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Advancing Sustainable Construction: A Comparative Analysis of Wooden and Steel Chassis through FEA

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ABSTRACT

Reducing the carbon footprint in the static holiday home industry is considered a challenging task, primarily because it heavily relies on steel structures. This study investigates the potential of using alternative materials, such as wood, as a replacement material for the main component in building static home frames. By combining finite element analysis (FEA) with experimental validation, this research evaluates the mechanical performance—specifically stiffness and deflection—of a wooden chassis compared to their steel counterparts under various loading conditions. The findings indicate that wooden chassis not only offer comparable structural integrity, but also exhibit superior stiffness and reduced deflection rates, making them a viable and environmentally friendly alternative to steel. Furthermore, this wooden chassis marks the first development of its kind in the UK static holiday home industry. This study primarily focuses on comparing the mechanical behavior of wooden and steel chassis in static holiday home constructions, indicating potential enhancements in structural integrity and performance. The results advocate for broader acceptance and implementation of wooden structures, highlighting their environmental and economic advantages, while paving the way for future investigations into sustainable material applications in the construction industry.

Keywords: Sustainable construction, Static holiday home industry, Finite Element Analysis (FEA), Wooden chassis, Steel chassis.

1. INTRODUCTION

The construction and manufacturing industries globally face the dual challenges of reducing carbon emissions and adopting sustainable practices [1]. In the UK, the static holiday homes industry, which predominantly uses steel chassis for structural support, exemplifies these challenges [2]. Annually, the market demands over 12,000 steel chassis, supplied by specialists such as Bankside company [3]. However, steel manufacturing is a carbon-intensive process, responsible for significant CO2 emissions. As the iron and steel sector is the second-largest energy consumer worldwide, accountable for the highest direct CO2 emissions at 1.5-1.6 Gt or 6% of global emissions, the need for sustainable alternatives is urgent [4]. The wooden frame has the lowest carbon dioxide emissions compared to steel and concrete [5]. The UK government's implementation of an energy policy framework, incentivizing the shift towards environmentally friendly practices, underscores this necessity [6]. A pioneering initiative by Willerby, in collaboration with Sheffield Hallam University, seeks to replace traditional steel chassis with a wooden alternative, employing FEA and physical testing to ensure efficacy and sustainability [7].

This paper delves into the environmental and economic advantages of wood over steel, highlighted by previous studies that show buildings constructed with wood significantly reduce greenhouse gas emissions. Moreover, wooden frames have been found to be 13% less expensive than their steel counterparts in traditional boat construction, offering a cost-effective solution [1]. Despite these advantages, a notable knowledge gap exists in applying FEA to design the first wooden chassis specifically for the static homes industry in the UK. This research aims to fill that gap by presenting a comprehensive study that compares the performance of wooden chassis to steel under identical load conditions.

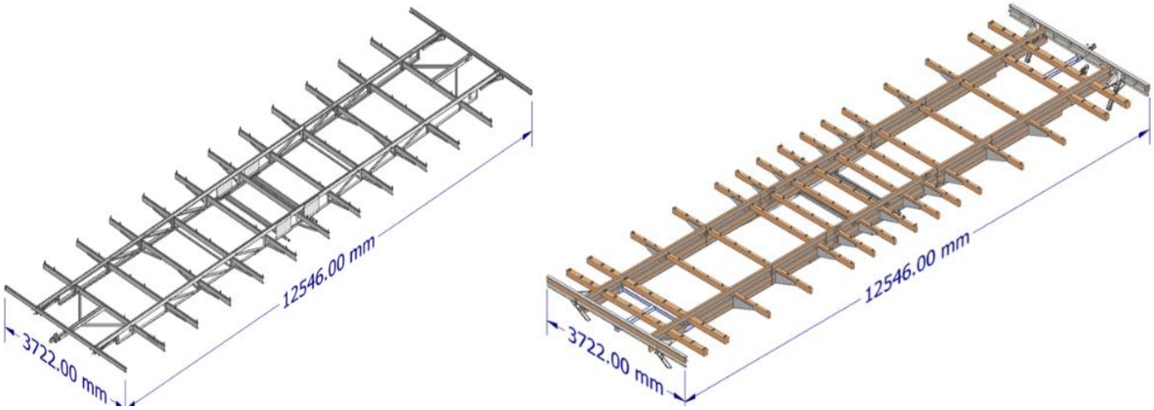
From a technical perspective, the material properties of steel and wood differ significantly. Steel exhibits isotropic behavior, maintaining consistent properties regardless of measurement direction. Wood, particularly species like spruce, is anisotropic, with Young's modulus values varying along and across the grain [8]. Such characteristics are critical in structural engineering and design, where wood's performance under load parallel to the grain is paramount [9]. Engineered wood products, which layer wood veneers for increased uniformity, offer a promising alternative by improving strength across various grain directions [10]. The plywood has homogenous properties and is widely affordable [11]. Adopting wooden chassis could lead to sustainability, cost savings, and reduced carbon emissions, leveraging wood's renewable nature and lower energy consumption during processing. By comparing wooden and steel chassis through FEA and subsequent physical tests, this paper not only contributes to the discourse on sustainable construction materials but also underscores the potential for significant environmental impact reduction in the static homes industry.

