TEMA: Technologies, Engineering, Materials and Architecture Rivistatema.it
Pesaro court registration number 3/2015 ISSN 2421-4574 (ONLINE)

Methodology for Improving Manufacturing and Assembly of Lightweight Prefab Systems

Ornella Iuorio[1*].
1 – Dipartimento ABC, Politecnico di Milano, Italy
* - ornella.iuorio@polimi.it

Abstract

The increasing adoption of prefabrication in the Global North reflects a response to the urgent demand for safe and affordable housing. This demand is compounded by the necessity to meet contemporary standards for aesthetic quality, structural safety, and energy performance, all within the context of the current climate and safety challenges. Prefabrication, underpinned by the principles of design for manufacturing and assembly (DfMA), offers a pathway toward modernizing construction practices. Specifically, lightweight steel profile technologies, particularly suited for low- and mid-rise buildings, offer an efficient solution to meet these evolving demands. However, to achieve widespread adoption, further optimization is necessary. The reduction of material use, fabrication waste, and production time, alongside cost reduction, will be critical in aligning prefabrication technologies with sustainable development goals. This paper presents an eight-step methodology in which manufacturing and assembling strategies are considered since product development and according to which materials and components are selected, prototyped, and tested to optimize both mechanical and environmental performance. The methodology has been validated through an academic and industrial venture that aimed to optimize a lightweight cold-formed steel volumetric system for housing applications. The study demonstrated to achieve a system that fully meets the structural requirements while also minimizing the use of material, waste, and production time. In doing so, this work contributes to a broader effort to modernize construction practices and address the dual imperatives of safety and climate resilience.

Keywords: prefabrication, automation, housing, building engineering, sustainability

1. Introduction

The recent report “Modernise or Die” by Farmer [1] called for the UK industry to increase the adoption of pre-manufactured solutions in the construction industry to tackle the housing shortage discussed in the country for over a decade. The report provided evidence of a government incapable of delivering at the scale and speed that was required to respond to the request for thousands of new homes. The report recommended boosting collaboration between industry, government, and academia to improve the development and acquisition of prefab systems that could provide sustainable and more affordable systems. In line with that, the UK government supported industrial ventures promoting knowledge transfers between academia and industry to develop innovative systems. This paper presents an iterative methodology for improving the manufacturing and assembly of prefab systems based on structural and manufacturing optimization. This methodology has been applied and validated within the research project “Optimization of cold-formed steel systems for large scale manufacturing of modular housing”, which aimed to develop a modular housing system for two-story single-family houses to be delivered across the UK and be characterized by having a high mechanical capacity, low embodied carbon and short production time. The system is based on the use of thin profiles, which are made of cold-formed steel (CFS) profiles which are manufactured by bending thin sheets of galvanized steel

10.30682/tema100022

into various shapes, providing high strength-to-weight ratios while being lightweight. The research project aimed to optimize the system by moving away from an "all-steel" design approach [2] that accounted only for the steel members for carrying the vertical and horizontal loads and, instead, develop a sheathing-braced design approach that can consider the bracing contribution provided by sheathing panels, when properly connected to the steel members. This methodology, which is codified in the USA [3], is still not codified for application in Europe and therefore requires experimental testing to be applied. The work aimed to shift the structural design of these CFS modular homes from the all-steel design to the sheathing-braced design to reduce the amount of material, facilitate manufacturing, and reduce embodied carbon. The iterative methodology for optimizing both the system and the manufacturing process had parametric design, prototyping, and experimental testing at its core. The interrelation between design, testing, and manufacturing process is of paramount importance for the development of affordable and safe construction systems. Indeed, several studies have emphasized the importance of the close integration of design, testing, and manufacturing processes in developing affordable and safe prefabricated housing systems. In the following sections, the developed methodology for optimizing Manufacturing and Assembly (DfMA) is discussed in section 2.1, with the results in terms of the manufacturing process discussed in section 3.1. The experimental testing methodology and results carried out to evaluate the mechanical behavior of the newly developed optimized system are discussed in sections 2.2 and 3.2, together with the comparison with the system commercialized before the optimization. Section 4 reports the main conclusions, highlighting the impacts of the research and reflecting on the multidisciplinary methodology.

