The condition assessment scheme for ancient timber structure using material and deformation analysis

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Abstract. A condition assessment is one of a crucial part of ancient structure, in which this phase will be the reference before giving a treatment and maintenance. The initial step after the visual inspection conducted will be the material properties analysis to the structure using Non-Destructive Test (NDT). Furthermore, the deformation analysis will be part of the onsite assessment for long term analysis of a structure. The deformation analysis part has a purpose of determining the movement. This paper will take one of Ancient timber structure as a study case. The building consists of a complex ancient timber structure representing mostly the characteristic of ancient buildings in Asia. Overall, it will focus on discussing the part of the general condition assessment scheme. The general overview of the process of on-site tests and deformation measurement is shown to represent the general need for assessing an ancient timber structure. As a result, the deformation analysis of the structure can the alternative for the next phase as reference for structural damage solutions.

1. Introduction

The Ancient Buildings are one of the vulnerable building which needs special treatment for assessment. Ancient timber structures which is a very important cultural relic may be defined using the materials database [1,4,5]. The related research to non-destructive test has been done by some researchers but not including the combination method to conclude the overall condition assessment. As the condition assessment is done to the ancient timber structure are mostly inadequate and lack of standard, the regarding problem might be an issue to be solved for further study. In the condition assessment part, some previous studies may show the single result to the test achieved. Feiyun Building as one of the ancient timber structures represents the complicated shape of which on-site test and deformation analysis may be the alternatives to solve without damaging the structure.

2. Tools and methods

The current codes may give some specific limitation based on every condition, in which it is a very rare situation to the ancient timber structure. This may be the reference for the further test conducted for each measurement done. Besides, the initial rapid inspection to define the grading is shown based on the previous report to the Building for the initial sample decision.

2.1. Stress wave measurement

Meanwhile, the manual procedure of the Stress Wave will consist of the steps below:

   (1) Set the tool (Insert drill bit to the drill tool). Insert the chart paper to the drill device until the small pin shows the resistance as the drilling bit enters the timber itself.
(2) Place the drill against the surface of the member that wants to be evaluated at a 90 degrees angle.
(3) From the drawing needle, Sound materials with good resistance between 50 to 75 % of the maximum level. When the reduced area with low quality the drawing needle will drop to the bottom line. After reaching the end of the drill to the member, reverse the drill button as it pulls out the drill.
(4) Pay intention to the drill bits usually lasts for a hundred drills before its sharpness last and has to be replaced. The data can be put in the electronic file or scanned digitally to computer units.

2.2. Micro drilling resistance
For the drilling resistance parameters which influence the result through the material dependent includes the anatomy of wood, moisture content, and depth of the drill hole. The graph result of each micro-drilling data may represent how the timber may have a defect or not. The smoother the graph seems, that means it represents the better timber condition. In this research, the micro-drilling meter involved ten columns. The micro-drilling is also done to verify and support the estimation of the physical and mechanical of the structure assessed, especially for timber materials. The drilling resistance graph is influenced by many factors, including alia wood moisture, drilling sharpness and angle direction of drilling [6].

![Figure 1](image-url)  
**Figure 1.** Graphic Test form of Micro-drill resistance diagram (east-west direction) column F2C33 micro-drill resistance diagram (38cm)

2.3. Deformation monitoring
One of the important ancient timber structure in China that is often selected as a sample case due to its specialty is the Feiyun Building. This building which is located in Shanxi province which overall shows the general condition (deflections, cracks, decays, etc.) of a sample case to the assessment using the SNDT onsite data. The members shown were indicated to have some structural problem including internal defects (knots, crack, fungal, deterioration etc.) and deformation (tilt and deflection). In this monitoring process, the Su-Guang total station (RTS010), in order to ensure the monitoring accuracy, the entire monitoring process is used in the total station, the total station parameters. The total station can be done by firstly, to decide the control point for coordinate (0,0) with a sign on it. Therefore, the internal processor will determine the northing, easting, and elevation which are the denomination of Coordinate x, y, and z, respectively. For the measurement of the tilt of column and beam deflection point, move the mode in the digital screen. Overall, the data will be recorded in the total station and soon can be copied to the database.

