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Structural system identification of thin web bridges by observability techniques considering shear deformation

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ABSTRACT

Despite its importance in some structures, shear deformation is systematically neglected by most static structural system identification methods. This paper analyzes for the first time in the literature the effect of this deformation in the static inverse analysis of thin web bridges. This study is focused on the observability techniques. The most recent formulation found in the literature is based onthe Euler-Bernoulli beam theory. This formulation is unable to identify correctly the characteristics of a structure (such as flexural stiffness) when shear deformation is not negligible. To solve this problem, the observability method is updated according to Timoshenko's beam theory. This formulation uses an algebraic method which combines a symbolical and a numerical application. Thus, the updated observability formulation is able to obtain not only the flexural stiffness but also the shear one. Besides this, a parametric equation of the estimates is obtained for the first time in the literature. Some examples of growing complexity are used to illustrate the validity of the the proposed formulation formulation.

1. Introduction

Damage in structures might produce changes in their mechanical properties. In order to quantify the magnitude of this damage Structural System Identification (*SSI*) might be used. This process is based on a subset of measured inputs and outputs (e.g. forces and/or displacements). Numerous papers about *SSI* have been written over the years. Sanayei et al. [1,2], Yan and Golinval [3] or Liao et al. [4], proposed various methods to deal with different problems in *SSI*.

The subset of measured inputs can be obtained by non-destructive tests that measure the structural response under a certain load case. According to the load nature, these tests can be classified as dynamic [5,6] or static [7–9]. Focusing on static tests, Sanayei and Onipede [10] presented an iterative optimization-based algorithm of the displacement equation error function for the parameter identification based on static test measurements. Banan et al. [11,12] proposed an optimization method to estimate member constitutive properties of the Finite Element Model, *FEM,* from measured displacements under static loading. Sanayei et al. [13] used measured strains in a real bridge under static truck loads for *FEM* updating. However, in all these methods it is assumed that shear stiffness does not govern the problem and, therefore, it is not taken into account. This assumption is traditionally used in most *SSI* methods (see [14]).

Matrix methods of structural analysis are universally accepted in structural design. These methods enable a rapid and accurate analysis of complex structures under both static and dynamic conditions. However, when applying matrix methods, the system must be modeled as a set of simple, idealized elements interconnected at the nodes. Matrix *SSI* methods are based on simplified structural models too. These include axial, shear and flexural deformation. Therefore, neglecting shear deformation can be assumed as a modeling error which is a simplifying assumption well justified in most of the structures. However, in some cases for both direct and inverse analysis, this modeling error can lead to unjustified rough results.

The assumption of neglecting shear deformation is explained by the fact that, for most structures, this effect is usually much smaller than the flexural one. Nevertheless, shear deformation might play an important role in some structures, such as deep beams. Eurocode EN 1992-1-1:2004 [15] defines deep beams as a beam for which the span is less than three times the overall section depth. ACI committee 318 [16], defines these elements based on two criteria: beams with clear spans equal to or less than four times the overall member depth or beams with concentrated loads within twice the member depth from the face of the support. In these structures, neglecting the shear deformation may affect adversely the stiffnesses estimated by *SSI* methods. Shear deformation also might be an important factor to be considered in some structures, for example, in high rise buildings (see [17,18]). In this

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field, Li et al. [19] modeled slender structures such as high rise buildings and chimneys as cantilevers with both flexure and shear deformation. Recently, Ebrahimian and Todorovska [20] presented a non-uniform Timoshenko beam model of a building, with piecewise constant properties along the height, together with an algorithm for structural system identification from earthquake records. In both works, shear stiffness is clearly taken into account on damage detection. However, other authors neglect this phenomenon. Kang et al. [21] presented a system identification scheme in time domain to estimate stiffness and damping parameters of a structure using measured acceleration. Lei et al. [22] proposed an algorithm based on the extended Kalman estimator approach for the identification of structural parameters and unknown excitation of high rise shear-type buildings with partial acceleration responses. These papers are limited to identify only the flexural stiffness and the story stiffness respectively.

According to Sahraei and Mohareb [23], shear deformation is traditionally neglected in thin-walled structures. Nevertheless, a number of studies discourage this assumption. Bhat and Oliveira [24] proposed the formulation of the shear coefficient of thin-walled prismatic beams. A formulation to incorporate the effects of shear deformation in thin-walled structures was proposed by Chen and Blandford [25] and Back and Will [26]. Shakourzadeh et al. [27] and Erkmen and Mohareb [28] studied the torsion analysis of thin-walled beams including the shear deformation effects. Van Phan and Mohareb [29] showed the importance of incorporating shear deformation effects when capturing predominantly torsional responses. Erkmen [30] studied the formulation for buckling analysis of thin-walled beams incorporating the shear deformation. Poul et al. [31] studied experimentally *CFRP* strengthened thin plated under shear loading. Chen et al. [32] analyzed the dynamic behavior of shear deformable sandwich beams. Hossain et al. [33] studied the impact shear resistance of double skin composite walls. Tong et al. [34] analyzed the behavior of plates subjected to combined bending and shear loading. Rasool and Singha [35] studied the non-linear behavior of shear panels. Kim and Choi [36], Henriques et al. [37] and Sabouri-Ghomi et al. [38] studied the effects of shear deformation in composite beams. Analyses of the effect of shear in thin web bridges can be found in [39,40].

