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Use of structural steel in residential construction

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Subject review

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Although structural steel for industrial use is successfully proven in the market of Southern and Southeastern Europe, examples of its use in residential construction are rare. A strong tradition of masonry and reinforced concrete construction still limits the use of materials like steel, despite examples of good practice in countries like Japan and USA. By reviewing the advantages and disadvantages and presenting the solutions to these disadvantages, especially in accordance with the three basic steel structure framing systems, it is clear that structural steel is a competitive and often rational choice for residential construction. The example of housing unit (villa) structural analysis illustrates the advantages and possibilities to reduce the disadvantages of the structural steel use, and thus clearly shows the possibilities of its use.

Key words:
steel, prefabricated construction, house, earthquake, fire, energy efficiency

Pregledni rad

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Primjena čeličnih konstrukcija u stambenoj izgradnji

Iako se čelik kao konstrukcijski materijal za industriju uspješno dokazuje i na tržištu južne i jugoistočne Europe, primjeri primjene u stambenoj gradnji su rijetki. Jaka tradicija gradnje ziđem i armiranim betonom još uvijek ograničava primjenu materijala poput čelika, unatoč primjerima dobre prakse iz zemalja poput Japana i SAD-a. Revizijom prednosti i nedostataka te prikazom rješenja tih nedostataka, posebno u skladu s tri osnovna sustava gradnje čelikom, može se uvidjeti da je to konkurentan i često racionalan izbor i za stambenu gradnju. Primjer proračuna stambene jedinice (vile) ilustrira prednosti i načine umanjenja nedostataka primjene čelika te na taj način zorno prikazuje mogućnosti njegove uporabe.

Ključne riječi:
čelik, montažna gradnja, kuća, potres, požar, energetska učinkovitost

1. Introduction

Application of steel structures in residential construction is characteristic of technologically more developed countries, while their share in residential construction in the area of southern and southeastern Europe is negligible. In addition to the technological prerequisite, the reasons for this situation should be sought in the strong traditional habits of our lands, where masonry and reinforced concrete structures still widely dominate, with only a slightly smaller share of wooden structures, present only in specific areas (where such construction is traditionally the most common one).

The use of steel in residential construction comes from the United States, and it boomed after World War II when metallurgical companies gained significant experience in steel works for war purposes. In USA, steel first began to be used in situations where other materials were not sufficient (for example, for structures of tall buildings), while the primary material for the construction of houses was always wood (which, in fact has not changed until today). Increased use of steel was also supported by changes in the prices of wood on the market, and typical beginnings are related to houses that are conceptually built according to the rules for wooden structures where wooden bearing elements were replaced by thin cold-formed profiles (Figure 1). In 1994, the U.S. *Department of Housing and Urban Development* presented illustration projects of steel houses to promote the use of steel in residential construction [1], which helped to further increase the application of steel in the sector.

Figure 1. House with a steel structure [2]

Another technologically developed country, on the opposite side of the Pacific Ocean, Japan, began with the process of introducing steel structures into residential construction after a devastating earthquake in Kobe in 1995 [3], as is clearly visible in the diagram of Figure 2.

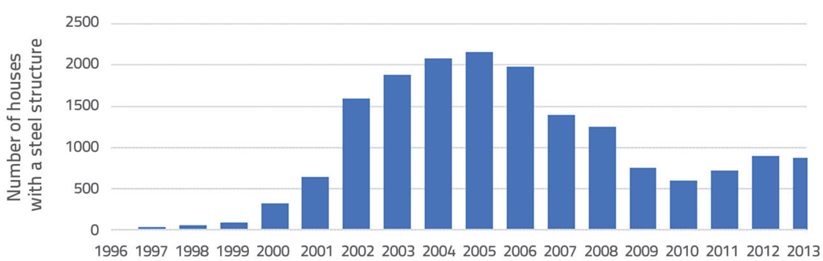


Figure 2. The number of houses with a steel structure in Japan in the period from 1996 to 2013 [3, 4]

At that time, about 50,000 temporary houses had to be built, of which 3,000 were imported from other countries, and which all had a steel structure. Given that such solutions proved to be very effective, this prompted the Japanese to start producing similar structures. A sharp jump in the number of steel houses in Japan occurred in 2001, when the application of the so-called Kozai Club construction method, which relied on steel structures, became popular. Kozai Club is an association of designers and manufacturers of steel structures who have worked on the development of the application of thin-walled cold-formed steel profiles for the construction of smaller family houses. This method of construction is the first to apply thin-walled cold-formed elements, not only as secondary elements, but also as primary elements of the load-bearing system (poles, beams and grids) [5]. Although there has been a decline in the number of houses built like this after 2005, the reason is not a decline in the popularity of this type of construction, but the general state of the market caused by the recession.

Japan remains one of the leading countries in terms of the percentage of steel used in the construction of family houses, as shown in Figure 3, which refers to data from 2005. Due to the advantages of using steel in cold environments, Sweden also has a large number of houses made of steel [6].

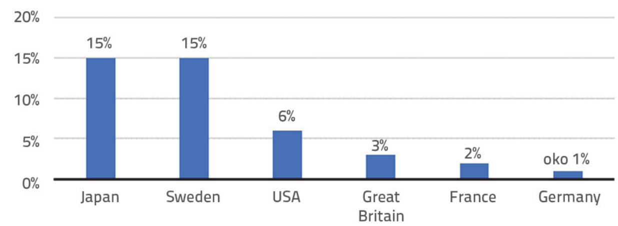


Figure 3. Percentage of detached steel houses in developed countries in 2005 [6]

It is evident from just a few examples that steel structures are generally not the first choice when it comes to residential construction, but they certainly have a number of advantages that in certain situations fully justify their application. This is especially true when it comes to better resistance to the effects of earthquakes [7], lesser weight of the structural part, great freedom in shaping and in cases where there is a pronounced possibility of adaptation and reconstruction. In this study, various methods of construction of residential buildings with steel structure will be commented on, and a concrete example of a residential building - villa will be examined to show the advantages of such a solution.

