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STEEL AND COMPOSITE STRUCTURES IN REHABILITATION AND INTERVENTION IN EXISTING BUILDINGS

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Abstract: This paper presents different criteria, requirements, and possibilities of steel and composite structures in rehabilitation and intervention of existing buildings. Firstly, the characteristics of the materials and techniques of the original building are studied, which are necessary for undertaking the structural analysis. Secondly, the specific conditions of each building are considered in accordance with the criteria and current standards. Thirdly, the possibilities of metal and composite structures in the rehabilitation and intervention of existing buildings are described, with recent projects developed by the authors highlighting their potential and versatility throughout the entire process.

1. Introduction

Rehabilitating and intervening in existing buildings have become a common practice in architecture and engineering. The reasons are diverse, among which the following can be highlighted: (i) changes in use and/or spatial redistribution, (ii) new loads from finishes and/or installations, (iii) design with new construction standards adapted to current regulations, (iv) detection of pathologies or malfunctions.

It is also important to consider a transversal factor related to the sustainability of buildings. In many cases, the demolition and reconstruction of buildings are not necessary; instead, reviewing, adapting, or reinforcing their condition is sufficient to extend their useful life.

From a structural perspective, the initial analysis focuses on understanding the technique and materials used in the original project to evaluate their behavior and resistance. Secondly, it is necessary to assess the specific conditions of the new project in accordance with the new criteria and current standards, as well as the possibilities for adaptation and intervention. Based on these premises, this paper focuses on studying the possibilities offered by steel and composite structures in existing buildings, drawing on projects developed by the authors.

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2. Characteristics of materials

The technology of steel structures in construction has progressed over the years in line with the understanding of the material and its application in different structures. Therefore, the first step in approaching intervention in existing buildings is to understand the construction era and the characteristics of the materials used.

The construction era can provide insight into the quality of materials used based on the standards at that time and references to other projects built during that period. With the initial data on the construction era, it is possible to estimate the quality of the steel used in its construction.

In any case, it is essential to conduct specific tests on the material to determine its characteristics, including, in particular: (i) quality, (ii) weldability, (iii) mechanical properties. Visual inspection can also determine the state of preservation and possible pathologies, as discussed in the section on current requirements.

Quality of steel is determined by its chemical composition, mechanical characteristics, and other factors such as ductility, resilience, fracture toughness, etc.

Weldability of steel is usually determined by chemical methods, obtaining the carbon content and the carbon equivalent. It is also necessary to consider the contents of phosphorus and sulfur for the considered steel quality. In rehabilitation projects, it is crucial to know if the existing steel is weldable for the planning of potential interventions and structural reinforcements.

Mechanical properties are typically obtained from tensile tests on samples extracted from the existing structure. These tests provide the stress-strain diagram, tensile strength (f_u), yield strength (f_y), deformation under maximum load (ε_{max}), deformation remaining at fracture (ε_u), and the modulus of elasticity (E). With this data, the quality of the steel for structural analysis and evaluation can be determined. In Figure 1, various samples taken from IPN-type steel beams and the results of a tensile test can be observed.