2. METHODOLOGY

In accordance with the concept evaluation datum method, which is used to compare a datum design with a new concept design [12], this study designates a steel chassis as the datum for comparative evaluation against a wooden concept chassis. The focus is on their structural performance within the static homes industry. The adoption of static analysis via SimSolid, a meshless software that significantly cuts computational time by forgoing traditional meshing, is driven by the static nature of the homes. Such homes are not designed for road use, leading to consistently static loads and boundary conditions. The application of a three-load case scenario is aimed not at replicating realistic conditions but at facilitating a direct comparison under controlled, available loads without necessitating the entire static home structure. This methodological approach, validated through physical testing of the wooden chassis under identical scenarios, not only conforms to concept evaluation datum method but also capitalizes on SimSolid's efficiency to rigorously examine the feasibility of a wooden chassis as a sustainable alternative to steel. This innovative strategy critically underscores the significance of leveraging wood, a cost-efficient and readily available material, for static holiday home construction. It highlights the transformative potential of adopting wooden materials in reducing the carbon footprint of the industry, offering a pivotal contribution to both sustainability and economic efficiency for manufacturers.

2.1 Datum Chassis and Wooden Chassis

The steel chassis consists of two longitudinal, lateral, front and back beams, as shown in Figure. 1a. The longitudinal beam is fabricated with an upper section of C-section beam, and the lower L-section is connected by L-section beams. The steel chassis is commonly used for light loads and is economical for holiday homes with weights up to 7,500 kg. The wooden replacement for the steel chassis has a weight of 613 kg compared to 689 kg for steel chassis and consists of two wooden longitudinal beams, wooden lateral beams, steel front and back beam, a steel drawbar, and axles, as shown in Figure. 1b . The axles in the wooden chassis remain steel to withstand the static home weight.



(a) (b)

Figure. 1. 3D CAD model: a) datum chassis, (b) wooden chassis.

The longitudinal beam comprises upper and lower sections, with the lateral beams sandwiched in between. The lower section is constructed from two rows of rectangular sections of TR26 beams, secured in place with gang nail plates. The upper section is made up of a single row of three TR26 wooden beams, which are connected to the lateral beams using angle brackets, as illustrated in Figure. 2. Plywood is utilized to stiffen the longitudinal beam and to seal the gaps between the upper and lower sections by covering both sides of the longitudinal beam. To reinforce the lateral beams and minimize vertical deflections, wooden brackets have been installed beneath them.

