VIBRATION BASED APPROACH FOR STRUCTURAL HEALTH OF IN RETROFITTING OR REHABILITATION OF CONSTRUCTION BUILDINGS

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ABSTRACT

Reports after reports have documented the fragility state of many buildings and called for the urgent attention because of their critical disrepair state due to aging and degradation. Delaying prompt actions implies a high risk of catastrophic failures and probable human loss. Retrofitting and rehabilitation provide remedies to reduce the vulnerability of those systems. Almost always, data about the structural health of the components in a building being considered for retrofitting or rehabilitation is required for any engineering calculations. Nonetheless, the true structural condition is challenging to the practitioners in many projects because of the complexity of geometry, framing systems, detailing of connections, workmanship, etc. This paper is an attempt to deal with these complexities in an easy to apply procedure yet leading to reliable and fast outcomes. It will present a novel approach to assess the stiffness of joints of aged members based on the rigorous vibration fundamentals that have been proven reliable. The procedure requires a widely available and affordable signal conditioner, and an algorithm that can be easily developed in a spreadsheet. The method has been successfully evaluated via numeric results obtained.

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

GENERAL

The need for structural rehabilitation or retrofitting of buildings is motivated by the following circumstances:

- The existence of visible defects in the building.
- Damage after a particular event, like an earthquake, that affects its stability.
- The change of the use of the building.
- Requirement imposed by new codes.

The assessment of its actual condition is a necessary step in the structural rehabilitation or retrofitting projects. This step is complex because of the aesthetical and architectural configurations, the structural system of the building, the weak or damaged areas in the building, and the types of structural components. These factors interact with each other and influence the structural performance of the components and the entire system. This in turn presents many technical challenges for diagnosticating, analysis, and rehabilitation or retrofitting tasks. For remedial solutions, practitioners rely on engineering calculations that require the assessment of the true structural condition of the building and its components.

The assessment of the actual condition of a building can comprise in-situ tests, laboratory tests, field tests, and other procedures and protocols as described by the authority in charge of the

projects. In general, tests are expensive and not simple to perform. From this perspective, non-destructive approaches have been adopted for fast yet reliable outcomes.
The remedial work is not sufficient in any retrofitting or rehabilitation project. Once the repair part is completed, the monitoring of the building during a certain period of time begins to help the elaboration of the retrofitting strategy. Monitoring procedures collect and store the acquired data and transmit it to a designated station. By comparing the results obtained from the monitoring of the building with the results obtained from its engineering modelling, it will be possible to either refine the modelling or modify the repair work. The monitoring phase could also be expensive and cumbersome. Thus, non-destructive approaches lend practical ways to overcome these obstacles.

The basic human needs include shelters to protect humans from environmental and other effects. Residential buildings meet this particular need. References 1, 2, 4 and 5 represent selected pertinent sources that depict the state of deteriorated buildings including residential and the methods used for assessing their structural health. One could see in these sources and many others the complexity of the technical tasks involved in the retrofitting and rehabilitation projects.

DESCRIPTION OF TECHNICAL PROBLEM

As described previously, remedial and monitoring activities require data obtained from tests performed on the building in rehabilitation or retrofitting projects. In general, the data is integrated with the engineering modelling of the building to render stresses, critical zones, the design of the eventual strengthening, etc.

The structural models of buildings incorporate the set of structural components used to represent the structural functioning of the building. Beams, columns, slabs, walls, are examples of the typical components. Using calculation methods and theories that are readily available, the model should adequately simulate the structural behavior of the building, as accurate as possibly accepted by the personnel involved in the project.

The modelling of existing buildings is, in general, more difficult and less reliable than in the case of new buildings. This is due to several factors, such as:

- The difficulty in adequately modelling its structural configuration.
- The uncertainties related to the characteristics of the materials and the components in the building system.
- The influence of past events such as earthquakes.
- The imperfect knowledge or available information about past repairs made.

Additional factors that compound the analytic modeling include the need for great experience and intuition about the structural behavior of building systems, local damages such as cracks, the actual constituent relationships; the

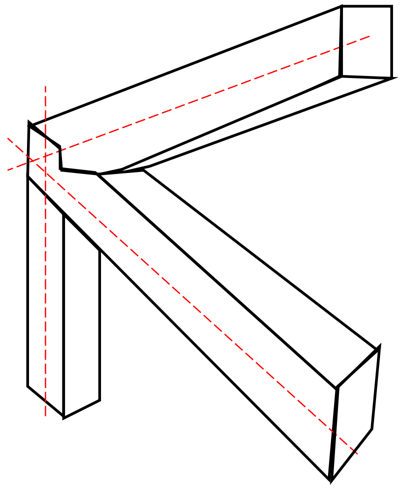

Fig. 1 A typical Structural Joint

alterations over time such as the creation of openings or the removal of components (headers, walls, etc.) or the increase in the height of some spaces, etc. These factors, individually or combined, affect the static and dynamic characteristics of the components and their assembly, thus complicate the engineering tasks involved in retrofitting or rehabilitation projects.

To elaborate, what should the characteristics of the connection shown in Fig. 1 be for engineering calculations? Is it a pin, rigid, or something else? What should be the answer if the connection is reinforced with binding strip, internal bolt, stirrup, or tension ties?

VIBRATION BASED APPROACH TO ASSESS THE STIFFNESS OF STRUCTURAL CONNECTIONS

The connection between beams and columns in framed structures are commonly assumed either pined or rigid. In reality, the actual stiffness is neither and 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. 2 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 2. The explicit forms of the stiffness $[K]_{6x6}$ and consistent mass $[M]_{6x6}$ matrices are 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

$$|[K] - \omega^2 [M]| = 0 \qquad (3)$$

In which ω denotes the natural frequencies of vibration.

