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Origami Tessellation Ceiling Panels to Improve the Room Acoustic Quality (Case Study: Lecture Hall of the Department of Architecture, Universitas Brawijaya)

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ABSTRACT
The lecture hall of the Department of Architecture, Faculty of Engineering, Universitas Brawijaya, is a room with a large volume of space. The room is close to M.T. Haryono Street, which has relatively dense traffic activity resulting in acoustic disturbance for lecturing activity inside the room. Thus, an improvement in the acoustic quality of the room is very much needed. Due to the high cost required to apply commercialized acoustic panels, this research experimented with coconut coir, corrugated cardboard boxes, and pro foam as acoustic panel alternatives. The simulation of three materials, each has a thickness of 4 inches and a total area of 87.88 m2, with four levels of origami pattern sparseness (Miura Ori, Ron Resch, Water Bomb, and Yoshimura) using Freeform Origami software shows a result of different volumes with convex, concave and flatforms. The convex and concave forms are chosen because both have good sound distribution qualities. The simulation is continued with SketchUp software on alternatives of four origami patterns to determine the effect on the reverberation time inside the room. The results show that the Yoshimura origami pattern achieves the best performance. It reduces the room reverberation time becomes 0.86 seconds.
Keywords: *Acoustic panel, pro foam, coconut coir, corrugated cardboard, origami tessellation*

1. INTRODUCTION

The lecture hall of the Department of Architecture, Faculty of Engineering, Universitas Brawijaya, is a multifunctional room with a large volume of space. Teaching and learning activities usually depend on internal and external factors, namely the condition of the surrounding environment. Acoustic quality standards for classroom and lecture hall is the noise level of 35 – 40 dB [1], the reverberation time of 0.6 – 0.8 seconds, and speech intelligibility must not be less than +15 dB [2]. The existing room condition is resulting in the reverberation time above the standard for a lecture hall. At the same time, the room is also close to M.T. Haryono Street, which has relatively dense traffic, resulting in deterioration of speech intelligibility inside the room. Because of that, a strategy to improve the room acoustic is needed, such as the use of acoustic panels.

There are several materials that can be recycled and used as acoustic panels. Coconut coir, corrugated cardboard, and pro foam are considered an excellent sound absorber at medium and high frequencies [3]. The combination of these materials as a diffuser can maximize the performance of the acoustic panels; when the frequency is too high, it can be absorbed beforehand, and when the frequency is too low, it can be directly propagated. The aim of choosing the origami tessellation pattern as a form of acoustic panels is to change the flat surface of the existing ceiling into an angled surface. Thus, sound distribution will become more even. Based on the issues described above, the researchers expected that using origami patterns as modular can maximize the performance of the prototype materials in improving acoustic quality in the lecture hall., besides the aesthetic and economic advantage.

2. RESEARCH METHODS

The research used a quantitative method in the form of numerical and simulation methods. The numerical method is done objectively with the calculation of background noise level of the lecture hall, signal to noise ratio, and the reverberation time. The research uses sound level meter, tape measure, and camera in the field measurement. The simulation is carried out first by simulating the kinematics of origami tessellation fold patterns based on its sparseness using Freeform Origami demo software. It was done in order for the reflection properties can be analyzed based on their shapes. There are four types of origami used in this research: Miura Ori, Ron Resch, Water Bomb, and Yoshimura.

Furthermore, the simulation using SketchUp software is carried out to determine the size of volume created by the change in the sparseness of origami tessellation patterns. The next step is the calculation of the reverberation time using the Sabine equation [4].

2.1. Data Collection

Primary data are obtained by direct observation of the lecture hall's existing condition in forms of outdoor and indoor noise intensity using the sound level meter. The measurement is carried out to obtain the background noise level. The level of speech intelligibility in the room is measured using the Signal to Noise Ratio (SNR) parameter. The tape measure is used to measure the room volume and the total area of elements inside the room to obtain the absorption coefficient value of non-structural and structural elements. The reverberation time is generated from the existing conditions using the Sabine equation.

Secondary data are obtained from literature studies and comparative studies of acoustic panels using origami tessellation patterns. The literature used is in forms of journals, articles, dissertations, and textbooks (background noise level, absorption coefficient, signal to noise ratio, and the reverberation time). Some scientific journals mention the absorption coefficient of material similar to coconut coir, corrugated cardboard, and pro foam with a thickness of 4 inches and the origami tessellation pattern used. The literature study is used as a guide to the research method.