2. Methodology for the development of Design for Manufacturing and Assembly

The methodological approach developed and validated in this work encompasses design informed by manufacturing and assembly, having prototyping and testing at its core.

2.1 Design for Manufacturing and Assembly

Design for Manufacturing and Assembly (DfMA) is an engineering approach that simplifies product design to make manufacturing and assembly processes more efficient, cost-effective, and reliable. It integrates design with production by considering the limitations and capabilities of manufacturing and assembly from the very beginning of the design phase. The ultimate goal is to reduce costs, enhance quality, and minimize production time [4, 5]. Prefabricated systems benefit from modularity and standardization, but only when design and manufacturing processes are tightly aligned. This integration ensures that design innovations are compatible with factory processes, allowing for faster assembly and fewer errors on-site [6, 7]. Additionally, testing at multiple stages, both in prototype and production, can verify the safety and performance of materials and joints, further improving the structural integrity of prefabricated housing.

This project focused on optimizing the structural system of a cold-formed steel (CFS) modular housing system, which was being introduced to the UK market, to improve factory production efficiency and reduce material waste. In CFS construction, load-bearing walls are the most critical components as they directly influence the structural integrity of the building [8, 9, 10, 11, 12]. Therefore, accelerating wall production was vital. A key challenge was to develop a lateral resisting system that moved away from a jungle of steel elements that were difficult to be integrated with the insulation and finishing system to streamline instead a more optimized system in which steel and finishing could be integrated. Therefore, the DfMA process (Fig.1) started by identifying standardized components that could be readily found in the market. Then, an assembly strategy of sub-components and complete modules was identified. The interrelation between those two brought to the selection of the most appropriate materials and components. Specifically,

10.30682/tema100022

in order to improve the time-consuming process of attaching CFS profiles to sheathing panels, which also needed to ensure safe movement along the production line, it was essential to optimize screw and sheathing patterns while still maintaining the necessary mechanical performance. Given that previous studies have shown a direct relationship between a CFS wall's shear capacity and the number of connections between the steel frame and sheathing [3, 9, 11, 13], this research explored, through prototyping and testing, how variations in screw spacing could impact structural performance. The aim was to automate the placing of the connection by enabling the use of a high-speed paneling system in wall assembly. To enable that, a larger flexibility in screw patterns was necessary. Therefore, an experimental investigation was conducted to evaluate the impact of different connection distances and patterns on mechanical performance, with the findings directly informing adjustments to the production process (discussed in sections 2.2 and 3). The defined system and production process were assessed through environmental impact analysis, and when this was satisfactory, the system became ready for lean production.

Figure 1: Design for Manufacturing and Assembly methodology.

2.2 Experimental campaign

Experimental testing was adopted to mechanically characterize the main structural components of the proposed composite system, in which CFS profiles collaborate with both oriented strand board (OSB) panels and cement panels (CP) to withstand both vertical and horizontal loads. Indeed, the mechanical performance of CFS structures sheathed with boards is influenced by the response of the shear walls under horizontal loads. Various factors directly influence the behavior of CFS shear panels, including the type and thickness of the sheathing board [8, 9, 10, 11, 12, 13], its placement (on one or both sides), the thickness of the CFS sections, loading conditions, aspect ratio [14], opening size [15], fastener type, and the spacing between the fasteners [2, 11, 13].

