



**Politécnico  
Castelo Branco**

Escola Superior  
de Tecnologia

## **Steel-Framed Residential Buildings: An Analysis of their Architectonic Potential and Feasibility**

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## **Resumo**

A construção com estrutura metálica tem vindo a ganhar relevância no setor da habitação devido à sua eficiência estrutural, flexibilidade arquitetónica e contributo para a sustentabilidade. Tradicionalmente associadas a edifícios industriais e comerciais de grande escala, as estruturas em aço são cada vez mais utilizadas em edifícios residenciais de pequena e média altura, constituindo uma alternativa viável às soluções convencionais em betão armado.

Este trabalho analisa o potencial arquitetónico, a viabilidade construtiva e o impacto urbano dos edifícios residenciais com estrutura metálica, com especial enfoque em edifícios multifamiliares até cinco pisos. A investigação aborda a interação entre arquitetura e estrutura, destacando a capacidade dos sistemas estruturais em aço para permitir vãos maiores, maior flexibilidade das plantas, redução do peso estrutural e adaptação dos espaços ao longo do tempo.

Do ponto de vista da engenharia estrutural, são analisadas as principais tipologias de sistemas em aço, incluindo pórticos contraventados, pórticos rígidos e soluções mistas aço-betão. São ainda discutidos aspetos relacionados com a rapidez de execução, prefabricação, proteção ao fogo e sustentabilidade, bem como uma análise comparativa com estruturas em betão armado, considerando critérios técnicos, económicos e ambientais.

Os resultados evidenciam que os edifícios residenciais com estrutura em aço representam uma solução eficiente e competitiva, conciliando desempenho estrutural, qualidade arquitetónica e adaptabilidade urbana.

## **Palavras chave**

Estruturas metálicas porticadas; Projecto de edifícios residenciais; Flexibilidade arquitetónica; Viabilidade construtiva.

## **Abstract**

Steel-framed construction has progressively gained relevance within the residential building sector due to its structural efficiency, architectural flexibility, and contribution to sustainable development. Traditionally associated with industrial and large-scale commercial applications, steel structures are increasingly being adopted in low- to mid-rise residential buildings, offering viable alternatives to conventional reinforced concrete solutions.

This study analyses the architectonic potential, construction feasibility, and urban impact of steel-framed residential buildings, with particular emphasis on multi-family structures up to five storeys. The research explores the interaction between architectural design and structural behaviour, highlighting how steel framing systems enable longer spans, flexible floor layouts, reduced structural weight, and enhanced adaptability over time. These characteristics allow residential spaces to respond more effectively to changing user needs while maintaining high performance standards.

From a structural engineering perspective, the work examines the main typologies of steel frame systems, including braced frames, moment-resisting frames, composite floor solutions, and modular construction techniques. Particular attention is given to construction speed, prefabrication processes, fire protection strategies, and sustainability considerations. A comparative analysis with reinforced concrete systems is also presented to assess economic viability, structural performance, and environmental impact.

The results demonstrate that steel-framed residential buildings constitute a competitive and efficient solution, capable of combining structural reliability, architectural quality, and urban adaptability. The findings support the broader application of steel construction in contemporary residential architecture and contribute to informed decision-making in future housing developments.

## **Keywords**

Steel-framed structures; Residential buildings design; Architectural flexibility; Construction feasibility.

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<b>Symbol</b>	<b>Description</b>
<b><i>A</i></b>	Cross-sectional area of structural member; Area of a room in an apartment
<b><i>b</i></b>	Beam width
<b><i>d</i></b>	Total floor thickness
<b><i>E</i></b>	Young's Modulus (Longitudinal modulus of elasticity)
<b><i>e</i></b>	Slab thickness
<b><i>f<sub>y</sub></i></b>	Yield strength of structural steel
<b><i>f<sub>u</sub></i></b>	Ultimate tensile strength
<b><i>G</i></b>	Shear modulus (Transversal modulus of elasticity)
<b><i>h</i></b>	Fixed floor-to-floor height
<b><i>H</i></b>	Clear Ceiling Height
<b><i>h<sub>b</sub></i></b>	Beam height
<b><i>I</i></b>	Moment of Inertia
<b><i>K</i></b>	Stiffness coefficient
<b><i>L</i></b>	Span length
<b><i>M</i></b>	Bending moment
<b><i>N</i></b>	Axial force
<b><i>g or q</i></b>	Uniformly distributed load
<b><i>V</i></b>	Shear force
<b><i>ν</i></b>	Poisson's ratio

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## List of abbreviations, acronyms and initialisms

<b>Abbreviation</b>	<b>Meaning</b>
<b>AESS</b>	Architecturally Exposed Structural Steel
<b>BF</b>	Braced Frame
<b>C2C</b>	Cradle-to-Cradle
<b>EC</b>	Eurocode
<b>EAF</b>	Electric Arc Furnace
<b>IPE</b>	European I-section profile
<b>HEA / HEB</b>	Wide flange steel profiles
<b>LSF</b>	Light Steel Framing
<b>MRF</b>	Moment-Resisting Frame
<b>RC</b>	Reinforced Concrete
<b>RHS</b>	Rectangular Hollow Section
<b>SHS</b>	Square Hollow Section
<b>SFRM</b>	Spray-Applied Fire-Resistive Material

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# **Chapter 1**

## **Introduction**



# 1. Introduction

## 1.1 General aspects and basic considerations

Essential to human existence, alongside sustenance and apparel, structures serve as the defining hallmark of civilization. Mankind's structural endeavours, spanning millennia, have consistently focused on protection from environmental and adversarial forces, facilitating passage across waterways, and fulfilling civic, physical and psychologic requirements. Fundamentally, structures are required for the following core functions, according [1]:

- Shelter and atmosphere: Providing enclosed space for climate, environmental and protection.
- Loads bearing: Sustaining static and dynamic loads (personnel, assets, and inventory) at specified locations.
- Storage and separation: Retaining and isolating several materials, substances, or fluids.
- Passageways and infrastructures: Bridges spans to allow the continuous movement of people, services and commerce.

The primary purpose of any structure is to carry loads and safely transfer them to the ground, distributing the stresses generated by the several internal forces, which are consequences of those loads.

Structures can be classified based on their use and need, covering a broad spectrum of categories: residential (houses, apartments), commercial (offices, shopping centers), institutional (schools, hospitals), exhibition (museums, sports stadia), and industrial (factories, warehouses). Other critical civil engineering structures include bridges, towers (water, utility pylons), and various special structures (e.g., offshore platforms, radio telescopes, among other cases).

Each of such classifications can be constructed using a variety of materials and structural systems. While the present work focuses specifically on steel structures, it is critical to recognize that steel is rarely used in isolation. Steel structures invariably require concrete foundations and often incorporate concrete shear walls, particularly in multi-storey buildings, to ensure the overall stability. Consequently, an initial discussion on materials and the general classification of structures will precede the subsequent detailed focus on steel structures.

The utilisation of steel structures in buildings, although depending on countries, markets and the existence of suppliers, has been increasingly applied over recent decades, given their great versatility, being able to be used in different types of solutions, such as residential, offices and commercial buildings, among other situations such as airports, railway stations and sportive complexes. The strength of steel to withstand heavy loads and large span distances, allowing for the creation of larger spaces without a significant number of internal columns, compared to more common solutions using reinforced concrete, translates into a great advantage with huge potential for exploration from the architectural design point of view. In addition,

steel structures are ideal for multi-storey buildings, as they provide greater stability and structural safety, combined with a reduction in overall weight and avoiding problems such as cracking.

On the other hand, when tubular profiles are used, for example, the architectural design of façades, but also in indoor spaces, can express high standards of aesthetics and slenderness given their exceptional performance, perfectly combining structural behaviour and constructional efficiency with attractive aesthetics.

From the earliest times, in what concerns evolution and characterization of modern structural materials, structural construction relied upon naturally occurring materials such as timber, stone, and fibres. The subsequent development of brick-making, rope-making, glass, and metalwork paved the way for the modern materials manufacturing industries.

The principal modern building materials include masonry, concrete (mass, reinforced, and pre-stressed), structural steel (in rolled and fabricated sections), and timber. Each material offers specific advantages for a given situation, allowing the same building type to be constructed using various structural approaches. For example, a multi-storey building can use load-bearing masonry, concrete shear walls, or a steel frame. A central duty of the designer is to find the best solution that balances economic, aesthetic, and utilitarian requirements.

**Table 1.1** - Key structural materials, principal applications and advantages/disadvantages

<b>Material</b>	<b>Primary Use</b>	<b>Advantages</b>	<b>Disadvantages/Requirements</b>
<b>Masonry</b>	Load-bearing walls or columns in compression, walls taking in-plane or transverse loads	Durability, fire resistance, aesthetically pleasing	Moderate building height limitation
<b>Concrete (Reinforced/ Prestressed)</b>	Framed or shear wall construction. Flooring and foundations for <i>all</i> buildings	High durability and fire resistance. Suitable for the tallest buildings.	Formwork and curing processes.
<b>Structural Steel</b>	Load-bearing frames in buildings, bridges, and special structures	High strength and speed of erection	Requires protection from corrosion and fire.

From the composition material properties point of view, structural steel is an iron alloy with carefully controlled amounts of carbon (typically less than 0.25%) and various other alloying metals, such as manganese, chromium, and vanadium, in trace amounts. These alloying elements are basic to control the grain size and, consequently, the steel's mechanical properties, resulting in high strengths, increased ductility, and fracture toughness. The inclusion of copper, for instance, leads to the corrosion-resistant steel *Corten*. High-carbon steel is also used for high-strength cables and tendons. Production processes, including cooling rates, have a significant effect on the material's microstructure, enhancing its properties. Modern steels exhibit markedly improved weldability, allowing for the guarantee of sound, full-strength, defect-free welds even in the thickest sections.

With regard to the specific mechanical properties of mild steel and the application of hot-rolled steel in residential structural frames, it is recognised that this material is, in fact, one of the most versatile and prevalent materials in civil engineering, as it owes its wide application to a set of well-defined and controllable mechanical properties, demonstrating remarkable elastic and plastic capacity. Such properties ( $E$  - Young's Modulus,  $\nu$  - Poisson's ratio,  $G$  - Modulus of distortion,  $f_y$  - yield stress and  $f_u$  - ultimate stress) are fundamental to successful structural design and help to ensure the safety and performance of the construction throughout its useful life. Interest in the use of hot-rolled steel profile frames for the construction of residential buildings, traditionally built with reinforced concrete solutions, has been leading the residential sector of the construction industry to integrate the use of frames made from this type of material, namely in strength grades S275 and S355 (more resistant and ductile enough), which are quite competitive and more affordable than S420 or S460. The special interest in this application stems from the several advantages already mentioned regarding rapid construction in housing/urban contexts.

Structural steel is hot-rolled into various shapes, such as universal beams and columns. For high-rise buildings where substantial loads must be carried, heavy rolled sections or built-up sections (H, I, and box sections) fabricated from plates are used. At the other end of the scale, lightweight cold-rolled purlins are used for roofing industrial buildings. Furthermore, wire, rope, and high-strength alloy steel bars are essential for suspended structures, such as cable-suspended roofs and suspended floors in multi-storey buildings.

Looking at design from an engineering perspective, and regarding the structural component and the constructive system, common systems include basic frames (with 2D and 3D arrangements), portal frames, trusses, and grid structures. The utilization of diagonal bracings, to resist global shear and moment internal forces, helps to prevent lateral movements when the influence of wind and seismic actions must be taken into account.

Also in accordance with Eurocode 1, Parts 1.1/2/3/4 [2], as well as with Eurocode 8 [3], it can be considered two different types of actions (loads) related to gravity:

- a) “Dead” loads, which comprise the permanent weight of the structure itself, as well as elements like mechanical equipment, ceiling and floor finishes, cladding, façades, and parapets. The dead load is essentially the amount of constant weight that a building must support during its operating life;
- b) “Live” loads, which take into account more transient situations, such as the effect of the weight of people moving on the buildings, reflecting the overload of utilisation, the action of snow, the action of temperature on the structure, the action of wind or the action of earthquakes.

From a static point of view, structural steel elements, although depending on their geometry (shape), are very resistant to tensile, bending, torsional and shear stresses. However, slender steel members can fail under axial compression or warping. The concept like Euler's buckling theory contribute to ensure they are strong enough, always requiring the inherent regulatory checks with regard to resistant capacity, as with other internal forces.

Buildings with steel structures are often governed by deflection limits (how much a beam bends) to prevent excessive movement. Pre-cambering can be used to counteract deflection, but it should be limited to about 80% of the dead load.

For longer spans, over 10-12 meters, the vibration phenomenon can be a governing factor, which limits should be checked, as they are crucial for an efficient structure's utilization.

On the other hand, from an architectural perspective the basic knowledge on steel structures involves understanding not only the principal shapes of cross-sections of steel elements but also the material's properties and the main basic structural systems, like frames and trusses. Nowadays, some key design considerations as bracing, buckling, and deflection are also important for a global understanding of the potential uses of steel in construction. It is fundamental to collaborate with engineers early in order to optimize designs and consider other aspects like fire resistance, sustainability, and finishes, which can be expressed in several architectural ways.

Braced frames with nominally pinned connections and vertical bracing (which may be steel bracing or a concrete core) offer a very cost-competitive structural solution, and are the most commonly used structural systems in buildings. In braced frames, columns are designed to resist mainly to compression forces. Rigidly framed structures are preferred if there is no opportunity for the use of vertical bracing, such as in fully glazed façades or in large-span structures. Columns used in rigid or continuous frames must be also designed to resist bending.

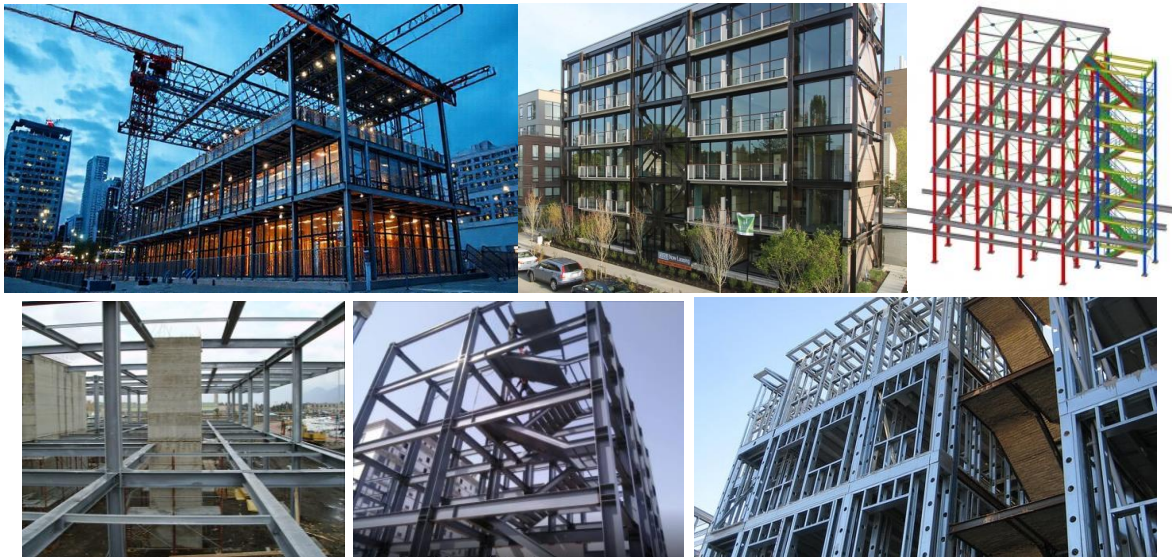
Most forms of steel framing used in steel construction may be grouped as follows:

- Braced frames or 'simple' construction, in which the beams and columns are designed to resist vertical loads only. In this case, the connections are known as nominally pinned.
- Rigid or continuous frames, in which the framed structure is designed so that the connections between the members are moment-resisting.

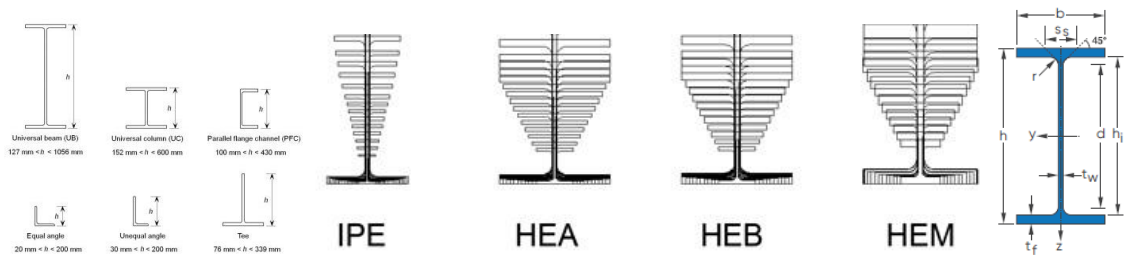
- Arch structures, in which forces are transferred to the ground, mainly by compression within the structure.
- Tensile structures, in which forces are transferred to the ground by tension (or catenary action) and by compression in posts or masts.

The open steel sections have parallel flanges orthogonal to the webs. The serial size varies in increments of about 50 mm depth for the shallower sections, and about 75 mm for the deeper sections. The internal dimensions between the flanges are constant, whilst the flange thickness and overall dimensions vary with section weight. The standardisation of hot-rolled steel sections has led to the adoption of standard connections, which have become familiar within the industry.

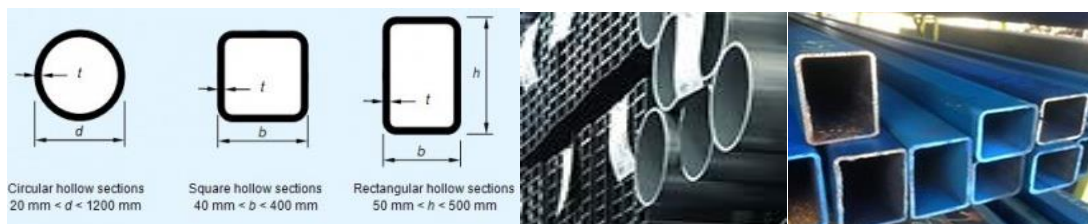
Figure 1.1a) shows several examples of steel frames traditionally used in buildings, according to the previously presented considerations.



a) Buildings with steel frames



b) Steel open sections: HEA/B/M (Wide flange beams) and IPE cross-sections for frames



c) Steel hollow sections (tubular profiles – CHS; SHS; RHS; EHS)

**Figure 1.1** - Steel frames and profiles in residential buildings, adapted from [4]

A wide range of steel components is also available to the Architect's designer guide [1] including:

- Hot-rolled (open) sections, such as I, H and L shapes (Figure 1.1b) – with a summary of European Sections and Merchant Bars);
- Structural hollow (closed) sections of circular, square, rectangular and elliptical shape (Figure 1.1c);
- Fabricated sections made by welding together steel plates;
- Cast steel components for repetitive uses, such as joints;
- Stainless steel components;
- Light steel components made from thin strip steel;
- ❖ Modular units made from light steel components.

British Steel Standards include a combination of BS EN standards for conformity and Eurocodes for design, such as BS EN 1090 for the execution of steel structures and Eurocode 3 (BS EN 1993) [5] for the design of steel structures, that specifies the rules for the design of steel structural elements, including general rules for design by calculation and design assisted by testing.

Also, a wide range of standard hot-rolled steel sections is produced from which designers can select the best profile, size and weight appropriate to a particular element/application. Such examples corresponds to beam sections (IPE, according to ArcelorMittal [6] and to EN 10365 for dimensions - more used for beams, or UB according to British Standards), column sections (HEA/B, according to ArcelorMittal [6] and to EN 10365 for dimensions - more used for columns, or UC according to British Standards), parallel flange channels (UPE - PFC), structural hollow sections (SHS/CHS/RHS), and angle sections (L).

Site connections in the frames' joints are usually made by bolting solutions, while the welding options are preferred for factory-made connections, where the room temperature and humidity can be better controlled.

Steel can be a focal point or concealed. Its appearance can be varied through finishes like paint, galvanizing, or intumescent coatings for fire resistance. Exposed steel needs protection in a fire. Different options include intumescent coatings, concrete encasement, or filling tubular sections with water. Steel elements can be used also for secondary frames, cladding support, or aesthetic solar protection. Several materials like brick, wood, and glass can be integrated with steel frames too. Additionally, the prefabrication process of steel components increases site productivity and speed of construction by up to 70%, and reduces the disruption to the locality during the construction process. Using steel construction, more adaptable space can be created, which leads to long life buildings that can serve a number of functions and future uses.

Discussing architectural/engineering advantages, it must be also mentioned the problematic of sustainability. From an environmental/ecological point of view, steel is a highly sustainable material, as it is 100% recyclable at the end of a building's lifecycle. The small amount of waste that is created in manufacture and construction is recycled. All steel construction systems can be re-used or recycled at the end of their life.

In summary, the structural plans for residential buildings made of structural steel are reproduced through technical documents that detail the assembly of elements such as beams, columns, slabs, and steel profiles, including joints, which are prefabricated with precision in metalworking units. This enables the fast and flexible construction of buildings, especially in bolted connections, with advantages associated with shorter execution times, reduced costs with less demanding foundations due to the lighter weight of the structures, as well as a highly flexible design allowing larger spans. Such type of projects is ideal for houses, but also for multi-familiar, commercial and industrial buildings.

## **1.2 Main objectives and motivation for the study**

Steel constructional technologies have achieved a high market share in several building sectors and the same technologies can be used in housing and residential buildings, where the main benefits include not only the speed of construction, the higher levels of quality, the reliability and longevity, but also the ability to provide more adaptable use of space.

Considering the architectonic potential as well as the flexibility of steel elements in the scope of structures for residential buildings, the principal objective of this work will be the analysis on the architectural advantages offered by steel structures, focusing on design freedom, which allows for the creation of large spans and more open and flexible floor plans. This is particularly important for habitation, as it allows spaces to be adapted to residents' needs over time.

The aesthetic aspect of steel is also important, both in buildings where the structure is exposed and in projects where it is dissimulated, showing the versatility of this structural material in creating different environments with their own style and personality, as evidenced nowadays in many examples across Europe.

Concerning construction and economic viability is focused on technical and economic aspects of construction, such as the efficiency and speed of construction using structural steel, comparing it with methods used in reinforced concrete.

On the other hand, prefabrication and modular construction is also an important aspect, highlighting how these technologies will contribute to reducing costs and construction times, which is fundamental for large-scale housing projects.

Finally, the impact on urban planning directly relates architecture, engineering and technology in the urban context, intersecting with urban planning itself. The work cover how steel construction can be an effective solution for a certain densification of cities in certain zones, allowing the construction of taller and more slender buildings in areas with limited space. On the other hand, the impact of the use of steel-structures in building blocks on the designated urban landscape, where exists availability of areas for construction, is also discussed.

### 1.3 Organisation of work and content

The content of the present work is divided into six fundamental chapters, which attempts to address the theme in a systematised form and as completely and comprehensively as possible.

Besides a series of basic aspects and introductory considerations, included in Chapter 1, as an introduction to the studied theme, Chapter 2 presents a set of characteristics typically associated with frame structures using structural steel (with hot-rolled steel in standardised profiles) as the resistant material, whose advantages and disadvantages are also compared with those observed when such frame systems for residential buildings are constructed using reinforced concrete as the resistant material. In fact, is presented a state of the art related with the principal steel structural systems, including the composite slabs as well as the bolted/welded joints and connections, without forgetting the technical challenges and solutions to fire protection, corrosion aspects and acoustics.

In Chapter 3, the architectural potential and the spatial flexibility design freedom is presented, problematizing the open spans and the floor plans flexibility and spatial adaptation over time. The structure's envelope housing model aesthetic aspects of steel is discussed interrelating exposed *versus* concealed structures. Indeed, some architectural criteria for steel residential buildings up to five stories (including the guarantee of clear floor spans, integrating services efficiently, and addressing the building envelope's thermal and acoustic) performance is presented and discussed.

Chapter 4 includes the preparation of a project which representativity can reflect case studies with focus on architectural potential (e.g., large spans, floor plan flexibility), focus on construction feasibility (e.g., efficiency, speed, prefabrication and modular construction - modularity) and focus on urban impact (e.g., densification or rehabilitation).