2.2. Simulation

The simulation is done using two software to determine the effect of geometry, volume, and acoustic material on sound reflection, reverberation time, and noise reduction.

1. The simulation using Freeform Origami Software is carried out to analyze the kinematics of origami tessellation fold patterns based on their shapes.
2. The simulation using SketchUp Software is carried out to find out the volume size created by the sparseness change in origami tessellation patterns.

The measurement is continued with the calculation of reverberation time using the Sabine equation after reducing the size of room volume with the acoustic panel volume and the calculation of noise reduction produced by acoustic panels using coconut coir, corrugated cardboard, and pro foam materials.

3. RESULT AND DISCUSSION

3.1. The Existing Condition

The noise intensity of the outdoor area cannot be separated in order to measure the speech intelligibility of the room. The measurement of outdoor noise intensity is carried out at 10 points on peak traffic hours and normal conditions.

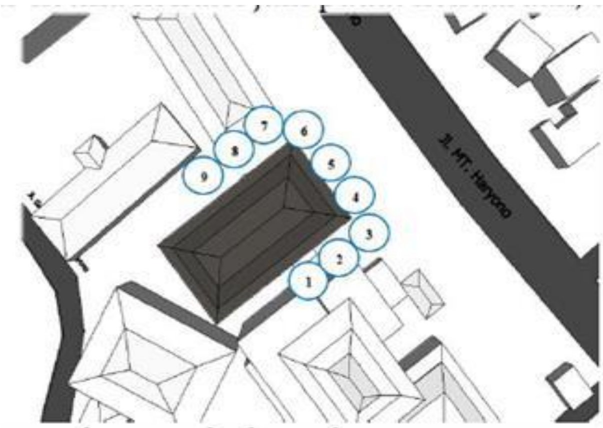

Figure 1 Measurement points for outdoor noise

Table 1 Outdoor noise intensity level

Measurement Points	Measurement Time		
	07:00 - 08:00	11:30 - 13:00	16:00 - 17:00
Point 1	57.9 dB	55.5 dB	59.5 dB
Point 2	60.3 dB	56.8 dB	63.2 dB
Point 3	66.0 dB	57.6 dB	59.3 dB
Point 4	60.5 dB	58.2 dB	60.4 dB
Point 5	66.4 dB	61.1 dB	61.9 dB
Point 6	66.1 dB	60.2 dB	74.4 dB
Point 7	60.1 dB	60.6 dB	69.3 dB
Point 8	59.3 dB	55.4 dB	60.2 dB
Point 9	58.0 dB	56.7 dB	61.2 dB

The results of the outdoor measurement are presented in table 1. Based on the Noise Criteria (NC) designation for the education area with a noise threshold of 55 dB, it can be concluded that the noise level outside the Department of Architecture building does not meet the standard.

Measurement of indoor noise intensity is done at ten measurement points closest to the sound source when the condition is empty or even filled with people. Measurement in an empty room condition is used to determine the average background noise level of the room. In contrast, measurement in a filled room condition is used to measure the speech intelligibility level.

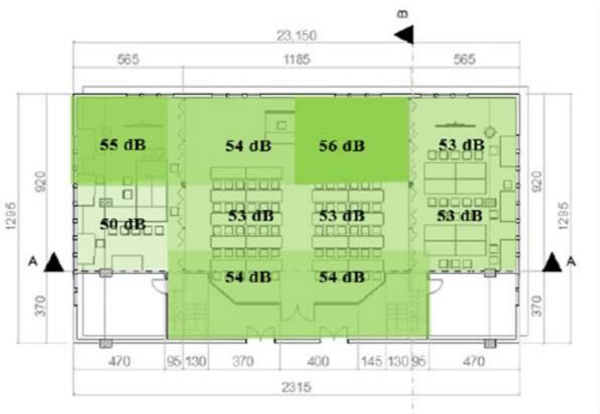

Figure 2 Measurement points for indoor noise

Based on Indonesian National Standard (SNI) regarding the sound level and reverberation time in buildings, Noise Criteria (NC) for a multifunctional room in educational buildings is 40 – 45 dB [1], it can be concluded that this room has not met the standard.

