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Solidified Natural Rubber Latex (NRL) as a Joint Material in Foldable and Kinetic Structures

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Abstract

The efficiency and reliability of foldable structure connections play an essential role in its overall performance, demanding a precise balance between flexibility, durability, and smooth functionality. Folded and foldable structures are gaining recognition for their creativity and adaptability in diverse engineering and architectural applications. This study investigates the innovative use of Natural Rubber Latex (NRL), in its solid state, as a connecting material in foldable structures, alongside its potential as a joint material for diverse structural applications, such as truss and kinetic structures. Solid-state NRL, known for its unique features such as high elasticity, flexibility, durability, and robust adhesion, combined with its water-resistant properties, stands out as an attractive option for strengthening the structural connections. NRL's natural origin and renewable nature fundamentally contribute significantly to its sustainability. Thus, the integration of NRL into movable structures aligns with the global efforts to adopt sustainable solutions and reducing environmental impact. The investigation focused on evaluating the effectiveness of NRL in connecting wood components within kinetic structures. The results indicate that NRL, once solidified, demonstrates the required flexibility for movement. By incorporating natural fibers, it can be customized to achieve increased rigidity when necessary. NRL also presents a practical choice for fatigue resistance and has the capability to meet tolerances during manufacturing and assembly processes. Another important aspect highlighted in this work is the single-material foldable structure, which addresses challenges associated with the use of multiple materials in such structures. Overall, this study serves as a starting point for more comprehensive investigations, combining experimental analysis and computational simulations, to thoroughly explore the mechanical properties and performance of NRL as a joint material. Future research will extend beyond wood to include other materials, with the overarching goal of establishing a methodology for designing connections made from NRL.

Keywords: foldable structures, natural rubber latex, composite material, joint, kinetic structures, elasticity, renewable material, sustainability, origami

1. Introduction

1.1. Motivation

The ongoing demand for sustainable construction practices, driven by the need to minimize environmental impact, drives the search for new alternative materials. Natural Rubber Latex (NRL) presents itself as a promising option, whether used independently or as a foundational material for composites. This study suggests using NRL as a key element in the joints of foldable and kinetic structures, taking advantage of its unique properties such as elasticity, durability, and flexibility. The aim is to evaluate NRL and NRL composites for developing joints that can be designed in various forms, alternating between rigid and flexible states based on different needs and usage scenarios. This innovative method marks a new investigation of using such raw materials for joints, which were previously disregarded in these applications.

Using solidified NRL as a joining material in foldable and kinetic structures provides several advantages. Firstly, NRL's elasticity allows joints to flex and adapt to changing conditions, reducing the risk of structural damage. Secondly, its durability ensures that joints can withstand repeated folding and unfolding without breaking down, extending the lifespan of the structure. Furthermore, NRL is a renewable and more sustainable material than synthetic rubber, contributing to the overall environmental sustainability of construction projects. Finally, the use of NRL in joints can simplify construction processes and reduce costs, as it can be easily molded and integrated into existing structural elements. Overall, NRL offers a flexible and effective solution for joining materials, providing benefits in terms of performance, sustainability, and cost-effectiveness.

1.2. State Of The Art

NRL, extracted primarily from the rubber tree, Hevea Brasiliensis, is the fundamental source for natural rubber production. Obtained through tapping process, which involves delicately creating shallow cuts in the tree's bark to allow the latex to flow into collection cups without harming the tree. The resulting latex is a complex blend containing water, rubber particles, proteins, alkaloids, lipids, and a variety of organic compounds, highlighting its unique properties. NRL's key strengths lie in its renewability, biodegradability, and elasticity. Sourced from various plants, NRL provides a renewable option with multiple extraction cycles. Its biodegradability aids in minimizing environmental impact, as it can naturally decompose. Moreover, bacteria and fungi can break down NRL, utilizing it as a source for carbon and energy[1, 2].

NRL is widely acknowledged as a flexible material and widely used in engineering practices. Recent research explores its role in enhancing concrete and mortar properties, particularly in pavements and earthquake-resistant structures [3, 4, 5]. Nakanishi et al. has proposed NRL as a substitute binding agent for particleboards in civil construction [6]. Fukahori's study highlights NR's effectiveness in shielding structures from vibrations and seismic events, emphasizing its reliability in providing protection for various structures [7].

