Damage identification in structural joints using the Virtual Distortion Method

A. Swiercz [1)], P. Kolakowski [2)] & J. Holnicki – Szulc [1)]
[1)] Smart-Tech Centre, Institute of Fundamental Technological Research, Polish Academy of Sciences, 02-106 Warsaw, POLAND
[2)] Adaptronica sp. z o.o., R&D company, 05-092 Lomianki, POLAND

ABSTRACT: This article is an encouragement to readers to participate in a benchmark competition regarding the identification of structural modifications. Participants will be rated in two categories: the first one concerns the identification of nodal connections (rigid or pin-joint). The second one is related to the identification of stiffness modifications of structural elements. In this work modeling of non-rigid nodal connections of members in 2D frame structures is briefly discussed. For modeling of nodal stiffness, the so-called virtual distortions are imposed in structural elements. Depending on assumed performance of structural nodes, different models of nodal connections can be applied.

1 INTRODUCTION

The Virtual Distortion Method (VDM) is a fast reanalysis tool covering many engineering applications including structural health monitoring (SHM) e.g. identification of defects like conductance loss in electrical circuits [1], delamination between composite layers [2], leakages in water distribution networks [3]. Damage identification in skeletal structures can be performed using this approach to point out defective elements with reduced longitudinal or bending stiffness as well as reduced mass (e.g. due to corrosion) [4].
Nodal connections are of high importance for safe operation of skeletal structures. This paper presents an SHM idea which is dedicated to identification of perturbations in such connections. In this work, the authors propose modeling of nodal connections which may be flexible, semi-rigid or prone to sliding movements in 2D frame structures. Using the VDM approach and depending on the type of nodal connections, appropriate initial strains (virtual distortions) are imposed in structural elements.

2 GENERAL CONCEPT OF THE VIRTUAL DISTORTION METHOD

For the truss finite element, there is just one component of strain ε_i and the corresponding virtual distortion ε_i^0. Virtual distortions applied to original structural elements modify their responses. The structure with introduced virtual distortions is called a modeled structure. On the other hand, let us consider a modified structure with some parameters actually modified. Demanding equality of strains and stresses for modeled and modified structure we get the following set of equations:

$$\mu_i \varepsilon_i = \varepsilon_i - \varepsilon_i^0, \tag{1}$$

$$\varepsilon_i = \varepsilon_i^L + D_{ij}\, \varepsilon_i^0, \tag{2}$$

where $\mu_i = \frac{\hat{E}_i \hat{A}_i}{E_i A_i}$ denotes introduced modification of axial stiffness in element i and ε_i^L refers to strain response of original structure in element i. The influence matrix D_{ij} introduced in Eq. (2), is a set of strain responses in element i caused by unit distortion $\varepsilon_j^0 = 1$ introduced in element j.

For the beam finite element there exist three components of strain. They can be found by solving the eigenproblem of the stiffness matrix for that element. Basic deformations corresponding to non-zero eigenvalues are illustrated in Fig 1. These are orthogonal strain components for the beam element.

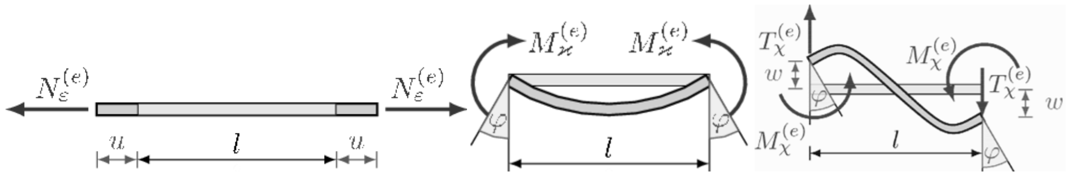

Fig. 1. Components of strain for finite beam element.

