Health Monitoring using the Frequency Response under Compressive Load

P. H. Arundas* and U. K. Dewangan

Department of Civil Engineering, National Institute of Technology, Raipur - 492010, Chhattisgarh, India 23arundasph@gmail.com, dewangan.umesh25@gmail.com

Abstract

Objectives: This paper presents a health monitoring criteria development aspect based on the frequency response spectrum under axial compressive load on wooden samples. **Methods/Statistical Analysis:** The compression tests are performed on different wooden specimens as per IS:1708 (Part VIII and IX):1986. The impact echo test is conducted at certain load intervals under increased compressive load and the frequency spectrum was monitored. A MATLAB based code is used to calculate the dominant frequency values of the sound signals corresponding to each impact echo test. The graphs for frequency and compressive load are plotted for different samples. **Findings:** Interesting conclusions were obtained from the frequency plots under compressive load before failure and after failure. It was observed that loading decreases the frequency values. But at the point of initial major crack, frequency was increased due to length reduction. **Applications/Improvements:** A health monitoring criteria can be developed based on the frequency response trends by observing these increased value of frequency when tested on the wooden samples. The damaged and undamaged state were predicted successfully.

Keywords: Compressive Load, Frequency Response Spectrum, Health Monitoring, Impact Echo Test, MATLAB

1. Introduction

Structural Health Monitoring (SHM) is the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. It involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system's health. The Structural Health Monitoring system installed on a building or any significant structure gives a lot of benefits and that are depend on the specific application. Monitoring reduces uncertainty. It discovers deficiencies in time and increases safety. It insures longterm quality. Finally, a proper structural management can achieve through SHM.

There are several methods to determine the health of wooden structures. Most of them are nondestructive

*Author for correspondence

tests and till date many researchers have successfully achieved it. Different sensors such as micro bending sensors, Fabry-Perot sensors, Raman scattering sensors etc. are introduced for the health monitoring of timber bridges¹. An air coupled Ultrasound method is introduced for glued laminated timber² and concluded that the variations of ultrasound amplitude due to heterogeneity of wood are considerably larger than a solid wood³ have demonstrated a smart timber bridge by efficient structural health monitoring. They achieved this through the development of different types of sensors for the detection of different parameters and development of data processing systems. Vibration based approaches including Ultrasonic techniques and low frequency techniques are useful for the delamination detection in the wooden structures. This is done in wood-based-composites also⁴. Another vibration based damage identification methods for beam or plate type structure is explained by⁵. They are included natural frequency-based methods, Mode shapebased methods, Curvature/strain mode shape-based methods in their study. Loading, significantly affects the vibration response of a structure. Based on the frequency under different types of loading, researchers have reached to numerous findings. These conclusions are significantly helpful for the development of structural health monitoring of various structures.

With increase in the load, crack will form on any structure. This crack causes the reduction in the value of stiffness and hence there will a reduction in the frequency also. The reduction of natural frequency due to flexural cracks or shear cracks in RCC members is obtained⁶. They concluded that since the further change of frequency is quite limited further flexural damage such as the exfoliation of concrete and the local buckling of reinforcements is unlikely identified. Support conditions also affect the vibration characteristics. The RCC beam with stiffer support shows comparatively lesser vibration characteristics than the one with a softer support. These are explained in modeling of the RCC beam by considering the degradation of vibration characteristics due to flexural damage^z. ⁸ conducted a study on the natural frequency of prestressed concrete beams experimentally. Based on this it is clear that length of the beam also affects the vibration characteristics. For small length, there will be high value of frequency. Machining process influences the acoustic properties of wooden boards. This was obtained from Frequency Response Function plots done by². From the studies conducted on the characteristics of wooden diaphrams¹⁰, a significant variation of frequency with displacement is obtained. This gives further clarification on the relation between frequency and stiffness of the wooden material under some loading.

In this paper, the frequency response of different wooden samples under different loads is explained by the help of some mathematical expressions.