2. Advantages of the use of steel in residential construction

By analyzing the aforementioned experiences from Japan, the USA and the EU, it can be noted that housing concepts with a load-bearing steel structure provide designers (architects and builders), and end users, with almost unlimited possibilities

Figure 4. Architectural design solution of an open space with steel supports [8]

Table 1. Basic advantages of the use of steel in residential construction

Construction	• quick execution without the need for technological breaks (e.g., waiting for concrete to harden); • homogeneous and persistent material, which makes the properties of the material easier to control and assess; • catalog selection of structural elements and means of connection and preparation in workshops – they enable acceleration of the performance of steel by 30% compared to classical construction methods [11]; • easier preparation of the construction site with less waste material on the construction site.
Use	• favorable ratio of resilience and weight represents a benefit when it comes to inertial actions, which provides residents with a feeling of increased safety and comfort of staying in such space; • high functionality and utilization of space (floor plan without "obstacles"); • fast moving into the building given the high speed of construction, but also the existence of a wide selection of "ready-made" prefabricated houses (as well as wooden structures) that can be very easily adapted to the user's requirements and quickly delivered.
Environment	• steel can be 100% recycled without losing its properties, and the estimated total recycling rate of structural steel in the world is around 85 % [11]; • nowadays, steel uses a third less energy than it did two decades ago [12]. • almost all water used during steel production passes through the recycling and cleaning process, while combustion gases are purified and reused [12].
Subsequent interventions	• due to the method of construction (workshops) and execution (installation on the construction site) of steel structural elements, it is relatively easy to reinforce them, insert new elements (expand the building floor plan and the height) and do other changes related to purposes of use; • complete removal of steel structures is much simpler than the removal of structures made of concrete and masonry, and in a large number of cases the structure or its parts can be used in another location.
Seismic resistance	• high strength, rigidity and ductility, in combination with a small mass make steel an ideal material for the most demanding and active seismic zones; • due to these properties, an extraordinary load from an earthquake is often not a critical case of load for the dimensioning of lower and simpler buildings, such as typical residential buildings – family houses and villas; • in the most demanding cases, it is possible to use various structural measures of passive earthquake protection in such a way that the certain parts of the structure are deliberately exposed to the earthquake with the aim of consuming earthquake energy and localizing damage.

in functional and aesthetic design, safety in use and rationality of the entire project. The already mentioned much greater freedom in shaping the interior space compared to other materials is certainly important to architects (Figure 4), and on the other hand, constructors can rationally take advantage of the high load-bearing capacity and ductility of steel structures with significantly lesser weight compared to traditional massive construction. These properties are especially important in the case of earthquake-active zones, in cases of increased risk of uneven foundation subsidence and with similar phenomena.

Visoka toplinska vodljivost čelika (λ = The basic advantages of steel structures from different points of view can be reduced to five basic categories (Table 1): construction, use, environment, subsequent interventions and seismic resistance. When it comes to shortcomings, there are three often-cited reasons for non-use, i.e., increased thermal conductivity, propensity to corrosion, and reduced fire resistance.

High thermal conductivity of steel (λ = 45 - 50 W/mK) compared to other building materials, especially compared to insulation materials such as plasterboard (λ = 0.16 W/mK) and mineral wool (λ = 0.03 W/mK) [9], poses a danger because at the point where there is discontinuity in thermal insulation, the so-called thermal bridges occur, i.e., local heat losses, which creates condensation and mold. Thermal bridges can be prevented by designing details such as thermal interruptions or by using alternative materials [9], but they can also be avoided by completely placing the steel structure inside the insulated envelope and locally insulating all steel elements that pass through the envelope. Figure 5 shows an example of the solution of the details of the joint of the steel column and the beam with properly installed thermal and sound insulation. It should be noted that the lining of the column with concrete is interrupted at the place where the horizontal plasterboard comes in.

Corrosion is a process of metal degradation that occurs on the surface by electrochemical interaction with the environment. Nowadays, there are very effective anti-corrosion measures so that this shortcoming of steel structures can be easily solved, both with active and subsequent anti-corrosive measures.

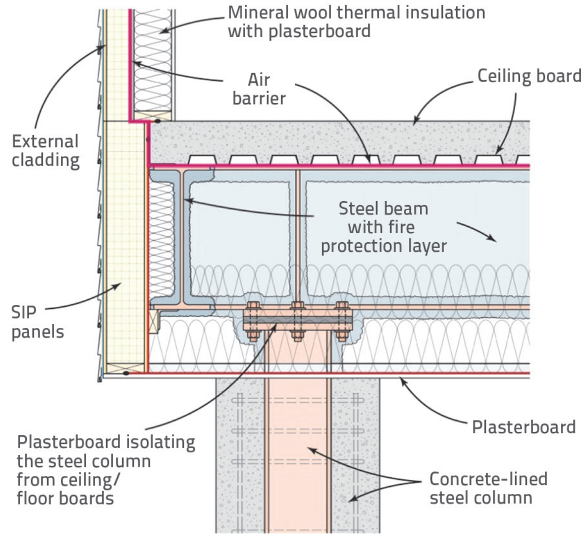


Figure 5. Example of properly installed thermal and sound insulation of steel structure according to [13]

Active measures are taken during design – selection of steel type, structural design, impact on environmental aggressiveness, treatment of contact surfaces between different metals, maintenance intervals, etc. Subsequent measures relate to the protection of steel surfaces from the environment by using coatings, sprays or jackets (and combinations thereof), either with the purpose of isolating the metal surface from the environment or acting as an anode (or both). In doing so, it is considered that low durability is up to 5 years, and high more than 15 years.
Fires that occur in family homes are not enough to melt steel, but they are able to weaken the load-bearing elements of the building. Therefore, steel elements without fire protection are often used in buildings from one to three floors, where the evacuation exit in case of fire is quick and simple and there is a low probability of collapse of the building until the moment of evacuation [14]. Such flooring is also the most common for residential construction in family houses, and if the buildings have several floors, it is generally necessary to design and perform fire protection, which can be divided into four main groups (Figure 6) [14]:

1. fire boards
2. fire mortars
3. fire coatings
4. concrete lining.

