Grading of sawn timber using the vibration technique - Locating imperfections based on flexural mode shapes

Min Hu¹, Marie Johansson², Anders Olsson³, Charlotte Bengtsson⁴, Anders Brandt⁵

Abstract  The present study aims at investigating the potential of using mode shape or mode shape curvature (MSC) for detecting defects in wooden beams. It includes modal analysis, Finite Element (FE) modeling and visual scanning. An FE model was created to investigate the effect of defects of different size and location on the mode shape/MSC. The mode shape/MSC showed a good potential to be used for finding defects. An experimental study on 17 boards of Norway spruce, dimensions of 50×150×3900 mm, was conducted using experimental modal analysis. The findings reveal that: (1) the mode shape/MSC studied in the FE-model could be used to locate defects, (2) the method is very sensitive to measurement noise and it requires an accurately measured mode shape, (3) an error analysis shows that it is not possible to achieve the accuracy needed using accelerometers.

Keywords  experimental modal analysis, finite element modeling, mode shape, mode shape curvature, resonance frequency, strength grading, visual scanning

Abbreviations  
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>FE</td>
<td>Finite Element</td>
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<tr>
<td>FRF</td>
<td>Frequency Response Function</td>
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<tr>
<td>MOE</td>
<td>Modulus of Elasticity</td>
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<tr>
<td>MSC</td>
<td>Mode Shape Curvature</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>SLDV</td>
<td>Scanning Laser Doppler Vibrometer</td>
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</table>

1. INTRODUCTION

Most strength grading methods are based on the relationship between one measured MOE value for each board and the bending strength. The fundamental assumption applied is that the measured MOE is valid for the whole board. However, for most pieces of timber this is not true because defects exist and break the even distribution of material properties. Many studies have shown that with better knowledge of local variation of MOE, a higher coefficient of determination (R²) with respect to bending strength can be obtained (Isaksson 1999, for example). Thus locating defects, an important

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step in obtaining the local variation of MOE, becomes an interesting subject for the purpose of strength grading.

One way of locating defects could be based on vibration technique, which has been popularly used for structural damage detection. The basic idea of this method is that damage-induced changes in the physical properties such as mass and stiffness will cause changes in modal parameters i.e. resonance frequencies, modal damping and mode shapes (Fan and Qiao 2010). The technique has been used to study large single defects in wood (Yang et al. 2002). The purpose of the present study is to study the potential of using mode shape/MSC to locate natural defects in wooden beams. The study combines FE modeling, visual scanning and experimental modal analysis. The method and results of FE modeling are presented in section 2; section 3 deals with experiments including material and method as well as some selected experimental results; in section 4, error analysis are performed; finally in section 5, a short discussion is presented and some conclusions are drawn.

2. FE MODELING

2.1. Method

A simplified FE model of a wooden board, of dimension 50x150x3900mm, was created using commercial software Abaqus to simulate locating defects using mode shape/MSC.

![Figure 1](image)

*Figure 1 – A simplified FE model of a wooden board which contains several groups of defects. (The lines in the beam shows the partitioning of the beam for the creation of equally spaced positions on both edges.)*

The round parts in darker colors in the model were inserted into the structure to simulate defects, for example knots. As shown in Figure 1, these ‘knots’ were assigned to different sizes and positions throughout the beam’s length and height. The beam model was a 3D-model using a total of 74956 linear hexahedral elements, which has an approximate size of 7.5mm. The material parameters employed are given in Table 1.

<table>
<thead>
<tr>
<th>E [GPa]</th>
<th>ρ [kg/m³]</th>
<th>ν [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear wood</td>
<td>12</td>
<td>500</td>
</tr>
<tr>
<td>Knots</td>
<td>2</td>
<td>500</td>
</tr>
</tbody>
</table>

The displacement of two edges - edge1 and edge2 which were highlighted in Figure 1, were extracted as the mode shape vector from the FE model. Afterwards the mode shape vectors were put into Matlab for further analysis: the difference between the mode shapes of the two edges were calculated and plotted; the curvatures of the two mode shapes were calculated using the Matlab built-in function `del2`; the difference between the MSCs of the two edges were also calculated and plotted; finally the difference between mode shapes and MSCs were correlated to the distribution of the defects in the beam model. The simulations were done for both flatwise and edgewise bending modes.