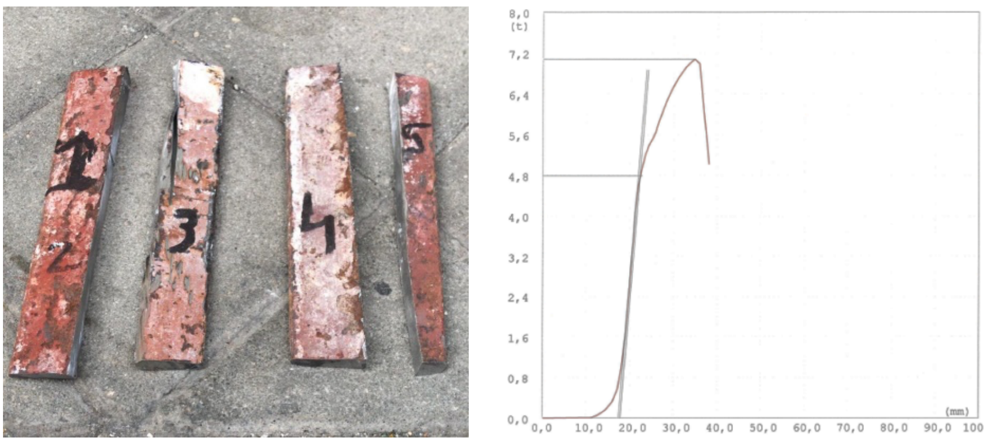

Fig. 1: Steel samples and tensile test results

3. Current requirements

In accordance with the new needs identified in the existing building undergoing intervention, it is necessary to assess the structural implications presented by the project. To do so, understanding the structural system and its operation is crucial. From this, the need to intervention in the existing structure will arise.

Typically, current projects involve an increase in loads compared to those considered in the original project (finishes, live loads, machinery, etc.) or changes in their distribution that require modifying the structural system (communication cores, facility conducts, etc.). These alterations may require reinforcement or reconfiguration of the existing structure to ensure adequate strength of the elements and proper behavior of the structural system.

Moreover, it is essential to review the overall and local stability of the existing structure against vertical and horizontal actions. Key aspects in this regard are often associated with a lack of bracing or a global stability system, buckling, and local instability of elements, excessive deformations, and vibration problems. All these aspects are related to the stiffness of structural elements, in global or local analyses.

Finally, it is also important to determine the current condition of the existing structure over the years. Environmental pathologies that can influence the proper behavior of elements, such as the presence of water and oxidation, or even breaks or delamination, are common. Protective and conservation measures must be taken in response to these issues.

Other protective measures are linked to the accessibility of the elements (embedded in walls or hidden by other elements) and fire protection of the structure. In this sense, it is essential to consider these aspects to comply with current standards requirements, which are generally more restrictive than those imposed by previous regulations. Special attention is required for fire resistance verification, where it is often necessary to resort to passive protections such as coating with constructive elements, vermiculite mortars, or intumescent paint.

Figure 2 shows different strategies for fire protection of the steel structure, including intumescent paints, vermiculite mortar projection, or coating with other constructive elements such as brickwork or gypsum boards.

Fig. 2: Fire protection of steel structures

4. Rehabilitation, reinforcement and intervention

Once the current situation of the building has been analyzed, including knowledge of its materials, the behavior of its structural system, and the current requirements, the following are some common interventions carried out in rehabilitation and reinforcement projects. The described interventions focus on the possibilities offered by steel and composite structures.

4.1 Increase of stability

4.1.1 Global stability

From a global perspective, there are buildings that were not originally designed with a bracing system or sufficient stiffness in their structure to perform adequately against horizontal actions, such as wind and seismic forces.

For these situations, one solution is to incorporate a new bracing system within the existing framework, provided the configuration allows it. In other cases, the strategy may focus on stiffening the connections to form rigid frames instead of articulated systems. A third strategy involves reinforcing the columns so that, acting as cantilever elements, they have sufficient stiffness to accommodate displacements resulting from horizontal actions. These strategies are feasible in buildings with a steel structure, allowing the solution to be adapted to spatial, design, and construction constraints.

An example of such situations is illustrated by an industrial complex consisting of buildings constructed from the 1960s. These steel structure buildings consist of HEB-type columns in cantilever and a framework grid in two directions as the structural system of the roof. These buildings were designed without a bracing system, and their lateral stiffness does not meet current standards requirements for wind actions.

One action in this project focused in incorporating a new bracing system into the built volume. The solution was to install steel tie rods formed by tensioned steel rounds, forming crosses both on vertical and horizontal surfaces, adapting to the geometry and use of the building. These elements were integrated into the structural framework without affecting the factory's daily operations. The roof bracing was done on the exterior side to avoid interference with existing machinery and installations. Figure 3 shows images of the new bracing system implemented in one of the buildings in the industrial complex.

Fig. 3: New bracing system in an existing industrial building

4.1.2 Local stability

From a local perspective, certain existing structural elements may require intervention to meet stability conditions against buckling.

Buckling primarily occurs due to compressive forces in elements with high slenderness. In the case of existing buildings, elements that typically may face stability issues are: columns, beams (lateral buckling), and small-sized elements. Buckling is a well-known problem, and strategies proposed to enhance behavior include: (i) reducing the load they bear, (ii) increasing the stiffness of the section, (iii) reducing the free length for buckling, and (iv) stiffening boundary conditions.

