Thermal Analysis of a Structural Solution for Sustainable, Modular and Prefabricated Buildings

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Abstract. In the construction field, the design principles for an efficient and operational use of buildings and a minimal impact on the environment are essential aspects of sustainable development. In this regard, several aspects must be taken into consideration, such as: durability, easy maintenance, flexibility in interior design, and reduced energy consumption. Decreasing energy consumption in buildings during the service life (heating / cooling / drinking water / electricity) can mean lower costs, but also a lower impact on the environment. The paper presents the thermal analysis for a GF+1F height structure, consisting of several identical, adjacent and / or overlapped metallic cubic modules. The spaces inside this cubes ensemble solve the functionality of a family home building. The good carrying capacity, the rapidity of execution, the superior degree of thermal insulation and the minimum losses of material in execution were the main advantages provided by this structural solution. Regarding the thermal comfort for the users of this constructive system, the thermal analysis showed that the internal temperatures are constant and uniform, without cold surfaces or temperature fluctuations. In addition, humidity is controlled and there is no risk of condensation.

1. Introduction

The measures that can be taken to improve energy efficiency in all economy sectors are mainly represented by:

- introducing products and technologies with high energy efficiency;
- promoting the use of renewable energy sources by end-users;
- reducing the environmental impact of industrial activities, and of producing, transporting, distributing and consumption of all forms of used energy;
- applying modern principles of energy management, modern energy control and management systems for monitoring, continued assessment of energy efficiency and energy consumption forecasting;
- granting financial and fiscal incentives, under the law, for investments based on energy efficiency principles;
- developing the market for alternative energy services.

The construction sector accounts for 40% of the total energy consumption in the European Union (EU). Reducing energy consumption in this domain is, therefore, a priority in energy efficiency targets. The buildings’ energy efficiency, governed by two fundamental principles, almost zero energy
consumption (NZEB), and durability (appropriate carrying capacity over the entire service life) implies:

- using renewable energy sources;
- constructing buildings with prefabricated, modular and standardized systems, to meet the quality requirements and achieve a balance between the energy needed to construct a building and the amount of energy saved during its service life;
- protecting the environment both during the construction and use of buildings, and through the use of low-toxicity, recyclable and renewable materials.

The construction sector is closely linked to the energy efficiency field by applying the provisions of the Energy Efficiency Directive 2012/27/EU. The provisions of this Directive require that in the coming years the EU member states to respect the policy of the European Union and thus, by the end of year 2020, to satisfy the proposed targets for reducing conventional energy consumption. According to Directive 2010/31/EU of the European Parliament on buildings energy performance, starting with year 2020, newly built houses in the EU must have almost zero energy consumption (NZEB).

Energy efficiency in constructions is a principle embodied in various forms: energy-independent buildings, passive / active buildings, eco-friendly buildings (eco-buildings) and green buildings. Passive buildings are of current interest; these are buildings with low energy consumption, their passivity being realized by the balance between the energy consumed from general systems and the energy produced by their own systems.

The design of passive constructions is based on the advantages offered by the site, the interior comfort requirements, as well as the superior performance of the existing construction products on the local market, in order to diminish energy consumption. Taking advantage of the site's opportunities, designers can incorporate energy efficient strategies and principles into the structural design, aiming to use renewable energy systems.

Green buildings (also known as green constructions or sustainable buildings) refer to the structural concept and use of processes that are responsible for environmental protection and are resource-efficient throughout the life cycle of a building: from design, construction, operation, maintenance, renovation to demolition.

Modulation creates the premises for buildings’ industrialization. By optimizing the work, modulation opens the way to the widespread use of prefabricated elements and can lead to significant decreases in material consumption. The use of prefabricated elements is one of the most important elements in the constructions’ industrialization process, with positive influences in ensuring quality and meeting sustainability requirements.

The paper presents the thermal analysis of a building with a GF+1F height regime, [1], made of several identical cubic modules, with metallic structure, placed adjacent and / or overlapped. The building was designed to meet the cumulative requirements of the following concept definitions: passive building, green building, modulation- prefabrication and durability. The good carrying capacity, the rapidity of execution, the superior degree of thermal insulation, as well as the minimum material loss on site were the main advantages provided by this structural solution.