To assess the lateral response of CFS shear walls under in-plane loading, an extensive experimental campaign was articulated in three phases [16, 17]. The first phase included 32 tensile strength tests for the steel material, 20 lap-shear tests on screws, and 27 shear tests to determine the shear strength of connections between steel profiles and either oriented strand boards or cement board panels. The second phase was devoted to full-scale wall tests on fully sheathed wall panels, and the third phase looked at the lateral behavior of walls with openings and allowed a comparison between the newly proposed system and the previous one having X-steel bracing. Specifically, in the second phase, four walls with a length of 2400mm and fully sheathed on one side of the CFS frame were tested under in-plane shear loading. The third phase, instead, aimed to evaluate the effect of openings on the shear response of CFS walls with a wall length

10.30682/tema100022

of 4800mm. In particular, three wall typologies with opening configurations were tested; representative of a ground floor rear wall (GF-RW) with a large opening, a ground floor front wall (GF-FW) with a door and a window opening, and a typical first floor (FF) with openings. These wall typologies were selected to represent the worst-case scenarios in terms of opening ratio among those to be manufactured by the housing provider, and they had a sheathing area ratio between 0,53 and 0,77. Moreover, two tests were performed on walls having the same geometrical configurations of GF-RW and FF but which represented the "Standard" system designed by the industry before the beginning of the research project led by the Author, and they used steel bracing to achieve the required shear capacity. These last two tests were performed to understand the changes in terms of wall shear strength and stiffness due to moving from a steel bracing to a sheathing braced approach. Figures 2 show the experimental campaign tests.

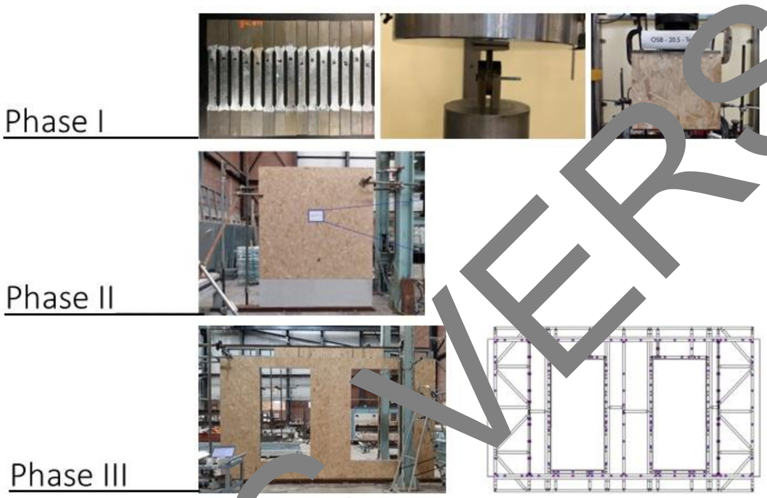

Figure 2. The overall experimental campaign, with Phase I to study the tensile strength of steel members, shear capacity of screws, and shear behavior of connections; Phase II to characterize the shear behavior of walls fully sheathed with OSB and CP; and Phase III to study the shear behavior of walls with openings and compare them with previously commercialized systems having steel bracings.

Each wall was constructed using studs, tracks, and blocking profiles made from C profiles (C100-41-1.6) with a steel thickness of 1.6 mm and a nominal grade of 450 MPa. The studs were spaced 600 mm apart. Three rows of blocking were installed: 6[illegible] mm from the bottom, at the mid-height of the wall, and 213 mm from the top. The lower blocking was positioned to accommodate cement panels (CP) at the bottom portion of the wall, helping to prevent humidity buildup (Fig.3). Full-height 15mm oriented strand board (OSB3) panels were installed in the central section of the wall to serve as the primary shear-resisting elements. Additionally, OSB panel strips were placed near the top of the wall, intended for later assembly in the production line. This allows flexibility when moving and lifting the wall during the module assembly process. Self-tapping screws were used to fasten the sheathing panels to the CFS members, with spacing ranging from 75 mm in the central part of the GF-RW to 300 mm for the OSB strips at the top of the walls (Fig.4). These variations were selected to meet the necessary shear capacity while enabling the use of high-speed paneling systems in the central areas. Fewer screws were used in areas where manual fastening with a hand screwdriver was required. In accordance with the perforated design method requirements, Simpson Strong-Tie HTT22E hold-downs were installed at the bottom corners of the walls during testing. The entire geometry of the tested walls with openings can be found in Kechidi & Iuorio, 2022 [17]. Additionally, ledger beams were placed at both the top and bottom of the wall, on the interior side, to simulate the presence of floors (Fig.3). The tests were conducted using displacement-