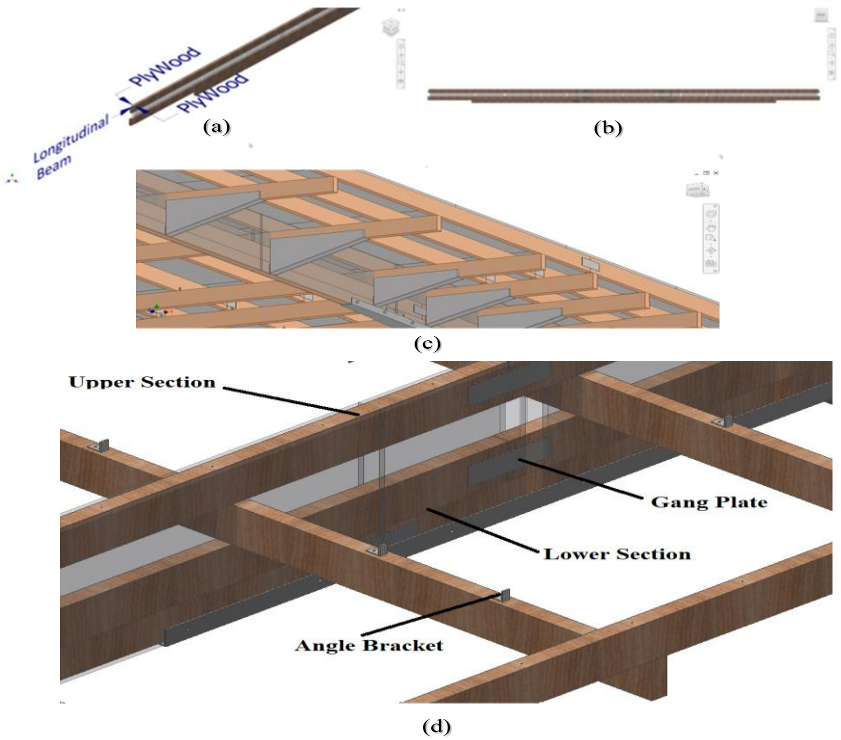


Figure. 2. Component of the chassis design: a) Plywood; b) Side view of the longitudinal beam; c) Lateral beams reinforcement; d) Upper and lower section, angle bracket, gang plate, and lateral beam.

2.2 Materials

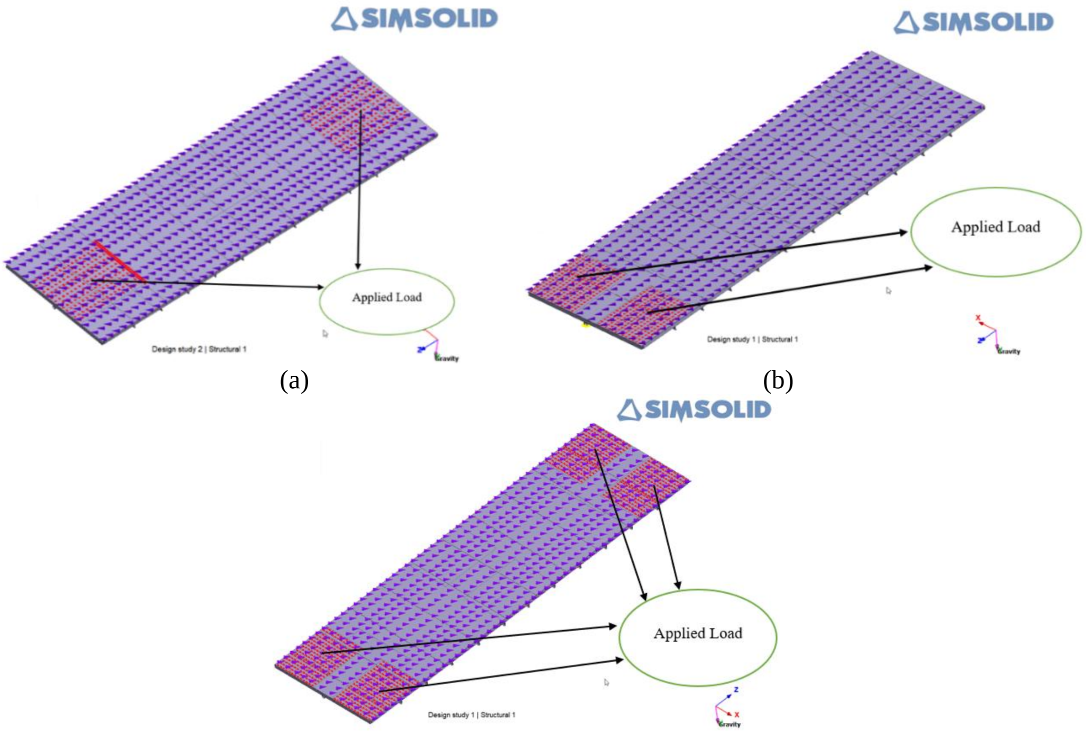
The datum chassis is constructed from S275 steel, while the wooden chassis is made from TR26 timber, spruce wood, plywood, and S275 steel for the axle set. The properties of these materials are presented in Table 1.

