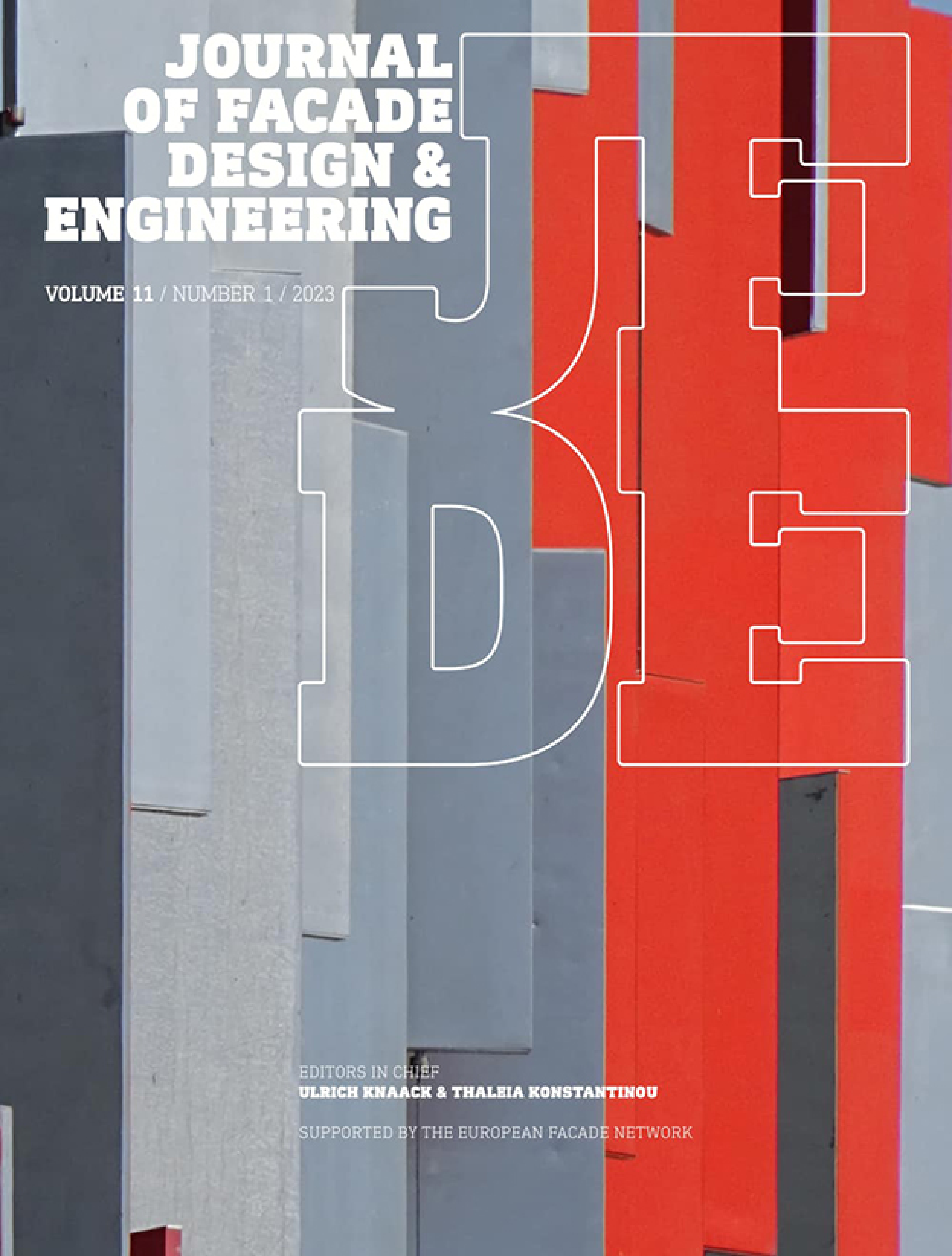

JOURNAL OF FACADE DESIGN & ENGINEERING

VOLUME 11 / NUMBER 1 / 2023

EDITORS IN CHIEF
ULRICH KNAACK & THALEIA KONSTANTINOU

SUPPORTED BY THE EUROPEAN FACADE NETWORK

Numerical Analysis of Aluminium Façade Components: Material Properties, Elastic-Plastic Response and Sustainable Impact

Augusto Mastropasqua[1*], Mauro Stefani[1], Paolo Rigone[2], Enrico Sergio Mazzucchelli[2], Paolo Giussani[2], Morteza Ammari[3]

* Corresponding author, research@mza-structuralengineering.com
1 MZA Research - Numerical Consulting ltd, London, United Kingdom
2 Politecnico di Milano, Department of Architecture, Built Environment and Construction Engineering, Milan, Italy
3 akt II (Tyrens Group), London, United Kingdom

Abstract

This paper commences with a scientific literature review of current research that underlines the environmental benefits to be gained from using smaller quantities of raw materials in the construction industry, with particular emphasis on a sustainable approach to façade design. Life cycle assessment modelling is advocated to validate the sustainability of building structures to achieve optimal solutions. A real-life application of the design of an aluminium façade bracket is presented, demonstrating that a weight reduction of up to 35-45% is attainable by exploiting the post-elastic properties of a material. The work described ranges from a discussion of the current conventional numerical techniques adopted by the industry to the most recent and advanced computational methods permitted by the introduction of Eurocode 9. This code facilitates a substantial enhancement in structural performance by incorporating an evaluation of the material's elastic-hardening behaviour and allows for a noteworthy reduction in component size and increased geometric design flexibility.

Keywords

façades and cladding components, material optimisation, elastic-plastic, elastic-hardening analysis

DOI

http://doi.org/10.47982/jfde.2023.1.02

1 INTRODUCTION

In recent years, several areas of research have explored new perspectives regarding ecological or even sustainable building design. Sustainability in building construction is meant to promote efficiency, reduce costs, and ensure a positive environmental impact (Akadiri, Chinyio & Olomolaiye, 2012). Undoubtedly, the construction industry has a significant impact on the natural environment through its use of building materials. According to the global footprint network, approximately 70% of raw material consumption exceeds what the planet can naturally regenerate. Moreover, the type of structural systems employed plays a pivotal role in the development of sustainable design, as building strategies and sustainable design principles are closely tied to it. Indeed, the structure and form of a building determine land use, material usage, energy consumption, greenhouse gas emissions, maintenance costs, risk management, and recycling. Therefore, achieving sustainability in the future requires that all major industrial sectors worldwide focus on understanding and significantly reducing their environmental footprints (Maxineasa, Isopescu, Baciu & Lupu, 2021). Life cycle assessment (LCA) is a methodology which investigates and sets the system boundaries concerning all industrial processes, from raw material supply, transportation, installation, usage and maintenance, repair or replacement, through to the end-of-life stage of dismantling or demolition, waste transportation, disposal, reuse, and recovery recycling.