3. Combinations with other building materials

The choice of primary building material significantly affects the rationality of the entire project. It is conditioned by a number of factors related to structural, technological, economic, aesthetic and other requirements relevant to the specific project. It is necessary to be aware of the fact that each material has its advantages and disadvantages, and therefore it is logical to conclude that combining more materials increases rationality, and often has a favorable effect on the other mentioned requirements on the structure and the building as a whole. In this sense, steel is very suitable for combining with other materials, since it is actually impossible to avoid it even when it is not a steel structure (reinforcement of concrete and cables in prestressed concrete, mechanical connecting agents, bearings and connecting sheets in wooden structures, etc.). From an aesthetic point of view, architects often combine it with other materials to ensure the combination of traditional and modern construction.
Wooden construction is technologically similar to steel construction, especially in the case of laminated structures, and the use of wood is especially justified in roof structures. Figure 7 shows an example of combining a steel and wooden structure on a family house, in which the steel frame system plays the role of the primary structure, while the secondary parts of the structure are wooden. Such a combination allows a large adaptation of the space in a functional sense, with a more comfortable feeling of living. It should be noted that the steel frame structure can be mounted in a single day [16]. By applying a facade system made of materials that are or resemble traditional materials, it is impossible to conclude from the outside that it is a building with a steel structure.
Concrete and steel buildings are executed in a technologically completely different way (in the case of monolithic concrete), but the combination of steel and concrete in a unique construction concept (so-called composite steel and concrete structures) provides rational solutions. In this sense, it is not only about economic indicators, but due to the advantage of both materials in a unique construction, better structural properties are obtained – concrete perfectly tolerates pressure and is more resistant to

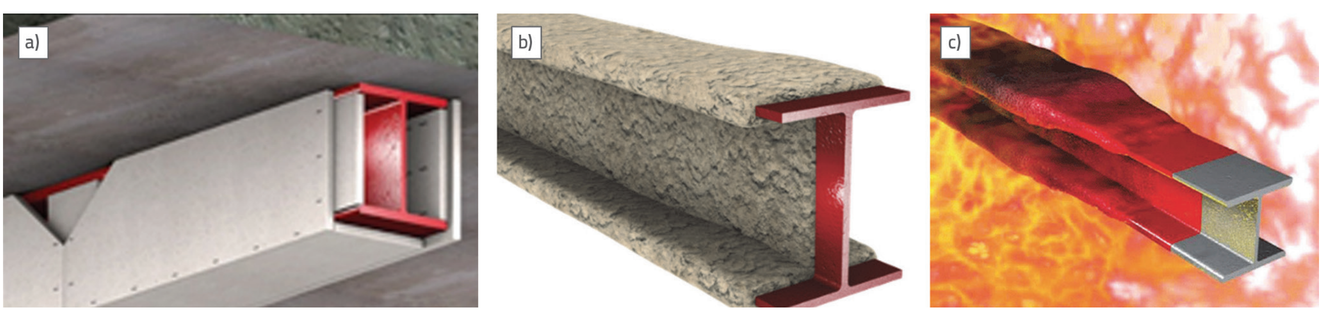


Figure 6 Basic methods of steel fire protection [15]: a) panel coating, b) fire mortar, c) fire coating

Figure 7. Family house built in a combination of steel and wood [16]

Figure 8. Family house made in a combination of steel and concrete [17]

fire and corrosion, while steel is excellent for tensile stresses and has extraordinary ductility. The result is the possibility of bridging larger spans in coupled beams, thinner inter-floor coupled panels and leaner coupled columns, and the construction is faster and more adaptable compared to commonly used reinforced concrete structures. In the case of family houses, coupled inter-floor slabs are especially interesting, due to a number of their advantages - speed and ease of execution, steel profiled sheet serves as a lost formwork, represents a safe working platform, and also serves to stabilize (i.e., for lateral holding) the steel profile to lateral-torsion buckling at the time of concreting and hardening of concrete. Figure 8 shows an example of a family house made in a combination of concrete and steel.

4. Residential construction

The basic advantages of steel in the context of residential construction have already been mentioned, but it should be further emphasized that the justification of the use of steel in this context should be observed through all phases of implementation – the design, the availability of contractors and skilled labor, the rationality of solutions in terms of set goals and comparative advantages with alternative solutions, the construction of the building and its maintenance in the period of use envisaged by the budget. In doing so, it should be taken into account that in addition to the steel structure, other materials, such as concrete, wall elements and wood, are also often used for the construction of residential buildings.
Depending on the chosen concept and load-bearing system, steel load-bearing and partition elements can be made of standard hot-formed and thin-shaped cold-formed profiles, and when building modern family houses, it is possible to identify three construction systems, different in terms of the level of prefabrication and the type of load-bearing structure [18]: lightweight panel; frame; modular construction systems.

4.1. Lightweight panel construction system

The basic feature of a lightweight panel construction system is the use of thin-walled cold-formed profiles, most often of the forms U, K, C and Z, with a wall thickness of 0.6 to 2.5 mm. The advantage of this method is very fast construction of the building, and it is possible to achieve spans of 6 m and the height of rooms of 4 m. This advantage of this method of construction has encouraged its application in developed countries such as Japan, Canada and the USA, thus becoming a direct competitor to prefabricated wooden houses. The basic disadvantage of this system is that individual profiles are usually not able to transfer loads independently, and two or more profiles connect with each other and only then form a load-bearing panel. Therefore, the performance is more sensitive to imperfections related to dimensions, and in budgetary terms, it is much more complex to prove sufficient resilience [6]. Figure 9 shows the load-bearing structure of an urban villa in which the load-bearing walls are formed from interconnected thin-walled cold-formed profiles, i.e., load-bearing panels.

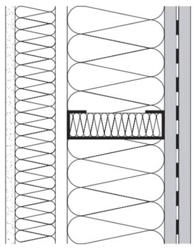
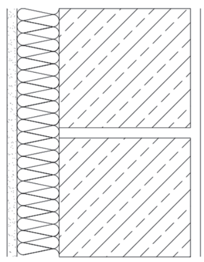
Figure 9. Construction of an urban villa with a lightweight panel construction system [19]

In a lightweight panel construction system, two basic variants of the system are distinguished, but their combinations are also possible (Figure 10):

- lightweight panel system with continuous walls (*balloon framing)*
- lightweight panel system with embedded walls *(platform framing)*.

With a lightweight panel system with continuous walls, the ceilings are directly connected to the front or side of the columns, which means that the columns in the walls are made continuously throughout the height. Ceiling beams rely on columns and thus close the space. This method of construction is more appropriate for multi-storey structures and for

Table 2. Comparison of the properties of the massive and lightweight construction of the external wall [6]

Construction of the external wall	Layer structure	Thickness	U-value	Sound attenuation coefficient
	**Steel structure** Outer sheath Insulation board Cement board Steel element and mineral wool Plasterboard and vapour barrier Plasterboard and emulsion paint	23.0 cm	0.25	51 dB
	**Wall with insulation** Outer sheath Mineral wool Block Mortar	34.5 cm	0.35	48 dB

locations with stronger winds due to very good air tightness [6]. Furthermore, this method of performance saves on the amount of necessary material for horizontal joining of elements, but this makes the performance a bit more complex.

