Revolutionizing Steel Structures: Bridging Research and Sustainable Design For Future Societal Impact

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This paper examines how advanced analysis, novel design and assessment methods, and digital technologies can support a more sustainable and circular steel construction sector. It identifies two key pathways towards environmentally responsible steel structural design: the use of innovative design and assessment methods enabled by digital technologies, and the establishment of a comprehensive framework for the reuse of reclaimed steelwork. The paper also identifies key challenges to improving the sustainability and circularity of steel construction and presents research projects addressing these challenges.

This research is highly relevant to **Drastic**'s **Spanish Demonstrator**, which focuses on the reuse of reclaimed structural steel from the dismantled Litoral Thermal Power Plant in a new circular warehouse in Balaguer. The Spanish Demonstrator therefore provides the practical application of the research presented in this paper, directly addressing the challenge of demonstrating how reclaimed steel can be reused to support the decarbonisation of the construction sector.

The connection to Drastic is strengthened by the involvement of project partner **UPC**, whose researchers are authors of the paper and are also involved in the Spanish Demonstrator. This provides a direct link between the research presented in the paper and Drastic's practical demonstration of reclaimed steel reuse.

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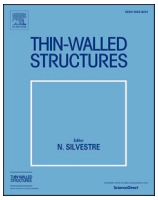



Revolutionizing steel structures: bridging research and sustainable design for future societal impact

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ABSTRACT

This paper delves into the transformative journey from advanced analysis in steel structures to establishing a design paradigm for the construction sector –responsible for 50 % of raw material extraction, 40 % of all energy consumption and 36 % of greenhouse gas emissions–, aligned with the European Green Deal requirements. In this context, the utilization of novel design and assessment methods, empowered by the use of digital technologies, and the establishment of a comprehensive framework for the reuse of reclaimed steelwork represent the two main paths towards a reliable and environmentally responsible steel structural design. The paper explores and underscores the main challenges that the research community needs to address for improving the sustainability and circularity of the steel construction sector, and presents two specific research projects that will contribute to address such shortcomings: the implementation of a fully documented demonstrator to showcase the reuse process for decarbonization, and the development of a holistic Decision Support System that integrates system-based advanced design methods, Structural Health Monitoring and Life Cycle Assessment. Ultimately, this paper aims to provide insights into multifaceted aspects of smart, sustainable steel structures, advocating for system-based approaches to reshape the future of structural engineering and to ensure a resilient and environmentally conscious built environment.

1. Introduction

The construction sector is the largest single economic activity and the biggest industrial employer in Europe, representing more than 10 % of the European Union's Gross Domestic Product and more than 50 % of the fixed capital formation. Hence, it is a key area for the implementation of contemporary EU policies including those related to sustainability, environment and energy, following the United Nations' Sustainable Development Goals. As a response to this scenario, the new trends in the construction sector follow two main principles: (i) architects and engineers must improve the quality of buildings and other engineering works, by establishing new principles for their design and maintenance, and (ii) the building and construction sector plays a major role in the quest towards sustainable development, and must therefore push significant innovation strategies to reduce the associated carbon emissions. In this context, it is necessary to contribute to the imperative paradigm change in not only the design of new structures through the reuse of reclaimed structural elements, but also in the management of existing steel structures, integrating novel reliability-based structural design methods and advanced finite element simulations with real-time information retrieved from Structural Health Monitoring (SHM) technologies, and the implementation of Life Cycle Assessment (LCA) frameworks for decision making processes.

Assuming a service life of 50 years for the building stock, the ratio of existing-to-new structures is around 30, with 3 to 6 structures being in their last 10 to 20 years of service life for each new structure designed according to the data reported in [1]. If the focus is particularly placed in Europe, the data shows that the EU experiences an annual addition of approximately 1.5 to 2 million new houses, corresponding to a construction rate between 0.7 % and 1 % relative to the existing housing stock, which varies across member states as a result of factors such as population growth, urbanization trends, and national housing policies [2,3]. Considering this, any contingency action to reduce the carbon footprint of the built environment and contribute to climate change mitigation must (i) reclaim structural members from infrastructure set to be demolished after their service life is reached, ensuring that a suitable standardization framework is available (at both technical and legal levels) to guarantee their reuse in the construction of new structures,

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and (ii) carry out a thorough assessment and estimation of the remaining lifetime of existing structures, and enable energy efficient retrofitting strategies and life extensions when possible.

Within this context, this paper aims to provide insights into the fundamental aspects of sustainable steel structures, with a special focus on two recent research efforts dealing with the reuse of steel components and the assessment of existing structures using system-based approaches to ensure resilient and environmentally conscious infrastructures: the "Demonstrating Real and Affordable Sustainable Building Solutions with Top-level whole life-cycle performance and Improved Circularity" DRASTIC project [4], which aims to address the untapped potential for decarbonisation and significant transformation within the European built environment, reducing the whole life-cycle carbon emissions through the reuse of components and materials; and the RE-STEEL project "From member to system REliability for the assessment and management of existing STEEL structures integrating SHM and LCA principles" [5], which plans to enhance the assessment of existing steel structures by using advanced system-based direct design methods and by integrating the information gathered from Structural Health Monitoring and Life Cycle Assessment (LCA) considerations into a holistic Decision Support System (DSS).