Chapter 5 presents the conclusions of the study, summarizing the main architectural and structural outcomes of the proposed steel-framed residential building. The chapter assesses the adopted solutions in terms of structural safety, seismic performance, architectural flexibility, and construction efficiency. A comparative evaluation of the analysed structural configurations is included. Finally, possible directions for future work are outlined, focusing on advanced seismic analysis, structural optimisation, and sustainable construction strategies for residential applications contexts.

Final chapter contains the list of references used in the development of this work. It includes scientific publications, technical standards, and design codes relevant to steel structures and residential building design. Special emphasis is given to Eurocodes, , as well as complementary academic and professional sources.

Several drawings, comparative tables or diagrams are presented in the annexes.

## **Chapter 2**

# **Structural Frame Solutions: Theoretical Fundamentals**



## 2. Structural Frame Solutions: Theoretical Fundamentals

### 2.1 Architectural and Structural Considerations

#### 2.1.1 Overview about interaction between architecture and structure

A structural-descriptive synthesis of steel frame systems for multi-family residential buildings (up to five stories) are presented focusing on the essential structural-architectural context and specifying frame typology, connection design, and overall construction efficiency.

Several details are indicated concerning engineering design and specifications for adopting steel frame systems (steel frames) in low-to-medium rise multi-family residential constructions. The selection of steel as the primary material is based on its intrinsic mechanical capacity to offer an optimized interface between the architectural freedom concept and the structural behaviour effectiveness.

- Architectural flexibility - The steel beam-column frame system facilitates the achievement of significantly longer clear spans than those typically attainable with reinforced concrete. This flexibility in span length is crucial for modern and adaptable residential *layouts*, eliminating intermediate columns and maximizing usable floor space.
- Structural integration - The system is conceived as a three-dimensional framework (3D frame), where global stability is ensured by the coordinated interaction of vertical elements (columns), horizontal elements (beams), and the floor system for slabs, not forgetting the bracing systems.

The use of structural steel in 5-storey residential buildings opens a range of creative opportunities for the architectural possibilities:

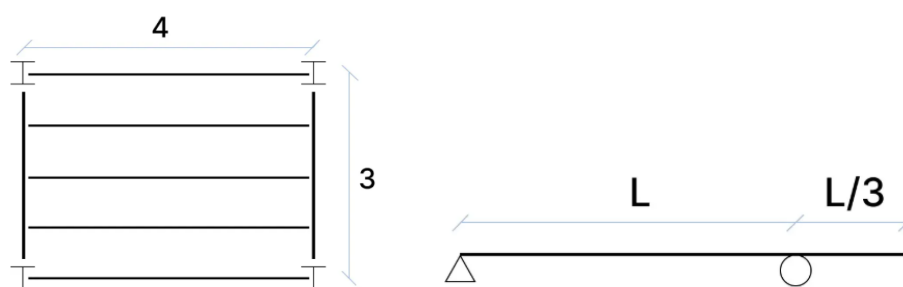
- ◇ Diverse façades: the steel structure allows for the use of a wide range of cladding materials, including full-height glass, fibre cement panels, brick or stone, to create a modern aesthetic or one that blends in with the surrounding urban environment.
- ◇ Large, bright openings: Steel's ability to support large openings allows for the design of façades with large windows, maximising natural light and offering panoramic views.
- ◇ Open interior spaces: The ability to create longer spans with steel beams reduces the number of internal columns, creating larger and open-plan living spaces.
- ◇ Bold architectural elements: Balconies, walkways and panoramic roofs can be easily integrated into the design, providing additional outdoor space and improving the quality of life for occupants.
- ◇ Structural expression: Steel can be left exposed, treated with intumescent paints, as a design element, displaying the supporting structure as part of the building's aesthetics.

The use of structural steel in 5-storey residential buildings also opens a range of different structural systems that can be used as valid options:

- Light steel framing (LSF): Ideal for low-and medium-rise buildings, once this system uses cold-formed steel sections for walls and floors. It is lightweight, energy efficient and quick to install.
- Shallow floor systems: Solutions such as “Slimdek” and “Slimflor” are particularly suitable for multi-storey residential buildings. They integrate steel beams within the thickness of the floor slab, reducing the overall height of the floors and offering greater flexibility for building services.
- Composite structures: These use steel for the load-bearing structure and concrete for the floor slabs. This system combines the advantages of both materials, ensuring good fire resistance and sound insulation while reducing costs compared to an all-steel frame.
- Modular construction: Particularly suitable for serial production, this technique involves the prefabrication of entire residential modules in the factory and subsequent assembly on site. It reduces construction time and minimises interference on site, making it ideal for projects in dense urban areas.
- Cantilever to back-span ratio of 3:1.

Concerning framing (Figure 2.1), space columns use a primary-to-secondary beam length ratio of 3:4. As a starting point for laying out a grid, a general rule for positioning columns and orientating beams is to follow a primary-to-secondary-beam ratio of 3:4, once according this ratio, standard grids might be 6,0 m column spacing in the primary direction and 8,0 m in the secondary.

The logic for this is that primary members typically take more load and work harder than secondary members do, so it is advantageous to reduce their effective lengths. Primary members will typically be far larger than secondaries, and thus positioning them in this way reduces material usage regarding section sizes and connection heft.



**Figure 2.1** - Beam length ratio and cantilever beam span to depth ratio

When working with cantilevers in beams with back spans, the ratio of the back span length to the cantilever length should generally be 3:1 (Figure 2.1). So a beam with a span of 6,0 m will become more efficient when introducing a 2,0 m cantilever at one end.

The adoption of steel frame systems fundamentally defends the interconnection between architectural vision and structural performance. Steel's mechanical capacity creates an optimized interface, offering architects the freedom to design open-plan spaces through significantly longer clear spans and fewer columns. This structural efficiency allows for diversified façades, large openings, and the seamless integration of bold design elements. Furthermore, steel facilitates structural expression, turning the supporting system into an integral aesthetic feature. By offering various typologies (from LSF to composite systems) the steel frame elevates both construction efficiency and the creative potential of modern residential design.

### 2.1.2 Frame system typology and engineering specifications

Steel frames for the building typologies are classified based on the stiffness and strength of their connections, which directly affects the correspondent mechanism of lateral stability.

In general, the basic frame's system typologies includes moment-resisting frames (MRF, assumed as rigid frames, with rigid/semi-rigid joints) and braced frames (BF, including pinned joints).

Table 2.1 presents the basic subdivision considered in the typification of structural systems for frames, specifying their primary characteristics, lateral stability mechanism and most relevant architectural advantages.

**Table 2.1 – Frame's system basic types**

<b>Frame Type</b>	<b>Primary Characteristic</b>	<b>Lateral Stability Mechanism</b>	<b>Architectural Advantage</b>
<b>Moment-Resisting Frames – MRF Rigid frames</b>	Bolted connections designed as rigid or semi-rigid, capable of resisting flexural moments.	Intrinsically provided by the frame (eliminates or minimizes the need for bracing).	Allows maximum façade freedom and utilization of large clear spans.
<b>Braced Frames BF</b>	Bolted connections classified as nominally pinned, transmitting only axial and shear forces.	Requires a vertical bracing (steel bracings) or rigid concrete cores (shear cores).	A more economical and faster solution if bracing is permissible within the <i>layout</i> .

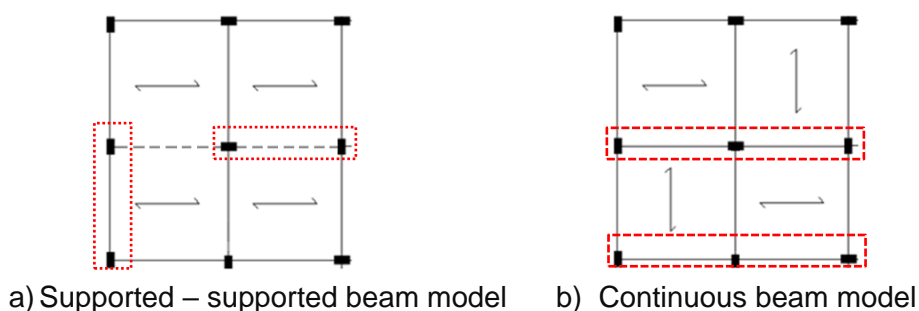
The framed structure consists of a set of beams and columns that intersect in space to form an organised mesh (or articulated grid), which is able to transmit vertical and horizontal loads from the floors (slabs) to the beams, from the beams

to the columns and finally from the columns to the foundations, which distribute the load on the ground (soil).

The loads acting on the floor are generally distributed nature, with particular conditions of concentrated loads. The transmission of loads from one element to another follows the rule of areas of influence.

In framed systems, floors mainly work under bending (where the compression is particularly important), so the measurement referred to is the area. The arrangement of the beams in the floor area determines the structure's model of the floor, which can follow two basic rules:

- a) In the first case, all the beams are loaded, so the distribution of loads is fairly uniform. The layout of each floor area will be similar to that of supported-supported beam (Figure 2.2a), a beam with two supports at its ends that prevent vertical displacement but allow for rotation.
- b) In the second situation, there will be a system of main beams and a system of secondary beams. The floors will have a layout similar to that of a continuous beam with multiple supports (Figure 2.2b), a structural element that spans over three or more supports, providing greater strength and efficiency than a simple beam. This model is advantageous for long spans because it reduces bending moments and deflections by distributing loads over multiple supports.



**Figure 2.2** - Floor support models

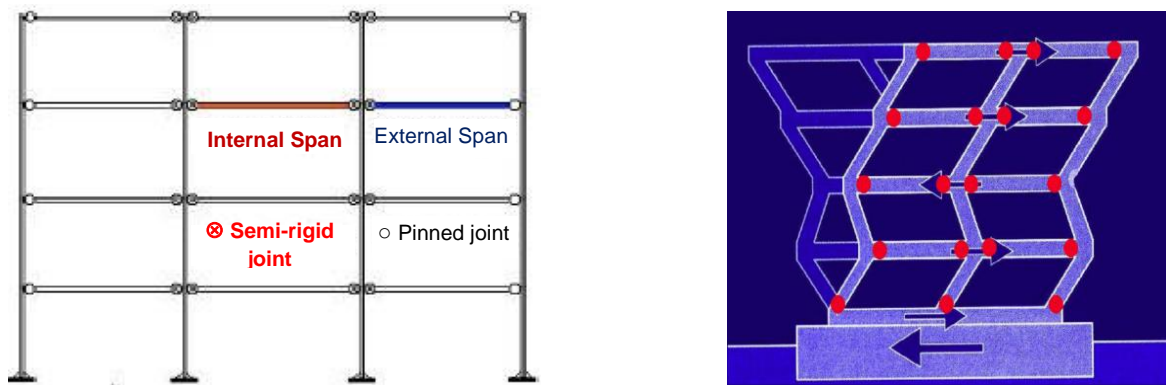
Beams are deflected elements because they mainly work under bending. The characteristic that opposes this bending moment effect is inertia, which depends on the geometry characteristics of the beam. In the case of steel-framed buildings, inertia depends on the geometry of the chosen profile. Two profiles of the same height can have very different moments of inertia, since the thicknesses of the flanges and webs can vary significantly from one another.

The layout of the columns in the plan must take into account the distribution of inertia with respect to the barycentric axes, in order to prevent the horizontal action of seismic acceleration from producing strong rotations of the decks.

The framed structure (Figure 2.3) is modelled as a frame subject to vertical loads (dead weight of structural elements, semi-permanent loads and accidental loads) and horizontal loads (wind and earthquake) applied to the decks.

The joints of steel frames, on the other hand, are closer to the operating scheme of supports and hinges, and their actual behaviour is effectively that of imperfect hinges or weaker fixed support. These structures therefore do not have the capacity to resist even weak horizontal actions (from wind or earthquakes) and must be integrated with stiffening elements arranged in two orthogonal directions (bracing).

The dimensions of the members are determined in accordance with the hierarchy of resistance criterion: the elements are designed according to how the structure is intended to “fail”, and the collapse mechanism is controlled by distributing the strength in an appropriate manner.



**Figure 2.3** - Framed structures and deformation tendency under horizontal actions

The bracing system consists of a braced frame with diagonals that converge at:

- ❖ beam-column joints;
- ❖ points on beams or columns where other diagonals converge.

The concentric reticular bracing can be divided into the following categories:

*A. Bracing with active tension diagonals*

The resistance to horizontal forces and dissipative capacities are assigned to the diagonal struts subject to tension forces, including the traditional disposition related to St. Andrew's Cross (Figure 2.4a).

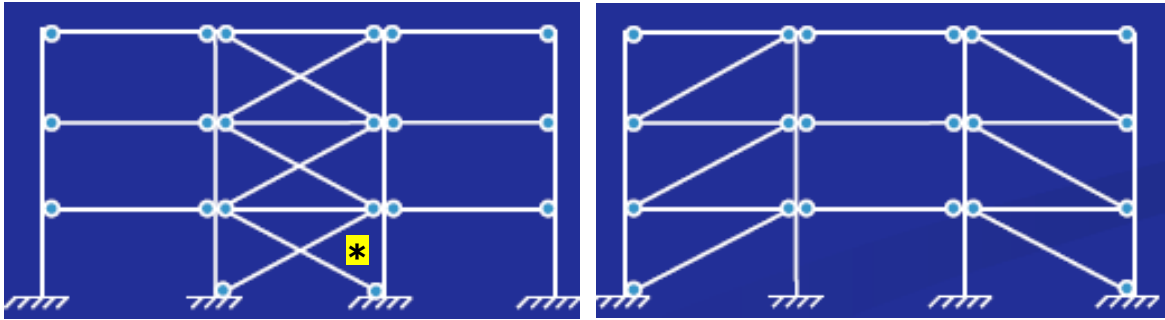
*B. V-Shaped braces*

Horizontal forces must be absorbed by considering both tensioned and compressed diagonals. The point of intersection of these diagonals lies on a horizontal member that must be continuous (Figure 2.4b).

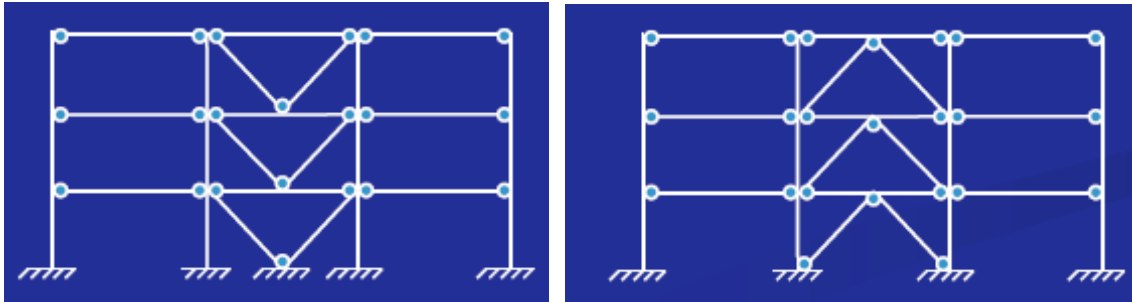
*C. K-Shaped braces*

This category should not be considered dissipative, as the collapse mechanism involves the column (Figure 2.4c).

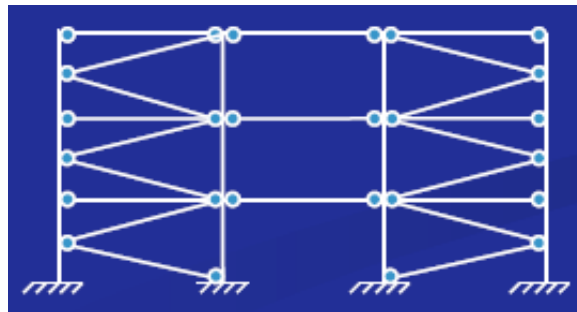
In order to achieve ductile behaviour, structures with concentric bracing must be designed so that the plastification of the tensioned diagonals precedes the failure of the connections and the instability of beams and columns.



a) Bracing with active tension diagonals (St Andrew's Cross \*), case A)



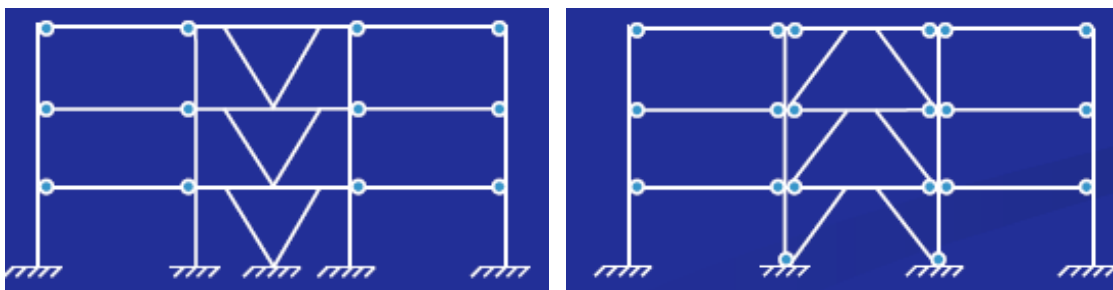
b) V-Shaped braces, case B)



c) K-Shaped braces, case C)

**Figure 2.4** - Framed structures and bracing systems - concentric bracing

On the other hand, eccentric bracing consists of a braced frame with diagonals that do not converge (at both ends) at a beam-column node or at a point where another diagonal converges. Eccentric bracing (Figure 2.5) divides the beams of the frames into two or more parts. One of these parts, called a “connection element” or “link”, is responsible for dissipating seismic energy through cyclic shear and/or flexural plastic deformation.



**Figure 2.5** - Framed structures and bracing systems - eccentric bracing

In general, the analysis of framed structures with braced system is governed according the following design rules:

1. The lateral loads are resisted by a system of diagonal cross bracings, as shown in Figure 2.4 and Figure 2.5, therefore only vertical loads are taken into account. Such method can be adopted to composite beams of those braced frames.
2. The choice of the column and beam sections is based on the concept of strong column/weak beam, which means failure takes place in the beams instead of the columns to avoid the collapse of the entire structure.
3. Steel beam and steel column sections of class 1 (or class 2), according EC3 (Part 1-1) are used to prevent local buckling. The concrete slab prevents the lateral torsional buckling of the composite beams.
4. Identical composite beams must be used on both sides of the steel column.
5. The beams must be temporarily propped during construction.
6. Semi-rigid/partial strength composite joints are considered only in the internal columns. Due to anchorage difficulty of reinforcement at the slab edge, pinned joints are assumed to the external columns.
7. Partial shear connection is considered in both sagging and hogging moment regions of the semi-continuous composite beams.

Figure 2.6 presents a typical configuration for a 3-span, 4-storey frame, including Saint Andrew's cross bracing in the first span (under horizontal and vertical loads), as well as the layout of bending moment diagrams for 1 span and 1 storey, considering the individualised horizontal (Wind or Earthquake,  $M_o$ ) or vertical load situation (permanent load –  $g$  or variable load –  $q$ ,  $M_v$ ).

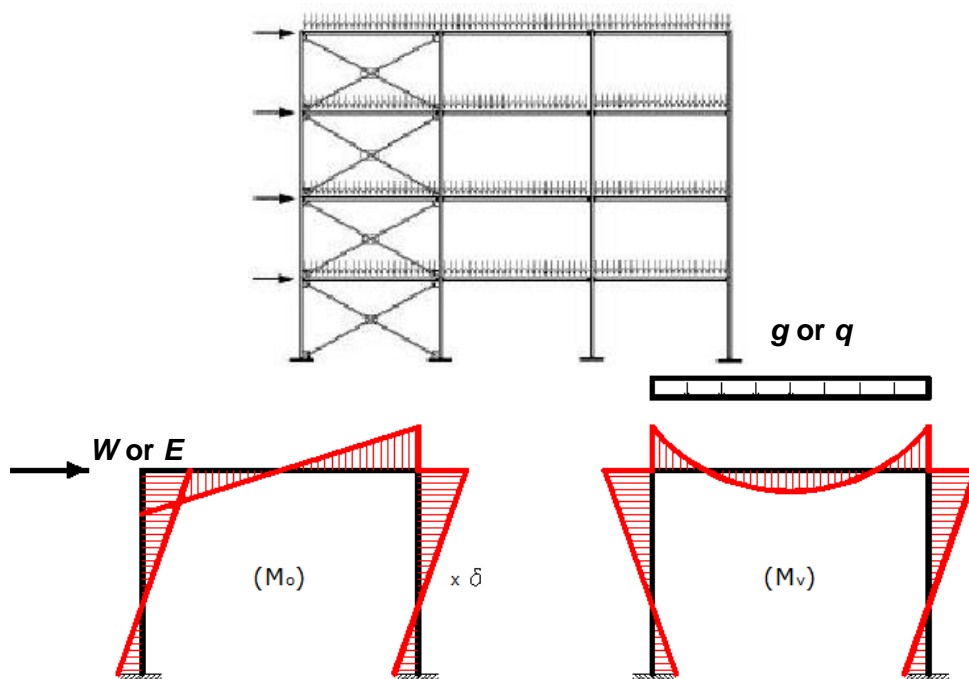


Figure 2.6 - Internal forces on frames: Example of braced building frame

For rigid frames (or semi-rigid as illustrated in Figure 2.7 – Type I) both transversally and longitudinally, the connections are designed to the moments induced by the vertical and horizontal loads. These type of structures have rather a small number of stories (no more than 20 – 30 storeys) and a big amount of manoeuvre at the building site is necessary.

In the case of rigid frames transversally with braced frames articulated with vertical braces longitudinally, the frames take over vertical loads and the horizontal forces are transferred to the vertical bracing of the structure.