Table 1. Material properties.

Material	Mechanical Properties						
	Young's Modulus GPa		Density $\mathrm{kg/m^3}$	Yield Strength MPa		Poisson's Ratio	
S275	210		7750	275		0.3	
Spruce Wood	Along grain	Cross grain	400 - 600	Along grain	Cross grain	Along grain	Cross grain
	8.4 – 10.3	0.6 – 0.9		35 - 45	1.7 – 2.6	0.35 – 0.4	0.02 – 0.04
TR26	11	0.37	444	50		0.3 - 0.4	0.02 - 0.2
Plywood	5 - 8		700 - 800	34.4 – 42.1		0.2 – 0.3	

2.3 Loads

Loads of 150 kg, 250 kg, and 500 kg are applied in various configurations to generate the load case scenarios. Each load case is designed to investigate a specific region of the chassis. Figure. 3a illustrates the first load case, where 250 kg is applied to both the highlighted front and back ends, to examine the longitudinal deflection. Figure. 3b shows load case 02, where a load of 150 kg is applied to each highlighted area. This load configuration is intended to investigate the deflection of the front lateral beam. In this case, the drawbar is fixed, as shown in Figure. 4b. Figure. 3c illustrates load case 03, a combination of longitudinal and lateral deflection with 150 kg applied at each corner.



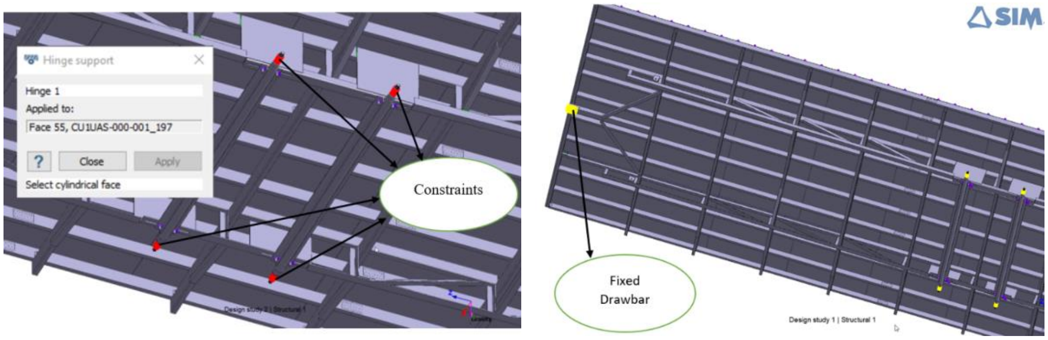
(a) (b)

(c)

Figure. 3 FEA models, load cases: (a) load case-01, (b) load case-02, (c) load case-03.

2.4 Constraints

In load cases 01, 02, and 03, both axles are restrained in all translational directions but are allowed to rotate, as shown in Figure. 4a. In load case 02, an additional constraint is applied to the drawbar to investigate deflections at the front lateral beams, as illustrated in Figure. 4b.


Hinge support
Hinge 1
Applied to:
Face 55, CU1UAS-000-001_197
Select cylindrical face

(a) (b)

Figure. 4. Constraints conditions: (a) for load case-01, 02 and 03, (b) additional constraints for load case-02.

2.5 Location Measurements

To carry out a comparative deflection study between the steel and wooden chassis, six positions were selected across each chassis to measure the longitudinal deflections for both chassis at the same positions, as shown in Figure. 5.

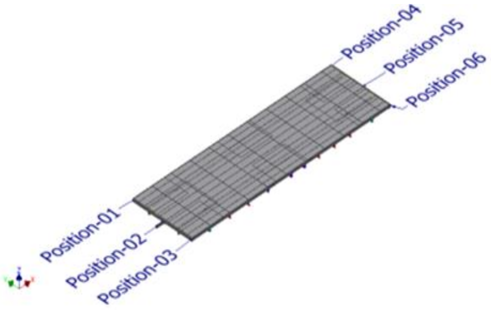


Figure. 5. Measurement locations on the chassis.