In the case of a lightweight panel system with inserted walls, separate wall panels are installed on each floor and attached to inter-floor structures, so this construction system is more suitable and common for lower buildings. Wall panels are used not only to take over the vertical load, but also to stiffen the building for the effect of horizontal load (they also act as shear walls). Therefore, the panels must be adequately anchored to the inter-storey structure in order to enable the transmission of both tensile and shear forces [6]. The advantage in relation to the previous system is the use of the mounted inter-floor structure as a working platform for the construction of the next floor.

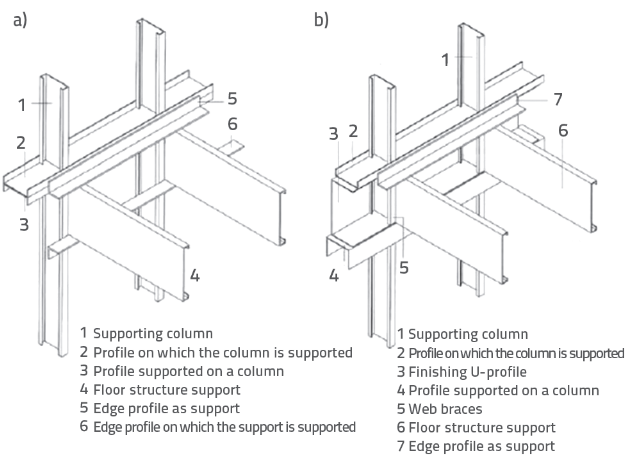


Figure 10. Variants of lightweight panel construction system [6]: a) Continuous walls, b) Inserted walls

It should be emphasized that it is also possible to apply combinations of these variants with the addition of hot-formed profiles in order to achieve greater ranges and stiffer connection of inter-storey wall panels. The use of lightweight panel systems results in significant savings in relation to massive construction with masonry and concrete, and the useful area of the building increases due to significantly less wall thickness (e.g., on a net area of 120 m^2, this increase in area can be from 5 to 10 % [6]). Furthermore, panel structures have better thermal and sound properties compared to traditional monolithic construction (Table 2).

Figure 11 shows the characteristic parts and elements of a typical house that is designed according to a lightweight panel construction system with only thinned cold-formed elements.

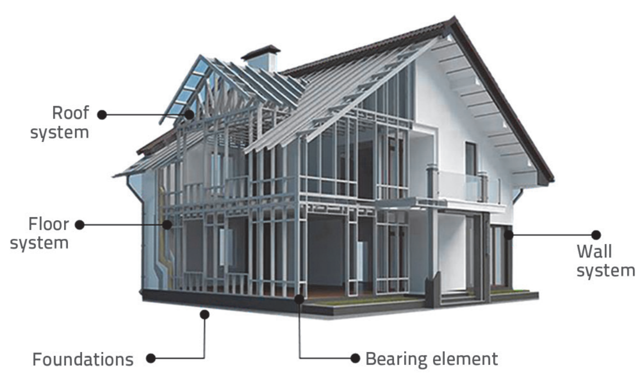


Figure 11. House with a lightweight panel construction system according to [20]

4.2. Framework construction system

This construction system is generally most applicable in steel structures of buildings, where hot-formed profiles are used

Figure12. Examples of frame construction of family houses, a) Simple, repetitive frames [21], b) Costa Rica – urban steel villa [22]

as supporting elements. A great advantage is the existence of standardized elements that can be used for all structural elements (Figure 12a). Given that such structural systems are well known in steel, but also in frames made of other materials, their properties do not need to be specifically explained. In this regard, it should only be noted that the behavior of such systems largely depends on whether there are special systems for stiffening structures for horizontal loads (e.g., couplings, shear walls, cores) or whether horizontal loads are taken over by means of framework action (when the method of execution of connections between connected elements is extremely important).

Typical ranges of frame systems are usually 6 to 9 meters or more, and the frames can also be placed in two vertical directions to ensure global stability and allow the correct takeover of horizontal forces without special stiffening. That is why this concept of construction provides architects and users of the building with complete freedom of interior design and great possibilities when defining the external appearance of the building. From an architectural point of view, these systems are the best solution because internal and external walls do not have to be, and most often are not, load-bearing. The internal walls of such systems are mostly executed as partition walls made of plasterboard or porous concrete. When choosing materials for exterior facades, in addition to the materials listed for interior walls, glass walls are often used to achieve a large source of natural light and an attractive aesthetic appearance (Figure 12b). The speed of execution of such structures is significantly higher than in the case of classical monolithic construction, which can be further accelerated by the use of stacked plates on trapezoidal sheets as inter-storey structures.

4.3. Modular construction system

Modular systems combine lightweight panel and frame systems, while retaining the best performance of these systems. Thus, from the concept with load-bearing frames (smaller) hot-formed profiles are used as a load-bearing structure by which the modules stabilize each other, while, following the example of lightweight panel systems, panels with thin-shaped cold-formed elements for partition elements are used in the modules. Such systems are very precisely crafted in workshops and therefore have a very high degree of prefabrication, and in addition to the construction itself, they also include the construction of partitions and the positioning of installations within the module. An example may be the *Legal & General* factory, which is the largest residential module manufacturing plant in the world. The factory is located in the UK and extends over an area of 51,000 m^2. In full operation it can produce around 2000 modular houses per year, and most of the manufactured houses are two- and three-bedroom houses with net areas of 80 to 120 m^2.

Module sizes mostly depend on the mode of transport, accessibility to the place of construction and the available space for the accommodation of the module. Due to transport requirements and economizing, the maximum width of the module is 3.5 m, and the maximum length is up to 16 m. Such structures are generally oversized compared to more common structures, but due to transport and assembly, some modules should be provided with greater rigidity and stability [23] (Figure 13).

Figure 13. Positioning the steel module of the house [24]

In this regard, it should be emphasized that the global stability of the building must also be ensured, viewed as a set of modules, so as not to allow the relative movement of individual modules during horizontal actions. The floor structure in the horizontal plane serves to stiffen the module, and in the vertical planes the necessary stiffening should be ensured by placing joints (typically

K or X joints), i.e., stiffening is achieved with rigid frames or vertical walls.