10.30682/tema100022

controlled quasi-static loading, following BS EN 594 (1996) [18], the standard currently used in the UK for testing walls of both wooden and CFS frames. This standard specifies the specimen setup and the loading protocol. The walls were pre-assembled in the factory and transported to the lab, where they were positioned vertically on a composite rectangular hollow base beam made from two welded U-sections and secured to the lab floor. A U-shaped spreader beam was placed on top of the walls to distribute the horizontal load evenly (Fig.5). Vertical and horizontal displacements were recorded using Linear Voltage Displacement Transducers (LVDTs). The test results are discussed in section 3.

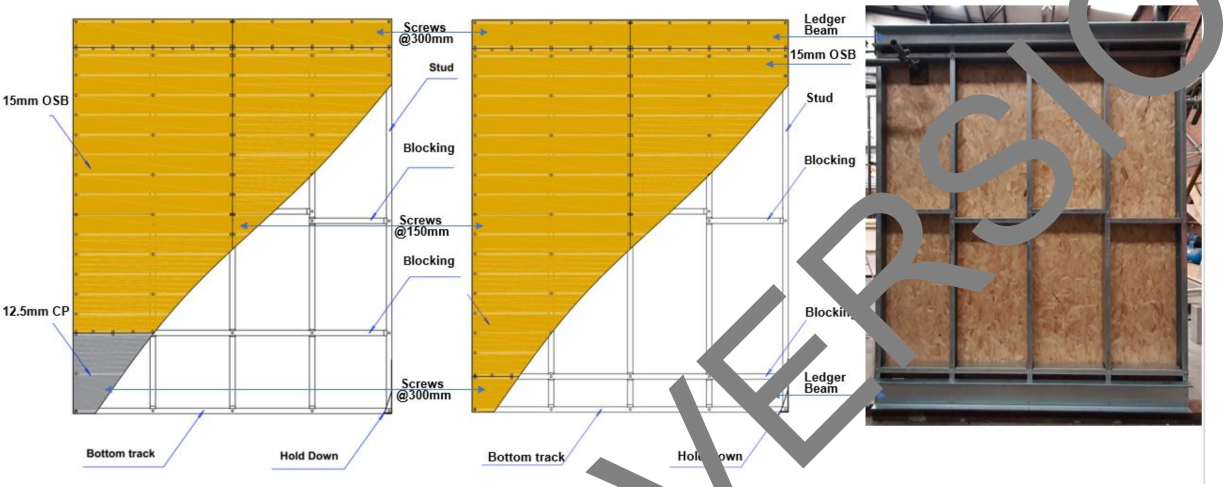

Figure 3 Geometry of the fully sheathed tested walls.

