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COMPARISON OF GENERAL TECHNICAL PARAMETERS, WORKABILITY AND FIRE PROTECTION OF ROLLED PROFILES VS. RHS STEEL FRAMES OF 3D-VOLUMETRIC MODULES

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Abstract. Prefabricated volumetric modules with steel frame have recently become a segmentation trend for real estate, commercial multi-storey housing and office buildings projects. The obvious benefits of reducing construction time, number of site activities and related overheads as well as better quality control system compare to on-site production, 3D volumetric construction still associated with significant risks related to relatively high construction cost, potential logistics issues and lack of proven point of reference and frameworks (so-called “best practices”).

Despite the fact that prefabricated modular construction known for almost a century, researches on design problems and limitations of practical implementation of volumetric modules today are still fragmentary and insufficient.

Numbers of researches focused on the improving of steel frames of three-dimensional volumetric modules and their performance-based optimization, related either to the design of effective joints (e.g. self-clamp joints) or study the problems of spatial stability of multi-storey modular buildings, considering the own weight of load-bearing structures as a criterion for design efficiency.

The case study illustrates that estimation of design efficiency of prefabricated volumetric modules with steel frames, besides the factors of durability and sustainability of the structure included required level of fire resistance, and the criteria of the economic efficiency of design also includes the fire protected surface area of the steel elements.

Keywords: prefabricated volumetric modules, efficiency, fire resistance, steel buildings

Introduction. The global challenges to the European Community related to the COVID pandemic (demand on temporary, prefabricated efficient medical buildings), the chronic shortage of affordable housing and, finally, the war in Ukraine with challenges of providing the shelter for displaced persons - have drawn special attention to three-dimensional volumetric prefinished building modules.

In the context of the so-called 4th Industrial Revolution, the construction industry has proven to be one of the most reactionary systems in many aspects compared to other manufacturing and technological industries, lagging behind in the optimization of production processes and quality control.

Three-dimensional prefabricated volumetric modules have proven to be a competitive alternative to traditional construction design solutions and techniques.

Although interest in prefabricated modular construction can be tracked to 1940s, researches on design problems and limitations of practical implementation of volumetric modules today are fragmentary and obviously insufficient. Along with reduced design flexibility and lack of real projects experience, it poses significant challenges for construction industry worldwide [1].

Problems are even in terminology and taxonomy – shall modular construction be referred to prefabricated construction, or separated as a class of unique building structures (Off-site Modular Construction) [1]? Shall panel systems be considered as modular ones, or such definition shall be limited to three-dimensional volumetric modules only?

Currently in Ukraine, modular buildings and structures defined as made of three-dimensional volumetric modules, primarily with a timber (wooden) and metal frame [2].

A new strategy framework: "Closing the loop - New circular economy package" [3] launched by the European Parliament at the end of 2015. According to it, the economic aspects of construction and the impact of human activity on the environment have led to shift in the emphasis of the construction industry from the research, development and implementation of new materials and structures towards the efficient use and reuse of well-known building materials.

Traditionally, timber-framed buildings are highly praised for their potential for contribution to a circular built environment and many studies focused on volumetric modular timber design [4].

However, steel and other alloys provide a number of benefits that make them equally attractive for modular building systems in the long run. Steel is a fully recyclable material, and the industrial joints of the steel framed modules allow them to be reused. Despite the relatively high initial cost, the durability of steel frame elements, allows a service life of decades for modular buildings and structures, reducing the maintenance cost.

Literature review. Research on the effectiveness of design solutions of three-dimensional volumetric modules is currently focused on several different approaches.

Research in the field of architectural design aimed at overcoming the limitations, associated with the size and shape of modules and, accordingly, space-planning solutions of modular buildings. Using a 'Design for Manufacture and Assembly (DfMA)" approach, a design-to-production workflow that shall be able to offer "mass-customization, responding to changing sites and client needs, with higher precision, production quality, sustainability, and greater efficiency" [5].

Significant number of researches focused on design of effective joints – either module-to-module or module-to-base. Effectiveness of Inter-modular connections (IMC) affects in-situ assembly activities and structural performance of modular buildings. Developing standardized automated connecting devices, with effective and safe self-locking mechanism that fulfill requirements for connections to be considered as semi-rigid in lateral stability problem is still one of the most challenging in the Modular Building Systems (MBS) design [6].

Some researches focused on modular kinematic design and morphology of spatial elements, studying possibilities of implementation origami-shaped structural elements as replacement of conventional steel or timber framing [7].