In addition to being fully portable, such structures leave great possibilities for adapting and upgrading existing buildings. As a basic disadvantage, the price of transport and assembly, which is somewhat more complex than in the case of standard steel structures, can be highlighted.

5. Example of a family house (villa) with a steel structure

5.1. General information

In order to explain the use of steel in real residential construction, an example was made that includes the characteristic aspects of the design and calculation of a family house – a three-storey villa, with axial floor plan dimensions of 20.6 x 12.4 m and a total height of 9.3 m, located in Zagreb. The ground floor is 3.18 m high, while the remaining two floors are 3.06 m high. On the first and second floor, part of the surface is constructed as a flat roof (i.e., terrace), and the ceiling of the second floor is divided into a passable flat part in a slope of 27° and a non-flat roof. One room of the house with axis floor dimensions of 6 x 12.06 m is designed as a gallery with a sloping glass roof.

All load-bearing elements of the structure are made of S 275 quality steel, and the reinforced concrete slab was designed to be made from C25/30 grade concrete. HEB profiles were used for columns, and IPE profiles for main and secondary beams and the staircase construction. All connections between the beams and columns, as well as the columns and the foundation structure, are designed as rigid, and the joint of the inter-storey secondary and main beams are envisaged in the project design as hinged. The static system of the structure is a frame-unsupported structure with a foam concrete filling, which is assumed to be separated from the steel structure by appropriate structural measures. This means that a model of a clean steel frame structure was used in the calculation, but it should be noted that it is also generally