2. The constructive solution description
The presented GF+1F building starts with the multiplication of a cubic module, having the bearing structure made of steel profiles with square tubular cross-sections for columns, and with rectangular tubular cross-sections for beams, [1-5].

The cube side is 4.00 m, Figure 1. At least 4 cubic modules are considered necessary to make a functional model for a 3-room apartment, and a supplementary cubic module is required for the staircase. A proposed functional model is illustrated in a three-dimensional representation in figure 2 [1].
The cube’s faces, forming the walls, are made of various hybrid construction products, which, besides ensuring the perimeter closings, incorporate systems for heating and ventilation based on energy from renewable sources existing at the site. In order to stiffen the structure, the floors are made of profiled steel sheets and reinforced concrete, cast in position on the construction site. The roof is of the terrace type, offering multiple possibilities: a green terrace which, by summing up its positive, ecological and economical characteristics, brings a relevant contribution to achieving the future-oriented sustainable architecture principles, or an uncirculated terrace, as a placement location for the energy production equipment from renewable sources.
inserted in the square section profiles, and then all the elements are fastened with bolts, as depicted in Figure 3. Therefore, a semi-rigid joint is created between the foundation, and the column and beams.

**Figure 3.** Joint between foundation – column – beams [1].

At the superstructure, the joints between the columns and beams are realized using a metallic element made of four profiles inserted into the columns and intersecting beams, as shown in Figure 4. All the elements are fastened with bolts. For this joint type, installing hybrid sandwich panels for perimeter closings or internal compartments is easy and fast, Figure 5.

**Figure 4.** Joint between columns – beams [1].

**Figure 5.** Sandwich panels mounting for exterior walls [1].
The mixed-structure slabs are made of reinforced concrete and folded metallic sheets having a double purpose: adding strength and also ensuring the co-operation of the vertical bearing elements under horizontal actions from wind or earthquake, Fig 6.b. The structure of the slab is shown in Figure 6.a.

![Intermediary slab: a. layers, [m]; b. folded metallic sheet detail, [mm].](image)

3. Thermal analysis of the building
The thermal analysis of the building has been carried out in conformity with the 2010 modified form of the Romanian Code C107/2005 “Normative regarding the calculation of thermal properties of building construction elements”, [6, 7]. The thermal performances have been assessed by considering an outside design temperature of \(T_e=-21^\circ C\) and an inside design temperature of \(T_i=20^\circ C\).

3.1. Calculating the normalized global thermal insulation coefficient
The normalized global thermal insulation coefficient, \(G_N\), has been determined by taking into account the number of building levels, \(N\), and the ratio between the envelope area, \(A\), and the building volume, \(V\). Table 1 presents the considered geometrical characteristics of the analysed building.

| Building element                                           | Area      |
|-----------------------------------------------------------|-----------|
| Exterior longitudinal wall 1 (matt part + joinery)        | 179.67 m² |
| Exterior longitudinal wall 2 (matt part + joinery)        | 179.67 m² |
| Exterior transversal wall 1 (matt part + joinery)         | 67.71 m²  |
| Exterior transversal wall 2 (matt part + joinery)         | 67.71 m²  |
| Exterior longitudinal wall 1 (matt part)                  | 162.93 m² |
| Exterior longitudinal wall 2 (matt part)                  | 162.93 m² |
| Exterior transversal wall 1 (matt part)                   | 67.71 m²  |
| Exterior transversal wall 2 (matt part)                   | 67.71 m²  |
| Exterior joinery – corresponding to longitudinal wall 1 (windows + doors) | 16.74 m² |
Taking into account that the building under study comprises of two levels and therefore \( N = 2 \) and \( A/V = 0.63 \), according to the stipulations from Annex 2 of the C107/1-2010 national standard, [6, 7], the \( G_N \) coefficient equals 0.51. In order to fulfill a proper level of global thermal insulation, the following condition must be satisfied, considering \( G \) as the global thermal insulation coefficient:

\[
G \leq G_N \quad \text{[W/m}^2\text{K]}
\]

### 3.2. Evaluating the global thermal insulation coefficient, \( G \)

In this section the following analysis phases have been performed:
- evaluating the unidirectional thermal resistances;
- numerical modelling and analysis of the thermal bridges specific to the considered building;
- determining the corrected specific thermal resistances of the envelope elements.

