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VIBRATION ANALYSIS OF AN AIRLIE BEACH HOUSE: A CASE STUDY IN AUSTRALIA

Summary. Airlie beach houses are quite common in the coastal areas of Australia. These houses, similar to other buildings, provide comfort for their residents. House comfort is not limited to temperature or sound pollution, vibration can be considered as another equally important factor. In this article, the vibration of an Airlie beach house was investigated. The base steel structure was modeled in SolidWorks and Space Gass for evaluating stress distribution and nodal displacement, respectively. To find the root cause of the distressing vibration of the house, which was felt with dwellings, the axial acceleration of the house's structure was determined. Some feasible solutions such as adding a fiber-reinforced polymer joist hanger, inserting additional rubber padding to the joist hanger, and attaching additional bracing, were discussed and a cost analysis was considered for the solutions. Eventually, the nature of the best solution, which was adding rubber, was tested experimentally.

Keywords: vibration, Airlie beach house, structure analysis

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1. INTRODUCTION

Vibration prevention is crucial for structure conformity at all levels of construction. Given the nature of small levels of vibration, minute displacement occurs causing fatigue in components, which can significantly reduce the lifetime of a given structure [6, 14]. It is worth noting that a similar situation occurs with machines [10-13, 18, 23].

Over the past decade, there has been a surge in demand for buildings that can be constructed quickly [21]. Fortunately, construction and design techniques have enabled the structural steel sector to satisfy this demand [7] and produce structures that are not only capable of satisfying the above requirements, but also remain competitive in the construction market in terms of the overall cost. This current trend of demanding larger floor areas with lightweight designs has resulted in requiring a greater understanding of the dynamic performance of floors subjected to environmental and human-induced activities [1, 25].

While the modes of vibration and the physics behind vibration are quite complex, understanding the fundamental meaning and source of vibration is relatively easy. The most common source of vibration in moving parts are unbalancing, which is causing the center of mass of a given object to oscillate back and forth [22]. These minor movements, which is called vibration, may occur due to several factors such as wind, earthquake, structural damage, traffic vibration, and water hammer, which will be discussed in detail in the following [9].

The effect of the air flowing through and around the house causes a vibration because of the influx of forces being constantly applied to the support beams. In principle, this wind vibration is exacerbated in structures that are raised off the ground in some fashion such as houses on stilts [2]. A cogent explanation is that the vibration has a big surface area to dissipate over and will continue throughout the structure.

While seismic activity causes the most significant displacement [17], it is far less common and should only be considered if the zone of construction will experience these seismic tremors.

As vehicles such as automobiles or trains move, their weight effects can cause waves propagation through the ground. Due to the road's speed limit, vehicles must travel at a constant pace and vibration from each car can occur in a regular pattern. Not only moving vehicles but also stationary automobiles in traffic can cause vibration [16, 26], and the larger a vehicle is, the more energy it will impart into the ground.

Another possible cause is a water hammer occurring in the pipeline throughout the house [8]. A water hammer occurs when a high-pressure, flowing water system is suddenly shut off and the pressure disperses back throughout the water lines.

Most investigations have considered regular houses, however, Airlie beach houses that are common on Australia’s coasts have not been included. Thus, in this article, vibration analysis of a specific Airlie beach house in Australia was studied. To find the maximum deflection of the house structure, subfloor bracing is modeled in Space Gass, and possible solutions for reducing the subfloor vibration was discussed. Furthermore, not only a cost analysis comparing the solutions financially was done but also experimental tests were conducted to evaluate the efficacy of the implied solution. According to the uniqueness of Airlie houses' structure and their scarcity in other parts of the world, researchers have not devoted as much attention as required to these structures. Although there is a huge void in analyzing these houses, this article attempted to cast light on one of the scientific aspects, that is, vibration, of these buildings.

2. THEORY OF VIBRATION

Vibration is primarily concerned with the relative movement of a mass. Thus, every vibration problem can be classed as one of two different categories, namely, continuous systems, and discrete systems [20]. Continuous systems are systems in which all the relevant mass is directly linked together, such as a beam experiencing bending. Discrete systems involve masses that are independent of each other, such as the horizontal vibration of a multi-story building.

