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ASSESSMENT OF BAMBOO-BASED ANTI-HAILSTORM STRUCTURES: EVALUATING STABILITY AND RESILIENCE AGAINST RAINFALL, WIND, AND HAIL EVENTS

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Abstract- *The purpose of this research is to determine how well bamboo-based anti-hailstorm structures provide stability and resilience in the face of a variety of unfavorable weather conditions, such as wind, rain, and hail events. The study also aims to investigate the benefits that using bamboo as a primary construction material has for the environment, as well as the structural integrity and material durability. Software analysis and simulations were used to evaluate the performance of these structures under simulated hailstorms, heavy rainfall, and high wind speeds. The results show that bamboo, because of its strength and flexibility, offers a viable, sustainable alternative to conventional materials.*

Index Terms— *anti-hailstorm, Bamboo Based Structure, structural design, Structural Analysis.*

1. Introduction

Hailstorms are a significant meteorological phenomenon impacting various parts of the world, particularly in regions such as North America, Europe, and parts of Asia and India also. In the United States, the Great Plains and the Midwest, known as "Hail Alley," experience frequent and severe hailstorms, causing extensive damage annually (Changnon, 2009). The economic impact of hailstorms is substantial, affecting agriculture, infrastructure, and personal property. In 2020 alone, hailstorm-related losses in the United States were estimated to exceed $8 billion, underscoring the need for effective mitigation strategies (NOAA, 2021). Environmentally, hail can devastate crops, leading to food supply issues and economic instability in affected regions. Developing resilient structures is crucial for minimizing the destructive impact of hailstorms. The creation of structural designs that can withstand hail is a crucial approach to minimizing their effects. It safeguards financial investments, promotes safer public spaces, helps to maintain ecological balance, and supports creativity; hence, it is an important part of disaster response plans and climate adjustments. People have tried different ways to protect against hail in the past and now. In earlier times, farmers used hail nets over their crops, and

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builders used stronger roofing materials. These days, we have more options. We now use new materials and designs that stand up better to hail. Things like shingles that don't break and stronger glass show promise in reducing hail damage. In areas in which bamboo is plentiful, farming, harvesting and production can help nearby economies by way of creating jobs. This can enhance network development and decrease their dependence on imported materials. Bamboo is one of the most sustainable constructing substances available. It grows unexpectedly (up to three ft consistent with day in a few species) and may be harvested in 3-five years as compared to traditional bushes, that may take a long time to develop Benefits of bamboo include its eco-friendliness, affordability, and physical traits. Bamboo offers a fresh option as an engineered material to build structures that protect against hailstorms. It grows fast, renews itself, and has little impact on the environment making it a green choice. What's more, bamboo is cheap and has impressive physical qualities, like being strong when pulled and easy to bend. These STADD PRO make it a good fit for structure structures that need to last and stand up to tough conditions.

2. Literature Review

Past studies on hailstorm effects and ways to reduce damage

Research on hailstorms shows they hurt farms, structures, and people's stuff. Changnon (2009) mapped out when and where harmful hail hit in the U.S. momenting. We need good ways to deal with it. People have tried different things to help, like hail nets stronger materials, and tech that can take hard hits. Givens et al. (2018) talked about how tough structures are key to losing less money and keeping important parts safe. These studies show we need fresh ideas to lessen how much damage hailstorms do.

Review of Bamboo's Mechanical Properties and Suitability for Construction

Researchers have studied bamboo's mechanical properties in depth showing it has great potential as a structure material. Janssen (2000) pointed out bamboo's strong tensile strength, ability to bend, and quick growth, which makes it a good choice for eco-friendly construction. Van der Lugt et al. (2006) looked at bamboo's environmental, economic, and practical aspects too. They found that bamboo works well for supporting structures because it lasts long and grows back. Bamboo's mix of strength and flexibility makes it great for structures that need to withstand things like hailstorms.