2.2. Selected results

The mode shape vector of each edge from the FE calculation had 101 components, i.e. ΔL (cf. Figure 1) between two neighboring points was 39mm.
2.2.1. Flatwise bending mode

The result of the first flatwise bending mode is shown in Figure 2. Figure 2(a) shows the mode shapes of edge1 and edge2, which are almost identical; Figure 2(b) shows the difference between the two mode shapes and the MSCs. Both of them have 5 peaks which clearly indicate the positions of 5 groups of defects in the beam model. Another observation made in Figure 2 is that knots located close to the ends of the beam cannot be detected. The reason could be that too little curvature occurs at ends of the beam.

![Figure 2](image)

**Figure 2** – The 1st flatwise bending mode: (a) the plot of mode shapes of edge1 and edge2; (b) the difference between the mode shapes of edge1 and edge2 (the thin line); the difference between the MSCs of edge1 and edge2 (the thick line).

2.2.2. Edgewise bending

Very similar results were obtained from the edgewise bending mode, shown in Figure 3. It should be noted that compared to the results of the flatwise bending mode in Figure 2, the peak levels obtained from the edgewise bending mode are higher.

![Figure 3](image)

**Figure 3** – The 1st edgewise bending mode: (a) the plot of mode shapes of edge1 and edge2; (b) the difference between the mode shapes of edge1 and edge2 (the thin line); the difference between the MSCs of edge1 and edge2 (the thick line).

3. EXPERIMENTS

3.1. Material and method

In the experimental study, a total of 17 boards of Norway spruce of dimensions 50×150×3900 mm, were investigated. Before testing, the boards were conditioned in a climate room which has a temperature of 20°C and a relative humidity of 65%. Two kinds of laboratory studies were performed – WoodEye scanning and experimental modal analysis.
3.2. WoodEye scanning

In order to obtain information on position and size of defects within boards, a visual scanning on each board was implemented using WoodEye scanner (Petersson 2010). The WoodEye scanner detects defects using a combination of cameras capturing normal images and images of the tracheid effect using a line of dot lasers. The scanner can deliver a list of the size and position of several types of defects such as sound knots, black knots, holes and dirt for example. A defect database of all 17 boards, which was used as a reference value throughout the present study, was obtained from WoodEye. Figure 4 shows an example of the size and location of the defects for one side of board number B12.

![Figure 4 – Knots located using the WoodEye scanner for one side of the board B12.](image)

3.3. Experimental modal analysis

3.3.1. Test setup

In total 4 sets of modal tests with different suspension conditions, excitation methods, measurement point number etc were carried out. The free-free boundary condition was aimed to achieve for all the measurements by using two different suspensions - the boards were hang horizontally via two rather soft rubber bands and the boards were suspended vertically via a rather stiff and thin rope. Additionally, the vibrations of boards were excited with two different ways - hammer blow and shaker excitation. The 4 sets of tests with detailed setups are listed in Table 2.

<table>
<thead>
<tr>
<th>Suspension</th>
<th>Excitation method</th>
<th>Flatwise</th>
<th>Edgewise</th>
<th>Number of measured points</th>
<th>Accelerometers used</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Horizontal Hammer impulse</td>
<td>yes</td>
<td>yes</td>
<td>27</td>
<td>14</td>
</tr>
<tr>
<td>M2</td>
<td>Vertical Shaker - pseudo random</td>
<td>no</td>
<td>yes</td>
<td>391</td>
<td>14</td>
</tr>
<tr>
<td>M3</td>
<td>Vertical Shaker – pseudo random</td>
<td>no</td>
<td>yes</td>
<td>131</td>
<td>1</td>
</tr>
<tr>
<td>M4</td>
<td>Horizontal Shaker - random</td>
<td>yes</td>
<td>no</td>
<td>79</td>
<td>2</td>
</tr>
</tbody>
</table>

To measure the frequency response, an FFT analysis system with 16 channels and a number of maximum 14 accelerometers (net weight 8g of each) were employed, in addition the impulse hammer and shaker. The accelerometers were attached to the boards using wax.