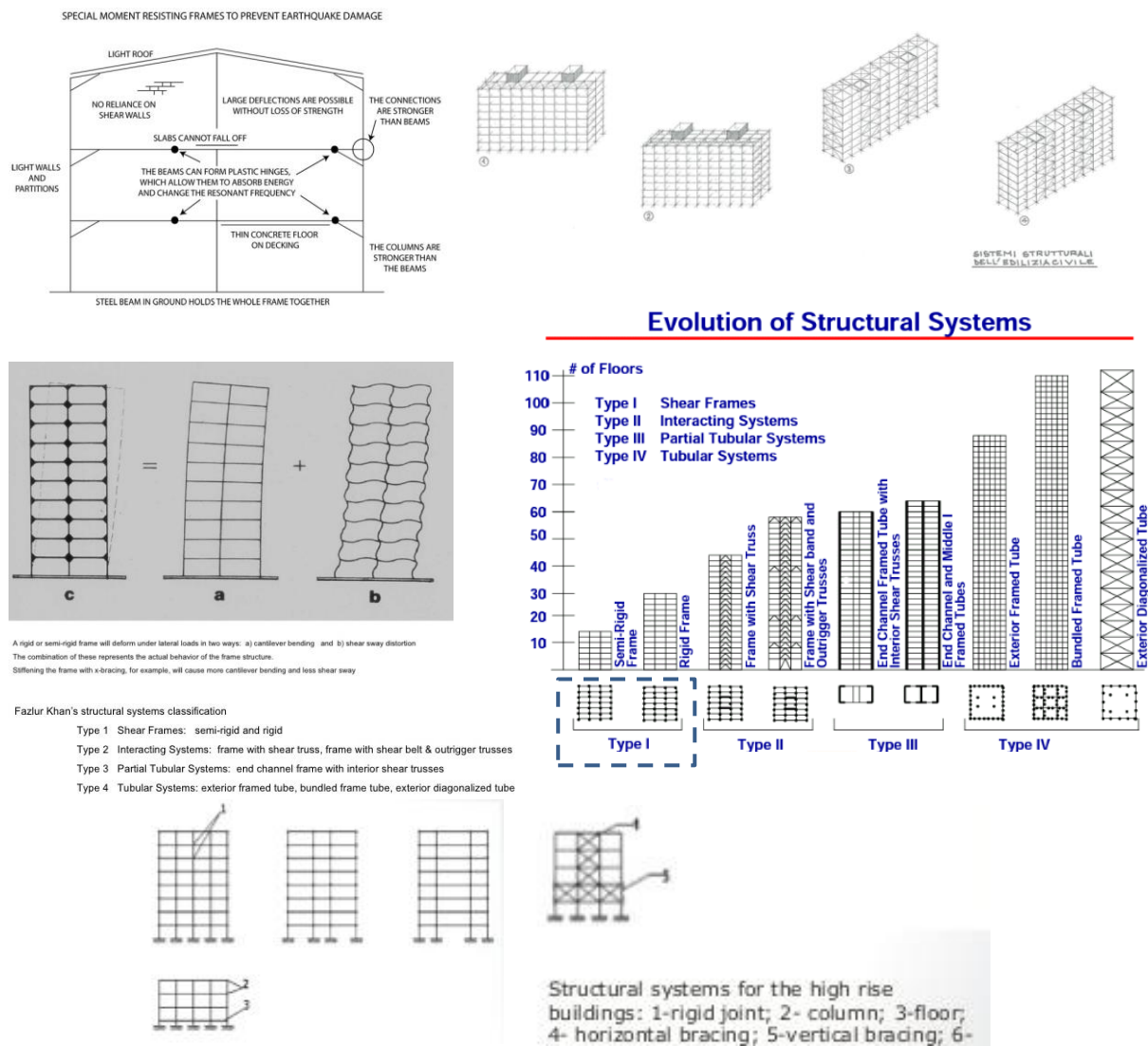


Figure 2.7 - Steel frames for buildings: frame's system types, adapted from Google

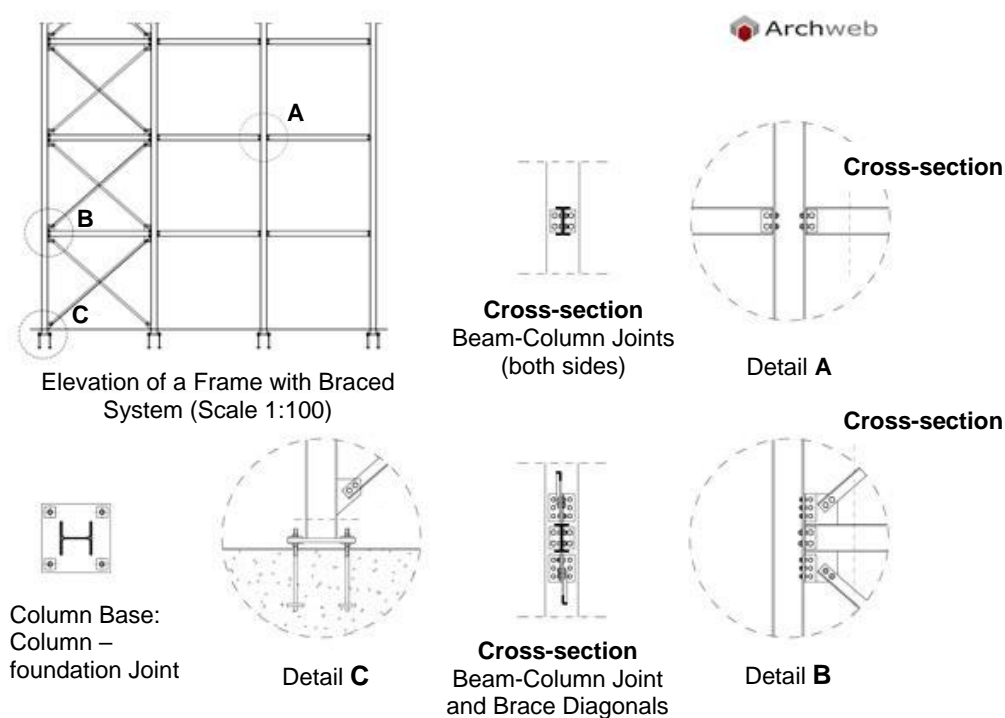
Concerning frames with both rigid and articulated joints, transversal rigid frames and longitudinal braced frames with articulated joints, which have at the lower part of the structure articulated joints, and the frames are provided with vertical bracing system. Rigid frames are used at the top of the structure (in general for up to 70-80 storeys).



### 2.1.3 Connections and floor systems

Joint and connection typology requires that erection is primarily achieved using bolted connections, specifically designed to guarantee the force transfer (shear or moment due to bending) demanded by the structural typology.

The preference for bolting over on-site welding ensures superior quality control and a clearly higher execution speed, which is traditionally associated with a lower overall cost. An example of a braced system frame including three types of joints with bolted connections is shown in Figure 2.9.



**Figure 2.9 - Steel frames: connections in a braced system frame, adapted from [7]**

More detailed examples of joints and connections between steel elements in frames, continuing from Figure 9 and specifying the general characteristics for steel frames and their common elements, are presented in Figures 2.10 to 2.13, including photos of the most typical typologies.

Figure 2.10 shows the typical schemes for principal beam - secondary (or auxiliary) beam joints traditionally used in framed structures, including the utilization of angle cleat plate with bolts. Figure 2.11 presents the typical scheme for principal beam - column joints with extended endplates, indicating different solutions for several situations of joints' stiffness. Figure 2.12 illustrates the traditional example of joint for a column prolongation (column - column joint), ensuring a column continuity in height. Several examples of column-base joints are shown in Figure 2.13, where it is possible to view different jointing options between the columns and their respective foundations.

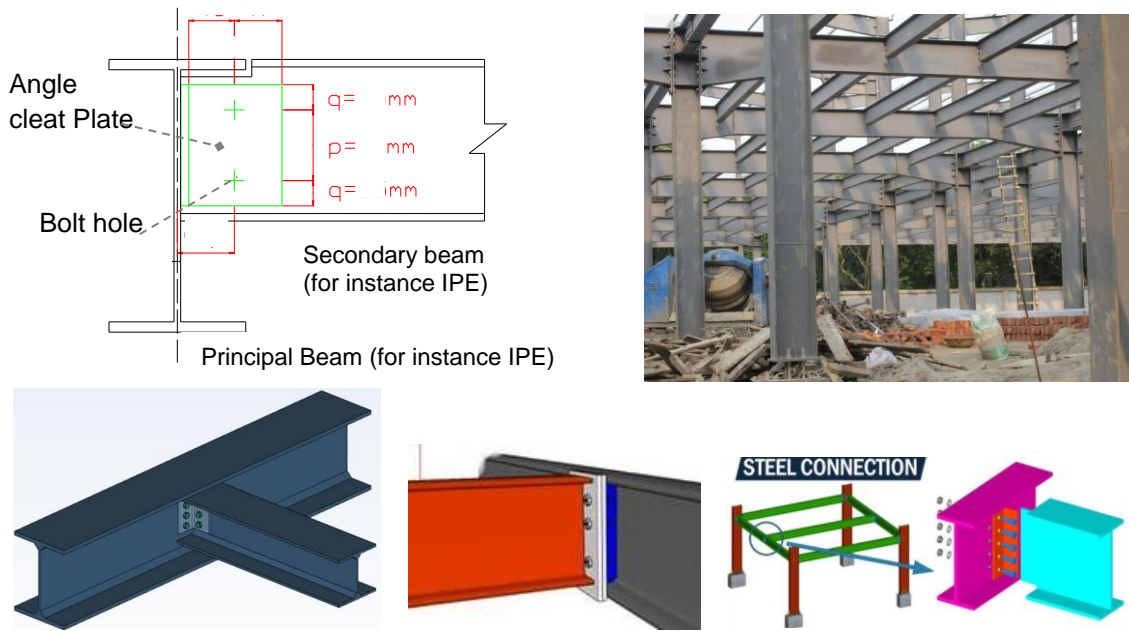


Figure 2.10 - Typical schemes for principal beam - secondary (or auxiliary) beam joints

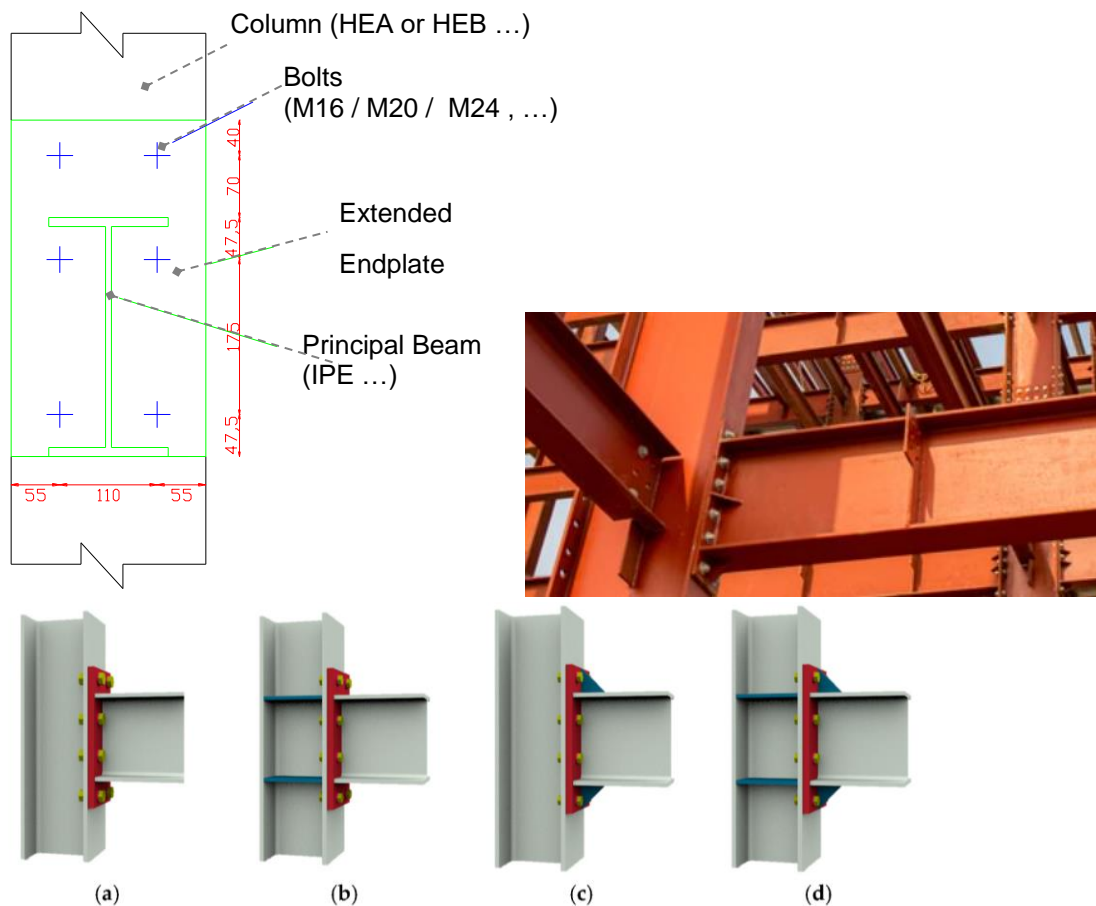
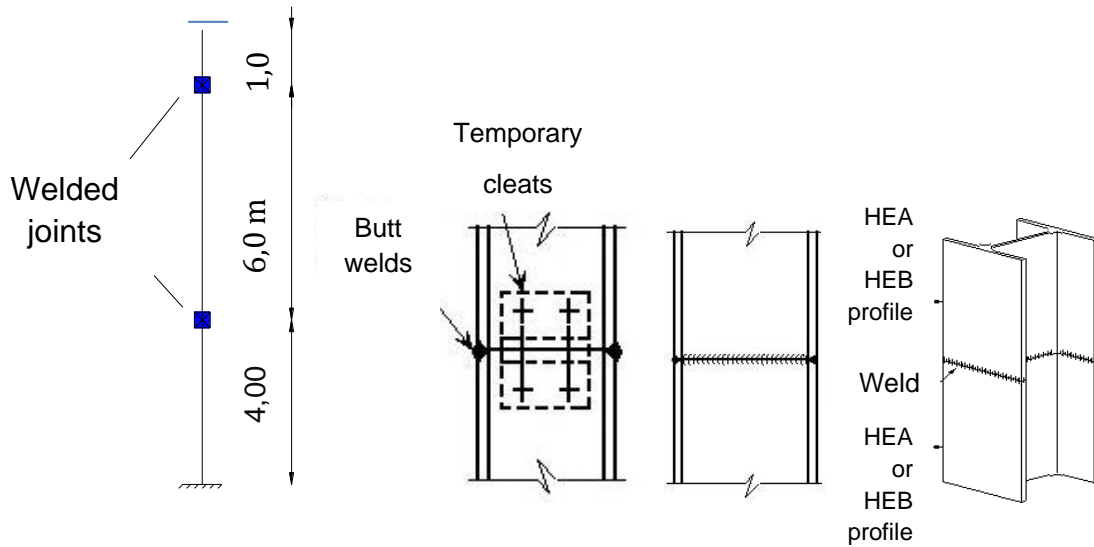
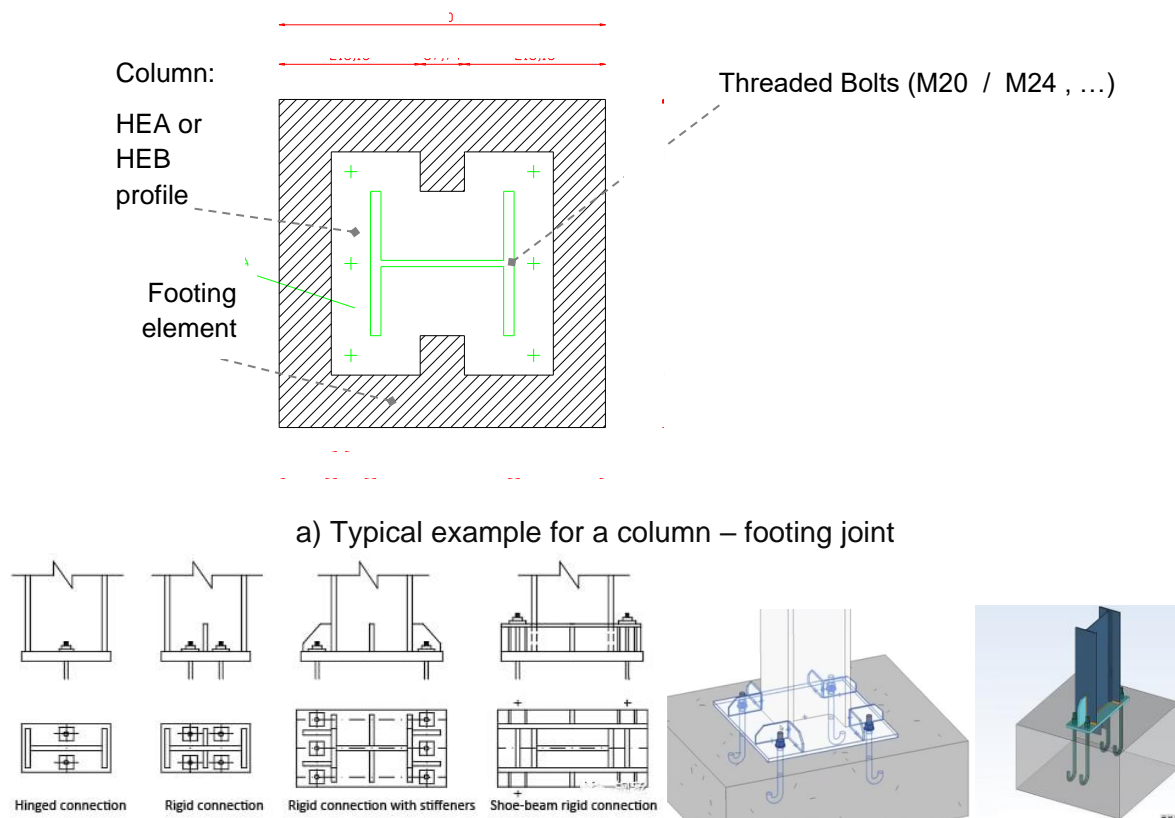


Figure 2.11 - Typical scheme for principal beam - column joints with extended plates (different solutions for different situations of stiffness and strength)



**Figure 2.12** - Typical example of joint for column prolongation: Column - column joint (column continuity in height)



**Figure 2.13** - Examples of column – footing joints

In addition to the aforementioned situations, composite slabs with steel decking origin that the floor system is invariably a composite slab, combining a profiled metal deck with a properly reinforced concrete layer above. Composite action is established using shear studs welded to the top flanges of the beams. This system

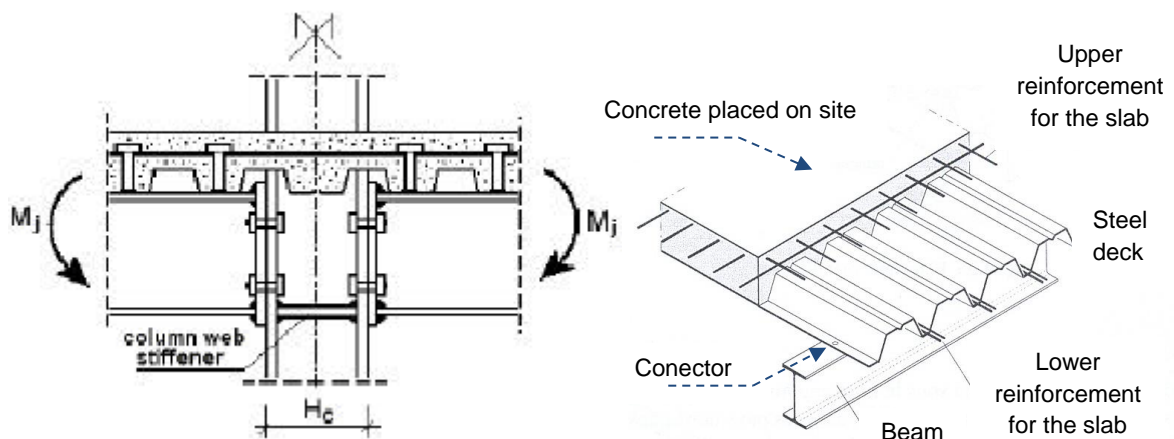
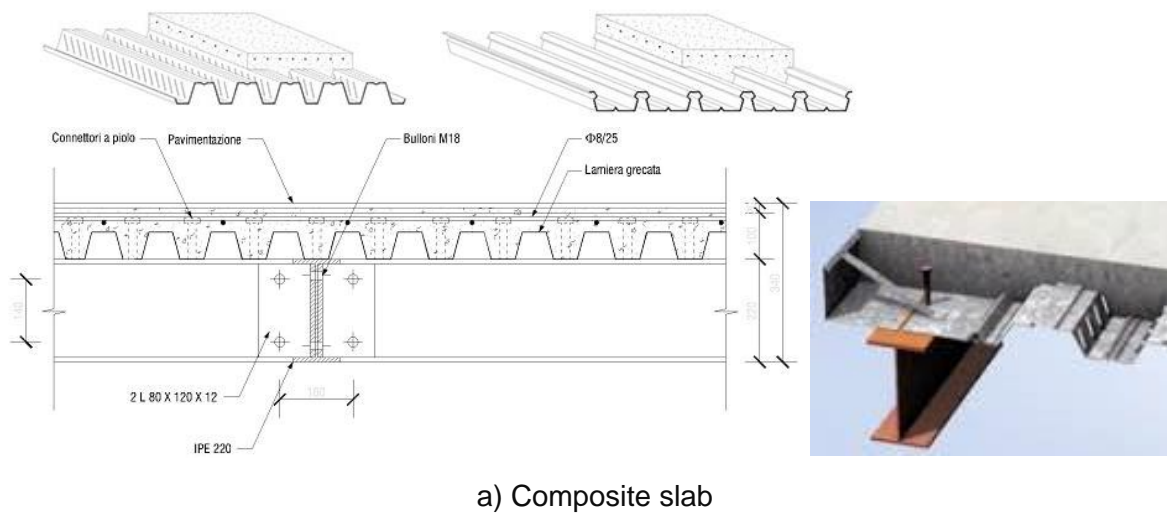
provides structural lightness, fast construction, and also contributes to the horizontal diaphragm effect in distributing lateral loads (e.g., due to wind or seismic actions).

Steel offers a range of solutions for floor construction that can be easily adapted to the structural grid and construction system chosen for the building.

The main characteristics that distinguish steel floors are lightness, reduced dimensions, speed of installation, ease of cutting and ease of creating openings for the passage of systems.

The main components of steel floors are corrugated sheets.

There are two main types of steel floors: composite steel-concrete floors and entirely dry floors. An example of a floor system constituted by a steel deck is shown in Figure 2.14.



**Figure 2.14** - Steel frames: Floor systems with a composite steel-concrete slab – traditional components, adapted from [Google]

Figure 2.15 shows a direct comparison between floor slabs constructed using reinforced concrete and a mixed steel-concrete combination. In particular, it shows topics such as the maximally permitted span for the structural grid, the indicative structural weight, generic dimensions for the floor cross-section, and an estimation of the carbon footprint in terms of environmental impact.

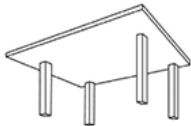
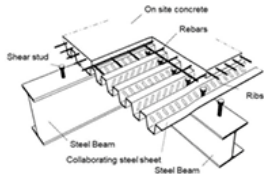

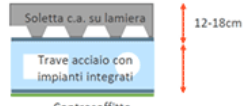
	Sistemi <i>flat slab</i>	Sistemi misti acciaio-calcestruzzo
		
dimensioni massime maglia strutturale	8 ÷ 10 m	15 ÷ 20 m
regolarità maglia strutturale	adatta a maglie irregolari	ottimizzata su maglie regolari
peso strutturale indicativo	600 ÷ 800 kg/m <sup>2</sup>	300 ÷ 400 kg/m <sup>2</sup>
stima carbon footprint	120 ÷ 180 kgCO <sub>2</sub> /m <sup>2</sup>	80 ÷ 160 kgCO <sub>2</sub> /m <sup>2</sup>
ingombro solaio		

Figure 2.15 – Systems’ slab comparison, adapted from [Google]

The decision between using steel (S) frames or reinforced concrete (RC) frames for residential buildings up to 5 stories requires assessing a balance of priorities, as described in Table 2.2. Therefore, a comparative synthesis presents advantages and disadvantages of steel *versus* reinforced concrete in that table.

Table 2.2 – Basic advantages and limitations of steel/reinforced concrete option for frames

Structural or Construction Characteristic	Steel (S) Advantages/Disadvantages	Reinforced Concrete (RC) Advantages/Disadvantages
<b>Construction Speed</b>	Very High (Off-site prefabrication, fast bolted assembly).	Slower (Time required for formwork, reinforcement, and concrete curing).
<b>Structural Lightness</b>	Lighter Structure (Reduces foundation costs and dimensions; a critical factor in low-rise buildings and site constraints regarding free areas).	Heavier Structure (Increases seismic loads and foundation demands).
<b>Sustainability/ Waste</b>	High (Steel is 100% recyclable, contributing to minimal on-site waste production).	Moderate (Cement process is energy-intensive, generating more formwork waste).
<b>Span Flexibility</b>	Maximum (Allows long spans and a more open floor plan).	Limited (Requires shorter spans, demanding larger column dimensions).

<b>Initial Cost and Labour</b>	Disadvantage: Higher initial material cost and need for more specialized labor.	Advantage: Greater availability of local materials and labour, with more stable costs.
<b>Fire Performance</b>	<i>Disadvantage:</i> Requires mandatory passive fire protection (with intumescent coatings or appropriate encasement/cladding).	<i>Advantage:</i> Inherently better due to concrete's thermal inertia and mass.

In summary, the steel solution is optimized for projects that prioritize fast-track construction, functional adaptability, and the reduction of seismic mass, whereas the concrete solution may be favored in contexts where initial cost and the availability of less specialized labour are limiting factors.