Two main characteristics of vibration are natural frequency and acceleration. Within every physical structure, there are natural frequencies. They are dependent on the relationship between mass and stiffness and how they are distributed throughout the structure. The acceleration of a vibrating system can be determined by analyzing the displacement. Acceleration is the second differential of displacement regarding time meaning the acceleration of a simply supported beam as a function of position and time can be found by differentiating Eq. (1) [19].

$$a(x,t) = \sum_{n=1}^{\infty} -4\pi^2 f_n^2 n_n \sin(2\pi f_n t + \emptyset_n)\ \sin\left(\frac{n\pi x}{L}\right) \tag{1}$$

There are multiple different methods of evaluating the acceleration of a system. Traditionally, the most obvious method was to represent the system in terms of the peak, or largest acceleration. However, this value does not indicate how long the system is subjected to this level of acceleration [24]. Alternatively, the root-mean-square (RMS), acceleration can be used. The RMS acceleration is calculated by Eq. (2).

$$a_{rms} = \sqrt{\frac{1}{t}\int_0^T a(t)^2 dt} \tag{2}$$

Where T, a(t), and t stands for the desired period, acceleration function, and time, respectively.

3. LOAD CASE SUMMARY

When determining the response of the subfloor bracing, numerous factors have the potential to cause vibration within the flooring. Due to the situational conditions of the structure and the level of vibration that is expected, certain loading scenarios have been considered.

3.1. Dead and live loads

The dead load of a structure comprises its weight, typically measured as a uniform pressure over the entire structure. The load involves the combined weight of the floors, walls, roof, internal supports, stairs, and any other form of permanently fixed equipment. For a single and multi-level residential building, a dead load of 0.75 kN/m is typically used for design purposes as per AS 1170.1 [15].

Live loads refer to the dynamic forces that are introduced during occupancy and intended use. They represent transient loads that are moved throughout the structure such as the weight of people, furniture, appliances, and other forms of moveable objects. Similar to the dead load, a standard live load of 3.25 kN/m for a residential structure can be obtained from AS 1170.1.

3.2. Wind loads

Wind-induced loads on the structure are the most likely candidate for the measured floor vibration due to geographical and climate influences on the property. Although the vibration displacement likely exceeds the amount viable to be caused by wind, this load case summary gives insight into the overall design of the house for its ability to disperse wind pressure. AS 1170.2 [4] provides Eq. (3) and an estimated wind pressure acting on the windward (North-West) side of the structure.

$$V_{sit} = V_R M_d M_z M_s M_t \tag{3}$$

Where V_R, M_d, M_z, M_s, and M_t are regional wind speed, wind direction multiplier, height multiplier, shielding multiplier, and topographic multiplier, respectively. Relevant measurements for calculating wind loadings on the house are represented in Table 1.

Tab. 1

Geometry features of the Airlie house

House Geometry Characteristics	Dimensions
Width	11.8 (m)
Length	18.5 (m)
Height	2.7 (m)
Roof Height	1 (m)
Roof Angle	3 degree

To determine the regional wind speeds for the location of the house, the relevant standard AS 1170.2 can be used. Assuming this house is designed to last for an average of 60 years, an importance level of ordinary, the relevant annual probability of exceedance is 1/500. Therefore, for the C zone, the wind speed VR is 66 m/s following AS 1170.2.

With the same procedure, M_d, M_z, M_s, and M_t are calculated equal to 1, and consequently, V_{sit} will be 66.

The force applied to the whole windward side of the house can be averaged as Eq. (4).

$$F = A\rho v^2 \tag{4}$$

In which A, ρ, and v are the surface area, the density of the air, and wind velocity, respectively. Therefore, the total force applied to the windward side of the house is 267.4 kN.

To determine the distributed pressure acting across the surface area of the subfloor bracing, this force was divided across along the length of the structure to provide a North-West facing the pressure of 14 kN/m. In addition to the load case developed as per AS 1170.2, a similar wind load case developed by the original engineers of the structure was also considered. This case was developed as per the design guidelines of AS 4055 [5] and incorporates similar topological and geographical modifying factors. Based on this standard, the distributed pressure across the North-West windward surface was found to be 8 kN/m.

Although the windward side of the structure will always experience the maximum wind-induced loading, it was decided that the South-West profile of the structure should be considered within the load case as well. Based on the orientation of the house, the South-West face of the structure also experiences a substantial volume of wind as well as potential updraft due to the high elevation above the pier footings. To account for this, the design process outlined in AS 4055 provided a distributed pressure load of 6 kN/m. This additional South-West load was considered for both load cases.