Recent advancements carried out on these two key paths towards reshaping the future of structural engineering are presented in detail, for the reuse of steel components in Section 2 and for the assessment of existing structures in Section 3, including technologies that will help the practical implementation of the previous strategies such as Structural Health Monitoring and Life Cycle Assessment. The potential of novel technologies such as Hybrid Testing to overcome some of the major gaps in the widespread of the two paths is explored in Section 4, and finally, an overview of the current development status of codes and standards that will ensure the regulatory framework of the sustainable construction sector is given in Section 5.

2. Reuse of steel components

2.1. Current context

Tackling both embodied and operational greenhouse gas (GHG) emissions, also known as whole-life carbon emissions, is crucial to contribute to more sustainable societies and to meet European guidelines. The EU aims for a 55 % reduction in greenhouse gas emissions by 2030 and to achieve climate neutrality by 2050. As such, a significant focus is placed on the building sector, which accounts for approximately 40 % of the EU's energy consumption and 36 % of its GHG emissions, emphasizing the importance of acting on both embodied carbon and whole-life carbon emissions in its policies and strategies. Within these key initiatives and strategies, the following are relevant to this study: (i) promotion of sufficiency measures, exploring strategies that focus on making the best use of the existing building stock, such as renovation and adaptive reuse, to minimize the need for new construction and the associated embodied emissions [6]; (ii) developing whole-life carbon emission benchmarks and measurement methodologies by harmonizing calculation methods and setting performance standards to guide the industry towards low-carbon practices [6]; and (iii) mandating to measure and report embodied carbon emissions, through standardized procedures, for new large-scale construction projects [7]. In view of this, and considering that embodied greenhouse gas emissions account for about 10–20 % of the EU's total building emissions, priority should be given to significantly reducing embodied carbon emissions, not only during refurbishment but also in new construction. In this framework, reclaiming and reusing structural steel during the refurbishment, retrofitting and new construction of buildings is considered a key strategy to reduce both embodied energy and carbon, increase the high-life cycle performance, and reduce life-cycle costs, making it more affordable for a wide and diverse group of building owners and users. However, the reuse of reclaimed steel is still limited to some applications, and it is important to follow special recommendations for data collection, inspection and testing to ensure that reclaimed structural steelwork can be reused with confidence [8].

2.2. Background technical evidence

In recent years, several projects have focused on assessing the environmental impact of steel and composite buildings, including the LVS3 "Large Valorisation on Sustainability of Steel Structures" project [9], in which life-cycle methodologies were developed and validated for steel structures, offering a comprehensive set of resources, including background documents, a design guide, and user-friendly software. Subsequently, a key technical effort towards making the reuse of steel components a reality was the PROGRESS "Provisions for a Greater Reuse of Steel Structures" project [10], whose main objective was to develop products, systems, methods and protocols that facilitate the reuse of various components of steel-framed single-storey buildings. The project addressed both deconstruction and reuse of existing buildings, and how new buildings should be designed, constructed and documented to facilitate future reuse. Its scope included primary structures (frames), secondary structures and multi-material hybrid components of the envelope, approaching the most important aspects of the circular economy in steel construction, the reuse of components, across the whole life cycle of construction steel products [11].

In particular, one of the main contributions of the PROGRESS project [10,11] was the establishment of the recommendations of the first quality verification protocols that should be undertaken on the reclaimed steelwork to assess the material and geometrical characteristics, which include both destructive and non-destructive testing. The results of such characterization protocols, together with the origin and prior information available on the reclaimed elements, allow their classification into one of three classes (Class A, Class B or Class C steel), and has a direct impact on the partial safety factors recommended for design. Class A steel includes steelwork reclaimed from a cancelled project (never erected) or steelwork for which the original material test certificates and inspection documents are available, and therefore minimal non-destructive testing is proposed as part of the quality verification protocol. On the other hand, Class B steel features reclaimed steelwork with no documentation for which material re-certification is required, representing most of the practical applications of reclaimed steelwork nowadays. For this type of reclaimed steel, a set of destructive and non-destructive testing are necessary to characterize mechanical properties and chemical composition. Finally, Class C steel covers those reclaimed elements for which no certificates are available and to which no testing protocol is applied, so it is only recommended for projects that represent a low risk for human safety.

In terms of design recommendations, the PROGRESS project concluded that the use of reclaimed members should be limited to structures not subjected to fatigue or seismic loading, and that elastic global analyses should be carried out on new structures built from reclaimed elements of any Class. Moreover, reclaimed steel was found to be sufficiently ductile to permit the use of a plastic cross-sectional resistance, following the fundamental design approach in prEN1993–1–1 [12], although it was recommended to avoid the use of plastic global analyses that require significant levels of ductility. Regarding the recommended partial resistance safety factors for reclaimed elements, the thorough reliability studies carried out in the framework of the project concluded that the use of the same γ_{M0} and γ_{M2} values used in the current version of prEN 1993–1–1 [12] for new steel can be safely assumed for cross-section verifications, since all the geometric and material characteristics will have been checked for every Class A and Class B steel members. For the γ_{M1} factor for instability, however, more conservative measures were recommended due to the existing uncertainties in member imperfections, including cross-sectional or torsional imperfections, even if residual stresses are thought to be similar to those found in new steelwork. As a result, a

value of $\gamma_{M1,mod} = 1.15$ is recommended for all reclaimed steelwork classes, with the exception of Class A steel that has never been erected, for which the original value of $\gamma_{M1} = 1.0$ might be adopted.

