

Structural Design and Wind Dynamic Analysis of the New Glass Envelope for Campo Marzio Railway Station in Trieste

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Abstract

The retrofit and requalification of the historic Campo Marzio railway station in Trieste (Italy) includes the reconstruction of its former vaulted glass roof, a suspended pedestrian walkway to host a restaurant, and a new main façade. The new steel and glass structures reinterpret the original early-20th-century layout through lightweight reticular arches and cold-bent laminated glass panels. The structural verification of the glass components involved seven different typologies for curved and planar panes, which were designed by means of dedicated FEM analyses. The dynamic response of the roof subjected to wind loading represents indeed an important step of the analysis, as the building is in the city of Bora wind. This issue is assessed through coupled CFD and structural simulations. RWIND 2 is first used to evaluate the spatial distribution of external and internal pressures, while nonlinear dynamic analyses are carried out in ABAQUS to capture the vibration modes and the possible aeroelastic amplification effects under turbulent flow. The integrated numerical approach ensures the structural safety and serviceability of the transparent envelope while preserving its architectural lightness and historical identity within a contemporary structural concept.

Keywords

Glass envelopes, Cold-bent glass, Steel structures, Wind action, Dynamic analysis

Article Information

- Digital Object Identifier (DOI): [10.47982/cgc.10.763](https://doi.org/10.47982/cgc.10.763)
- Published by [Challenging Glass](#), on behalf of the author(s), at [Stichting OpenAccess](#).
- Published as part of the peer-reviewed [Challenging Glass Conference Proceedings](#), Volume 10, June 2026, [10.47982/cgc.10](https://doi.org/10.47982/cgc.10)
- Editors: Christian Louter, Freek Bos & Jan Belis
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1. Introduction

The reuse and transformation of historic railway stations represent a recurring challenge in contemporary architecture and structural engineering. In this context, glass structures play a central role in mediating between preservation requirements and the need for new functional and public spaces, while simultaneously raising complex structural issues. Large-span glass roofs, in particular, require an integrated design approach in which geometry, supporting steel systems, glass typologies and loading conditions are treated as a whole rather than as independent components.

The former Campo Marzio railway station in Trieste (Italy) offers a paradigmatic case study. The current requalification project aims to restore the spatial role of the original hall through the reconstruction of a large transparent roof, combined with new steel-and-glass additions including a suspended pedestrian walkway and a contemporary glazed façade. From a structural perspective, the project is particularly challenging due to the coexistence of lightweight steel structures, large-format glass panels—both planar and cold-bent—and the extreme wind environment of Trieste, dominated by the Bora wind.

This paper presents an integrated architectural and structural investigation of the new glass envelope of the Campo Marzio station, with specific focus on: (i) the structural concept of the steel supporting systems; (ii) the design criteria and typological differentiation of the glass components; (iii) the finite-element modelling and verification of planar and cold-bent laminated glass panels; and (iv) the assessment of wind-induced dynamic effects through coupled CFD and structural analyses. The proposed methodology demonstrates how advanced numerical tools can be effectively combined to ensure structural safety and serviceability while preserving architectural lightness and historical continuity in a large-span glass application under severe wind conditions.

2. Historical background and project overview

2.1. Historical and architectural significance of Campo Marzio station

The Campo Marzio railway station in Trieste was conceived at the beginning of the 20th century as the terminal node of the Transalpina railway, a strategic infrastructure aimed at strengthening the direct connection between the Adriatic port of Trieste and Central Europe. The original layout consisted of a monumental U-shaped building combined with a large iron-and-glass vaulted roof covering the passenger platforms, which represented a key architectural and technological feature of the period (see Fig. 1(a)).

Following the First World War, the station progressively lost its strategic role, leading to the cessation of passenger services and to the dismantling of the original vaulted roof (see Fig. 1(b)). Despite its functional decline, the complex retained a strong historical and symbolic value, later reinforced by its reuse as the Railway Museum of Trieste and by its protection under national heritage regulations. This historical framework provides the cultural basis for the contemporary requalification project, in which the reconstruction of a transparent vaulted envelope reinterprets the original spatial and structural identity through modern glass and steel technologies.