Despite NRL's benefits, its production faces sustainability challenges, notably linked to environmental and social concerns. Issues such as deforestation and habitat loss associated with rubber plantations lead to biodiversity depletion and soil degradation. Furthermore, labor rights and fair wages in rubber-producing regions highlight the necessity for sustainable solutions [2, 8]. To address these challenges, concerted efforts are essential in promoting responsible cultivation, supporting communities, and encouraging sustainable trade practices. Various initiatives aim to create more sustainable approach, exploring alternative plants and eco-friendly cultivation techniques. Organizational bodies like the Forest Stewardship Council and Fair Rubber Association support for responsible practices throughout NRL production [9]. On the other hand, Dandelion and Guayule emerge as promising NRL alternatives, growing in various climates and reducing transportation-related environmental impacts. Extensive researches support their feasibility, offering avenues to address sustainability challenges and enhance reliability in rubber production. [9]. Continental, a tire producer, has taken initiative by introducing bicycle tires developed from Dandelion rubber and is now planning to expand into car and truck tire production. These initiatives represent a significant steps towards embracing sustainable rubber sources. They signify a notable shift towards replacing rubber sourced from rubber trees with that derived from Dandelions and potentially other plants in the future [10].

2. Solid-State NRL as a Joint Material

2.1. Timber Kinetic Structures

Kinetic and foldable structures find applications in technical fields, serving various functions like movable elements that open and close. Developing these structures is complex due to the diverse materials involved, including fixed elements, planes, longitudinal elements, and movable components like joints and hinges. In the mechanical field, rigid elements are typically used to ensure precision in displacement, often employing bearings for movable elements. On a constructive scale, flexible materials such as rubber or poly-materials, as referenced in papers [11, 12, 13], play a significant role in enhancing structural adaptability and performance. These materials facilitate a wide range of mobile structures, with applications in architectural scale and flexible work environments . The integration of these flexible materials with timber has received limited study. Therefore, the rest of this paper delves into exploring the diverse applications of this material combination in timber.

2.2. Methodology and Design Parameters

A study was conducted to investigate the incorporation of bio-reinforcements into an NRL matrix, with the aim of developing a sustainable composite material. The composition of NRL-based material involves blending NRL with various particles to enhance its mechanical properties and functionality. The particles are blended with NRL, which is subsequently solidified to incorporate the particles within. This blending not only utilizes the stretching ability and flexibility of the NRL but also optimizes the strength and structural integrity provided by the particles. The study extensively investigated wood chips as matrix reinforcements (as shown in Figure 1), conducting a thorough examination of their properties. The findings suggest a strong bond between NRL and wood chips, indicating potential for customization by adjusting NRL content and type, as well as varying wood chip types, to meet specific engineering needs. Additionally, comprehensive examination of the material's mechanical properties revealed highly promising results in terms of strength and elasticity.

Figure 1: NRL-Wood Chip Composite Material

Studying the interaction between timber and NRL or NRL-composite was an essential step before developing practical samples. It was found that the bonding capacity between NRL and timber is significantly affected by the contact surface area, the roughness of timber surfaces, the type of timber, and the curing time. Specifically, increasing the contact surface area and roughness enhances the bonding capacity. Based on this understanding, two main components were developed: ball joints and hinges. Ball joints (also known as punctual joints or connections at a single point) allow rotation in three or two axes while maintaining fixed translation, making them ideal for connecting two straight elements. On the other hand, hinges (linear joint) enable rotation around a single axis, serving as connections between two planar elements. Each of these components can be further classified as either static or kinetic. Static joints are designed to limit the translation and rotation of connected elements, whereas kinetic joints enable movement or rotation along a predefined axis. Figure 2 provides a comprehensive visualization outlining the diverse range of structure types that can be feasibly developed by using NRL or NRL-based composite as a joint material.