Following the PROGRESS project, another current RFCS-funded project addressing the challenges in both deconstruction and reuse of exiting steel buildings, and in the design of new buildings, is the ADVANCE project "Accompanying measure for Dissemination, Valorisation and Collaborative Exploitation of circularity of constructional steel products" [13]. The main objectives of the project are to provide guidance for the successful reuse of existing components or structures and design of new ones with improved reusability, and to introduce recommendations for product/waste status and material testing protocols for recertification of steel products from the PROGRESS project.

2.3. Demonstrators: practical implementation

While the results of the PROGRESS [10] and ADVANCE [13] projects are fundamental for the establishment of the regulatory framework for the design with reclaimed steel members and the widespread of this new practice, having examples of real and fully documented implementation case studies to showcase the entire reclaim and design process, as well as to identify the main challenges that still require attention, is also key. With this objective in mind, the DRASTIC project "Demonstrating Real and Affordable Sustainable Building Solutions with Top-level whole life-cycle performance and Improved Circularity" [4] plans to address the untapped potential for decarbonisation and significant transformation within the European built environment via the reduction of whole life cycle carbon. The project is geared around 5 demonstrators with different innovative designs, construction/renovation methods, and technological circular system solutions and a wide variety of typologies, including steel buildings (the Spanish demonstrator). It aims at developing a toolbox integrated in a common digital building data platform also addressing transparency, quality performance and multi-cycle traceability.

The Spanish demonstrator focuses on the reuse of steel components with a special emphasis on enforcing traceability and the circularity of the steel construction sector, as well as in the potential use of white slag as replacement of cement. The Process Chain (PC) for the successful reuse of steel components, described in detail in [14], will be followed in the development of the demonstrator to test the Process Chain from a practical point of view, and to propose the necessary modifications for designing reused steel components confidently according to Eurocode 3 in the future. This particular demonstrator is led by CELSA Group, and the value chain actors and stakeholders contributing to the demonstrator are UPC, SORIGUÉ, LEZAMA, ADEC and GBCE; it will focus on the reuse of the steel members reclaimed from the Litoral de Almería Thermal Power Plant (South-East of Spain), which has been already deconstructed (see Fig. 1).

Using the material recovered from the donor structure, a steel warehouse will be built in Balaguer (North-East of Spain). In the process, the quality of the reclaimed steel members will be thoroughly assessed and the feasibility of selective deconstruction and reuse of structural steel elements will be evaluated. The specific steps towards the successful implementation of the Demonstrator within the context of the Process Chain proposed in [14] are described in the following sections.

2.3.1. Step 1 – Reclaim: Deconstruction & Preparation

The first step is to perform a thorough analysis of the information available on the donor structure in the form of reports, original drawings and onsite visits (see Fig. 2) for demolition/dismantling, as well as the estimation, if possible, of the prior loading history of the elements and connections. This is followed by a detailed inventory of the elements to be reused and the study of the suitability of the different demolition alternatives available, following the rules and recommendations in [15]. In this particular case, the structure is a small 14.5 × 6 m warehouse built in 2017 by Enel Engineering & Construction–Endesa, with an average height of 3.4 m, and made from HEB140 columns and IPE240 and IPE180 beams using S275JR steel.

2.3.2. Step 2 – Component Survey: Inspection & Testing

The proposed circular alternatives should be compared with the *Business as Usual* solutions, and assist the decision-making process. The development of the solutions includes the design, choice of materials and formulation, and the development of new or extension of existing quality control protocols to ensure the performance of products containing recovered and reusable elements. In order to be able to have a good traceability of all the components, a pre-dismantling labelling was carried out on all recovered products (see Fig. 3). The labels were scanned and connected to the traceability platform to incorporate the results into the BIM building model, and later, the results of the quality control and labelling of the new solutions will be connected to the traceability platform for each demonstrator.

The original intention was to adopt a traceability system that endured the dismantling, transportation, recondition, assessment and



Fig. 1. Litoral de Almería Thermal Power Plant, and donor structure.

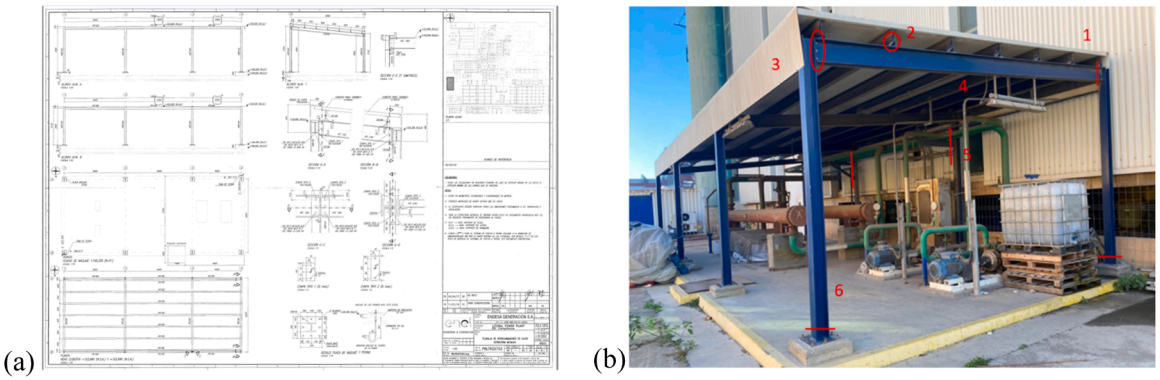

Fig. 2. (a) Original drawings and (b) visual inspection of the donor structure.