4. MODEL DEVELOPMENT

With two wind-induced load cases developed, a suitable model is required to accurately represent the floor response and the effectiveness of the subfloor bracing. Based on the original floor plan details and photos of the property provided by the homeowner, a structural model of the subfloor bracing was developed in Space Gass before any construction (Figure 1).

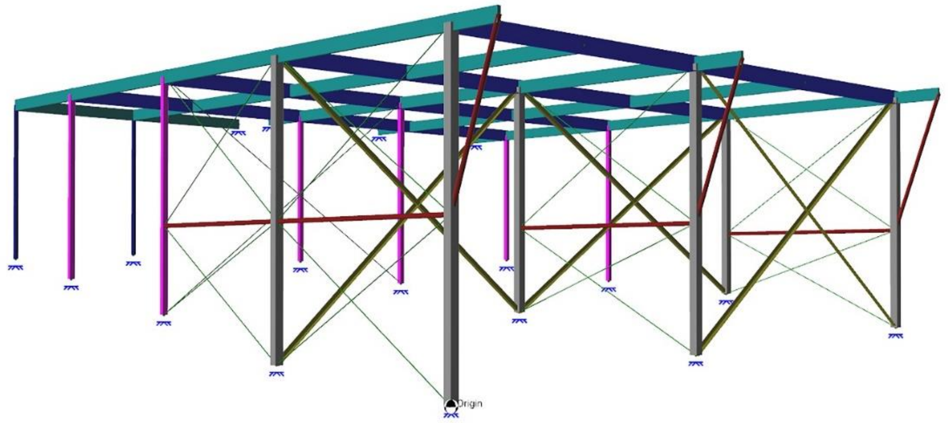

Fig. 1. Space gass model of subfloor bracing

The scope of the project was decided to be limited to only consider the steelwork from the top of the pier footings up to the timber floor beams and joists. This decision was made to simplify the analysis process as it is likely that critical levels of vibration exist within this region. Sections of the property that were removed to simplify the model include the front entry balcony, external stairway, and all structural components that exist above the floor beams.

The subfloor bracing consists of steel square hollow section (SHS) columns that are bolted to the tops of the pier footings and the bottom flange of the steel bearers. The timber floor beams are bolted to and run perpendicular to these bearers and are the main structural support for the joists. The larger SHS columns are strutted together with circular hollow section (CHS) members and then all connected nodes are braced with threaded rods. For sections where no CHS members strut between columns, equal angle EA members are fixed back to back at the corners of the columns. With the critical components of the structure modeled, the load cases can be applied (Figures 2 and 3).

Non-linear static analysis was used to determine nodal displacement values at locations where structural members are connected. The displacement values at every node were then analyzed to determine the location of the greatest vertical displacement (Figure 4).