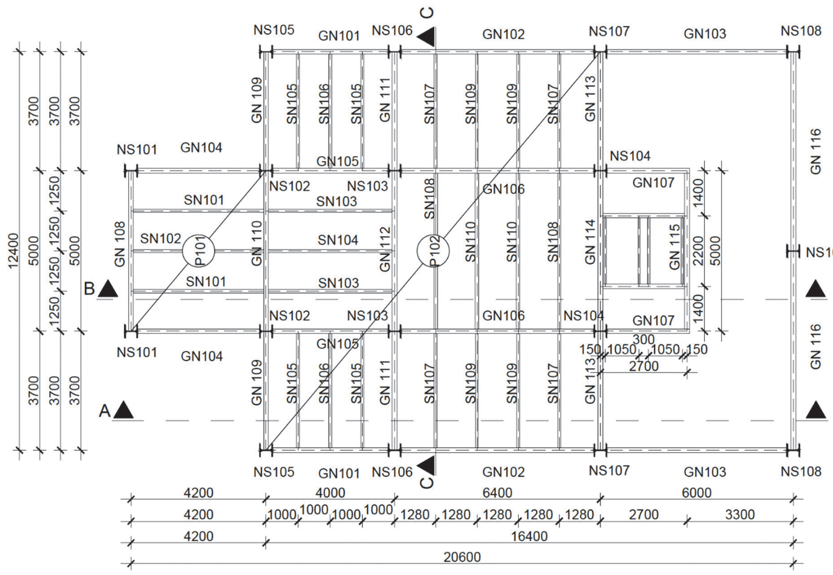


Figure 14. Floor plan and plan of ground floor positions

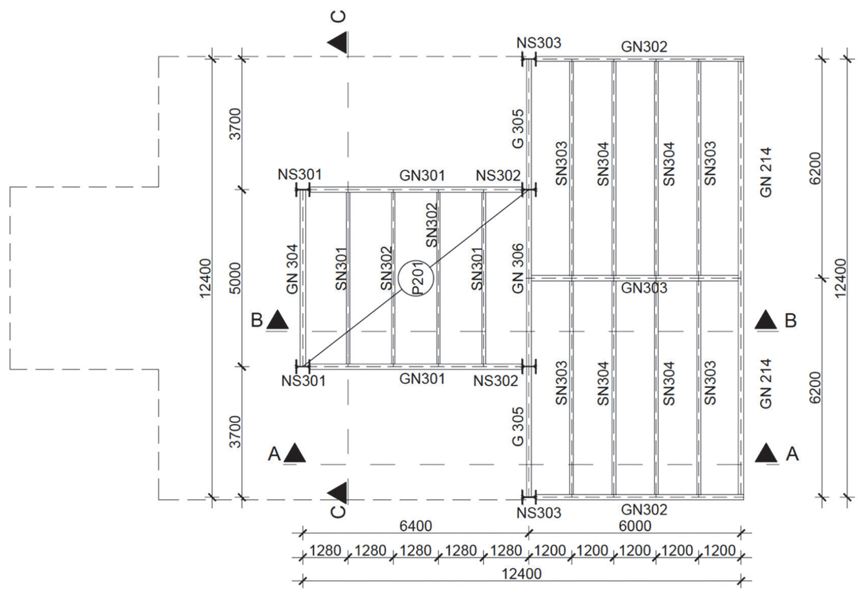


Figure 15. Floor plan and plan of positions of the 3rd floor

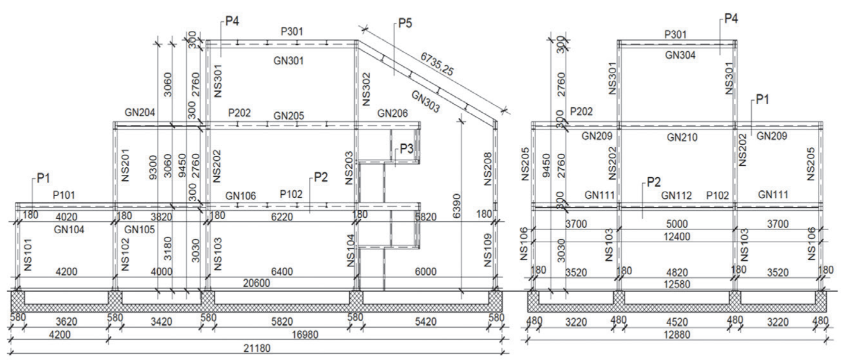


Figure 16. Cross-sections B-B and C-C

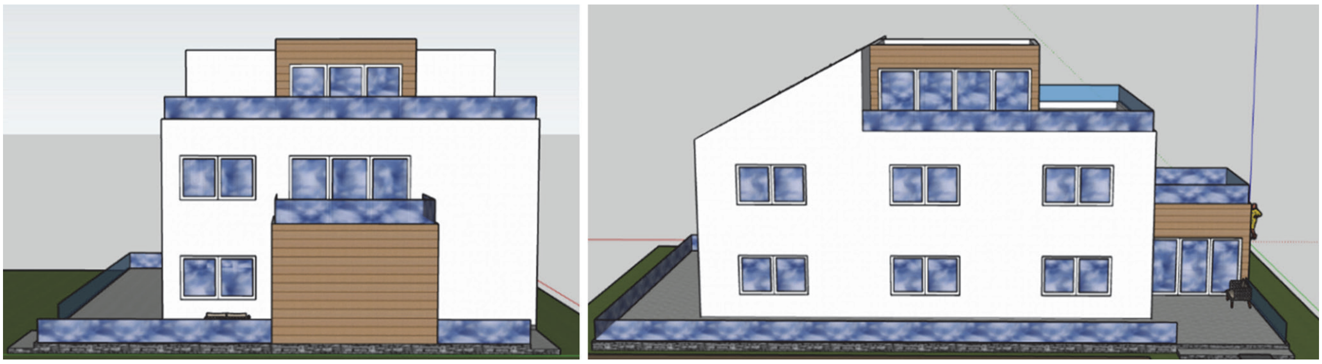


Figure 17. North and East facade of the house

possible to take into account the interaction of steel frames with the fill which significantly increases the horizontal stiffness of the building [25, 26]. The inter-storey structure is designed as a reinforced concrete slab, 15 cm thick, laid over the steel grillage structure of the main and secondary beams. Characteristic graphic substrates for design are presented in Figures 14-17.

5.2. Structural load analysis

When analyzing the load for the said structure, its dead weight, which consists of layers and the elements of the inter-floor structure (P2), the flat roof (P1), the non-flat roof (P4), the staircase (P3), the sloping glass roof (P5) and the terrace fence (O1), was taken into account. In addition to the dead weight, usable loads were adopted by purpose - categories A for P1, P2 and P3 and as H for surfaces P4 and P5, in accordance with HRN EN 1991-1-1 [27]. The snow was adopted for the area of Zagreb, as well as the wind, along with the category of terrain III and in accordance with the HRN EN 1991-1-3 and HRN EN 1993-1-4 standards [28, 29]. For earthquakes, according to [30] class of foundation soil B, spectrum type 1, comparative acceleration in soil 0.25 g, building importance factor 1.0 and behavior factor 4.0 were adopted. The calculation of the structure for the fire performance was carried out assuming a fire load according to the standard fire curve (which represents a conservative approach), and cases for fire resistance of grades R 30 and R 60 were analyzed [31]. All loads were entered into the construction model made with the SCIA Engineer software package [32].

5.3. Dimensioning of the structure

In the sizing process, it was ensured that the utilization of critical structural elements was not below 80%, and for the purpose of rationalization in construction and simpler construction, the same profile sizes were adopted for individual characteristic positions. After the calculation and adoption of structural elements on the basis of loads which are not related to earthquakes, the calculation of the structure's seismic response was made. First, the regularity of the building in the ground plan and elevation direction was analyzed in accordance with the recommendations of the HRN EN 1998-1-1 standard [30], where it was concluded that the structure is regular in relation to the floor plan, but its elevation is irregular, and the earthquake calculation was carried out using the spectral method. Due to the height irregularity of the building, the behavior factor was reduced by 20%. Figures 18 and 19 show the forms of oscillations for the first and third mode shape, and the obtained basic periods for the first mode shape were T_1=0.68 s for X direction and T_1=0.88 s for Y direction.
Table 3 shows the calculated masses of steel structure per floors for the entire building, and a factor of 0.24 was used to calculate the part of the serviceability load in earthquake combinations. Thus, the total calculated mass of the building was 219.68 t, and the total seismic force at the base of the building for the direction X was 139.02 kN and for the direction Y 107.43 kN.

