UDC 624.014 **doi:10.31650/2707-3068-2025-29-34-40**

COMBINED CONTRIBUTION OF PU FOAM AND GYPSUM FIBRE SHEATHING ON THE BEHAVIOUR OF LIGHTWEIGHT STEEL C-PROFILE IN A COMPOSITE WALL PANEL

***Krolo P.**, PhD, Associate Professor
paulina.krolo@gradri.uniri.hr, ORCID number: 0000-0002-7244-4140
***Lukačević L.** mag.ing.aedif., PhD student
llukacevic@sudent.uniri.hr, ORCID number: 0000-0003-0597-7235
**Faculty of Civil Engineering University of Rijeka*,
Radmile Matejčić 3, Rijeka 51000, Croatia
Palijan I., mr.sc.
ipalijan@palijan.hr, ORCID number: 0000-0001-8899-1731
Palijan d.o.o.,
Diljska ulica 1, 10000 Zagreb, Croatia

Abstract. The research focuses on evaluating the mechanical contribution of the PU foam and sheathing to the load-bearing capacity, stiffness, and failure modes of the LSF system. Two groups of specimens were tested under axial compression: (1) bare LSF structures consisting solely of cold-formed C-profiles, and (2) composite panels consisting of the same LSF frame, a PU foam core injected under pressure, and external gypsum fibreboard sheathing. The experimental results demonstrate a substantial enhancement in structural performance due to composite action. Composite panels achieved an average load-bearing capacity of 316.7 kN, more than double that of the bare LSF structures, which averaged 133.4 kN. In addition, the composite panels exhibited significantly higher ductility, with average vertical displacements at peak load reaching 10.27 mm, compared to 5.43 mm for the LSF frames. The initial stiffness of the composite system was also markedly improved, reaching 45.76 kN/mm approximately 1.5 times greater than that of the LSF structure alone. The PU foam, injected in a controlled industrial process, ensures a uniform and firm bond with both the steel frame and the sheathing, enabling effective composite action and resistance to local and global buckling. Visual inspection and load-displacement analysis confirmed that while the bare LSF structures failed by local and out-of-plane buckling, the composite panels maintained stability and failed primarily through localized crushing, without global loss of structural integrity. These findings underscore the structural benefits of using composite panel systems and provide a foundation for the development of design models and future standardization of this type of construction element.

Keywords: Light steel frame; composite wall panel; polyurethane foam; load-bearing capacity, failure mode

Introduction. Structures made of Light Steel Frames (LSF) are used worldwide as building systems capable of achieving low energy consumption. This is due to their lightweight, production under controlled conditions, fast and precise assembly, shorter construction time, potential for reuse and recycling, automated manufacturing processes, high execution accuracy, reduced transport costs, and the possibility of using modern insulation materials as an integral part of energy-saving construction. Because of these advantages, LSF systems are recognized as alternatives to traditional masonry and reinforced concrete structures.

In recent years, composite walls with LSF structures filled with lightweight materials have emerged as relatively new products in the construction industry. Numerous studies have investigated the structural performance of these walls [1–3], with favourable findings. Incorporating various load-bearing materials into the wall frame fill can provide additional bracing, prevent local buckling of the LSF frame, and simultaneously improve the wall's axial compressive strength, seismic performance, and ductility. In addition to filling LSF composite walls with lightweight materials to enhance their structural performance, another approach involves reinforcing the walls with sheathing boards.

Several studies have examined the influence of sheathing on the load-bearing capacity of LSF composite walls [4–6], concluding that sheathing can limit deformation and global buckling.

The company Tehnoplast profili d.o.o., in collaboration with the Faculty of Civil Engineering at the University of Rijeka and the company Palijan d.o.o., has developed an advanced system of nearly zero-energy prefabricated buildings using innovative composite wall and ceiling panels. The panel essentially consists of an LSF structure, gypsum-fibreboard sheathing, and a polyurethane (PU) foam infill. A key difference from existing panels lies in the PU foam filling process, which is injected under pressure in controlled factory conditions, unlike conventional panels filled on-site. This ensures uniform distribution of the foam within the panel, enabling bonding to both the sheathing and steel structure and facilitating composite action of all components [7]. Thus, beyond providing thermal and acoustic insulation, the PU foam contributes to the load-bearing capacity of the steel structure, which is otherwise vulnerable to buckling.