The literature review shows that the effect of shear deformation is mainly based on the structural response at the element level. The studies about structural system identification including this phenomenon are restricted to dynamic excitations and the effects on static tests are not studied. This is the case of the observability techniques [41,42]. As most of the static methods presented in the literature, this method neglects the effect of the shear deformation into the structural system identification analysis. This paper analyzes how sensitive observability techniques are to shear deformation effects. Moreover, in order to take the shear deformation into account, a new formulation including the shear effects in observability simulation is proposed. All numerical simulations are based on measurement error free data obtained from numerical analyses. This paper will focus on evaluating the modeling error linked with shear effects, being numerical and measurement errors on structural system identification by observability treated elsewhere [43,44].

This article is organized as follows. In Section 2 the original observability method for structural system identification is briefly presented. This technique does not include the shear deformation. To illustrate the important role of this deformation in the identification of structures and to motivate the paper an example is analyzed. Section 3 introduces a new formulation to include the shear deformation into the observability analysis. To illustrate the application of this algorithm, a step by step example is presented. In addition, a numeric example is analyzed. Section 4 presents the application of the proposed algorithm for the structural system identification of a composite thin web bridge during its cantilevered construction. Finally, the conclusions obtained are displayed in Section 5.

2. Observability analysis without shear deformation

The stiffness matrix method is the most common implementation of the Finite Element Method (*FEM*) for structural analysis. The implementation of this method requires that the structure is modeled as a set of simple, idealized elements interconnected at the nodes. The material and stiffness properties of these elements are then compiled into a single matrix equation which governs the behavior of the entire idealized structure. In 2D, the traditional stiffness matrix [K] for a six degrees of freedom (two deflections (u and v) and one rotation (w) at the initial and final beam element nodes), beam element of length L and constant cross-section is:

$$[K]=\begin{bmatrix} \frac{EA}{L} & 0 & 0 & -\frac{EA}{L} & 0 & 0 \\ 0 & \frac{12EI}{L^3} & \frac{6EI}{L^2} & 0 & -\frac{12EI}{L^3} & \frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{4EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{2EI}{L} \\ -\frac{EA}{L} & 0 & 0 & \frac{EA}{L} & 0 & 0 \\ 0 & -\frac{12EI}{L^3} & -\frac{6EI}{L^2} & 0 & \frac{12EI}{L^3} & -\frac{6EI}{L^2} \\ 0 & \frac{6EI}{L^2} & \frac{2EI}{L} & 0 & -\frac{6EI}{L^2} & \frac{4EI}{L} \end{bmatrix} \quad (1)$$

where E, A and I are Young's modulus, area and inertia respectively.

2.1. Direct analysis of the stiffness matrix method

In static structural analysis, a statement of the equilibrium conditions together with strength of materials theory leads to a relation between forces and displacements that has the form of the following system of equations:

$$[K]\cdot\{\delta\}=\{f\}, \quad (2)$$

where $\{\delta\}$ and $\{f\}$ are the vectors of displacements and forces, respectively, in which the stiffness matrix is a singular matrix that leads to a system with infinite solutions For a more detailed explanation about the unicity of the solution of his kind of polynomial equation systems the reader is addressed to [50,51].

2.2. Inverse analysis of the stiffness matrix method by observability techniques

As it was mentioned in the introduction, in actual structures, unknown parameters, such as the flexural stiffness EI_j or axial stiffness EA_j of element j, may appear into the matrix $[K]$. These unknowns might be due to damage (e.g. by material degradation, such as carbonation or corrosion, or accidental actions, such as fires or impacts) or other uncertainties (e.g. lack of knowledge about the mechanical properties of the material). If the external forces introduced into a structure in a non-destructive test are known and some displacements are measured, the observability method can be applied into the *SSI* to found the values of these unknown parameters. Taking Eq. (2) where the matrix $[K]$ is partially unknown and with the aim of determining the value of the unknown stiffnesses (EA_j *and* EI_j) a modified system of equations can be rewritten as:

$$[K^*]\cdot\{\delta^*\}=\{f\}, \quad (3)$$

in which the products of unknowns are located in the modified vector of displacements $\{\delta^*\}$ and the modified stiffness matrix $[K^*]$ is a matrix of known coefficients with different dimensions than the initial stiffness matrix $[K]$. The new system leads to a non-linear problem due to the fact that unknown parameters, such as axial stiffness EA_j and flexural stiffness EI_j of the cross sections are multiplied by the unknown horizontal displacements (u_i), vertical displacements (v_i) and rotations at the *ith* node (w_i) of vector $\{\delta^*\}$. This fact implies that non-linear products of variables, such as $EA_j u_i$, $EA_j v_i$, $EI_j u_i$, $EI_j v_i$ and $EI_j w_i$ might appear, leading to a polynomial system of equations. These kinds of problems usually appear in science and engineering fields, (see [46,47]). Depending on the known