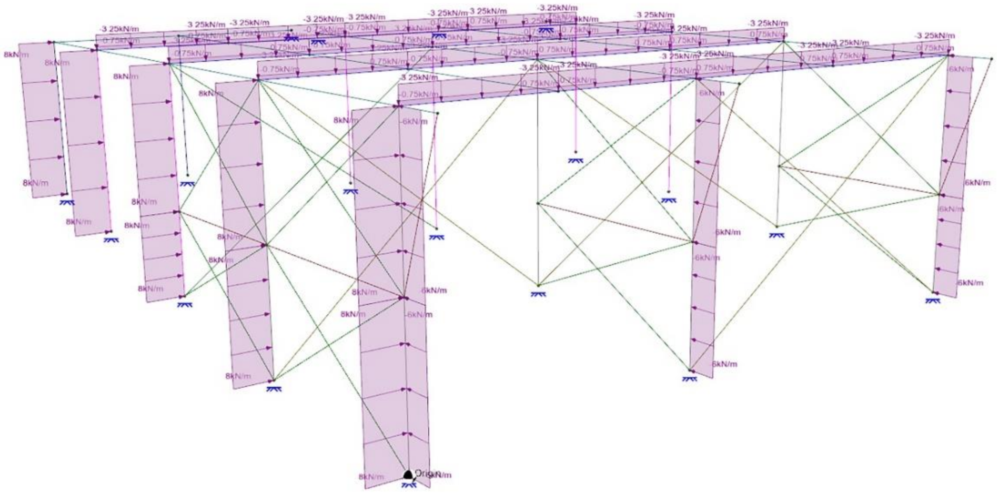

Fig. 2. AS 4055-2012 case with live and dead loads

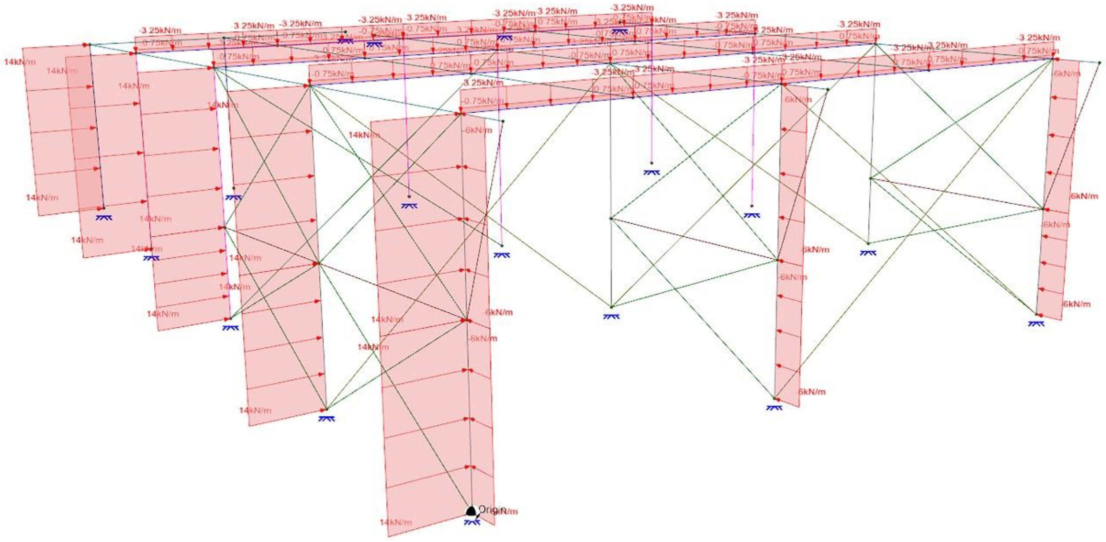

Fig. 3. AS 1170.2-2002 case with live and dead loads

Additionally, to measure stress distribution in the beam members, they were modeled in SolidWorks and the results are presented in Figure 5 and 5. As seen in Figure 5, the house is largely suspended off the ground but does have a large roughly six by six by a three-meter concrete slab in the back corner. The slab should be causing a large amount of rigidity to the immediate structure if mounted securely since any vibration near the slab will need to move the slab itself or the house would start being damaged in that area. Figure 6 shows a simulation of the bending and axial stress in all the steel members of the house. The estimated max stress found in the bearers is 150 MPa, which is well under the 360 MPa standard AS/NZS 3679.1-350 [3].