2.6 FEA Results

Figure. 6 illustrates the longitudinal deflection measurements for both wooden and steel chassis under various load conditions. The analysis indicates that the wooden chassis demonstrates stiffer performance than the steel chassis in load case 01 and 03. Furthermore, the wooden chassis is found to be significantly stiffer by a factor of six when considering the lateral deflection of the front and back lateral beams. This enhanced stiffness is attributed to the wooden brackets installed beneath these beams.

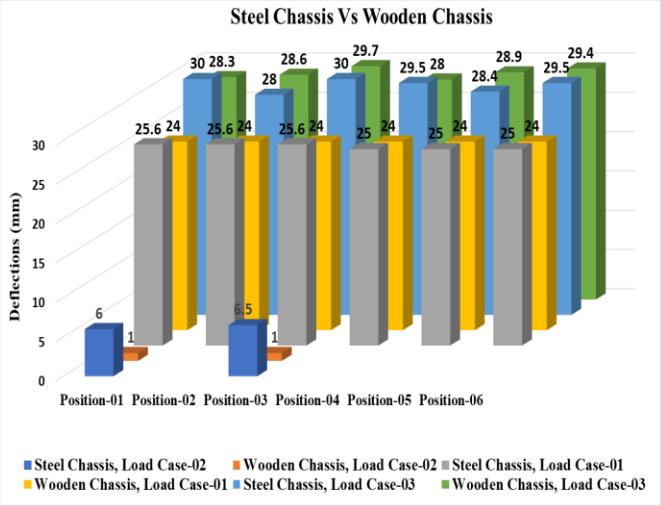


Figure. 6. Steel datum chassis Vs Wooden chassis.

In load case-03, an applied load of 150 kg at the four corners resulted in deflections ranging from 28 mm to 30 mm for the steel chassis, as depicted in Figure. 7.

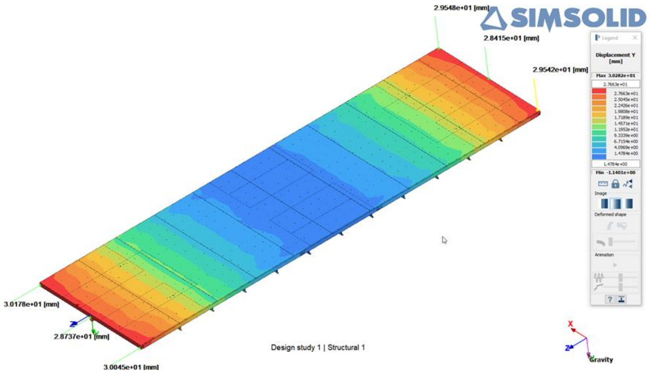


Figure. 7. Deflections for datum chassis, load case-03.

When load case-03 was applied to the four corners, the maximum stress was anticipated at the middle of the chassis. This load case resulted in a stress of 125 MPa, as illustrated in Figure. 8.

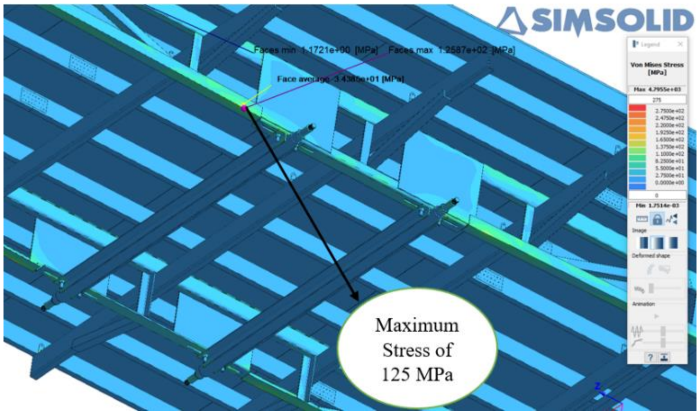


Figure. 8. Maximum stress of 125 MPa, datum chassis.

Figure. 9 illustrates the deflection resulting from applying load case-03 to the wooden chassis, which ranges from 28 mm to 29 mm.