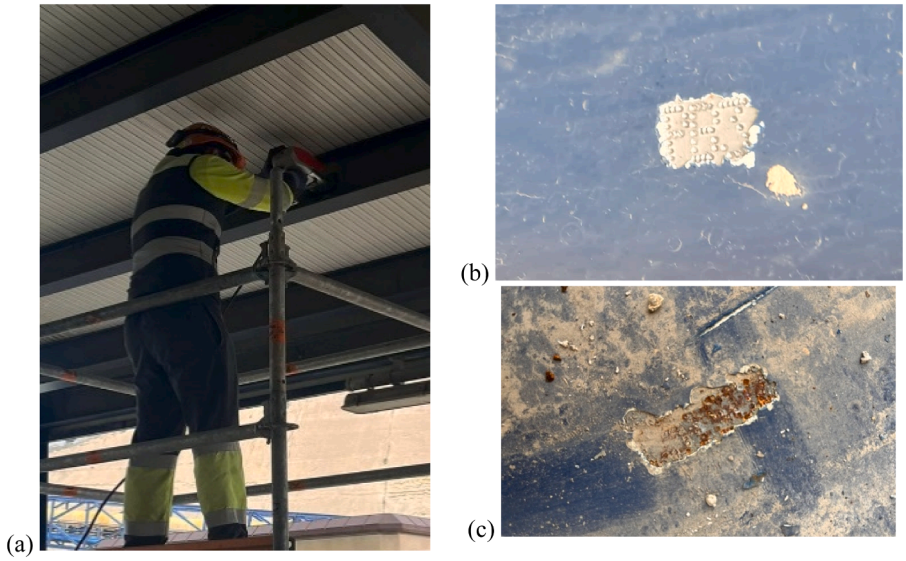

Fig. 3. (a) Labelling marking process, (b) immediate result and (c) status after 9 months.

stockage phases, and consequently a permanent marking system was selected (see Fig. 3(b)), since the attachment of QR or alternative codes was deemed inappropriate. The adopted solution, however, was found to be unsuitable due to the corrosion of the marking system after only 9 months, as it can be seen in Fig. 3(c), and alternative solutions are being explored at the moment.

2.3.3. *Step 3 – Component Assessment & Classification*

The component assessment is being carried out according to the rules of FprCEN/TS 17440 [16] and EN 1990–2 [17], and depends on the information available from the donor structure according to the principles described in [14]. Based on that, the most suitable characterization tests (measurement of residual and initial stresses, evaluation of fatigue and brittle fracture performance, measurement of geometric imperfections, section loss due to corrosion and characterization of mechanical properties) and structural behaviour tests on elements (beams and columns) will be performed at the LATEM Laboratory at UPC.

2.3.4. *Steps 4 & 5 – Stockage & Market Placing*

Once the pre-demolition study and labelling system were finished, the structure was carefully deconstructed (see Fig. 4) and a stockage system of the steel components has been developed, which uses the information and classification system defined in the previous steps for the digital books. Likewise, ensuring that the degradation of the components (e.g., due to corrosion) does not occur and maintaining the mechanical



Fig. 4. Selective dismantling process.

safety for a future market placing are key features of the stockage procedure.

2.3.5. *Steps 6 & 7 – Design & Structural Modification*

The design of the new structure, the demonstrator, will be performed using the measurements obtained in Step 3, and through advanced finite element modelling calibrated from the experimental tests (see Fig. 5).

Parallel to this, a numerical parametric data generation will be carried out to assess the influence of the variability observed in the input

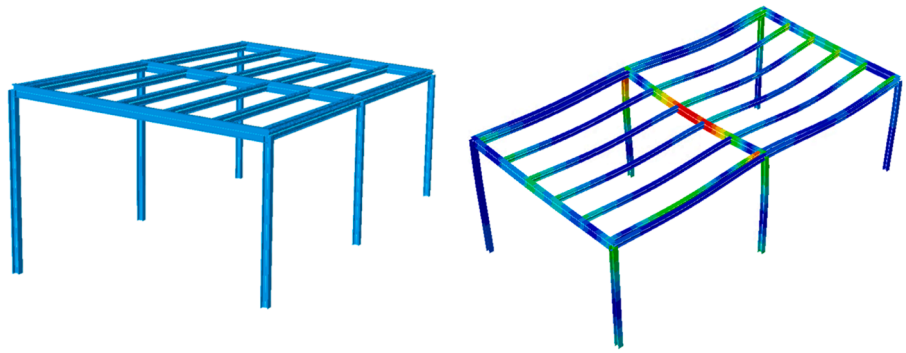

Fig. 5. Design of the new structure with reused elements and structural analysis.

characteristics (i.e., imperfections, initial stresses, mechanical properties) on the capacity of steel beams and columns. The procedure will allow evaluating the suitability of the partial safety factors γ_{M0} and γ_{M1} for a reliable reuse of steel components, comparing them with the recommendations set out in [11]. In addition to that, the reliability of the entire system will be assessed through system-based reliability studies, in which the predicted probabilities of failure will be compared to those obtained under the assumption that the structure is built from new steel components.