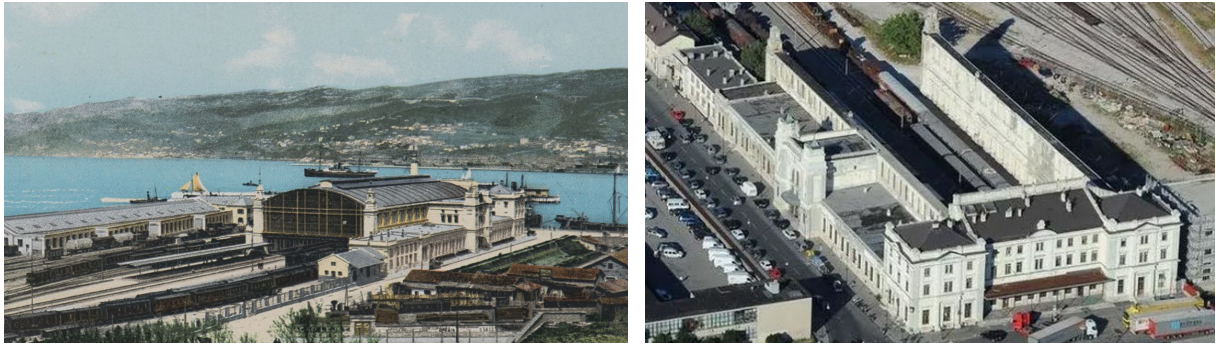


Fig. 1: Historical images of the railway station: (a) original layout and (b) building prior to the renovation project.

2.2. General project concept and spatial strategy

The requalification project is aimed at preserving the historical identity of the complex while introducing new public and functional uses. The project integrates the creation of a covered public square within the former railway yard, the reconstruction of a large transparent vaulted roof, the insertion of a suspended pedestrian walkway, the adaptive reuse of part of the historic building as a railway-themed hotel, and the construction of a contemporary glass-clad overbuilding along the Riva Traiana front.

The new glass roof represents the core spatial element of the intervention, reinterpreting the geometry of the original vault through a lightweight steel reticular system (see Fig. 2). The main ribbed vault is intersected by a transverse barrel vault above the aerial walkway, generating a complex three-dimensional geometry. In contrast to the historically derived geometry of the roof, the glass overbuilding is deliberately conceived as a contemporary addition, establishing a clear dialogue between conservation and innovation.

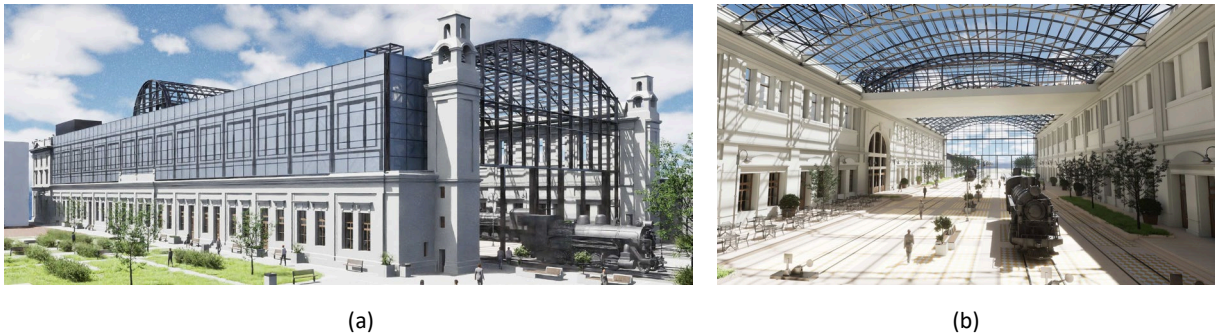


Fig. 2: Rendering of the requalification project: (a) external and (b) internal view.

3. Structural concept and global modelling approach

The structural design is based on a clear separation and controlled interaction between the existing masonry building and the new steel-and-glass additions. The historic structure is preserved as a gravity-dominated system, while the new interventions are conceived as lightweight steel structures with autonomous load paths. Vertical loads from the new roof are transferred to the existing masonry through a continuous steel cordon, while horizontal actions are selectively restrained to avoid overstressing the historic fabric. Sliding supports are introduced to accommodate thermal movements and differential deformations between old and new structures. The structural model is shown in Fig. 3(a).

A global finite-element model was thus developed to capture the interaction between the existing building and the new structural systems; see Fig. 3(b). The model accounts for the different stiffness contributions of masonry and steel components, the presence of sliding interfaces and the combined effects of wind, temperature and seismic actions. This global framework provided the basis for the subsequent detailed analyses of the steel and glass subsystems.

