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LOW-COST BIOMASS CONSTRUCTION TECHNOLOGY SYSTEMS WITH SMALL-DIAMETER ROUND TIMBER AS MAIN MATERIAL AND ITS CARBON REDUCTION EFFICIENCY

Ying Wu[1], Hongpeng Xu[2] , Jianmei Wu[3], Yuncheng Ji[4]

ABSTRACT: Modern wood architecture conforms to the theme of ecological sustainable development, but the shortage of forest resources restricts the development process of modern wood architecture. Cheap and easily available small-diameter round timber shows broad application prospects, which main sources are wood products from plantation, fast-growing forest, the forest harvesting residues, sub-small fuel wood and logs that do not reach the structural standard. The purpose of this paper is to provide a technical system of small-diameter round timber as main material, which aims at saving materials and reducing cost in small to medium scale buildings, and further improves the carbon reduction efficiency of wood structure buildings. Through the research path of architectural typology, that is, Construct technology system -- Technical performance verification and Carbon reduction efficiency analysis -- Translation and extension, both model analysis and data calculation for the single-rod lattice system were performed. The main contents are as follows: Firstly, a biomass building technology system tailored for rural development in Northeast China is proposed, encompassing the "small log structure technology system" and the "straw material enclosure technology system." The construction methodologies of these two systems are elaborated upon respectively. Secondly, based on the logical analysis of force and force transfer in modern timber building structures, the characteristics of materials and structural forms are defined. Orthogonal simulation tests and visual data analyses of influencing factors were conducted using SAP2000 and 3D3S software to determine the spatial construction thresholds of the three structural systems. Thirdly, based on the heat transfer principle of building envelope structures, the thermal physical properties of the straw material-based envelope technology model and the key influencing factors of building heating energy consumption are identified. Multi-factor simulation tests and visual data analyses were performed using DesignBuilder software to define the construction mode of the envelope system and the thresholds suitable for construction. Finally, building models of large, medium, and small scales are established, and the carbon reduction benefits of the three are comprehensively compared. With the increase in construction scale, the advantages of carbon reduction and cost savings gradually diminish, leading to the proposal of an optimized method for biomass building design.

KEYWORDS: Modern wood technology; Small-diameter round timber; Biomass construction technology system; Design Method

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1 – INTRODUCTION

As global attention has increasingly focused on carbon emissions from buildings and the environmental impact of building material production, the use of timber structures and biomass materials in construction has emerged as a critical strategy for nations to adjust their construction industry mechanisms. For instance, over the past two decades, Sweden has implemented its "Bio-Innovation Program," which aims to encourage the application of wood in construction to facilitate fundamental changes in the market economy. Similarly, Finland, Norway, and countries in North America have introduced policies to promote the adoption of timber structures and biomass building materials [1-2]. In contrast, China is still in the early stages of exploring the practical application of biomass materials in construction. In 2020, aligned with the United Nations Framework Convention on Climate Change (UNFCCC), China officially proposed the "3060" dual-carbon strategic goal [3]. Despite this, the significant and rising carbon emissions from buildings and construction continue to pose major challenges for China's construction industry in achieving the dual objectives of "carbon reduction and sustainability" and "energy efficiency improvement" [4]. Consequently, leveraging biomass materials as primary building materials, combined with technical advancements and performance optimization, offers a promising pathway to address climate change, achieve the dual-carbon goals, and enhance public awareness regarding the impact of the built environment on health through its ecological advantages [5].

1.1 RESEARCH BACKGROUND

The utilization of biomass materials in building construction boasts a long history, encompassing straw bale buildings, bamboo structures, and wooden frameworks. From the early rudimentary shelters to contemporary high-tech constructions, biomass materials have consistently played a pivotal role.The carbon reduction and sustainable properties of wood as the building material are attracting great attention [6]. In recent years, the development process of low-cost and low-tec construction of wood architecture was restricted by the shortage of building timber and increasing construction cost [7]. In the face of this contradiction, fast-growing forest products are gradually included in the application of building materials [8], which are high-stock and low-cost. In addition to wood-based composite materials, wood modification, or wood-based panels [9], the use of small-diameter round timber as building structural materials are also emerging [10], which main sources are wood products from plantation, fast-growing forest, the forest harvesting residues, sub-small fuel wood and logs that do not reach the structural standard. In the 1960s, governments in forested areas around the world are increasingly facing a major forestry challenge: the excess of trail logs (100-250 mm in diameter), which puts forests at increased risk of damaging high-intensity fires, disease, and insect attacks [11]. According to statistics, in China alone, in the past 30 years, the area of plantation has increased by nearly 2 times, and the stock volume has increased by 15 times [12], and the small log is the forest product from the thinning operation of plantation and fast-growing forest. Many studies around the world have shown that the use of small-diameter wood as a structural element with a complete circular cross-section and minimal factory processing provides a high market value and increased returns [13].