Discussion of Structural Methods Used in Structural Analysis

Structural methods have become crucial in structural analysis to simulate how materials behave in different conditions. Tools like structural analysis using STADD PRO software make it possible to run detailed simulations of how structures respond to environmental moments such as hail, wind, and rain. Knight and Knight (2001) used ETABS to assess how well different materials held up under hail impact giving us useful insights into their effectiveness. These methods help researchers to forecast potential

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ways structures might fail and to improve structural designs to make them tougher. By adding bamboo's mechanical properties to these computer models, we can better evaluate its performance and guide the creation of strong structures that can withstand hailstorms.

3. Methodology

3.1 Bamboo and steel properties for structural analysis

In Maharashtra, only four bamboo varieties have been grown for a long time on a large scale. These include Manvel (Dendrocalamus strictus), Katang or thorny bamboo (Bambusa bambos), Managa (Dendrocalamus stocksii), and Chivari or Ooda. Only the first three are economically exploited. From that, Manvel bamboo is a popular structure material due to its lightweight and strength. Corrugated Galvanized steel pipes of diameter 0.1143m are considered from IS 1239 (part 1): 2004 steel tubes, tubulars and other wrought steel fittings — specification Table 3. Dimensions and Nominal Mass of Steel Tubes (Clauses 8.1 and 10.1.1.1).

Fig. Dendrocalamus strictus (Manvel)

Fig. Galvanized Iron 0.1143m diameter pipes

The Indian Forest Survey Report (IFSR) 2021 states that 13,526 square kilometers of Maharashtra are covered in bamboo.

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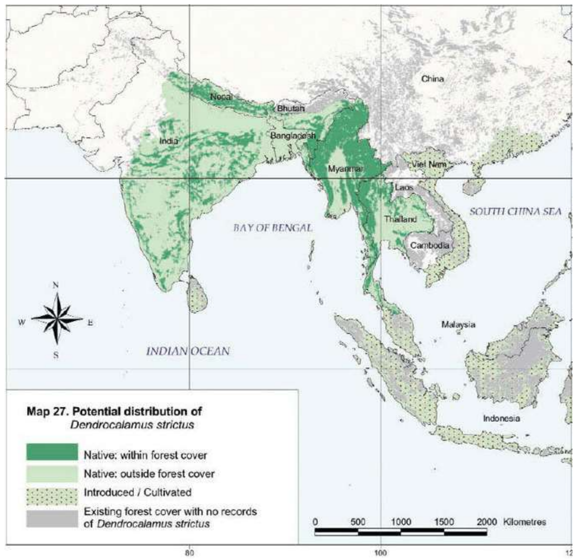

Fig. Dendrocalamus strictus in India

Bamboo's mechanical characteristics can be modeled in the structural system, which is the urgent issue for analysis. Material parameters such as bamboo's large tensile resiliency, elasticity, and losslessness have been taken into account in the STADD PRO simulations.

3.2 Description of Structural Model and Simulations Employed

STADD PRO V8I software which could simulate complex interactions and moment responses and deflection in materials beneath one-of-a-kind situations. The group created models to mimic actual-existence scenarios including environmental factors and material homes to study how nicely bamboo structures face up to hail influences. Their simulations included varying load conditions and combinations to in shape the short nature of hailstorms ensuring they evaluated the structure's capacity to remain intact.

3.3 Load Parameters

The simulations considered a variety of environmental parameters to correctly mirror the situations bamboo-based totally structures would face at some stage in hailstorms. Key parameters protected:

- **Rainfall and Hail Intensity:** India sometimes experiences intense rainfall events, leading to flash floods and landslides, especially in hilly and coastal areas. These events can produce rainfall rates exceeding 100 mm (4 inches) per hour in some cases. For structural analysis, combined hail and rain water load calculated on Inclined members for distance = 3.6977 m from joint is taken as point load running per meter is W= 0.7501 kN/m