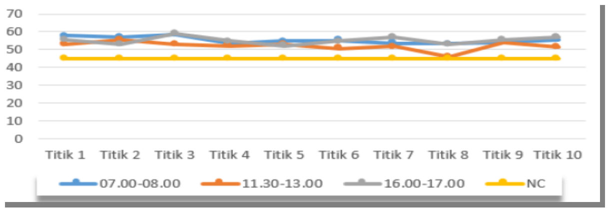

Figure 3 Indoor noise intensity level in empty condition

The value of Signal to Noise Ratio (SNR) in the occupied room is used to measure the speech intelligibility level during the conversation. SNR can be obtained by reducing the sound pressure level from the sound source (by assuming the lecturer sound level is around 70 dB) to the level of indoor noise.

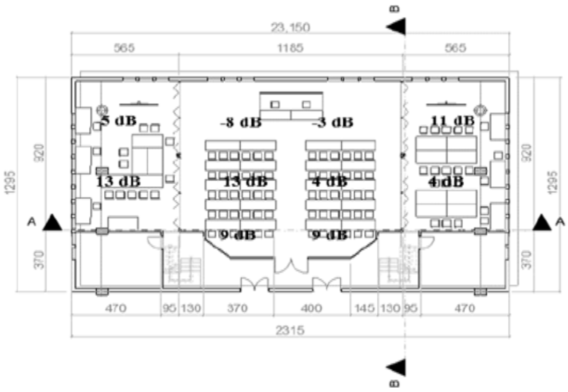

Figure 4 SNR value at ten measurement points for indoor noise

According to Canning et al. [5], the upper sidewall of a classroom requires an absorbent acoustic element. Based on that, the reflected sound spread can be reduced by applying an acoustic panel combination of coconut coir and corrugated cardboard in order to a clearer voice of the lecturer during teaching activity. The lower sidewall requires a reflective acoustic element so that the voice of the lecturer during teaching activity can be heard even by students who sit in the side row close to the wall. Reflective acoustic element is also needed on the lower sidewall of the room as high as the human ear when sitting for the voice of lecturer can be heard clearly. Meanwhile, the floor requires an absorbent acoustic element to avoid reflection from the sound of footsteps. However, the calculation results indicate the reverberation time after applying the acoustic panel recommendation below 0.50 standard if the floor is given an absorbent element. Based on that result, it is decided for the floor to not given an absorbent element to avoid the room for being off.

Table 2 The surface area of Lecture hall materials after applying coconut coir and corrugated cardboard acoustic panel

Materials Classification	**Surface Area (m^2)**	**Material Absorption Coefficient (α)**		
		500 Hz	**1000 Hz**	**2000 Hz**
Ceramic floor	56.56	0.01	0.01	0.02
Plastered and painted brick walls	57.17	0.02	0.02	0.02
Gypsum ceiling	56.46	0.05	0.04	0.07
Wooden sills	9.07	0.10	0.07	0.06
Blackboard	7.68	0.01	0.01	0.02
Glass window, 5 mm	8.67	0.18	0.12	0.07
Wooden door	1.86	0.09	0.07	0.06
Wooden chair	84.6	0.10	0.12	0.12
Lecturer's wooden chair	1.12	0.10	0.12	0.12
Wooden table	61.2	0.10	0.12	0.12
Lecturer's wooden table	3.28	0.10	0.12	0.12
Coconut coir acoustic panel	38.00	0.36	0.62	0.78
Corrugated cardboard acoustic panel	38.00	0.35	0.39	0.70

Based on Signal to Noise Ratio standard for Lecture hall, it should not be less than 15 dB. The noise caused by activities on the main road has an impact on speech intelligibility so that the voice of the lecturer cannot be heard to the maximum level.