2.3.6. *Step 8 – Construction, Installation & Future Optimization*

Once the previous steps have been completed, the demonstrator will be constructed and installed using the reclaimed components according to the relevant specifications, and all the information will be implemented in the DRASTIC Digital Building Logbook. After the installation of the new structure is finalized, its technical performance for further optimisation and future exploitation will be evaluated and measured to prospect the scaling potential of the solution by developing advanced finite element models. Inputting measured mechanical characteristics, initial stress states and initial geometric imperfections, the numerical model will allow to assess the capacity of the new structure in the Ultimate and Serviceability Limit States, providing a benchmark reference for future monitoring and maintenance.

3. Assessment of existing structures using system-based direct design methods

3.1. *Current context*

These assessments and retrofitting actuations, or demolition decisions, require analysis methodologies different from those used in the design of new structures, because the effects of the construction process and possible alterations, deterioration, misuse and other structural changes respect to their as-built state need to be taken into account. Therefore, the reliability assessment of existing structures is fundamentally different from that traditionally used to design new structures, and several studies [18,19] have found that the direct application of conventional analysis methods to the assessment of existing structures often leads to a high degree of conservatism and important economic consequences. This is why the assessment of existing structures requires the application of more advanced methods, as a rule beyond the scope of design codes for new structures, and why the development of new technical guidelines for the assessment and retrofitting of existing structures will provide the scientific basis to master this new challenge and enable engineers and architects to achieve sustainable, safe and economical designs.

The assessment of existing structures is generally comprised by four features: (i) the methodologies for gathering information and updating basic variables for the representation of actions and material properties, (ii) the structural analysis for the quantitative verification of structural elements and systems, (iii) the adherence to the reliability requirements and prerequisites specified in current standards, and (iv) the evaluation of its reliability against the adopted target reliability index. There can be significant benefits to be gained from using updated data in the assessment of structures, and by considering alternative structural analysis models that represent more accurately the limit states being assessed.

This is addressed in detail in the RE-STEEL project “From member to system REliability for the assessment and management of existing STEEL structures integrating SHM and LCA principles” [5], which aim to enhance the assessment of existing steel structures in two fundamental ways: (i) by adapting the newly developed advanced system-based direct design methods for steel structures as suitable structural analysis methodologies in the assessment of existing structures, and (ii) by providing guidance on the use of structural health monitoring data (SHM) collected from existing structures for the adaptation of maintenance and building management strategies, broadening purely economic decisions to incorporate sustainable Life Cycle Assessment (LCA) considerations.

3.2. *System-based Direct Design Methods*

The current methodology for the design of new structures is based on traditional limit state criteria following a two-step approach, where a structural analysis is performed first and limit states are subsequently checked for members and connections, assuming that the ultimate capacity of the structure is reached when the first member or connection reaches its ultimate limit state. Provisions for these checks are given by structural codes for the particular materials, e.g., Eurocode 3 for steel structures, in which design parameters and their random variations are modelled by nominal or characteristic values based on partial coefficient methods.

However, the exponential growth of the computational power of desktop computers and advances in design software during the past decades have made it possible to accurately predict the behaviour and failure of complex structural systems, providing designers with the opportunity to progress from the current two-step member-based design method to direct system-based design methods such as the Direct Design Method (DDM), which is based on a geometric and material nonlinear (advanced) analysis that incorporates effects known to substantially affect the behaviour and strength of systems using the finite element method.

A clear indication of the relevance and future predominance of these new system-based methods is their recent implementation in major international structural codes for steel structures (AS/NZS 4100 – Steel Structures [20], AISC 360 – Specification for Structural Steel Buildings [21]), and the new prEN 1993–1–14 – Design assisted by finite element analysis [22], recently developed in Europe. However, it is important to consider that in the case of nonlinear analysis the interactions between action effects and structural response are relevant and must be taken into account when evaluating uncertainties, and a suitable and

consistent verification format needs to be developed based on the partial factor method. Since current design provisions do not prescribe suitable values for the system partial resistance factors $\gamma_{M,s}$ to be adopted to meet the reliability requirements for structural systems, these are currently under development for the variety of structural types and materials covered by these design codes using robust reliability frameworks that include the possible deviations for actions and properties, uncertainties associated with modelling, and acceptable target reliability indices β_0 for new structural systems.

The benefits of system-based direct design methods over the traditional two-step member-based design approach are threefold [23]: (i) the strength of structures can be directly evaluated from finite element (FE) simulations with the DDM, eliminating the need for checking member and connection resistances using codified strength equations, (ii) it leads to lighter and more economical designs, with material requirement reductions of up to 15 %, and (iii) it provides an accurate and representative estimation of the reliability of the complete structure (in opposition to member-based approaches), and thus, the probability of failure becomes a specific and measurable property of the structure. While the practical implications and benefits of the two first aspects are clear for both new and existing structures, the third advantage becomes crucial in the context of assessing the current state of a structure, because it allows planning and optimizing retrofitting actions rationally by defining suitable target reliability indices and corresponding system partial resistance factors $\gamma_{M,s}$, which in turn allow the characteristic system strength and structural retrofitting requirements to be determined. In addition to this, the adoption of probabilistic approaches in the assessment and retrofitting process would allow the explicit consideration of multiple aspects linked to the remaining or extended service life (including target reliabilities and design values of loading) in a more consistent and systematic manner.