The aim of this paper is to investigate the contribution of the PU foam core and sheathing to the load-bearing capacity and stability of the LSF structure. This was achieved through experimental research on LSF structures and LSF structures sheathed with gypsum-fibreboard and filled with PU foam (composite panel). The influence of PU foam and sheathing on the behaviour of the LSF structure was analyzed including load-bearing capacity, ductility and failure modes. Current EU building regulations do not provide specific guidelines for this type of structural element, so the results of this research may serve to define the relevant parameters necessary for developing resistance design models, thereby providing a scientific basis for future standardization.

Test setup and description. Uniaxial compression tests were conducted on two groups of specimens: LSF structures C0 (Figure 1a) and composite panels C (Figure 1b). The LSF structure was made of cold-formed thin-walled C-profiles, using standardized S550GD grade steel. The nominal thickness of the C-profiles is t = 1.15 mm. The C-profiles are connected with M6 self-tapping screws of grade 10.9. Angle brackets were placed at the ends of vertical elements within the cross-section. The composite panel specimens consist of the aforementioned a LSF structure (1), PU foam infill (2) with a nominal density of 45 kg/m³, and lining (3) made of Fermacell® gypsum fiberboards12.5 mm thick.

The dimensions of the LSF structure are 1800×2000×89 mm, while the composite panel measures 1800×2000×160 mm. The LSF structure specimens are labelled as C0-x, where the first letter C denotes compression testing (C – compression), the second symbol 0 refers to specimens consisting only of the LSF structure, and the third symbol x denotes the specimen number from 1 to 4. Composite panel specimens are labelled as C-x, where the first letter C denotes compression testing of composite panels, and the second symbol x denotes the specimen number from 1 to 5.

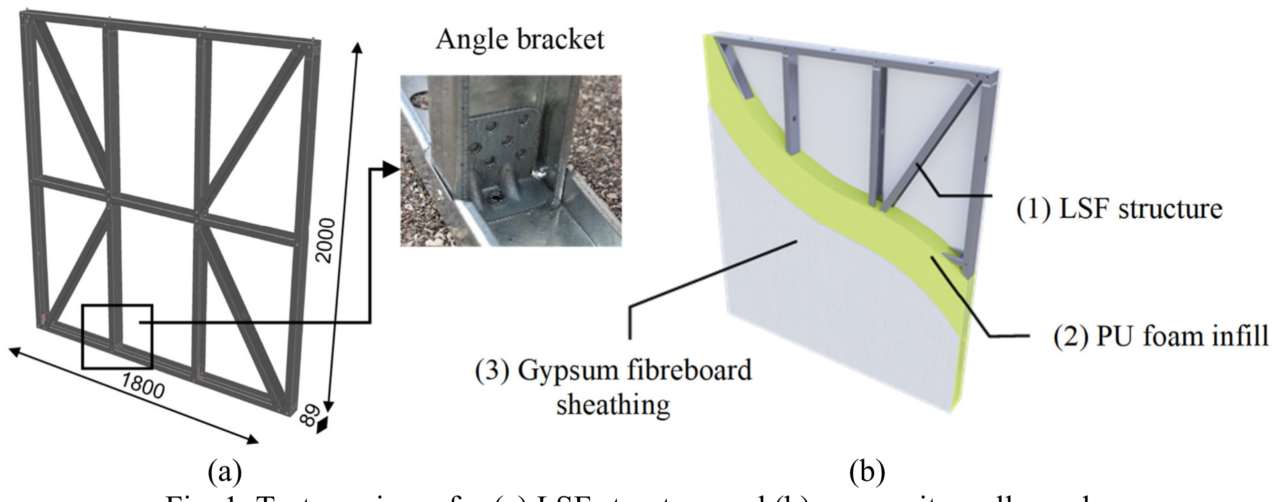

Fig. 1. Test specimen for (a) LSF structure and (b) composite wall panel

The compression tests of the specimens were carried out in the Structure Laboratory at the Faculty of Civil Engineering in Rijeka, using a Zwick/Roell actuator with a capacity of 500 kN. A total of four LSF structure specimens and five composite panel specimens were tested. The specimen was placed in a vertical position and fixed to the loading beam using four M12 grade 10.9 bolts. The specimens were bolted to the web and flange of an HEB140 profile via angle brackets located at the bottom ends of the vertical elements.