Webster (2004) divides the life cycle impact into four categories for LCA and evaluation of the environmental impact of building systems over their lifetimes: (a) initial effects, which include the construction and manufacture of raw materials; (b) energy use during the life cycle of the building system; (c) the consequences of refurbishment; (d) the end-of-life effects, or the environmental repercussions following the life cycle. LCA must consider a number of crucial issues, including energy consumption, resource use, and green gas and pollution production. The initial impacts are mainly influenced by the building and construction type. Renovations, maintenance, and refurbishment depend more on the structural materials and less on the structural form. The disposal of structural materials has an end-of-life impact on the life cycle assessment (Wang & Adeli, 2014).

The European Technical Committee CEN/TC 350 'Sustainability of construction works' carries out and represents some of the efforts of the industry and academic and research institutions, providing guidelines and standard recommendations for the optimal use of processes and building materials. It also introduced the Environmental Product Declaration (EPD) to assure material conformity and the full consistency of the industrial process to obtain it in accordance with the European Standard EN 15804. The standard exclusively covers material supply, transportation, and manufacturing, whereas subsequent stages such as use in buildings, maintenance, repair, waste processing, and disposal are currently regulated by EN 15978 'Sustainability of construction works - Assessment of environmental performance of buildings - Calculation Methods. In particular, EN 15978 indicates that façades and architectural cladding are part of the superstructure, Level 1 Group.

Therefore, EN15804 and 15978, as well as the entire set of relevant guidelines, now represent a mandatory approach to the correct assessment of ecological and sustainable material usage. However, when referring to façades and cladding components made of aluminium, which also need to be designed for safety and protection purposes as indicated in CPR305/2017, a lack of information appears in terms of structural design methodology. For these elements, it is rather common to refer to Eurocode 9 EN 1999-1-1 (CEN 2007), which encompasses an exhaustive set of technical recommendations ranging from the design material properties to the section classification, resistance, and stability requirements. It is precisely this 2007 standard that allows engineers the possibility to thoroughly and exhaustively use different criteria for modelling the stress-strain response of structures. An interesting review in this regard can be found in Georgantzia, Gkantou & Kamaris (2021) and Gardner, Yun & Walport (2023).

2 SUSTAINABLE APPROACH FOR FAÇADE DESIGN

2.1 THE CONCEPT OF SUSTAINABILITY

The concept of sustainability focuses on the condition of the biophysical environment of the earth, particularly regarding the use and depletion of natural resources. It is more a matter of finding a sort of permanent state to support the people on Earth or a part of it without endangering the health of human beings, animals, and plants (Sadollah, Nasir & Geem, 2020). Sustainability can be defined as a way to design a product using natural renewable resources in a manner that does not eliminate or degrade them (Zabihi, Habib & Mirsaeedie, 2012). It is a multi-disciplinary concept (FIG 1). A sound and thorough analysis of every factor and element contributing directly or indirectly to this concept leads to an objective understanding and method of evaluation of sustainability (Abu-Rayash & Dincer, 2019). The Intergovernmental Panel on Climate Change (IPCC) stated that one of the available pathways to limit global warming to 1.5°C above pre-industrial levels is that global carbon emissions need to fall to 45% from 2010 levels by 2030 and continue a steep decline to zero net emissions by 2050. One sector that addresses this reduction process is building construction and operations, which accounted for 36% of global final energy use and 39% of energy-related carbon dioxide (CO_2) emissions in 2017 (Wallace, Marvuglia, Benetto & Tiruta-Barna, 2014).

Due to the significant economic, environmental, and social impacts of the construction industry on society, various sectors have put a lot of effort into improving the primary environmental performance of buildings. While most of the existing literature reports on the sustainability assessment of buildings as a whole, research on the sustainability performance of individual building components (e.g., beams, columns, walls, façades) is insufficient. Building façades and their related structures can significantly influence the sustainability performance of the entire building as they are some of its most important components.

Several strategies have been presented in literature concerning sustainable building design from the perspective of structural engineering. In this regard, we can refer to the following examples. Maxineasa et al. (2021) developed an overall concept of environmental performance by investigating the effect of various structural steel parts on the Earth's ecosystem regarding sustainability issues and the effects of an over-the-floor reinforced concrete slab. The paper also offers up-to-date information on the environmental performance of the analysed structure, providing reassuring conclusions for those in the construction industry regarding the use of steel as a material, which can contribute to the current global effort to reduce the environmental burden that the construction industry places on the environment.

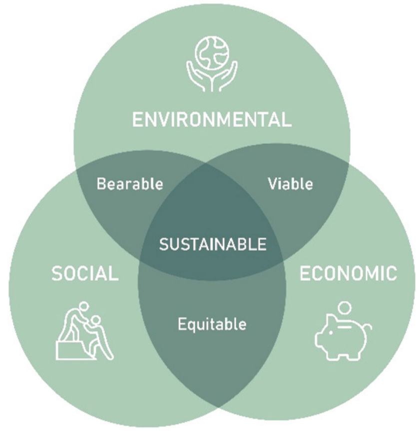

FIG. 1 Concept of sustainability and the three-phase interpretation.

The strategies presented by Anderson and Silman (2009) for structural engineering design that reduces greenhouse emissions include material selection, structure reuse, material efficiency optimisation, thermal mass effects, and future adaptation. Radlbeck et al. (2006) point out that aluminium has exceptional qualities for sustainable design, such as low weight and low maintenance requirements, strong corrosion resistance, and the capacity to be recycled. The authors assert that aluminium structures, if designed and executed properly, may ultimately outperform steel in the long run, both economically and ecologically.

By considering and prioritising materials with lower environmental footprints, it becomes possible to reduce a project's overall environmental impact. In addition to improving energy efficiency standards in the construction sector, we also need to improve the types and amounts of materials used. It is possible to reduce the negative effects of massive materials used in the design of buildings by finding different solutions and/or using different materials. For instance, by considering structural systems that can be disassembled, by design optimisation of construction profiles, or by using various highly recyclable structural materials (Maxineasa et al., 2021). Sustainability can be achieved through building design, but its performance must be quantitatively assessed. This must be done in the context of optimising the environmental impact and/or life cycle assessment (LCA) of buildings (Sarma & Adeli, 2002).

2.2 MATERIAL OPTIMISATION OF FAÇADE COMPONENTS

Optimisation is widely recognised as one of the key tools for achieving sustainability. It involves a systematic search process tailored to a specific problem, considering its unique conditions and constraints. The primary objective of optimisation is to identify the most feasible solution that best addresses the problem at hand. By leveraging optimisation techniques, complex scientific and engineering challenges can be effectively tackled, enabling the discovery of innovative and sustainable solutions (Sadollah et al., 2020).