Target reliability indices are specified in standards, including EN 1990 [24], but are primarily intended for the design of new structures, which can differ significantly from the values assumed by society for making the retrofitting of existing structures economically viable [25]. For example, the 2020 *fib* Model Code draft [26] recommends target reliability levels for new and existing structures that are based on the values specified in ISO 2394 [27] and the JCSS Probabilistic Model Code [28] for a one-year reference period.

Hence, the adoption of system-based direct methods for the assessment of existing structures can be especially beneficial, as it may eliminate or reduce the required retrofitting actuations if the strength of the system is predicted more accurately. Furthermore, it can also assist in the assessment of the reliability levels resulting from different potential retrofitting actuations on the structures, contributing to more rational decision-making processes that can be integrated with SHM and LCA techniques. In addition, if the uncertainty in the structural performance is reduced using data gathered from the structure, it would be possible to adopt less conservative system partial safety factors for the same level of target reliability, further reducing the required retrofitting actuations (see Fig. 6).

3.3. Structural Health Monitoring Systems

Among other authors, Küttenbaum et al. [29] have highlighted the importance of procuring measured information that represents the properties and conditions of existing structures to make optimal decisions based on reliability considerations, and using the procured data as input information in the computational models to refine the reliability assessment, or by updating the original stochastic models through Bayesian inference to reduce the associated uncertainties. In the era of digitalization and ubiquitous use of sensors, advanced measurements of structural performance are proving indispensable when carrying out condition assessments, although a consistent interface between metrology and reliability analysis is still lacking, as monitoring data is generally available for serviceability conditions, for which the structural

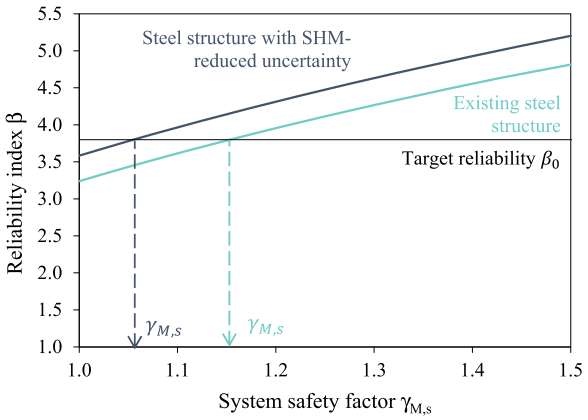

Fig. 6. Potential influence of SHM in uncertainty reduction and calibration of $\gamma_{M,s}$ factors.

behaviour can differ significantly from the ultimate limit state response [29].

The extensive instrumentation of structures is nowadays a common (yet not consolidated) practice [28], as the application of wireless technology in the monitoring of civil engineering infrastructure using Internet of Things (IoT) and other SHM methods is quite mature, but mostly focused on concrete structures, bridges, or structures during the construction phases. Further research is needed on the postprocessing of data compared to existing methods for sensors, actuators, network communication and cloud computing (see Layers 1 to 3 in Fig. 7). The way from raw monitoring data to valuable information for decision-making is the key issue in the management of existing infrastructure. In addition, the time required for a proper analysis and management of these data (often in the order of weeks) precludes its use to make real-time decisions (practical application of Layers 4 and 5), making structural health monitoring and damage assessment of civil engineering infrastructure a complex task [30].

Comprehensive structural health assessment can be performed through the efficient use of real-time data obtained from various types of IoT sensors and/or remote sensing techniques, which monitor structural performance parameters and export these to cloud-based data storage systems. This is why SHM technology can significantly benefit from the definition of Key Performance Indicators (KPIs) to monitor structures efficiently, making real-time assessment possible and accelerating the decision-making process. The RE-STEEL project is currently working on building the blocks required to fill the gap between metrology and analysis (i) by developing a clear methodology to integrate SHM data in the performance and reliability analysis of existing structures, using data from real steel structures to reduce the uncertainty of key random input variables, as per [31], and (ii) by identifying the relevant KPIs for the future instrumentation strategies of existing structures. While this methodology is still under development, the underlaying idea is that the information extracted from SHM will allow to update the statistical models originally used to calibrate the partial resistance factors prescribed in the codes through Bayesian inference, which in turn will result in statistical models with reduced uncertainties for the input variables identified as KPIs. Using these new models, which are particular to the structure under consideration and hence present lower variabilities, additional updated structural reliability analyses can be performed following the procedures set out in prEN 1990–2 [17] to calibrate specific partial resistance factors that will typically be lower than those prescribed in the reference codes.

When the traditional structural analysis methodologies are replaced by the new advanced system-based direct design methods, SHM data will enable the optimal monitoring and management of structures which, based on system reliability considerations, are able to define and assess different residual working lives and possible retrofitting



Fig. 7. Layers of the IoT structure for SHM (modified from [30]).

scenarios, and to integrate this with Life Cycle Assessment (LCA) strategies to conform a thorough Decision Support Systems (DSS).

