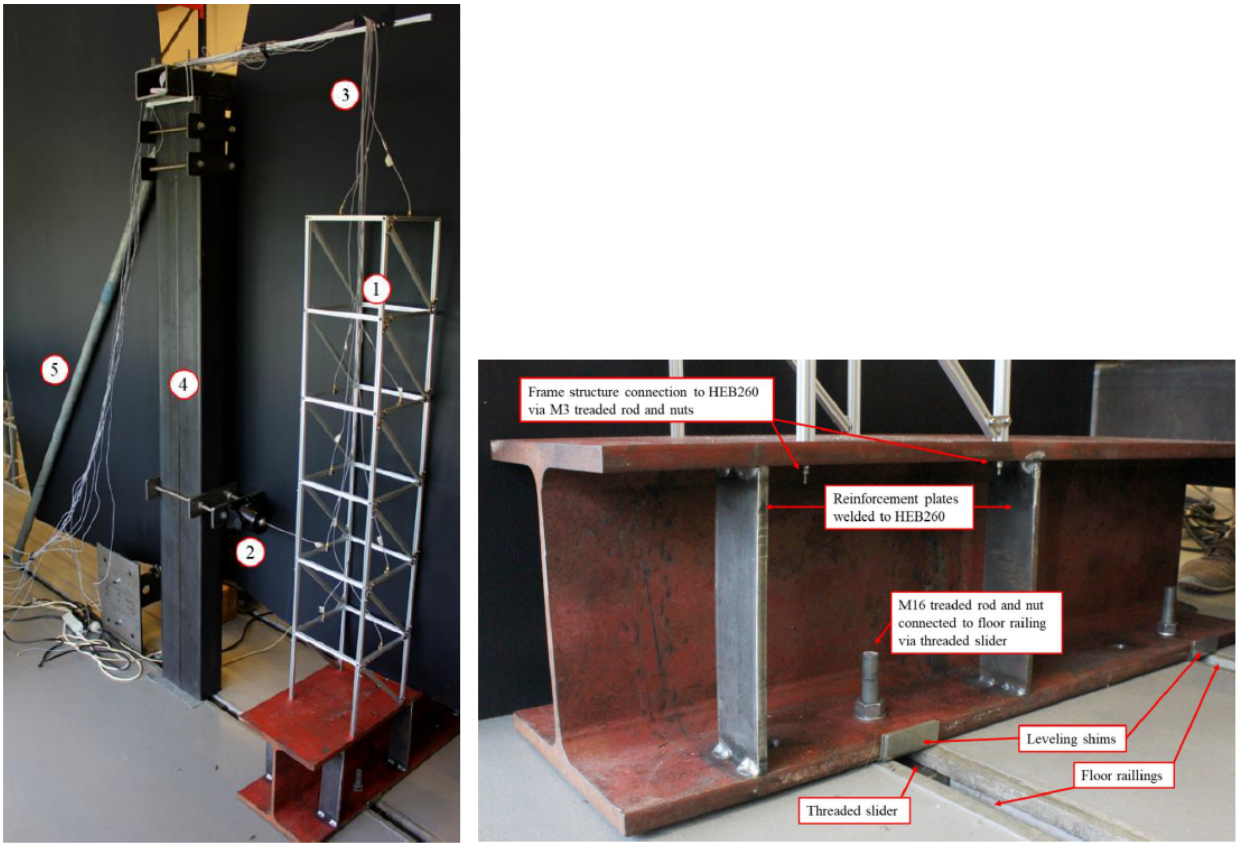
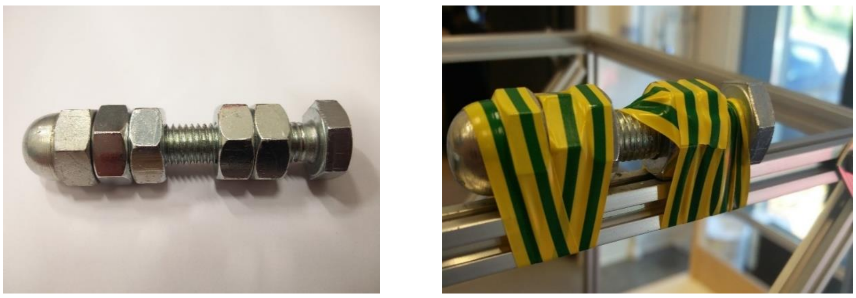


Figure 1: Experimental setup with indication of 1) frame structure, 2) actuator, 3) cables connecting the accelerometers, 4) steel column and 5) support cylinder for the steel column.