For the beam finite element, Eq. (1) and Eq. (2) remain valid, however, strain, virtual distortion, and modification parameter μ_i have three components:

$$\varepsilon_i = \left[\frac{u_i^{(2)} - u_i^{(1)}}{l_i}, \frac{\varphi_i^{(2)} - \varphi_i^{(1)}}{l_i}, \frac{6}{l_i}\left(\frac{\varphi_i^{(1)} + \varphi_i^{(2)}}{2} - \frac{w_i^{(2)} - w_i^{(1)}}{l_i}\right)\right] \text{ or } \varepsilon_i = [\varepsilon, \varkappa, \chi], \tag{3}$$

$$\varepsilon_i^0 = [\varepsilon^0, \varkappa^0, \chi^0], \tag{4}$$

$$\mu_i = \left[\frac{\hat{E}_i \hat{A}_i}{E_i A_i}, \frac{\hat{E}_i \hat{J}_i}{E_i J_i}, \frac{\hat{E}_i \hat{J}_i}{E_i J}\right], \tag{5}$$

where ε_i is expressed by local nodal displacements, $\mu_i^{(2)} = \mu_i^{(3)} = \frac{\hat{E}_i \hat{J}_i}{E_i J_i}$ denote introduced modification of bending stiffness in element i. Forces corresponding to strain components can be calculated for the modified and modeled structure according to the formulae:

$$N_i = \hat{E}\hat{A}\varepsilon, \qquad N_i = EA(\varepsilon - \varepsilon^0) \tag{6}$$

$$M_i = \hat{E}\hat{J}(\varkappa + \xi\chi), \qquad M_i = EJ\big(\varkappa - \varkappa^0 + \xi(\chi - \chi^0)\big), \tag{7}$$

$$T_i = -\frac{2}{l_i}\hat{E}\hat{J}\chi, \qquad T_i = -\frac{2}{l_i}EJ(\chi - \chi^0), \tag{8}$$

where N_i, M_i, T_i denote the longitudinal force, bending moment, and transverse force, respectively for the beam finite element, whereas $-1 \le \xi \le 1$ is a dimensionless coordinate.

3 MODELING OF NON-RIGID JOINTS USING VDM

Typically, software tools offer an implementation of rigid or pin-joint connections and sometimes rotational springs. The authors propose to model a wider range of nodal connections in frame structures, depending on nodal bending moment or nodal angle of rotation. The considered models are presented in Fig. 2:

a) rotational spring connection of bilinear elastic-elastic characteristic with the limit bending moment M_i^e;

b) rotational spring connection of bilinear rigid-elastic characteristic with the limit bending moment M_i^p;

c) pin-joint connection limited to an angle of rotation φ_i^l, which is dedicated to modeling of riveted joints prone to sliding rotations.

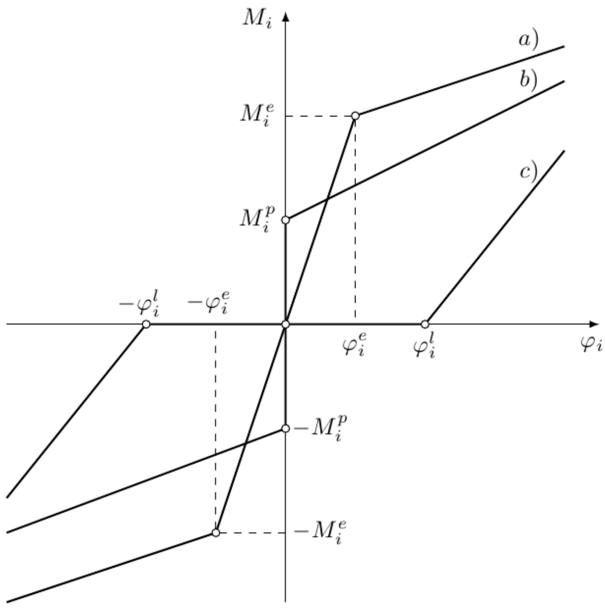

Fig. 2. Models of nodal connections.

Modeling of the above mentioned characteristics can be also covered by virtual distortions. To this end, components of virtual distortions for finite element are linearly composed in order to introduce designed nodal rotations φ_1 or φ_2 (see Fig. 3).

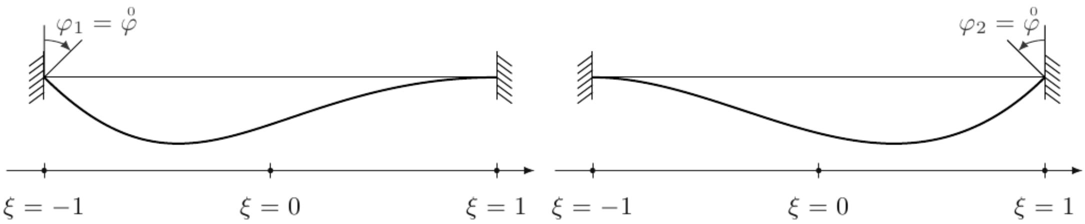

Fig. 3. Imposed nodal rotations for finite beam element.