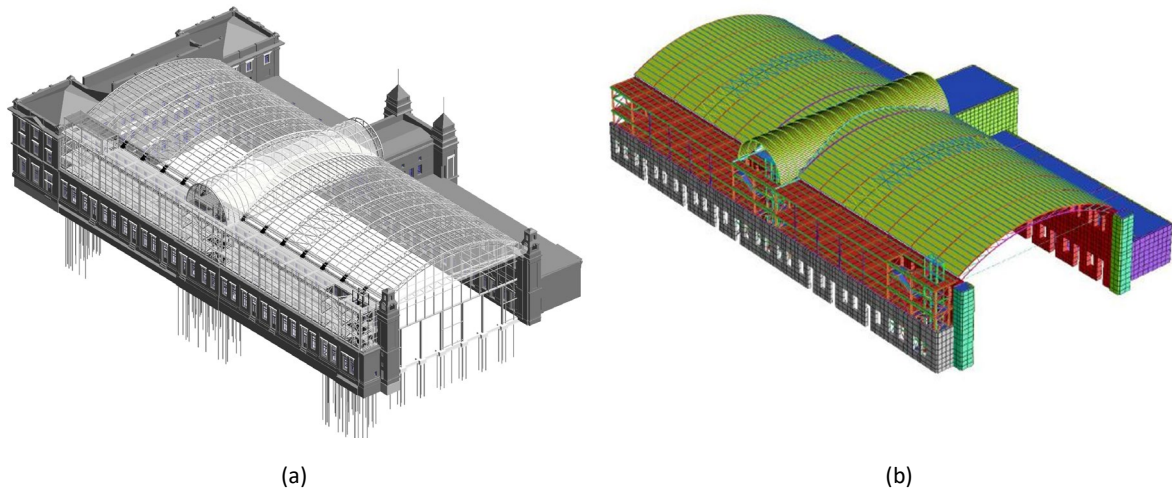


Fig. 3: (a) View of the 3D structural model and (b) corresponding model in STRAND7 R3.1.

4. Steel supporting structures for the glass envelope

The glazed roof is supported by a sequence of reticular steel arches spanning approximately 37 m. Each arch supports secondary members and glass panels through discrete mechanical fixings. The arches are arranged at constant spacing and connected by horizontal bracing systems to ensure global stability. Pinned and sliding supports are adopted at opposite sides of each arch to control horizontal thrust and accommodate thermal movements, while post-tensioned steel ties contribute to limiting horizontal reactions under permanent loads.

In parallel, the main glazed façade facing the railway yard is conceived as an independent steel structure designed to resist significant wind pressures and suction effects. The façade system consists of vertical tubular mullions and horizontal transoms forming a reticular frame that supports the glass panels. Connections to the existing masonry are localized and designed to minimize stress transfer to the historic fabric, ensuring structural compatibility and reversibility.

5. Glass typologies and design criteria

The design of the glass envelope was based on a differentiated typological approach, developed to address the wide variability of geometric configurations and performance requirements. This strategy allowed each glass component to be optimized with respect to curvature, support conditions, load transfer mechanisms and performance criteria.

Seven distinct glass typologies (GL-01 to GL-07) were identified (see Table 1 and Fig. 4). The main glazed roof is composed of cold-bent laminated glass panels, subdivided into typologies GL-01 and GL-02 according to their position along the vault. Panels located near the ridge are characterized by lower curvature demands and more uniform support conditions, while panels closer to the eaves are subjected to larger geometric deviations and higher suction effects due to wind action. In transition

areas, where the main vault intersects the transverse barrel vault above the suspended walkway, curved insulating glass units (GL-03 and GL-04) were adopted to accommodate the complex three-dimensional geometry and to ensure continuity of the envelope. Vertical enclosures are realized through planar glass elements with different structural roles. Insulating glass units (GL-05 and GL-06) are used for the façades of the restaurant volume suspended within the hall, where thermal performance and user comfort are primary requirements. Laminated glass panels (GL-07) are instead employed for the main closing façade of the covered square, where structural performance under wind loading and compatibility with the supporting steel frame govern the design.

Table 1: Table for identifying the glass typologies.