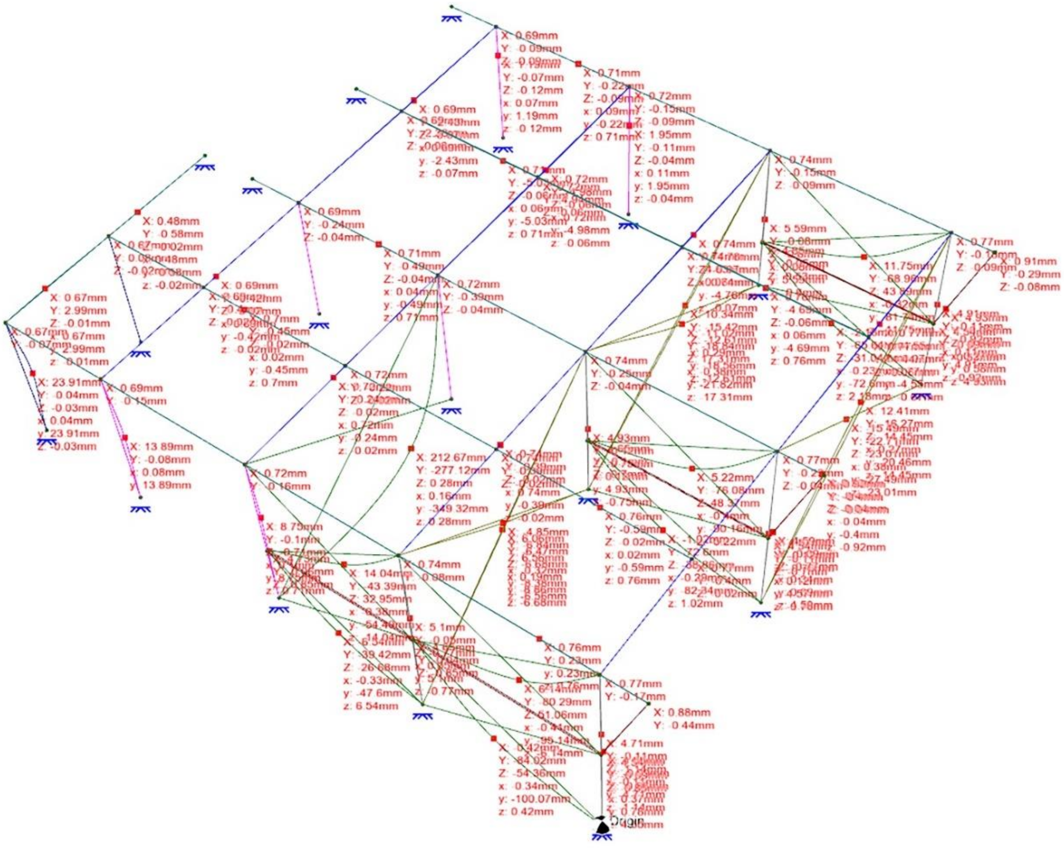

Fig. 4. AS 1170.2 load case nodal displacements

Fig. 5. SolidWorks model of the house

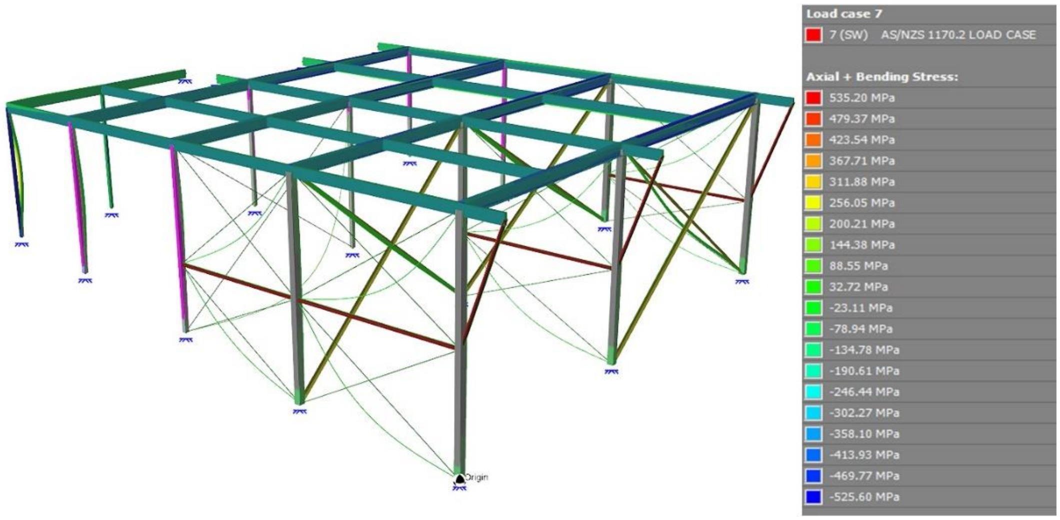

Fig. 6. Axial and bending stress distribution in the structure

5. DESIGN AUDIT

The following design audit is to analyze the house located at Lot 72 Kingfisher Terrace, Jubilee Pocket (Figure 7). On any building, the wind will cause a natural vibration, such vibration will be almost unnoticeable to people. Such vibration is considered background and contributes to the random noise measuring equipment will detect. When comparing standard wind loading graphs to the measured acceleration data, some similarities explain the noise present in the data.

As seen in Figures 8 and 9, the house experiences an illogical amount of vibration relative to the conditions subject to the house. There are no nearby trains passing by, no excessive wind could cause this level of vibration, and damage is not detected either.