In the same project mentioned in the previous section, another action involved reinforcing the existing steel columns, as there was also a need to accommodate new loads resulting from the current use of the building. The reinforcement consisted of enclosing HEB-type profiles with flanges, resulting in increased resistance to vertical loads and greater stiffness against lateral actions, also improving their behavior against buckling. Figure 4 illustrates the intervention carried out on the columns.

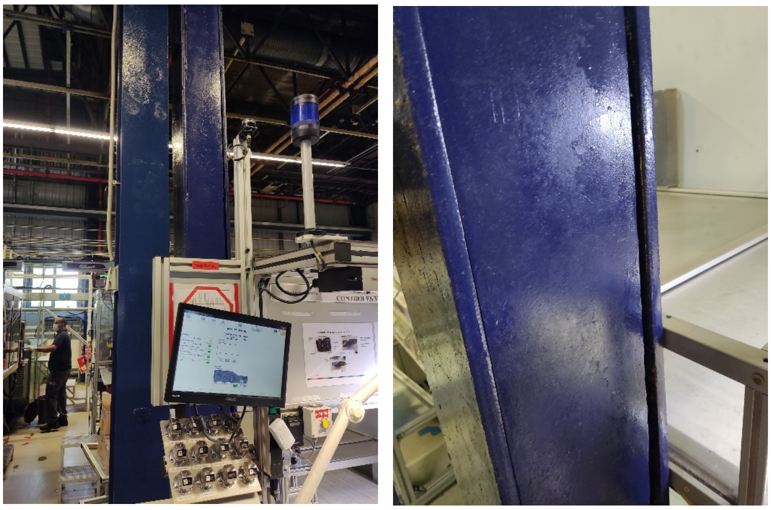

Fig. 4: Reinforcement interventions for local stability in columns

4.2 Columns intervention

In addition to local interventions to address buckling issues in structural components, it may also be necessary to act on columns due to changes in their configuration and/or insufficient load-bearing capacity.

If a higher load-bearing capacity is required, columns can be reinforced with plates or additional lateral profiles (illustrated in Figure 4), provided that the supports are weldable steel. When columns are not weldable or are made of another material (such as reinforced concrete), the strategy typically involves creating a new encased external jacket around the existing column, increasing the area and inertia of the section.

Additionally, the design may require the replacement or removal of a column to create a more open space or due to spatial reconfiguration. This intervention can occur on a single floor (by supporting the column on the floor to be worked on) or involve the complete removal of that support. The most common strategy is usually to install new beams under the slab to transfer the load to adjacent columns, if possible. In this case, the need to reinforce existing columns with the increased load due to shoring must be verified.

In an office building in Vizcaya, a complex shoring operation was carried out on a column in an existing reinforced concrete structure. For this, a transfer beam was placed under the existing floor and connected to the existing concrete columns, which required reinforcement due to the increased load. This reinforcement was done with an external encasement enveloping the existing column. Figure 5 shows the phase prior to the demolition of the existing intermediate column.

Fig. 5: Shoring and reinforcement intervention in columns

In these interventions, special attention must be paid to the connections between the new and existing structures, ensuring the transfer of forces between elements (existing slab – new beam; existing beam – new beam; new beam – existing column; existing column – column reinforcement). Also, if necessary, the capacity of the existing foundation should be reviewed.

4.3 Beams and slabs intervention

4.3.1 Existing steel beams

If there is an increase in loads or changes in layout in the new project for an existing building, it is common for some beams to require intervention to ensure compliance with current strength, stiffness, and stability requirements.

Like buckling, there are different strategies to address this issue. Some of them include: (i) structural reinforcement with metal elements, (ii) structural reinforcement as a composite system, and (iii) the inclusion of new elements. The case of the composite system is discussed in the next section on a new layer of compression in slabs.

Structural reinforcement with steel elements is usually the most direct option, provided that the steel is weldable and space and design conditions allow for it. A common solution that increases both strength and stiffness involve supplementing the existing steel section with an additional piece (typically T-shaped profiles). This intervention can be performed either from the bottom or the top, depending on accessibility and available height. Reinforcements from the bottom are more common, as they are more accessible and direct. However, if the top face of the beams is accessible, this possibility can also be considered.