1.2 RESEARCH OBJECTIVES

Aiming to address the imbalance between "environmental advantages" and "economic benefits" of biomass building technology in the rural development of Northeast China, this study proposes a technical approach for the research and development of biomass buildings in Northeast China. The goal is to achieve carbon reduction and increased efficiency by adhering to the principle of "low-carbon sustainability, low cost, material conservation, and accessible construction technology."This study primarily examines the necessity of synchronously implementing a low-cost biomass building technology system (including small log structure technology and straw material enclosure technology) as a carbon emission reduction strategy in Northeast China, along with conducting relevant research. This paper focuses on designing biomass farmhouses of varying scales suitable for Northeast China and further correlates the integrated biomass farmhouse systems with building scale through detailed calculations and evaluations of carbon reduction benefits. On one hand, this analysis elucidates the relationship between building scale and carbon reduction efficiency. On the other hand, by comparing the currently prevalent brick-concrete buildings and light wood structure systems in Northeast China, the study clarifies the mechanisms linking specific construction scales, construction modes, and the carbon reduction benefits of biomass farmhouses.

2 – METHODOLOGY

Through the research path of architectural typological, that is, Construct technology system -- Technical performance verification and Carbon reduction efficiency analysis -- Translation and extension, taking small and medium-sized wooden buildings as the research counterpart. The purpose of constructing lattice unit structure system with small-diameter round timber is to improve the efficiency of building structure and the economy of wood building structure system. The specific research methods and contents are shown in Figure 1.

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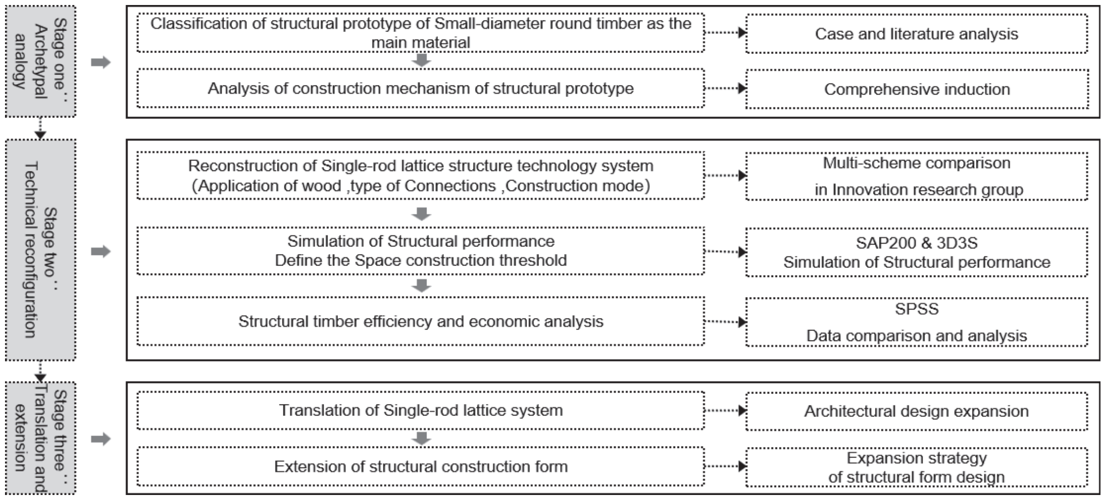

Figure 1. Research framework.

2.1 LOW-COST BIOMASS CONSTRUCTION TECHNOLOGY SYSTEM

According to statistical data, the construction cost of rural wooden buildings in Northeast China primarily comprises structural systems, enclosure systems, decoration, and construction costs. Among these components, the structural system and enclosure system account for over 90% of the total construction cost. Consequently, this study focuses on addressing two critical issues within the biomass building technology system. The first issue pertains to utilizing low-cost wood to construct spaces that meet rural usage requirements. The second involves employing affordable biomass materials available in rural areas to develop enclosures with superior thermal and physical properties, thereby achieving both cost reduction and carbon emission mitigation in buildings. Based on this, the technical system of rural biomass farmhouses is divided into a "structural technical system" and an "enclosure technical system." Using inexpensive and readily accessible materials — small-diameter logs for the structural system and straw for the enclosure infill — the study investigates corresponding technical system solutions. This research lays the groundwork for subsequent simulations of the technical performance of both systems, as illustrated in Figure 2.

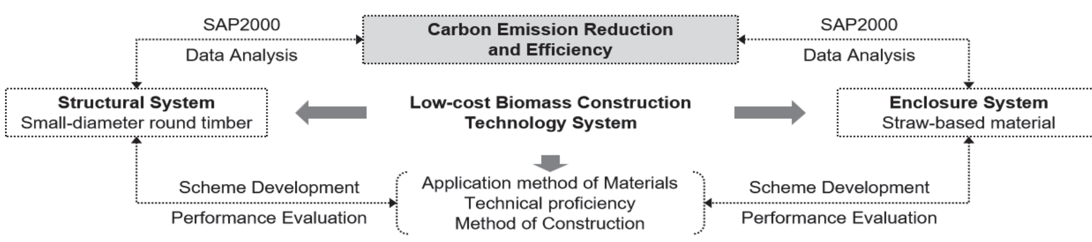

Figure 2. The Fundamental Constitution of the Biomass Construction Technology System.