The bending moment for a non-rigid node (according to Fig. 2) can be expressed by the relation:

$$M_i = k\varphi^0, \tag{9}$$

where k is the coefficient characterizing non-linear behavior of nodal rotations.
For the modeled structure we can write:

$$M_i = M_i^L + M_i^R = EJ(\varkappa^L + \xi\chi^L) + EJ(\varkappa^0 + \xi\chi^0). \tag{10}$$

Fulfilling the requirement of equality of strains and internal forces for the modeled and modified structure, we get the set of equations (Eq. (2), Eq. (10)) for determining virtual distortions modeling the non-rigid nodal connection (Eq. (9)).

4 BENCHMARK FRAME STRUCTURE

A benchmark test of a 2D frame structure presented in Fig 4 is announced for identification of non-rigid nodal connections as well as modification of structural elements. The structure is modular and consists of 11 steel elements and 10 nodes. All elements have theoretical length equal to 0.51*m* whereas the total span of the structure is equal to 2.04*m*. In the original structure, elements have uniform, rectangular cross-section (b=8*mm*, h=80*mm*), whose orientations are presented in Fig. 5, and have all rigid nodal connections.

Displacements and rotations at nodes 1, 2 and 9, 10 are fixed. The testing load can be applied by the user only in plane of the structure to nodes 3-8, with the restriction that the structure will work in the elastic regime. The structure will be basically excited by one load applied to one node, however the user can request several loads applied subsequently (not at the same time) to various nodes for solving the identification problem. The direction of the loadings is determined by angle α (see Fig. 4) and is limited by the nodal mechanism to the range α=(–π/4, π/4).

The users define their own time-varying excitation signal and select the measured nodal points (X- and Y-direction of acceleration). Measured data (gathered by the Bruel&Kjaer PULSE system) will be collected in the same points for the original and modified structure for the same test loading. The data corresponding to excitations defined by each user will be available via internet (smart.ippt.gov.pl). More detailed information concerning this structure can be found using the above mentioned web page.

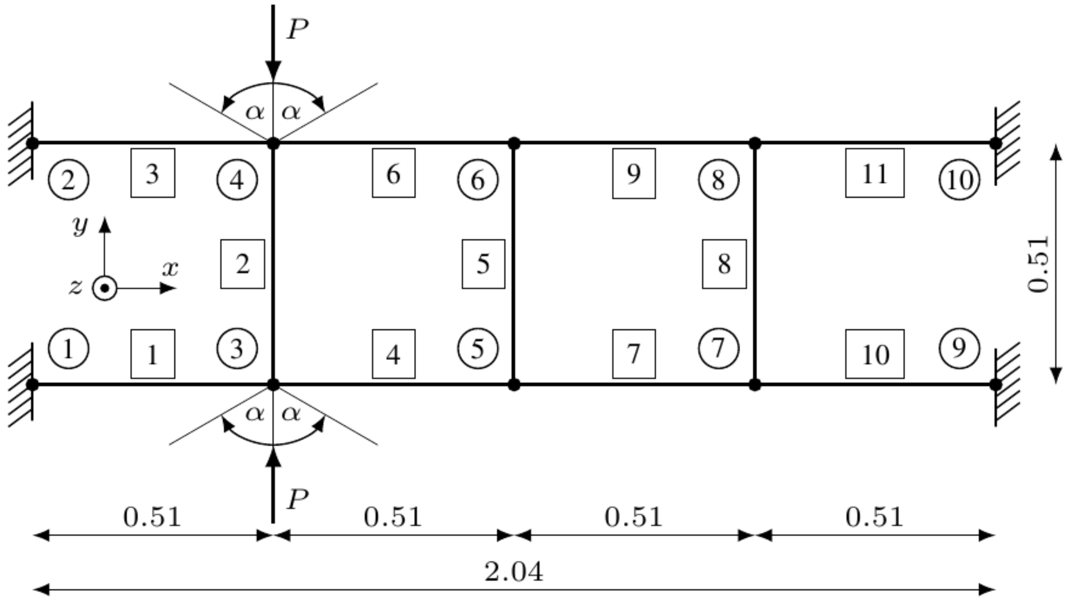

Fig. 4. Two dimensional benchmark frame structure.

