INTEGRITY STUDY OF COOLING TOWER WOODEN STRUCTURE AFTER 15 YEARS OPERATION

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ABSTRACT

In order to assess the integrity of the wooden structure of Cooling Tower (CT) Unit 1 after 15 years of operation, Star Energy Geothermal Wayang Windu Ltd. conducted physical, chemical and mechanical testing of the wood. The testing was applied to the used wood as well as spare wood.

Chemical tests revealed that surface degradation had reached up to 2.5mm depth. Mechanical tests concluded that allowable stress for compression parallel to the grain was slightly lower than NDS 2005 specification and Modulus of Elasticity (MOE) was significantly lower. When the value of MOE is significantly lower, the stiffness of the structure decreases and can cause a higher level of vibration.

Due to this situation, dynamic analysis of the machine and structure has been conducted. It has revealed the phenomenon of resonance and flow induced vibration. Resonance vibration has been successfully reduced, but flow induced vibration sometimes still occurs.

Based on this assessment, it can be concluded that the CT can still be reliably operated, but deformation and vibration will occur at higher levels. Further study to assess the fatigue life of the wooden structure has been planned to provide permanent mitigation.

1. INTRODUCTION

Cooling Tower (CT) Unit 1 SEG WWL has been operated since 2000. The structure of the CT is made of wood. Wooden structures have advantages as they are fast to build, replenishable and possibly of lower initial cost. However, wooden structures naturally decay and this may result in structural failure.

The CT Unit 1 structure supports eight cells of CT Fans. Each cell has one set of motor-gearbox fans (see Figures 1 and 2).

The vibration levels of the motors and gearboxes are monitored continuously through an online monitoring and protection system. They are also measured and analyzed monthly using a hand-held vibration analyzer for predictive maintenance purposes.

It has been reported since 2013 that for some cells vibration of the motor and gearbox had significantly increased. Examples of vibration level trends are shown in Figure 3. Through frequency spectrum analysis, as shown in Figure 4, it can be ascertained that the vibration is not caused by machinery components, but is induced by resonance or process flow.

The magnitude of the excitation forces can be considered constant since there is no change in the process flow of CT Unit 1. Therefore, it is suspected that the CT structure stiffness has decreased and consequently the vibration has increased. Because of this situation a detailed study of the degradation of the wood properties as well as a dynamic analysis were conducted.