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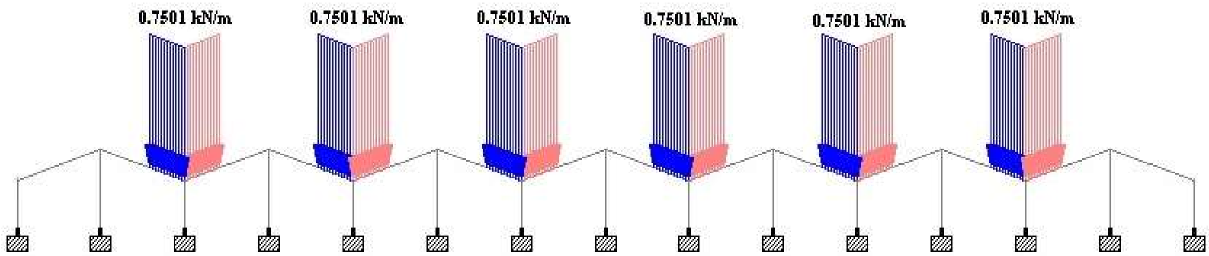

Fig 1. Calculated Rainwater and hail load

- **Wind Speed:** For the wind speed parameters, In June 2020, At 110 km/h (70 mph), Cyclone Nisarga made landfall in Maharashtra, its strongest June storm since 1891. As per beaufort wind scale wind speed for hailstorm structure analysis is considered as 134 kmph. As per ASCE -7 2010, exposure category B and lattice framework is considered for structure idealization.

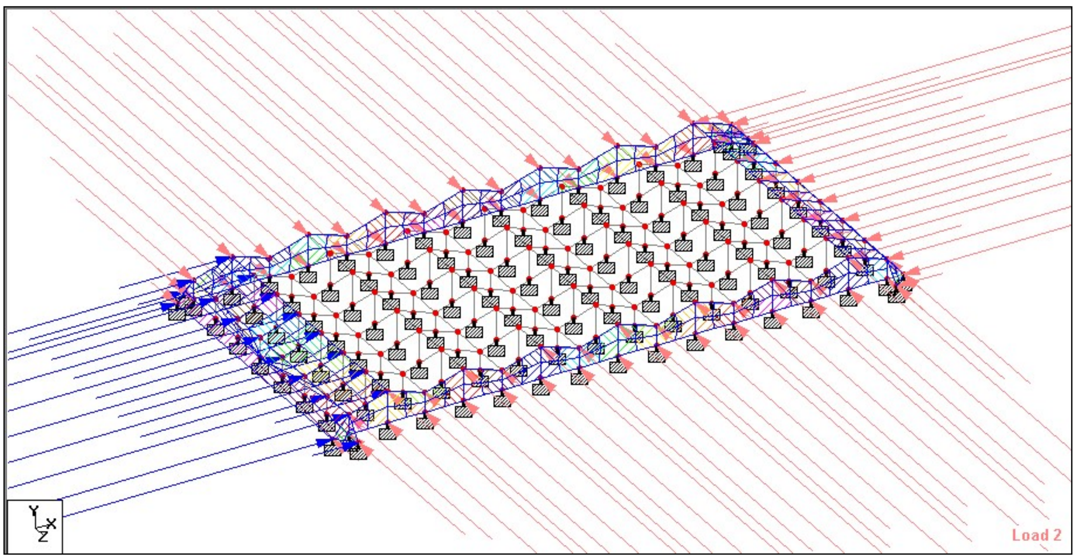

Fig 2. Wind load idealization

3.4 Data for Structural Analysis

- **Rainfall Intensity and Hail Load (kN/m)**: Calculated rainfall rates representing varying levels of storm intensity. Rainwater load is 0.39kN/m and hail load is 0.36 kN/m on sloped members.
- **Wind Speed (m/s)**: The maximum wind speed used for structural analysis is 134 kmph, which is derived from historical storm records and the Beaufort scale.
- **Dimension of Hailstorm structure :**

