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Nondestructive characterization of tie-rods by means of dynamic testing, added masses and genetic algorithms

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ABSTRACT

The structural characterization of tie-rods is crucial for the safety assessments of historical buildings. The main parameters that characterize the behavior of tie-rods are the tensile force, the modulus of elasticity of the material and the rotational stiffness at both restraints. Several static, static–dynamic and pure dynamic nondestructive methods have been proposed in the last decades to identify such parameters. However, none of them is able to characterize all the four mentioned parameters. To fill this gap, in this work a procedure based on dynamic testing, added masses and genetic algorithms (GA) is proposed. The identification is driven by GA where the objective function is a metric of the discrepancy between the experimentally determined (by dynamic impact testing) and the numerically computed (by a fast and reliable finite element formulation) frequencies of vibration of some modified systems obtained from the tie-rod by adding a concentrated mass in specific positions.

It is shown by a comprehensive numerical testing campaign in which several cases spanning from short, low-stressed, and almost hinged tie-rods to long, high-tensioned, and nearly clamped tie-rods, that the proposed strategy is reliable in the identification of the four unknowns. Finally, the procedure has been applied to characterize a metallic tie-rod located in Palazzo Paleotti, Bologna (Italy).

1. Introduction

Metallic tie-rods are largely used in historical buildings and contribute to their overall structural response. When buildings undergo to repair, restoration or retrofitting, information about the status of tie-rods are of primary importance. For this reason, the structural characterization of tie-rods has been the focus of intensive research in the last decades (see [1] and the references therein). In this context, nondestructive identification procedures work towards the characterization of such systems by exploiting experimental data, structural models and optimization techniques.

The nondestructive procedures currently available for the structural characterization of tie-rods can be grouped in static, static–dynamic and pure dynamic approaches. Static methods, see for example [2–4], in spite of minor differences, are based on measures of displacement and/or strain at few cross-sections of the tie-rod due to applied static loads. Even if the data post-processing is quite straightforward [4], these methods are extremely sensitive to the experimental error in

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the measures of displacement. In addition, since tie-rods are usually positioned at considerable heights, the need of measuring vertical deflections with respect to a reference fixed base makes static methods difficult in practice.

Mixed approaches try to identify the unknown parameters by combining static and dynamic measures [5,6]. The frequencies of vibration and the modal shapes of the tie-rod, which can be obtained by hammer impact testing and Fourier transforming the recorded accelerations, are usually considered as dynamic measures. Even if such methods can exploit additional dynamic information for the characterization, they are still affected by the shortcomings related to deflection measurements.

Such drawbacks are avoided in pure dynamic procedures [1,7–13], where, in general, the difference between the experimental and the calculated natural frequencies of vibration is minimized in order to identify the unknown parameters.

For example, in Lagomarsino and Calderini [11], an algorithm based on the first three frequencies measured by dynamic test, on an Euler–Bernoulli beam model and on the *Line Search* method, a gradient based searching algorithm, is presented. The unknown variables are the axial tensile force, the bending stiffness of the beam and an identical stiffness of the rotational springs at the ends. In a very recent work by Amabili et al. [1], a technique that employs four to six frequencies, a Timoshenko beam model and the *Nelder–Mead* minimization procedure (also known as the downhill search method), is proposed. The part of the rod inserted in the masonry wall is modeled as a beam on elastic foundation of unknown stiffness. The axial force and an identical foundation spring constant are the considered unknowns.

However, if a beam structural model is assumed for the tie-rod, to verify the tie-rod structural efficiency a general identification procedure should be capable of identifying the tensile force, Young's modulus of the material and both boundary conditions. In fact if the stiffnesses of the restraints are not properly evaluated, the estimates of modulus of elasticity and tensile load are likely to be inaccurate. This might occur in arches or vaults where the tie-rod boundary conditions at the two sides can be quite different (see Fig. 1), and equal constraints should not be assumed unless verified by additional experimental tests that add complexity to the method.

To the best of authors' knowledge, none of the works related to the structural characterization of tie-rods is able to characterize the tie-rod bending stiffness, the tie-rod tensile force, and the rotational stiffness of the springs at both tie-rod ends. In addition, the available identification methods are based on sensitivity or gradient-based searching algorithms. Therefore, the success of such methodologies is strictly dependent on the initial values of the target parameters that in historical buildings can be difficult to assess.

To fill this gap, the aim of the present work is to propose an identification procedure:

(i) capable of identifying the tie-rod Young's modulus, the applied tensile load, as well as different stiffnesses of the constraints;
(ii) insensitive from the initial values assumed for the structural parameters;
(iii) computationally straightforward (the numerical framework has to be easy to implement);
(iv) feasible to execute (the experimental procedure has to be simple and rapid).

To address these purposes, the following strategy has been followed. An optimization scheme driven by genetic algorithms (GA) has been adopted [14]. Even if often employed in inverse problems [15–18], GA have never been used in this context. As well known, differently from gradient-based optimization procedures, GA optimization results are minimally affected by the initial guess of the target variables. The basic idea of GA is to select an optimal individual from a population of individuals that represent potential solutions of the problem. In this study, each individual is a 4×1 vector of unknowns, i.e. Young's modulus, the tensile force and the rotational stiffnesses of both the elastically restrained ends. By applying genetic operators, the solution evolves generation-by-generation to the global optimum. Each individual is evaluated via an objective function here designed as

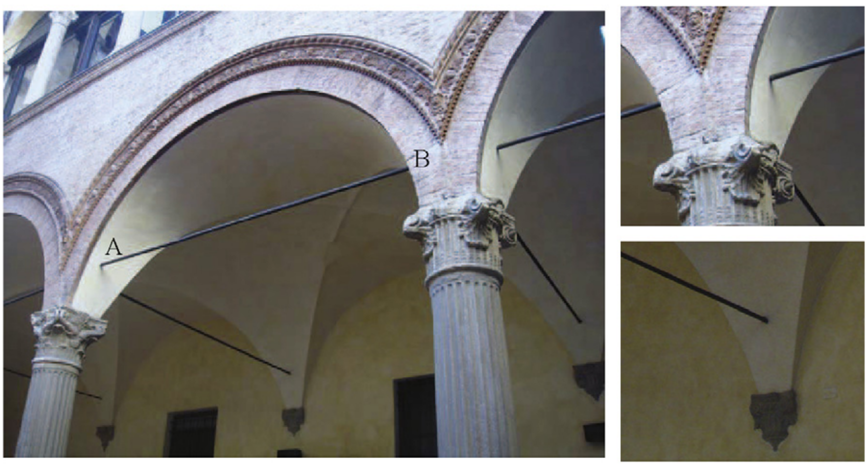

Fig. 1. Metallic tie-rods in a historical building. Note the insertions of the tie-rods into the Corinthian capital and into the masonry wall.