Glass	Typology	Glass composition	Curvature (m)	Location
GL-01/02	Cold-bent laminated	8 + 8 heat-strengthened glass / 1.52 PVB	35	Roof ridge / eaves
GL-03/04	Cold-bent insulating	10 toughened HST / 18 / 5+5 heat-strengthened glass with 1.52 acoustic PVB	35 / 6.2	Vault intersection
GL-05/06	Planar insulating	10 toughened HST / 18 / 5+5 heat-strengthened glass with 1.52 acoustic PVB	-	Restaurant façades
GL-07	Planar laminated	8 + 8 heat-strengthened glass / 1.52 PVB	-	Main façade

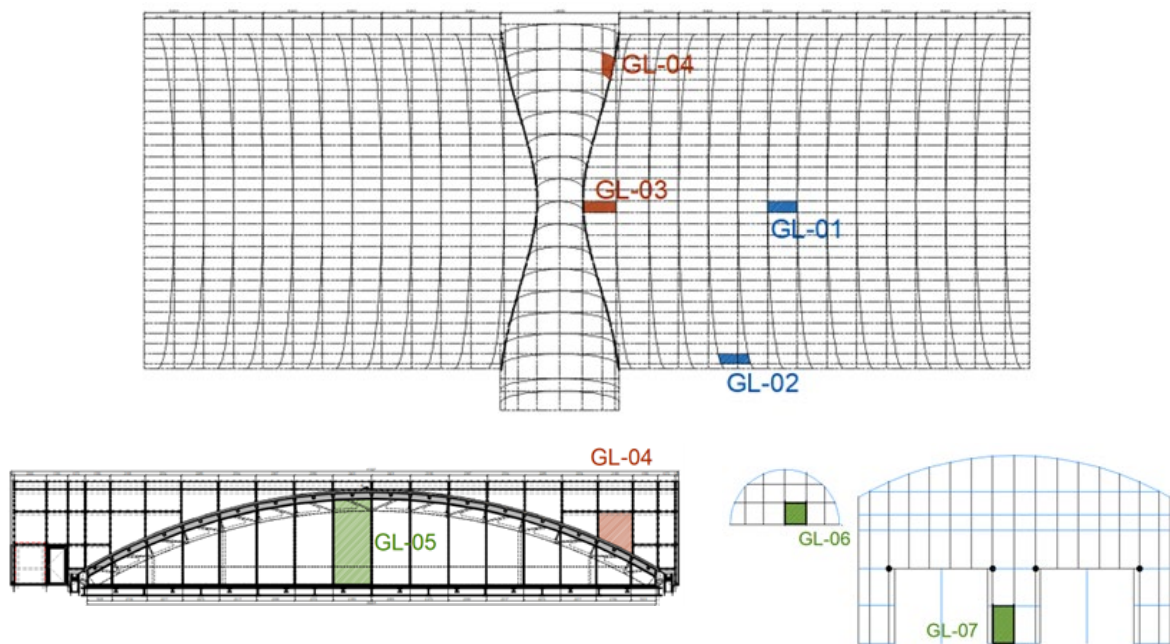


Fig. 4: Diagrams for identifying the glass typologies.

The adoption of cold-bent glass for the main roof represents a key architectural and structural choice of the project. Cold bending allows the realization of curved transparent surfaces using planar glass elements, exploiting elastic deformation imposed during installation rather than manufacturing curvature through thermal processes. In the Campo Marzio roof, cold-bent laminated glass panels are curved in situ by controlled fastening to the steel substructure, with curvature radii on the order of several tens of metres. This solution provides a visually continuous envelope while maintaining manufacturing efficiency and geometric precision. The behaviour of cold-bent glass panels has been

extensively studied both experimentally and numerically (e.g., Demontis et al. 2022; Fildhuth et al. 2014) and applied in built projects (e.g., McDonnell et al. 2018).

Across all glass typologies, the design criteria placed strong emphasis on serviceability requirements. Allowable deflections were defined to ensure visual quality, avoid damage to seals and gaskets, and maintain compatibility with aluminium frames and steel supports. Mechanical connections were conceived to allow rotations and differential movements, limiting stress concentrations at fixings and edges. These design assumptions provided a coherent framework for the subsequent finite-element modelling and verification of the glass components, ensuring consistency between architectural intent, structural behaviour and long-term performance (according to EN 16612 and CNR-DT 210).