The impact of the construction industry on the environment is significantly influenced by the production of building materials. According to the most recent report from the Global Environment

Facility (GEF), humans consume raw materials at a rate more than two-thirds higher than the Earth's natural regenerative capacity. The selection of a structural system holds paramount importance in creating sustainable designs as it is intricately linked to building strategies and sustainable design principles. Moreover, the structure and form of a building determine the amount of land used, the use of materials, the amount of energy consumed, the number of greenhouse gases released, the cost of maintenance, risk management, and even recycling. Therefore, all global industrial sectors must focus on understanding and achieving sustainability in the future, with the goal of drastically reducing their environmental footprints (Maxineasa et al., 2021). Optimisation can be defined as a process meant to achieve the best use of available materials for their sustainability. To obtain the best-optimised results, various criteria are considered in the procedure. They must include the following items:

- Availability of the material being evaluated
- Production costs
- Local climatic conditions
- Environmental impact
- Durability
- Predicted service life based on LCA models
- Material transportation (whether local or imported)
- The related environmental impact

The building industry is the largest consumer of raw materials in the world today. Therefore, a significant reduction in raw material consumption should be a fundamental guiding principle for the future. Another important consideration is the waste of resources during production, the construction process, and throughout the lifetime of the completed building. The reuse of materials after demolition should be considered. Models for the recycling process should be defined and promoted at all levels (Makenya & Nguluma, 2007).

The material selection during the engineering design phase has a significant influence on the amount of energy used and the amount of greenhouse gases (GHG) released over the whole product life cycle. Improper material choices will increase energy use and environmental pollution, ultimately leading to the product's failure on the market. It will also be detrimental to a company's reputation and interests (Bi, Zuo, Tao, Liao, & Liu, 2017). It is highly impractical to select materials during the design stage based solely on the usage phase. For example, focusing merely on reducing greenhouse gas (GHG) emissions in one phase may lead to an increase in GHG emissions in other phases. This underscores the importance of adopting a comprehensive strategy, such as LCA (Geyer, 2007).

3 STRUCTURAL ANALYSIS OF ALUMINIUM FOR CURTAIN WALL FAÇADES

3.1 OVERVIEW: STANDARDS AND DESIGN APPROACH

In section 2.2, the subject of material optimisation has been introduced, considering factors such as material availability, production cost, climatic conditions, durability, service life, transportation, and associated environmental impact. In the case of the building envelope or façade, the vast combination of architectural trends, technological solutions, materials used (such as glass, metal panels, stone), and the shape compatibility of components creates a complex scenario. In this sense, aluminium components used as connecting brackets play a fundamental role. Different solutions facilitate the interconnection of the exterior architectural cladding to the interior living space of a building, simultaneously ensuring lightweight components, ease of installation, and effective transmission of design loads from the exterior to the interior (FIG 2). Nowadays, aluminium is the key solution for fabricating the mechanical chain, particularly in bracket industrialisation, to ensure static stability and resistance. Over the years, the material has gained importance due to its easy availability, durability, affordable production cost and industrial machinability, which permits the creation of complex shapes.

Alongside its machinability, aluminium is structurally characterised by a recognised elastic-hardening progressive response. In FIG 3, four common alloys are shown by their stress-strain relationship under tensile load for a conventional strain range $\varepsilon = 0.00$ to 0.08. Eurocode 9 (CEN, 2007), Annex E, now offers an accurate description of the tensile response of aluminium, encompassing the elastic phase through the post-elastic phase and extending up to the ultimate strain (ε_u). This comprehensive characterisation allows structural engineers to assess the behaviour of aluminium more accurately and allows them to leverage its plastic-hardening properties effectively.

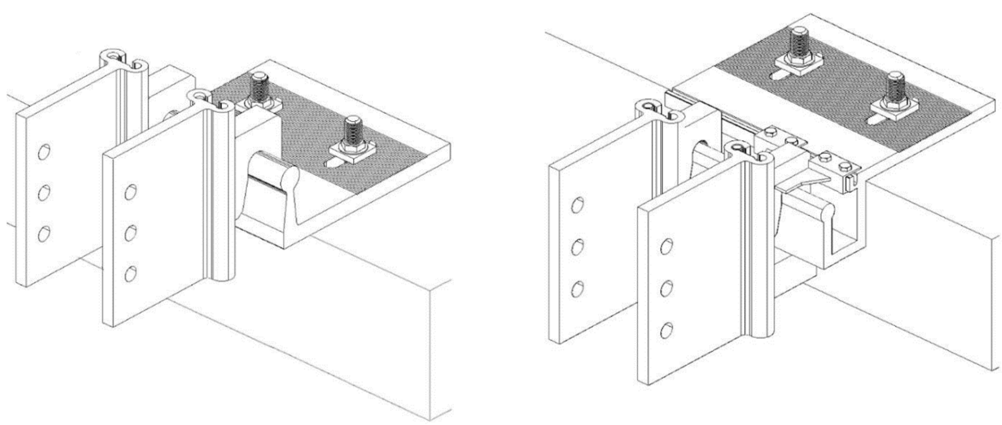

FIG. 2 Two different bracket configurations for the mullion-to-floor slab interconnection.

However, before delving into the elastic-plastic or elastic-hardening design applicability of the EC9 standardised alloys, it is crucial to address the current national and European design regulations in a comprehensive discussion. Curtain walling systems comply with Construction Product Regulation (CPR305/2011, 2011), which is a European Union (EU) regulation that sets out the rules for the harmonised performance of construction products within the EU, and with standard EN 13830 (2015). EN 13830 specifies the requirements for curtain walling systems designed to serve as building envelopes, offering weather resistance, safety, energy efficiency, and heat retention. The standard also provides test methods, assessments, and calculation criteria to evaluate the performance of these systems and ensure compliance with the specified requirements. The standard defines curtain walling as a component of the building envelope comprising a framework typically composed of horizontal and vertical profiles interconnected and anchored to the building's supporting structure. It incorporates fixed and/or openable infills and fulfils the necessary functions of an internal or external wall or its part without contributing to the load-bearing or structural stability of the building. Curtain walling is a self-supporting construction that transfers dead loads, imposed loads, environmental loads (wind, snow, etc.), and seismic loads to the main building structure. It can also be replaced independently of the main building structure (CPR305/2011, 2011).

The entire building must adhere to the Basic Requirements for Construction Works (BRCWs) outlined in the general scope of the (CPR305/2011, 2011), specifically:

1 Mechanical resistance and stability
2 Safety in case of fire
3 Hygiene, health, and the environment
4 Safety and accessibility in use
5 Protection against noise
6 Energy economy and heat retention
7 Sustainable use of natural resources

Curtain walling systems, along with other building products, play a crucial role in enabling entire buildings to meet the aforementioned basic requirements. According to mandate M/108 issued by the Commission to CEN/CENELEC (1994), for curtain walling systems, the first basic requirement, i.e., Mechanical resistance and stability, pertains solely to the main structure of the building. Therefore, curtain walling is considered a non-structural product related to the fourth requirement, i.e., Safety and accessibility in use. In general, curtain walling sytems are composed of three main elements: the fixings (including fixings and brackets, etc), the frame, and the infill panel.