3.1 Damage emulation

The damage is introduced as a mass perturbation in different areas on the frame structure, see figure 2. The mass perturbation weighs 0.121 kg, which is approximately 6.31 % of the total mass of the frame structure. To appreciate the impact of adding the mass perturbation to the structure, we conduct an Experimental Modal Analysis (EMA) of the structure in its healthy configuration and with the mass perturbation added on the topmost level. The EMA is performed by use of a single actuator that delivers a sine sweep ranging from 0.1 Hz to 60 Hz, which ensures that the first three eigenmodes of the frame are excited. As observed from the resulting frequency response functions depicted in figure 3, the mass perturbation yields a clear damaged-induced shift in the eigenfrequencies.



(a) (b)

Figure 2: Pictures of a) bolt and nuts serving as mass perturbation and b) the perturbation applied to the structure.

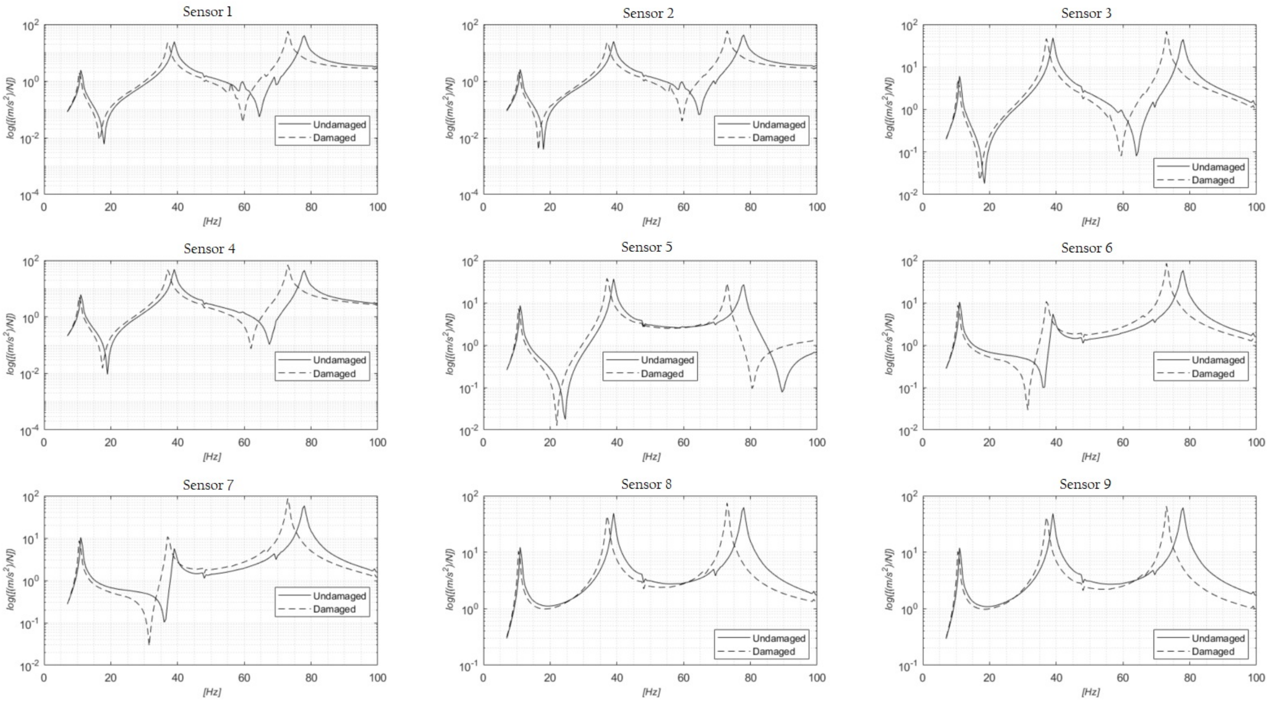


Figure 3: Frequency response functions for the structure in reference and damaged states.