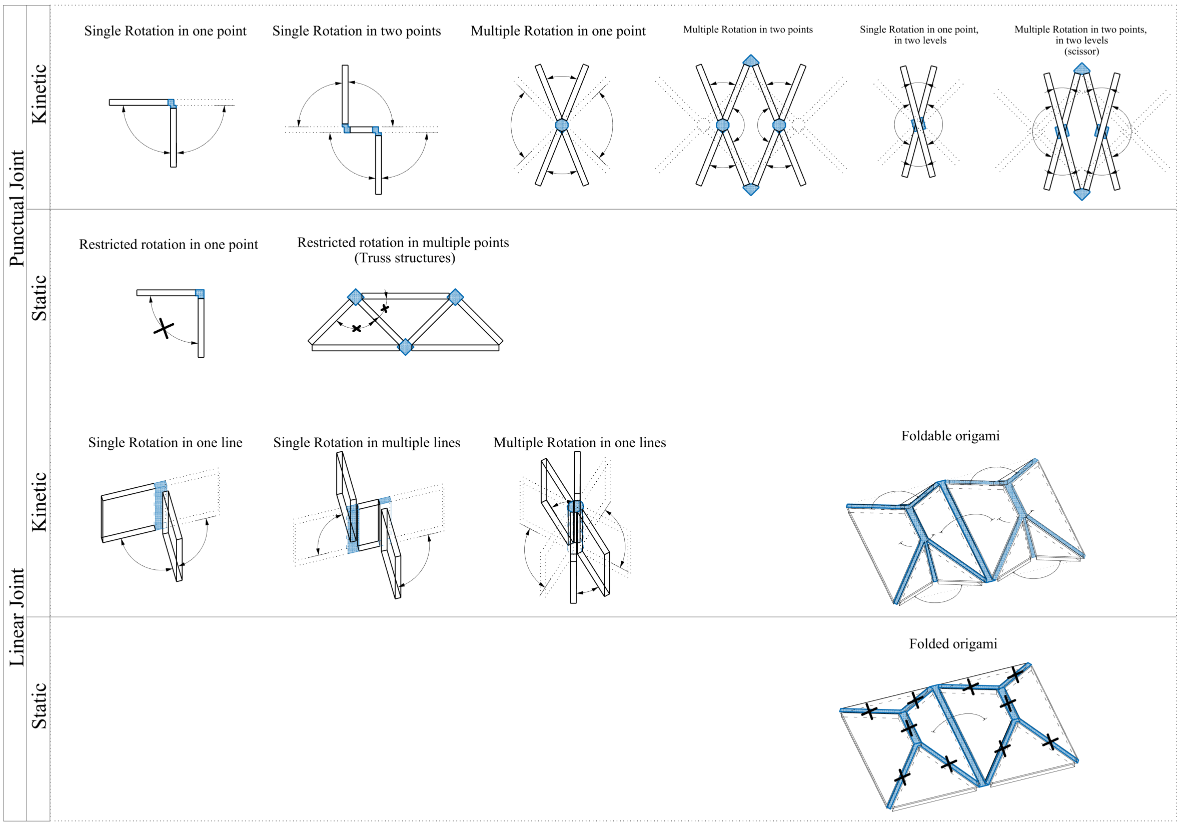

Figure 2: Methods for designing kinetic and foldable timber structures using NRL or NRL composite.

3. Experimental Implementations

Both NRL and NRL-based composite materials were used as joint materials in the fabrication process, tailored to specific requirements. The NRL-based composite was prepared using a manual mixing and pouring method to ensure precise quantities of its components. The process involved preparing the timber components to the desired dimensions and shapes and roughening their surfaces to enhance adhesion with the NRL. Customized molds were then prepared to accommodate the joint, ensuring that fresh NRL or NRL-based composite was contained without any leaks. Following this, all prepared specimens underwent a drying phase at room temperature before subsequent testing.

3.1. Punctual joint Experiments

Selected kinetic structures with point joints were developed for initial testing to assess the suitability of NRL as a joint material and its ability to allow desired movement. Specifically, single rotation at one point and multiple rotations at two points were chosen. Figure 3 depict the final products of these structure types with their respective movements. It was observed that the movement aligned with the desired axis, particularly in the case of single rotation at one point. The flexibility of the joint is influenced by the quantity of wood chips and NRL type, allowing for adjustment to achieve either a fully fixed or movable joint. For the static point joints, a truss structure sample was assembled using NRL composite material, as depicted in Figure 4. The objective is to create flexible joints suitable for applications where moving or dynamic loads are predominant.

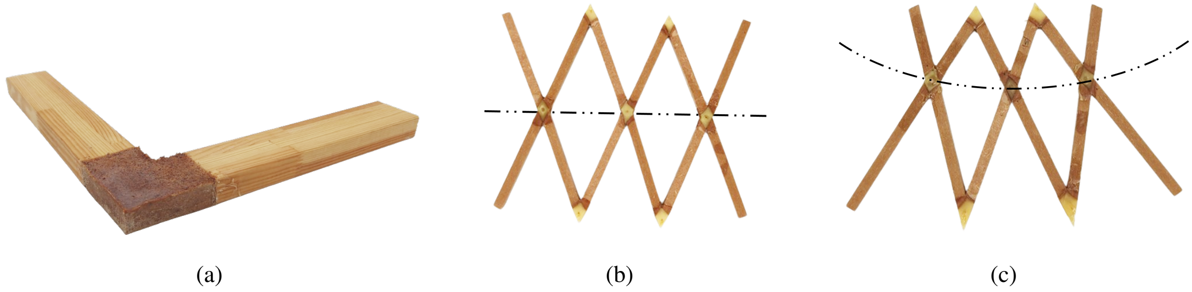
(a) (b) (c)

Figure 3: Punctual kinetic joint structures:(a) single rotation at one point; (b) multiple rotations at two points in straight line; (c) multiple rotations at two points in curved line