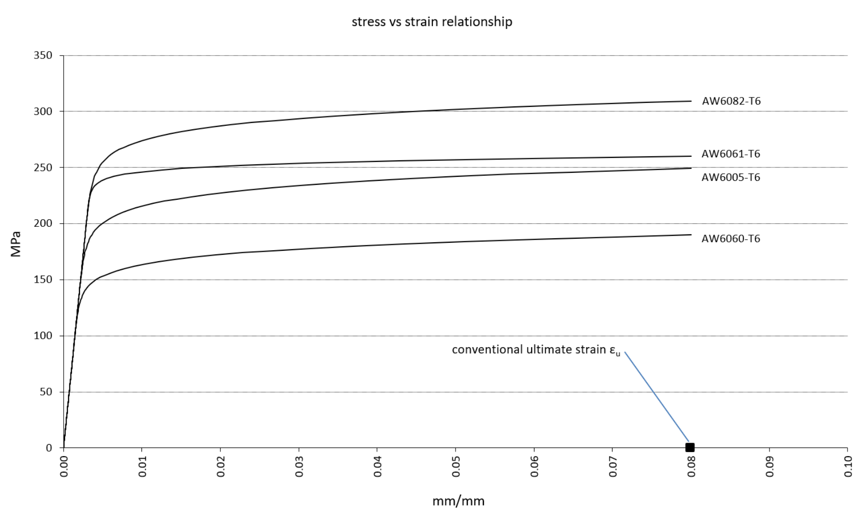

FIG. 3 Typical elastic-hardening progressive response for four characteristic aluminium alloys (up to ε= 0.08).

The bearing capacity of these components must be verified under defined conditions to meet the essential requirement for "Safety in use". In this sense, the classes of consequences play a fundamental role in the façade risk-assessment classification (European Committee for Standardization, 2002; CNR-DT 210/2013, 2013), allowing for the fact that the failure of the curtain walling framework of the infill panels does not typically have the same economic and/or human consequence as the failure of the building structure. An interesting discussion can be found in (Bedon, Amadio & Noé, 2019).

Modern structural design codes are established to provide a simple, safe, and economically efficient basis for the design of structures under normal loading and environmental conditions. The primary principle of limit-state design for structural components is to define an acceptable level of risk and ensure it is never exceeded. This is achieved through the appropriate choice of design situations, design equations, and representative values. The design values used in the design equations are selected to ensure an adequate and sufficient level of reliability for all relevant failure modes of the considered structures. This practice allows for straightforward reliability verification of a given design through a simple comparison of resistances and load effects. Since resistances and loads are subject to uncertainties, partial reduction factors for the strength and partial amplifying factors for the actions are defined. These factors guarantee the required performance level in terms of the probability of failure.

As mentioned above, European Standard EN13830 (2015) defines the technical characteristics of curtain walling systems and encompasses a comprehensive set of requirements and offers test methods, assessments, calculation methods, and compliance criteria for related performances. However, it does not include specific codes for non-structural elements. Therefore, existing codes for building structures, such as Eurocodes and National Laws, should be utilised in the design and evaluation of non-structural elements, including curtain walling systems.

The practice code, whether based on National, European (EN), American (USA), Australian (AU), or other updated guidelines and codes, does not specifically regulate the connecting elements (brackets) in an application-specific manner. In the European market, the curtain wall aluminium (alloy) frame is commonly designed following Eurocodes (EC9), and the calculation and verification process for these elements adhere to a standardised procedure which relies on common standardised structural elements. This process involves following specific codes such as EC3 (2005) and AISC360 (2016) or AS4100 (2016) for steel structural elements, etc. In this sense, the AISC Specification provides the generally applicable requirements for the design and construction of structural steel buildings and other structures. This standard has been approved by ANSI as an American National Standard. On the other hand, the AS is the Australian Standard for Steel Structures, approved on behalf of the Council of Standards Australia.

It should be highlighted that all these standards are conceptually based on the semi-probabilistic method, which means that the uncertainty of the basic variables, such as the strength of the materials and the loads acting on the structure, are taken into account by using characteristic values and partial safety factors. This approach employs the characteristic values derived from the available statistical data as the calculation values within the design procedure. The characteristic value for an action represents the value with a defined probability of either being exceeded or not being reached during the relevant reference period. The partial factors are then used to account for the remaining uncertainties in the design process (European Committee for Standardization, 2002). Moreover, the most recent codes allow for post-elastic behaviour in the semi-probabilistic approach, ensuring a certain degree of plastic behaviour throughout the loading event. This means that the plastic deformation capacity of metal alloys can be harnessed in structural design, resulting in supplementary strength that can be incorporated into the design procedure. However, this is only possible if local buckling in sections does not compromise the overall equilibrium stability of the load-bearing system. Therefore, the well-known concept of “section classification” is often adopted by designers and engineers to ensure that structures are designed to be both safe and efficient. This is a method of classifying structural sections according to their buckling resistance, which allows for selecting sections that are suitable for the loads and conditions that they will be subjected to. However, given its computationally heavy workload, designers may resort to verification methods based on fully elastic requirements. It is important to note that the local stability requirements for structural sections should not be blindly applied to façade elements such as aluminium brackets. This is because these components have a remarkable inherent stability capacity that can be easily demonstrated. This characteristic enables pronounced post-elastic behaviour, which provides a significantly higher resistance capacity than is possible using linear assumptions. This results in advantages such as reduced bracket volumes, lightweight components, and cost-effective production.

3.2 MECHANICAL RESPONSE: THE ELASTIC-HARDENING APPROACH ACCORDING TO EUROCODE 9

The mechanical properties of the aluminium alloy AW6005A-T6, which the hook bracket to be investigated is made of, can be obtained from Eurocode 9 (CEN, 2007). For this case, these properties are determined by the fundamental ductility parameter $\xi=\xi(\varepsilon_u)$ and the temper parameter T=T6. The standard allows the continuous elastic-hardening distribution to be represented by the Ramberg-Osgood formulation, described by equations (1) and (2).

$$\varepsilon = \frac{\sigma}{E_0} + \varepsilon_{0.el} * \left(\frac{\sigma}{f_{0.el}}\right)^n$$ equation 1

$$n = (ln\frac{\varepsilon_{0.el}}{\varepsilon_{0.x}}) * (ln\frac{f_{0.el}}{f_x})^{-1}$$ equation 2

In this formulation, σ represents the independent variable of the distribution. The initial elastic modulus, denoted as E_0, is 70 GPa. The conventional residual deformation at yielding is $\varepsilon_{0.el} = 0.002$ (0.2%), while the conventional deformation at the ultimate load is $\varepsilon_u = 0.08$ (8%). Additionally, $f_{0.el} = 200$ MPa represents the conventional yielding stress at 0.002 of the residual deformation ($\varepsilon_{0.el}$). To obtain the hardening parameter n, two characteristic points are considered: $\varepsilon_{0.x} = 0.076$ (7.6%) and $f_x = 250$ MPa. Note that these reference points can be selected anywhere in the residual strain range, from $\varepsilon_{0.x} = 0.001$ (0.1%, linear regression for elastic applications) to $\varepsilon_{0.x} = \varepsilon_{0.max}$, where $\varepsilon_{0.max}$ is the linear regression obtained from the maximum stress experienced by the sample for plastic applications, with $f_x = f_{max}$, as indicated by EC9, §E.2.2.2 (4).