2. Theoretical Basics

The relationship between frequency and stiffness is given in Equation 1. When the load increases, the stiffness will reduce. So the frequency also will reduce.

$$f = 2\pi \sqrt{\frac{k}{m}} \tag{1}$$

Length of the sample also affects the frequency response. For large length, frequency value will be small. When cracks are formed, the material's solid length will reduce. So for some loads, there will be a chance of getting high value of frequency. In the case of a simply supported beam, the mathematical expression for natural frequency and the length is given by⁸ as follows,

$$f = \frac{\pi}{2} \sqrt{\frac{EI}{mL^4}}$$
(2)

When the experiment conducted on the simply supported beam⁸, it is found that the natural frequency of the beam reduces with axial compression if it carries axial load (termed as beam-column). If the frequency is measured at regular intervals, the nth natural frequency (ω_n) is given by

$$\omega_n^2 = \left(\frac{n\pi}{L}\right)^4 \frac{EI}{m} - \left(\frac{n\pi}{L}\right)^2 \frac{P}{m}$$
(3)

From the study of frequency response of differently machined wooden boards⁹, the ith mode frequency with mechanical properties of a homogeneous square plate is given by

$$f_i = c_i t \sqrt{\frac{E}{\rho \left(1 - \nu^2\right) L^4}} \tag{4}$$

From the bending vibration test conducted on a cantilever beam¹¹, a closed form solution of the nth circular natural frequency (ω_{nf}) is found out by,

$$\omega_{nf} = \alpha_n^2 \sqrt{\frac{EI}{mL}}$$
(5)

It is clear that any type of load on any structure will create cracking. This crack can be located by the help of frequency domain which is formed by using a Fourier transformation. For this, the peak values in the frequency domain are used. The depth of crack and the frequency from an impact echo test¹² are related by

$$f = \frac{C_p}{2d} \tag{6}$$

Sometimes frequency values may be constant with increase in load. This is because of the constant stiffness when load is increased. We know that the relation of stiffness, load and deformation as Equation 7,

$$k = \frac{w}{\Delta} \tag{7}$$

When load increases the deformation of the material also increases. So if the load and deformation changes with constant proportion, the stiffness will not change.

From the above all expressions it is clear that, loading is directly or indirectly affects the frequency values. There are a lot of parameters those affect the frequency such as stiffness, length or size, mass, modulus of elasticity, density, poison's ratio etc. In this paper, it is mainly focussed on stiffness and length of the material which influence the value of frequency. Equation 1 shows the direct relation between frequency and stiffness. So we can say that the loading induces the reduction of stiffness hence reduces the frequency. From equation 2 and 4, it is clear that frequency is inversely related to the length. Equation 3 gives the effect of length and load on the frequency value. These all are helpful to explain the frequency response of wooden samples under compressive load.

3. Experimental Setup

The experiment consists of compression test along with impact echo test. The specimens of babool, sal, teak and bija are used according to IS 1708(Part VIII and IX)¹³. There are two types of compression test for timber according to IS code. One is compression parallel to the grain and other is compression perpendicular to the grain. For the first case, specimens of 5cm x5cm in cross section and 15cm length are used and for the second case, 5cm x5cm in cross section and 20cm length specimens are used. Ten specimens are used for each type of wood. Then the compressive load is increased. At each 20KN load interval, the impact echo test is conducted.

A rebound hammer is used to create a uniform impact on the specimens. The frequency values for each impact are recorded using the transducer which is operated based a MATLAB program. After recording the frequency values for different wooden specimens, the dominant frequency values for each impact are found out by the help of a Fast Fourier Transform based MATLAB code. The experimental arrangements are shown in Figure 1. The schematic diagrams of the experiment are shown in Figure 2.

4. Result

After calculating the dominant frequency values, the graphs for frequency and compressive load are plotted for different wooden samples in the two cases of compression. The behaviour of frequency with axial compression for each specimen is explained.

4.1 Compression Perpendicular to the Grain

Figure 3 shows the frequency response of the different wooden specimens under axial compression perpendicu-



b) Compression Parallel to Grain

Figure 1. Experimental arrangement for compression test and impact echo test. a) Compression perpendicular to grain b) Compression parallel to grain.



b) Compression Parallel to Grain

Figure 2. Schematic diagram for compression test and impact echo test.