2.2 TECHNICAL STRUCTURAL SYSTEM OF SMALL-DIAMEIER ROUND TIMBER

As illustrated in Figure 3, the fundamental "beam-column" force transmission mechanism of the frame structure is employed to define the force transmission paths for each member. The stress mechanism of this technical model is closely tied to the cross-sectional type of the linear members, ensuring that the direction of internal force transmission aligns with the structural form's force transmission direction. This allows the frame structure to accommodate the internal force transmission requirements of the roof truss unit, while lateral thrust is effectively transferred through beams and tie rods. Small-diameter logs exhibit dual advantages in both tensile and compressive strength, which play a critical role in balancing lateral thrust. By leveraging the geometric principle of "multi-line forming plane," the small-diameter logs can integrate their inherent shape and material properties within the basic framework system. Through simple nodal connections, they achieve optimal structural stability for building load transfer. Furthermore, the structural system enables the formation of flat sections via straightforward cutting processes, which can then be combined with shaped metal connectors to facilitate efficient joint connections for wooden components, thereby reducing the complexity of wood structure construction.

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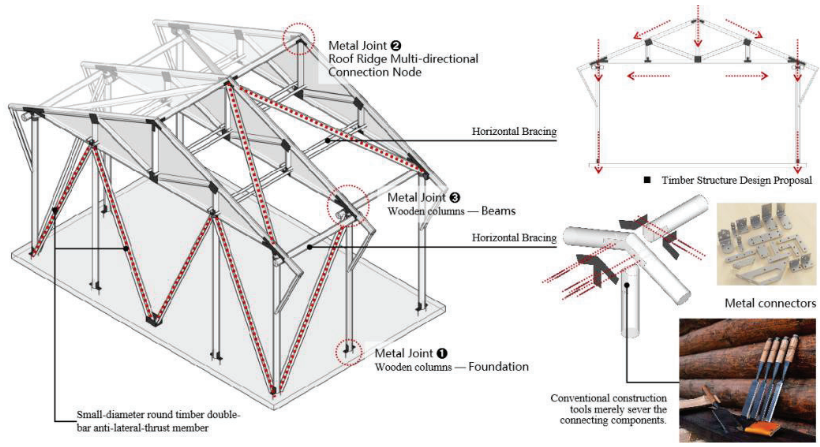


Figure 3. Analysis of technical system construction of small-diameter round timbe.

2.3 STRAW-BASED MATERIAL ENCAPSULATION TECHNOLOGY SYSTEM

In the traditional construction practices of Chinese rural architecture, thatch, straw, and clay are frequently utilized as primary materials for enclosure structures. These biomass materials are cost-effective, readily accessible, and exhibit favorable thermal properties. For instance, in Northeast China, the Hezhen people traditionally construct eaves walls using straw and mud braids, which not only adapt effectively to the cold winter climate but also enhance wall durability. Nevertheless, buildings constructed with traditional biomass materials often suffer from poor structural stability. To address this issue, yellow mud is typically mixed on-site to form stable bricks suitable for use in building envelopes. However, this process is labor-intensive and time-consuming, leading to its gradual obsolescence. From the perspective of low-technology construction and integrated assembly components in rural architecture, this study focuses on straw, the most abundant material currently available (which could potentially be substituted with other lightweight thermal insulation materials such as thatch or reed), combined with low-cost oriented strand board (OSB) panels to develop a stable structural unit for enclosure walls. The specific construction method is illustrated in Figure 4.

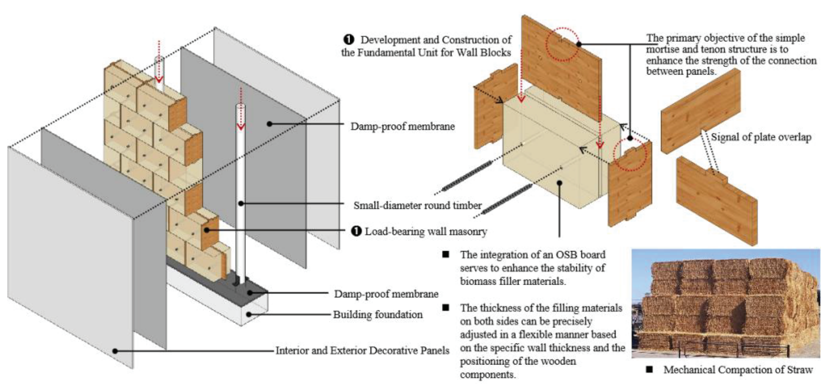
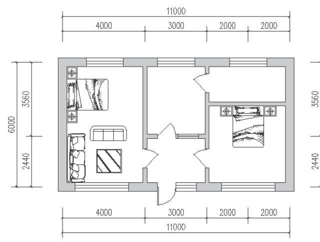
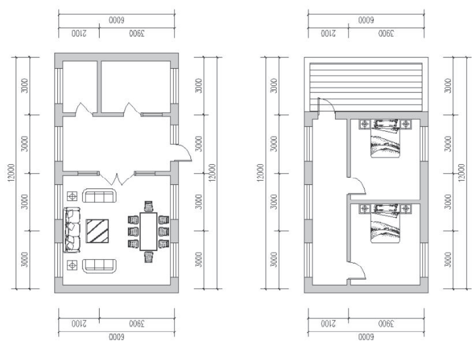
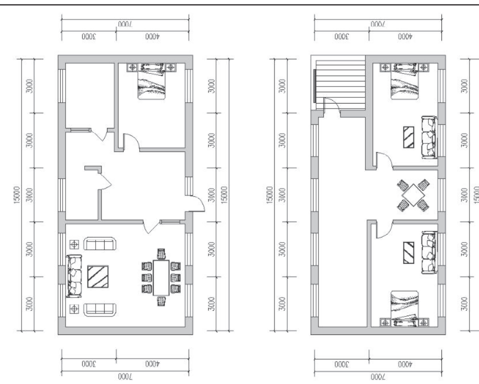