For the specific case at hand, the n-parameter is determined, according to the plastic range under investigation, by setting $f_x \equiv f_u$ with reference to the EN AW 6005-T6 alloy mechanical properties. The graphical representation of the Ramberg-Osgood relationship can be observed in FIG 4.

The Ramberg-Osgood distribution is then logarithmically transformed to generate the true stress-strain curve, commonly known as the Cauchy curve, to take the geometric necking of the material into account during the high-strain deformation process. The mathematical transformations are described by equations 3 and 4.

$$\varepsilon_{true} = ln(1+\varepsilon)$$ equation 3

$$\sigma_{true} = (1+\varepsilon) * \sigma$$ equation 4

It is worth mentioning that the conventional ultimate strain ε_u = 0.08 is commonly used to facilitate the technical discussion across all types of aluminium. However, Eurocode allows for customising the ultimate plastic strain for each specific alloy type, providing flexibility in its application.

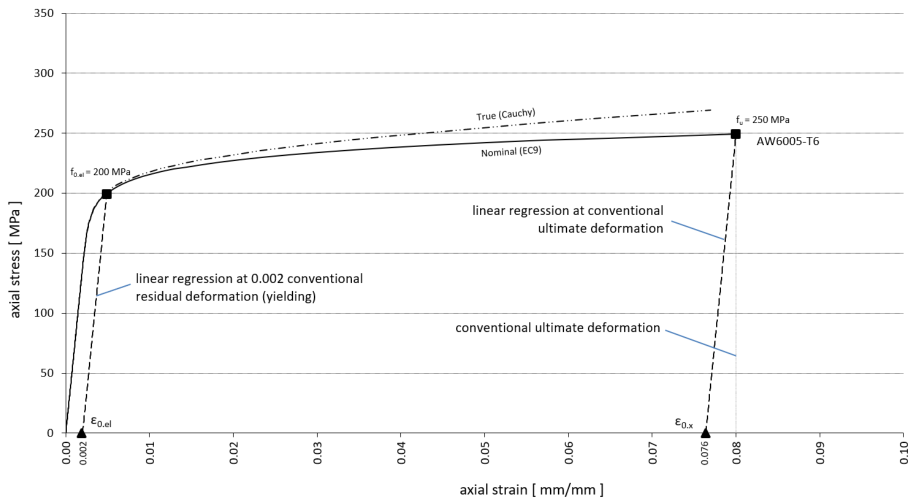

FIG. 4 Ramberg-Osgood stress-strain relationship for the aluminium alloy EN AW6005-T6.

4 ANALYSIS METHODOLOGY AND COMPUTATIONAL MODELLING

4.1 CASE STUDY: DESCRIPTION

The CMA-CGM complex in Marseille (FIG 5), designed by Zaha Hadid Architects, exemplifies an intriguing application of the elastic-hardening approach for verifying the aluminium façade brackets. The headquarters tower, standing at a height of 143 metres, features a concrete core, whilst two steel-glass architectural systems complement the remarkable form of this structure. The structure is enveloped by around 42,500 m^2 of single and double-skin façades, with the distinctive design featuring 3,569 glass-aluminium unitised panels, each with unique geometrical characteristics.

The connection between the façade system and the floor slab is achieved through a sophisticated assembly of brackets, enabling the structural and kinematic requirements of the façade-building interaction. The bracket geometry is meticulously designed to accommodate the varying inclination of the façades and effectively transmit external wind pressure to the concrete floor slabs (FIG 6). Considering the unique wind exposure of the building, which is situated on the seafront, and the substantial size of the unitised systems, reaching approximately 6 m^2, the brackets must be designed to minimise the transfer of ultimate limit tensile forces (ULS) of up to 18 kN.

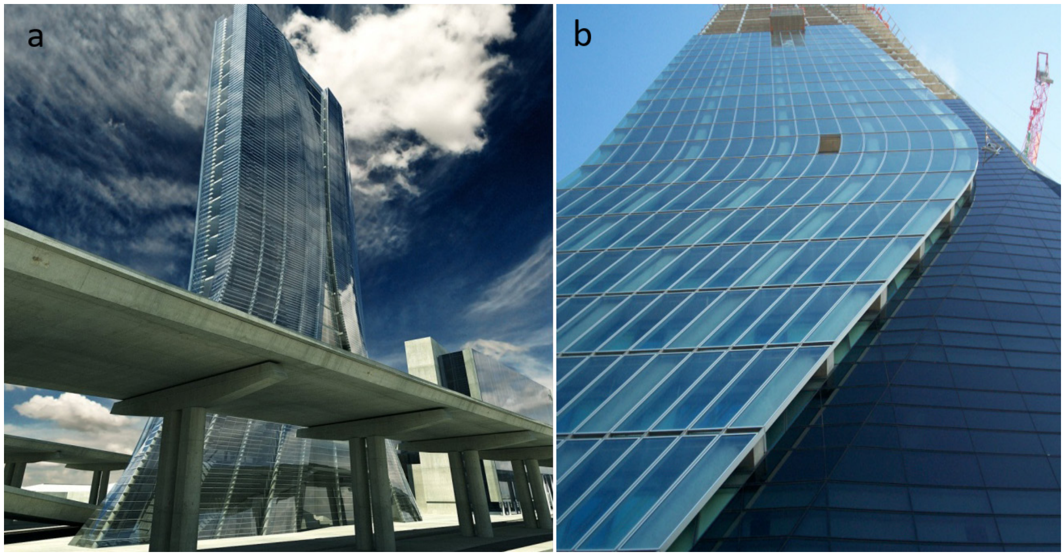

FIG. 5 The new CMA-CGM Headquarters in Marseille by Zaha Hadid Architects. a) render, b) installation phase.

This accounts for the characteristic values of pressure and suction, which can reach up to 3.80 kPa. Notably, the aluminium systems utilised in the CMA-CGM façades are designed to effectively accommodate the post-elastic behaviour of the material. In particular, the design incorporates continuous elastic-hardening criteria.

To illustrate this, a detailed study is presented focusing on one of the three bracket types, commonly known as the "hook" due to its distinctive shape (FIG 6, component 2). This dedicated analysis provides a comprehensive understanding of the bracket's behaviour and performance.