3. Assessment scheme
3.1. Scope
The scope of the research will only include the on-site test to the Ancient Timber Structure in which it will be the Feiyun Building as the case study. The assessment can be the pilot project also to the other typical ancient timber structure with typical on-site test. Meanwhile, for the detail scope, the research will only include as follows:
(1) The rapid visual inspections are done firstly due to the general condition as to see further intact members so that further SNDT test can be conducted.
(2) The use of the SNDT consist of the Stress Wave analysis and Micro Drilling or resistograph.
(3) The SNDT test point was only taking the tangential and radial section in which the longitudinal section is not possible due to the position and condition of the structure.

(4) The Beams and columns are the tested components and the components that represent the structure, while the rest components (Douguong, Foundation, Rafter, etc.) were too vulnerable to be conducted.

(5) The coordinate points that are taken for the deformation analysis of the total station monitoring are the points that forms the main structure which from the top are the Yong Ding Columns of three floors.

3.2. Scheme Flow

The flow of the condition assessment research to the ancient timber structure will consist of two main roots which are the material properties part based on the SNDT, following the deformation analysis network which was based on the total station measurement. In the end, the general condition of the structure can be summarized from the points tested based on the general percentage damage detection.

**Figure 2.** SNDT tools to the Feiyun Building; (a) Stress Wave; (b) Micro Drilling Test; (c) Moisture Content Analyser

The scheme of the material properties estimation using the SNDT will consist of the part whether the data sample might be used to represent the materials. In which as the data fits and follow the shape to the PDF. Then, therefore the estimation of the material properties related to the SNDT can be done.

**Figure 3.** The Flow of the Condition Assessment and Total Station Measurement
Therefore, as the member data between micro-drilling, stress wave, and total station are ten members among it, the researcher decided to use the sliced of the three components. In which it can be used to see whether the general condition assessment can be analyzed.

3.3. Assessment Classification
The assessment as it includes tests of: the visual inspection, material properties (stress wave and micro-drilling), and total station monitoring, hereby in this part, some of the categories have been made to qualify the state of an ancient timber structure.

3.3.1 Visual inspection grading
Based on the view, the use of the visual inspection of materials can be combined based on the function of the structure. This research has also defined the damage grading according to the assessment to the visual inspection as shown in Table 5-3.

| State     | Grade | Risk      | Dealing Suggestion |
|-----------|-------|-----------|--------------------|
| Non-Hazardous | A     | Safe      | May not take Measures |
|           | B     | Safe      | Partially take Measures |
| Dangerous | C     | Dangerous | Should Take Measures |
|           | D     | Dangerous | Should take immediate Measures |

In addition, based on the standard code for the maintenance and strengthening of timber buildings, the Damage level is divided into four damage level based on Table 5-4. Which the general description is similar to the four other categories above [7]. Therefore, further classification and description each category are explained to discover and identify the situation and condition of the member.

| Damage Level | Classification Criteria for Structural Components |
|--------------|---------------------------------------------------|
| 1            | No or slight damage on component                  |
| 2            | Only a few damaged spots require repairs, but not affecting buildings function and safety |
| 3            | Some damage locations or joints have influenced buildings function and safety, but no imminent danger |
| 4            | Components might be a risk, the accident could occur at any time, and repair measures must be carried out immediately |
The grading will help to state the level and urgency for each member whether it has to be treated in the next stage. As to make it sure, beside to be checked visually, an SNDT and repeatedly test and make sure. Therefore, a further assessment for the internal check is necessary.

3.3.2 Material properties assessment

Therefore, the material properties estimation was combined based on each variation of the data base, in which the value depends on the test conducted to the structure. Meanwhile, for the damage point of the SNDT using the stress wave detection and the micro-drilling states as the previous four categories also.

### Table 3. Damage Points to Overall structure

| No | Level       | Grade | Value  | State                  |
|----|-------------|-------|--------|------------------------|
| 1  | Non-Hazardous | A     | 0-25%  | Very Low Damage Point  |
|    |             | B     | 26-50% | Low Damage Point       |
| 2  | Dangerous   | C     | 51-75% | High Damage Point      |
|    |             | D     | 76-100%| Very High Damage Point |

3.3.3 Deformation state

Besides, the deformation monitoring will consist of the ‘Global Congruence’ test which tests the observed points of the structure, in which each points can also be observed in more details using the snooping test. This could state whether the point observed is ‘stable’ or ‘unstable’ based on the law on which if it is over than the fisher value, then it is stated as ‘unstable.’ The coordinate points observed here are the generally observed object. Meanwhile the local observation was done by the tilting data.