#### 2.1.4 Introductory case study

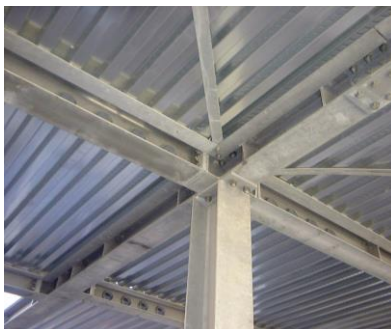
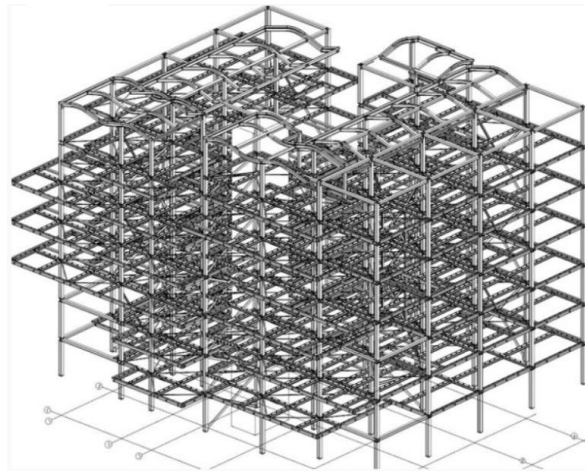
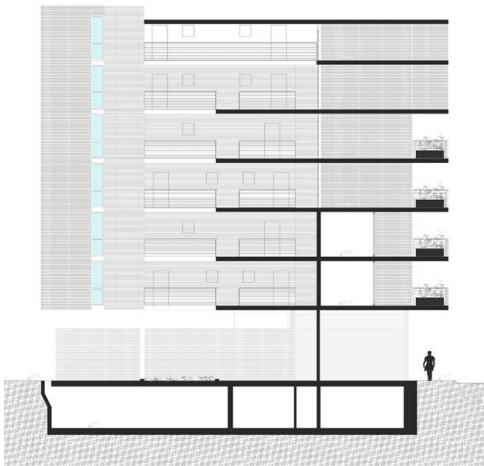
The building example illustrated in Figure 2.16, correspondent to “Via Piave” Residential Complex [8], has seven floors, including the attic, and also has a basement that serves as a garage. The flats, five or six on each floor, are distributed on three sides around a central circulation space, for a total of 36 residential units. The external volume is defined mainly by the terraces and overhangs, which vary according to the different heights.

From a construction point of view, the originality of this building is found in its steel frame (Figure 2.17), which extends from the ground floor to the roof. It was above all the choice of this material that allowed for greater design freedom, reducing the size of the structural elements and speeding up construction times. The integrity of the materials is guaranteed by the galvanisation of the steel elements, specifically designed to counteract the salinity of the air. A play of beams and corrugated sheet metal gives life to the decks, which have a reinforced concrete completion layer only 25 cm thick.

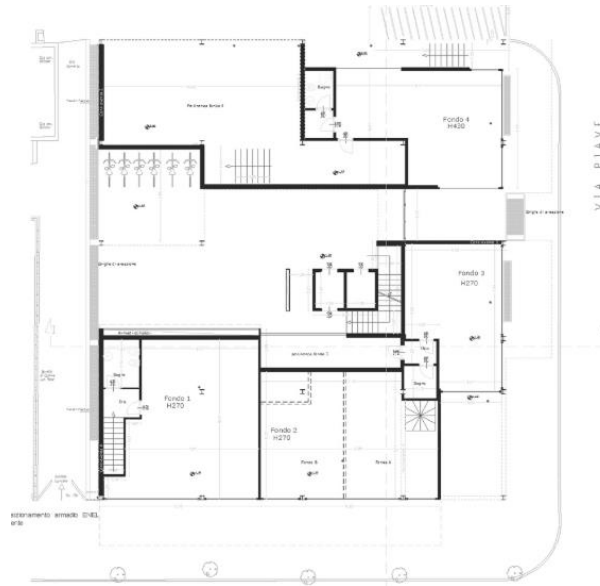
The building's resistance to horizontal forces is ensured by five appropriately positioned vertical truss beams, in addition to the reinforced concrete lift and staircase partition. The roof is partly curved, clearly remembering the waves of the nearby sea, and consists of steel load-bearing beams.

The apartments have a very simple internal layout, designed to meet the needs of tourists. In most cases, they have three rooms, organised into a living room-kitchen and bedrooms, and always have access to terraces. These terraces, which vary in size, are designed to provide shade for the numerous windows of the apartments. The complex is completed by a courtyard protected by a timber grid, together with the external cladding, partly in terracotta and partly in cement plaster, which gives all the residences a warm and relaxing appearance.

The description provided for the aforementioned example helps to explain some of the different reasons earlier presented regarding the use of steel elements in association with other materials, exploring precisely the corresponding interconnection between fluid lines, the combination of different materials, and large and open spaces.



**Figure 2.16** - Steel structure in a residential building - "Via Piave" Residential Complex, adapted from Fondazione Promozione Acciaio [8]



**Figure 2.17** - Steel structure in a residential building, adapted from Fondazione Promozione Acciaio [8]

## 2.2 Fire Protection

### 2.2.1 Basic considerations

In the process of creating architectural solutions it's essential to keep in mind that fire can strike anywhere and anytime, so it's crucial to plan for the worst. Building codes specify the number of hours a structure must withstand a given temperature, based on a variety of characteristics of the building in case. There are three key considerations when creating a fire protection plan life safety, fire suppression, and protection of the structure.

Even non-combustible materials such as steel can be affected by high temperatures. However, because structural elements are not usually loaded to their full design strength, even bare steel may have sufficient load-carrying capacity to withstand the effects of fire.

The main part of architectural design and sufficient planning is to know which material to use and how to use it. With it, we must consider the condition and while creating steel construction, keep intumescent coatings in mind.

The constructions must be designed and built in such a way that in the event of an outbreak of fire,

- the load bearing capacity of the construction could be assumed for a specified period of time,
- the generation and spread of fire and smoke within the works are limited,
- the spread of fire to neighbouring construction works is limited,
- the occupants can leave the works or can be rescued by other means,
- the safety of rescue teams is taken into consideration.

To meet the regulatory requirements, engineers have to work closely with architects, contractors, manufacturers and suppliers in the design of multi-storey buildings for the fire scenario. Although many issues are primarily covered in the architectural design, engineers need to be aware of fire safety with particular reference to structural fire engineering.

In some circumstances, engineers may have to use a wide range of fire safety strategies and design. Fire engineering approaches to ensure that a multi-storey building meets all mandatory fire safety requirements.

The parts of the Eurocodes relevant to fire design of multi-storey steel-framed buildings with composite floors, include:

- EN 1991-1-2, Eurocode 1. Actions on structures exposed to fire [1].
- EN 1993-1-2, Eurocode 3. Steel structures – Structural fire design.
- EN 1994-1-2, Eurocode 4. Composite structures – Structural fire design.

In addition to the general requirements, principles and rules, such documents also recommend the partial factors and design effect of loads to fire design.

They provide a series of equations and models for the calculation of temperature rise, critical temperature and load bearing resistance of a structural member in fire conditions. Such guidelines provides engineers with a wide range of fire safety strategies for the design of multi-storey buildings. For less experienced designers those publications provides also guidance on the use of datasheets to meet the legal fire safety requirements. More experienced engineers will find that the simple calculation models in the Eurocodes are straightforward to apply and will result in a more economical solution.

### **2.2.2 Intumescent coatings**

Intumescent coatings are epoxy-based, paint-like mixtures applied to the primed steel surface. When subjected to high heat, these coatings expand to many times their original thickness, forming an insulating blanket that protects the steel member from heat. These coatings allow for fire ratings of up to four hours.

Intumescent coatings can effectively balance architecturally exposed structural steel design elements with fire rating requirements. However, intumescent coatings are more expensive, costing several times the price of common spray-applied systems.

It's an effective way to prevent steel structures from collapsing in extremal and emergency situations, while ensuring the resident's safety. Therefore, in a final budget calculations it can add a bit, but will have positive outcome in the future.

### 2.2.3 Gypsum

Besides, intumescent coating another efficient way is to use gypsum. Gypsum is commonly used for fire protection, and it comes in a variety of formats. Adding lightweight mineral aggregates such as vermiculite and perlite can significantly increase the effectiveness of gypsum-based fire protection systems.

Gypsum wallboard, meanwhile, can be installed over cold-formed steel framing or furring and comes in a few different varieties. Type X wallboards have specially formulated cores that provide greater fire resistance than regular wallboard of the same thickness. And Type C has more additives to gypsum core that make it slightly more fire-resistant.



Figure 2.17 - Adapted from [Thespruce, cdrecycling]

### 2.2.4 Spray-applied Fire-Resistive Material (SFRM)

The most widely used fire protection materials for structural steel are mineral fiber and other cementitious materials that are sprayed directly onto the contours of beams, columns, girders, and floor/roof decks.

These materials are proprietary, so it is particularly important to mix and apply each product according to the manufacturers' instructions.

### 2.2.5 SFRM and Intumescent Coatings

After the general review of the two solutions of fire resistance, SFRM and intumescent coating, it's important to differentiate usage of them with various properties and characteristic values.

The polarity between spray-applied fire-resistive materials (SFRM) and intumescent coatings are summarized in Table 2.3 (Steel Construction Institute, 2019 and American Institute of Steel Construction, 2020).

**Table 2.3 - Differentiation of SFRM and Intumescent Coating**

<b>Feature</b>	<b>Spray-Applied Fire-Resistive Material (SFRM)</b>	<b>Intumescent Coating (Paint)</b>
<b>Composition</b>	Made of cement-based or fibrous materials (like gypsum, vermiculite, mineral wool).	Made of special paints that contain chemicals which expand when heated.
<b>Application method</b>	Sprayed thickly on steel using a spray gun.	Applied in thin layers using a paint roller, brush, or spray.
<b>Thickness</b>	Much thicker (typically 10–50 mm).	Very thin (usually 0.3–3 mm).
<b>Appearance</b>	Rough or textured, usually covered with finishes. Not visually attractive.	Smooth and decorative, can be colored or glossy — often left exposed.
<b>Aesthetic use</b>	Mostly for hidden structures (inside ceilings, service areas, industrial buildings).	Ideal for exposed steel architecture where appearance matters (residential, offices, museums).
<b>Fire protection mechanism</b>	Acts as an insulating barrier — physically resists heat transfer.	Expands (intumesces) in a fire to form a foam layer that insulates steel.
<b>Cost and maintenance</b>	Usually cheaper, but less aesthetic.	More expensive, but gives an attractive finish.
<b>Durability</b>	Can chip or absorb moisture if not protected.	More durable if maintained properly.

### 2.2.6 Suspended Ceiling Systems

Suspended ceiling systems protect floors, beams, and girders are presented in Figure 2.18. Screen protection isolates the structure from an advancing fire by the interposition of elements that form a continuous wall. In a vertical position they serve as wall panels; when horizontal, they are suspended ceilings. All products used must have been tested for fire resistance.

The fire resistance of the ASBs is achieved by partial encasement in the composite slab. Generally, 60 minutes of fire resistance can be achieved by ASB sections, increasing up to 120 minutes when protected with board materials, a suspended ceiling, or intumescent coatings. Therefore, ASB systems provide a practical and efficient solution for achieving enhanced fire performance in composite floor construction.



**Figure 2.18** - Visual representation of suspended ceiling systems, adapted from [Vibratec, Uksuspendedceilings]

### 2.2.7 Concrete and masonry

In past decades, concrete was the most widely used material for structural steel fire protection, though its relatively high thermal conductivity does not make it a particularly efficient choice. As a result, concrete is no longer widely used for the purpose of fire protection.

A notable exception is the growing use of composite construction as illustrated in Figure 2.19, such as concrete-encased steel columns. Concrete and masonry are also sometimes used to protect steel columns for architectural purposes or when substantial resistance to physical damage is required.



**Figure 2.19** - Concrete-encased steel columns, adapted from [Advanceseng, Sciencedirect]

## 2.3 Sound Isolation and noise control

Acoustic performance comes down to the selection and assembly of building elements, not the material types and framing systems. A good design will create the desired sound characteristics using any material and any frame system.

Effective acoustic insulation of separating walls and floors between living spaces is very important to the health and wellbeing of the building occupants. For transmission of airborne sound, the acoustic performance is characterised by a sound reduction index ( $D_{nT,w}$  in dB) between rooms, based on a standard test to EN ISO 717-1, which covers a range of frequencies over 16 one third octave bands from 100 to 3150 Hz. For impact sound, which only applies to floors, the sound transmission  $L_{t,w}$  across a floor due to a standard tapping machine should not exceed a maximum value.

For acceptable acoustic performance, the minimum airborne sound reduction is 45 dB for walls and floors between separate living spaces. This performance parameter is verified by test measurements of completed buildings which also take account of local acoustic transmission through junctions, such as at floor to wall junctions.

In order to ensure an acceptable degree of acoustic comfort, national regulations draw up requirements in accordance with building end-use. The occupants of a building must be protected from different noises:

- Airborne noise: vibrations which begin in the air. This is the sound of voices or internal and airborne ambient noise, or road traffic as external airborne noise.
- Structure-borne noise: resulting from shock and solid-borne vibrations. These are the sounds of footsteps, fallen objects, impact.
- Noise from equipment: generated by the operation of equipment, these are air-borne vibrations emitted through their media. These are the sounds of ventilation, heating, sanitary appliances.

The transmission of noise from the outside to a room, or from one room to another, occurs through vibration. This can be distinguished as:

- Direct transmission: through the wall which separates the receiving from the originating area.
- Lateral transfer: through the walls which are connected to the partitioning wall.
- Parasitic transmissions: these result from single points in the partition wall (air intakes, ducts or installation defects).

Acoustic insulation provided by a partition lies in its ability to resist the transmission of sound from one side to the other.

The acoustic performance of a steel building depends on the composition of the various partitions: external and internal, vertical and horizontal. Construction solutions are available which can achieve the very highest levels of performance.

## **2.4 Sustainability and Resilience**

### **2.4.1 Sustainability: General Overview**

For an architect, one of the essential approach should be the creation of sustainable space that will positively affect residents, environment and future generations.

In this case structural steel becomes the proper option, as it is infinitely recyclable, which makes it a superior material for green construction. In fact, domestically produced structural steel contains an average of 93% recycled content, and 98% of that steel is recycled back into new products at the end of a structure's life. That's one reason the U.S. Green Building Council's LEED Green Building Rating System gives maximum credit to structural steel for its contribution to a structure's overall rating.

The ability to recycle steel over and over again makes it a unique cradle-to-cradle material, in contrast with other materials that can only be used once. Over the past three decades, the steel industry has reduced greenhouse gas and overall emissions by 36% and increased the water recycling rate of steel production to 95%.

As the green building movement grows, more and more building owners, architects, engineers, and contractors are selecting structural steel framing systems to meet sustainable design and construction goals.

### **2.4.2. Cradle-to-Cradle Life Cycle of Structural Steel and Comparison with Reinforced Concrete**

#### **2.4.2.1 Cradle-to-Cradle Life Cycle of Structural Steel**

The cradle-to-cradle (C2C) framework evaluates materials across the entire life cycle while emphasizing their ability to remain in continuous, closed-loop cycles with minimal downcycling. Structural steel is considered one of the most C2C-compatible construction materials due to its high recyclability and stable material properties.

##### **a) Raw Material Extraction**

Structural steel is produced from iron ore, recycled scrap, or a blend of both. Modern production technologies—especially Electric Arc Furnace (EAF) steelmaking—allow steel to be manufactured using up to 100% scrap steel, drastically reducing energy use and carbon emissions compared to traditional Basic Oxygen Furnace (BOF) processes. Although extraction and primary steelmaking

are energy-intensive, ongoing improvements in renewable energy integration and hydrogen-based steelmaking continue to reduce environmental impacts.

### **b) Manufacturing and Fabrication**

Steel billets or coils are processed into beams, columns, rebars, or other structural profiles. Fabrication involves cutting, welding, and surface preparation. Steel components are typically manufactured to precise dimensions off-site, reducing material waste and improving construction accuracy. Industrial by-products (e.g., mill scale, slag) are often reused in other industries, supporting circularity.

### **c) Construction Phase**

Steel elements arrive on-site prefabricated, minimizing waste and reducing construction time. Bolted and welded connections allow for easy disassembly. The lightweight nature of steel structures typically results in reduced foundation loads and lower material consumption compared to concrete.

### **d) Use Phase**

During the service life of a building, steel provides:

- High structural strength
- Excellent performance under extreme loading
- Low maintenance when appropriately protected against corrosion  
Coatings such as galvanization or fire protection materials can be renewed without affecting the steel's recyclability.

### **e) End-of-Life: Disassembly and Recycling**

Steel is **indefinitely recyclable** without degradation of mechanical properties. More than **98%** of structural steel from buildings is recovered at end-of-life in Europe and North America. The key advantages are:

- Components can be reused directly (C2C loop).
- Scrap steel is melted and repurposed into new structural steel (closed-loop recycling).
- Steel retains full material quality even after repeated recycling cycles.

**Table 2.4 - Comparison with Reinforced Concrete in a Cradle-to-Cradle Context**

<b>Aspect</b>	<b>Structural Steel</b>	<b>Reinforced Concrete</b>
<b>C2C Compatibility</b>	Excellent – fully recyclable, reusable	Poor – composite material, difficult to separate
<b>Recyclability</b>	90–100% recyclable	Recycling usually results in downcycled aggregates
<b>Circular Use</b>	Components can be disassembled and reused	Concrete demolition produces mixed waste
<b>Carbon Footprint</b>	High in production but improving rapidly	High due to cement production (approx. 8% of global CO <sub>2</sub> emissions)
<b>End-of-Life</b>	Closed-loop recycling	Mostly downcycled into road base, not structural concrete

#### 2.4.2.2 Environmental Comparison between basic structural materials

##### a) Recycling Potential

- ◇ **Steel:** Fully recyclable with no loss of quality.
- ◇ **Concrete:** Reinforcement steel can be recovered, but the concrete matrix becomes rubble. Recycled concrete aggregates cannot match the mechanical properties required for high-performance structural concrete.

##### b) Production Emissions

- ◇ Steel production emits approximately 1.8–2.0 t CO<sub>2</sub> per ton of steel (BOF), though EAF production emits much less (~0.3–0.7 t CO<sub>2</sub>/ton depending on energy source).
- ◇ Cement production alone emits 0.6–0.9 t CO<sub>2</sub> per ton of cement, making reinforced concrete one of the highest-emission construction materials.

##### c) Circularity and Longevity

- ◇ Steel structures can be adapted, dismantled, and reused with limited waste.
- ◇ Concrete structures are difficult to dismantle without destruction; modifications often require demolition.

##### d) Waste Generation

- ◇ **Steel:** minimal waste, and almost all waste is reprocessed.
- ◇ **Concrete:** substantial demolition waste; difficult to return to high-value applications.

**Table 2.5 - Comparison of structural steel and reinforced concrete**

<b>Stage</b>	<b>Structural Steel</b>	<b>Reinforced Concrete</b>
<b>Mill / Raw-Material Production</b>	Overall carbon emissions have been reduced by 36% since 1990 and steel production has a water-recycling rate of 95%, resulting in a net consumption of only 70 gallons per ton.	The cement/concrete sector is responsible for large CO <sub>2</sub> emissions (often cited at ~8-9% of global CO <sub>2</sub> ) during raw-material extraction and cement manufacture.
<b>Fabrication / Production</b>	More than 1,700 steel fabricators in the U.S. supply fabricated structural steel for building and bridge projects.	A study showed that in reinforced concrete columns increasing concrete strength from 30 MPa → 50 MPa allowed ~15% reduction in concrete volume and up to ~22% reduction in steel reinforcement.
<b>Construction and Erection</b>	Steel is fabricated off-site to strict tolerances and can be erected quickly in the field, meaning fewer workers on the job-site, safer working conditions, shorter construction schedules and reduced emissions from construction equipment.	The construction phase (on-site casting, formwork, curing) typically has higher on-site energy/transport/formwork demands.
<b>Building Operation / Use</b>	Long-span beams with open, column-free spaces attract potential occupants. In addition, steel framing can more easily be adapted for future changes in loading conditions, vertical expansion and changes in occupancy when compared to other framing systems.	High thermal mass/inertia of concrete can benefit occupant comfort and building energy performance, but adaptability for structural change (e.g., vertical expansion, re-use) is more limited compared to steel.
<b>Deconstruction / End of Life</b>	Beams, columns and other structural steel elements removed from a building can be re-fabricated for use in new structures without having to be melted and rolled; remaining steel elements are captured as scrap and used to create new steel products.	Structural elements are often demolished, crushed and reused as aggregate rather than reused in their original form.

<p><b>Scrap Collection / Recycling</b></p>	<p>By weight, 81% of all steel products are recovered for recycling at the end of their life. This includes 85% of automobiles, 82% of appliances, 70% of containers, 72% of reinforcing bar, and 98% of structural steel.</p>	<p>Although recycling of concrete and reuse of crushed aggregate is practiced, the closed-loop reuse of structural concrete elements remains very limited.</p>
<p><b>Scrap Processing / Recycling Process</b></p>	<p>Steel is the most recycled material in the world, with domestic mills recycling more than 70 million tons of scrap each year. Currently structural steel includes ~93% recycled content.</p>	<p>Concrete production and recycling studies show that using recycled concrete aggregates (RCA) for new concrete can reduce environmental impact.</p>

**2.4.3. Resilience- General Overview**

The material’s resilience - how it performs during and after an extreme event - is a basic consideration for any project. Structural steel’s inherent resilience as a material can address the owner’s desire to maintain select building functions after an extreme event, especially when coupled with purposeful design decisions addressing resilient requirements.

After such an event occurs, structural steel is more easily repaired and/or replaced than other materials. Resilience following a blast or terrorist attack is a newer concern that further challenges the engineer’s ability to design for drift. Current building codes address occupant safety during an extreme event but do not address not a structure’s functionality and recovery following the event. Structural steel’s durability, strength, elasticity, toughness, lack of combustibility, and resistance to decomposition make it a uniquely resilient choice for safe structures that last.

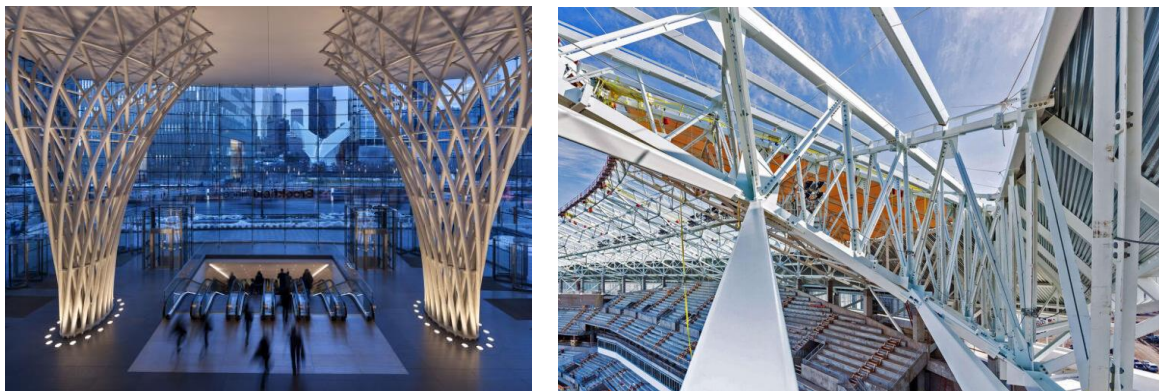
**2.5 Architecturally Exposed Structural Steel**

**2.5.1 Introductory aspects**

Architecturally exposed structural steel puts the aesthetic focus on the structural integrity of a building. The striking visual impact of these iconic structures is possible because steel is fabricated in a nearly limitless range of shapes, tapered forms, curves, colours, and finishes.

Figure 2.20 presents two examples of architecturally exposed structural steel. For clarity, the Architecturally Exposed Structural Steel (AESS) category system is typically only applied to fabricated structural steel elements such as anchor rods, base plates, beams, bracing, canopy framing, columns, connection materials, crane

stops, girders, lintels, posts, shear stud connectors, and trusses. Unfinished, reused, galvanized, or weathering steel members may all be fabricated with AESS requirements.



**Figure 2.20** - Architecturally Exposed Structural Steel, adapted from [Waltersgroupinc] and [Waltersgroupinc]

AESS components get the royal treatment during fabrication, shipment, and erection to avoid blemishes and unwanted surface appearance. Workers take extra care when handling the steel and removing temporary braces or fixtures. For some categories, all backing and runoff tabs are removed, and welds are ground smooth. Oil, grease, dirt, and loose mill must also be removed from basic, unpainted steel for an attractive, striking finish.