Figure 4. Development of theonstruction method for biomass material enclosure systems.

2.4 CASE STUDY DESCRIPTION

The scale of rural buildings in Northeast China varies between 54 m^2 and 210 m^2. The interior spaces typically have heights ranging from 2.4 m to 2.8 m, widths from 10m to 15m, and depths from 5 meters to 8 meters [15]. The architectural style predominantly features double-slope roofs. Within this scope, this study examines the application scenarios of three distinct biomass building scales, primarily constructed with small logs. Table 1 include Type A Small House (73.32 m^2), Type B Medium House (140.21 m^2), and Type C Large House (219.83 m^2). Biomass farmhouses of varying construction scales were compared with brick-concrete structures and light wood structures of equivalent area. Additionally, modern wood structure systems were considered due to their relatively high cost-effectiveness and construction efficiency, providing significant reference value. These reference types will serve as control groups for cross-sectional comparisons with the carbon reduction benefits achieved by biomass buildings in terms of size and material usage.

Table 1: Characteristics of study scenarios and floor plans

	Building exterior and main characteristics	Floor plans
Type.A Small Building		
Type.B Medium Building		
Type.C Large Building		

2.5 CARBON REDUCTION EFFICIENCY ANALYSIS

To address the issues of carbon emissions, construction costs, and technical suitability throughout the life cycle of biomass buildings, this study integrates complex calculation methods and processes. Drawing on the conventional calculation methods for building life cycle carbon emissions (LCA), building life cycle cost (LCC), and construction benefit evaluation approaches, this paper proposes the evaluation characteristics of the "carbon reduction benefit" of biomass buildings in Northeast China. The evaluation path is simplified, and an analysis is conducted from two perspectives: "calculation boundary" and "index type and calculation method."

Absorption Stage——Fixed carbon content

"Carbon sequestration stage" refers to the process of selecting building materials with "carbon sequestration properties," such as wood, straw, and other readily available biomass materials. These materials absorb and store atmospheric carbon dioxide during their growth phase, which is subsequently retained in the form of building components [16]. This phenomenon can be considered an extension of plant-based carbon sinks [17]. The specific calculation method involves quantifying the relationship between the quantity of biomass materials used in actual construction and their carbon content, followed by a systematic aggregation of these values. This calculation approach is presented in Formula 1. Based on the aforementioned calculation boundaries, this study evaluates and compares the life cycle carbon emissions of biomass construction system. As the biomass material, the carbon absorption stage primarily calculates carbon content based on dry density and the proportion of carbon elements in carbon dioxide for various types of material [17].

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$$C_{Ab.} = \frac{1}{P_C} \cdot \sum_{i=1} \rho_i \cdot V_i \cdot C_{c.i} \quad (1)$$

$C_{Ab.}$—Absorption stage, carbon sequestration capacity per unit area of the structural system, $kgCO_2/m^2$;
P_C—the carbon content ratio within the carbon dioxide molecule;

ρ_i — The dry density of Type i timber or wood-based structural materials, kg/m^3;
V_i — The volume of timber or wood-based structural material per unit area, m^3;
$C_{c.i}$ — Carbon content of Type i logs or wood-based structural materials (carbon sequestration capacity), %;

Table 2: Embodied stage carbon emission estimation method

Life-cycle of building structures	Computing method	
JG. Production stage	$C_{JG.} = \sum_{i=1}^{n} E_{JG.i} \cdot EF_{JG.i}$	$C_{JG..}$—Production stage, Carbon consumption per unit area for the building's structural system, $kgCO_2/m^2$; $E_{JG.i}$—The quantity of timber utilized per unit area for constructing the structural framework, m^3; $EF_{JG.i}$—Carbon Emission Factors of Structural Materials for Building Type i, $kgCO_2/m^2$;
YS. Transport to site	$C_{YS.} = \sum_{i=1}^{n} V_i \cdot D_i \cdot T_i$	$C_{YS.}$—Production stage, Carbon consumption per unit area for the building's structural system, $kgCO_2/m^2$; V_i—Quantity of materials utilized for the construction of structural components of type i, m^3; D_i—Transportation Distance of Structural Materials for Type i Buildings, km; T_i—The carbon emission factor per unit volume transport distance for building structural material type i under the corresponding transportation mode, $kgCO_2/(t \cdot km)$;
SG. Construct	$C_{SG.} = (S + 1.99) * A$	$C_{SG.}$—Total carbon emissions associated with building demolition, $kgCO_2/m^2$; S—The number of ground floors in small and medium-sized buildings; A—Gross Floor Area, m^2;