Measurement of reverberation time is carried out to determine the sound quality distribution inside the room. The calculation is done using the Sabine equation with a frequency of 500 – 1000 Hz through the following equation:

$$R = \frac{0{,}16V}{At} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$

The equation used for the frequency above 2000 Hz:

$$R = \frac{0{,}16V}{At + xv} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

with:
R = Reverberation time (s)
V = Room volume (m3)
At = Absorption of total space
x = Air coefficient of 0.007

Table 3 Calculation of reverberation time in the lecture hall without acoustic panels

500 Hz	1000 Hz	2000 Hz
$R = \frac{0{,}16 \times 1413{,}59}{117{,}09}$	$R = \frac{0{,}16 \times 1413{,}59}{126{,}22}$	$R = \frac{0{,}16 \times 1413{,}59}{129{,}22 + (0{,}007 \times 1413{,}59)}$
= **1,93 detik**	= **1,79 detik**	=**1,73 detik**

Calculation of the reverberation time of without acoustic panels indicates that the reverberation time of the multifunctional room has not meet the standard of 0.6 – 0.8 seconds. Thus, it is necessary to install acoustic panels using pro foam material with a thickness of 4 inches which is very good at absorbing sound at high frequencies. Based on the calculation, reverberation time obtained from the use of pro foam material ranges from 0.92 – 1.01 seconds, where the minimum reverberation time is 0.6 seconds, and the maximum reverberation time is 0.8 seconds, which conform to the standards.

3.2. Simulation

3.2.1. Freeform Origami Software simulation

Based on measurements made by pressing the space key on Freeform Origami software keyboard shortcuts, each origami tessellation pattern shows a time difference that varies in the folding process. Miura Ori pattern requires 4.64 seconds, Ron Resch pattern requires 2.88 seconds, Water Bomb pattern requires 4.87 seconds, and Yoshimura pattern requires 5.72 seconds in its folding process. For that reason, the determination of the three design alternatives is taken by cutting the time by ¼, ½ and ¾.
From the four simulated origami tessellation patterns, each pattern stretches to form a different space. This proves that flat shapes formed using different patterns can produce spaces with different volumes.

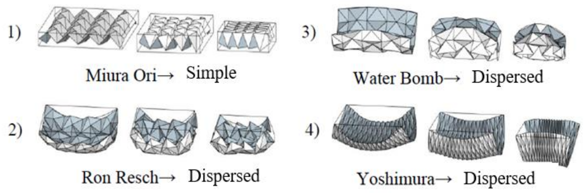

Figure 5 Classification of form and characteristic of the sound distribution of four design alternatives based on Suptandar [6].

3.2.2. SketchUp simulation

Volume of each alternative created by changing the sparseness level of four origami tessellation patterns can be calculated using SkethCup software Entity Info. After knowing the volume of each alternative origami tessellation pattern, the reverberation time is calculated using Sabine equation.

Figure 6 Application of acoustic panels using origami tessellation patterns inside the object researched

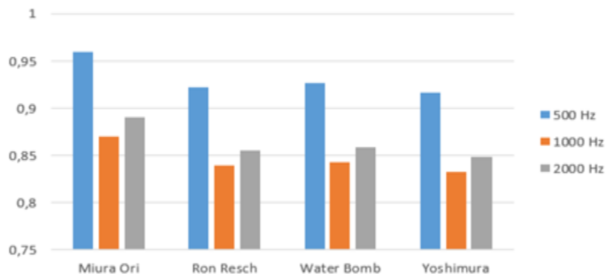

Figure 7 Comparison chart of 4 alternative ranges selected from four origami tessellation patterns researched

Based on the calculation of the average room reverberation time at a frequency of 500 – 2000 Hz using four origami tessellation patterns, the results obtained are 0.9 seconds, 0.87 seconds, 0.88 seconds, and 0.86 seconds where the best alternative is Yoshimura origami pattern.

4. CONCLUSION

The alternative acoustic panel using coconut coir and corrugated cardboard boxes is still not meeting the standard of background noise level, speech intelligibility, and reverberation time. However, it can reduce 34.02% even when it is still not optimal since it is above the standard of 40 dB. In speech intelligibility, it has met the standard, which is above +15 dB. While using pro foam with origami tessellation pattern can reduce the reverberation time inside the room by increasing the absorption coefficient or reducing the room volume based on the Sabine equation. The use of the Yoshimura origami pattern as an alternative is proven to create the largest room volume in order to reduce the average reverberation time inside the lecture hall, reaching 0.86 seconds. In addition to reducing reverberation time, the use of pro foam acoustic panel with origami tessellation pattern is proven to reduce the background noise level inside the lecture hall in order to improve speech intelligibility. It also shows that organic and inorganic waste can be used to improve the acoustic quality where the noise problems come from the closeness location to the busy main road.

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