## 2.5.2 AESS Categories and Applications

Architecturally Exposed Structural Steel (AESS) refers to steel structural elements that are intentionally left visible as part of the architectural expression of a building. In such cases, the steel structure is not merely a load-bearing system but also contributes directly to the aesthetic, spatial, and experiential qualities of the architecture. Because these elements remain exposed, AESS requires higher standards of fabrication, finishing, and detailing than conventional structural steel.

AESS is commonly classified into categories based on the level of visual exposure and architectural importance. Lower AESS categories are typically used in areas where the steel is visible but not a primary design feature, such as service zones or secondary spaces. In these cases, standard fabrication tolerances and finishes may be acceptable. Higher AESS categories apply to highly visible structural elements located in public or representative spaces, where the steel structure plays a central architectural role. These applications demand stricter requirements regarding surface quality, weld appearance, alignment, and finishing, often involving additional fabrication processes and quality control.

The application of AESS is particularly relevant in contemporary architecture, where structural honesty and material expression are key design principles. In residential, commercial, and cultural buildings, exposed steel frames can enhance spatial openness, allow for slender structural members, and contribute to flexible interior layouts. Moreover, AESS is frequently employed in entrance halls, atriums, circulation spaces, and façades, where the visibility of the structure reinforces the architectural identity of the building.

Overall, the use of AESS requires close coordination between architects, structural engineers, and fabricators from the early design stages. When properly detailed and executed, AESS systems successfully combine structural performance with architectural quality, transforming structural elements into defining components of the built environment.

**Table 2.6 - AESS TYPES**

<b>AESS Category</b>	<b>Requirements / Description</b>
<b>AESS 1</b>	<ul style="list-style-type: none"> <li>• Edges ground smooth</li> <li>• Continuous weld appearance</li> <li>• Weld spatters removed</li> </ul>
<b>AESS 2</b>	<ul style="list-style-type: none"> <li>• Uniform/smooth welds</li> <li>• Fabrication marks not apparent</li> <li>• One-half standard fabrication tolerances</li> </ul>
<b>AESS 3</b>	<ul style="list-style-type: none"> <li>• Mill marks removed</li> <li>• Butt and plug welds ground smooth and filled</li> <li>• HSS seams oriented for reduced visibility</li> <li>• Joint gap tolerances minimized</li> </ul>
<b>AESS 4</b>	<ul style="list-style-type: none"> <li>• Weld-show through minimized</li> <li>• Surfaces filled and sanded</li> <li>• HSS seams not apparent</li> <li>• Welds contoured and blended</li> </ul>

## **2.6 Comparison of Steel and Reinforced Concrete Structures**

### **2.6.1 General Overview**

Steel structures for residential building frames are more modern because they are faster to build, more lightweight, more flexible and sustainable, enabling large spans and a very appealing aesthetic. Reinforced concrete remains a robust and durable option, with applications such as the use of resistant cores (in reinforced concrete walls for lift and staircases) to increase stability. On the other hand, prefabricated systems speed up the construction process, making them a competitive option. The choice between steel and reinforced concrete clearly depends on the type of project, with steel being more advantageous in terms of fastness, span width and sustainability. The concrete option is preferred for its

robustness (although often assumed empirical) and durability, as well as being more suitable for exploiting the aesthetics of the material in projects that require large masses.

Major comparisons that must be made when choosing each type of material for structural frames concerns the question of whether construction companies have access to qualified and specialised workforce. This situation is more relevant and demanding when the solution focuses on the choice of structural steel, given the manufacturing in industrial production units of the vast majority of structural parts and elements for the majority of constructions in terms of structure. The labour required for the construction of reinforced concrete frames is, in most cases and excluding special cases, less specialised than in the case of steel frames.

Metal-mechanics companies, usually responsible for manufacturing and assembling steel frames, have much more specialised workers on their staff than companies that only have the qualifications and skills to build in reinforced concrete. However, the specialised skills of formwork carpenters and ironworkers make all the difference when dealing with structures and constructions that are more challenging in the second example mentioned above.

The choice between steel or reinforced concrete frames for low/medium-rise residential buildings (up to 4 or 5 storeys) naturally depends on the priorities and nature of the project, such as deadline, cost, aesthetics and durability.

Steel and reinforced concrete are the two most commonly used structural systems in low- to mid-rise residential buildings, each offering specific advantages and limitations. Steel structures are characterized by rapid construction due to off-site prefabrication, reduced structural weight, and high dimensional accuracy. These characteristics allow for greater architectural flexibility, longer spans, and easier future adaptations or vertical extensions. Steel systems are particularly advantageous in projects where construction speed and design flexibility are key requirements.

However, steel structures require additional measures to ensure adequate fire resistance and acoustic performance, especially in residential applications. Without proper detailing, lightweight steel floors and partitions may be more susceptible to sound transmission. Initial costs may also be higher in regions where steel construction is less common.

Reinforced concrete structures are widely adopted in residential buildings due to their durability, good inherent fire resistance, and satisfactory acoustic and vibration performance. Their high thermal mass can contribute to improved indoor comfort and energy efficiency. For buildings up to five storeys, reinforced concrete solutions are well established, cost-effective, and familiar to most construction teams.

On the other hand, reinforced concrete construction generally involves longer construction times due to on-site casting and curing processes. Structural modifications and future adaptations are more complex, and the higher self-weight results in increased foundation demands. Ultimately, the choice between steel and reinforced concrete should be based on project-specific requirements, balancing construction efficiency, performance, and long-term adaptability.

### 2.6.2 Steel Frames

Steel is often seen as a much more advanced and efficient option for this type of construction, as well as being a much more sustainable option, which is critical today given environmental and ecological considerations. Tables 2.7 and 2.8 present advantages and disadvantages inherent to steel frames.

**Table 2.7** - Advantages of steel framed constructions

<b>Key Advantages</b>	<b>Details</b>
<b>Speed of Construction</b>	The parts/elements are prefabricated and assembled on site, significantly reducing construction time (especially when compared to concrete curing time), which can lead to a faster return on investment. Bolted connections are more competitive than welded connections, except in special situations and less common structures.
<b>Structural Lightness</b>	The global self-weight of the structure is lower, which means less robust foundations and, consequently, lower foundation costs, a very important factor in lower buildings.
<b>Flexibility and Span Length</b>	It allows greater architectural freedom in the creation of interior spaces without intermediate pillars, making it suitable for large spans, ideal for more modern and adaptable residential layouts.
<b>Sustainability (Waste)</b>	It produces less waste on the construction site being the steel material itself 100% recyclable.

**Table 2.8** - Disadvantages of steel framed constructions

<b>Key Disadvantages</b>	<b>Details</b>
<b>Initial Cost and Labour</b>	The initial cost of the material and the need for much more specialised labour (workforce) for assembly can be higher.
<b>Fire Performance</b>	The elements require passive fire protection (such as intumescent paints or suitable coatings) to ensure the stability of the structure in the event of a fire.

### 2.6.3 Reinforced Concrete Frames and Comparison with Steel Frames

Reinforced concrete is traditionally the most widely used material in Portugal. It is robust and has also benefited from certain innovations that have made it more competitive. Tables 2.9 and 2.10 present advantages and disadvantages inherent to reinforced concrete frames.

**Table 2.9 - Advantages of reinforced concrete frames**

<b>Key Advantages</b>	<b>Details</b>
<b>Robustness and Durability</b>	It is known for its intrinsic greater resistance to fire and for being very durable, requiring little maintenance over time. However, in certain environments, it degrades over time without special protection.
<b>Material Cost (Portugal)</b>	The final material, which includes aggregates such as gravel, cement, sand and water, is generally more affordable for construction companies, requiring less specialised labour being more common in the traditional Portuguese construction market.
<b>Flexibility of Form and Aesthetics</b>	It allows parts such as beams, columns and slabs to be moulded into any shape, provided that the desired formwork geometry is provided.
<b>Stability</b>	The incorporation of resistant cores (reinforced concrete walls, common in staircases/lift shafts) increases the overall stability of the structure against wind and seismic action.

**Table 2.10 - Disadvantages of reinforced concrete frames**

<b>Key Disadvantages</b>	<b>Details</b>
<b>Construction Time</b>	The execution of reinforced concrete elements, including the formwork, reinforcement, concreting and curing time required to achieve the desired strength class, makes the process much more time-consuming than steel, since steel arrives on site in several parts to be joined together, already possessing its full individual strength.
<b>Weight and Foundations</b>	It is a heavy material for lattice elements, above all, for slabs, which may require deeper and more expensive foundations, depending, of course, on the nature of the soil and the geometry of the foundation elements.
<b>Sustainability (Production)</b>	Cement production consumes a lot of energy, and its traditional use usually leads to greater waste (rubble) on site. The use of precast concrete elements helps to reduce these two disadvantages.

According to above mentioned sources and following the correspondent guidelines, it is possible to establish several architectural criteria for steel residential

buildings up to five stories include ensuring clear floor spans, integrating services efficiently, and addressing the building envelope's thermal and acoustic performance.

Key design factors are integrating the structure with the façade, providing appropriate vertical and lateral support, and ensuring the building's stability under loads like wind and seismic forces.

The design must also account for site conditions, foundation systems, and construction methods like prefabrication to meet safety, speed, and cost requirements.

In order to establish a more detailed comparison between reinforced concrete and steel spans typically used in frames for the residential buildings projects, Table 2.11 also presents a summary of information regarding the

- . span/effective depth ratio,
- . typical slab thickness (span/ratio),
- . deflection limit,
- . punching shear control perimeter (flat slab),
- . typical column grid spacing,
- . approximately beam depth (preliminary design),
- . typical floor system depth (beam plus slab),
- . approximately self-weight for each structural material, and
- . economical story height.

The general units are indicated for the several situations.

The preliminary design and project considerations are guided by Eurocode 2 for reinforced concrete elements and Eurocode 3 for structural steel elements.

Based on the considerations mentioned before and the requirements for a project related to a residential building, the main criteria to be taken into account for the design of the aforementioned typology of buildings are presented below.

Table 2.11 – Comparison between reinforced concrete and steel spans used in frames

Parameter	Reinforced Concrete ( EC2 )	Steel ( EC3 )	Units / Notes
Typical beam span range	6 – 10 m	8 – 14 m	m
Typical slab span (1-way)	4 – 6 m	(uses composite deck)	m
Typical flat slab span (2-way)	6 – 9 m	Composite: 6 – 14 m	m
Span / effective depth (L/d)	18–20 (simply supported) 25–30 (continuous) 8–10 (cantilever)	18–20 (non-composite) 22–25 (composite) 8–12 (cantilever)	dimensionless ratio
Effective span (definition)	Clear span + ½ bearing at each end	Centre-to-centre of supports	—
Typical slab thickness (span/ratio)	≈ L/20 to L/30	≈ L/25 to L/30 (composite floors)	ratio / derived mm
Deflection limit	Span / 250	Span / 250 – Span / 300	ratio
Punching shear control perimeter (flat slab)	1.5 – 2 × d from column face	Similar when composite slab used	multiple of effective depth (d)
Typical column grid spacing	6 – 9 m	8 – 14 m	m
Cantilever maximum ratio (L/d)	8 – 10	8 – 12	dimensionless
Approx. beam depth (preliminary)	L/20 to L/25	L/18 to L/22	ratio
Typical floor system depth (beam + slab)	500 – 700 mm	300 – 600 mm	mm
Self-weight (approx.)	24 – 25 kN/m <sup>3</sup>	78.5 kN/m <sup>3</sup> (material) but 3–4× lighter per system	kN/m <sup>3</sup>
Economical story height	3.2 – 3.6 m	3.0 – 3.4 m	m

### **i) Structural and spatial criteria**

- Clear floor spans: Use long-span beams to minimize the number of internal columns, creating flexible column-free living spaces.
- Column and beam grid: Align columns on a grid that is practical for apartment layouts and, in the case of mixed-use buildings with parking, for car park spaces.
- Service integration: Plan for the efficient integration/distribution of building services, such as plumbing, electrical, and HVAC systems, into the structural design.
- Podium structures: For buildings with podiums, design long-span beams with large web openings to allow for horizontal service distribution.
- Structural form: Work with engineers to develop a structural concept that provides both vertical support and lateral stability, which is crucial for resisting wind and seismic forces.
- Adaptability: Design for long-term use and future adaptability, such as through the use of relocatable partitions and open roof systems.

### **ii) Building envelope and façade criteria**

- Lateral support: Provide vertical and lateral support for the cladding system. Ensure the façade system has adequate support and is compatible with the steel structure.
- Thermal performance: Minimize thermal bridging (a common issue in steel construction) by placing insulation correctly and detailing the junctions between different materials, through methods like external insulation and slotted studs.
- Opening integration: Ensure that windows, doors, and other openings are properly incorporated into the structural design. Interfaces: Agree on the interface details between the steel frame, cladding, roofing, and infill walls with the structural engineer.
- Prefabrication: Consider opportunities for prefabricating façade panels, potentially with cladding attached, to speed up construction.
- Acoustic performance: Consider the acoustic performance of the façade, as steel-framed systems can achieve good levels of sound reduction.

### **iii) Performance and safety criteria**

- Load resistance: Ensure the structure can safely support all anticipated vertical and horizontal loads, including wind and seismic forces.
- Fire safety: Incorporate appropriate fireproofing measures and design for the required fire resistance ratings to prevent fire spread.
- Acoustic performance: Meet minimum airborne sound reduction requirements between living units, typically 45 dB.
- Durability: Design for the specified design life, adhering to corrosion protection standards like ISO 12944.

#### **iv) Construction and site criteria**

- Site conditions: Consider how site conditions, such as soil type, will influence the foundation system.
- Construction method: Factor in construction speed and access for crane age and material storage. Leverage steel's potential for faster construction by considering the speed of erection and prefabrication opportunities. Be mindful of site constraints, such as crane age limitations and space for storing materials and components.
- Coordination: Agree on appropriate geometric tolerances and interface details with the contractor for foundations and temporary structures to ensure the design is constructible. Coordinate with the structural engineer on foundation requirements, which are influenced by site conditions and the superstructure's load

## **Chapter 3**

# **Architectural and Structural Efficiency of Steel Frames**



### 3. Architectural and Structural Efficiency of Steel Frames

#### 3.1 Steel Frame Analysis: Span-to-height or depth Ratios

(According to ArcelorMittal Profiles, and Eurocode 3 Deflection Control)

The analysis of span length ( $L$ ) versus structural depth ( $d$ ) in steel-framed residential buildings is best evaluated using two distinct but related metrics that validate the architectonic potential:

- a) Architectural Metric: The relationship between Span Length ( $L$ ) and Clear Ceiling Height ( $H$ ) within a fixed floor-to-floor height ( $h$ ). This directly demonstrates the gain in usable space.
- b) Structural Metric: The relationship between Span Length ( $L$ ) and Total Floor Thickness ( $d$  or  $e$ ), with beam height  $h_b$  + slab thickness  $e$ . This focuses on the structural efficiency (the traditional  $L/d$  ratio).

This dual-ratio approach, based on ArcelorMittal European profiles and adherence to Eurocode 3 (EN 1993-1) deflection limits, is crucial for demonstrating steel's versatility and flexibility, which influences the structural efficiency.

#### 1. Span Length ( $L$ ) versus Total Floor Thickness ( $d$ ) Ratio

The classic structural efficiency ratio ( $L/d$ ) is an important parameter for the evaluation floor thickness. A high ratio (e.g., 30:1) signifies a shallow structural system for a long clear span.

Achieving a high  $L/d$  ratio while satisfying the stringent Eurocode 3 Serviceability Limit State (SLS) for deflection (e.g.,  $\delta_2 \leq L/350$ ) is the technical evidence of steel's superiority.

Table 3.1 focuses on the structural system only, where the total floor thickness  $d$  is the sum of the steel beam height ( $h_b$ ) and the composite slab thickness ( $e$ ), presenting five examples if a span length of 8 m, 9 m, 10 m, 11 m, and 12 m, respectively, is considered.

The correspondent ratios appear lower than the 25:1 target because  $d$  includes the slab thickness ( $e$ ) and the selection prioritizes meeting the strict deflection/vibration limits for residential comfort.

The HEA profiles demonstrate higher efficiency due to their wider flanges, leading to better stiffness-to-weight.

The beam height ( $h_b$ ) shown in Table 3.1 was determined using a process of estimation and iteration, primarily governed by the strict deflection limits specified by Eurocode 3 (EN 1993) for residential comfort, rather than just the strength of the beam.

Table 3.1 - Structural Efficiency Ratio ( $L/d$ )

Span Length ( $L$ ) [m]	Proposed Arcelor Mittal Profile	Beam Height ( $h_b$ ) [mm]	Slab Thickness ( $e$ ) (Composite Deck) [mm]	Total Floor Thickness $d = h_b + e$ [mm]	Structural $L/d$ Ratio	Eurocode 3 Deflection Control
8	IPE 330	330	130	460	17.4:1	$\delta_2 \leq L/350$
9	IPE 360	360	130	490	18.4:1	$\delta_2 \leq L/350$
10	IPE 400	400	140	540	18.5:1	$\delta_2 \leq L/350$
11	HEA 400	388	140	528	20.8:1	$\delta_2 \leq L/350$
12	HEA 450	440	150	590	20.3:1	$\delta_2 \leq L/350$ and Vibration

A step-by-step methodology was used to select the IPE/HEA profiles.

## 2. Establishment of Governing Criteria (Eurocode 3)

### A. Design Loads (Based on EN 1991-1-1)

For a typical multi-storey residential building floor, the characteristic loads were assumed:

- Variable/Live Load,  $Q_k = 2.0 \text{ kN/m}^2$  (Category A: Residential, per EN 1991-1-1).
- Permanent/Dead Load,  $G_k = 4.0 \text{ kN/m}^2$  (Includes slab/deck self-weight, ceiling, services, and an allowance for partitions).
- Tributary Width: A reasonable value, such as 3.0 m was assumed between secondary beams.

These area loads are converted to a uniformly distributed line load on the beam,

$$q = Q_k \times \text{Tributary Width.}$$

### B. Critical Deflection Limit (Serviceability Limit State - SLS)

The most critical factor for residential comfort is the deflection that occurs after the installation of sensitive finishes (like plaster or rigid walls). A common and conservative limit adopted in European National Annexes is:

$$\delta_2 \leq L/350$$

This limit requires high stiffness, which means the Moment of Inertia ( $I_y$ ) of the beam must be large, necessitating a certain beam height ( $h_b$ ).

### 3. Iterative Sizing Process

The height was not calculated directly from a single formula but selected by working backward from the required stiffness ( $EI_y$ ) and then selecting the most appropriate ArcelorMittal profile.

#### - Step 1: Preliminary Estimation of Required Inertia, $I_y$

For a simply supported beam with a uniformly distributed load ( $q$ ), the maximum deflection ( $\delta$ ), obtained by the method of integration of the differential equation of the elastic line, it is given by

$$\delta = 5 q L^4 / (384 EI_y)$$

To satisfy the Eurocode limit ( $\delta \leq L/350$ ), the required moment of inertia must be:

$$I_{y,req} \geq 5 q L^4 / (384 E(L/350)) \Leftrightarrow I_{y,req} \geq 5 \cdot 350 \cdot q L^3 / 384 E$$

- ◇  $q$  (SLS line load) = Calculated using  $Q_k$  (live load) only for  $\delta_2$  (or a combination of  $Q_k$  and a portion of  $G_k$  depending on the specific National Annex rule for  $\delta_2$ ).
- ◇  $L$  (Span) = 8,0 m, 9,0 m, ..., 12,0 m.
- ◇  $E$  (Elastic Modulus for Steel) = 210 GPa = 210,000 N/mm<sup>2</sup>.

#### - Step 2: Selection of ArcelorMittal Profile

Using the calculated  $I_{y,req}$ , and consulting the properties tables for standard European profiles (IPE, HEA) from ArcelorMittal data (similar to the information in the search results) to find the smallest profile whose  $I_y$  property meets or exceeds the required value.

**Table 3.2** - Actual and approximation values of moment of inertia ( $y$  axis) for selected profile for beams (considering only 3 spans)

Span ( $L$ )	$I_{y,req}$ (Approximation)	Selected Profile	$I_y$ (Actual value)	$h_b$ (Actual)
8 m	11,00 cm <sup>4</sup>	IPE 330	11,77 cm <sup>4</sup>	330 mm
10 m	20,00 cm <sup>4</sup>	IPE 400	23,13 cm <sup>4</sup>	400 mm
12 m	40,00 cm <sup>4</sup>	HEA 450	47,400 cm <sup>4</sup>	440 mm

For longer spans (11 m, 12 m), the HEA profile (wide flange) becomes more efficient than the IPE profile because its shape provides a much larger  $I_y$  for a relatively smaller increase in overall depth, which is ideal for satisfying the strict  $L/350$  deflection limit while maintaining a high span-to-depth ratio.

### - Step 3: Verification (Strength)

Although deflection usually governs, the selected profile must also be verified against the Ultimate Limit State (ULS) for bending moment ( $M_{Ed}$ ) and shear force ( $V_{Ed}$ ) according to Eurocode 3,  $M_{Ed} \leq M_{c, Rd}$  and  $V_{Ed} \leq V_{c, Rd}$ .

For typical residential loads, the profiles selected based on the deflection criterion are almost always sufficient for strength in S275 or S355 steel grade.

In summary, the determination of  $h_b$  and the corresponding IPE/HEA section was driven by the Serviceability Limit State (Deflection), which is the key to demonstrating the  $L/d$  efficiency and superior  $L/H$  architectural potential of the steel frame.

### 4. Span Length ( $L$ ) versus Clear Ceiling Height ( $H$ ) Ratio

This constitutes the Architectural flexibility metric. Assuming a constant Floor-to-Floor Height ( $h$ ) (e.g., a standard 3.0 m for residential buildings), a thinner floor system ( $d$ ) directly results in a greater Clear Ceiling Height ( $H$ ), calculated as

$$H = h - d - (\text{Finishes/MEP})$$

This gain in  $H$  is highly valued in modern architecture, with  $h$  = total height.

Table 3.3 demonstrates the impact of the structurally efficient floor system on the final architectural space, assuming a Floor-to-Floor Height ( $H$ ) of 3000 mm and an allowance for ceiling finishes/MEP of 100 mm (by hypothesis). So,

$$H (\text{Clear Ceiling Height}) = h - d - 100$$

**Table 3.3 - Architectural Flexibility Ratio ( $L/H$ ) for 5 spans**

Span Length ( $L$ ) [m]	Floor Thickness ( $d$ ) [mm] (Table 1)	Clear Ceiling Height ( $H$ ) [m]	$L/H$ Ratio (Architectural)	Clear Height Gain versus Concrete*	Architectonic Potential
8	460	2.440	3.28 : 1	≈ +100 mm	Standard comfort achieved efficiently.
9	490	2.410	3.73 : 1	≈ +100 mm	Excellent space utilization.
10	540	2.360	4.24 : 1	≈ +150 mm	Enables free plan with superior $H$ .
11	528	2.372	4.64 : 1	≈ +170 mm	Ideal for luxury/open-loft designs.
12	590	2.310	5.19 : 1	≈ +110 mm	Max. $L$ for residential, maintaining excellent $H$ .

The Clear Height Gain is estimated against a typical concrete solution for the same span, which might have a floor thickness ( $d$ ) of 600 mm to 700 mm (due to lower  $L/d$  ratio), thus proving steel's efficiency.

### **Conclusion for Deliverable**

The AutoCAD schematic representation should clearly contrast the two-part result:

- a) Table 1: Use the chosen IPE/HEA sections to demonstrate a high structural  $L/d$  ratio that meets Eurocode 3 deflection limits.
- b) Table 2: Use the resulting thin floor depth  $d$  to demonstrate the maximum possible clear ceiling height ( $H$ ), which is the ultimate goal of architectonic flexibility and quality of living space.

This dual focus rigorously justifies steel's advantages over concrete, proving both structural feasibility and architectural potential.

This question refers to a specific structural design comparison, likely from an engineering or architecture report, typically comparing a new structural system against a traditional reinforced concrete system.

## **1. Clear Ceiling Height ( $H$ ) Calculation**

The Clear Ceiling Height ( $H$ ) was calculated using the formula you provided, based on the fixed design parameters assumed for the residential building.