In the rehabilitation project of an office building in Madrid with steel beam floors, the reinforcement of some steel beams with T-shaped inserts was proposed both from the top and the bottom of the existing beams, adapting to the circumstances of each space. These interventions can be seen in Figure 6.

Fig. 6: a) Steel beam reinforcement intervention. b) Intervention of new opening with new structural elements

Another possible strategy focuses on not intervening directly in existing elements but instead placing new beams that support part of the overload. These elements can be defined as secondary beams between existing beams or as additional elements that collect a certain tributary area of the structural elements.

In the restoration of existing buildings, there is often a need to create new openings for vertical communications or facility conductions. In these cases, the affected elements can be directly reinforced if the opening is compatible with the existing floor distribution, or new structural elements can be arranged to frame the projected opening. To illustrate this intervention, Figure 6 shows the placement of metal beams under an existing floor for a new opening in the refurbishment of an office building in Madrid.

4.3.2 New compression layer in floor slabs

In steel beams floor slabs, the solution described in the previous section, addressing each element individually, can be employed, or a more general and superficial strategy can be adopted.

In this case, the solution involves placing a new compression layer of reinforced concrete over the existing steel beams, connecting both elements to form a composite section. This strategy offers multiple advantages, including increased load-bearing capacity, enhanced stiffness to reduce deformability and vibration issues, formation of a diaphragm effect in plan, optimization of material behavior, etc.

The new layer can be directly executed on the existing floor structure if it can bear the weight of fresh concrete, or some formwork elements (flat or corrugated sheets) can be introduced. Connection with the existing metal joists is ensured through connectors fixed to the beams embedded in the new compression layer.

Additionally, the use of lightweight structural concrete for this new compression layer is worth considering. While it may exhibit some reductions in mechanical properties (lower compressive strength and lower modulus of elasticity) compared to conventional concrete, the weight reduction is often beneficial for both the floor slabs and the overall building (supports and foundation). This consideration is particularly relevant in buildings where no intervention in the existing foundation is planned, and therefore, the load level of the new project should not exceed that of the original building.

In this regard, the reinforcement intervention with a compression layer was proposed for all the floor slabs in the previously mentioned office building in Madrid. The rehabilitation involved removing the existing non-reinforced mortar layer to expose the beams and placing a new layer of reinforced lightweight concrete, connected to them. This strategy succeeded in increasing load-bearing capacity and stiffness without the need for additional steel reinforcements. Additionally, no intervention in the foundation was necessary as the overall load level of the building did not increase. Figure 7 shows an image of the connectors and reinforcement of the compression layer constituting the reinforcement performed on the floor slabs.

Fig. 7: Intervention of new reinforcement with new compression layer

4.4 Foundation intervention

As a general practice, foundation interventions are typically addressed using reinforced concrete elements. However, certain circumstances may require the use of steel elements due to spatial or execution constraints.

In some instances, steel beams are used as a base to transfer loads from the base of supports to new foundations or to raise the level of existing foundations. Specifically, it can be used to modify a direct foundation to a deeper one if required by the project. This steel system connects the base of the existing pillar to a new foundation.

Another situation arises when it is necessary to install temporary elements to carry out intervention under existing columns. These substantial shoring structures connect with the existing structure to facilitate complex and extensive interventions.

In a residential project in Barcelona, for instance, it was necessary to create steel systems and micro-pile towers to excavate two basement levels beneath an existing building. The steel system acted as a temporary structure connecting the existing columns to the micro-piles. As the excavation progressed, temporary towers were formed, bracing the micro-piles with steel angles until reaching the required level. Once at this point, new steel columns were placed under the existing ones with their new foundation (employing the already executed micro-piles), and the entire temporary steel system was dismantled. Figure 8 illustrates the excavation process for the first basement, with the structure of the existing building suspended from these temporary towers.

Fig. 8: Temporary stabilization for excavation

4.5 Alterations on the existing structural system

Finally, interventions that alter the existing structural system to promote behavior suitable for the new project's needs can be considered. It is challenging to categorize the various possibilities, as each building in this case has its specific characteristics. However, all actions that modify the existing configuration to create a new structural system could be considered.