6. Modelling and verification of glass components

6.1. FEM modelling of planar and cold-bent glass

The structural verification of the glass components was carried out through a multi-level modelling strategy, combining simplified analytical tools with dedicated finite-element analyses. This approach was adopted to address the intrinsic limitations of conventional glass design software when applied to geometrically complex and cold-bent laminated panels.

In a first phase, planar glass models with simplified boundary conditions were analysed using the software SJ MEPLA to obtain preliminary estimates of stress levels and deflections under characteristic load combinations. Subsequently, given the significant curvature imposed on the roof panels through cold bending, a more advanced modelling strategy was required to capture the actual structural behaviour of the glass elements. Dedicated finite-element models were therefore developed in SAP2000 to explicitly reproduce the imposed curvature of the panels (see Fig. 5(a)) and the associated pre-stress state. The induced curvature generates internal stresses within the glass that interact with external actions (see Fig. 5(b)). Consequently, both the geometry of the steel support system and the sequence of installation play a decisive role in determining the final stress and deformation state of the glass panels.

The modelling strategy was based on a two-step procedure. In the first step, the glass panels were subjected to self-weight and to prescribed displacements at the supports, corresponding to the target geometry imposed by the steel substructure. This step allowed the cold-bending process to be simulated and the associated geometric pre-deformation and stress state to be quantified. In the second step, variable actions such as wind pressure and suction were applied to the already deformed configuration, enabling a correct superposition of cold-bending effects and external loads. For the resistance verification, a cumulative damage approach was adopted in accordance with the provisions of CNR-DT 210.

Glass panels were modelled using shell elements, with appropriate mesh refinement to accurately capture stress gradients near supports and fixings. Boundary conditions were defined to reflect the actual mechanical behaviour of the connections, allowing rotations and in-plane movements where relevant. This modelling framework ensured that both global panel behaviour and local effects at supports were realistically represented.

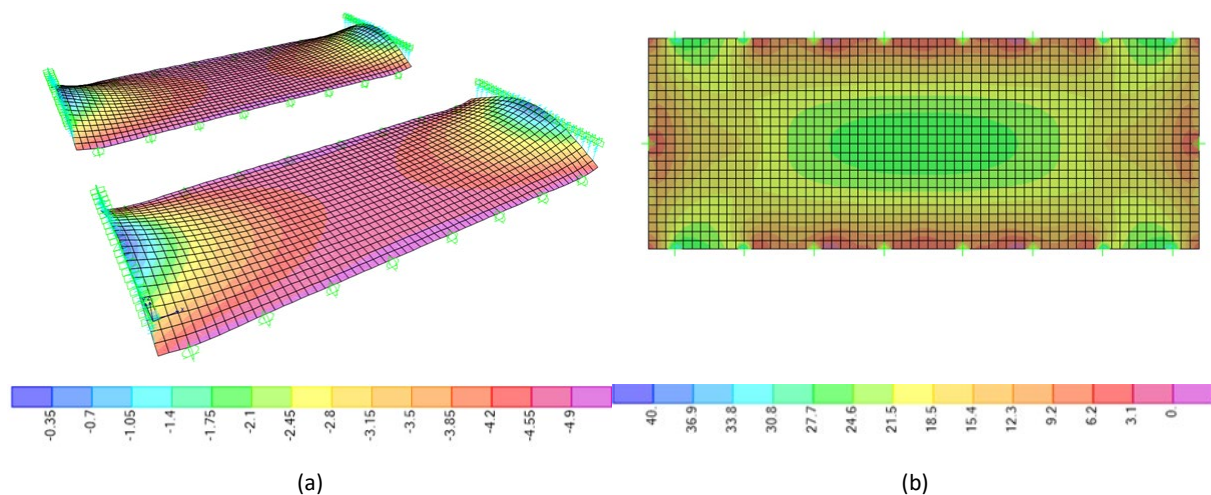


Fig. 5: Computational models developed with SAP2000: (a) initial configuration of the glass panels after cold bending (displacements in mm), and (b) example of stress distribution in a glass panel (stress in MPa).

6.2. Interlayer behaviour and equivalent thickness approach

A critical aspect in the modelling of laminated glass panels is the mechanical behaviour of the interlayer, which is strongly dependent on load duration and temperature. Given the variability and uncertainty associated with interlayer properties, a deterministic modelling of viscoelastic behaviour was considered impractical for the scope of the present study. Instead, a bounding approach was adopted to bracket the structural response of the laminated glass panels.