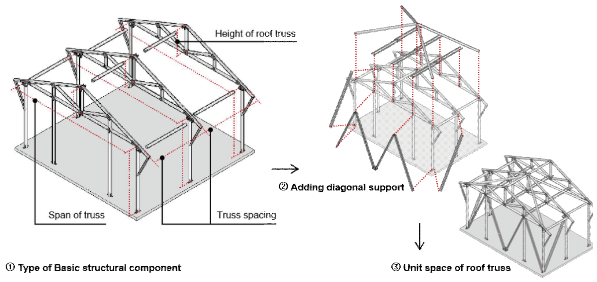
Embodied Stage——Embodied carbon

The "carbon consumption stage" refers to the aggregate carbon emissions across five phases of the building life cycle: material processing, component transportation, construction, operation and maintenance, and dismantling. In the context of rural buildings, which are predominantly self-funded, self-built, or jointly constructed with "low-technology" approaches [18], the statistical indices primarily rely on the actual consumption of building materials [19]. Additionally, a longer construction period results in greater carbon emissions during the demolition stage. Scholar Zhang Yousheng from Taiwan identified a fitting relationship between the number of building floors and carbon emissions in the current stage of building carbon emissions research, proposing an estimation method. This study adopted this method to estimate the carbon emissions associated with the dismantling process of the small-diameter round timber structural system.

3 – CONSTRUCTION TECHNOLOGY SYSTEMS DESCRIPTION

3.1 APPROPRIATE SPATIAL THRESHOLD OF THE STRUCTURAL SYSTEM

Combined with the basic material of small-diameter round timber, this research constructed a system of rod-tied structures and carried out the force analysis of the construction mechanism in different structural prototypes. Then it defined the force and force transfer logic of various structural prototypes. For the innovation of building form and technology, a construction method suitable for small-diameter round timber is proposed from three aspects, which is the type of timber, the type of joint, the construction mode, and its material methodsAs depicted in Figure 5, each component of the small-diameter round timber structural system, along with the critical factors influencing the stability of the system, was identified and labeled. Furthermore, the displacement of key nodes within the structural system was evaluated based on the simulation test methodology outlined in Section 2.2.



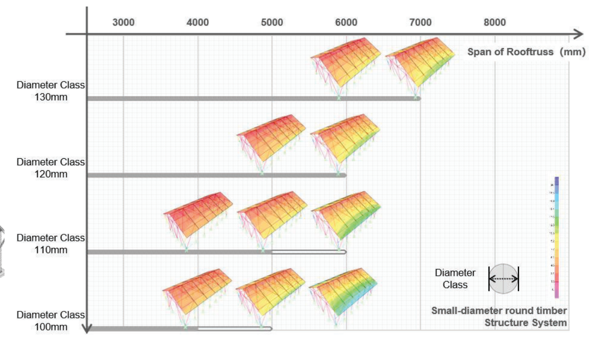
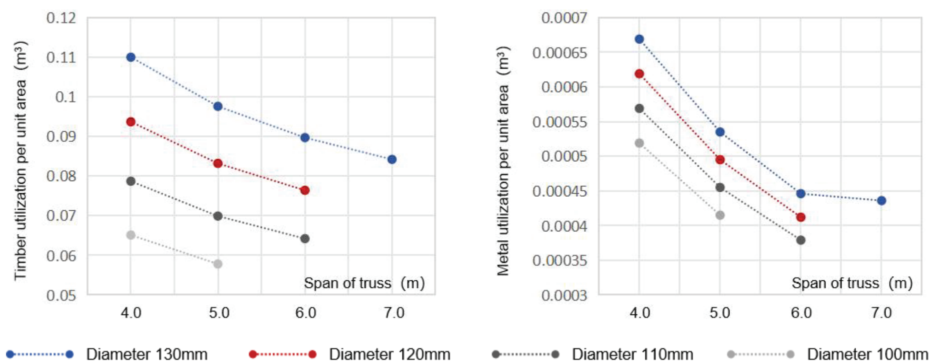


Figure 5. Donstruction diagram of small-diameter round timber structure

Figure 6. Simulation analysis of roof truss span.

Stress calculation and simulation analysis were conducted using 3D3S and SAP2000 based on the properties of Northeast Larch small-diameter round timber [14]. The objective was to verify the bearing capacity and stability of the small-diameter round timber structure system. Subsequently, specific space construction thresholds for the system was defined, considering a diameter class range of 100mm to 130mm for the small-diameter round timber. By evaluating the structural stability through key node displacement and permissible stress ratio of the roof truss, it was determined that the key node displacement met the requirements outlined in the 'wood structure design standard' (GB 50005-2017). The appropriate construction threshold for roof truss span is determined to be between 3.0m and 8.0m.