To ensure a rigid bolted connection without slippage between the specimen and the loading fixture, the bolts were tightened with a torque wrench to a tightening torque of 51 Nm. Slip resistance between the fixture and the specimens was provided by the clamping force of the bolts, corresponding to 50% of the tensile strength of M12 grade 10.9 bolts. Loading of the test specimen was performed via a loading beam to ensure uniform load application. To achieve even load distribution, an additional beam was placed on top of the loading beam with a distance between the hinge supports of 1055 mm. Figure 2 shows the test setup for the LSF structure specimens, including the specimen support beams, upper and lower reaction beams and the loading beam. To prevent specimen overturning and potential stability loss, a LSF supporting frame (Figure 3) laterally supported both the LSF structure and composite panel specimens.

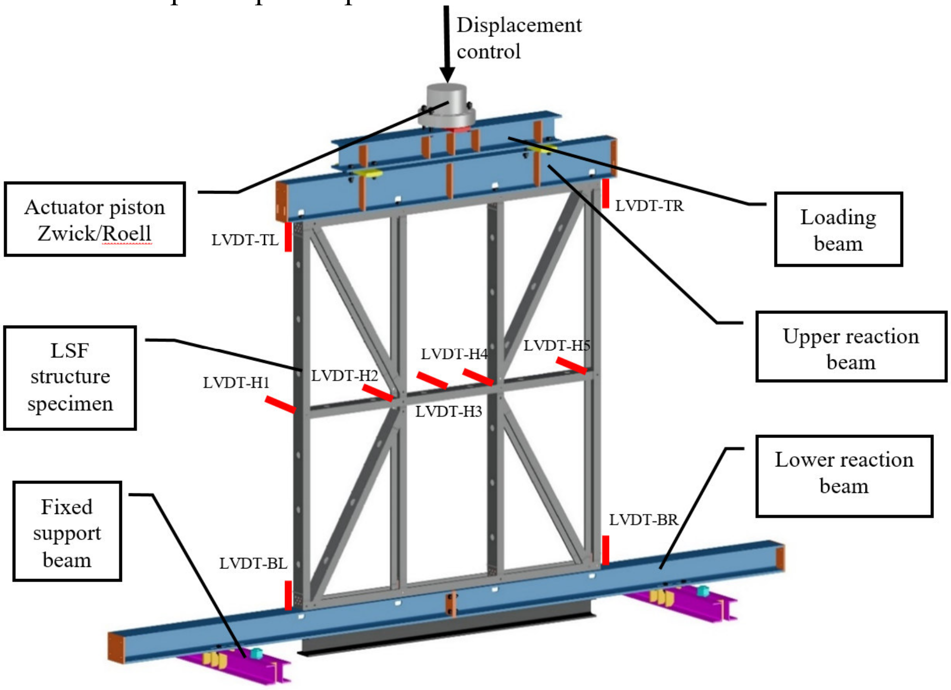

Fig. 2. Compression test setup

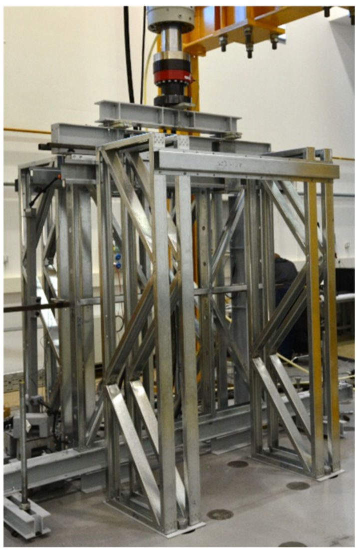

Fig. 3. LSF supporting frame

Compression tests were conducted in accordance with the recommendations of ASTM E72-15. The load was applied using a vertically positioned actuator with a capacity of 500 kN, operated in displacement control mode, with a displacement rate of 2.5 mm/min. The load was applied to the specimen as a distributed line load, parallel to the specimen.