Other explore more traditional approach and study the efficiency of steel frame of three-dimensional volumetric modules and their performance-based optimization is related either to the design of joints or study the problems of spatial stability of multi-storey modular buildings [8], considering the own weight of load-bearing structures as a criterion for design efficiency.

Review Aims and Scope. Among the factors of durability and sustainability of the structure the required level of fire resistance is one of the most important, and the criteria of the economic efficiency of design also includes the fire protected surface area of the steel elements.

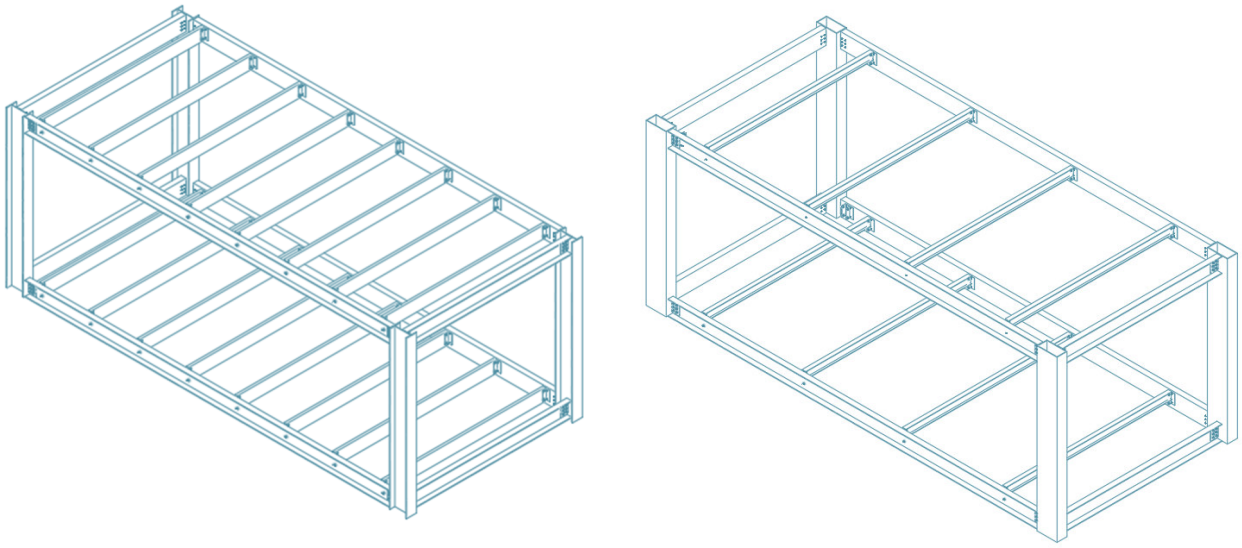
Research Methodology. For comparison purpose, four type of modules of overall size 3825×7650×3360 mm were designed by 3D modelling software Autodesk Advance Steel with a frame made of rolled profiles (IPE i-beam) and square rigid hollow sections (RHS), respectively, with two options for flooring and ceiling decking:

1. a thin reinforced concrete (RCC) slab on a galvanized corrugated sheet (supported on reduced joists) and
2. composite panels (supported on regular joists) (see Fig.1, a.,b.).

Overall 4 types of modules were compared by:

1. weight of steel frame elements;
2. structural weight of frame and deck;
3. surface area of steel elements.

Research results. The results of the comparison of structural solutions in factors of the dead weight of steel structures, the construction weight of the structural elements of the module and the cost, including fire protection of steel structures by applying intumescent paint for the requirements of fire resistance class R120, are shown in the following diagrams (the most effective of the solutions for each comparison category stated as 100%).



a. b.

Fig 1. Design of steel 3D volumetric module frame.
a. IPE steel frame with regular joists distribution for composite panel deck
b. RHS steel frame with reduced joists for RCC deck