As an example, Figure 9 shows an image of the analysis model developed for a public building in Extremadura. The original structure of this building was based on a system of beam and columns frames. The project proposed reconfiguring the existing beams as the lower chord of new truss beams. With this modification, the beams, which initially worked under bending moments, now experience predominantly tensile forces, altering and optimizing their initial behavior. The creation of this new truss beam is not only a formal play but also achieves an increase in stiffness and load-bearing capacity to meet the requirements of the new project while respecting the existing elements.

Thus, the potential of steel structures to create new design scenarios that are considered from the initial design phase is highlighted. Understanding these strategies allows for the incorporation of these possibilities in the rehabilitation project.

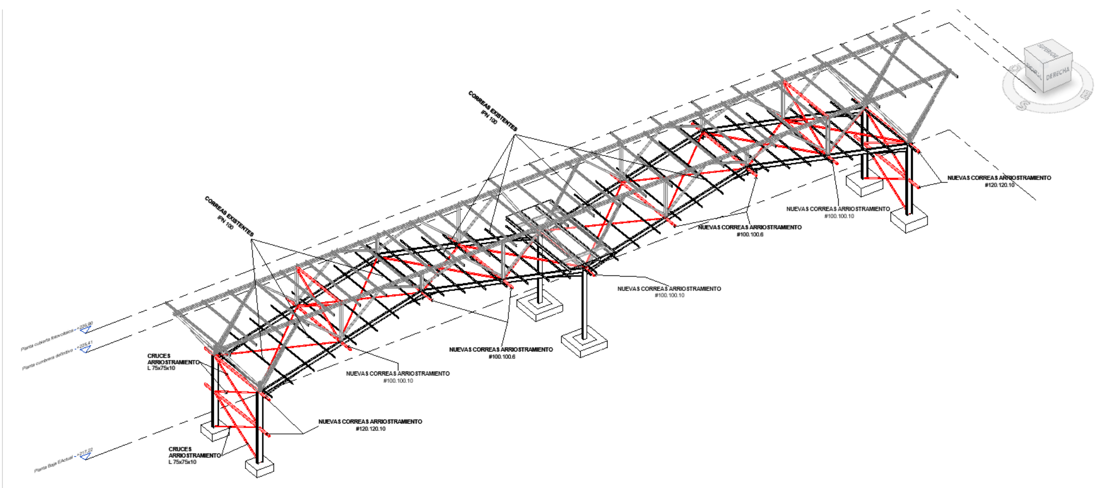

Fig. 9: Structural system alteration

5. Conclusions

The possibilities of steel and composite structures in intervention and rehabilitation have been discussed and illustrated with recent different projects (use, space, configuration, needs, etc.).

Steel structures are characterized by being very clear systems in their approach, making the understanding of their operation easily analyzable. Based on the knowledge of the material, system, and project requirements, interventions can be carried out on all structural elements, taking into account their characteristics and needs.

Thus, operations to increase stability (both local and global), intervention in columns, beams, and slabs, as well as modifications to the structural system, have been reviewed. The ease of intervention is a common feature in this type of structure, as they can be characterized quickly, and reinforcement strategies are straightforward and well-established in the construction industry. Moreover, they offer possibilities and opportunities for development and innovation.

Strategies for incorporating new elements (bracing system, new beams, columns, etc.), reinforcement of existing elements (addition or supplementation of sections, construction of composite sections), and optimization and alteration of the structural system have been presented.

All these strategies have demonstrated their viability in recent projects, with easy implementation and integration into the proposed spatial configuration. In this regard, it is worth noting that intervention and rehabilitation in existing buildings can be seen as an opportunity to improve the overall behavior of structures, optimizing materials according to current techniques and integrating into the compositional discourse of the project from its early stages.

In the current context of environmental awareness and responsibility, it is essential to highlight and value projects involving the rehabilitation, reinforcement, and intervention in existing structures as a reference for sustainable and responsible construction. In this context, metal structures exhibit tremendous versatility, capacity, and potential for adaptation and restoration.

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