#### 3.2.1. Determining the unidirectional thermal resistances, \( R \)

In order to evaluate the unidirectional thermal resistances, \( R \), the expression (1) has been used. The resulted values are presented in Table 2.

\[
R = R_I + R_e + \sum_k R_k = \frac{1}{\alpha_i} + \frac{1}{\alpha_e} + \sum_k \frac{\delta_k}{\lambda_k}
\]

where:
- \( \alpha_i \) - convective heat transfer coefficient of the inner surface of the element, [W/m\(^2\)K];
- \( \alpha_e \) - convective heat transfer coefficient of the outer surface of the element, [W/m\(^2\)K];
- \( \delta_k \) - thickness of the layer „k”, [m];
- \( \lambda_k \) - thermal conductivity of the layer „k”, [W/mK].

| Construction element | \( R \) [m\(^2\)K/W] |
|----------------------|----------------------|
| Exterior wall        | 6.25                 |
| Slab on grade        | 7.84                 |
| Roof terrace         | 8.42                 |
3.2.2. Numerical modelling of the thermal bridges and evaluating the linear thermal transfer coefficients, $\Psi$. The RDM 6 software has been used with the goal of analysing the thermal bridges characteristic to the considered construction. During the assessment, 3 vertical and 7 horizontal thermal bridges have been examined, and the resulted values for the linear thermal transfer coefficients, $\Psi$, are presented in Table 3.

Table 3. Linear thermal bridges coefficients.

| No. | Analysed thermal bridge                                                                 | Value of $\Psi$, [W/(m·K)] |
|-----|----------------------------------------------------------------------------------------|-----------------------------|
| 1.  | "outer corner" vertical thermal bridge                                                  | $\Psi_1=\Psi_2=0.03$       |
| 2.  | "exterior and interior walls intersection" (between apartments) vertical thermal bridge | $\Psi_1=0.09$               |
| 3.  | "joinery profile – window lateral sill" vertical thermal bridge                         | $\Psi_1=0.07$               |
| No. | Analysed thermal bridge                                                                 | Value of Ψ, [W/(m·K)] |
|-----|----------------------------------------------------------------------------------------|-----------------------|
| 4.  | “attic” horizontal thermal bridge                                                      | Ψ₁=0.33, Ψ₂=0.21     |
| 5.  | “exterior wall and slab over ground floor intersection” horizontal thermal bridge       | Ψ₁=0.12, Ψ₂=0.19     |
| 6.  | “exterior wall and slab on grade intersection” horizontal thermal bridge               | Ψ₁=0.31, Ψ₂=0.35     |
| No. | Analysed thermal bridge                                                                 | Value of $\Psi$, [W/(m·K)] |
|-----|-----------------------------------------------------------------------------------------|------------------------------|
| 7.  | “interior wall and slab on grade intersection” (between apartments) horizontal thermal bridge | $\Psi = 0.08$                |
| 8.  | “slab on grade and metallic profiles intersection” horizontal thermal bridge              | $\Psi = 0.16$                |
| 9.  | “joinery profile – window lintel” horizontal thermal bridge                               | $\Psi = 0.07$                |
| 10. | “joinery profile – window sill” horizontal thermal bridge                                | $\Psi = 0.07$                |
3.2.3. Evaluating the specific thermal resistances, $R'$. The specific thermal resistances corrected with the value of the envelope elements thermal bridges coefficients are presented in Table 4. The resulted values have been attained by using the expression (2), where $l$ is the length of the thermal bridge, and $U'$ is the thermal transmittance of the element.