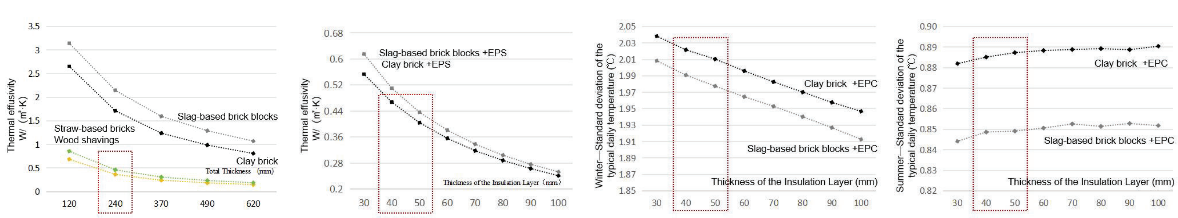


（a）Structural timber volume analysis

（b）Analysis of metal usage of connectors

Figure 7. Material utilization efficiency in small log structural systems.

Notably, when the diameter class of the small-diameter round timber reaches 130mm, it satisfies the standard requirements for displacement at each node in a roof truss span of 7.0m. However, if the span of the roof truss extends to 8.0m, partial reinforcement of the structural system becomes necessary to ensure stability, as depicted in Figure 6.From the analysis of material quantities utilized in the small log structural system, the components are categorized into two aspects: small log members and metal connecting parts employed to join the structural elements. Firstly, based on the spatial construction threshold suitable for the upper part of the small log structural system, the consumption of small log members was systematically calculated, with the results presented in Figure 7(a). Secondly, according to the nodal connection method of the small log structural system described in Section 2.2, the steel quantity used in metal connectors was calculated, as illustrated in Figure 7(b).



（a）Comparison of Thermal effusivity

（b）Comparison of standard deviation of the typical daily temperature

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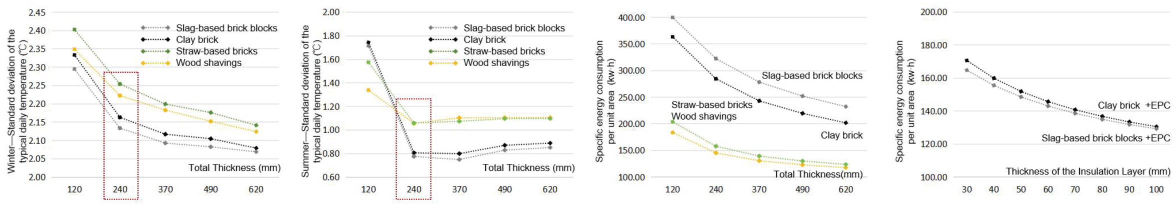

（c） Comparison of standard deviation of the typical daily temperature—— heavy material with insulation layer

（d） Comparison of Specific energy consumption per unit area

Figure 8. Comprehensive analysis of key thermal physical property indices for enclosure systems

3.2 THICKNESS OF ENCLOSURE SYSTEM AND APPROPRIATE THRESHOLD

In addition, given the suitability of the cold climate in Northeast China, the size of the fundamental building unit for the enclosure structure is determined through an analysis of its economic thickness. DesignBuilder was utilized to simulate and analyze enclosure walls made from various materials, with the thickness of the primary enclosure material serving as the key variable parameter. This simulation examined its influence on the thermal and physical properties of biomass buildings in Northeast China. Additionally, the common thicknesses of the enclosure wall (i.e., 120mm, 240mm, 370mm, 490mm, and 620mm) were analyzed. A 370mm thick heavy block with external industrial organic insulation board (e.g., polyurethane rigid foam, EPS, XPS, etc.) was also evaluated, with the insulation layer ranging from 30mm to 100mm in increments of 10mm. A comparison was made among three critical influencing indicators: "comprehensive heat transfer coefficient of the enclosure structure," "standard deviation of typical daily temperature (σ) during the winter (summer) season," and "energy consumption per unit area during the heating period," as illustrated in Figure 8.

3.3 BIOMASS CONSTRUCTION TECHNOLOGY SYSTEM

3.4.1. Carbon reduction analysis of small-diameter round timber lattice system

According to the carbon reduction calculation method outlined in Section 2.5 and the regulations on carbon emission factors related to building materials as specified in the "Building Carbon Emission Calculation Standard", the carbon emissions of biomass-based building schemes at three scales described in Section 2.4 were calculated for each stage, as illustrated in *Figure 9.* Among these, the carbon sequestration per unit area of biomass buildings accounted for 6.52% to 11.33% of the total carbon emissions of buildings. This indicates that biomass materials contribute significantly to actual consumption, thereby enhancing carbon sequestration. In the three building scales analyzed, the carbon emissions generated during the transportation of components and construction accounted for less than 5% of the total carbon emissions and can therefore be considered negligible in the calculations. The carbon emissions per unit area during the production phase accounted for 2.57% — 9.03% of the total emissions, with biomass materials exhibiting higher carbon emissions per unit area compared to inorganic heavy materials. However, the operational carbon emissions per unit area of brick-concrete construction were 18.85%—24.64% higher than those of the other two building types. Furthermore, as building scale increases, low-cost biomass construction demonstrates more pronounced advantages in reducing carbon emissions.