Specifically, two limit coupling conditions were considered for the interlayer: a monolithic limit, corresponding to a rigid coupling between glass plies, and a layered limit, representing a highly flexible interlayer response. These two limit cases were modelled through equivalent thickness configurations, derived according to established methodologies for laminated glass. The monolithic limit provides an upper bound in terms of stiffness, while the layered limit represents a conservative lower bound, leading to larger deflections and higher stress levels in the glass plies.

By analysing these limit conditions, it was possible to obtain an envelope of stresses, deformations, and fixing forces for each glass typology. This approach proved to be particularly effective for cold-bent panels, where the interaction between imposed curvature and variable loads is sensitive to laminate coupling. The results of the analyses confirmed that the governing design conditions may shift depending on whether serviceability or ultimate limit states are considered, further justifying the need for a bounded modelling strategy.

6.3. Serviceability criteria and fixing forces

Serviceability limit states played a dominant role in the design of the glass components and their supporting systems. Deformation criteria were defined to ensure visual quality, user comfort and structural compatibility between glass panels, aluminium profiles and steel substructures. For insulating glass units, particular attention was paid to limiting relative deflections between panes in order to prevent glass-to-glass contact under combined loading and climatic effects.

The explicit separation between deformations induced by cold bending and those caused by external actions proved to be essential for a correct serviceability assessment. By quantifying the portion of deflection attributable to the imposed curvature, the additional deformation due to wind loading could be evaluated independently, avoiding overly conservative interpretations of total displacement values.

In parallel, the finite-element models were used to extract reaction forces at the glass supports and point fixings, with particular focus on uplift forces induced by wind suction. These forces were subsequently used for the design and verification of the fixing systems and supporting structures. By deriving fixing forces directly from the deformed configuration of the glass panels, consistency was ensured between glass performance, connection capacity and the global deformability of the supporting steel structure.

7. Wind action and dynamic response of the glazed roof

7.1. Wind climate and CFD assessment

Due to the well-known severity of the Bora wind in the Trieste area, the assessment of wind-induced effects on the glazed roof required a dedicated investigation beyond standard quasi-static approaches. The Bora wind, characterized by short-duration gusts and very high peak velocities, represents one of the most critical wind environments in Europe and has a direct impact on large-span lightweight structures. For this reason, the wind action on the roof envelope was evaluated through computational fluid dynamics (CFD) simulations performed with RWIND 2, reproducing a virtual wind tunnel test capable of accounting for the complex interaction between wind flow and architectural geometry.

The three-dimensional geometry of the Campo Marzio station was reconstructed from the project drawings and complemented by a simplified representation of the surrounding urban context, derived from satellite data, in order to capture shielding and channelling effects induced by adjacent buildings.

Following a preliminary sensitivity study, a mesh cell size of 0.18 m was adopted for the analyses. A steady flow simulation with a RANS K-epsilon turbulence model was carried out by assuming a convergence criterion based on the residual pressure value. The residual target value was set to 1E-4. The CFD model resulted in 2,499,892 cells and 3,361,225 nodes.

The wind input was defined through a logarithmic vertical velocity profile calibrated according to CNR-DT 207/2008 recommendations and further supported by experimental data recorded by the ARPA FVG monitoring station located at the “Molo F.lli Bandiera”. While the available experimental dataset did not allow a statistically complete definition of the reference wind speed, it provided valuable indications on the most recurrent and severe Bora events affecting the site.

A parametric investigation of wind directions was carried out, leading to the analysis of six reference cases, including both code-based directions and site-specific Bora-dominated directions. Among these, winds acting longitudinally to the roof axis (between 210°N and 257°N) were identified as the most critical in terms of pressure and suction effects on the glazed surface. The CFD results, as shown in Fig. 6, highlighted a complex pressure distribution, characterized by strong external suction on the curved roof surfaces and by significant internal pressure due to the presence of large openings at track level. Unlike closed envelopes, the roof is therefore subjected to a pressure differential resulting from the superposition of external suction and nearly uniform internal pressure, a condition explicitly retained for the subsequent structural analyses.