$$U' = \frac{1}{R} + \frac{\sum \Psi_i}{A} + \frac{\sum \lambda_i}{A}, \quad R' = \frac{1}{U'}$$  \hspace{1cm} (2)

| Element | Thermal bridge | $\Psi$ [W/mK] | $l$ [m] | $\Psi \cdot l$ [W/K] | $R$ [m$^2$K/W] | $U'$ [W/m$^2$K] | $R'$ [m$^2$K/W] |
|---------|----------------|---------------|--------|---------------------|---------------|----------------|---------------|
| Outer corner | 0.03 | 16 | 0.48 |
| Exterior and interior walls intersection | 0.09 | 16 | 1.44 |
| Joinery profile – window lateral sill | 0.07 | 14.40 | 1.01 |
| Attic | 0.33 | 20.72 | 6.84 |
| Exterior wall and slab over ground floor intersection | 0.12 | 20.72 | 2.49 |
| Exterior wall and slab on grade intersection | 0.19 | 20.72 | 3.94 |
| Joinery profile – window lintel | 0.31 | 20.72 | 6.42 |
| Joinery profile – window sill | 0.07 | 7.90 | 0.55 |
| Longitudinal wall 1 – total | A = 162.93 | 23.72 | 6.25 | 0.31 | 3.23 |
| Outer corner | 0.03 | 16 | 0.48 |
| Exterior and interior walls intersection | 0.09 | 16 | 1.44 |
| Joinery profile – window lateral sill | 0.07 | 14.40 | 1.01 |
| Attic | 0.33 | 20.72 | 6.84 |
| Exterior wall and slab over ground floor intersection | 0.12 | 20.72 | 2.49 |
| Exterior wall and slab on grade intersection | 0.19 | 20.72 | 3.94 |
| Joinery profile – window lintel | 0.31 | 20.72 | 6.42 |
| Joinery profile – window sill | 0.07 | 7.90 | 0.55 |
| Longitudinal wall 2 – total | A = 162.93 | 23.72 | 6.25 | 0.31 | 3.23 |
| Outer corner | 0.03 | 16 | 0.48 |
| Exterior and interior walls intersection | 0.09 | 16 | 1.44 |
| Joinery profile – window lateral sill | 0.07 | 14.40 | 1.01 |
| Attic | 0.33 | 7.81 | 2.58 |
| Exterior wall and slab | 0.12 | 7.81 | 0.94 |

Table 4. Values of the specific thermal resistance.
### Table 5

| Element | Thermal bridge | \( \Psi \) [W/mK] | \( I \) [m] | \( \Psi \cdot I \) [W/K] | \( R \) [m²K/W] | \( U' \) [W/m²K] | \( R' \) [m²K/W] |
|---------|----------------|-----------------|---------|----------------|----------------|----------------|----------------|
| over ground floor intersection | 0.19 | 7.81 | 1.48 |
| Exterior wall and slab on grade intersection | 0.31 | 7.81 | 2.42 |
| Transversal wall 1 – total | | | | | | | |
| Outer corner | 0.03 | 16 | 0.48 |
| Attic | 0.33 | 7.81 | 2.58 |
| Transversal wall 2 | | | | | | | |
| Exterior wall and slab over ground floor intersection | 0.12 | 7.81 | 0.94 |
| Exterior wall and slab on grade intersection | 0.19 | 7.81 | 1.48 |
| Transversal wall 2 – total | | | | | | | |
| Attic | 0.21 | 57.07 | 11.98 |
| Roof terrace – total | | | | | | | |
| Roof terrace | Attic | 0.21 | 57.07 | 11.98 |
| Slab on grade | | | | | | | |
| Exterior wall and slab on grade intersection | 0.35 | 57.06 | 19.97 |
| Interior wall and slab on grade intersection | 0.08 | 24 | 1.92 |
| Slab on grade and metallic profiles intersection | 0.16 | 40 | 6.40 |
| Slab on grade – total | | | | | | | |
| | | | | | | | |

### 3.2.4. Evaluating the overall effective thermal insulation coefficient, \( G \).

Table 5 presents the values of the global thermal insulation coefficient, \( G \), that was determined by using the expression (3).