3.4. Life Cycle Assessment

Life Cycle Assessment (LCA) methods are well-established in many industrial sectors but the social, economic and environmental indicators achievable using LCA are now also drawing attention in the construction sector [32]. The incorporation of LCA to the management of existing structures will deliver a comprehensive and systemic approach to the environmental evaluation of existing structures. Recent studies based on Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) of single-storey industrial buildings compared the environmental and economic impact of industrial steel structures (using climate change indicators such as GHG emissions, resource use, eutrophication and cost indicators), and showed the environmental benefits, together with the structural feasibility, of a strategy based on the reuse approach in construction [33].

4. Hybrid Testing

The use of hybrid simulation by combining, in real time, virtual models of complex structural systems (such as buildings, bridges, infrastructures, etc.) with the physical experiment of critical subsystems (e.g., frames, walls, elements, etc.) will contribute to the integration of the advanced numerical simulations with direct system-based design methods. This will, in turn, enable a synchronous and bidirectional flow of information between the virtual representation of a complex structural system and the physical laboratory test of a structural element that composes it. In other words, this advanced structural testing technique allows virtual modelling of an entire complex structural system, while physically testing only a part/component of it in the laboratory. Hybrid Testing infrastructure presents several advantages over the traditional testing setups, since it combines physical world resources with cloud-based environments, offering more flexible and scalable testing facilities. In particular, among the most relevant advantages of Hybrid Testing, the following can be highlighted [34–36]: (i) scalability, allowing to scale testing environments using numerical simulations when testing facilities are insufficient, making them ideal for load and performance testing, (ii) cost efficiency and resource optimization, reducing the need for investment in complex infrastructure and taking advantage of legacy facilities, (iii) improved test coverage and safety, providing access to more diverse testing environments and unusual configurations without risking the core infrastructure, and (iv) integration with modern tools such as monitoring.

Some specific application examples that illustrate the versatility and effectiveness of Hybrid Testing methods in structural engineering and the integration of advanced computational techniques are mentioned herein. In 2024 Akl and Ezzeldin [37] tested two-story, low-aspect-ratio reinforced concrete shear walls from nuclear facilities to assess their seismic performance using Hybrid Testing methods. The combination of the physical testing of wall segments with numerical modelling of the surrounding structure allowed evaluating force-displacement responses, stiffness, ductility, and damage patterns under different earthquake scenarios, and to overcome issues related to specimen sizes, actuator capacities, space limitations, and the ability to simulate the large mass associated with nuclear facilities. Similarly, Del Carpio et al. [38] tested a large-scale steel moment-resisting frame through collapse using Hybrid Testing, in which substructuring techniques and time-stepping integration methods, developed with the aim of reducing the number of required actuators while adequately approximating the boundary conditions, were evaluated for the specific case of structures exhibiting large levels of nonlinear responses. Analysing a different structural configuration, Alhameedi [39] applied the Hybrid Testing method to a steel truss, in which the critical element of the structure was tested while the remaining truss was modelled numerically and coupled with the experimental setup. The integration of the data collected from the physical substructure into the hybrid simulation was successful, and a satisfactory accuracy was achieved without large experimental testing or sophisticated numerical modelling. Finally, research efforts focused on the development and assessment of machine-learning-based metamodels are worth mentioning [40], which intend to optimize the large number of degrees of freedoms that need to be computed in real-time when relatively complex structures are analysed.

Initially, the use of Hybrid Testing was mainly focused on earthquake engineering for simulating the nonlinear dynamic response of large structural systems in facilities with limited capacities, but the main challenge for using this testing framework is the correct application of the interface boundary conditions between the numerical and the physical subdomains [41]. Under these conditions, Hybrid Testing could have great potential in combination with advanced numerical simulations, as it would allow to calibrate the system partial resistance factors $\gamma_{M,s}$ required for direct system-based design methods by testing only some critical parts of the structure in the laboratory and simulating the remaining parts of the structure using advanced finite element (FE) analysis software. The challenge of developing the main controllers for a correct hybrid simulation is being addressed by different research groups nowadays, such as the technology developed in the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre of the European Commission concerning the new generation of servo-hydraulic real-time digital controller/acquisition system adopted in large scale experiments [42]. Based on this technology, the Laboratory of Technology of Structures & Materials (LATEM), at the Department of Civil and Environmental Engineering at UPC, is facing its 4.0 digital transformation to foster new lines of research and innovation in the construction sector through the successful financing of the LATEM 4.0 project "Multilevel materialization, digitalization and experimentation of structures by means of cyber-physical systems of Construction 4.0" [43], funded by the Ministry of Science and Innovation of Spain through the Next Generation EU funds. It will be the first Multi-Axis Subassemblage Testing (MAST) system in Spain, and it will upgrade the LATEM laboratory to a cutting-edge experimental facility, as the

most prestigious Civil and Structural Engineering laboratories worldwide, e.g., UC Berkeley, ETH Zürich, Tongji University, among others.

Virtual models of complex structural systems (such as entire buildings, bridges or large infrastructures) will be integrated in real time with the physical experiment of critical subsystems (frames, walls or elements), as illustrated in Fig. 8. In addition, the physical response obtained in the laboratory will be digitalized with high fidelity by means of a monitoring system with distributed fiber optics sensing.