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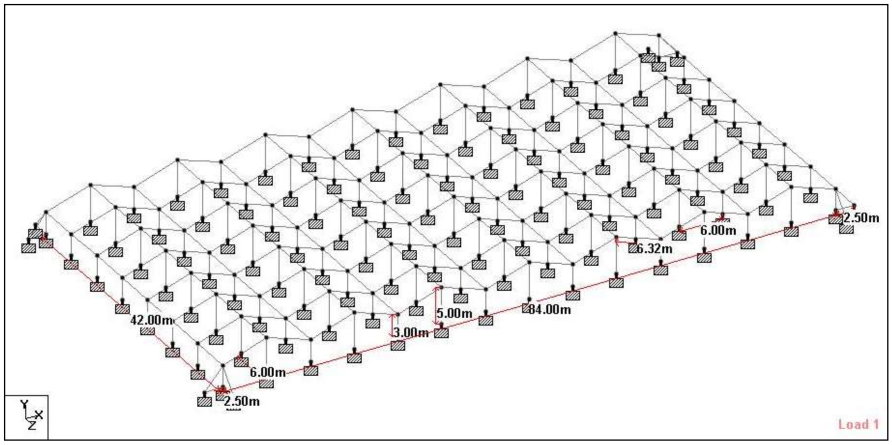

Fig 2. Dimension of prototype

- **3.5 Structural Idealization:**

The structure for analysis includes diameter of 0.1143 m. The outer members, shown in red, are taken as steel pipes with an outer diameter of 0.1143 m and a thickness of 0.0036m, or steel pipe with a diameter of 3 inches. HDPE polythene green shade net, which is utilized in agriculture, is used with their specification.

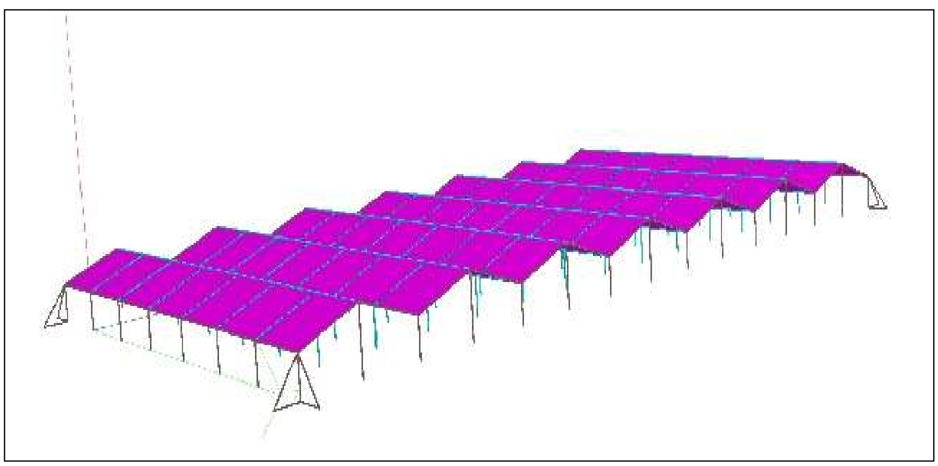

Fig 2. Dimension of prototype

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- **Properties of material:**

Sr. No.	**Name**	**E (Kn/mm^2)**	□□□ □□□	**Density (kg/m^3)**	□ **(/°C)**
1	BAMBOO1E+007	10.000	0.180	591.435	58E -3
2	STEEL	205.000	0.300	7.83E+3	12E -6

- **Loading case and combination**

Number	**Load**
1.	Self-Weight of structure
2.	134 Kmph
3.	0.39 Kn/m
4.	0.3601 Kn/m

Number	**Load Combination**	**Factor**
5	Dead	1.70
6	Dead	1.30
7	Dead	1.70
	Wind	1.70
8	Dead	1.70
	Wind	-1.70
9	Dead	1.30
	Wind	1.30
10	Dead	1.30
	Wind	-1.30