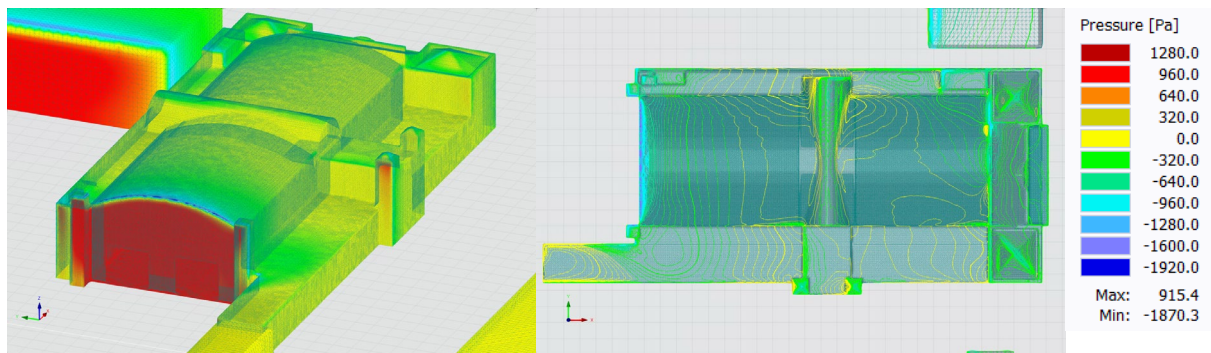


Fig. 6: Example of CFD simulation results in RWIND 2.

7.2. Finite Element modelling

To investigate the wind-induced dynamic response of the roof, the pressure fields derived from the CFD simulations were transferred to a detailed finite-element model developed in ABAQUS. To limit computational cost while preserving physical representativeness, the model focused on the two end bays of the roof, which were identified as the most stressed regions based on the CFD results (see Fig. 7(a)).

The model explicitly includes steel arches, supporting structures, glass panels, tension ties and arch constraints; see Fig. 7(b). Hinged and sliding supports were reproduced through connector elements, allowing the simulation of both constrained and free horizontal movements, including the effect of end-stop devices limiting the maximum sliding displacement. Glass panels were modelled as shell elements rigidly tied to the supporting steel substructure, while steel members were modelled using both beam and shell elements. All materials were assumed linear elastic, an assumption consistent with the limited stress levels observed in the analyses and with the objective of capturing global dynamic behaviour rather than local nonlinear effects.

Special attention was devoted to the modelling of glass–structure interaction. To investigate the influence of the additional stiffness provided by the glass panels on the global response, additional analyses were carried out using a reduced fictitious elastic modulus for the glass panels, representing a conservative lower-bound stiffness scenario. This approach allowed the sensitivity of the dynamic response to the bracing provided by glass to be explicitly assessed.

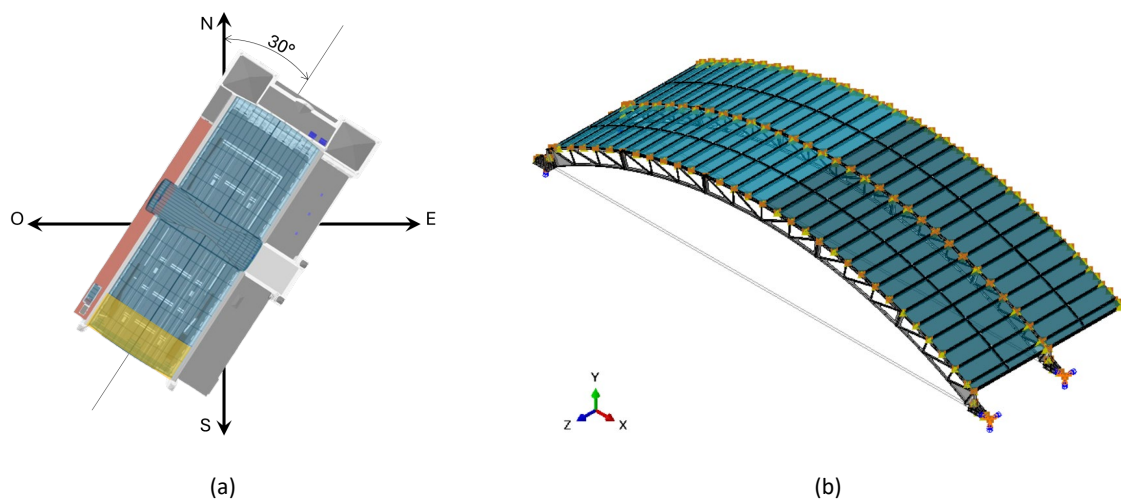


Fig. 7: Numerical model: (a) portion of the roof considered (highlighted in yellow) and (b) corresponding model in ABAQUS.