3.3.2. Selected results

The modal analysis results of one board B12 using test setup M4 are shown in Figure 5. In this case 2 accelerometers were used, which were placed respectively on two edges (equivalent to edge1 and edge2 in the FE model) of the board. To accomplish the measurement, the two accelerometers were moved synchronously 79 times to obtain the mode shape of the entire board. It was however difficult to extract any useful information from the achieved mode shapes or the MSCs.
Figure 5 – The lowest 4 flatwise bending modes: (a) mode shapes of two edges; (b) the difference between MSCs of two edges of the board B12.

4. ERROR ANALYSIS

4.1. Accuracy estimation

Although great effort was paid to improve the quality of modal tests, the measured mode shapes were not good enough to point out the defects as clearly as shown in Figure 2 and 3, i.e. from the FE analysis. It shows that this method requires a very high accuracy of the measured mode shape. The accuracy needed for this method can be estimated by a simulation in Matlab: introduce random noise to FE modeling results of mode shapes; calculate the difference of mode shapes and the difference of MSCs and observe the changes; increase the noise gradually to a certain level on which the information shown in Figure 2(b) gets destroyed.

Figure 6 – Influence of random error (with a RMS value of 0.01%) introduced to mode shapes on the difference of mode shapes/MSC.

Figure 6 shows the difference of the mode shapes and the MSCs after a normally distributed random error with mean value of 0 and Root Mean Square (RMS) value of 0.01% is introduced to the mode shapes - the thick line is the same as shown in Figure 2(b) which indicates defects correctly and clearly; the thin line shows the same items but after the random error is introduced. It can be seen that with a random error with a RMS value 0.01%, the useful information is almost drowned in the noise. So, it could be assumed that the accuracy required for the measured mode shape must be better than 0.01%.
4.2. Error tracking and estimation

When the accuracy required for this method is known, the natural following step is error tracking from the measurements and to estimate the level of those errors. There are some errors that can be traced such as position error, angle error, mass loading effect and modal parameter estimation error etc.

4.2.1. Position error

In position error, the ‘position’ means the accelerometer position where it is mounted in the reality. For example a certain position on the specimen intended to be measured should be at 1.000m from the end. If the accelerometer were placed at 1.001m i.e. 1 mm wrong from the right, it would cause an amplitude error of measured FRFs, i.e. the measured mode shapes. A simulation in order to investigate the level of amplitude error of FRFs induced by a normally distributed random position error with the RMS value of 0.5 mm was carried out as following: a theoretical mode shape (Sundström 1998) according to Euler-Bernoulli beam theory for the first bending mode with free-free boundary condition is created and plotted as a function of positions:

\[ Y(x) = C_1 \cosh(\mu x) + C_2 \sinh(\mu x) + C_3 \cos(\mu x) + C_4 \sin(\mu x) \]  

(1)

Where \( Y \) = displacement, i.e. the mode shape amplitude on each certain position, \( x \) = a sequence of (101 components used) positions on the specimen, \( \mu, C_1, C_2, C_3, C_4 \) = constants which are determined by boundary conditions, in this case \( \mu = 4.730; C_1 = C_3 = -1.0178; C_2 = C_4 = 1. \)

Add the random noise described as above on the sequence of position, and plot the mode shape of the new positions. The noise level on the mode shapes caused by position error is estimated to be 0.8%, shown in Figure 8(a).

4.2.2. Angle error

Due to roughness of the beam surface and thickness of the wax used to mount accelerometers, the accelerometers can be mounted with an angle away from the direction which is intended to be measured, which will result in amplitude error of FRFs. Figure 6 is a simple sketch to explain the angle error.