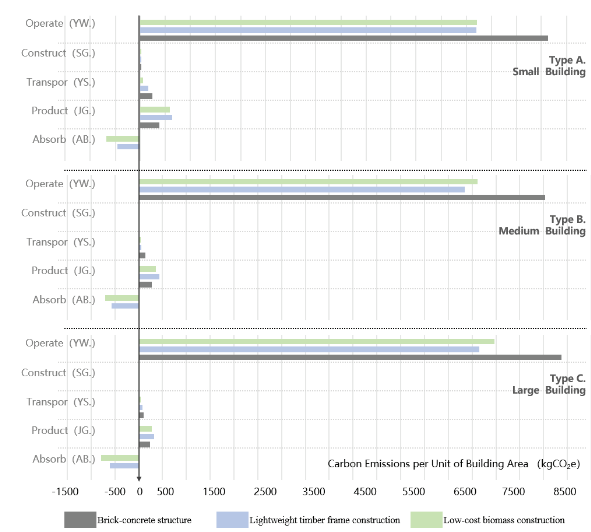

Figure 9. Comparative analysis of carbon emissions across stages of the building life cycle

3.4.2. Economic efficiency analysis of lattice system

As illustrated in Figure 10, buildings of the three scales are systematically compared and analyzed based on two critical factors: life cycle carbon emissions and construction costs. Specifically, as the building scale increases, both the per-unit-area carbon emissions and construction costs for Light Wood Frame Construction and Low-Cost Biomass Construction exhibit a gradual decline. Notably, the cost reduction for Light Wood Frame Construction is more pronounced. However, a comprehensive evaluation of carbon emissions and costs reveals that Light Wood Frame Construction does not possess significant advantages. In contrast, Low-Cost Biomass Construction is better suited to rural construction conditions and scales. Although Brick-Concrete Construction features the lowest construction cost among the three types, it lacks ecological and sustainability benefits relevant to rural architecture.

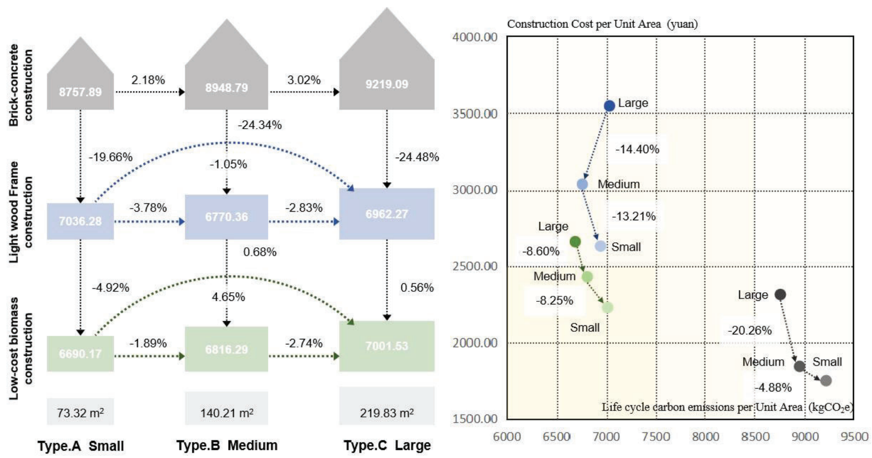

Figure 10. Comprehensive comparison of building construction cost and life cycle carbon emissions

4 – CONCLUSION

This study investigates the imbalance between the "environmental advantages" and "economic benefits" of biomass buildings in the rural development of Northeast China. Grounded in the principles of "low-carbon sustainability," "low-cost material conservation," and "low-tech construction," it proposes a technical framework for biomass buildings in Northeast China aimed at reducing carbon emissions and enhancing efficiency. By conducting simulation analyses on key technical challenges within the small-diameter log structure system and the straw material enclosure system, the study delineates their spatial thresholds and construction models. Furthermore, it systematically compares the brick-concrete structure system, the light wood frame system, and the proposed biomass building system across different construction scales. The comparison evaluates life cycle carbon emissions and costs, ultimately proposing practical and guiding pathways for implementation.

This article primarily focuses on the following these aspects:

In light of the contradiction between carbon reduction requirements and construction efficiency in biomass buildings, this study clarifies the carbon reduction construction principles for biomass farmhouses in Northeast China. Furthermore, it proposes a biomass building technology system tailored to the development needs of rural areas in Northeast China, encompassing the "small log structure technology system" and the "straw material enclosure technology system." Specifically, quantitative research on the small log structural system was conducted, involving logical analysis of force and force transfer based on modern timber structural design principles. This analysis identifies key influencing factors related to material behavior and structural morphological characteristics, including the height-to-span ratio of roof trusses, roof span, and roof truss spacing. Subsequently, orthogonal simulation tests and visual data analyses were performed using SAP2000 and 3D3S software. By comparing the displacement of critical nodes, the stress ratios of loaded components, and the proportion of failed components within the structural system, spatial construction thresholds for the three structural systems were determined. Based on the principle of heat transfer in building envelope structures, this study defined the thermal and physical properties of envelope technology models based on straw materials, as well as the key influencing factors of building heating energy consumption, specifically the material usage method for straw materials and the construction techniques of the envelope. Subsequently, multi-factor simulation tests and visual data analysis were conducted on these influencing factors using DesignBuilder software. The comprehensive heat transfer coefficient, standard deviation of typical daily temperatures during winter (and summer) seasons, and unit-area energy consumption during the heating period for the two types of envelope structures were compared and analyzed. Based on these results, the construction mode and applicable threshold of the envelope system were determined. Finally, building models of large, medium, and small scales were established to comprehensively compare the carbon reduction benefits of three small-scale biomass buildings. It was found that as the construction scale increased, the advantages of carbon reduction benefits gradually diminished. Furthermore,