During testing, displacements were measured using LVDT devices (Figure 2). Vertical relative displacement was measured using four LVDTs placed near the panel edges on each side of the specimen, mounted on the upper and lower reaction beams (LVDT-BL, LVDT-BR, LVDT-TL, and LVDT-TR). Horizontal deflection of the specimen was measured using five LVDTs placed on one side of the specimen at mid-height (LVDT-H1 to LVDT-H5).

The end of the test was defined as a drop in vertical force exceeding 20% for steel structure specimens, and 60% for composite panel specimens.

Test results. The results of the compression tests are presented in Table 1. The maximum force F_{max} was recorded just before failure. The vertical displacement Δv was measured at the maximum force, and the stiffnes Ev was determined from the load–displacement ratio, expressed in kN/mm. Load–displacement curves, expressed in N and mm, are shown in Figure 4. Steel structure specimen C0-1 was a trial specimen tested at a displacement rate of 1 mm/min, which proved to be too slow; therefore, the remaining specimens were tested at a rate of 2.5 mm/min. When calculating average values, the results of trial specimen C0-1 were not taken into account.

The results of the conducted tests indicate significant differences in the mechanical behaviour between the LSF structure and the composite panel, particularly in terms of load-bearing capacity, vertical displacements, and system stiffness. The average maximum force sustained by the LSF structure was 133.38 kN, whereas the composite panel achieved a substantially higher value of 316.7 kN, representing more than a twofold increase in load-bearing capacity compared to the LSF system. Regarding deformation capacity, the average vertical displacement (Δv) at peak load was 5.43 mm for the LSF structure and 10.27 mm for the composite panel. These results indicate a greater deformation capacity of the composite panel, implying higher ductility in comparison to the conventional LSF structure.

Table 1 Results of compression test

Specimen	F_{max} [kN]	Δv [mm]	E_v [kN/mm]	Failure mode
LSF structure				
C_0*	133,38	5,43	31,02	-
C_0-1	131,07	4,53	30,13	Local buckling of C-profile webs and flanges, failure by out-of-plane buckling
C_0-2	136,98	5,76	29,96	
C_0-3	129,09	4,98	32,39	
C_0-4	134,07	5,56	30,70	
Composite panel				
C*	316,71	10,27	45,76	-
C-1	314,27	12,47	47,51	Local buckling of C-profile webs followed by compressive failure (crushing) of the web
C-2	315,04	9,16	42,00	
C-3	316,05	11,87	45,59	
C-4	322,37	8,87	47,91	
C-5	315,82	8,96	45,77	

**average value*

** Δv – relative vertical displacmenet obtained by equation $\Delta v = 0.5\times((X_{LVDT-TL} - X_{LVDT-BL}) + (X_{LVDT-TR} - X_{LVDT-BR}))$*

The load–displacement curves obtained for the LSF structure specimens (labelled as C0) and composite panels (labelled as C) reveal pronounced differences in mechanical behaviour, particularly in the elastic and post-elastic deformation phases. Analysis of the elastic portion of the diagrams indicates that the composite panels demonstrate greater elastic deformation capacity before entering the plastic region, suggesting a higher level of initial stiffness and greater resistance to deformation at lower load levels.

The average initial stiffness of the LSF structures is 31.02 kN/mm, whereas the composite panels achieve an average stiffness of 45.76 kN/mm. This represents an increase of approximately

1.5 times in favor of the composite panels, confirming their superior load transfer capability and resistance to deformation in the initial loading phase.

After reaching the maximum load, the load–displacement curves of the LSF specimens show a sudden drop in capacity, caused by local buckling of profile elements, specifically the flanges and webs. This local instability progressively develops into a global loss of structural stability, ultimately resulting in failure. In contrast, the composite panels maintain load-carrying capacity beyond the peak point, indicating greater ductility and improved stability.