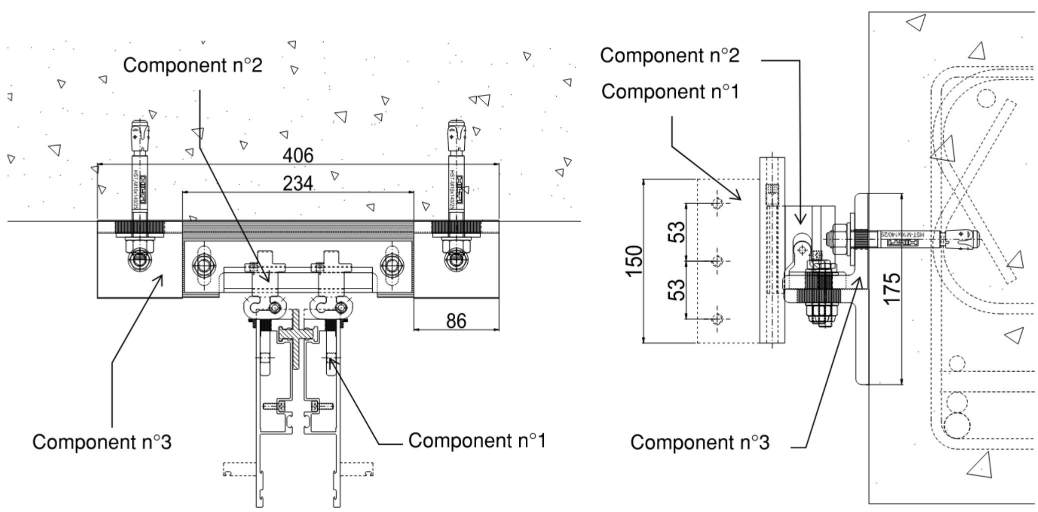

FIG. 6 The aluminium brackets system used for the façade-building interaction (dimensions in mm).

The geometric model is created using the Catia software by Dassault Systems, whilst the FE computational setup is implemented through Abaqus, also by Dassault Systems.

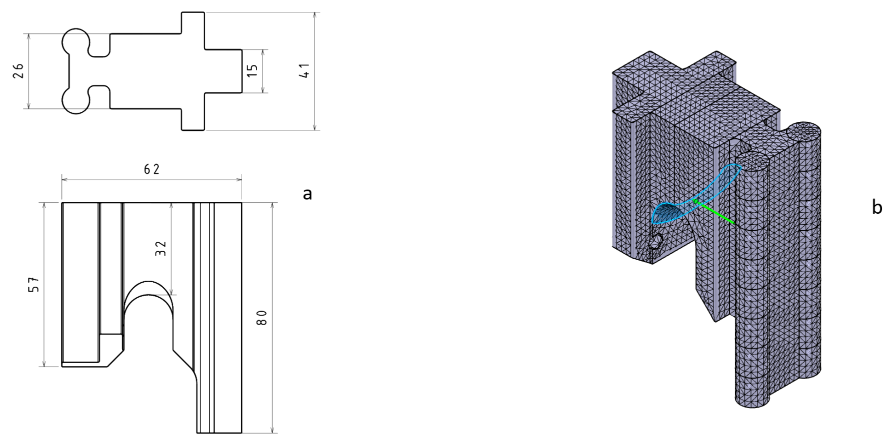

FIG. 7 The bracket case study: the hook. a) the geometry in mm, and b) the computational model.

A 3D mesh is generated using second-order tetrahedral elements, resulting in a continuous distribution of 62,105 finite elements and 35,385 nodes. The component is constrained along its *dog-bone* insertion edge (the right part of the component in the right-hand picture of FIG 7) with a non-linear elastic support that allows compression-only behaviour. Additionally, a parametric suction load is applied to the contact area of the throat (the left part of the component in the right-hand picture of FIG 7).

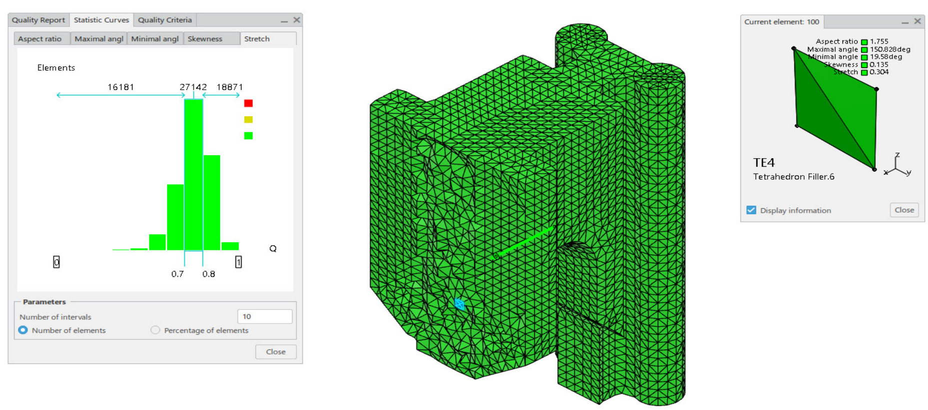

FIG. 8 The computational model (statistic quality mesh check, by Simulia/Abaqus).

The use of this type of restraining-load assumption is suggested during the mechanical verification phase as it accurately replicates the realistic kinematic and mechanical behaviour of the component in terms of internal deformation, providing reliable results. Consequently, the distribution of internal stress and strain within the component can be considered to be a fundamental parameter for assessing its structural suitability. The mesh refinement was achieved using a skin-to-core algorithm (i.e., external-to-internal), ensuring an average element length of 2.00-2.50 mm for each finite element of the skin (source mesh) and maintaining invariancy of the sequential generation of elements throughout its volume. This leads to a uniform distribution of the finite elements across the component, as depicted in FIG 8.

4.2 NUMERICAL OUTPUT AND DISCUSSION

Incremental analysis is performed, considering both material non-linearity (NLM) and geometric non-linearity (NLG). Focusing on the mechanical response in terms of stress and strain, two distinct load levels are identified: the ultimate elastic load UL_{00} (corresponding to an equivalent plastic strain PEEQ of 0.00) and the ultimate plastic load UL_{08} (corresponding to a PEEQ of 0.08, conventionally regarded as the limit point according to Eurocode 9). FIG 9 and FIG10 illustrate displacement and stress contours for UL_{00} and $UL_{08,}$ respectively.