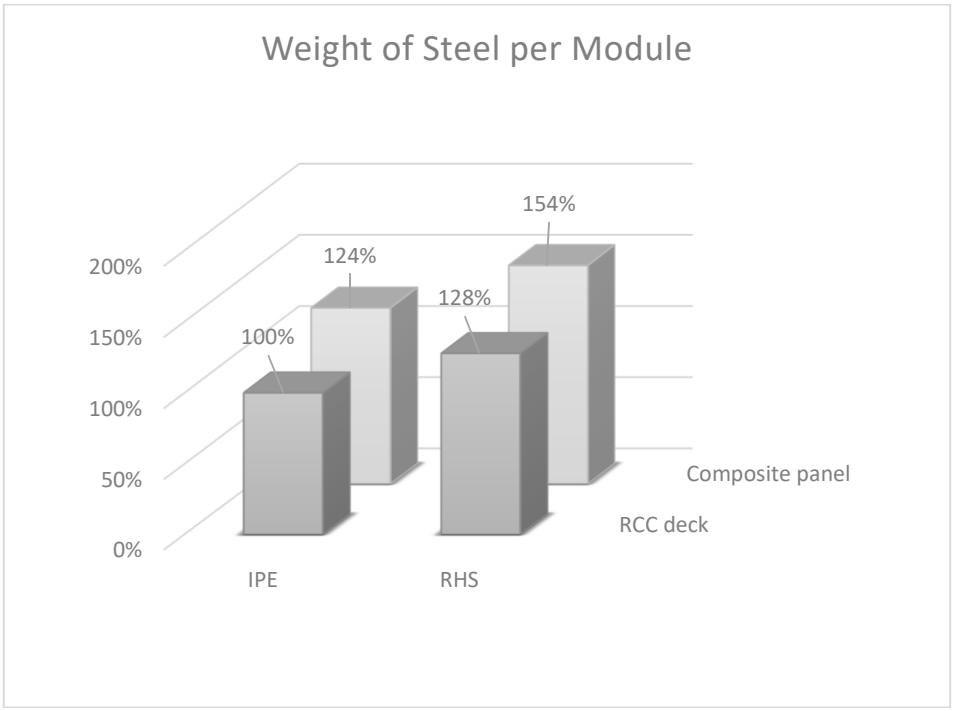


Fig. 2 Steel frame own weight/performance ratio

As shown on the diagram (see Fig.2) best own weight/performance ratio provided by using for module's frame steel IPE rolled profiles with reduced number of joists for RCC deck.

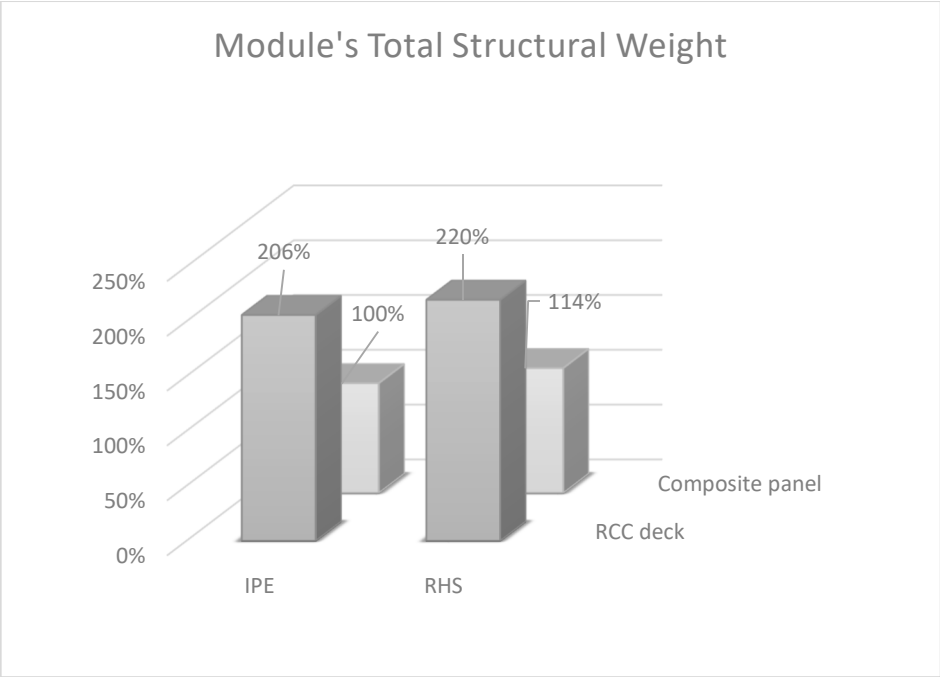


Fig. 3 Total weight/performance ratio

IPE rolled profiles frame also is the most effective solution for reducing total structural weight of the modules, option with regular joists and composite deck (see Fig. 3).