\[
G = \frac{\sum \left( \frac{A_j \tau_i}{R'_j} \right)}{\nu} + 0.34 n = \frac{\sum \left( \frac{A_j \tau_i}{R'_j} \right)}{\nu} + 0.34 n
\]

where:
- \( t_i \) - conventional inside design temperature [°C],
- \( t_e \) - conventional outside design temperature [°C],
- \( t_j \) - temperature at the outer side of the envelope [°C], which can be the outside design temperature or the temperature from the unheated spaces/rooms that are placed outside the building envelope;
- \( \tau \) - exterior temperatures correction factor;
- \( A_j \) - the area of the building element “j” [m²], having the specific thermal resistance \( R' \);
- \( n \) - ventilation rate [h⁻¹];
- 0.34 - the ratio between the mass caloric capacity and the apparent density of air.
### Table 5. The global thermal insulation coefficient.

| Building element               | A  | \(U'\) | \(R'\) | \(\tau\) | \(\frac{A \cdot \tau}{R'}\) |
|-------------------------------|----|--------|--------|--------|-----------------|
| Exterior longitudinal wall 1  | 162.93 | 0.31  | 3.23  | 1     | 50.44          |
| Exterior longitudinal wall 2  | 162.93 | 0.31  | 3.23  | 1     | 50.44          |
| Exterior transversal wall 1   | 67.71  | 0.27  | 3.70  | 1     | 18.30          |
| Exterior transversal wall 2   | 67.71  | 0.27  | 3.70  | 1     | 18.30          |
| Exterior joinery L1           | 16.74  | 1.30  | 0.77  | 1     | 21.74          |
| Exterior joinery L2           | 16.74  | 1.30  | 0.77  | 1     | 21.74          |
| Exterior joinery T1           | 0     | 1.30  | 0     | 1     | 0              |
| Exterior joinery T2           | 0     | 1.30  | 0     | 1     | 0              |
| Roof terrace                 | 161.85 | 0.19  | 5.26  | 1     | 30.76          |
| Slab on grade                | 161.85 | 0.21  | 4.76  | 0.50  | 17             |

Heated volume \(V = 1294.77\,[m^3]\)

\[\sum \frac{A \cdot \tau}{R'} = 228.72\]

\[G = 0.35\,[W/(m^3 \cdot K)]\]

\[G = 0.35 < G_N = 0.51\]

### 4. Conclusions

Structural steel can be regarded as an innovative construction material. In the last years, in the current context of global sustainable development, the steel manufacturing industry has made tremendous progress towards minimizing the environmental impact of their products. Due to the high mechanical proprieties and the development of a large number of structural elements’ forms, steel represents one of the most common material choices for resolving different civil engineering issues. Generally, structural steel is used for constructing long span bridges and skyscrapers, but nowadays, this material is used more and more to assemble various residential buildings.

The article presents an analysis of a structure which satisfies the following general requests: a good load carrying capacity, rapid assembly on the construction site, and an adequate management of natural resources consumption in the pre-operation stage. All the above mentioned can constitute decisive facts for future users, but one of the most important is represented by the thermal behaviour of the building, and it is this particular detail that is put under evaluation in this analysis.

The considered steel construction can be regarded as an advanced and innovative one, offering a high level of structural modularity and mobility. The study has shown that the proposed solution offers a high level of thermal resistance. Analysing the numerical modelling and the undertaken evaluations, we can conclude that the construction global thermal insulation coefficient is considerably lower than the one imposed by the Romanian national standard. This fact has direct influence over the level of the energy consumed in order to satisfy a proper level of indoor climate conditions. Taking into account that the Romanian construction sector uses an impressive amount of energy obtained from non-
renewable resources, minimizing consumption levels will have an important positive effect over the environment.

The good carrying capacity, the rapidity of execution, the superior degree of thermal insulation, as well as the minimum material loss on site are the main advantages of this structural solution, and beside this fact, they demonstrate that the proposed solution might be included in the list of solutions efficient energetic and of protective environmentally.

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Acknowledgements
This paper was realized in the framework of the project EFECON – ECO-INNOVATIVE PRODUCTS AND TECHNOLOGIES FOR ENERGY EFFICIENCY IN CONSTRUCTION, POC/71/1/4 - Knowledge Transfer Partnership, Cod MySMIS: 105524, ID: P_40_295, Project co-financed by the European Regional Development Fund.

Furthermore, the authors acknowledge the contribution and thank SC NEXT STUDIO SRL which provided insight that greatly assisted the research.