### Table 4. Deformation State

| No | Test Conducted     | Value                                    | Result | State          |
|----|--------------------|------------------------------------------|--------|----------------|
| 1  | Global Congruency  | $\frac{\hat{\sigma}^2_{\text{ad}}}{\sigma^2_{\text{ad}}} \leq F_{1-\alpha, \infty, r}$ | Accepted | Overall Stable |
| 2  | Snooping Test      | $|W_{d_i}| \leq F_{1-\alpha, 0, 1}$         | Accepted | Undeform Point |
|    |                    |                                          | Rejected | Deformed Point |

The monitoring points to the specific member which is stated as unstable or deformed should take a further detailed analysis and treatment in which this part of the assessment will be more accurate as the more points to be analyzed. Therefore, to classify whether the member tilt is in a high risk or not, then the classification to the percentage of the tilt data value can be classified as follows:

### Table 5. Tilting Level for Column

| No | Level       | Grade  | Value   | State                  |
|----|-------------|--------|---------|------------------------|
| 1  | Non-Hazardous | A     | 0-25%  | Very Low Tilt Movement |
|    |             | B     | 26-50% | Low Tilt Movement     |
| 2  | Dangerous   | C     | 51-75% | High Tilt Movement    |
|    |             | D     | 76-100%| Very High Tilt Movement |

The state as its mostly defined to four different categories will help the assessor to take action to the members observed in which the state is in danger or safe level or to simplify it. The state will be known as general as Low movement or High movement. In which, same as the rapid survey, that the states are divided into four grade and two level (Non-Hazardous and Dangerous).
4. Result and mapping

4.1. Visual inspection and damage detection

As the first condition assessment are done using a inspection which is analyzed visually. Therefore the result can be one of the consideration for further test. The visual inspection as the initial step has given some grading condition for each member of the structure in which the components with grades A and B may be considered as a non-hazardous state, besides the C and D are classified as a dangerous state. In Feiyun Building, a percentage of 87% columns and 97% of beams are classified as grades A and B. The overall results shows that more than 90% of the examined structural members are categorized as A and B. Therefore, to validate and a deeply analysis of the material properties and internal defects to the member of the structure, the process continues to the SNDT method which may take part in individual damage points.

Figure 5. (a) The result of Member Grading by Rapid Survey and Visual Inspection [3]; (b) Bar chart for the overall Percentage Damage of the test conducted in Feiyun Building

Therefore, based on the rapid survey, the SNDT shows that 89.4% are identified as grade C with internal defects by the rapid assessment method, and a 16.7% of the other members beside the grade C are identified to have internal defects. In which based on the common definition of the grading class, this building is stated as a non-Hazardous building based on the visual inspection of the on-site test. Therefore, the visual inspection as the initial inspection shows a good condition of the structure. As shown that the most detectable device to analyze the internal defects of the timber structure is mostly shown using the stress wave. For the Micro drilling is best used in the same point and time to the stress wave which will not only shows the damage points but also may give the following information to the material properties of the members observed and tested. Meanwhile, the visual inspection will mostly only represents the defects which are seen by visible eyes. Therefore, over all the percentage internal damage effect in which the cracks are detected to the Feiyun Building members are all majority below 50%, except the stress wave which is found about 54% crack detected.

4.2. Tilt monitoring

The instrument which is the total station is also mounted and known to calculate the up and end point not only to define the coordinate system but also the slope or tilting action of each column member by adding the difference square between x and y from the top to the column foot, therefore the tilt value from the monitoring can be achieved. The tilting which is the part of deformation monitoring to detect the member movement is also conducted to get the percentage tilt happening to each member column. Based on the tilting monitoring to the column in which is divided into four categories of level or classification, the overall and specified column observation can be shown as the figure below between the average of the total measurement done. With a total of 129 members, the Feiyun Building overall shows a safe state of a structure. This is shown that the only member which is categorized as High tilt or dangerous state are member F2C28, F2C29, F2C53, and F2C54. Therefore these member needs
further treatment or protection for the next step of preservation. Meanwhile, the other member’s shows a number of 92 which has a very low tilting level and a total of 33 which is stated as low.