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an optimization method for biomass building design was proposed.

5 – REFERENCES

[1]https//im.dk/Media/637602217765946554/National_Strategy_for_Sustainable_Construktion.pdf

[2] https：//www.vidingehem.se/kvarter/vallen

[3] Zujian Huang, Hao Zhou, Zhijian Miao et al: Life-Cycle Carbon Emissions(LCCE)of Buildings:Implications,Calculations,and Reductions.J. Engineering, 2024, 35(4):115-139.DOI:10.1016/j.eng.2023.08.019.

[4] Ying Wu , Hongpeng Xu, Jianmei Wu, Yuncheng Ji:The low-cost technical system of rural sustainable wood construction and its suitability based on the small-diameter round timber of fast-growing Northeast Larch.J.Case Studies in Construction Materials,2025,DOI10.1016/j.cscm.2025.e04276

[5] Uniben Yao Ayikoe Tettey, Ambrose Dodoo, Leif Gustavsson: Effect of different frame materials on the primary energy use of a multi-storey residential building in a life cycle perspective. J. Energy Build 185 (2019) 259– 271. doi: org/10.1016/j.enbuild.2018.12.017

[6] Tettey U Y A , Dodoo A , Gustaysson L .Effect of different frame materials on the primary energy use of a multi storey residential building in a life cycle perspective[J].Energy & Buildings, 2019, 185(FEB.):259-271.DOI:10.1016/j.enbuild.2018.12.017.

[7] Bayatkashkoli A , Hemmati T .Effect of number of joints and layer arrangements in components on the mechanical strength of chairs made from small diameter poplar[J].International Wood Products Journal, 2015, 6(4):2042645315Y.000.DOI:10.1179/2042645315Y.0000000014.

[8] Bukauskas A , Mayencourt P , Shepherd P ,et al.Whole Timber Construction: A State of the Art Review[J].Construction and Building Materials, 2019, 213:748-769.DOI:10.1016/j.conbuildmat.2019.03.043.

[9] Wiedenbeck,Scholl,Blankenhorn,et al.Lumber Volume and Value Recovery from Small-Diameter Black Cherry, Sugar Maple, and Red Oak Logs[J].BIORESOURCES, 2017, 2017,12(1)(-):853-870.DOI:10.15376/biores.12.1.853-870.

[10] Levan-Green S L , Livingston J .Exploring the Uses for Small-Diameter Trees[J].Forest Products Journal, 2001, :51(9):10-21.

[11] Wolfe,Moseley.Small-diameter log evaluation for value-added structural applications[J].FOREST PROD J, 2000.

[12] Mengyuan M , Yidong L .Analysis on Development Trend of China's Plantation in New Era[J].World Forestry Research, 2019.

[13] Buelow P V , Torghabehi O O , Mankouche S ,et al.Combining parametric form generation and design exploration to produce a wooden reticulated shell using natural tree crotches[C]//Creativity in Structural Design.2018.

[14] Wu GF, Zhu EC, Ren HQ et al: Application of small-diameter round timber as structural members in light frame construction. JOURNAL OF ASIAN ARCHITECTURE AND BUILDING ENGINEERING. 21(3): 1029-1039.

[15] Teng Shao, Hong Jin, Lihua Zhao. Current Situation and Improving Strategiesfor Northeast China's Rural Housings [J]. OPEN HOUSE INTERNATIONAL2017,42(4):70-77.

[16] Corradini G , Pierobon F , Zanetti M .Product environmental footprint of a cross-laminated timber system: a case study in Italy[J].The International Journal of Life Cycle Assessment, 2019, 24(5):975-988.DOI:10.1007/s11367-018-1541-x.

[17] Zeug W , Bezama A , Thrn D .Application of holistic and integrated LCSA: Case study on laminated veneer lumber production in Central Germany[J].The International Journal of Life Cycle Assessment, 2022, 27(12):1352-1375.DOI:10.1007/s11367-022-02098-x.

[18] Xiaocun Zhang, Fenglai Wang. Life-cycle assessment and control measures forcarbon emissions of typical buildings in China[J]. Building and Environment, 20l586:89-97.

[19] Xiaocun Zhang,Fenglai Wang.Assessment of embodied carbon emissions forbuilding construction in China:Comparative case studies using altemativemetods[J].Energy and Buildings,2016,130:330-340.