As shown in Figure 7, a relationship between the correct acceleration and the real measured acceleration exists as:

\[ a_m = a_c \cdot \cos(\phi) \]  

(2)

Where \( a_m \) = the measured acceleration, \( a_c \) = the correct value of acceleration, \( \phi \) = the angle error.

The same relationship that exists between the correct FRF and the real measured FRF can be derived. In order to estimate influence of the angle error on the measured mode shape, a simulation was performed using Matlab: the same theoretical mode shape function with 101 components as equation (1) was used; a normally distributed random angle error with a mean value of 0° and RMS value of
were created; next step, the real measured amplitude of FRF, i.e. the real measured mode shape was calculated according to equation (2); finally, the influence of the angle error on the mode shape was estimated and plotted. The level of noise introduced to the mode shapes by the angle error is estimated to be 0.04%, as shown in Figure 8(b).

![Figure 8](image)

Figure 8 – The noise level on the mode shapes induced by: (a) the position error; (b) the angle error.

Comparing Figure 8 to Figure 6, it can be observed that the error level induced by the position error and the angle error to the mode shapes are both beyond 0.01%, which means the information shown in Figure 2b are drowned in the noise.

4.2.3. Mass loading effect (Brandt 2011)

When an accelerometer is attached to the test specimen the acceleration to be measured will be altered due to the mass of accelerometer. Additionally, in order to catch mode shape of the entire specimen, the accelerometers have to be moved several times. For each time the accelerometers are moved, the structure of the test specimen changes. To investigate the mass loading effect, a simulation based on the beam model, which is described in section 2.1, has been carried out. Six point masses of 10 g were first placed on 6 nodes on the edge1 (cf. Figure 1), the analysis run to extract the 6 FRFs; then the 6 point masses were moved to the next 6 nodes on edge1, and run the analysis again to extract 6 more FRFs; repeat this procedure until a total of 60 FRFs were extracted from the simulation. These FRFs were used for modal parameter (mode shape) estimation in Matlab for edge1. The influences of mass loading on the MSC are obvious. Figure 9(a) shows the MSC of edge1 without any masses, which indicates the defects properly. However, in Figure 9(b) the same MSC but calculated in the case with mass loading, where the effect of the defects are no longer visible.

![Figure 9](image)

Figure 9 – The influence of mass loading on MSC of edge1: (a) the MSC of edge1 without mass loading; (b) the MSC of edge1 with mass loading.
4.2.4. Other error sources

There are some other possible errors involved for which the size of the error is difficult to estimate, for example, parameter estimation error. Parameter estimation is the process used to obtain the modal parameters that best describe the measured data from a measured set of FRFs by a mathematical modal model. In this process except the quality of the measured of FRFs, the number of the measured set of FRFs, the selections of number of poles to calculate etc are also critical for the curve fitting. Different choices of these factors give rise to an uncertainty of the estimated modal parameters including the mode shape.

5. DISCUSSION AND CONCLUSION

In the present study, both FE modeling and experimental studies were performed to locate defects in timber beams. Based on the results from FE modeling and experiments, the potential of using modal parameters namely mode shape/MSC to locate the imperfections within wooden beams were evaluated. The conclusions can be summarized as follows. (1) From FE simulations, the mode shape/MSC shows a good potential for detecting and locating, i.e. the method of using mode shape/MSC to detect imperfections works in theory. (2) The method is very sensitive to measurement errors. It requires an accurately measured mode shape. The accuracy level required on the measured mode shape is estimated to be about 10^-4. (3) It is very difficult to achieve the accuracy needed using accelerometers for modal test. The reason is that some errors - position error, angle error and mass loading - caused by using accelerometers cannot be overcome, and any they are big enough to fail the method. (4) Thus, a new way of measuring mode shape is needed. For example, using Scanning Laser Doppler Vibrometer (SLDV) may be worth a try (Chen et al. 1998). SLDV is a non-contact instrument for vibration measurement, which prevents the position error, angle error and mass loading which the accelerometer cannot overcome. (5) Other dynamic parameters, i.e. resonance frequency (Olsson et al. 2010) and modal damping for locating imperfections can be used to gain more knowledge of defects of timber beams.

REFERENCES