 ISSN: 2321-8169
1696 - 1698

Vibration-Based Nondestructive Assessment of Rotational Stiffness of Structural Connections

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Abstract: This paper proposed a novel approach to assess the rotational stiffness of structural frame members using nondestructive vibration-based procedure. The procedure is useful for rehabilitation and retrofitting aging structures. Once the vibration signals of a frame member are measured and analyzed, a reverse engineering algorithm could be used to solve the vibration characteristic equation for the stiffness. The required signal conditioner and software are readily available and inexpensive.

Keywords: *Buildings, Connections, Nondestructive, Rehabilitation, Retrofitting, Stiffness, Structures, Vibration*

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I. INTRODUCTION

Report after report reinforces the prevailing critical disrepair state of aging and degrading structures. If ignored, those conditions could lead to catastrophic failures with probable human loss. Retrofitting and rehabilitation of structures are thus needed to reduce the vulnerability of those systems. There are many benefits from retrofitting and rehabilitation such as reduced loss of lives and damage to facilities, and the continuity of the society daily functioning. Thus, the retrofitting of structures is an essential component of long term infrastructure sustainability.

The decision of whether a structure needs rehabilitation or retrofitting or not requires information about its health in order to perform engineering calculations. Nonetheless, the true condition of structure are challenging in many situations because of the complexity of geometry, framing systems, detailing of connections, workmanship, etc.

This paper introduces a novel approach to detect the stiffness of connections which are essential for any engineering analysis. The approach is vibration-based, simple analytically, easy to conduct, and economic. The approach uses the rigor engineering mechanics fundamentals in conjunction with well-established and tested algorithm for solving equations in reverse orders.

II. ANALYTICAL AND EXPERIMENTAL FORMULATION

The connection between beams and columns in framed structures are commonly assumed either pined or rigid. In reality, the actual stiffness fall somewhere between these two extreme cases. Flexible connections are thus suitable to represent actual connections. Flexible connections provide moment capacity within the pin to rigid range.

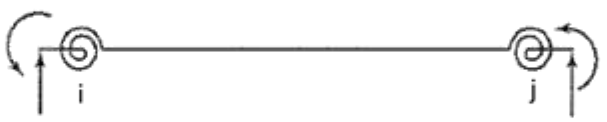

Fig. 1 Frame Element with Semi-Rigid Connections

Consider a frame element of length L and cross-sectional moment of inertia I with flexible joints at its ends with stiffness K_i and K_j, where I and j designate the ends, as shown in Figure 1. The explicit forms of the stiffness $[K]_{6x6}$ and consistent mass $[M]_{6x6}$ matrices are easily available in many references. It should be noted that the elements of these matrices include the following connection parameter C_i

$$C_i = \frac{L\,K_i}{E\,I + L\,K_i} \tag{1}$$

in which L is the member length and E is the modulus of elasticity of the element material. The equation of motion for free vibration of this element is

$$[M]\,\{\ddot{x}\} + [K]\,\{x\} = 0 \tag{2}$$

Where x is the displacement. The vibration characteristic value equation is thus

$$|[K] - \omega^2\,[M]| = 0 \tag{3}$$

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in which ω denotes the natural frequencies of vibration.

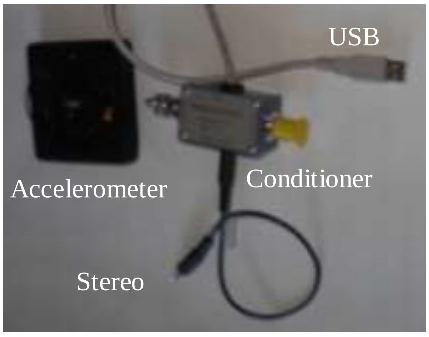

Fig. 2 Signal Conditioner

The vibration signals of frame elements can be measured in field tests using portable and affordable signal conditioners like the one shown in Fig. 2. Each signal can then be analyzed using FFT from which the fundamental frequency ω is determined. Equation 3 can then be solved using iterative techniques for the connections stiffness K_i and K_j.

In this paper, the solution of Equation 3 is conducted backward to obtain an input that would result in the given input. Given the state and objective of the equation, a search is provoked to reduce the difference between the two. The iterative search is performed on the initial state to produce a new state, and the process is recursively applied to this new state and the objective state. In general, a solution is found through trial and improvement iterative procedures.

This paper suggests the following complete procedure for the assessment of the rotational structural stiffness of an actual frame member

1. Determine the cross-sectional moment of inertia and modulus of elasticity of the member.
2. Measure and analyze vibration signal to determine the frequencies. This step is well developed in practice. There are many methods for vibration measurements and signal analysis. Usually, the FFT is used to determine the frequencies.
3. Solve equation 3 iteratively for K_i and K_j.

The described procedure has been analytically verified on a number of cases with known solution. Though this study is in progress, the obtained results are satisfactory to plan for the next phase with a broader scope than the one for the paper.

III. CONCLUSION

With the widespread aging infrastructure and economic challenges worldwide, retrofitting and rehabilitation of structures are the forefront of many engineering projects more than ever before. The primary goal in those projects is to extend the service life of structures and/or strengthen them for higher loads capacity. To conduct analytic computations, information about the actual properties of the systems are required. Nonetheless, the true condition of structures are usually complex and at the same time complicate obtaining the required information. This situation calls for reliable procedures to assess the structural condition of existing structures. The presented procedure is a part of an in progress study in the area of structural nondestructive evaluation.

This study replies to that call. It proposed a novel approach to assess the rotational stiffness of structural frame members using nondestructive vibration-based procedure. Using widely available and non-expensive equipment and algorithms, the dynamic signals of the members can be recorded and analyzed. Then, a reverse engineering solution could be found for the rotational stiffness of the member' connections. The suggested procedure has a number of advantages including its nondestructive approach, ease of applications routinely. It was previously demonstrated on utility poles in order to determine the size of extend of damages.

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ISSN: 2321-8169
1696 - 1698

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