These results clearly illustrate the advantages of composite panels in terms of initial stiffness, structural stability, and ductility, thereby confirming their superior mechanical response compared to LSF structures without sheathing and infill.

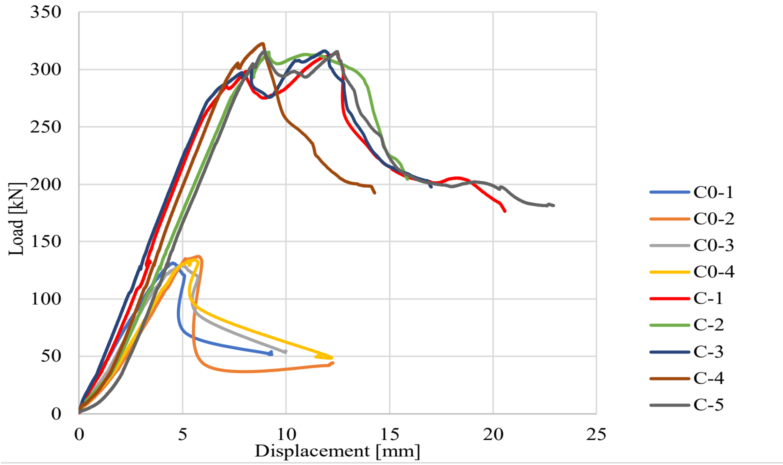

Fig. 4. Load-displacement curve

Visual inspection of the steel structure specimens and composite panel specimens after testing revealed the governing failure mechanisms. In the steel structure specimens, local buckling of the compressed flanges and webs of the C-profiles occurred first, followed by a loss of panel stability through global out-of-plane buckling (Figure 4a). In the composite panel specimens, local buckling of the C-profile webs was observed, followed by web crushing (Figure 4b). No global instability or out-of-plane buckling was observed in the composite panel specimens.

(a) (b)

Fig. 5. Failure modes of a) LSF structure and b) composite wall panel

Conclusions. The experimental research conducted on light steel frame (LSF) structures and composite wall panels composed of LSF, PU foam, and gypsum fibreboard sheathing has demonstrated significant improvements in mechanical performance due to composite action. The main conclusions are as follows:

- Composite wall panels exhibited more than twice the average load-bearing capacity compared to bare LSF structures (316.7 kN vs. 133.38 kN). This highlights the significant structural contribution of both the PU foam infill and the gypsum fibreboard sheathing.
- The composite panels showed higher average vertical displacements at maximum load (10.27 mm) compared to the LSF structures (5.43 mm), indicating improved ductility and energy dissipation capacity.
- The initial stiffness of composite panels (average of 45.76 kN/mm) was approximately 1.5 times greater than that of the LSF structures (average of 31.02 kN/mm), suggesting better resistance to deformation under service loads.
- LSF structures mainly fail due to local and global buckling of thin-walled steel profiles, composite panels failed due to localized crushing of C-profile webs without global instability. This confirms that foam infill and formwork significantly improve the overall stability of the panels.
- The results clearly show that the combined contribution of PU foam and gypsum fibreboard enables effective composite action, leading to a synergistic improvement in structural behaviour, including strength, stiffness, and stability.

These findings support the use of PU foam-injected composite panels in lightweight construction and suggest that their structural behaviour should be considered in future design models and building regulations. Further research is recommended to explore long-term performance, fire resistance, and behaviour under seismic or cyclic loads.

Acknowledgment. This research was funded by “Prefabricated buildings of almost zero energy produced in an industrial way”, grant number KK.01.2.1.02.0046, financed from the European Fund for Regional Development with the financial support of the University of Rijeka.

References

[1] Mousavi, S.A.; Zahrai, S.M.; Bahrami-Rad, A. Quasi-static cyclic tests on super-lightweight EPS concrete shear walls. Eng. Struct. 2014, 65, 62–75.

[2] Xu, Z.; Chen, Z.; Osman, B.H.; Yang, S. Seismic performance of high-strength lightweight foamed concrete-filled cold-formed steel shear walls. J. Constr. Steel Res. 2018, 143, 148–161.