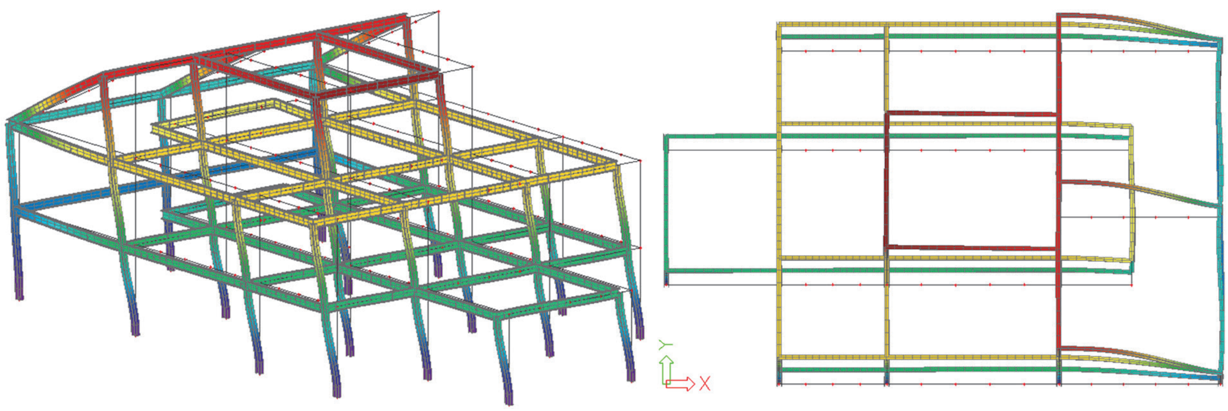


Figure 18. Display of the first oscillation mode of the structure

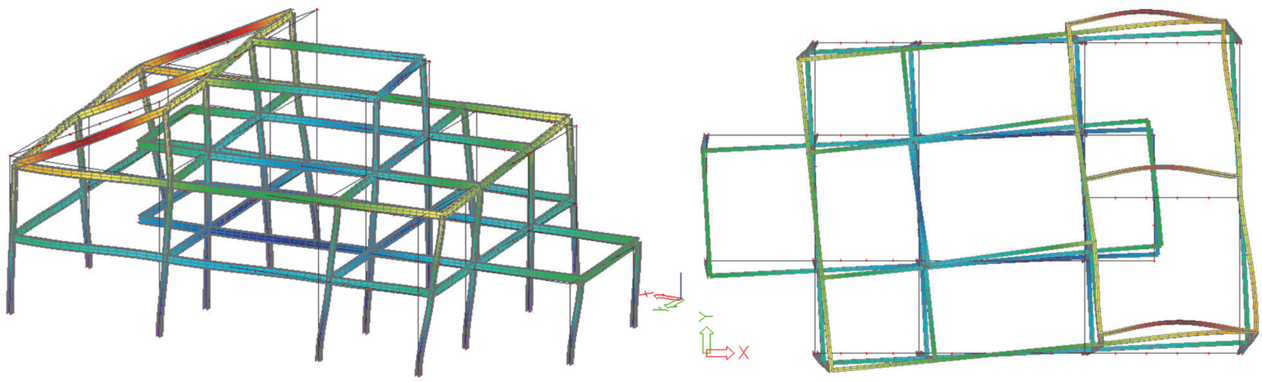


Figure 19. Display of the third oscillation mode

Table 3. Total mass of steel elements

Floor	Pillars HEB 180	Beam IPE 300	Secondary beams IPE 180 i 220	Stairs IPE 140	Weight Total
Ground floor	3942.91	5359.40	1812.32	374.75	11489.38
1st floor	1645.06	5220.56	2225.20	234.14	9324.95
2nd floor	470.02	1700.77	1025.76	0.00	3196.54
Total	6057.98	12280.73	5063.28	608.88	24010.87
				Usvojeno [kg]:	24010.90

Table 4. Utilization and absolute values of effects of actions in the relevant poles of the structure – position NS 103

Results		Non-earthquake combination	Earthquake combination (direction X)	Earthquake combination (direction Y)	Max
Utilization	%	96.00	43.00	62.00	96.00
My	kNm	20.61	18.42	16.78	20.61
Mz	kNm	13.17	0.78	13.03	13.17
Vz	kN	9.67	7.0	2.84	9.67
Vy	kN	7.89	0.64	8.14	8.14
N (tlak)	kN	538.39	170.07	176.41	538.39

Table 4 shows that the amounts of internal forces and utilization are not critical for any of the earthquake load combinations. Figure 20 shows the displacement of the earthquake poles in the *X-direction*, for which checks of the inter-storey displacements were made to meet the condition $d_r/v \leq 0.005 \cdot h$, where d_r is a designed inter-storey displacement, *h* is the height of the floor and *v* is a reduction factor that takes into account the smaller return period of the earthquake related to the limit of usability.

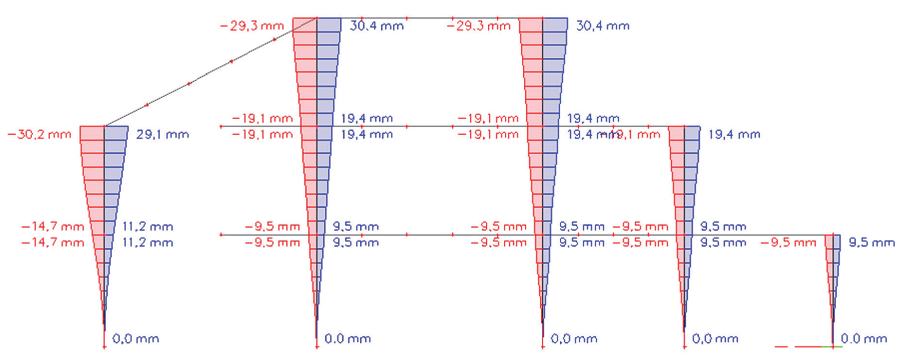


Figure 20. Displacement of earthquake poles in X direction

5.4. Fire performance of the structure

Fire protection of steel profiles is provided in the form of lining of main beams, columns and secondary beams with 1 cm thick plasterboards, which also serve as thermal insulation. The budget stipulates that the elements protected by plasterboards are affected by fire on three sides. For Class R 30 and Class

R 60 fires, all elements met the load-capacity criteria. Figure 21 shows the utilization for the fire load of 30 minutes.

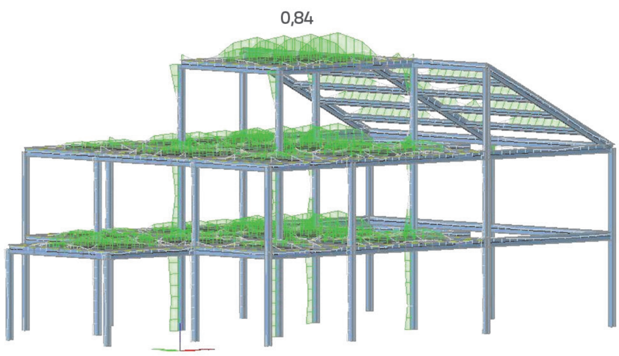


Figure 21. Fire load utilization (30 minutes)

5.5. Analysis of parameters of construction physics

When analyzing the parameters of construction physics, in addition to the already described properties of the building, it was assumed that the building is detached, that is free-standing, and that it uses gas, electricity and water, with the following data:

- layers of external walls are cement plaster, porous concrete block, polymer-cement glue, EPS and plaster
- layers of the ceiling of the flat roof are cement plaster, reinforced concrete, vapour control barrier, vapour barrier, EPS, PE film, cementitious screeds, waterproofing, cement mortar and ceramic tiles
- the layers of the ceiling between the heated floors are cement plaster, RC, EPS, cementitious screeds and parquet
- layers of the ceiling of the non-flat roof are cement plaster, reinforced concrete, vapour control barrier, vapour barrier, EPS, PE film, cementitious screeds, waterproofing, sand and gravel
- non-flat sloping roof is made as a three-chamber glass roof
- steel columns and beams lined with plasterboard and filled with mineral wool (Figures 22 and 23)
- external joinery, new PVC joinery with the value U=0.80 W/m^{2}K.

The calculation of the relevant parameters of thermal and acoustic protection in accordance with the requirements for thermal conductivity of the Republic of Croatia was carried out with the help of the Knauf KI Expert plus software [33] for the purpose of defining the energy class. The calculated value of the specific annual required heat energy for heating for the family house in question is $Q''_{H,nd}$ = 39.68 kWh/(m^2/a), which places it in energy class B and it can be concluded that the building meets the conditions of thermal conductivity. The glass roof of the building had the greatest impact, and for example by changing this part of the roof to a classic roof cover or an appropriate solution, the energy class would increase. With the correct choice of details and the use of appropriate thermal insulation, steel columns and beams meet the thermal resistance condition of the element, that is, U [W/m ^{2} K] is less than 0.3. The choice of characteristic details is shown in Figures 22 and 23, noting that due to additional fire resistance, it would be more advisable to use mineral wool as thermal insulation instead of the used EPS Styrofoam.