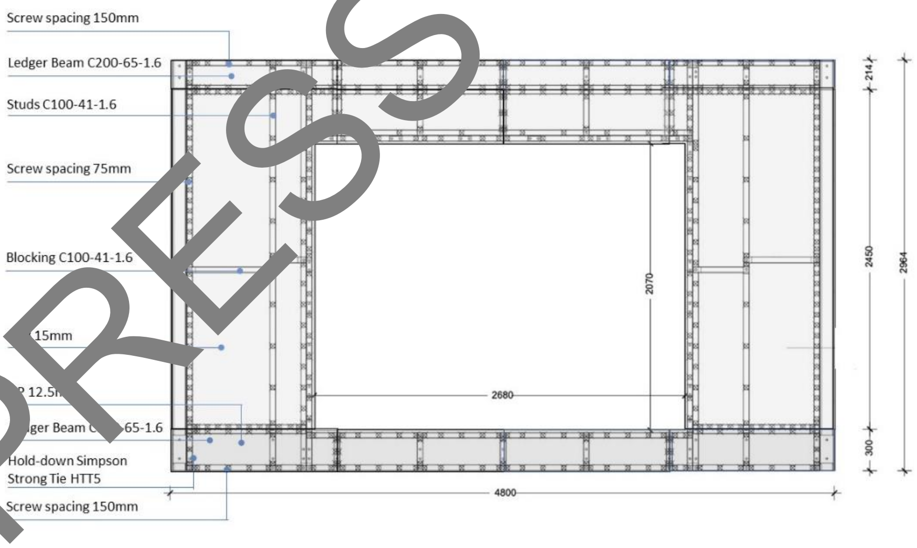

Figure 4 Geometry of the wall with opening (typology GF_RW)

10.30682/tema100022

Figure 5. Test rig of the walls with openings: a. ground floor with 2 openings (GF-FW); b. ground floor with one large door (GF-RW); c. first floor (FF-FW) with two openings.

3. Results

3.1. Design for Manufacturing and Assembling

A high-speed panelizing system (Fig. 6a) was introduced to automate the process of attaching sheathing boards (the outer layer of the wall) to the CFS wall frame. This is typically a highly repetitive process, usually done by hand with a screwdriver, but by automating it, the DfMA-driven production line drastically reduced assembly time while maintaining accuracy and quality. Indeed, a typical CFS wall segment of, for instance, 2400mm length x 2700mm height, sheathed on one side, when designed to resist high lateral loads, can require having screws spaced at 100mm on the edge and 300mm in the center, having as such as 180 screws. Locating them at a precise distance from the edge of the panel is essential to avoid local failure of the panel. Therefore, their manual placing can take several minutes. Instead, the particular configuration of sheathing boards and the screw pattern, defined based on the results of the experimental campaign on connection systems (phase 1) and wall systems (phases II and III), allowed to place 60 screws per minute. This system allows for the wall panels to be produced at a faster rate, improving production efficiency. The walls were then flipped vertically to be completed in a line-based manner, similar to an automotive assembly line. Each station in the line is designed to add a specific component, such as insulation, waterproofing, vapor barrier, and applying exterior finishes (Fig. 6c). Then walls and floor systems were connected, and all the services were integrated, up to realizing complete volumetric units, corresponding to the ground floor and first floor of the house systems to be delivered on-site. The design ensured that the components fit together seamlessly, reducing the need for adjustments or rework during assembly. The DfMA approach ensured that all connections between floors and walls were simplified for fast and secure attachment, allowing the modules to come together in an efficient workflow. The result was a modular volumetric housing system with consistent quality that could be produced quickly, up to six full volumetric units per week.

Figure 6. Production line of the developed modular system showing: a. Ground floor assembly; b. High-speed panelizing system for connecting the sheathing boards to the wall steel frame; c. Line production of the walls; d. Assemblage of the floor and wall system, e., line production of the volumetric modules; f. Modules ready to be transported on-site for assembly.

3.2. Experimental test results

Observations from the wall tests revealed that the CFS frame tended to deform into a parallelogram shape, while the sheathing boards tended to rotate. However, due to the presence of ledger beams at the top and bottom of the walls, along with the specific sheathing configuration—full-height panels in the center and shorter panels at the top and bottom—the central section of the walls experienced greater deformation. This determined pull-through of the screws predominantly around the edge of the central panels. In particular, the central sheathing panels underwent more significant rotation. This was true for both walls without and with openings. This demonstrated that small screw spacing was necessary in the central parts of the walls, as they were the most subjected to deformation, while larger spacing could have been adopted in the top and bottom strips. The following subsections discuss results for the second and third phases in detail.

3.2.1. Test results for fully sheathed walls

Test results indicated that wall collapse was primarily dictated by the sheathing-to-frame connections in all GF specimens. At the global level, the steel frame deformed into a parallelogram, causing a rigid rotation of the sheathing panels. This led to the tilting and pull-through of the screws, followed by cracking in the CP panels and the breaking of the panel corners at the edges. Table 1 summarizes the results, showing that the GF walls had an average maximum strength of 41.79 kN and an average stiffness of 2.32 kN/mm, while the FF walls demonstrated an average strength of 62.48 kN and stiffness of 2.04 kN/mm. This indicates that walls with only OSB panels have at least 1.5 times the shear strength compared to similar walls with CP panels at the bottom.