The vibration signals of frame elements can be measured in field tests using portable and affordable signal conditioners like the one shown in Fig. 3. This type of conditioner is USB operated thus works with any computer hardware such as laptops or similar portable devices. There is also free or relatively cheap yet proven reliable software for recording the signals.

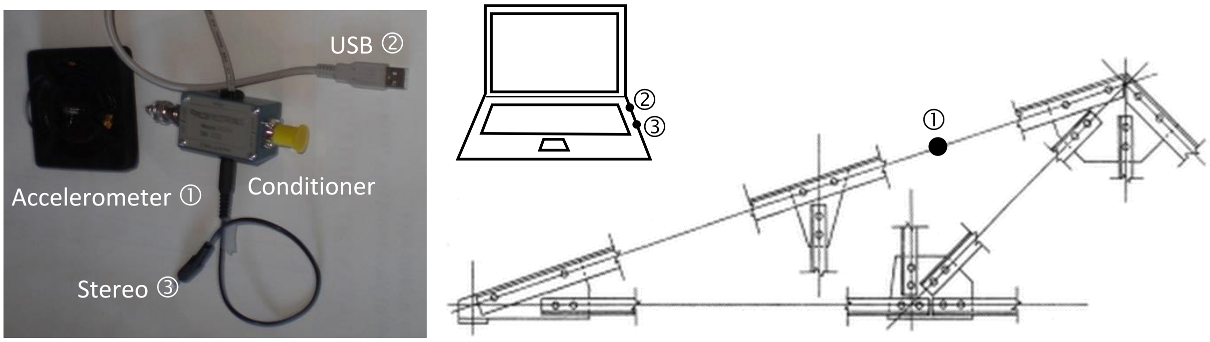

Fig. 3 A USB Signal Conditioner and Field Set-up

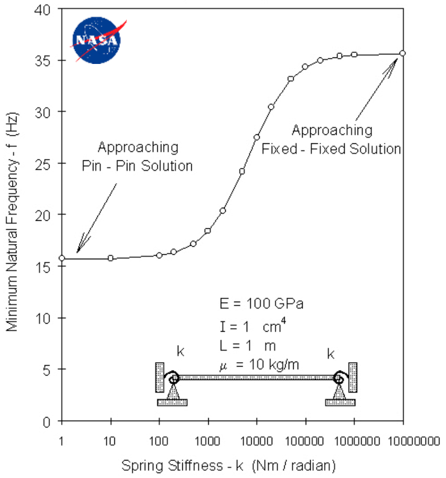

Fig. 4(a) Frequency-Stiffness (NASA)

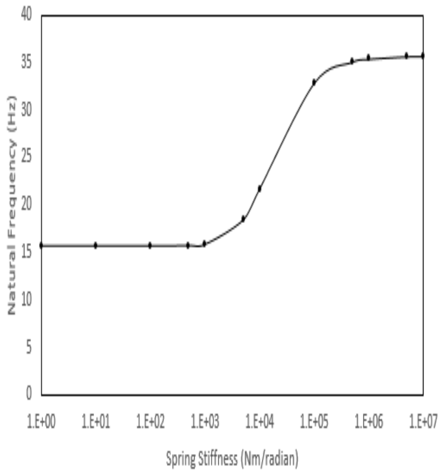

Fig. 4(a) Frequency-Stiffness (Paper)

Each recorded signal can then be analyzed using FFT from which the fundamental frequency ω is determined. The FFT algorithm is also available in many mathematic software or could easily be developed using any programming language.

Equation 3 can now 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 measured 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.

Putting the described direct, easy to perform, and inexpensive procedure together, this paper suggests the following complete protocol for the structural assessment of the joint stiffness of an actual frame member in a building under rehabilitation or retrofitting:

1. Determine the cross-sectional geometric and the material properties of the member.
2. Use a USB conditioner connected to a laptop to detect the vibration of the member.
3. Analyze the recorded signal to determine the natural frequency.
4. Solve Equation 3 iteratively for K_i and K_j.

The above described procedure has successfully been tested using a number of selected problems with known analytic solutions. Using the Finite Element Method, NASA (3) investigated the broad spectrum of joint stiffness from pin to rigid using the ratio of the rotational stiffness to the flexural stiffness of structural members as shown in Fig. 4a. NASA's data was used to run the method proposed in this paper and the results are shown in Fig. 4b. It is seen that the results from NASA and the proposed method are in agreement with insignificant differences. This success is considered as a first step of an in-progress long project. In residential buildings, the proposed method is useful to assess the joints of wood, metal such as steel and light gage, and concrete framing systems such as trusses. In addition, the presented approach has been used in other applications such as non-destructive assessment of defective utility poles. In these two developments, the intent is to provide means to deal with the vulnerability of aging infrastructure exposed to unprecedented and no longer predictable environmental and man-made loadings.

CONCLUSIONS

This paper proposed a novel approach to assess the stiffness of structural frame members using nondestructive vibration-based procedure. The procedure is useful for rehabilitation and retrofitting aging buildings. The field application of the method includes the four steps described in the paper and its analytic validity was checked by comparison with available methods like that from NASA (3). Once the vibration signals from a member are measured and analyzed, a reverse engineering procedure could be applied to solve the vibration characteristic equation for the stiffness. The required signal conditioner and software are readily available and inexpensive.

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