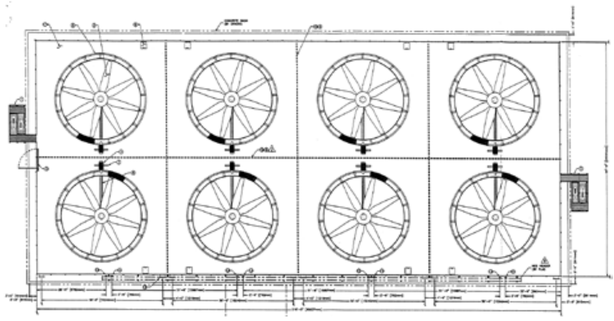

Figure 1. Top view of CT Unit 1

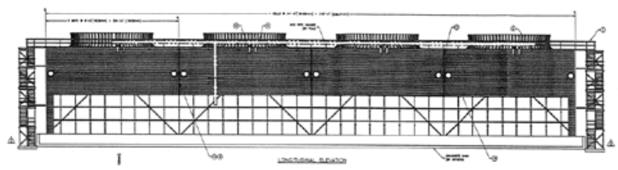

Figure 2. Longitudinal elevation of CT Unit 1

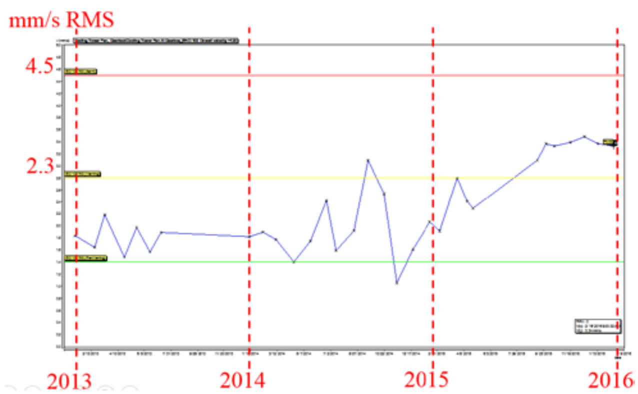

Figure 3. Vibration level trend

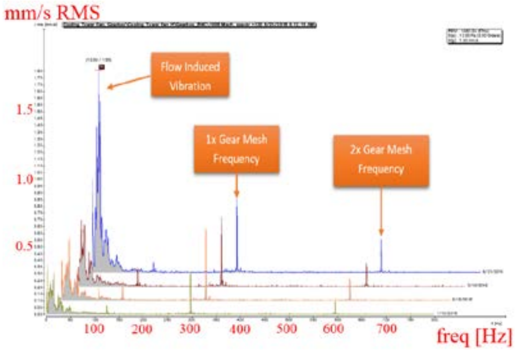

Figure 4. Frequency spectrum of gearbox vibration

2. WOOD PROPERTIES TEST

2.1 Wood Sampling

The location of the used wood sampling is depicted in Figure 5. There are two locations: upper (J, P) and lower (L, M). At the upper area, the wooden samples were not exposed to cooling water. They were only exposed to vapour and non-condensable gas (NCG). At the lower area, the samples were always exposed to cooling water. At each location, two samples were taken. One sample was located at an area exposed to sunlight, while the other at one that was not exposed to sunlight. By sampling wood at various locations and exposure conditions, a distribution of the wood properties was obtained.

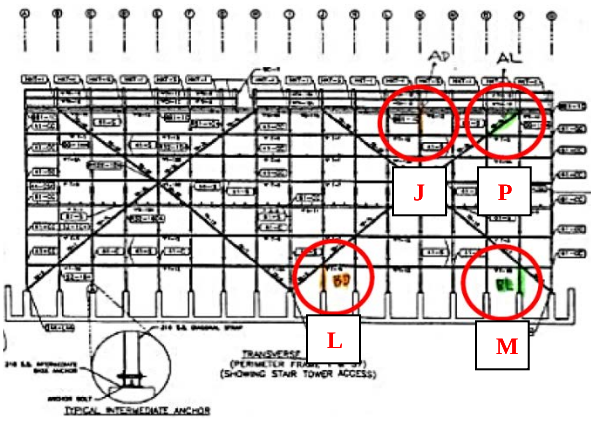

Figure 5. Location of wood sample

2.2 Species Identification

Figure 6 shows a transverse section at 40x magnification. The anatomical structures indicate that the wood samples were Douglas fir (*Pseudotsuga menziesii*) and Redwood (*Sequoia sempervirens*). Wood samples J and P were Douglas fir, while wood samples L and M were Redwood. The main visible difference is the presence of resin channels. Douglas fir has a resin channel whereas in the Redwood there are no resin channels (Hoadley 1990).

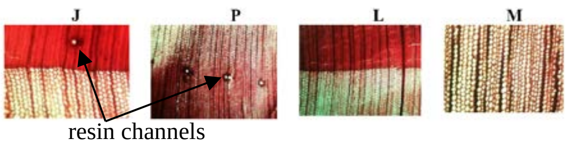

Figure 6. The transverse section of the sample (40×)

2.3 Depth of Degradation

Specific gravity measurement is a means used to quantify the depth of wood degradation. The wood sample was shaved each 0.5mm depth. Wood volume and weight before and after the shaving was measured to obtain the specific gravity. Deterioration depth was determined when the specific gravity was lower than the control. The control was the inner side of the samples which were assumed to be free from deterioration. The measurement results can be seen in Figure 7.

Based on this measurement, it can be concluded that after 15 years of operation the maximum deterioration depth is 2.5 mm at sample J and so, the rate of degradation is 0.17mm/year. This rate will be used to calculate the remaining life.