4. Structural Simulations Analysis

4.1 Simulation 01: All members are taken as steel pipes with diameter 0.114m and 0.0036 mm thickness.

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				Axial	Shear		Torsion	Bending	
	Beam	**Node**	**L/C**	**Fx** (kN)	**Fy** (kN)	**Fz** (kN)	**Mx** (kNm)	**My** (kNm)	**Mz** (kNm)
Max Fx	495	243	8:GENERATE	**31.481**	0.139	0.059	0.005	-0.097	-0.003
Min Fx	495	212	7:GENERATE	**-30.638**	-0.225	0.002	-0.032	0.027	0.242
Max Fy	425	4	4:ICE WATER	0.176	**1.985**	0.001	0.001	-0.005	1.881
Min Fy	295	152	4:ICE WATER	0.403	**-1.830**	-0.005	0.000	-0.021	1.676
Max Fz	453	213	4:ICE WATER	5.047	0.021	**0.432**	-0.002	-0.424	0.023
Min Fz	389	183	4:ICE WATER	5.049	0.021	**-0.442**	0.002	0.442	0.023
Max Mx	496	241	4:ICE WATER	-0.274	0.015	-0.101	**0.076**	0.130	0.021
Min Mx	495	243	4:ICE WATER	-0.270	0.015	0.101	**-0.075**	-0.130	0.021
Max My	453	214	4:ICE WATER	5.047	0.021	0.432	-0.002	**0.872**	-0.041
Min My	389	184	4:ICE WATER	5.049	0.021	-0.442	0.002	**-0.885**	-0.041
Max Mz	425	4	4:ICE WATER	0.176	1.985	0.001	0.001	-0.005	**1.881**
Min Mz	260	121	8:GENERATE	-0.619	-0.488	-0.021	0.002	0.036	**-0.789**

Table 01. Beam End Force Summary of Steel Structure

	Beam	**L/C**	**X** (mm)	**Y** (mm)	**Z** (mm)	**Resultant** (mm)
Max X	231	7:GENERATE	**3.352**	-0.066	-0.184	3.358
Min X	39	8:GENERATE	**-3.479**	0.010	-0.167	3.483

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Max Y	359	8:GENERATE	-1.080	**0.281**	0.391	1.183
Min Y	359	7:GENERATE	1.112	**-0.324**	-0.434	1.237
Max Z	427	7:GENERATE	0.945	0.000	**1.006**	1.380
Min Z	363	7:GENERATE	0.945	0.000	**-1.008**	1.381
Max Rst	231	8:GENERATE	-3.479	0.010	0.167	**3.483**

Table 02. Beam Displacement Detail Summary

Simulation 02: All structural members are taken as Bamboo (Dendrocalamus Strictus) with diameter 0.1143m.

				Axial	**Shear**		**Torsion**	**Bending**	
	Beam	**Node**	**L/C**	**Fx** (kN)	**Fy** (kN)	**Fz** (kN)	**Mx** (kNm)	**My** (kNm)	**Mz** (kNm)
Max Fx	495	243	8:GENERATE	**30.742**	0.053	0.024	0.002	-0.038	0.002
Min Fx	495	212	7:GENERATE	**-30.218**	-0.086	0.004	-0.007	0.017	0.091
Max Fy	425	4	4:ICE WATER	-0.230	**1.976**	-0.001	0.000	-0.003	1.871
Min Fy	321	178	4:ICE WATER	0.389	**-1.830**	0.009	-0.000	0.032	1.677
Max Fz	453	213	4:ICE WATER	5.002	0.020	**0.381**	-0.005	-0.377	0.021
Min Fz	389	183	4:ICE WATER	5.002	0.020	**-0.389**	0.005	0.392	0.021
Max Mx	496	241	4:ICE WATER	-0.396	0.017	-0.090	**0.062**	0.117	0.023
Min Mx	495	243	4:ICE WATER	-0.389	0.017	0.091	**-0.062**	-0.118	0.022
Max My	453	214	4:ICE WATER	5.002	0.020	0.381	-0.005	**0.767**	-0.040

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Min My	389	184	4:ICE WATER	5.002	0.020	-0.389	0.005	**-0.774**	-0.040
Max Mz	425	4	4:ICE WATER	-0.230	1.976	-0.001	0.000	-0.003	**1.871**
Min Mz	1	1	8:GENERATE	-1.993	-0.162	0.008	0.001	-0.015	**-0.254**