5. Codes, standards and guides

In 2012, the European Commission issued the Mandate M/515 with a detailed work programme to amend the current Eurocodes to include existing structures and extend the scope of structural Eurocodes. In response, the CEN/TC250 committee created a specific Working Group WG2 – Assessment and retrofitting of existing structures, responsible for developing the required new rules to complement EN 1990 – Basis of structural and geotechnical design [24], and EN 1991 – Actions on structures [44]. Following the initial report [18] developed by WG2, the final report was shaped into the Technical Specification FprCEN/TS 17440 [16] as an amendment to the new prEN 1990 [24], representing a significant advancement in closing the gap between standardised design and assessment/retrofitting of structures. Consequently, amendments to each Eurocode shall include an Annex to provide the recommended modifications to current Eurocode clauses to include existing structures. For steel structures, this will be prepared by the Working Group 23 CEN/TC250/SC3 – Assessment and retrofitting of existing iron and steel structures, created in 2025.

As evidenced in this paper, and elsewhere, reliability analysis is a fundamental part of any structural engineering activity, and recent works [1,45,46] on the application of the new provisions given in FprCEN/TS 17440 [16] highlight the importance of not only carrying out a proper assessment of existing structures, but also the differences that the reliability analysis should consider compared with that of new structures. Hence, closing these regulatory gaps through the development of standards and comprehensive guidelines that explicitly target the assessment of existing structures is a matter of great urgency [47].

Similarly, and although the use of reused steel dates back to the mid-20th century and some design guidelines have been developed since then to establish the conditions for its use, there is still a lack of specific regulations to ensure the safe design of structures with reused steel [48]. In fact, the European design code on structural steel does not deal with reused steel components explicitly. With the aim of addressing this, the CEN/TC250/SC3 committee, responsible for Eurocode 3, has started the organization of AdHoc Groups or new Working Groups for the development of standards for the implementation of steel reuse in construction. In this line, the recent "Guidance on Establishing European Design Rules for *Re*-Used Steel Components" [49] has been published with the main objectives of (i) identifying all relevant aspects, interrelations and constraints under which a future European design standard of such components can be carried out, and (ii) providing guidance on how a code part could be conceptualised and structured.

6. Conclusions

Due to the remarkable contribution of the construction sector to the global carbon emissions, the need for a radical change in the design paradigms of steel structures towards more sustainable practices is critical. In this line, this paper underscores the fundamental aspects that will contribute to enhancing the sustainability and the circularity of the construction sector by integrating advanced analysis techniques with digital technologies, particularly regarding reuse initiatives that will allow reducing embodied carbon and enhancing life cycle performance, as well as the integration of system-based assessment and retrofitting strategies.

The viability and environmental benefits of reusing steel components in new construction, and the potential for reducing the embodied carbon footprint of new structures, is currently being assessed in the ongoing DRASTIC project, which aims at successfully reclaiming and repurposing steel members from an existing structure (donor structure) to demonstrate the feasibility of the process. The thorough process of inspection, testing, and structural assessment, guided by the latest European standards, will ensure that reused materials meet all the necessary safety and performance requirements, and a scalable model applicable across Europe will be provided.

On the other hand, the development of a comprehensive decision support system, underpinned by advanced system-based analysis methods and information about the structural condition available through efficient use of SHM and LCA methods, will transform the assessment and retrofitting of existing structures, supporting informed decision-making towards sustainable construction practices. The transition from traditional member-based design methods to direct system-based approaches demonstrates improved structural efficiency, reliability, and cost-effectiveness. The underlying idea, that the computed strength and variability of structural components change with time and with the information made available through structural health monitoring systems, has practical significance. The main challenge that needs to be addressed relies in providing a rigorous yet simple methodology to include time as a variable in the reliability analyses, and to quantify statistically the change in failure probability accordingly.

In summary, the presented research emphasizes the crucial role of innovation, sustainability, and collaboration in revolutionizing steel structures, paving the way for a resilient, environmentally conscious built environment in the future. While there is progress in standard and code development, both regarding the assessment and retrofitting of existing structures and the reuse of reclaimed steel components, gaps remain in addressing specific aspects, highlighting the need for further regulatory strategies and research.

CRediT authorship contribution statement

Esther Real: Writing – original draft, Methodology, Conceptualization. **Itsaso Arrayago:** Writing – original draft, Methodology, Conceptualization. **Enrique Mirambell:** Writing – review & editing, Conceptualization.

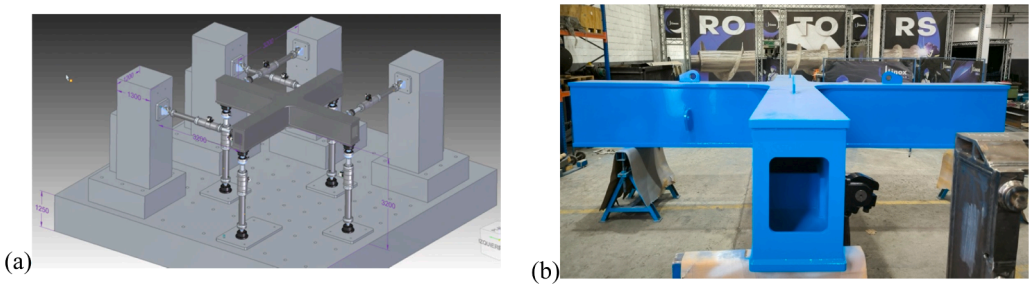

Fig. 8. (a) Setup of the LATEM 4.0 hybrid testing system; (b) Detailed view of the steel crosshead.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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