[3] Hegyi, P.; Dunai, L. Experimental study on ultra-lightweight-concrete encased cold-formed steel structures Part I: Stability behaviour of elements subjected to bending. Thin-Walled Struct. 2016, 101, 75–84.

[4] Miller, H.T.; Pekoz, T. Behavior of Cold-Formed Steel Wall Stud Assemblies. J. Struct. Eng. 1993, 119, 641–651.

[5] Tian, Y.; Wang, J.; Lu, T.; Barlow, C. An experimental study on the axial behaviour of cold-formed steel wall studs and panels. Thin-Walled Struct. 2004, 42, 557–573.

[6] Wang, J.; Tian, Y.; Lu, T. The role of frame members and sheathing in partition wall panels subjected to compression. Thin-Walled Struct. 2005, 43, 983–1002.

[7] Bakran, A.; Krolo, P.; Lukačević, L.; Palijan, I. Experimental Investigation of the CFS-PU Composite Wall Panel under Axial Compression. Buildings 2023, 13, 1897. https://doi.org/10.3390/buildings13081897

СУМІСНИЙ ВПЛИВ ПІНОПОЛІУРЕТАНУ ТА ОБШИВКИ З ГІПСОВОЛОКНА НА ПОВЕДІНКУ ЛЕГКОГО СТАЛЕВОГО С-ПРОФІЛЮ В СКЛАДІ КОМПОЗИТНОЇ СТІНОВОЇ ПАНЕЛІ

Кроло П., д-р наук, доцент
paulina.krolo@gradri.uniri.hr, ORCID: 0000-0002-7244-4140
Лукачевич Л., магістр інж. буд., аспірант
llukacevic@sudent.uniri.hr, ORCID: 0000-0003-0597-7235
Факультет цивільного будівництва, Університет Рієки
Radmile Matejčić 3, 51000 Рієка, Хорватія
Паліян І., магістр наук
ipalijan@palijan.hr, ORCID: 0000-0001-8899-1731
Palijan d.o.o.
вул. Дільська 1, 10000 Загреб, Хорватія

Анотація. Дослідження зосереджене на оцінці механічного впливу пінополіуретану (PU) та облицювання на несучу здатність, жорсткість і механізми руйнування системи з холодногнутого сталевого каркасу (LSF). Проведено випробування двох груп зразків під осьовим стиском: (1) необлицьовані LSF-конструкції, що складаються виключно з холодногнутих С-профілів, та (2) композитні панелі, які включають той самий сталевий каркас, серцевину з пінополіуретану, доданого під тиском, і зовнішнє облицювання з гіпсоволокнистих плит. Результати експерименту демонструють суттєве покращення конструктивних характеристик завдяки композитній дії. Композитні панелі досягли середньої несучої здатності 316,7 кН, що більш ніж удвічі перевищує показник необлицьованих LSF-конструкцій (у середньому 133,4 кН). Крім того, композитні панелі показали значно вищу пластичність, із середнім вертикальним переміщенням при максимальному навантаженні 10,27 мм проти 5,43 мм для сталевих каркасів. Початкова жорсткість композитної системи також значно зросла – до 45,76 кН/мм, що приблизно у 1,5 раза більше, ніж у каркасу без наповнення. Пінополіуретан, доданий у контрольованому промисловому процесі, забезпечує однорідне та міцне зчеплення як зі сталевим каркасом, так і з облицюванням, що забезпечує ефективну композитну дію та підвищений опір до локальної та загальної втрати стійкості. Візуальний огляд та аналіз кривих навантаження-переміщення підтвердили, що тоді як LSF-конструкції зазнавали локального та позаплощинного випинання, композитні панелі зберігали стабільність і руйнувалися переважно через локальне зминання без загальної втрати несучої здатності. Ці результати підкреслюють переваги використання композитних панельних систем і закладають основу для розробки проєктних моделей і майбутньої стандартизації такого типу конструктивних елементів.

Ключові слова: холодногнутий сталевий каркас; композитна стінова панель; пінополіуретан; несуча здатність; механізм руйнування.