### **A. Assumed Design Parameters**

1. Fixed Floor-to-Floor Height ( $h$ ): A standard residential 3.0 m was assumed.  
 $h = 3000 \text{ mm}$
2. Fixed Allowance for Finishes and Services (100 mm): This fixed value accounts for the thickness of the floor finish above the structural slab and the space needed for a suspended ceiling, lighting fixtures, and minor MEP (Mechanical, Electrical, Plumbing) services *below* the structural depth.
3. Variable Total Floor Thickness ( $d$ ): This value is taken directly from the Table 1 (the structural efficiency table), representing the steel beam height ( $h_b$ ) plus the composite slab thickness ( $e$ ).

### **B. Calculation Formula**

The calculation for each row is:

$$H = h - d - 100 \text{ mm}$$

### C. Example Calculation (for 10 m span)

Using the values from the 10 m row:

- $h = 3000$  mm
- $d = 540$  mm (from Table 1)
- Fixed Allowance = 100 mm

$$H = 3000 \text{ mm} - 540 \text{ mm} - 100 \text{ mm} = 2360 \text{ mm}$$

## 2. Clear Height Gain *versus* Concrete Calculation

The clear height gain *versus* concrete quantifies the height advantage achieved by the more structurally efficient steel system compared to a hypothetical, traditionally sized reinforced concrete system for the same span.

### A. Assumed Concrete Benchmark

To calculate the "gain," a representative total floor thickness ( $d_{\text{concrete}}$ ) had to be estimated for an equivalent reinforced concrete structure designed to the same span and Eurocode deflection standards.

- Concrete Efficiency: For a large residential span, concrete beams typically operate at a lower  $L/d$  ratio (Span-to-Depth) to control deflection and vibration, often ranging from 15:1 to 20:1.
- Estimation: A conservative average of the required total concrete floor depth for the 8 m to 12 m range was assumed to be approximately 650 mm to 700 mm (including the beam depth, slab, and fire protection).

For the purpose of the table, a fixed Reference Concrete Floor Thickness ( $d_{\text{Ref}}$ ) of 690 mm was used as a baseline average for comparison.

### B. Calculation Formula

The gain is calculated by comparing the steel system's total floor thickness ( $d$ ) against the reference concrete floor thickness ( $d_{\text{Ref}}$ ):

$$\text{Clear Height Gain} = d_{\text{Ref}} - d_{\text{Steel}}$$

### C. Example Calculation (for 10 m span)

Using the values for the 10 m row and the assumed concrete baseline:

- $d_{\text{Ref}} = 690$  mm (Reference Concrete Thickness)
- $d_{\text{Steel}} = 540$  mm (Steel Thickness from Table 1)

$$\text{Clear Height Gain} = 690 \text{ mm} - 540 \text{ mm} = 150 \text{ mm}$$

This result is presented in the table as  $\approx +150$  mm. This demonstrates that using the IPE 400 steel beam saves 150 mm of vertical space compared to the typical concrete alternative, which can then be added to the clear ceiling height.

Why the HEA profile achieves a better  $L/d$  ratio than the IPE profile, as suggested by the 11 m and 12 m spans?

On the structural and geometric reasons why the HEA profile is often more efficient than the IPE profile for achieving a high  $L/d$  ratio, especially at longer spans like 11 m and 12 m in residential construction.

This difference is key to the analysis as it directly relates to design freedom and optimizing the clear ceiling height.

### IPE versus HEA: Optimizing the $L/d$ Ratio

The Span-to-Depth ratio ( $L/d$ ) is maximized when a beam provides the highest possible stiffness (resistance to deflection) for the least possible overall depth. This stiffness is mathematically represented by the beam's Moment of Inertia ( $I_y$ ).

#### 1. Geometric Differences

The core difference lies in how the steel cross-section is distributed.

Table 3.4 - Comparison between IPE and HEA efficiency

Feature	IPE (I - European Profile)	HEA (H - European Profile - Light)
Shape	Taller and narrower web; narrow flanges.	Wider flanges; shorter overall depth for the same nominal weight/series.
Flange Width ( $b_f$ )	$b_f < h$ (Flange width is less than height).	$b_f \approx h$ (Flange width is approximately equal to height).
Efficiency Goal	Optimal use of material for general bending.	Optimal stiffness for deflection/vibration control.

#### 4. Stiffness and the Moment of Inertia ( $I_y$ )

The moment of inertia ( $I_y$ ) dictates a beam's stiffness and resistance to bending and deflection. For an I-section,  $I_y$  is largely determined by the flanges, as they are positioned farthest from the neutral axis.

➤  $I_y \approx 2 A_f h^2/4$

where  $A_f$  is the flange area and  $h$  is the overall height.

The HEA profile achieves superior stiffness for a given depth ( $h_b$ ) for two main reasons:

- Wider Flanges: The wider flanges of the HEA profile (where  $b_f$  is nearly equal to  $6h$ ) place more material farther away from the center of the beam. This increases the Moment of Inertia ( $I_y$ ) compared to an IPE section of the same or slightly greater depth.
- Reduced Self-Weight (HEA versus HEB): The HEA profile is the “light” version of the H-beam series (HEB is “standard” or heavier). This provides a large moment of inertia without excessive self-weight, making it highly efficient.

### 5. Application to Residential Spans (11 m and 12 m)

At shorter spans (8 m to 10 m), the IPE profile often provides enough stiffness to meet the  $L/350$  deflection limit while being cost-effective.

However, as the span increases to 11 m or 12 m, the required inertia  $I_y$  increases sharply (once  $I_y \propto L^3$ ). To meet this requirement:

- a) If using IPE: You would have to select a very deep section (e.g., IPE 500 or IPE 550) which would significantly reduce the clear ceiling height, reducing the  $L/d$  ratio.
- b) If using HEA: You can choose a shallower section (e.g., HEA 400 or HEA 450) that possesses a high  $I_y$  due to its wide flanges. This provides the necessary stiffness to control deflection/vibration while minimizing the overall beam depth ( $h_b$ ), thereby maximizing the  $L/d$  ratio and maintaining a high  $H$  (clear ceiling height).

In conclusion, the HEA profile is the superior choice for longer residential spans because its geometry provides the high moment of inertia needed to satisfy the restrictive Eurocode 3 deflection criteria with the minimum structural depth, directly supporting the project’s goal of architectural flexibility and superior floor plans.

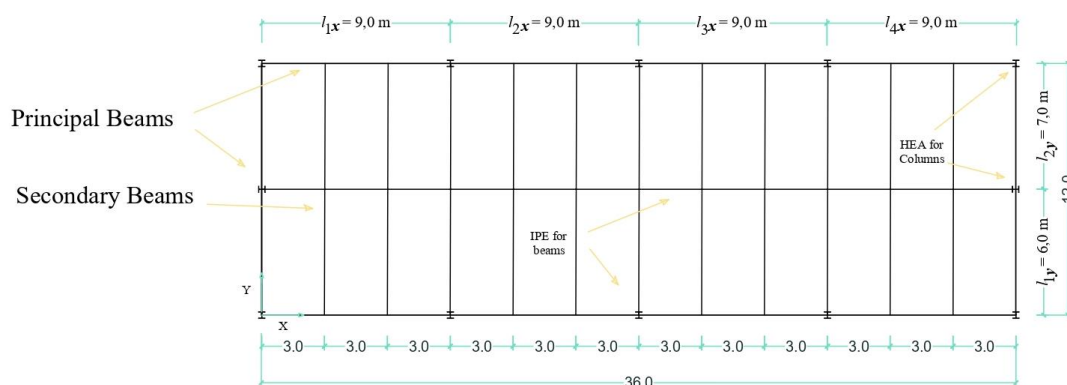


Fig. 3.1 - General plan view of a structural distribution for a building

A layout with 2 spans of 6 m each in the y direction and 4 spans in x direction (with 9 m + 9 m + 9 m + 9 m) requires 4 column lines in the x direction, including 5 columns each. Combining the 3 column lines in the x direction, the total number of columns is indeed 3 rows in x x 5 rows in y = 15 columns.

### 1. Updated Geometry and Layout

The structural geometry is confirmed as:

- X- Direction (Length) - 36 m with 4 spans: 9 m + 9 m + 9 m + 9 m
  - Requires 5 column lines in x.
- Y- Direction (width) - 12 m with 2 spans : 6 m + 6 m
  - Requires 3 column lines in y.
- Total Columns: 5 x 3 = 15 columns.

### Beam Count

The total number of main beams per floor will be:

- Beams in x-Direction : 4 spans x 3 rows = 12 beams (aligned in the X-direction)
- Beams in y-Direction : 2 spans x 5 rows = 10 beams
- Total Beams: 12 + 10 = 22 per floor.

### 2. Optimal Column Orientation (HEA/HEB)

The building dimensions remain 36 m x 12 m.

- Critical Direction: x - Direction (36 m), which imposes the highest demand on lateral stiffness.

### Conclusion on Orientation

To maximize the structure's resistance and stiffness in the 36 m direction (x), the strong axis of the columns must be aligned parallel to this length.

- Best Option - All 15 columns must have their strong axis oriented in the x-direction.
- This choice ensures that maximum column moment of inertia ( $I$ ) contributes to resisting lateral forces (seismic/wind) along the long side.

### 3. Estimated Lateral Stiffness (K)

We now correct the stiffness calculation using the 15 columns and the correct floor heights ( $h_{base} = 4.0$  m and  $h_{upper} = 3.0$  m).

## A. Data and Premises Adopted (Finalized)

Table 3.5 - Final values for building's columns statistics

Description	Symbol	Value (Adopted)	Notes
Total Number of Columns	$n_{col}$	15	5 lines in x x 3 lines in y
Column Profile (Estimate)	$I_C$	HEA 300	$I_y \approx 0.001336 \text{ m}^4$ (Strong axis along x)
Flexibility Factor	$f_{flex}$	0.6	Assumed for moment-resisting steel frames.

## B. Calculation of Base Floor Stiffness ( $K_{base}$ ) - estimation

This calculation determines the resistance of the ground floor (4.0 m height) in the critical x-Direction.

1. Ground Floor Column Stiffness ( $h = 4.0 \text{ m}$ ): (As calculated previously)

$$K_{column, 4m} \approx 6,589 \text{ kN/m}$$

2. Total Lateral Stiffness of the Base Floor ( $K_{base, x}$ ):

This is the sum of the rigidities of all 15 columns acting in parallel, adjusted for beam flexibility.

$$K_{base, x} = n_{col} \times f_{flex} \times k_{column, 4m}$$

$$K_{base, x} \approx 15 \times 0.6 \times 6,589 \text{ kN/m}$$

$$K_{base, x} \approx 59,301 \text{ kN/m}$$

## C. Upper Floor Stiffness ( $K_{upper}$ )

This calculation determines the stiffness of the residential floors (3.0 m height).

1. Upper Floor Column Stiffness ( $h = 3.0 \text{ m}$ ): (As calculated previously)

$$k_{column, 3m} \approx 12,470 \text{ kN/m}$$

2. Total Lateral Stiffness of an Upper Floor ( $K_{upper, x}$ ):

$$K_{upper, x} \approx 15 \times 0.6 \times 12,470 \text{ kN/m}$$

$$K_{upper, x} \approx 112,230 \text{ kN/m}$$

#### 4. Conclusion: Structural Stability and Rigidity

**Table 3.6** - Comparison between calculated stiffness and relative stiffness for residential and commercial zone of the building

Floor	Height ( $h$ )	Calculated Stiffness ( $K_x$ )	Relative Stiffness
Upper (Residential)	3.0 m	112,230 kN/m	100%
Base (Commercial)	4.0 m	59,301 kN/m	53%

The increased number of columns (from 9 to 12) results in a proportional increase in stiffness for both floors.

The conclusions are strengthened:

1. Lateral Rigidity is Low: While 59,301 kN/m is better than the previous estimate, pure moment-resisting steel frames for a 5-storey building with 36 m length are still unlikely to meet the stringent drift limits (displacement / height) required by Eurocode 8 without additional elements.
2. Soft-Story Effect Confirmed: The base floor is only 53% as stiff as the upper floors. This soft-story configuration is highly undesirable and potentially dangerous in seismic zones, as the columns on the ground floor absorb a disproportionate amount of the lateral deformation.
3. Mandatory Countermeasure: It is structurally mandatory to include bracing elements (e.g., steel diagonals, cross-bracing) or a reinforced concrete core (stairs/elevator shaft) in the X-direction to stiffen the structure significantly, especially the base floor, and meet seismic design requirements.

While increasing column inertia ( $I$ ) is mathematically possible to increase stiffness ( $K$  proportional to  $I$ ), it is rarely the best or most economical solution for controlling drift in multi-story steel frames.

Here is an analysis comparing increasing column inertia versus introducing bracing:

#### Comparing Solutions for Lateral Stiffness

##### Solution 1: Increasing Column Inertia ( $I_c$ )

This involves using significantly larger and heavier column profiles (switching from HEA 300 to HEB 400 or larger).

**Table 3.7 - Pros and Cons concerning building aspects on solution 1**

Pros	Cons
<b>No Architectural Changes: Keeps the floor plan open (crucial for the commercial ground floor)</b>	<b>Inefficient:</b> Stiffness ( $K$ ) increases linearly with $I$ , but the cost, weight, and fabrication difficulty increase much faster
<b>Improves axial load capacity (for compression/bending Moment)</b>	<b>Geometric Bottleneck:</b> Even a massive column might not provide enough $K$ to solve the drift problem effectively, especially for a 36 m long building
	<b>Worsens Soft-Story:</b> The stiffness difference between the 4.0 m base floor and 3.0 m upper floors remains high, unless the column sizes are dramatically stepped between floors

Example Impact: To double the stiffness, it is necessary to double the column's  $I$ . Moving from an HEA 300 ( $I_y \approx 1,336 \text{ cm}^4$ ) to an HEB 400 ( $I_y \approx 3,767 \text{ cm}^4$ ) more than doubles the inertia but vastly increases the material cost and column size.

### **Solution 2: Introducing Bracing (Shear Walls or Steel Diagonals)**

Bracing changes the structural mechanism from flexible moment frames to rigid trusses (or shear walls).

**Table 3.7 - Pros and Cons concerning building aspects on solution 2**

Pros	Cons
<b>Extreme Efficiency: Stiffness is increased by factors of 5 to 10 with minimal added material compared to increasing column size</b>	Architectural Impact: Diagonals or shear walls block openings or interfere with internal layouts (e.g., apartment walls)
<b>Cost-Effective: Often the most economical way to control drift and meet seismic requirements</b>	Design Constraints: Bracing must be continuous from foundation to roof, which can conflict with the commercial ground floor layout
<b>Eliminates Soft-Story: Braced frames (or shear walls) can be detailed to provide uniform stiffness throughout the height, solving the 4.0 m versus 3.0 m height discrepancy</b>	

### **3.2 Conclusion and influence for apartment area distribution**

While increasing column inertia is a valid calculation step, in the context of a 5 - storey building with a soft-story risk, the required column size to achieve adequate stiffness would likely become impractically large and expensive. Introducing bracing is the standard, most economical, and structurally superior method to control lateral deformation in steel structures.

#### **Apartment Number and Distribution (RGEU Standard)**

The structural analysis confirmed a floor plate of 36 m x 12 m for a multi-family residential building. The architectural distribution focuses on maximizing the usable area and fitting RGEU typologies (T1, T2, T3, T4).

##### **1. Determining Usable Depth**

Given the 12 m depth, the most efficient layout for residential buildings is a Central Corridor to access units on both sides.

- Total Depth ( $y$  - direction): 12.0 m
- Central Corridor Width (approximately): 2.0 m (Standard accessibility requirement)
- Usable Depth per Unit:  $(12.0 \text{ m} - 2.0 \text{ m}) / 2 = 5.0 \text{ m}$

A 5.0 m usable depth is excellent, comfortably accommodating the main rooms (living room, bedrooms) for all typologies.



## **Chapter 4**

# **PROJECT DESIGN: ARCHITECTURAL AND STRUCTURAL SOLUTION FOR A RESIDENTIAL BUILDING**



## 4. PROJECT DESIGN: ARCHITECTURAL AND STRUCTURAL SOLUTION FOR A RESIDENTIAL BUILDING

### 4.1 Preliminary considerations

The aim of this section is to provide an answer concerning project design, introducing considerations containing qualitative aspects (in terms of being better or worse in relation to the influence of gravitational loads and horizontal actions) and quantitative solutions (in terms of inertia and stiffness), in the following order of options: *a)*, *b)*, *c)*, *d)* and *e)*. They must be assessed in accordance with the rules of EC3-1-1 and EC8 (for the steel structures).

The ultimate goal of this chapter is to present a building project based on the considerations introduced earlier and the requirements underlying the design criteria.

Thus, the basic problem consists of designing the best structural plan for a 5-storey residential building, with the first floor intended for commercial use, with a ceiling height of 4 m, and the other 4 floors each with a height of 3 m. The plan dimensions are described below. The intention is to include two resistant cores for the lift shaft and stairwell for architectural circulation reasons.

The summary of the orientation possibilities for the corresponding HEB section columns would be given by the following design hypotheses, whose ultimate interest will naturally be their optimisation for cartesian orientation, i.e. positioning the strong axis of each profile oriented according to *X* or *Y*.

For the geometric description of the structural plan, a 36 m x 12 m reticular frame grid is considered, with four 9 m spans (along the cartesian *X* direction) and two 6 m spans (along the *Y* direction), with 3 longitudinal frame rows (designated Frames A, B and C) and 5 transverse rows (designated Frames 1, 2, 3, 4 and 5, respectively), thus totalling 15 columns, as planned in the residential building initially presented.

The aim is therefore to optimise, by means of a summary table, the respective advantages (the parameters and conclusions of which are adequately justified in accordance with the bibliographical references introduced above) for the following five situations:

- a)** All columns positioned with the strong axis of the section oriented in the *X* direction;
- b)** All columns positioned with the strong axis of the section oriented in the *Y* direction;
- c)** The columns of frame A and frame C (10 in total) oriented with their strong axis in the *Y* direction and the columns of frame B (5) oriented with their strong axis in the *X* direction (i.e. rotated 90 degrees from the others);

- d)** the columns of frames A and C oriented with their strong axis in the X direction and the columns of frame B oriented with their strong axis in the Y direction (the opposite situation to that in point c);
- e)** the three columns of frame 1 and the three columns of frame 5 oriented with their strong axis in the X direction, with the remaining nine columns of frames 2, 3 and 4 oriented with their strong axis in the Y direction.

Thus, the technical analysis focuses on optimising the structural plan of a 5-storey residential building (36 m x 12 m), evaluating five variants of the orientation of the 15 HEB columns in relation to the requirements of Eurocode 3 (Design of steel structures) and Eurocode 8 (Design of earthquake-resistant structures). So, we will have,

### 1. Basic Parameters and Stiffness Concepts

For HEB section profiles, the bending stiffness is significantly different between the strong axis ( $y-y$ ) and the weak axis ( $z-z$ ). In qualitative terms, for the calculation of the lateral stiffness of a rigid frame (symbol MRF – Moment Resisting Frame), inertia contributes directly to the stability and control of relative displacements between floors (drift), according to Brandonísio [2009].

- Relative Inertia: For a typical HEB profile, the inertia ratio ( $I_y / I_z$ ) is generally between 2.5 and 3.0.
- Horizontal Actions (Wind/Earthquake): The Y direction (12 m) is the most sensitive to overturning and lateral deformation due to the building's lower overall moment of inertia, requiring a greater concentration of strong axes, according to Brandonísio and SCI.
- Torsion: The existence of concrete cores (for lift/stairwells) creates centres of rigidity which, if they do not coincide with the centre of mass, induce a torsion effect. The orientation of the peripheral columns is therefore essential to increase torsional rigidity.

### 2. Comparative analysis of options a) to e)

Table 4.1 study the optimisation of the configuration for the orientation of the strong axis of the columns in the structural plan of the building. In particular is presented the

- Strong Axis Orientation Configuration for each profile according to X or Y direction;
- Stiffness in X ( $K_x$ ) and in Y ( $K_y$ );
- Structural and Construction Assessment.

**Table 4.1 - Configuration for the orientation of the strong axis of the columns in the structural plan of the building**

Point	Strong Axis Orientation Configuration for each profile	Stiffness in X ( $K_x$ )	Stiffness in Y ( $K_y$ )	Structural and Construction Assessment
a)	All according to X	Maximum	Minimum	<b>Poor:</b> The building is extremely flexible in the transversal direction (Y). High risk of not complying with service limit states (vibrations/deformation)
b)	All according to Y	Minimum	Maximum	<b>Reasonable:</b> Protects the shorter direction (Y), but neglects longitudinal stability (X). May require additional bracing in X
c)	Frames A and C according to Y; Frame B according to X (10 - Y // 5 - X)	Medium	High	<b>Good:</b> Ensures transverse stiffness in the façades and some longitudinal stability in the central alignment. Balanced solution for gravitational loads
d)	Frames A and C according to X; Frame B according to Y (10 - X // 5 - Y)	High	Low	<b>Inefficient:</b> Places the greatest stiffness in the direction that is already naturally more stable (36 m), leaving the 12 m direction unprotected
e)	Frames 1 and 5 according to X; Remaining frames according to Y (6 - X / 9 - Y)	High	High	<b>Optimised:</b> Creates a rigid 'box'. The end columns (X) lock the torsion and total length, while the core (Y) supports the transversal direction

### 3. Qualitative and Quantitative Justification (according to EC3 and EC8)

#### A. Gravitational Loads (EC3-1-1)

The mixed orientation (option e) allows the main beams (9 m spans according to X or 6 m spans according to Y) to connect preferentially to the strong axis of the columns, reducing the effects of instability (buckling) due to composite bending, according to Brandonísio.

## B. Horizontal Actions and Earthquakes (EC8)

EC8 recommends structural regularity and redundancy.

Relative Stiffness Calculation ( $K$  proportional to  $I$ )

Assuming, for instance, that  $I_y \approx 3$  and  $I_z \approx 1$ , for option e), we will have

- $K_x = (6 \times 3) + (9 \times 1) = 27$  units;
- $K_y = (9 \times 3) + (6 \times 1) = 33$  units.

This configuration approximates the stiffnesses in both directions, avoiding a 'less favourable axis' and improving the overall dynamic behaviour.

## C. Interaction with Resistant Cores

The concrete cores for staircases/lifts will bear most of the horizontal load. Point e) best complements these cores, given that the columns in frames 1 and 5 (extremities) act as torque arms to resist the overall torsion induced by the eccentricity of the cores, as indicated by those authors.

## 4. Final Solution and Recommendation

Option e) is considered the technically superior solution.

### Architectural Advantage

By orienting the strong axes of the end pillars along the  $X$  direction, the HEB profile beams are aligned with the side façade, facilitating the closure of gaps and thermal/acoustic insulation without excessive protrusions inside the flats, in accordance with publication MSB01 (guide for architects).

Table 4.2 - Recommended guidance - point e)

Alignment	Columns	Strong Axis Orientation	Main Function
Frames 1, 5	1A, 1B, 1C, 5A, 5B, 5C	Direction X	Longitudinal bracing and torsional stiffness
Frames 2, 3, 4	Remaining 9 columns	Direction Y	Transversal wind resistance and principal beam support

This solution thus guarantees the required scientific rigour, optimising steel consumption in view of the structural safety required by the Eurocodes described.

In addition to the five options a) to e) analysed before, there is an advanced configuration, often referred to as option f) Peripheral Orientation in a 'Ring' or Star,

which is scientifically very interesting for elongated rectangular buildings (such as this one measuring 36 m x 12 m).

#### Option *f*) - 'Chessboard' or Differentiated Peripheral Orientation

In this solution, the strategy focuses on maximising overall torsional inertia (the moment of inertia of the floor plan as a whole) and redundancy in the event of a reversal of forces.

Configuration:

- Corner Columns (1A, 1C, 5A, 5C): Oriented with the strong axis according to *X*.
- Intermediate Columns of the Periphery (Frames 2, 3, 4 in lines A and C): Oriented with the strong axis according to *Y*.
- Central Alignment Pillars (Line B): Alternating orientation (in a 'checkerboard' pattern) or all according to *Y* to maximise transverse rigidity.