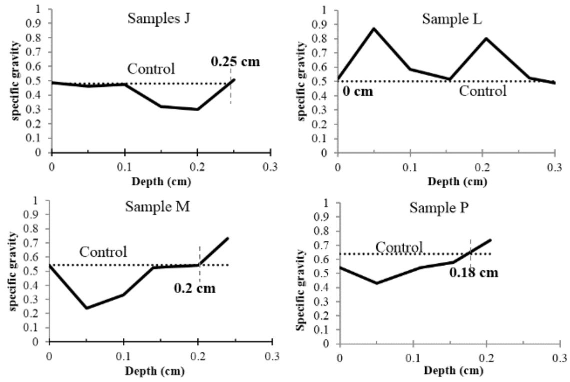

Figure 7. The Specific gravity at various depths

2.4 Mechanical Properties

Wood is not designed, it is harvested. It is not like steel which has specifications of minimum strength or chemistry. It is not like concrete which has a mix design. Wood may have natural defects such as knots, checks, etc. as shown in Figure 8. Those defects reduce the strength so an engineer must compromise with this wood characteristic. ASTM D2915 introduces a concept of allowable stress. Allowable stress is the maximum applied stress to wood which has a very low possibility of failure.

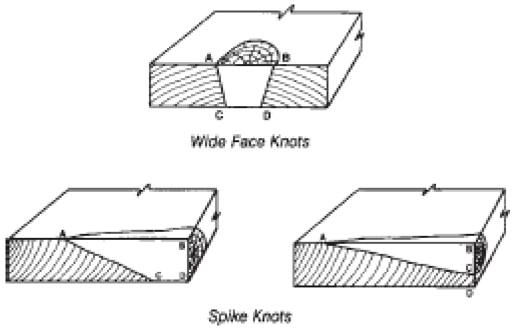

Figure 8. Example of knots as defined in ASTM D2915

The test results as processed become the strength characteristics; that is the 5% lower percentile limit. The strength characteristics are then reduced by an adjustment factor in accordance with ASTM D2915 to obtain the allowable stress. The concept for determining allowable stress is demonstrated schematically in Figure 9. Based on ASTM D2915-03, the formula to calculate allowable stress is shown below.

$$F_i = \frac{\bar{F}_i - 1.645 S_i}{A_F} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

F_i = allowable stress
$\bar{F}_i$ = average stress obtained from the test
S_i = standard deviation
$1/A_F$ = reduction factor based on ASTM D2915-03 (see Table 1)

Table 1. Reduction factor to relate test statistics to allowable properties (ASTM D2915-03)

Property	Factor
Modulus of elasticity	1
Bending strength	1/2.1
Tensile strength	1/2.1
Compressive strength parallel to grain	1/1.9
Shear strength	1/2.1
Compressive strength perpendicular to grain	1/1.67

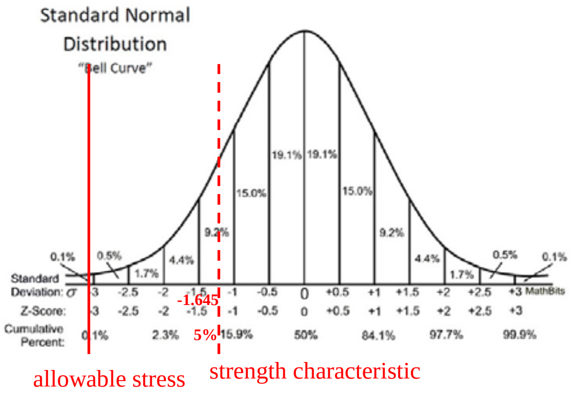

Figure 9. Fifth percentile and adjustment factor for determining allowable stress

There were five mechanical properties tested in this study: compression parallel to the grain, compression perpendicular to the grain, tensile parallel to the grain, shear parallel to the grain and static bending. All testing was based on ASTM D143. Testing was conducted by a Universal Testing Machine (UTM) in dry air conditions.