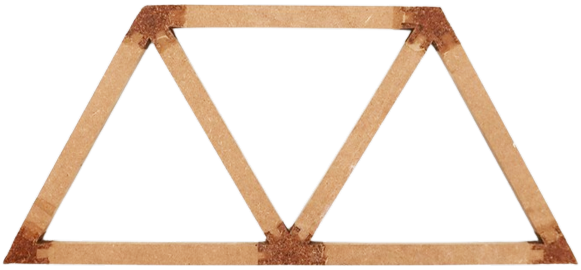

Figure 4: Punctual static joint structure

3.2. Linear joint Experiments

For the linear joints, the primary focus was on constructing origami patterns capable of rotation. Two origami patterns are illustrated in Figure 5, namely the Yoshimura pattern and chicken wire pattern. A significant challenge was to execute a thick origami structure where the thickness of timber parts is not


(a) (b)

Figure 5: Linear kinetic joint structures:(a) chicken wire origami pattern; (b) Yoshimura origami pattern

negligible. As a general guideline, it was observed that a joint width should ideally be 1.5 to 2 times the thickness of the timber parts to ensure proper folding. Furthermore, the thickness of the joint is directly correlated with the thickness of the timber. To enable folding while ensuring robust bonding between NRL and timber, the joint thickness is ideally maintained at 0.5 to 1 times the thickness of the timber. In fatigue experiments, the joints were tested by folding and unfolding numerous times, and they remained stable without cracks, indicating their suitability for foldable structures as well as folded ones.

3.3. Punctual and linear joints in hybrid structure

The previous experiments resulted in the development of a hybrid structure that combines point and linear joints, serving as a functional structural system. The combination of multiple transformable systems is often employed to reduce degrees of freedom or to activate movement more precisely [13]. Joints with multiple rotations at two points, also known as scissor systems, can be combined with folding systems provided they share the same movement trajectory [12]. In this experiment, various shapes are integrated using a dual-planar scissor system and longitudinal folding panels that connect both scissor systems, enabling precise directional movement.

The development of this scissor system, compared to the example from Section 3.1 depicted in Figure 3 (b) and (c), incorporates superimposed perforated bars with NRL inserted into the gaps. This design creates a joint with minimal torsional resistance, facilitating single-point rotation at two levels, as illustrated in Figure 2. These scissor mechanisms are connected at their odd bars with folding panels previously bonded with NRL. This experiment highlights another application of NRL in advancing foldable and movable structures. Future experiments will explore the development of more complex configurations, combining flexible panels such as monolithic folding (to be discussed in Section 3.4) with these or other hybrid transformable systems.

(a) (b)

Figure 6: Scissor and folding hybrid structural system with NRL: (a) Deployed system state; (b) Collapsed system state.

3.4. Monolithic foldable structure

It has always been challenging to integrate two materials in foldable structures and utilize them effectively, as there is often a solid part that cannot move and a joint part that needs to be flexible. To address this, an innovative approach was developed to create a single-material foldable structure using a composite material, specifically the NRL-based composite with wood chips. The concept involves designing a pattern with varying thicknesses, where the more rigid parts are thicker than the joints. This thickness variation determines the mobility of each part. Constructing such structures eliminates many problems associated with using different materials and allows for the design of complex shapes and patterns. This approach results in a continuous, homogeneous structure with varying thicknesses. Figure 7 illustrates a preliminary example of the chicken wire pattern. However, further enhancements can be made to optimize the shapes and improve structural efficiency.

(a) (b)

Figure 7: Monolithic foldable structure: chicken wire origami pattern

4. Conclusions

In conclusion, the exploration of solid-state NRL as a connecting material in foldable structures presents promising avenues for enhancing structural efficiency and sustainability. The study highlights NRL's unique properties, including elasticity, durability, and robust adhesion, making it an attractive option for strengthening structural connections. The investigation into NRL's effectiveness in connecting timber components within kinetic structures reveals encouraging results. NRL demonstrates the necessary flexibility for movement and can be customized to exhibit increased rigidity when required. Additionally, NRL presents practical advantages such as fatigue resistance and the ability to meet tolerances during manufacturing and assembly processes. In addition to exploring NRL's potential as a joint material, the study introduces an innovative concept: the monolithic foldable structure. This approach eliminates the complexities associated with integrating multiple materials by utilizing a single composite material, specifically the NRL-based composite with wood chips. By varying the thicknesses within the structure, more rigid parts and joints are effectively distinguished, allowing for controlled mobility. This novel approach not only simplifies construction processes but also enables the design of complex shapes and patterns. Moving forward, further research will focus on comprehensive investigations combining experimental analysis and computational simulations to thoroughly explore NRL's mechanical properties and performance as a joint material. Additionally, future studies will extend beyond wood to include a broader range of materials, aiming to establish a methodology for designing connections made from NRL. Overall, NRL holds significant promise as a sustainable and effective material for enhancing the efficiency and reliability of foldable structure connections.

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