**Table 4.3 - Structural Configuration Comparison (EC3/EC8):**  
Updated Comparison, including the points *e*) and *f*)

<b>Criterion</b>	<b>Item <i>e</i>) (Previously the best)</b>	<b>Item <i>f</i>) (Peripheral Configuration)</b>	<b>Justification according to EC3/EC8</b>
<b>Stiffness Distribution</b>	Concentrated at the ends (Frames 1 and 5)	Distributed along the entire perimeter	Option <i>f</i> ) creates a more effective "tube" behavior
<b>Torsion Control</b>	Very good	Excellent	By orienting corners in <i>X</i> and the rest in <i>Y</i> , torques are countered in both directions
<b>Constructive Advantage</b>	Simple (division by frames)	More complex (column-by-column orientation)	Requires greater precision in assembly and joint detailing
<b>Interaction with Cores</b>	Depends on the core position	Highly flexible	Adapts better if the cores are not centered

### Quantitative and Qualitative Analysis of point *f*)

#### 1. Axial and Flexural Stiffness (EC3-1-1)

By 'closing' the corners in the *X* direction and the intermediate points in the *Y* direction, we ensure that whatever the direction of the wind or earthquake, there is always a significant group of columns working according to the orientation of the strong axis.

Quantitatively, if we have 4 columns with a strong axis oriented along  $X$  and 11 along  $Y$ , the stiffness in  $Y$  ( $K_y$ ) becomes fundamental to combat the slenderness of the building (12 m), while the 4 corner columns along  $X$  ensure that the building does not cut longitudinally in a saw-like pattern.

## 2. Ductility and Earthquakes (EC8)

EC8 values hyperstaticity. Point  $f$ ) is superior because, in the event of local failure or plastification of a frame, the varied orientation of the remaining columns offers more robust alternative load paths than if all the columns of a frame were in the same direction.

## 3. Impact on Architecture for the building (Apartment Typology)

This solution proves to be very much in line with architects' preferences for this type of structural grid (9 m x 6 m):

- Corner columns with a strong axis oriented along  $X$  are better 'hidden' in corner walls.
- The central columns (Line B) oriented along the  $Y$ -axis align with the dividing walls between flats or corridors, minimising the intrusion of steel projections into the living rooms.

Final Conclusion: Which is the Best Option?

Thus,

- Point  $e$ ) corresponds to the most balanced solution for rapid execution and simplified calculation.
- Point  $f$ ) proves to be a 'high engineering' solution, ideal for buildings where the concrete cores (stairs/lifts) are small or off-centre, as the pillars play a 'Herculean' role in torsional stability.

As the basic objective is to seek scientific rigour and maximum performance, point  $f$ ), or a variant of  $e$ ), is the winning solution. However, for the present work it is recommended that point  $e$ ) be selected as the essential basic solution and point  $f$ ) as a final optimisation to achieve maximum seismic safety and architectural integration.

The question remains of how to evaluate an equivalent stiffness (or inertia) according to each of the  $X$  and  $Y$  directions for the solutions referring to the previous points  $e$ ) and  $f$ ) ? Such a numerical calculation is presented for each of these options.

In order to assess the equivalent stiffness according to the  $X$  and  $Y$  directions rigorously and in accordance with Eurocode 3 (EC3), we must focus on the contribution of the moments of inertia relative to the HEB profiles.

In a rigid frame system, the lateral stiffness of a column ( $k$ ) is proportional to its moment of inertia ( $I$ ) in the direction of analysis. For an HEB profile, we have:

- $I_y$  (Strong Axis) - Bending resistance around the web (higher value).
- $I_z$  (Weak Axis) - Bending resistance around the flanges (lower value).

For comparative numerical calculation purposes, we will use an HEB 300 profile (common in 5-storey buildings), where:

- $I_y = 25170 \text{ cm}^4$  (moment of inertia according to the Strong Axis)
- $I_z = 8560 \text{ cm}^4$  (moment of inertia according to the Weak Axis)
- The inertia (stiffness) ratio is  $I_y = 2.94 I_z$

## 1. Numerical calculation relating to point e)

Configuration:

Frames 1 and 5 (6 columns) with strong axis orientation according to X;

Frames 2, 3 and 4 (9 columns) with strong axis orientation according to Y.

- X direction:

6 columns oriented according to X (Strong Axis of section  $\Rightarrow I_y$ )

9 columns oriented according to Y (Weak Axis in relation to X  $\Rightarrow I_z$ )

$$I_{eq,X} = (6 \times 25170) + (9 \times 8560) = 151020 + 77040 = 228060 \text{ cm}^4$$

- Y direction:

9 columns oriented according to Y (Strong Axis of section  $\Rightarrow I_y$ )

6 columns oriented according to X (Weak Axis in relation to Y  $\Rightarrow I_z$ )

$$I_{eq,Y} = (9 \times 25170) + (6 \times 8560) = 226530 + 51360 = 277890 \text{ cm}^4$$

**Qualitative Analysis** - The equivalent inertia (stiffness) in the Y direction is approximately 22% higher than that in the X direction. This proves to be beneficial, since the Y direction (with a length of 12 m) is the most vulnerable to global instability (2<sup>nd</sup> order P-Delta effects, EC3-1-1).

## 2. Numerical Calculation for item f) (Peripheral Optimisation)

Configuration: 4 corners in X; remaining 11 columns (periphery and centre) in Y.

$\Rightarrow$  X direction:

- corner columns in X (Strong Axis:  $I_y$ )
- 11 columns in Y (Weak Axis in relation to X:  $I_z$ )

$$I_{eq,X} = (4 \times 25170) + (11 \times 8560) = 100680 + 94160 = 194840 \text{ cm}^4$$

$\Rightarrow$  Y direction:

- 11 Y columns (Strong Axis:  $I_y$ )
  - X corner columns (Weak Axis in relation to Y:  $I_z$ )
- $$I_{eq,Y} = (11 \times 25170) + (4 \times 8560) = 276870 + 34240 = 311110 \text{ cm}^4$$

**Qualitative Analysis** - This solution strongly favours the transversal direction (Y), with stiffness in Y being 60% greater than in X. It is the ideal solution if the building is very slender in Y or if transverse wind loads are dominant.

**Table 4.4** - Stiffness in X or Y direction, ratio for both situations

Solution	Stiffness in X ( $I_{eq,X}$ )	Stiffness in Y ( $I_{eq,Y}$ )	Ratio Y/X	Structural Observation
e)	228 060	277 890	1.22	<b>Balanced:</b> Good for buildings with central cores
f)	194 840	311 110	1.60	<b>Specific:</b> Maximum protection against 'falling' in Y

### Conclusion and Selection Criteria

1. Lateral Stability (EC3): Point *f*) offers the greatest safety against global buckling in the shortest direction (12 m).
2. Seismic Behaviour (EC8): If the building has well-centred concrete cores (stairs/lifts), point *e*) is preferable as it is more regular and balanced. If the cores are at one end, point *f*) helps to compensate for torsion due to high peripheral stiffness.
3. Suggestion for Descriptive Report: Use point *e*) as the standard solution, justifying that the inertia distribution (with a ratio of 1.22) is sufficient to ensure stability without sacrificing the longitudinal ductility required in steel structures.

And the architectural justification for that last structural option (point *e*)) according to the RGEU to be implemented in the building identified above, with an area equal to  $(9 \text{ m} \times 4) \times (6 \text{ m} \times 2) = 432 \text{ m}^2$ , types T2, T3 and T4 for the flats per floor? How to justify?

There are three possible cases for such a distribution, varying the T2, T3 and T4 on the right or left side of the structural plan, considering the area for the stairwell and the area for the lift shaft. It is feasible to insert the results in an area table.

To justify point *e*) with columns of frames 1 and 5 oriented with their strong axis in the X direction, and the rest oriented along the Y axis, from an architectural point of view and in accordance with the RGEU (General Regulations for Urban Buildings), we must focus on the integration of structural elements into the interior layout and the organisation of the T2, T3 and T4 typologies.

The great advantage of point e) is the freedom in the floor plan. By orienting the strong axes of most of the columns (the so-called 'core' of the building) in the transversal Y direction, the projections of the columns (HEB profile flanges) are 'embedded' in the partition walls between flats or between internal divisions, which normally follow this direction to allow natural lighting through the longitudinal façades (Frames A and C).

### **Justification according to the RGEU and Architectural Concept**

1. **Minimum Areas and Compartmentalisation:** The RGEU defines minimum areas for rooms and bedrooms. The orientation of the columns along the Y-axis relative to their strong axis minimises 'dead corners' in rooms, facilitating compliance with regulatory usable areas.
2. **Rationalisation of Façades:** The end columns (as in frames 1 and 5) with their strong axis along the X-axis allow for larger window openings at the corners of the building, which is aesthetically enhanced in superior apartments (3 and 4 bedrooms).
3. **Circulation Centres:** The central area between frames 2 and 3 or 3 and 4 is ideal for the placement of staircases and lifts, freeing up the light fronts for bedrooms and living rooms.

### **Proposed Floor Plan (Total Area = 432 m<sup>2</sup>)**

Considering an estimated area of 42 m<sup>2</sup> for the central core (stairs + 2 lifts + landing), there is 390 m<sup>2</sup> of gross area per floor.

#### **Case 1:** seeking balance (2x 3-bedroom + 1x 4-bedroom)

- Left (Frames 1-2): T2 (approx. 100 m<sup>2</sup>).
- Centre: Core + apartment entrances.
- Right (Frames 3-5): T4 (approx. 190 m<sup>2</sup>) occupying the larger end.
- Remaining: Additional T2.

#### **Case 2:** for large families (2x T3 + 1x T2)

- Left: T3 (approx. 145 m<sup>2</sup>).
- Right: T3 (approx. 145 m<sup>2</sup>).
- Centre/Front: T2 (approx. 100 m<sup>2</sup>) connected to the core.

#### **Case 3:** seeking maximum density (3x T2 + 1x T3)

- Radial distribution around the core, taking advantage of the 9 m spans to define the width of each flat.

### Table of Areas and Typologies (Example)

This table systematises the feasibility of the typologies for the purposes of justification in the descriptive memory.

**Table 4.5 - Areas and typologies per floor and other characteristics**

Typology	Suggested Gross Area	RGEU Requirement (Example)	Location on the Floor Plan (point e)	Structural Advantage
<b>T2</b>	95 to 110 m <sup>2</sup>	Living room $\geq$ 12 m <sup>2</sup> , Bedrooms $\geq$ 10.5 m <sup>2</sup>	Intermediate Areas	Y-oriented columns hidden in divisory walls
<b>T3</b>	130 to 150 m <sup>2</sup>	+1 Bedroom, Larger kitchen	Extremities (Left/Right)	Takes advantage of the rigidity of frames 1 or 5
<b>T4</b>	180 to 200 m <sup>2</sup>	Suite + 3 Bedrooms	'L' or Total End	Maximum possibility of opening windows in X-orientated corner columns
<b>Core</b>	$\approx$ 40 m <sup>2</sup>	Stair width 1.20 m	Geometrical Centre	Central bracing next to columns oriented along Y

### Conclusion for Presentation

Point e) is the most viable because it allows the:

1. **Axis Compatibility:** The columns oriented along the Y axis align with the natural separation of rooms in two-, three- and four-bedroom flats.
2. **Flexibility:** It allows for variation in typology per floor (e.g., 1<sup>st</sup> floor T2s, 4<sup>th</sup> floor T4) without altering the main steel structure.
3. **Efficiency:** It ensures that the concrete core (stairs) works in conjunction with the more rigid steel frames, guaranteeing the vibration comfort required for residential use.

And the construction of the walls in the case of point e) in terms of the structural plan? How the situation is coordinated and made compatible with the inclusion of St. Andrew's cross bracing in the Y direction?

The coordination between the structural plan in point e), the construction of the walls and the inclusion of Saint Andrew's cross bracing (whether K-bracing or X-bracing) requires an 'integrated design' strategy.

In point e), we have the columns of frames 2, 3 and 4 oriented with their strong axis along Y, which facilitates the integration of vertical bracing elements in that direction.

Details on how to reconcile these elements are provided below, following the good practices of EC3 and the requirements of RGEU:

### 1. Strategic Location of Braces (Y Direction)

In order not to compromise the flexibility of T2, T3 and T4 typologies, Saint Andrew's Cross bracing must be positioned in alignments that coincide with:

- Divisions between flats: Walls separating two neighbouring flats (excellent acoustic and thermal insulation, as the bracing is 'embedded' in the double wall).
- Service cores: staircases or lift shaft walls.
- Blind corners: areas of the façade without windows.

### 2. Construction Coordination: The 'Sandwich' System

The physical compatibility between the steel (HEB profile + rods or bracing profiles) and the walls (masonry or light steel framing) is achieved through the concealment technique:

- Plasterboard walls - This is the most effective solution. The X-shaped bracing is assembled and the wall is built 'around' it. The wall thickness should be slightly greater than the width of the HEB flange (e.g. 20-25 cm wall for a 300 HEB) to ensure complete coverage and avoid acoustic bridges.
- Traditional masonry - Requires the use of brushes or the interruption of the brickwork next to the metal profiles. It is less recommended due to the difficulty of ensuring watertightness and a perfect finish next to the steel diagonals.

### 3. Impact on typologies (T2, T3, T4)

The global solution concerned point e) allows transversal frames 2, 3 and 4 to function as 'backbones'.

- ◇ In the case of T4: The bracing can be placed on the frame that separates the social area (living room) from the private area (bedrooms).
- ◇ In the case of T2: The bracing can be placed on the wall separating the common corridor.

**Table 4.6 - Compatibility issues and technical solution for point e) :**  
**Technical Compatibility Table**

<b>Element</b>	<b>Compatibility Issue</b>	<b>Technical Solution for point e)</b>
<b>St Andrew's Cross</b>	Obstruction of passageways (doors/windows)	Position only in 6 m spans (Y direction) that coincide with blind walls between rooms
<b>HEB columns (Axis Y)</b>	Recesses in walls (corners)	As the strong axis is in Y, the column 'runs' along the transverse wall, allowing for smooth surfaces in the rooms
<b>Installations (RGEU)</b>	Crossing of pipes with diagonals	Provide for water/wastewater passages outside the braced spans or use hollow core beams
<b>Acoustics</b>	Transmission of vibrations through steel	Use of resilient strips (neoprene) between the steel structure and the masonry/plaster finish

#### **4. Structural Justification (EC3 and EC8)**

By placing the Saint Andrew's Crosses in the Y direction (the shorter 12 m direction), we are:

1. Reducing Slenderness: The building becomes much more rigid to lateral displacement caused by wind.
2. Centralising Rigidity: If the bracing is placed symmetrically in relation to the staircase core, the Centre of Rigidity approaches the Centre of Mass, complying with one of the basic recommendations of EC8 to minimise torsion.

#### **5. Conclusion**

The solution related with point e) is clearly the most 'friendly' for the architect. The orientation of the columns along Y creates natural 'channels' for the transverse walls, where the St. Andrew's crosses can be hidden without sacrificing the aesthetics or functionality of the two- to four-bedroom flats. The result is a clean floor plan, where the structure is felt for safety, but not seen in everyday life.

And what about the thermal aspect ? How can rock or mineral wool be inserted into these walls according to solution e)?

For solution e), the integration of thermal insulation (rock wool or mineral wool) must be planned to mitigate the linear thermal bridges created by the high conductivity of steel and to ensure compliance with energy efficiency requirements (SCE).

The orientation of the columns, whose strong axis is positioned according to Y, and the presence of bracing in the form of a St. Andrew's cross facilitate the creation

of a technical ‘sandwich wall’. Details on how to insert these materials are provided below:

### 1. Box-in-Box or Double Wall System

As HEB columns are quite wide (e.g., 300 mm), mineral wool should not only fill the space between the columns, but also wrap around the structure itself.

- Filling the gap (between diagonals): In frames where there are St. Andrew's crosses, rock wool (in high-density panels) is cut and adjusted to fill the triangles formed by the steel bars. This ensures the continuity of the thermal barrier and significantly improves sound insulation between flats.
- Coating of the beams: To avoid thermal bridging on the face of the column, a layer of insulation (either thinner rock wool or extruded polystyrene) should be applied between the HEB beam and the plasterboard (*Pladur*).

### 2. Construction Detail in the Y Direction - point e)

Concerning the case of point e), the central columns are oriented with the beams parallel to the longitudinal façades.

- External Thermal Break: It is recommended to apply an *ETICS* (Capotto) system with rock wool to the exterior of the steel structure. This keeps the steel protected within the thermal envelope, preventing condensation.
- Air Chamber and Internal Insulation: Mineral wool is inserted between the column and the final cladding on the inside. Rock wool is preferable in these areas due to its greater fire resistance (passive protection of the steel structure, in accordance with EC3-1-2).

### 3. Advantages of Rock Wool in this Configuration

- Passive Fire Protection: Rock wool can withstand temperatures above 1000°C. By wrapping the columns and bracing in point e) with this material, critical fire resistance time (R30 or R60) is gained.
- Acoustic Absorption: In 5-storey residential buildings, impact and airborne noise becomes critical. Mineral wool helps to ‘dampen’ the vibrations that the steel structure tends to propagate.

## Specification Table for Descriptive Memory

Table 4.7 - Recommended material and function for façades' isolation

Localization	Recommended Material	Suggested Thickness	Function
Frames with Bracing	Rock Wool (Panel)	80 to 100 mm	Thermal + Acoustic + Fireproof
HEB Column Enclosure	Mineral Wool (Blanket)	40 mm	Linear Thermal Bridge Cut
Façade (External)	Rock Wool (ETICS)	60 to 80 mm	Thermal Inertia and Steel Protection

#### **4. Coordination with RGEU and SCE (the Energy Certification System for Buildings)**

The insertion of mineral wool must ensure that there are no continuous air gaps that could act as chimneys in the event of a fire. The solution correspondent to the point e) allows the slab (usually mixed steel-concrete) to interrupt the vertical continuity at each floor level, and the properly sealed rock wool to ensure the required thermal and smoke tightness.

Thermal compatibility in solution e) is achieved by occluding the bracing in dry walls filled with high-density rock wool, simultaneously ensuring thermal insulation, acoustic protection between fires and the fire resistance of the steel structure.

### **4.2 Proposed Project**

The proposed project consists of a multi-family residential building designed using a steel structural system. The design integrates architectural functionality with structural efficiency, taking advantage of the flexibility, strength, and modularity offered by steel construction.

The overall approach aims to ensure safety, durability, and comfort while meeting current technical standards and residential requirements.

From an architectural perspective, the building layout is organized to provide well-defined residential units, efficient circulation, and adequate common spaces. The spatial arrangement prioritizes functional zoning, separating private living areas from shared circulation and service zones. Proper orientation, window placement, and floor organization are adopted to enhance natural lighting and ventilation within the apartments, contributing to improved indoor comfort and energy efficiency.

Structurally, the building is based on a steel frame system composed of columns, beams, and floor slabs that work together to transfer vertical and horizontal loads safely to the foundations. However, it must be referred that part of the transfer of horizontal loads to the footing system is responsibility of the reinforced concrete resistant cores also, which provide lateral stability in each of the directions in plan too.

Steel framing allows for larger spans and reduced structural elements within the living spaces, providing greater flexibility in apartment layouts and future adaptability.

The structural system is designed to resist permanent loads, variable loads, and horizontal actions, such as wind and seismic effects, in accordance with applicable regulations.

In developing the structural plan, the steel frame system was organized to respond to both functional and spatial needs of a multi-family residential building.

The layout uses short spans of 3,0 m where compact spaces like service areas or corridors are located, and longer spans of 9,0 m in living areas, allowing open and flexible apartment layouts.

Such combination of spans creates a rhythm in the structure that efficiently balances load distribution with usable interior space.

One challenge arose when a steel beam intersected the stairwell. Rather than compromising circulation, the beam was adapted into a U-shaped configuration, maintaining structural continuity while preserving the safety and accessibility of the stairs. This solution illustrates how architectural requirements and structural constraints were resolved simultaneously, highlighting the adaptability of steel framing.

However, the simplest solution is to join the beams in either direction in plan to the reinforced concrete core, which can serve as either a lift shaft or a stairs box.

Taking into account all the considerations previously presented in Chapter 3 and in the first part of Chapter 4, a project was developed by the author, whose fundamental drawings are presented and described in the latter part of this chapter.

Therefore, Figure 4.1 shows the architectural drawings made by the author referring to the frontal and posterior elevations of the designed residential building.

Additionally, Figure 4.2 shows the drawings correspondent to the lateral façades elevations of the same residential building project.

The sections of the designed multi-storey residential building, both in longitudinal and transversal directions, are shown in Figure 4.3.

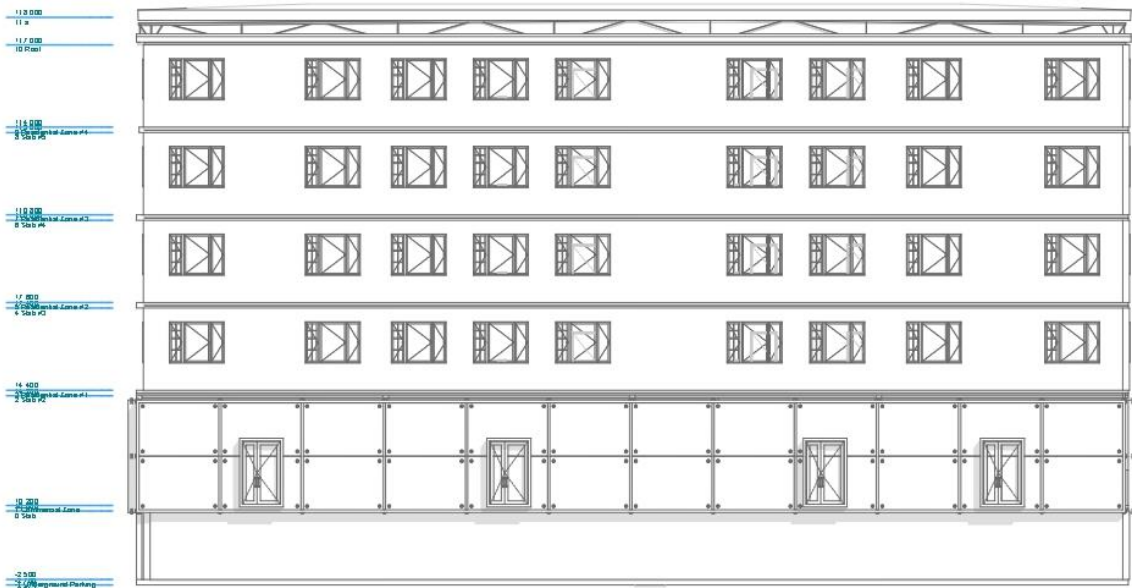
In Figure 4.4 are included the floor plans of the multi-storey building numbered by -1, 0 and 1, and corresponding to the parking floor, commercial floor and first residential floor. Figure 4.5 illustrates the other floor plans for the remaining residential floors of the building's project (housing zone for the floors 2, 3 and 4).



South Elevation

1:200

a) Main Façade view



North Elevation

1:200

b) Posterior Façade view

**Figure 4.1 - Elevations of the designed multi-storey residential building:  
Architectural drawings**



**Figure 4.2** - Elevations of the multi-storey building: views of the lateral façades

The building layout is organized to create clearly defined residential units supported by efficient circulation routes and functional common spaces. The spatial arrangement emphasizes logical zoning, separating private living areas from shared circulation and service zones to enhance usability and privacy. Particular attention is given to orientation, window placement, and floor organization in order to maximize natural lighting and ventilation, thereby improving indoor environmental quality and contributing to energy efficiency.