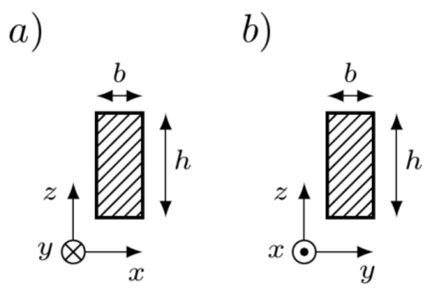

Fig. 5. Orientations of the elements: a) for element no.: 2, 5, 8; b) for element no.: 1, 3, 4, 6, 7, 9, 10, 11.

5 IDENTIFICATION PROBLEMS

Two identification tasks are defined:

1. Identification of nodal connections. The nodes 3 to 8 are designed to have the possibility of gradual switching between the rigid and non-rigid connection. In the extreme case, the elements can work as pin-joint connections and this case will be available for identification. Let us notice, that the number of combinations of modifications per

node is equal to 4. For example for node no. 3 (see Fig. 4), the hinge can exist at the end of the element no. 1, 2 or no. 4. By adding an extra hinge in an element adjacent to node no. 3, the pin-joint connection is created in this node.

Users are encouraged to use their own identification strategy for pointing out the modified nodal connections. The number and location of modifications will be the same for each user. The measured data for user-defined test loading will be accessible via internet (protected by password).

2. Identification of stiffness parameters of structural elements. The original structure (uniform cross sections, rigid nodal connections) is also designed for replacement of any element with another one of modified rectangular cross section and made of the same or different material. Users are asked to solve the identification problem according to their own procedures and to indicate the modified elements with an assessment of their axial (E_iA_i) and bending stiffness (E_iJ_i). In order to ensure comparable degree of complexity of the problem, each user will get the same number of modifications to be identified. Similarly to the previous identification problem, the measured data corresponding to user-supplied excitation (location, time-variation) will be available via internet protected by password.

6 EVALUATION AND SCORING

Among many possible definitions of evaluation of the identification problem, the authors decided to take into account following criteria: the total number of excitations, total number of sensors and quality of results of the identification problem:

$$F = n_L + n_S + F_r \tag{11}$$

where n_L is total number of testing loads, n_S is total number of sensors and F_r depends on result accuracy of the identification problem:

1. For identification of rigid or pin-joint connections. Let the vector **V** consist of the dot products of subvectors $\mathbf{v_i}$. The subvectors $\mathbf{v_i}$ are created for each element *(i)* and have 2 coordinates which may take the values of 0 or 1. Each coordinate is related to the identified connections of the element at its both ends – either rigid or pin-joint. If the connection is identified correctly then the corresponding coordinate is set to 0, otherwise it is set to 1. Then value of F_r is the sum of the vector **V** components:

$$F_r = \sum_i V_i \tag{12}$$

2. For identification of stiffness parameters of structural elements. The basis for calculations of F_r is the identified longitudinal and bending stiffness for each element according to the formula:

$$F_r = \sum_i \left(\left| \frac{(EA)_i^{real} - (EA)_i^{ident}}{(EA)_i^{real}} \right| + \left| \frac{(EJ)_i^{real} - (EJ)_i^{ident}}{(EJ)_i^{real}} \right| \right) \tag{13}$$

where $(EA)_i^{real}$ and $(EA)_i^{ident}$ denote the axial stiffness of the real and identified modification of an element i and modified one, respectively, whereas $(EJ)_i^{real}$ and $(EJ)_i^{ident}$ denote the bending stiffness real and identified modification, respectively.

7 CONCLUSIONS

The aim of the proposed benchmark is a comparison of different identification techniques dedicated to SHM problems. Two problems to be solve concerning plane frame structure are presented. The first one consists in the identification of nodal connections (rigid or pin-joint), whereas the second one concerns the identification of replaced original elements by finding their location and accessing changes in axial and bending stiffness. The results obtained by benchmark users will be rated according to the discussed criteria. More detailed information on the structure, technical data, measurement conditions can be found on the mentioned web page.

ACKNOWLEDGEMENTS

The financial support from the projects "Smart Technologies for Safety Engineering - SMART and SAFE" – TEAM Program – granted by the Foundation for Polish Science and "Health Monitoring and Lifetime Assessment of Structures" – MONIT – POIG.0101.02-00-013/08-00 from the EU Structural Funds in Poland is gratefully acknowledged.

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