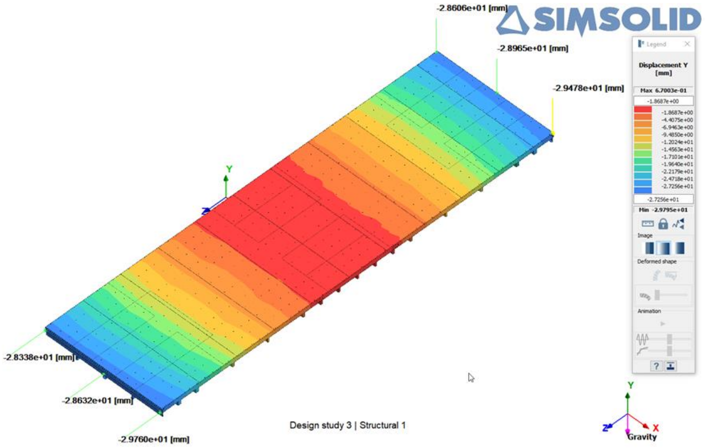


Figure. 9. Deflections for wooden chassis, load case-03.

The wooden chassis generated a stress of 10 MPa located at the middle of the longitudinal beam, as shown in Figure. 10.

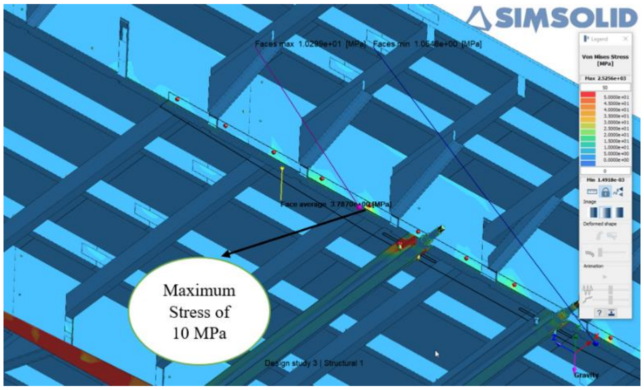


Figure. 10. Maximum stress of 10MPa, wooden chassis.

3. EXPERIMENTAL STUDY OF THE WOODEN CHASSIS

3.1 Process of Experimental Study

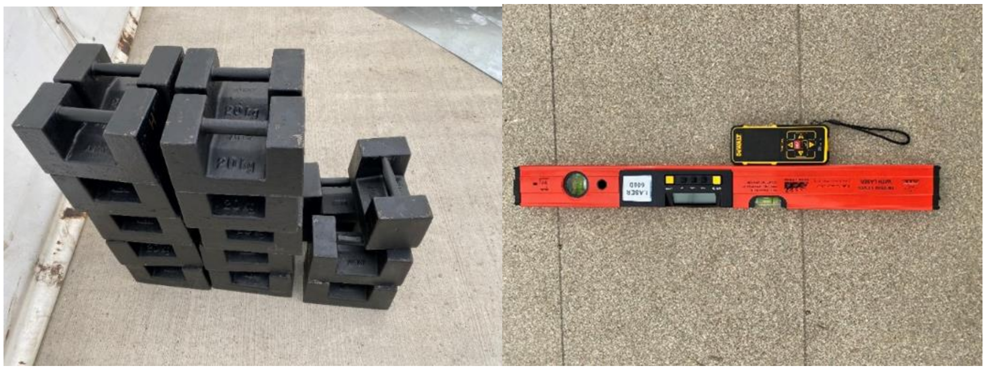
To maintain commercial sensitivity, Willerby engaged an innovation center based in Hull, away from the company site, to conduct physical tests on the wooden chassis, as the company is surrounded by competitors. Therefore, three load case scenarios were chosen to compare the two chassis, since building up the habitation structure outside the company premises is not feasible. Figure. 11a depicts the assembly process, beginning with the connection of longitudinal beam parts using gang plates. This was followed by the affixing of plywood to both sides of the longitudinal beams. The next step involved installing lateral beams into the plywood cut-outs, after which a jack was utilized to elevate the chassis for mounting onto the steel axles. Subsequently, joists were aligned with the lateral beam and secured in place using angle brackets. The final stage entails laying chipboard over the joists, which was then fastened with screws. The constraint conditions mirror those utilized in FEA, with both axles being free to rotate yet fixed in the vertical direction, as depicted in Figure. 11b.

(a) (b)

Figure. 11. (a) The assembly process of the wooden chassis, (b) Constraint condition for the wooden chassis.