Table 2 shows a comparison of the allowable stress obtained from this test compared to the NDS 2005 value. The allowable stresses of bending, tensile parallel to the grain and shear were still higher than the NDS 2005 value. The allowable stress of compression perpendicular to the grain was significantly lower, while compression parallel to the grain was slightly lower than the NDS 2005 value. So, close attention should be paid to the connections which support the load perpendicular to the grain.

Compared to NDS 2005, the average MOE was significantly lower, while the minimum MOE was still higher. It can be deduced that the current MOE has decreased, giving a lower structural stiffness. Lower structural stiffness causes a higher deflection and may induce resonance vibration. This finding confirms that the increased vibration may have been induced by a resonance phenomenon.

Table 2. Allowable stress and MOE (kgf/cm^2) of samples compared to NDS 2005 for dimensions smaller than 12.7 × 12.7 cm

Criteria	Fb	Ft//	Fs	Fc^	Fc//
Douglas fir					
Testing results	136	74	32	10	74
NDS 2005 value	112	67	12	44	77
Rest of strength[1)] in %	**21**	**10**	**167**	**-77**	**-4**
Redwood					
Testing results	136	217	25	10	72
NDS 2005 value	98	67	10	46	84
Rest of strength[1)] in %	**39**	**224**	**150**	**-78**	**-14**

Table 2 (*continued*)

Criteria	MOE	
	Average	**Minimum**
Douglas fir		
Testing results	47386	36984
NDS 2005 value	112491	40778
Rest of strength[1)] in %	**-58**	**-9**
Redwood		
Testing results	47596	37400
NDS 2005 value	91399	33044
Rest of strength[1)] in %	**-48**	**9**

Note:
MOE = Modulus of elasticity, Fb= bending strength, Ft// = tensile strength parallel to the grain, Fs = shear strength, Fc^ = compression perpendicular to the grain, Fc// = compression parallel to the grain.
[1)] rest of strength is the ratio of difference between testing result with NDS 2005

2.5 Creep Testing

Creep testing aims to determine the strength of the wood under static long-term loading. Measurements were made, on average, for 10 days for each sample. The test sample was bend-tested by a center point loading configuration as shown in Figure 10 for 10 days. The specimen for creep testing and mechanical testing had the same dimensions and span length. Creep testing was preceded by a static bending test to get a deflection on failure, initial deflection, maximum load and Modulus of Rupture (MOR). Some values were necessary to determine the remaining service life of the wood. Raw data examples of creep testing are presented in Figure 11.

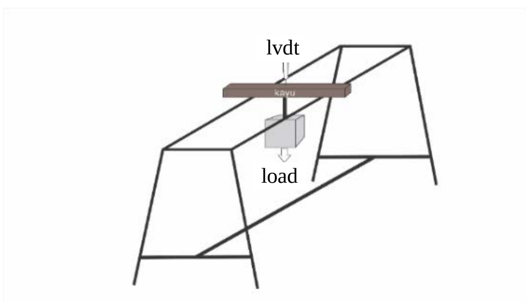

Figure 10. Creep testing illustration

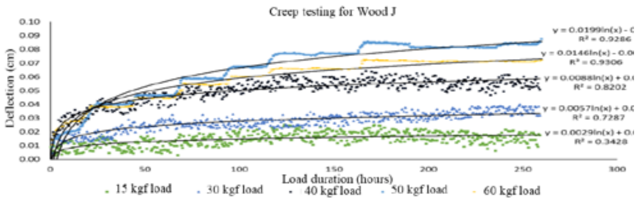

Figure 11. Raw data example of creep testing

Mathematical calculation can derive the formula below:

$$\sigma = \frac{MOR}{P_{\max}} sT^{m} \frac{\left(b - \frac{f}{17}T\right)\left(h - \frac{f}{17}T\right)^{2}}{bh^{2}} \quad \text{.... (2)}$$

Where:
σ = maximum bending stress which will be still acceptable for a certain period in the future (kgf/cm^2)
MOR = modulus of rupture obtained from static bending test
P_{max} = maximum load obtained from static bending test
s, m = constants obtained from linear regression of creep testing result
b = width of beam section (cm)
h = height of beam section (cm)
T = loading period (years)
f = deterioration depth (cm)

Substituting all required data into formula (2) results in a graph showing correlation between stress and failure time as shown in Figure 12. Based on this graph, it can be concluded that the remaining service life due to bending load for each timber is 98, 86, 136 and 120 years for timbers J, L, M and P, respectively. This remaining life is relatively long, and so it can be stated that the structure can sustain a bending load for long-term operation.