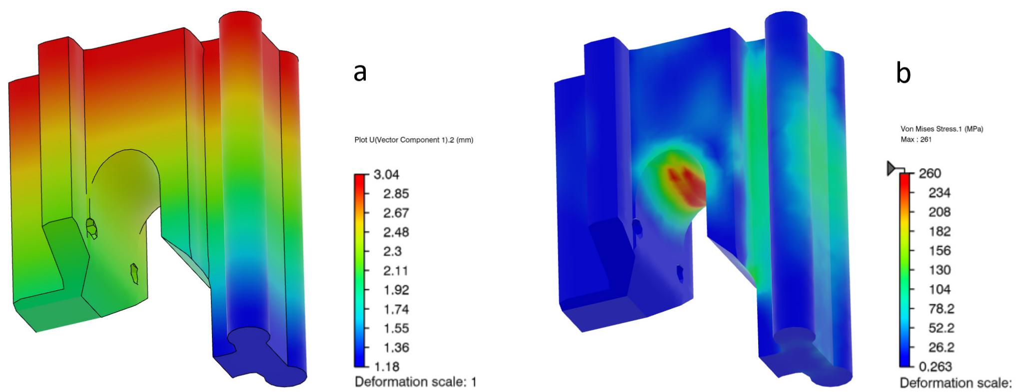

FIG. 9 a) displacement (in mm) and b) Von Mises stress (in MPa), at ultimate elastic load UL_{00}

As anticipated and in line with the numerical findings, the throat section of the component proves to be the most critical part, primarily due to its reduced height. Under the suction load of the façade or cladding panel, the cross-section mentioned is usually subjected to a tensile force and a resulting bending moment. This bending moment is generated due to the misalignment between the point of external force application and the restrained surface (FIG 7, right). More precisely, the numerical results illustrate that the maximum stress and strain concentrations occur in the lower region of the throat section, where the highest tensile stress is experienced.

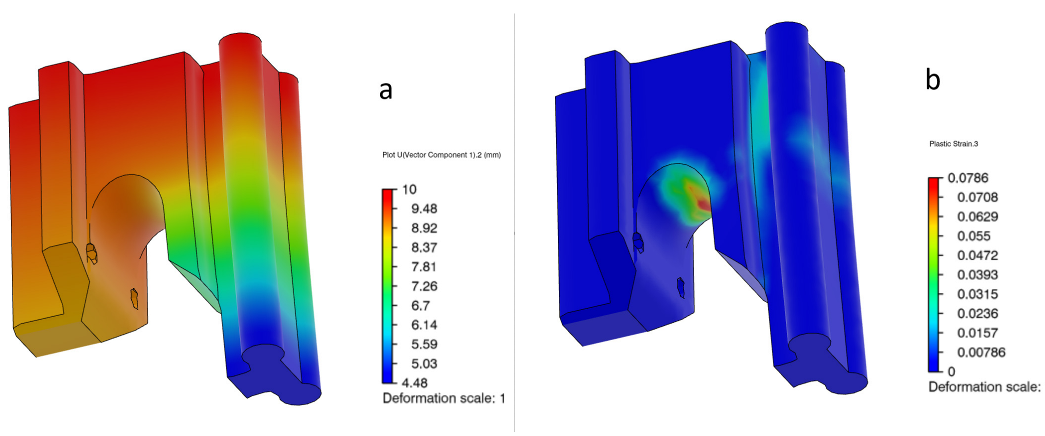

FIG. 10 a) displacement (in mm) and b) equivalent plastic strain PEEQ, at ultimate plastic load UL_{08}

Furthermore, it is possible to deduce from FIG 11 that the ultimate elastic load is UL_{00} = 20 kN whilst the ultimate plastic load is UL_{08} = 84 kN. The final design situation, therefore, shows 18 kN as the ultimate design load, 20 kN as the ultimate elastic strength and 84 kN as the ultimate plastic strength. This results in an efficiency plastic ratio $\chi_{epr} = UL_{08}/UL_{00} = 4.20$. This ratio represents the extra-load capacity that the component can provide, allowing its material to "move" from the elastic limit (i.e. the post-elastic onset) to the plastic limit. Significant levels of over-strength in the component (χ_{epr} >1.00) can be reached even with modest values of ε_u, such as 0.02 or 0.03. It should be noted that for the specific case of the Zaha Hadid Tower in Marseille, a reduced plastic limit UL_{02} (corresponding to a PEEQ of 0.02) was set, despite Eurocode 9 actually allowing for a full capacity exploitation of 8%.

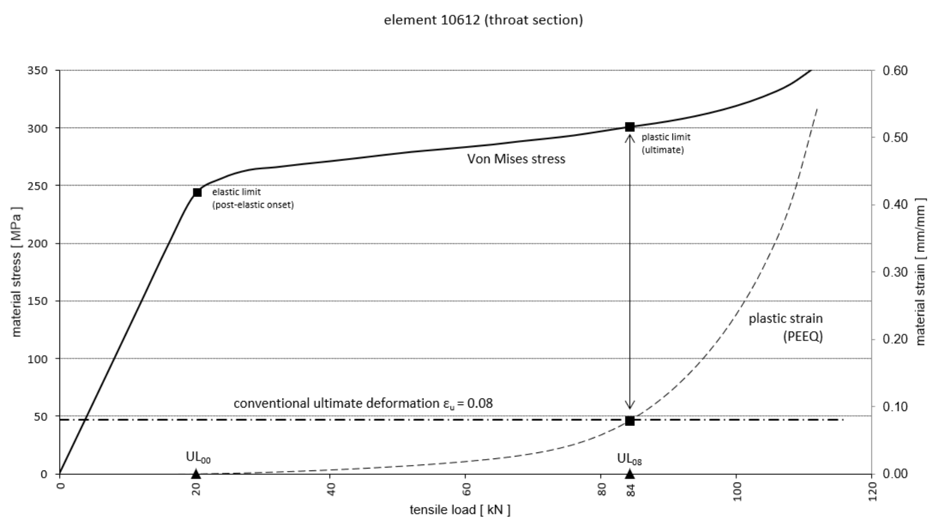

FIG. 11 Stress-strain response of the material in the critical throat section (FE10612).

However, it is important to note that the façade designer must always ensure that the kinematic stability of the component is maintained throughout the incremental load analysis. It is worth noting that aluminium components used in façades and cladding systems are typically characterised by a high level of compactness, which renders them well-suited to elastic-plastic or elastic-hardening analysis, particularly under tensile loading conditions. It should be noted that the non-linear finite element analysis described for the "hook" bracket sample mentioned above can be readily extended to other aluminium components. This allows for similar conclusions regarding the exceptional capabilities of aluminium in terms of exploiting post-elastic properties for a wide range of brackets commonly employed in façade engineering applications. A comparative analysis was conducted for several brackets of the Zaha Hadid Tower in Marseille using a fully linear hypothesis (i.e. using UL_{00} as the design limit point). This showed a weight increase in the range of +35 to +45% of the included components compared to the plastic analysis utilised, which assumed UL_{02} (corresponding to an equivalent plastic strain PEEQ of 0.02).

5 CONCLUSIONS AND FUTURE PERSPECTIVES

The efforts and the investments being applied in current industrial research, such as *ecological design*, *sustainable design* and life cycle assessment, have been described. The building industry is the world's largest consumer of raw materials, which is why a significant reduction in raw material consumption should be a fundamental objective for the future.