Table 03. Beam End Force Summary of Bamboo Structure

	Beam	**L/C**	**X** (mm)	**Y** (mm)	**Z** (mm)	**Resultant** (mm)
Max X	135	7:GENERATE	**17.080**	-13.211	0.309	21.595
Min X	37	7:GENERATE	**-16.075**	-12.886	1.387	20.649
Max Y	391	4:ICE WATER	-2.314	**7.365**	-0.597	7.743
Min Y	361	4:ICE WATER	1.331	**-67.906**	0.561	67.922
Max Z	389	4:ICE WATER	0.480	-0.169	**8.580**	8.595
Min Z	453	4:ICE WATER	0.481	-0.169	**-7.864**	7.880
Max Rst	361	4:ICE WATER	1.331	-67.906	0.561	**67.922**

Table 04. Beam Displacement Detail Summary

Simulation 03: For composite structure with all outer structural members are considered as steel pipes with outer diameter 0.1143m and 0.0036 thickness i.e 4 inches hollow pipe and all inner members are taken as Bamboo (Dendrocalamus Strictus) with diameter 0.1143m i.e 3 inches considered from IS 1239 (PART 1): 2004 steel tubes, tubulars and other wrought steel fittings — specification Table 3. Dimensions and Nominal Mass of Steel Tubes (Clauses 8.1 and 10.1.1.1)

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				Axial	Shear		Torsion	Bending	
	Beam	**Node**	**L/C**	**Fx** (kN)	**Fy** (kN)	**Fz** (kN)	**Mx** (kNm)	**My** (kNm)	**Mz** (kNm)
Max Fx	495	243	8:GENERATE	**31.368**	0.188	0.062	0.013	-0.092	0.062
Min Fx	495	212	7:GENERATE	**-30.563**	-0.282	0.003	-0.043	0.020	0.307
Max Fy	423	2	4:ICE WATER	0.383	**1.946**	-0.009	0.004	-0.001	1.800
Min Fy	321	178	4:ICE WATER	0.404	**-1.830**	0.005	-0.001	0.022	1.677
Max Fz	453	213	4:ICE WATER	5.139	0.022	**0.563**	-0.001	-0.538	0.023
Min Fz	389	183	4:ICE WATER	5.136	0.022	**-0.583**	0.002	0.592	0.023
Max Mx	359	152	8:GENERATE	-4.769	0.564	0.110	**0.169**	-0.311	0.550
Min Mx	423	2	8:GENERATE	-4.769	0.564	-0.110	**-0.169**	0.311	0.550
Max My	453	214	4:ICE WATER	5.139	0.022	0.563	-0.001	**1.150**	-0.043
Min My	389	184	4:ICE WATER	5.136	0.022	-0.583	0.002	**-1.158**	-0.043
Max Mz	423	2	4:ICE WATER	0.383	1.946	-0.009	0.004	-0.001	**1.800**
Min Mz	324	151	8:GENERATE	-0.643	-0.595	-0.007	-0.062	0.020	**-1.331**

Table 03. Beam End Force Summary of Composite Structure

	Beam	**L/C**	**X** (mm)	**Y** (mm)	**Z** (mm)	**Resultant** (mm)
Max X	39	7:GENERATE	**12.510**	-0.056	0.158	12.702
Min X	231	8:GENERA	**-12.878**	0.010	0.141	13.079