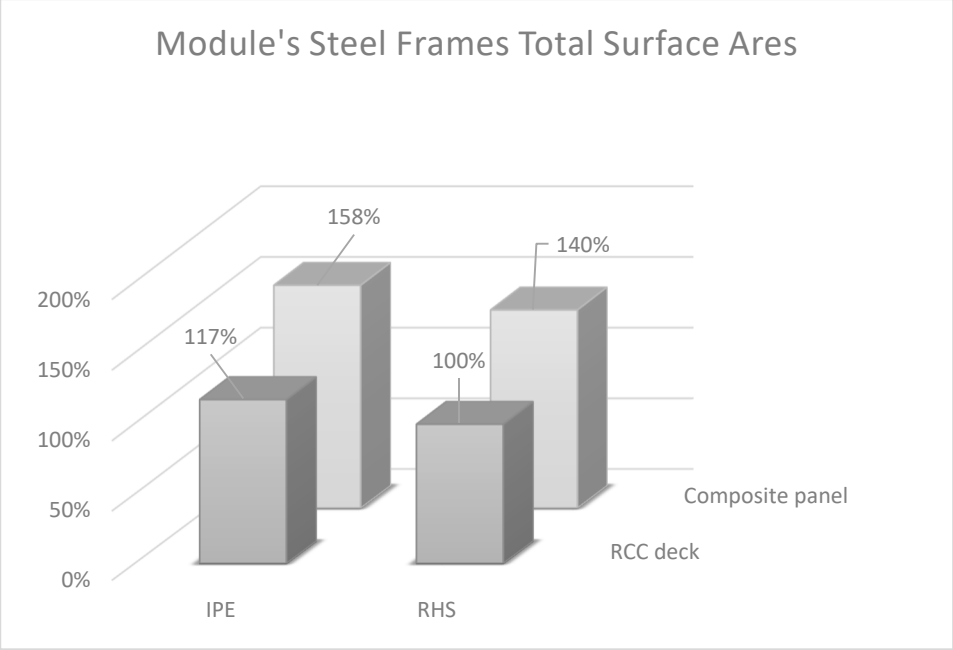


Fig. 4 Total surface/performance ratio

On the contrary, module's steel frame of RHC with reduced number of joists for RCC deck has minimal surface area for the fire protection treatment (see Fig.4)

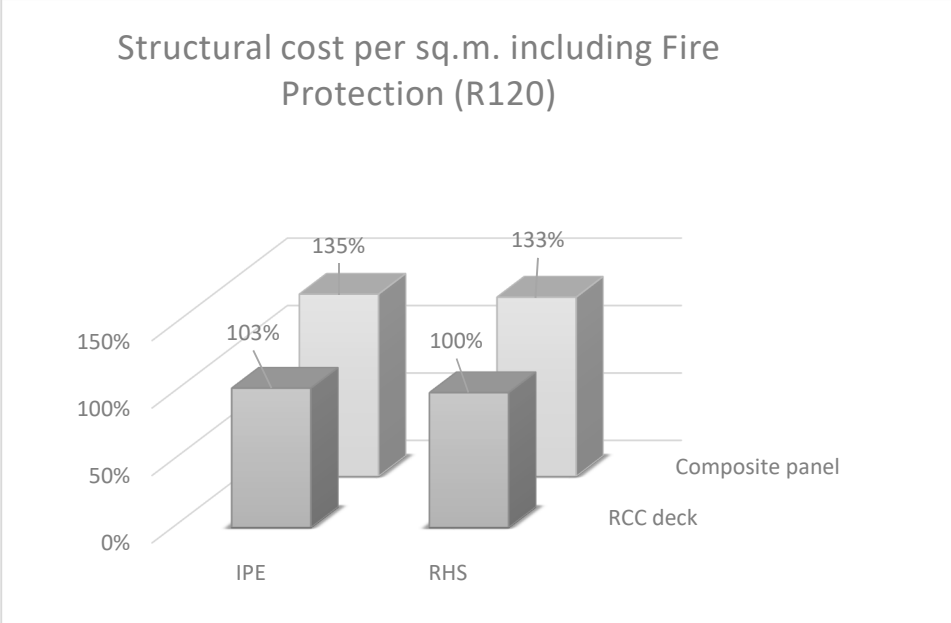


Fig. 5 Structural cost per sq.m. including Fire Protection (R120)

Comparison of structural cost of steel fabrication, RCC and composite panel decks along with fire protection material (intumescent paint) demonstrates that modules with RCC deck either with IPE or RHS frames are more cost effective compare to modules with composite panel deck (see Fig. 5).

Conclusions.

1. The cross-sections of the module frame elements in the form of I-beams are more economically effective in terms of steel consumption per sq.m. of total area, however, the difference in steel consumption and higher RHS costs is practically compensated by the smaller surface area of steel RHS elements for applying intumescent paint (for fire resistance class R120 and more).

2. To ensure the lowest construction weight of the module, it can be recommended to use composite panels instead of RCC decks, unless this is specified by technological or operational requirements.

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