Table 1. Test results for fully sheathed walls in terms of shear strength and stiffness.

	Wall	Test number	Shear Strength	Stiffness
			[kN]	[kN/mm]
Phase II	GF	2	44.12	2.48
		3	39.46	2.17
		Mean	41.79	2.32
	FF	2	60.92	1.95
		3	64.04	2.13
		Mean	62.48	2.04

GF stands for Ground floor; FF stands for First Floor

Test results for walls with openings

In terms of failure mode, in the case of the walls with two openings (GF-FW and FF-FW), the first cracks appeared in the top right and bottom left corners of the opening farthest from the applied horizontal load (details G and M in Fig.7), followed by cracks at the other corners. In these walls, the bottom sheathing panels showed no significant deformation. The GF-RW walls exhibited significant diagonal cracks at each corner, with extensive propagation in both the OSB and bottom CP panels (Fig. 8). The results in terms of shear strength at F_{max} and stiffness, as defined by BS EN 594 (2011), are reported in Table 2 for walls with openings (labeled as GF-FW, GF-RW, and FF-FW) and the two walls with opening and steel bracing (labeled as GF-K, and FF-K).

Figure 7. GF-FW wall before and after testing, with wall failure details of the: balcony right corner [B], bottom left corner [C], bottom right corner [D], door top corner [E], relative displacement between top and central panel [S].

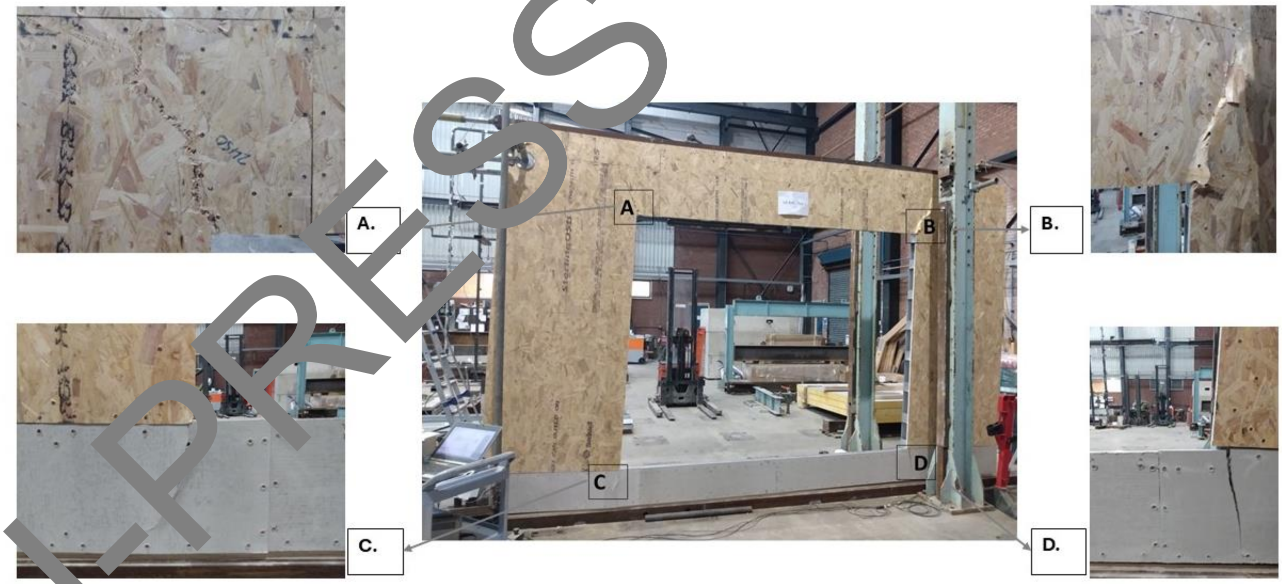

Figure 8. GF-RW wall after testing, with wall failure details of each opening corner.