A real-life application of material reduction has been described in one of the first large-scale applications in building design regarding the aluminium used in façades. It's been demonstrated that the mechanical post-elastic properties of aluminium alloys offer remarkable design advantages. The analysed case study demonstrated that by employing the Ramberg-Osgood formulation, as outlined in Eurocode 9, Annex E, it can significantly enhance the ultimate load strength of aluminium brackets and, more generally, other common components used in the field of façade and building engineering. In fact, the current standard analysis method widely used in the industry for such components does not fully incorporate one of the fundamental aspects of the ultimate limit state philosophy, which is the utilisation of post-elastic resources. It has been observed that by conventionally setting the ultimate strain ε_u in the range of 0.02 to 0.08, as allowed by Eurocode 9, the following benefits can be achieved:

A Significant improvement in the ultimate design load capacity of the components
B Optimisation of the component's volume and weight, leading to implications related to sustainability and life cycle assessment (LCA) factors.

It is recommended that post-elastic numerical analysis is utilised during the design and validation of aluminium façade components to achieve weight savings, ensuring that they meet the assembly's displacement and stability requirements. Moreover, ongoing research is expected to advance towards a broader application of the Ramberg-Osgood elastic-hardening progressive response to other brackets and components. It will be necessary to conduct specific laboratory tests to precisely validate and calibrate the obtained results. Lastly, it is worth mentioning that in parallel with the application of advanced non-linear numerical analysis techniques to achieve component weight loss, appropriate studies should be carried out to interrelate these savings to the LCA measurement factors.

Acknowledgements

The authors wish to thank the Interministerial Delegation for Numerical Transition of the Principality of Monaco for the support provided under the Fonds Bleu programme (funding code SFB-20210417-202D) and the Department of Architecture, Built Environment and Construction Engineering of Politecnico di Milano, for the research programme *Design methods for sustainable high-performance building façades and aluminium optimisation criteria for brackets and components according to Eurocode 9*.

References

Abu-Rayash, A. & Dincer, I. (2019). Sustainability assessment of energy systems: A novel integrated model. *Journal of Cleaner Production*, 212, 1098-1116. https://doi.org/10.1016/j.jclepro.2018.12.019

ANSI/AISI360-16. Code of standard practice for steel buildings and bridges. American Institute of Steel Construction, 2016.

Akadiri, P. O., Chinyio, E. A. & Olomolaiye, P. O. (2012). Design of a sustainable building: A conceptual framework for implementing sustainability in the building sector. *Buildings*, 2(2), 126-152. https://doi.org/10.3390/buildings2020126

Anderson, J. E. & Silman, R. (2009). A life cycle inventory of structural engineering design strategies for greenhouse gas reduction. *Structural Engineering International*, 19(3), 283-288. https://doi.org/10.2749/101686609789675918

AS4100:1998 (R2016) + AMDT1-2012. Steel structures. Technical committee BD/1, Australian Standards, 2016.

Bedon, C., Amadio, C. & Noé, S. (2019). Safety issues in the seismic design of secondary frameless glass structures. *Safety*, 5(3), 80. https://doi.org/10.3390/safety5030080

Bi, L., Zuo, Y., Tao, F., Liao, T. W. & Liu, Z. (2017). Energy-aware material selection for product with multicomponent under cloud environment. *Journal of Computing and Information Science in Engineering*, 17(3), 031004. https://doi.org/10.1115/1.4036103

CEN. (2007). Eurocode 3: Design of steel structures – Part 1-1: General structural rules and rules for buildings (EN1993-1-1:2005).

CEN. (2007). Eurocode 9: Design of aluminium structures – Part 1-1: General structural rules (EN1999-1-1:2007).

CEN. (2012). EN15804:2012 + A2:2019 - Sustainability of construction works – Environmental product declaration – Core rules for the product category of construction products.

CEN. (2012). DS/EN 15978:2012 - Sustainability of construction works – Assessment of Environmental Performance of Buildings – Calculation Method.

CEN/CENELEC. (1994). Mandate M/108, Curtain walling – 04/33 External walls (including cladding), internal walls and partitions.

CNR-DT 210/2013. *Istruzioni per la Progettazione, L'esecuzione ed il Controllo di Costruzioni con Elementi Strutturali di vetro* [Guide for the Design, Construction, and Control of Buildings with Structural Glass Elements]. National Research Council of Italy. http://www.cnr.it/it/node/2630

CPR305/2011. *Regulation (EU) No 305/2011 of the European Parliament and the Council.*

EN 13830. (2015). Curtain walling – Product standard. CEN European Committee for Standardization.

Gardner, L., Yun, X., Walport, F. The Continuous Strength Method – Review and outlook. *Engineering Structures*, 275 (2023) 114924, https://doi.org/10.1016/j.engstruct.2022.114924

GEF. Global Environment Facility, https://www.thegef.org/

Georgantzia, E., Gkantou, M., Kamaris, G.S. Aluminium alloys as structural material: A review of research. *Engineering Structures*, 227 (2021) 111372, https://doi.org/10.1016/j.engstruct.2020.111372

Geyer, R. (2007). Life cycle greenhouse gas emission assessments of automotive material: The example of mild steel, advanced high strength steel and aluminum in body in white applications. Methodology report. WorldAutoSteel.

Maxineasa, S. G., Isopescu, D. N., Baciu, I. R. & Lupu, M. L. (2021). Environmental performances of a cubic modular steel structure: A solution for sustainable development in the construction sector. *Sustainability*, 13(21), 12062.

Makenya, A. R. & Nguluma, H. (2007). Optimization of building materials and designs towards sustainable building construction in urban Tanzania. In *CIB World Building Congress, Construction for Development* (pp. 2083-2093).

Radlbeck, C., Dienes, E. & Kosteas, D. (2006). Aluminium structures – A sustainable future? *Structural Engineering International*, 16(4), 339-344. https://doi.org/10.2749/101686606779695994

Sadollah, A., Nasir, M. & Geem, Z. W. (2020). Sustainability and optimization: From conceptual fundamentals to applications. *Sustainability*, 12(5), 2027. https://doi.org/10.3390/su12052027

Sarma, K. C., Adeli, H. (2002). Life-cycle cost optimization of steel structures. *International Journal for Numerical Methods in Engineering*, 55(12), 1451-1462.

Wallace, R. J., Marvuglia, A., Benetto, E. & Tiruta-Barna, L. (2014). A new approach to optimization with life cycle assessment: Combining optimization with detailed process simulation. In J. Suzuki & K. Koyamada (Eds.) *International Conference on Computational Science and Its Applications* (pp. 707-720). Springer. https://doi.org/10.1007/978-3-319-09177-8_51

Wang, N. & Adeli, H. (2014). Sustainable building design. *Journal of Civil Engineering and Management,* 20(1), 1-10. https://doi.org/10.3846/13923730.2013.872724

Webster, M. D. (2004). Relevance of structural engineers to sustainable design of buildings. *Structural Engineering International*, 14(3), 181-185. https://doi.org/10.2749/101686604777963887

Zabihi, H., Habib, F., Mirsaeedie, L. Sustainability in building and constructions: revising definitions and concepts. *International Journal of Emerging Science and Engineering*, 2(4), 570-578, December 2012.