4 Damage localization

As previously mentioned, the SDLID method is a model-based approach, meaning that a theoretical model must be used to shape the inputs. A finite element model consisting of 108

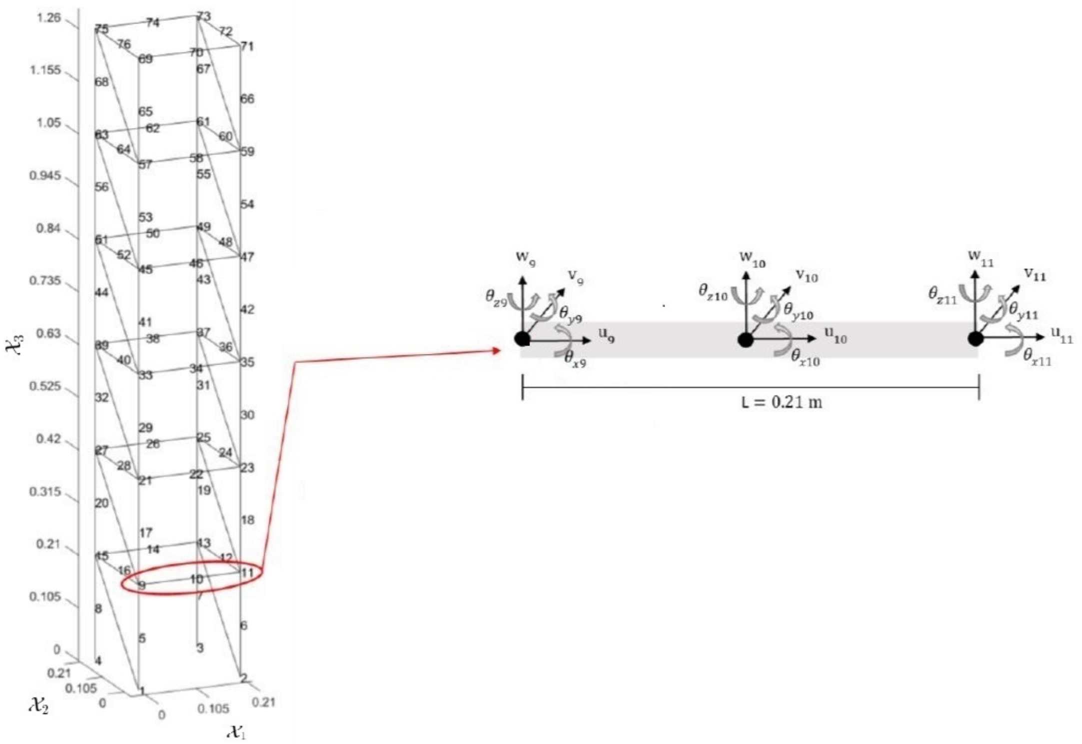
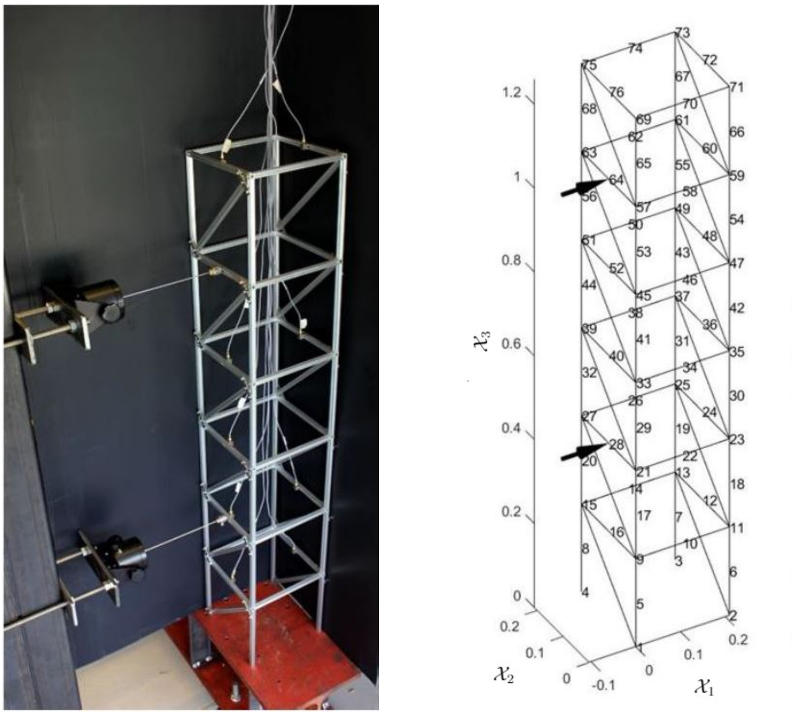


Figure 4: Finite element model of the frame structure and two highlighted beam elements, illustrated with the nodes and DOF.

Euler-Bernoulli elements has been established, see figure 4. The model has a total of 480 DOF of which 24 are fixed to represent the kinematic boundary conditions.

In the experimental study, two actuators are, as mentioned, attached to the frame structure to introduce a harmonic excitation; see figure 5, which also shows the positions of the accelerometers. The two harmonic inputs have a driving frequency of $\Omega = 0.7\omega_1$, where ω_1 is the first cyclic eigenfrequency, see figure 5 for the actuator positions. With two inputs, one gathers that the constraint of $p > q$ is violated if all six DOF in a node are to be suppressed. However, since the inputs only excite in one plane and the displacements and rotations are relatively small, suppressing just the translational DOF in the excitation direction is sufficient.