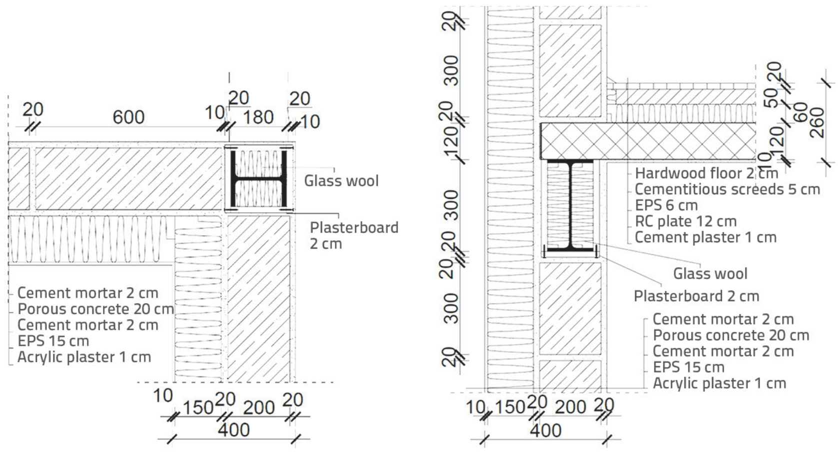


Figure 22. Characteristic details of the edge pole (left) and edge beam (right)

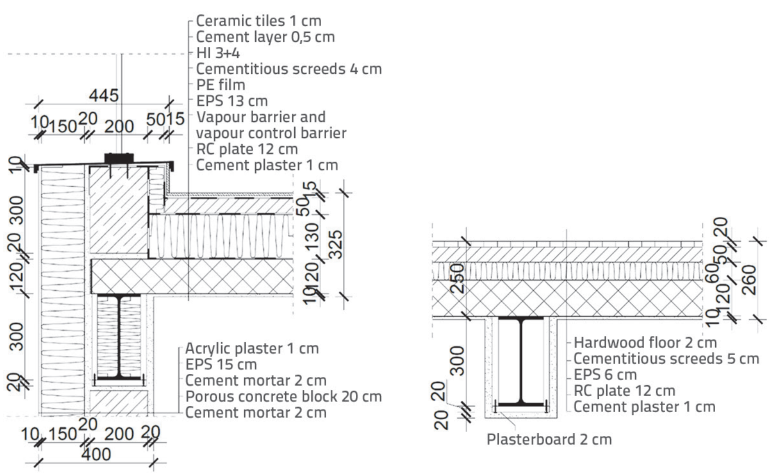


Figure 23. Characteristic details of the terrace fence (left) and inner beams (right)

5.6. Quantities for construction and comparison with monolithic construction

In the context of the current market state and the pronounced volatility of the markets, it is very difficult to write about specific construction prices. For the purpose of simplicity, construction costs are usually presented according to the level of scope of works and per square meter of construction, and if it is a turnkey system, the price depends on a large number of parameters, including the degree of personalization that the investor wants to achieve during the finishing works and furnishing.

Therefore, in order to use the characteristic monolithic residential construction using the bounded masonry and the construction of steel, we considered it appropriate to choose the expression of the quantities of structural materials necessary for the construction of a family house that has been previously discussed in this paper. In this sense, the steel construction variant gives a steel consumption of 65 kg/m^2 (49 kg structural steel and 16 kg reinforcing steel) and the concrete consumption of 0.06 m^3/m^2, to which the consumption of concrete for the foundation should be added - which can be roughly estimated as equal for both structural concepts. It should be noted that in this case, the external lining of the building does not have to be made in the form of a masonry filling as in the example under consideration (but, for example, by using sandwich panels and plasterboards), and also all internal walls are partition walls so they can be made of plasterboards. On the other hand, the classic monolithic concept with a bounded masonry gives a concrete consumption of 0.43 m^3/m^2, reinforcement consumption of 42 kg/m^2 and masonry of 0.32 m^3/m^2 (the assumed wall thickness is of 25 cm). The aforementioned costs of materials for the construction represent the basis for direct comparisons of the indicative construction prices, at the time when it is intended to be done, with the prices that were valid at that particular point in time.

When it comes to the time component of construction, an example of a frame steel structure for which the installation of the entire structure was done in a single day was already given in chapter 3. In this sense, comparisons with classical monolithic construction are exclusively on the side of steel, although the slab is envisaged as reinforced concrete. Namely, given that all the elements are already finished when they arrive to the construction site, the installation does not depend on external influences and there are no preliminary works such as the formation of reinforcement elements, the construction of the formwork, the installation of the supports, and the very concreting and waiting for the reaching of sufficient concrete strength so that the construction can continue (the aforementioned preliminary works are not required). The paper [34] provides an estimate of 7.37 days required for the construction of a single floor in the case of monolithic frame reinforced concrete construction at higher-storey facilities (it should be noted that typified higher-storey buildings are considered in order to accelerate construction). In the case of the use of a steel structure, the entire assembly could be done in a just a few days [34].

6. Conclusion

Steel structures have traditionally not been used for residential construction in Southeast Europe, but the positive sides of such constructions are often overlooked. The current construction of residential spaces is based on experience, local availability of materials and the known advantages of these materials, but the world around us is rapidly changing. In certain situations, the use of some other materials, such as steel, is fully justified in today's context.

This paper presents various methods of building, but it also presents the experiences of countries with a significantly richer history of use and application of steel. It can be concluded that the prerequisites for such construction are now fully realized on the market, and when taking into account the seismic vulnerability of certain areas in the Republic of Croatia, it is quite certain that both basic concepts (framework and lightweight panel) can successfully compete with the application of other building materials.

The disadvantages of steel in residential construction are well known, but with the development of awareness of energy-efficient construction, a large number of new materials came to the market of thermal insulators and the existing materials have been significantly enhanced. Such a development of the situation certainly promotes the possibility of using steel for these purposes as well. Examples of such construction exist and there is a gradual increase in the use of steel in this sector, but this is still far from enough in relation to all of the possibilities and opportunities.

On the example of a relatively complex form of a house (villa), the advantages of steel were shown, that is, the existing new solutions were implemented in the context of Zagreb, and the consumption of material of 49 kg/m^2 clearly shows that it is a competitive material when it comes to the selected sector of residential villas.

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