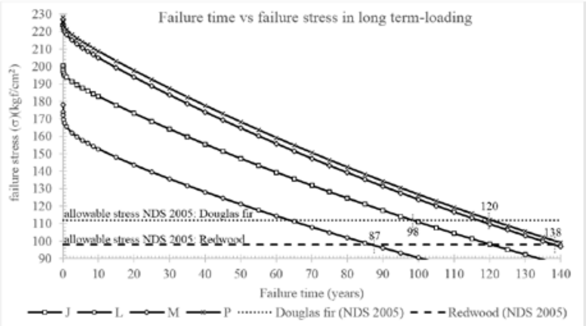

Figure 12. Failure stress v.s time obtained from creep testing

3. STRUCTURAL DYNAMIC ANALYSIS

To determine mitigation action for vibration reduction, a structural dynamic analysis was performed. A flowchart of the analysis is shown in Figure 13.

By using multichannel vibration measurements, the vibration mode was obtained as shown in Figures 14 and 15. A structural model was developed to present the behavior of the current structure (Figure 16 shows the structural model), and then simulations of the structure with modifications were conducted to find the optimum modification for vibration reduction. By trying some modification scenarios, the optimum one was obtained as depicted in Figure 17. As shown in Figures 18 and 19, the computer modelling predicts that the vibration at 9.75Hz would decrease 87.69%, while the vibration at 16Hz would decrease 85.69%.