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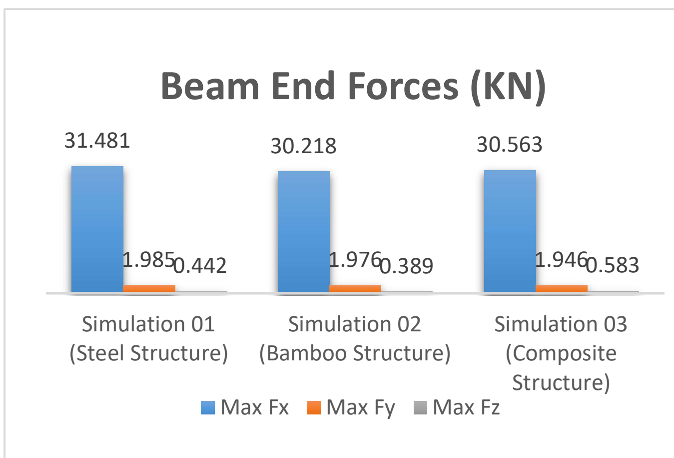
		TE				
Max Y	47	7:ICE WATER	7.652	**0.676**	1.537	7.832
Min Y	47	8:ICE WATER	-7.905	**-1.009**	-1.522	8.113
Max Z	427	7:GENERATE	0.817	0.004	**3.723**	3.812
Min Z	363	7:GENERATE	0.817	0.004	**-3.724**	3.812
Max Rst	231	8:ICE WATER	-12.878	0.013	-0.163	**12.878**

Table 04. Beam Displacement Detail Summary

4.2 Comparative simulation analysis

1. Beam End Forces: The analysis of beam end forces for a predefined simulation reveals that the maximum values of end forces in the X, Y, and Z directions have reached their peak, as shown in the chart.



Since all forces are observed within the same ranges, no particular comparison for the analysis of all simulations is necessary.

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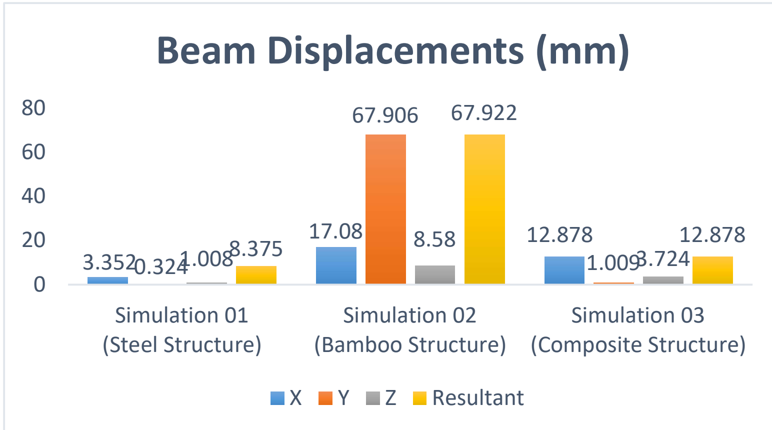
2. Maximum deflection in beam:



The stability analysis of bamboo-based anti-hailstorm structures under various simulated conditions highlighted the outstanding performance of these structures. Simulations have tried to test how scenarios of rainfall intensity, wind speed, and rain water and hails affect the structural integrity and resilience of bamboo constructions.

As the conditions of the storms worsened (rainfall and hail deposition of 0.7501 kN/m, the structures were subject to larger displacements and moment levels as compare to steel structure. Under these extreme conditions, the structural displacement was up to **12.878 mm** and the maximum axial force recorded was **31.368 kN**. According to the report, the deformations were considerable, and the failures were mostly significant enough to indicate the limit of the bamboo's strength, thus it is the upper limit of bamboo's resilience.

4.2 Comparison between Bamboo-Engineered Composite Structures and Conventional Steel Structures

The comparative analysis proved the unique pros and cons of bamboo. As a result of the high tensile strength and flexibility of bamboo structures, they performed extraordinarily well under dynamic loading conditions, which are usually the case during hailstorms. They exhibited energy absorption capabilities that were far better than the others. This quality helped them to be more impactful. In the case of moderate hail conditions, the bamboo structures were more efficient than the conventional materials in terms of lower displacement and reduced moment concentrations. More specifically, the steel constructions had no or very low distortions and the moment values were not changed much under high wind states and heavy hail raining because of their basic properties.