Fig. 7. The finished design of the Airlie house

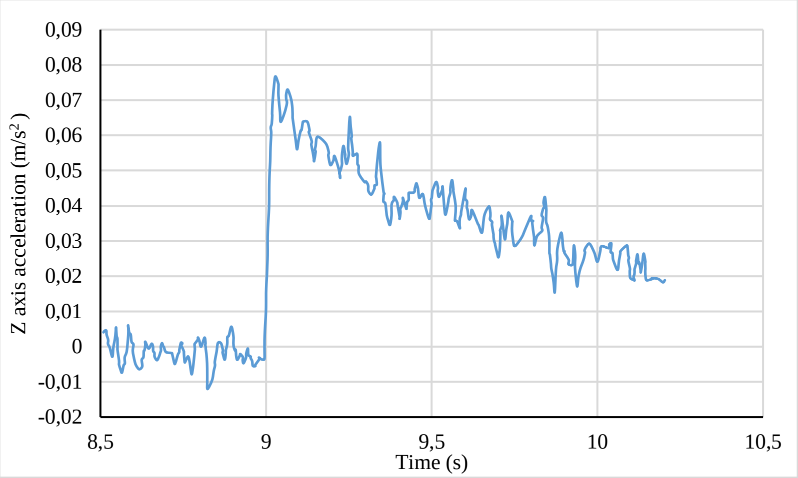

Fig. 8. Axial acceleration of the structure

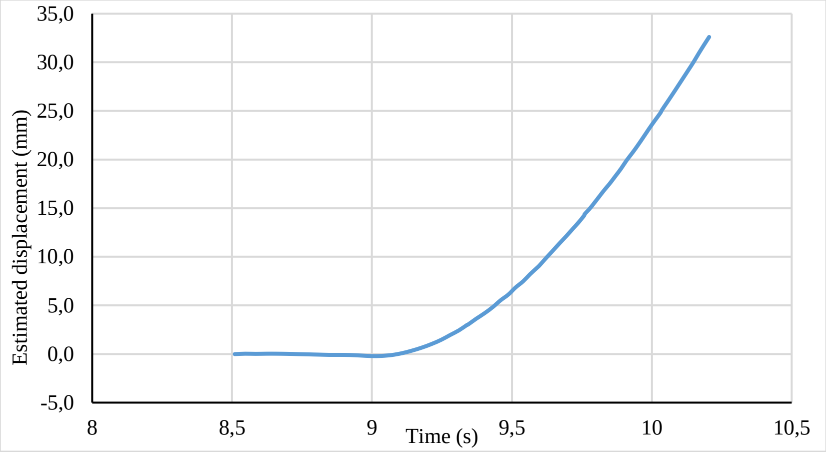

Fig. 9. Estimated displacement

Further analysis is needed to determine the root cause; however, based on the studies done in this report, the house design is valid and does not need any structural changes as it is up to standards.

5.1. Solution

The first solution is to counter the most sag found in the house's floor supports. The bracing will go between the supports on either side of this point. By adding additional bracing, the rigidity of the structure may lessen any vibrations or reduce their effect. If the vibration cannot be prevented by an increase in rigidity, then the additional bracing will have practically no effect. The bracing will be a copy of the existing bracing designs on the house to maintain conformity, corresponding to the equal angle bracing in fab drawings.

The other solution is to replace the current joist hangers with a fiber-reinforced polymer variant. The polymer nature of the hangers will allow any vibrations to be absorbed and lessened at the base of the floor. The polymer joist hangers could also have additional rubber padding added to the platform where the joists rest as seen in Figure 10. This solution will work if the vibrations are passing through the supports into the floor or they are transferring through the floors. If the vibrations are caused above the joists, then the hangers will have a lessened effect.

Fig. 10. Fiber-reinforced polymer joist hanger

5.2. Experimental testing

The physical testing was conducted via a vibrational motor acting on a steel plate. A strain gauge was placed on the steel and recordings were taken of the strain over time. This process was then repeated for the case where rubber acted between the steel and the motor. The setup of the experiment can be seen in Figure 11.

Fig. 11. Experimental setup

The results of this experiment are shown in Figure 11. The strain without the rubber glanced from the positive into the negative. The case with the rubber, however, showed a constant positive strain, proving that the rubber reduced the extent to which the steel moved.

To quantify these results, the factor by which the rubber had reduced the movement in the steel must be determined. To do this, the ratio by which the change in strain occurs must be produced. This will give an accurate idea of how the rubber effects the changes in the steel.

Taking the change in strain, the average of the ratio between these changes will give a rough idea of how much the rubber reduces the changes in strain by a ratio.