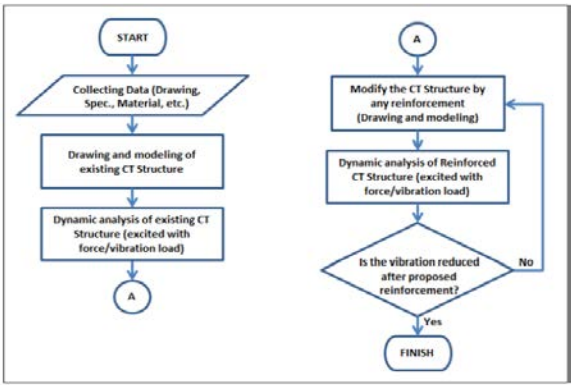

Figure 13. Flowchart of the dynamic analysis

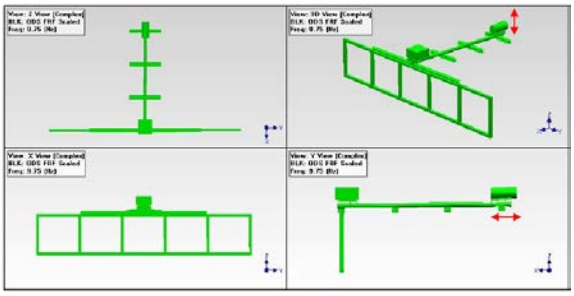

Figure 14. Vibratory movement of Torque Tube at frequency of 9.75Hz

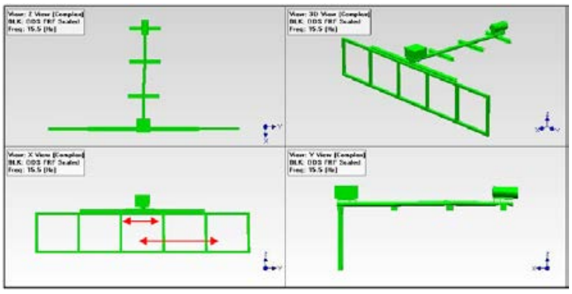

Figure 15. Vibratory movement of Torque Tube at frequency of 16Hz

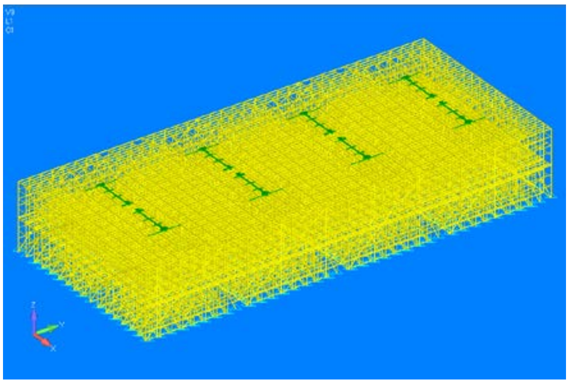

Figure 16. General model of cooling tower structure and torque tubes

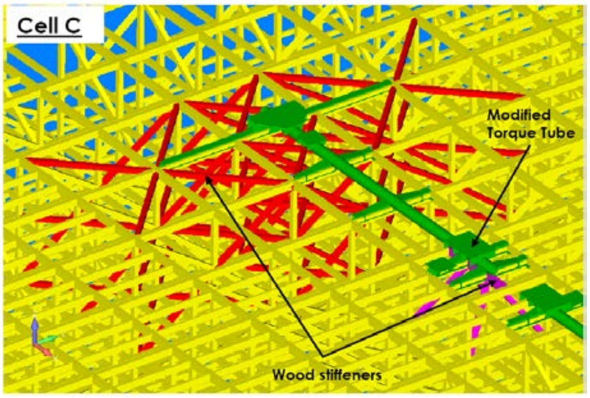

Figure 17. The optimum structure modification based on computer modelling

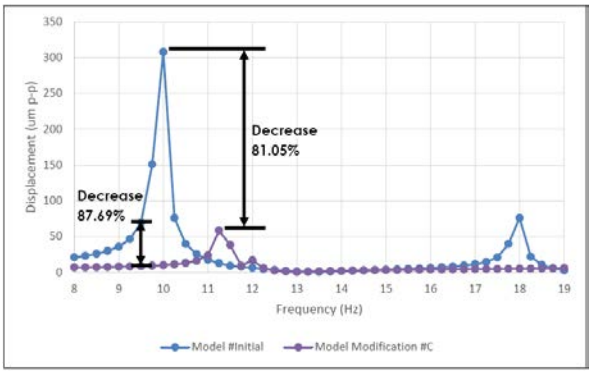

Figure 18. The frequency response of Model Modification at frequency 9.75Hz

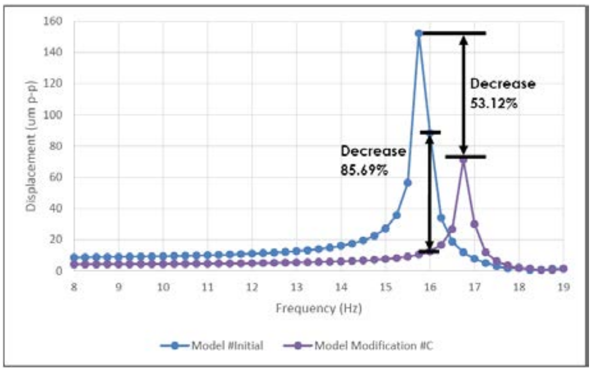

Figure 19. The frequency response of Model Modification at frequency 16Hz

As recommended by this study, structural modifications were carried out. Vibration levels before and after the modifications are shown in Table 3. They clearly indicate that vibration at points M1V, M2V and G1H decreased significantly, but vibration at points M1A and M2A just slightly decreased. Vibration at points M1A and M2A fluctuated, but the highest vibration level was still below Zone D (danger zone). Therefore, it can be considered that the vibration level after structural modifications is acceptable.