5. Recommendations for Optimizing Structural Design and Materials

Strengthening the Composite Anti-hailstorm bamboo constructions can be done through a range of

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design and material improvements. Hybrid materials are used in the first instance, for instance, mixing bamboo with steel or other high-strength composites would provide structural integrity and weather resistance. This combination can utilize bamboo's flexibility and tensile strength while other materials provide rigidity and durability. The use of advanced joinery techniques and materials that are able to sustain high moment and impact forces is the key factor. Regular maintenance and inspection protocols can be implemented in order to discover and solve the problems that may become the cause of the major failures.

6. Conclusion

6.1 Summary of Key Findings

The study conducted in the Bamboo-based Composite Anti-hailstorm structures has established that it is possible to build resistance based endurable structures from bamboo even for extreme weather conditions. The simulations also demonstrated that under use of various material, hailstorm intensities, bamboo structures experienced small movements and moments while sustaining structural integrity well. Nevertheless, in case of extreme weather conditions such as high rainfall, hails and severe wind speeds (134kmph), the behavior of bamboo structure deteriorated leading to considerable deformation along with higher moment levels which exhibited indicative patterns towards possible failures configuration. The analysis provides some insights on the strength and inherent weaknesses of bamboo, emphasizing potential guidelines for design improvements and a possible usage of auxiliary materials to reinforce it in terms of high endurance. The study highlights the ability of bamboo to become the eco-friendly and cheap material for structure anti-hailstorm structures mainly in parts with moderate hailstorm activity. Nevertheless, in the case of the areas which are at high risk of severe weather conditions, the combination of bamboo and steel materials hybrid designs would be an option that could strengthen the structural performance and resilience. These results encourage further investigation and improvement of bamboo-based construction techniques to ensure their optimum use and applicability in different environmental conditions.

6.2 Implications for the Development of Resilient Anti-Hailstorm Structures

The study's findings have significant implications for future construction practices, particularly in regions prone to moderate hailstorms. Bamboo, with its high tensile strength and flexibility, offers a sustainable and cost-effective alternative to conventional materials like steel and concrete. Bamboo can absorb and disperse the energy from hail impacts, minimizing structural damage, thanks to its natural elasticity. It can be used in regions that frequently experience severe weather because of its robustness, which allows it to endure high wind speeds. Improvements to Durability: Although bamboo is naturally hardy, long-term performance depends on treatments that increase water resistance and stop rot.

By incorporating bamboo into the design of anti-hailstorm structures, it is possible to achieve both

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economic and environmental benefits. However, the research also highlights the necessity for hybrid designs, where bamboo can be reinforced with other materials to withstand extreme conditions. This approach can optimize the performance of anti-hailstorm structures, making them more robust and durable.

6.3 Future Research

Future research should explore advanced joinery methods and material treatments for improved bamboo durability and thermal resistance to mitigate some of the common failure modes found in this study. Careful research investigations are thus necessary to formulate a detailed maintenance plan and monitoring strategies for long-term sustainability of bamboo infrastructure. Lastly, the extension of software modeling incorporate a broader range of environmental conditions and loading scenarios can improve bamboo design as well as application.

7. Results

Ensuring that the structure is stable in every weather condition is made possible by adding items that will fortify them, for example, metal braces, or concrete footings. Optimizing the design by using the right wind resistance and water drainage can enhance the performance of anti-hailstorm bamboo-based structures. From this, it is clear that although bamboo-based constructions represent a method of protection from hail and adopt other weather, they should be made with thought, and treatment accounted for to make sure that they will last for a long time, preserving stability and strength. The tests have shown that the structures made of bamboo (hardly) stand with difficulty when the wind is light (on to around 40km/h) the more the wind, the less the structure would be able to stand. Conversely, the structure turned out to be durable, and the flexibility made the structure alive under the power of the wind. The material's ability to bend was of (134kph), and at the height of the wind, when the waves were about to 1m to the south or southeast, the waves increased in speed.

The bamboo-based structures provided good resistance against small to medium-sized hailstones. The bamboo was able to act as a buffer by stretching and loosening the pressure on the loft instead.

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