For this testing, a set of steel blocks were used, with each block weighing 20 kg, as shown in Figure. 12a. In the FEA model, as depicted in Figure. 3b, a load of 250 kg was applied at both the front and rear ends of the chassis. Therefore, 13 steel blocks will be placed at each end of the chassis to replicate this load. Given that the analysis was static, the FEA results can be adjusted by a factor of 1.04 to align with the physical measurements. This procedure will be replicated for load cases 02 and 03.

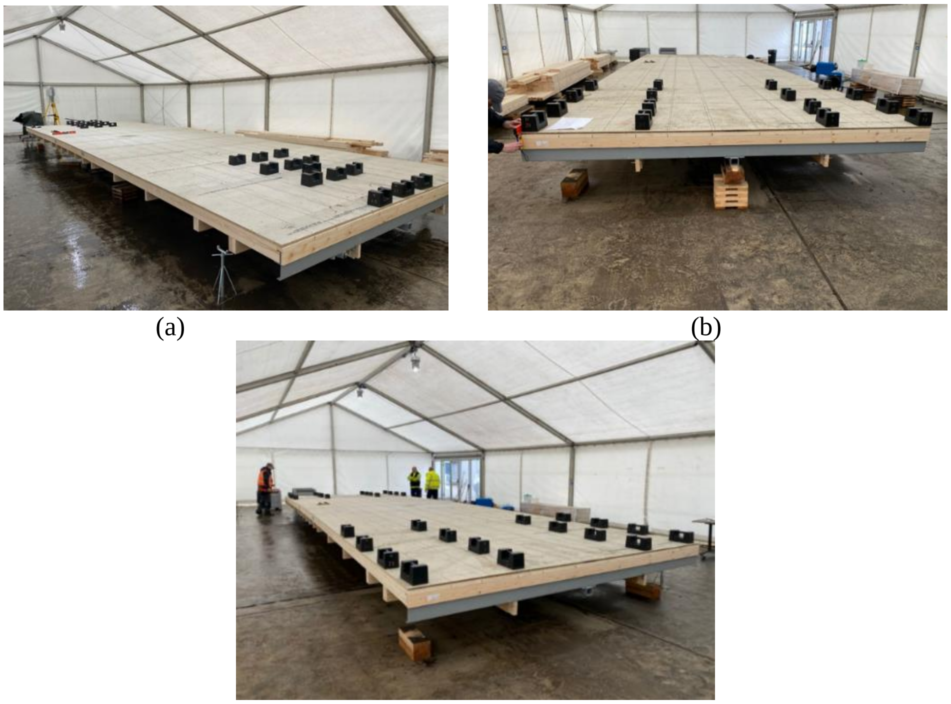
To replicate the load locations used in the FEA studies, the chipboard was marked to accommodate the three load cases. In the unloaded condition, all positions shown in Figure. 5 were measured relative to the ground using level and laser measuring tools to establish a datum. The level ensured that the laser measuring tool is aligned parallel to the chipboard during measurements and perpendicular to the ground. Given that the expected deflection ranges from 20 mm to 30 mm, a laser distance measurer is suitable for this test, as shown in Figure. 12b.



(a) (b)

Figure. 12. (a) steel blocks, (b) Measuring tools.

In load case-01, a load of 260 kg, represented by steel blocks, was applied to each end of the chassis, as depicted in Figure. 13a. A drawbar is integrated into the wooden chassis and constructed from steel, prevents the chassis from being towed on the production line. This particular load case aims to investigate the deflections of the front lateral beams, with the drawbar fixed in the vertical direction, as illustrated in Figure. 13b. In load case-03, where a load of 160 kg was applied to each corner of the chassis, as shown in Figure. 13c.



(a) (b)

(c)

Figure. 13. Physical load cases: (a) load case-01, (b) load case 02, (c) load case -03.

3.2 Experimental Results and Discussion

3.2.1 Load Case-01

Measurements were taken under both loaded and unloaded conditions to establish a datum and determine the actual deflection at each position. Notably, during the physical testing of the wooden chassis, an inclination was observed at both ends. This phenomenon could be attributed to two primary factors. First, despite the testing team's careful efforts to apply the load evenly to avoid this issue, there was still a slight human error. Second, the components of the wooden chassis may have accumulated strain energy due to the conditions encountered in real-life usage.