Comparison of the frequency spectrums before and after structural modifications is presented in Figures 20 and 21. Those figures clearly show that vibration at frequency 9.75Hz axial direction and 16Hz horizontal direction decreased dramatically, but vibration at 15.75 Hz axial sometimes fluctuated.

Dynamic analysis identified resonance at frequencies 9.75Hz axial and 16Hz horizontal only. There was no resonance at frequency 15.75Hz axial. Structural modifications were aimed to reduce vibration at frequencies 9.75Hz axial and 16Hz horizontal but were not intended to reduce vibration at 15.75Hz axial. However, since vibration at 15.75Hz axial occurred intermittently, not continuously, it can still be accepted.

Table 3. Vibration level before and after structural modifications

Point	Overall Vibration mm/s rms		Vibration Acceptance Criteria ISO 10816-3
	Before	After	
M1V	8.19	2.28	Zone A/B: 2.3 mm/s rms Zone B/C: 4.5 mm/s rms Zone C/D: 7.1 mm/s rms Long term operation: less than 4.5 mm/s rms Trip level: 1.25 x 7.1 mm/s rms = 8.875 mm/s rms
M1H	2.41	1.65	
M1A	8.91	6.36	
M2V	6.68	3.29	
M2H	1.58	1.36	
M2A	8.96	5.47	
G1H	9.10	3.60	

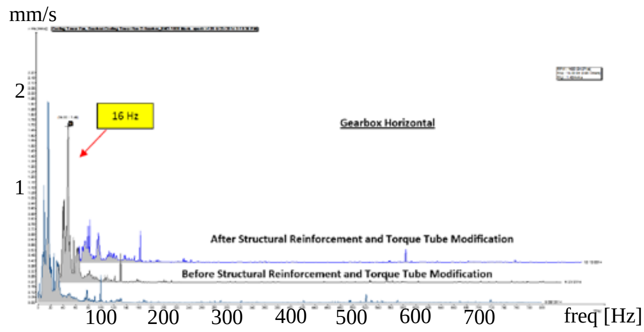

Figure 20. Frequency spectrum of vibration at point G1H

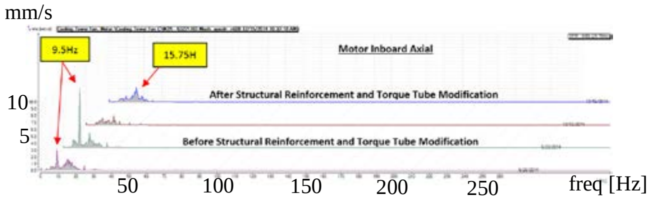

Figure 21. Frequency spectrum of vibration at point M2A

CONCLUSION

After 15 years of operation, the wood allowable stresses were still acceptable, except in compression perpendicular to the grain which was significantly lower than the NDS 2005 value. Close attention should be paid to the connections which support load perpendicular to the grain.

Based on creep testing, the remaining service life will be relatively long (at least 86 years) and so it can be stated that the structure can sustain bending loads for long-term operation.

The current value of MOE was significantly lower than the NDS 2005 value. This has resulted in lower structural stiffness and causes higher deflection. It also produces resonance vibration. Dynamic analysis identified the resonance vibration and was used to recommend structural modifications. After applying the modifications, the vibration level was successfully reduced and so the reliability of CT Unit 1 can be maintained at an acceptable value.

Further study is recommended to assess the remaining life due to fatigue. This is required since high vibration induced by flow sometimes still occurs, even though resonance vibration was successfully reduced.

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REFERENCES

ASTM International: ASTM D2915-03 Standard Practice for Evaluating Allowable Properties for Grades of Structural Lumber, 2003

Effendi Tri Bahtiar, M. Miftah Rahman: Remaining Life Estimation of Cooling Tower Wooden Structure Star Energy Geothermal (Wayang Windu) Ltd., 2015

Khuschandra: Dynamic Analysis of Cooling Tower Structure Unit #1, 2014

Richard J. Kristie: Wood Is Not Designed, It Is Harvested, Principal Wiss, Janney, Elstner Associates, Inc. Northbrook, Illinois, 2012