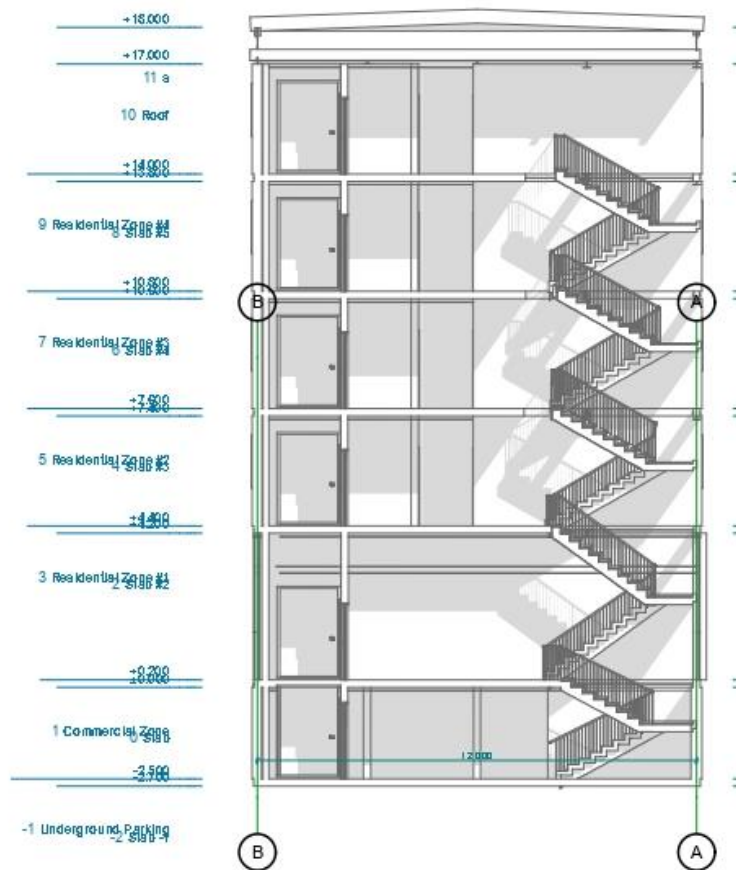
To further enhance daylight penetration, laminated glass panels (as can be seen in the drawings of the Figures 4.1 and 4.2) are incorporated as architectural elements within the design, clearly highlighting the aesthetic aspect of the frontal façade.

In accordance with the works of Mesquita *et al.* [20], [21] and [22], a transparent laminated glass panels structure is introduced at the ground floor, creating visual openness and allowing greater natural light to enter the building's interior spaces. In addition, linear glass panels are integrated along each floor level, acting as continuous light-transmitting elements that improve vertical illumination and reinforce the architectural rhythm of the façade.

These glazed components not only increase daylight availability but also contribute to a sense of transparency and visual connection between interior and exterior environments.

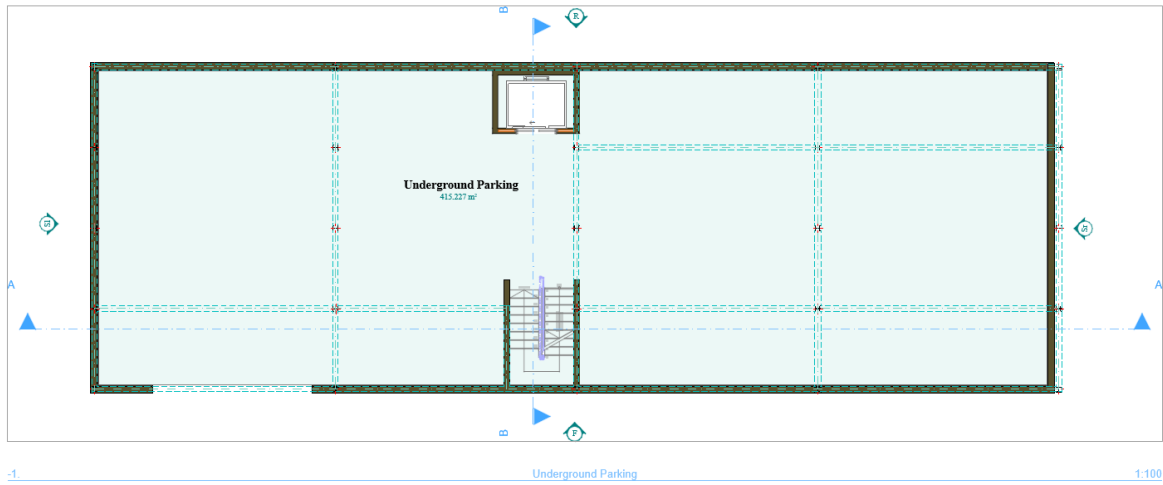


A Building Section 1:200

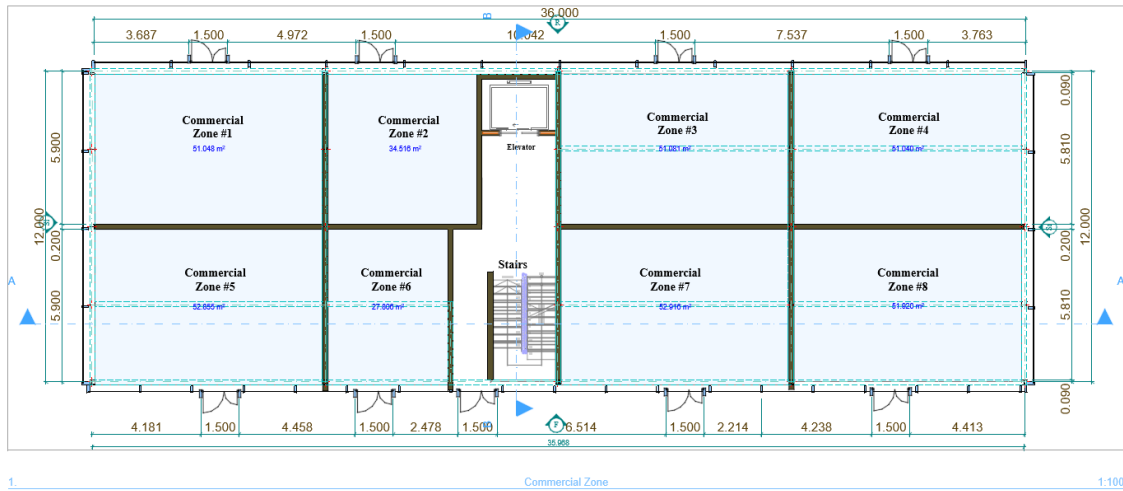


B Building Section 1:200

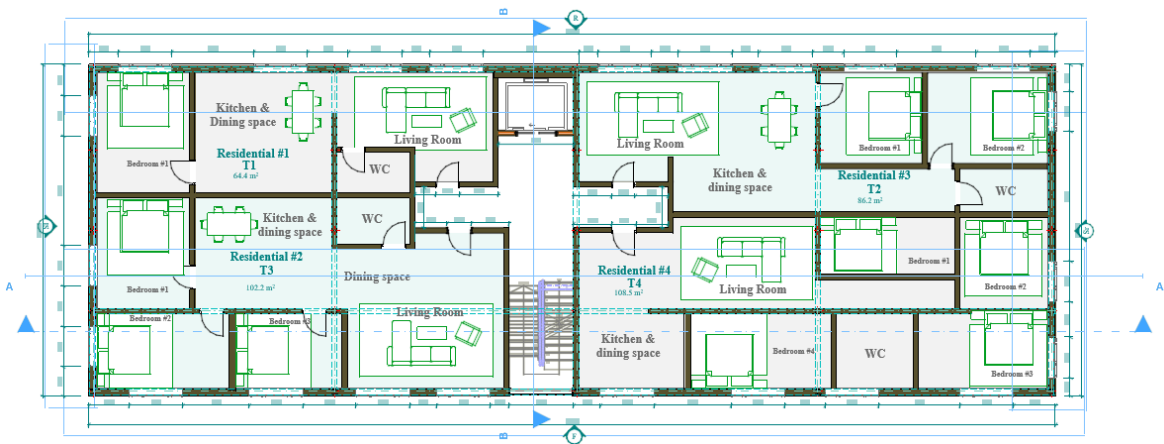
Figure 4.3 - Sections of the multi-storey residential building: longitudinal (A) and transversal (B)



a) Underground parking



b) Ground floor: commercial zone



c) First floor: Housing zone

Figure 4.4 - Floor plans of multi-storey building (-1, 0 and 1)



Figure 4.5 - Floor plans of multi-storey building: housing zone (2, 3 and 4)

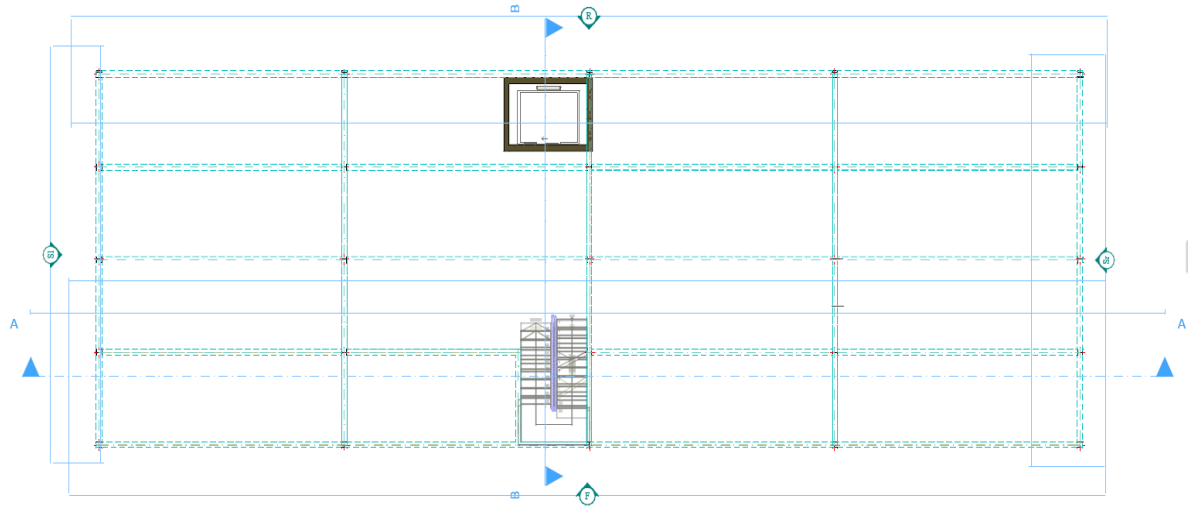


Figure 4.6 - Structural drawing – Typical floor plan

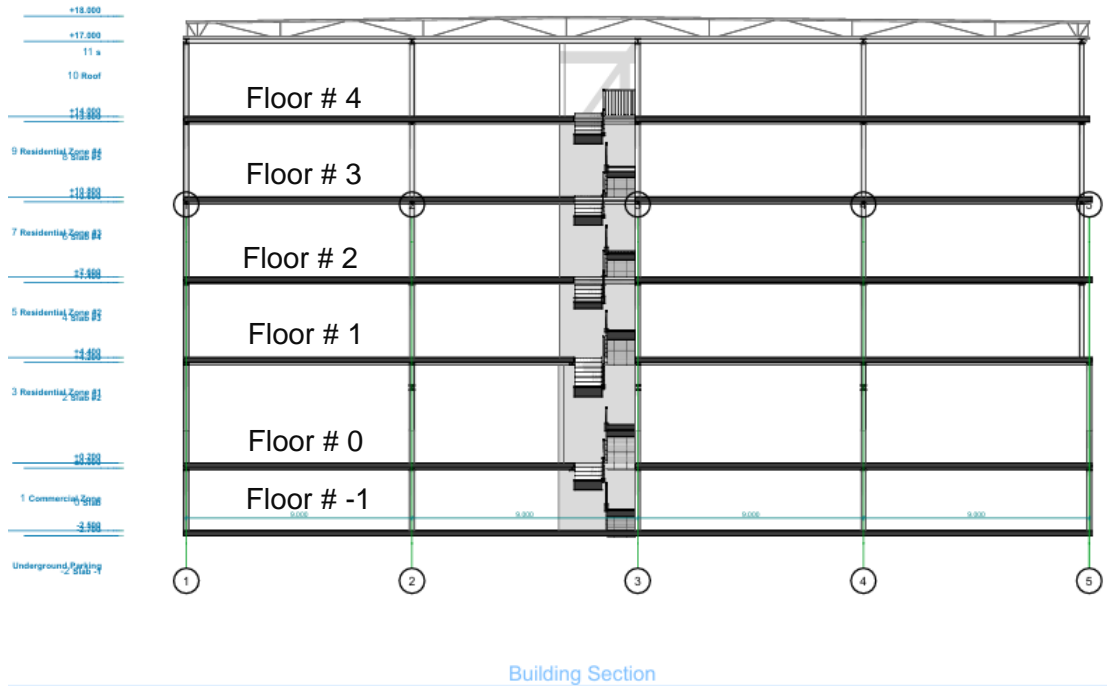
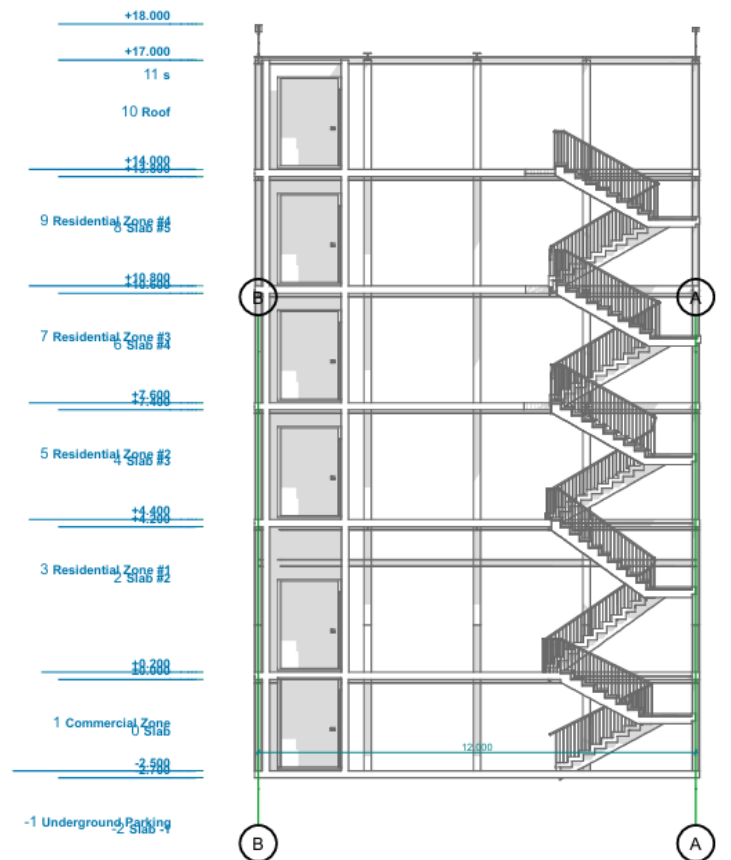


Figure 4.7 - Structural drawing- Sections



**Figure 4.8 - Structural drawing – Another section**

The architectural and structural solutions were developed simultaneously to ensure compatibility between space planning and load-bearing elements. This coordinated approach results in an efficient structural grid that supports the architectural design while optimizing material use and construction performance.

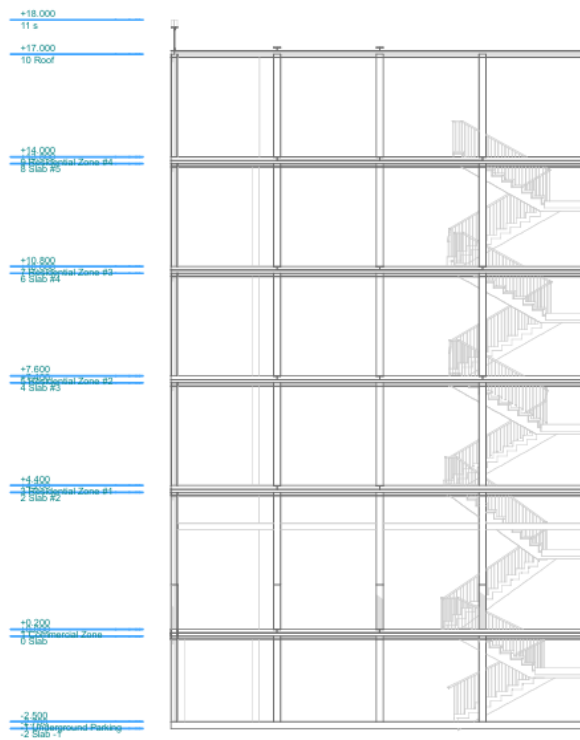
The resulting steel frame, composed of beams, columns, and slabs, efficiently transfers vertical and horizontal loads to the foundations while minimizing intrusions in the interior spaces.

By coordinating structural logic with architectural planning, the design achieves both practical functionality and aesthetic flexibility, demonstrating the feasibility and design potential of steel-framed residential buildings.



East Elevation

1:200



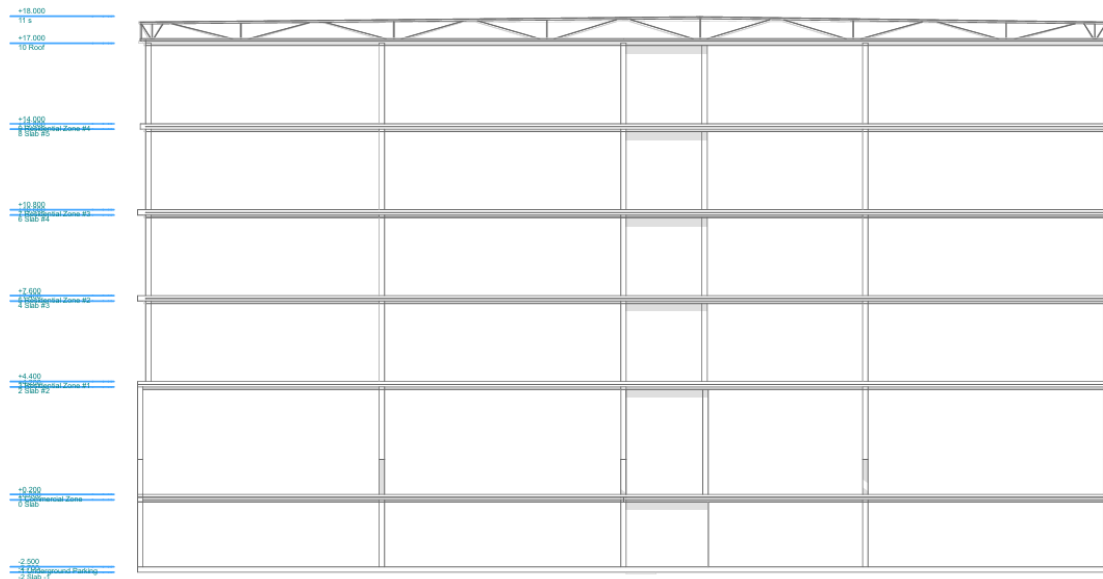
1

West Elevation

1:200

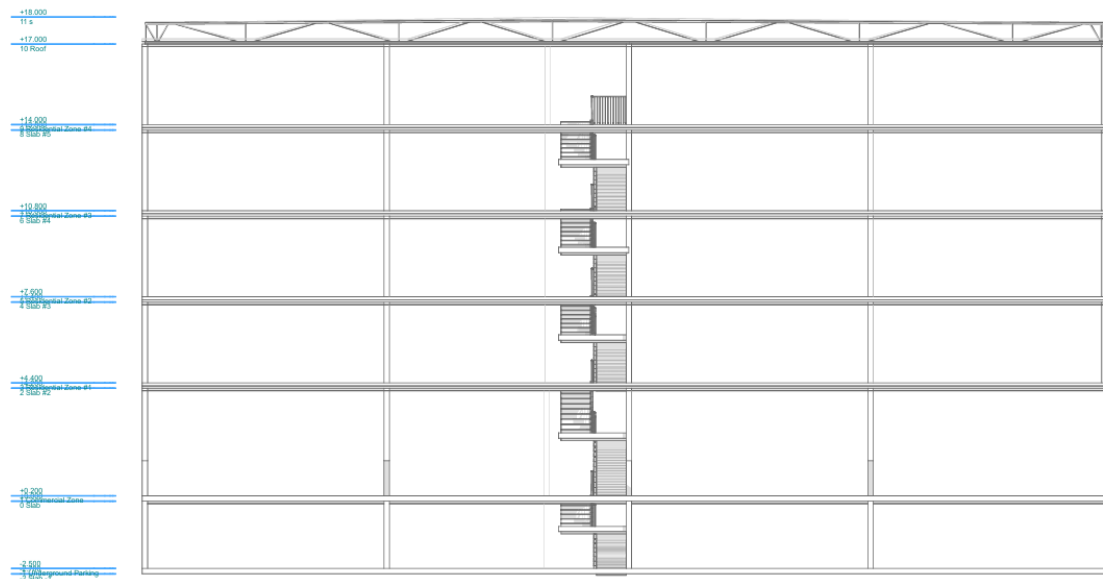
(Cont.)

(Cont.)



North Elevation

1:200



South Elevation

1:200

Figure 4.9 - Structural drawings – Elevations

## **Chapter 5**

# **CONCLUSIONS AND FUTURE WORK**



## 5. CONCLUSIONS AND FUTURE WORK

### 5.1 Conclusions

The present work focused on the design and analysis of a multi-family residential building with a steel structural system, aiming to achieve an optimal balance between structural safety, seismic performance, architectural flexibility, and construction efficiency. The study demonstrates that steel structures represent a highly suitable solution for residential buildings, particularly in contexts where flexibility of layout, speed of construction, and structural efficiency are required.

The structural design was developed in accordance with the provisions of Eurocode 3 (EC3) for steel structures and Eurocode 8 (EC8) for earthquake-resistant design, while also respecting architectural regulations and functional constraints typical of residential buildings. The adopted steel frame system, combined with bracing elements, proved effective in ensuring adequate resistance to vertical and horizontal actions, including seismic loads.

A comparative analysis of different column orientation strategies was carried out to evaluate their influence on global stiffness, torsional behaviour, and overall seismic performance. The results confirm that the orientation of the strong axis of HEB columns has a significant impact on the structural response. Proper orientation contributes to reduced lateral displacements, improved stiffness distribution in both principal directions, and better control of torsional effects.

Among the analysed configurations, option (e) was identified as the most balanced and practical solution, providing sufficient stiffness in the transversal direction while maintaining regularity and simplicity from a construction perspective. Although the advanced peripheral configuration (option (f)) showed superior performance in terms of torsional control and seismic robustness - particularly in cases with eccentric or reduced concrete cores - it also introduced higher constructive complexity, making it less advantageous for standard residential applications.

From an architectural point of view, the selected structural solution allows a rational and coherent integration of the steel system into the residential layouts, accommodating T2, T3, and T4 typologies without compromising spatial quality or regulatory compliance. The coordination between the steel frame, Saint Andrew's cross bracing, partition walls, and thermal–acoustic insulation systems confirms that high structural performance can be achieved while preserving architectural clarity and user comfort.

Furthermore, the use of mineral and rock wool insulation enhances thermal efficiency, acoustic performance, and fire resistance, reinforcing the suitability of

steel-framed solutions for multi-family residential buildings. Overall, the results highlight the potential of steel structures to provide safe, efficient, and adaptable solutions for contemporary residential construction.

## 5.2 Future Work

Future developments of this study could include a more detailed static and dynamic analysis of the structure, considering modal behaviour and time-history seismic actions to further refine the assessment of seismic performance and analysis. The inclusion of second-order effects and non-linear behaviour in advanced numerical models would allow a more accurate evaluation of ductility, damage mechanisms, and energy dissipation capacity in terms of the analysis of the overall project.

In addition, the optimisation of steel profiles through parametric design and computational tools could lead to further reductions in material consumption, structural weight, and embodied carbon. In any case, the natural development of this type of work should be transposed to the design of all structural elements, from the roof to the foundations, including composite steel-concrete slabs, beams, columns and reinforced concrete shear walls, checking dimensions and verifying resistance capacity of all elements in accordance with the clauses of EC3, EC2, EC4, EC7 and EC8.

From an architectural and environmental perspective, future research could explore hybrid construction systems, such as steel-timber solutions, the use of low-carbon or recycled steel, and the implementation of life-cycle assessment methodologies.

From an urban planning perspective, a study could also be carried out on the impact on a given urban area of the typology selected for the flats, as well as on the resident population that such a building could accommodate. A comparative analysis could be carried out between different architectural typologies in the context of different structural alternatives.

In conclusion, the present work provides a solid methodological and technical basis for the design of medium-rise steel-framed residential buildings, demonstrating that careful coordination between structural engineering and architectural design can result in efficient, safe, and flexible housing solutions suitable for modern urban contexts.

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