(a) (b)

Figure 5: Frame structure in a) experimental setup with accelerometers and actuators and b) its numerical representation with the actuator positions.

The frame structure is tested in the healthy state and in five different damaged states, where the mass perturbation is located at node $\aleph = 12, 36, 52, 60$ or 76. These nodes, which are indicated in figure 6, are also chosen as the subdomains to be interrogated consistently. The interrogations are conducted by suppressing steady-state accelerations in the excitation direction, and by doing so for each damaged state, we get the damage metrics—according to equation (4)—plotted in figure 6. As the red dot in each plot marks the damage location, it is evidenced how the SDLID method allows for successful localization of the mass perturbation in all damaged states.

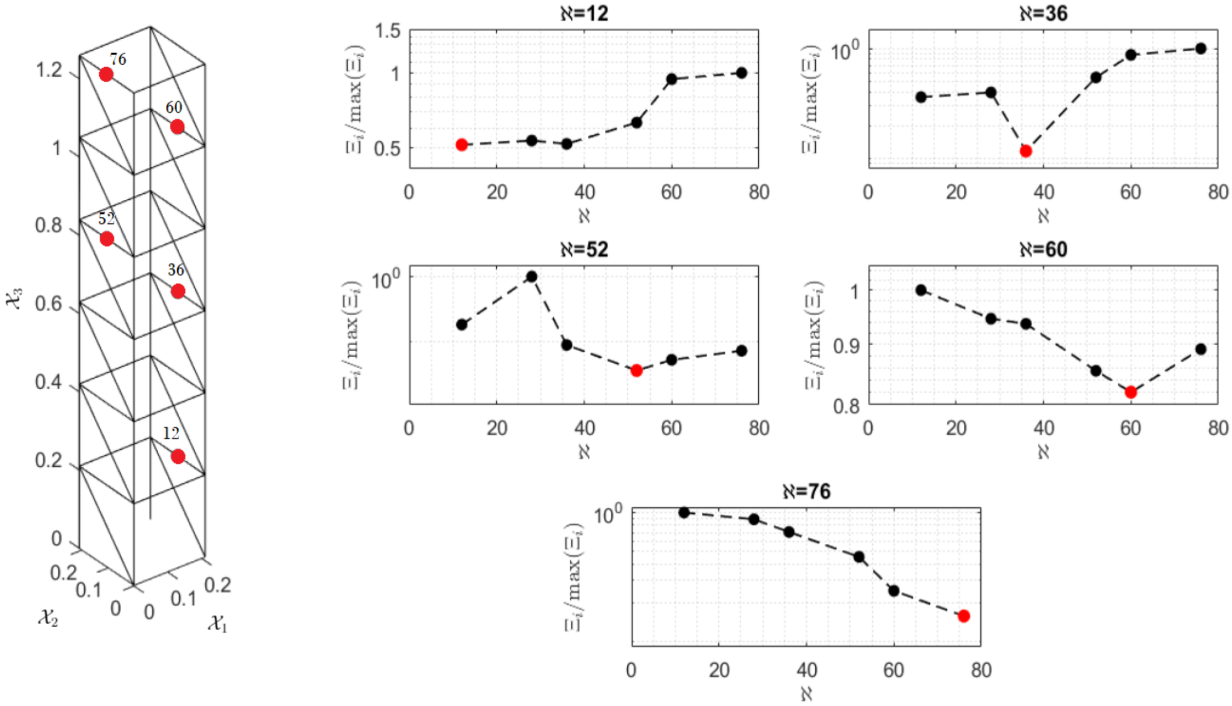


Figure 6: Damage localization results. The structure, depicted on the left side, illustrates the positions of the damage.

5 Conclusion

The principle of the SDLID method is to apply a set of inputs and then interrogate for damage by rendering dormant certain kinematic quantities (depending on the damage type to be located) in one structural subdomain at a time. Damage is, as such, located when the steady-state output governed by the shaped inputs is identical prior and posterior to the introduction of damage.

In the present paper, the SDLID method is tested in an experimental setup with a frame structure, which is subjected to two harmonic inputs and introduced to different mass perturbations. By shaping the available inputs to suppress steady-state accelerations in one subdomain at a time, it is found that the SDLID scheme succeeds in locating all the mass perturbations, albeit with rather poor resolution in some cases.

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