### 4.3. Floor Mapping

The floor mapping will only include the column as this member takes all the condition assessment measurements including the visual inspection, stress wave analysis, micro-drilling resistance, coordinate measure, and tilt measurement. Therefore, the combination of the result for some particular member test taken can be seen. Based on the classification of the condition assessment previously, the points observed can be summarized as in the table. Therefore, the results of the combination above with the analysis from the deformation of a year of measurements may help to do mapping by following the classification symbol of the figure. In which, for the Snooping test of nine points network Points observed shows that for the Vertical Deformation, the whole points are categorized stable. Meanwhile, there are movements for the horizontal side for member F1C1, F1C7, F1C10, F3C1, F3C4, F3C6, and BD01 or known as ‘unstable.’ While, the F1C4 and F3C10 are stated as ‘stable.’ For some of condition assessment points shows a good grading of timber which maybe were classified from the outer visual inspection, meanwhile in some points which conducts the SNDT to the member detects internal cracks. This can be found in F1C12, F1C18, F2C6, F2C11, F2C36, which the grading are good (A and B) but the internal damage/cracks are detected. Also, to some of the members which have bad grading (C) but no internal cracks are detected. The next discovered thing to F2C53 and F2C53 in which the materials are good and no cracks found based on the SNDT, but the reinforcement to the movement has to be considered as the tilt level is categorized as High.

| Damage Grading Level | Stress Wave & Micro Drilling Crack Detection | Tilt Level for Column | Deformation State |
|----------------------|---------------------------------------------|-----------------------|-------------------|
| Grade D/Level 4/Very Hazardous | = Crack | = Very High Tilt Movement | ≠ unstable points |
| Grade C/Level 3/Hazardous     | = No Crack                                  | = High Tilt Movement  | ✓ stable points   |
| Grade B/Level 2/Safe        |                                            | = Low Tilt Movement   |                   |
| Grade A/Level 1/Very Safe   |                                            | = Very Low Tilt Movement|                  |

![First Floor Mapping](image1)
![Second Floor Plan](image2)
![Third Floor Mapping](image3)

**Figure 6.** Mapping of Condition Assessment to the Feiyun Building

### 4.4. Further treatment

As the condition assessment that is done to the structure, the general result which is both related to the micro-damage (crack, decay, etc.) which is considered as the local deterioration and also macro change which can be seen from the deformation monitoring was able to be reference information for further action. The remedial and preservation work could be considered depending on the condition of the materials including the internal damage. In this case, the internal reparation can be done. Meanwhile, the deformation monitoring using the total station will help in detecting global damage and deformation which happens to the structure itself. Further treatment may include several actions to repair including...
retrofitting, injection, bolting, which it has to be carefully treated as the part of ancient timber structures are the sensitive parts of the structure.

5. Conclusion
The condition assessment will overall covers the SNDT test which includes stress wave analysis and Micro Drilling resistance, then the deformation monitoring which includes the total station measurement to the column. In which the end the internal damage effects and the external deformation can be observed. Below are the general point that can be concluded from this chapter:

1. The condition assessment in this research will only consist of the onsite test which includes the visual inspection, SNDT, and total station measurement.
2. Based on the visual inspection, ancient timber structure such as Feiyun Building are vulnerable to be examined directly. Meanwhile, the visual inspection overall states that the members are mostly in the A and B condition which is safe, and in the state of 1 which is a non-hazardous building.
3. Overall, the Feiyun Building is stated still in level one condition with majorly more than 90% of the examined structural members are categorized as A and B. Overall, the obtained data from the on-site test can be used as a reference for the condition assessment of the ancient structure.
4. For the general tilting shows a safe result, in which none members are in a Very High Tilting condition. F2C53 and F2C53 in which the materials are good and no cracks found based on the SNDT, but the reinforcement to the movement has to be considered as the tilt level is categorized as High

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