In contrast, within the FEA environment, this issue is absent due to its idealized nature, where the software uniformly applies the load across all nodes. The front end tends to incline towards position 01, while the back end leans towards position 04, as shown in Table 2. Acknowledging this from the outset, the testing protocol was designed with positions 02 and 05 strategically located at the midpoint of the front and back ends, respectively. This arrangement ensures accurate deflection measurements for the chassis and mitigates twisting at both ends.

Table 2. Physical measurements, load case-01.

Physical Measurements	Positions Measurements (mm)					
	01	02	03	04	05	06
Datum	801.4	796.3	790.2	639.1	641.3	635.1
Loaded chassis	768.6	762.4	747.9	614.3	608.8	596.6

Actual deflection	32.8	33.9	42.3	24.8	32.5	38.5
FEA Deflections	24.1	24.1	24.1	24.1	24.1	24.1
Relative deference (%)	26.52	28.91	43.03	2.82	25.85	37.40

3.2.2 Load Case-02

Measurements were conducted on the chassis in both unloaded and loaded conditions to establish a datum and determine the actual deflection. At positions 01 and 03, the observed deflections were 1.6 mm and 1.5 mm, respectively, compared to the FEA predictions of 1 mm for both positions. This indicates a relative difference of 38% for position 1 and 33% for position 03, as shown in Table 3.

Table 3. Physical measurements, load case-02.

Physical Measurements	Positions Measurements (mm)		
	01	02	03
Datum	765.5	Fixed	746.4
Loaded chassis	763.9	Fixed	744.9
Actual deflection	1.6	Fixed	1.5
FEA Deflections	1.0	Fixed	1.0
Relative deference (%)	38.0	Fixed	33.0

3.2.3 Load Case-03

Measurements were taken in both loaded and unloaded conditions to establish a datum and determine the actual deflection at each position. A similar obstacle occurred in this case, with inclinations observed at both the front and back ends. Position 02 and 05 yielded physical deflections of 40 mm and 36.7 mm, respectively, whereas the FEA results indicated deflections of 28.1 mm for both positions, resulting in relative difference of 30% and 33%, respectively, as shown in Table 4.

Table 4. Physical measurements, load case-03.

Physical Measurements	Positions Measurements (mm)					
	01	02	03	04	05	06
Datum	801.4	796.3	790.2	639.1	641.3	635.1
Loaded chassis	764.8	756.3	734.0	590.8	604.6	596.1
Actual deflection	30.6	40.0	56.2	48.3	36.7	39.0
FEA Deflections	30.1	28.1	30.1	30.1	28.1	30.1
Relative deference (%)	18.0	30.0	64.0	38.0	33.0	23.0

In summary, FEA has provided a crucial guideline for the design of new chassis configurations. A relative difference in deflection ranging from 25% to 38% at positions 02 and 05, which are unaffected by chassis twisting issues, is deemed acceptable within the static holiday home industry standards. This discrepancy between FEA predictions and physical test results indicates that the FEA model tends to forecast a stiffer chassis response. This deviation can be partially ascribed to the simulation's representation of connections between components, which are likely modeled to be more rigid than in reality. Furthermore, the material properties input into the FEA model, typically considered to be average values, may not fully capture the complex variations inherent in the actual materials used. This difference in material properties might also contribute to the observed discrepancy, resulting in a simulation outcome that predicts stiffer behavior than is seen in physical tests. In essence, a discrepancy range of 25% to 38% represents a good balance between theoretical predictions and real-world outcomes, offering a practical, safe, and economically viable approach for chassis design and evaluation in the static home industry.

4. CONCLUSION

This study has explored the replacement of traditional steel chassis with wooden alternatives in static holiday home constructions, highlighting a significant advancement towards sustainable building practices. Through FEA and experimental validation, wooden chassis were found to exhibit superior stiffness and significantly lower deflection rates compared to steel, suggesting not only feasible structural integrity but also enhanced performance.

Future research directions include conducting long-term performance studies on wooden chassis, assessing their environmental impact through life-cycle analysis, exploring economic viability, and investigating advanced material treatments to enhance durability and resistance. Expanding material testing to include a variety of wood types and engineered wood products could further optimize construction practices, making a compelling case for the construction industry's shift towards more sustainable and innovative material applications.

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