Notably, GF-FW and FF-FW displayed similar shear strengths, around 59.5 kN, though GF-FW was stiffer. GF-RW, despite having a large opening and a 75mm screw spacing in the central area, showed a higher shear strength of 62.4 kN but lower stiffness (1.82 kN/mm) due to the large opening.

When comparing the results obtained in Phase II and III, it appears evident that the opening mostly influences the stiffness of the walls. Indeed, when comparing the FF-FW with opening, with a similar without opening (from phase II), the stiffness decreased by about 6.4%. It is also evident that reducing the screw spacing has a more significant contribution to the shear strength of the walls.

Comparing walls with openings braced only by sheathing panels to those with steel bracing reveals that steel bracing slightly increases shear strength. However, in terms of stiffness, GF-FW exhibits greater stiffness than GF-K. Despite this, these wall systems are rarely used to their total shear capacity in low-rise buildings up to two stories. Walls without steel bracing fully meet the required capacity, even with large openings. Since unbraced walls reduce material waste, lower embodied carbon, and speed up construction, they were the preferred option.

Table 2. Wall tests results

	Wall	Test	Shear Strength	Stiffness
			[kN]	[kN/mm]
Phase III	GF-FW	1	55.62	2.02
		2	61.4	[illegible]
		3	61.61	[illegible]
		Mean	59.4	2.35
	GF-RW	1	64.3	1.79
		2	64.9	1.71
		3	58	1.95
		Mean	62.40	1.82
	FF-FW	1	58.68	1.7
		2	[illegible]	1.87
		3	[illegible]	1.94
		Mean	59.51	1.84
	GF-K	1	64.41	1.36
	FF-K	1	[illegible]	1.91

4. Conclusions

Early-stage collaboration between designers and manufacturers can significantly reduce material waste, improve construction speed, and lower overall costs. Integrating testing throughout the design and production phases can identify and address potential issues such as structural performance, thermal efficiency, and durability early, leading to more reliable outcomes. Automated production systems, guided by digitally integrated designs, can lead to precision in assembly, reduced labor costs, and minimized rework. When combined with rigorous testing protocols, these processes ensure that housing systems meet safety standards and maintain affordability. This paper presented an iterative methodology, which was developed and validated to optimize a prefab system, which leverages the composite action between CFS profiles and sheathing panels while simplifying the manufacturing and assembly process. At its core, the methodology involves prototyping and testing, and it is informed by the challenges to be overcome to speed up the manufacturing process. For this specific case, the main challenge was to automate screwing connections while providing the required lateral capacity to the system. The experimental testing demonstrated the achievement of a system that fully met the structural requirements while also minimizing the use of material, waste, and production time. In particular, in terms of minimizing material, moving from a steel-braced approach to a sheathing-braced approach, allowed to reduce the use of steel by 12%. This had a significant impact not only in terms of manufacturing efficiency but, in particular, in terms of environmental impacts, with the new system achieving an embodied carbon (EC) of 254 kgCO2e/m², compared to 290 kgCO2e/m² obtained for the standard system, representing a 12.5% reduction in CO2e. Since steel components are the main contributors to the carbon footprint of lightweight steel systems, optimizing their use is essential, as highlighted in previous studies.

10.30682/tema100022

The proposed methodology in which manufacturing and assembling strategies are considered since product development and according to which materials are selected, prototyped, and tested to evaluate both mechanical and environmental performance can significantly impact Italian research, which is advancing sustainable constructions. Indeed, by addressing embodied carbon in construction materials and processes, the methodology can push the Italian building sector towards more environmentally friendly practices. This is particularly important in Italy, where sustainability and energy efficiency are growing priorities in the context of the EU's Green Deal and climate goals. Moreover, looking specifically at prefabrication techniques, the presented study can demonstrate how prefabrication can lower construction time and carbon footprint, making it more attractive for local industries. In the future, optimizing prefabricated construction through this methodology can create opportunities for Italian manufacturers and suppliers to gain a competitive edge, fostering growth in the green economy and boosting exports of innovative building systems.