Figure 3. Typical frequency vs. load diagram of different wooden materials for compression perpendicular to the grain. a) Babool b) Sal c) Teak d) Bija.

lar to the grain. It can be seen that in the beginning stage of the compressive load, the values of frequency are reduced for all the specimens. It is because of the reduction in the stiffness due to loading. Frequency is directly proportional to the square root of stiffness. The interesting observation can see that, in some portions of the frequency curves, the frequency is not changing with increase in the load. Here it can say that the stiffness is not changing with the load. The reason is, the specimen is subjected to some deformations. These deformations are increased with compressive load. Both of these are increased in a constant proportion. Hence the stiffness became constant and the frequency also became constant. From the damage detection of retrofitted beam¹⁴ it is observed that, stiffness can become constant when load increases. After certain increment in the load, the frequency values are increased. These are found in specimens of babool, sal and bija. It is due to the change in the size of the specimen. After the formation of crack length of the specimen is reduced. So this reduction in the length is affected the frequency value. Frequency and length are inversely proportional. Further increment in the load caused a decrease in the frequency value for most of the wooden samples. But when compared to babool, sal and bija it is observed that the frequency variation in teak specimens is less (Figure 3 c).

4.2 Compression Parallel to the Grain

Figure 4 shows the frequency response of the different wooden specimens under axial compression parallel to

the grain. Here it is observed that in all wooden samples, the initial variation of frequency is same as in the first case (compression perpendicular to the grain). The length reduction of babool after crack formation is very less. So the frequency values are increased slightly (Figure 4a). But from the Figure 1a, it is clear that the increase of frequency after length reduction is very large. In sal, the frequency response under compression parallel to grain is same as in the first case (Figure 3b). The frequency variation of teak specimens is also same as in the first case (Figure 4c, Figure 4c). In bija specimens, the frequency value is first decreased as previous and then increased. Further loading decreased the frequency and finally it became a constant value up to failure (Figure 4d).







Figure 4. Typical frequency vs. load diagram of different wooden materials for compression parallel to the grain. a) Babool b) Sal c) Teak d) Bija.

5. Discussion

From all the frequency response spectrum of different wooden samples under axial compression shown above, it is clear that loading influences the vibration characteristics deeply. When load is increased, the deteriorating chance will be high. The cracking tendency will increase. Then the frequency of the material will decrease due to the reduction in the stiffness. That can be easily observed in all graphs plotted above. Another thing observed is, the wooden material undergoes for lateral displacement with loading. So when load increases the displacement also increases. Because of this, the stiffness of wooden materials became constant (Equation 7). So the frequency values became constant with increase in compression. These can be identified by observing the different portions of all graphs shown in Figure 3 and 4. An interesting thing is observed that, there is an increase in frequency with increase in the load. This is because of the length reduction of the wooden samples after cracking. For small length, the value of frequency will be high. The above all inferences are quite useful for the prediction of the health performance of the wooden materials.

6. Conclusion

After drawing inference from the graphs of Babool, Sal, Teak and Bija under axial compressive load it can be concluded that the frequency behaviour of Teak is uniform for both compression perpendicular and parallel to the grain. Beyond a particular value of load, the frequency values in teak specimens became constant due to constant stiffness (based on Equation 1). Another important conclusion was obtained that, whenever the initial major crack was formed, in that point of loading frequency values were increased which is a clear indication of crack formation.

7. References

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NOTATIONS USED

- The following symbols are used in this paper:
 - f = frequency
 - E = Young's modulus of the material
 - I = moment of inertia of the section
 - m = mass per unit length of the beam
 - L = span of the beam
 - l = length or width of the wooden specimen
 - n = an integer value indicating the mode number

P = axial force on the beam (positive, if N is compressive; negative, if N is tensile)

- C_i = constant depends on i (i represents the mode number), board thickness, poisson's ratio and size of the
 - specimen
 - t = wooden board thickness

 ρ = density of the board

v = Poisson's ratio

 α_n = parameter calculated based on eigen values of the nth frequency

- C_p = velocity of the longitudinal wave d = depth of crack or depth of the structure
- k = stiffness
- w = load