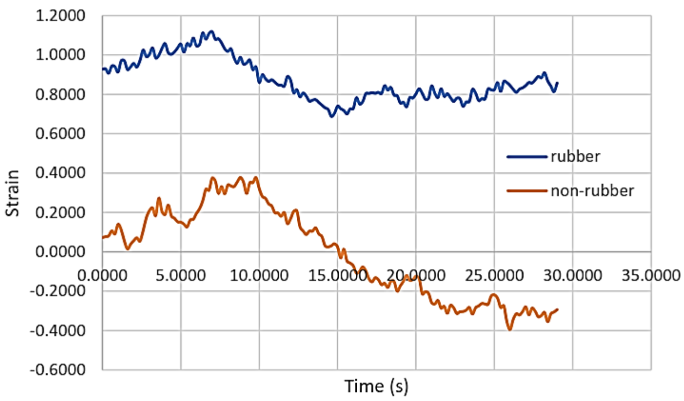

Fig. 11. Physical testing results

From these ratios, the rubber was determined to reduce the change in strain by 4.55x. This should be proportional to the overall displacement as strain is merely a measurement of elongation. Although this is not as accurate, it shows a rough idea of the level of vibration reduction. If we take the initial value of 30 mm of displacement and aim to reduce it to below 1 mm of displacement.

Therefore, the vibration needs to be reduced by a factor of 33.333 times to reach below 1 mm. Taking the amount by which the rubber reduces vibration and dividing by this value will give the rough rubber thickness required. That is, 7.326 times the thickness of 5 mm gives 36.63 mm. Thus, 36.63 mm of rubber is required to reduce the vibration assuming ideal conditions and rubber strain reduction is linear. The recommended amount of rubber is 40 as the original value of 36.63 mm will be rounded up to add a level of vibration reduction.

5.3. Cost analysis

A summary of the cost analysis for the proposed solution is represented in Table 2. The solutions are divided between a low cost or high cost. The additional bracing solution would be low cost with a replication of current bracing in the suggested area. The cost of materials would be approximately $50, and the cost of labor would be between $100 and $200.

The alternate solution of replacing the steel joist hangers with fiber-reinforced polymer joist hangers would cost substantially more. The materials would cost $220, and the labor costs could easily exceed $1000 with the need for specific equipment to support the roof given the awkward position of the joists making it harder to install.

Tab. 2.

Cost analysis

Item	**Type**	**Dimensions**	**Material Cost**	**Quantity**	**Total Unit**	**Total Cost**
Galvanized Steel Column	SHS	150x 4 mm	$50/m	6	29.1 m	$1455
	SHS	100x 4 mm	$40/m	6	22.5 m	$900
	SHS	75x4 mm	$28/m	2	6.3 m	$176
F14 HWD	Post	75x75 mm	$20/m	2	3.2 m	$64

Concrete	Square Footing	1.5x1.5x 1.5 m	$\$250/\text{m}^3$	12	38.5 m^3	$9610
	Pier Footing	0.45x 1.2 m	$\$250/\text{m}^3$	2	0.38 m^3	$95
	Pier Footing	0.6x 1.2 m	$\$250/\text{m}^3$	2	0.68 m^3	$170
	Slab	6.36 x 6.19x0.1 m	$\$250/\text{m}^3$	1	3.94 m^3	$984
Bracing	Equal Angle	75x75x6 mm	$20/m	6	46.9 m	$938
	Rod	Φ16 mm	$4/m	2	11.2 m	$44.8
	Rod	Φ 12 mm	$3/m	8	45.6 m	$136

6. CONCLUSIONS

Vibration is an important factor when house comfort is considered. In this article, an Airlie beach house in Australia was evaluated from a vibration point of view since the dowelling reported an uncomfortable vibration. The results of this report show that the data presented was more than what was expected due to various factors. The project was broken down into three components; determining the cause, conducting an audit on the house, and finally coming up with a solution to reduce the vibration. Although many factors were considered, the most likely cause expected would be a live loading with a wind load added on. The results from the audit show that the design of the house was acceptable and that everything was up to standard in that regard. Finally, multiple solutions were made, depending on cost, etc. An experimental test was carried out with the aid of a vibrational motor operating on a steel plate. The outcomes of the experiment revealed that adding a rubber can reduce the vibration of the connected steel to the vibrational motor. While there is no conclusive way to find out if this will solve the vibration of the house, it is believed that the solutions should reduce the vibration by some factors; however, given the limited scope of the project further testing and investigation is required.

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