5. Acknowledgments

The Author acknowledges the contribution provided by Nigel Banks and Smail Rec[illegible]idi to the experimental testing.

6. Author Contributions

Conceptualization, visualization, writing - original draft, writing - review and editing, methodology, funding, project administration: O.I.

7. Funding

The research discussed in this paper has been developed under a Knowledge Transfer Partnership (KTP #11543) with the University of Leeds and Ilke Homes.

8. References

1. Farmer M (2016) The Farmer Review of the UK Construction Labor Model. Modernise or Die. Published by The Construction Leadership Council. United Kingdom
2. Iuorio O (2007) Cold-formed steel housing, Pollack Periodica, 97-108.
3. American Iron and Steel Institute (2015) North American standard for seismic design of cold-formed steel structural systems, AISI S400, Washington, D.C., USA.
4. Abdelmageed S, Zayed T (2[illegible]0) A study of literature in modular integrated construction - Critical review and future directions, Journal of Cleaner Production, 277.
5. Navaratnam S, [illegible]go T., G[illegible]nawarde[illegible]., Henderson D. (2019) Performance review of prefabricated building systems and future research in Australia, Buildings, [illegible](2).
6. Zhenmin Y, Che[illegible]uang S, Yaowu W (2018) Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings, Automation in Construction, 88: 13-22.
7. W[illegible]im M, S[illegible]ra P V, [illegible]go T (2020) Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction – a review. International Journal of Construction Management: 3014-3022.
8. Schafer [illegible] (2011) Cold-formed steel structures around the world. A review of recent advances in applications, analysis and design, Steel Construction, V 4, Issue 3.
9. Se[illegible]tte, R. and Nolan, D., (2009). Reversed cyclic performance of shear walls with wood panels attached to cold-formed steel with pins. Journal of Structural Engineering, 135(8), pp.959-967.
10. [illegible]amim, I., DaBreo, J. and Rogers, C., (2013). Dynamic testing of single- and double-story steel-sheathed cold-formed steel-framed shear walls. Journal of Structural Engineering, 139(5), pp.807-817.
11. Iuorio, O., Fiorino, L. and Landolfo, R., (2014). Testing CFS structures: The new school BFS in Naples. Thin-Walled Structures, 84(0263-8231), pp.275-288.
12. Wang, J., Wang, F., Shen, Q. and Yu, B., (2019). Seismic response evaluation and design of CTSTT shear walls with openings. Journal of Constructional Steel Research, 153, pp.550-566.
13. Lange, J. and Naujoks, B., (2006). Behavior of cold-formed steel shear walls under horizontal and vertical loads. Thin-Walled Structures, 44(12), pp.1214-1222.
14. Iuorio O., Fiorino L., Macillo V., Terracciano M.T., Landolfo R., (2012). The Influence of the Aspect Ratio on the Lateral Response of the Sheathed Cold Formed Steel Walls, Missouri University of Science and Technology.
15. NAHB Research Center, (1997). Monotonic tests of cold-formed steel shear walls with openings. Prepared for the U.S. Department of

10.30682/tema100022

Housing and Urban Development, the American Iron and Steel Institute, and the National Association of Home Builders.

16. Iuorio O., Kechidi S, Banks N. (2021) Experimental investigation into the performance of cold-formed steel walls sheathed with OSB and cement-based panels, Proceeding of Eurosteel 2021 Conference, 525-529.)
17. Kechidi S, Iuorio O. (2022) Numerical investigation into the performance of cold-formed steel framed shear walls with openings under in-plane lateral loads. Thin Walled Structures. 175
18. BS EN 594:1996 (2011) Timber structures. Test methods. Racking strength and stiffness of timber frame wall panels. BSI, London, UK.

10.30682/tema100022