7.3. Spatial and temporal pressure definition

A key aspect of the adopted methodology is the realistic representation of both the spatial variability and the temporal evolution of wind action. The spatial distribution of wind pressure acting on the external surface of the roof was described through analytical fitting surfaces obtained by post-processing the CFD results. Pressure values were extracted from RWIND on a regular grid (Fig. 8(a)) and subsequently fitted using a polynomial surface through a dedicated MATLAB script (Fig. 8(b)). This procedure allowed the application of a continuous pressure field in ABAQUS, avoiding the simplifications inherent to uniform or zonal pressure assumptions typically adopted in design practice.

The temporal evolution of wind loading was defined through a pressure time-history representative of a gust event. The adopted time-history was extracted from experimental wind tunnel measurements performed on a structure of comparable geometry and normalized to match the peak pressures obtained from the CFD analyses (Rizzo and Bedon 2023). This approach enabled the reproduction of the short-duration, high-intensity nature of Bora gusts. The time-dependent pressure field was applied consistently to the external roof surface, while a uniform and constant internal pressure was simultaneously applied to account for wind ingress through the large openings at track level.

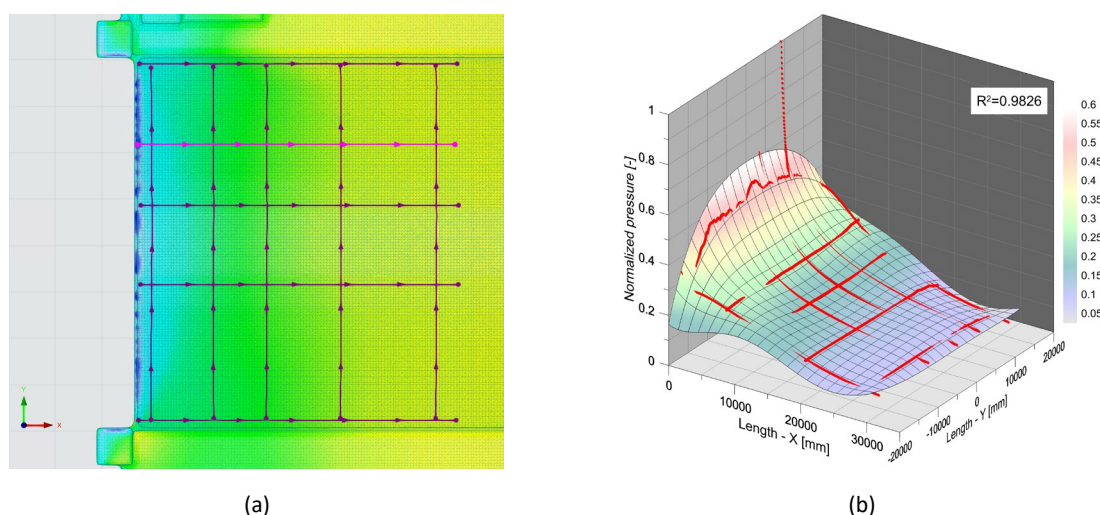


Fig. 8: (a) Grid used for extracting pressure values from RWIND and (b) surface fitting in MATLAB.

7.4. Dynamic results and sensitivity analyses

Dynamic implicit analyses were performed accounting for self-weight, pre-tension in the tie system and wind-induced pressures acting simultaneously on the external and internal surfaces of the roof. Fig. 9 (a) and (b) illustrate typical time-histories of acceleration and vertical displacement for a control point at the top of the arch. The results show limited vertical displacements and modest stress levels in the steel arches, as detailed in Table 2 for different wind directions. Time histories of acceleration and displacement reveal a stable structural response, with no evidence of resonance phenomena or significant dynamic amplification.

The dynamic contribution of wind action remains limited, with root-mean-square amplification factors well below thresholds commonly associated with aeroelastic instability. Sensitivity analyses carried out using a reduced fictitious elastic modulus for the glass panels resulted in increased displacements (up to 9.5 times for the vertical displacement); however, the horizontal displacement remained limited to 28.4 mm, well within the admissible limits of the sliding supports and the end-stop devices (50 mm). These results confirm that, despite the extreme wind environment, the glazed roof exhibits a

controlled and robust dynamic behaviour, validating the adopted steel-and-glass structural concept for a large-span transparent enclosure under severe Bora wind conditions.

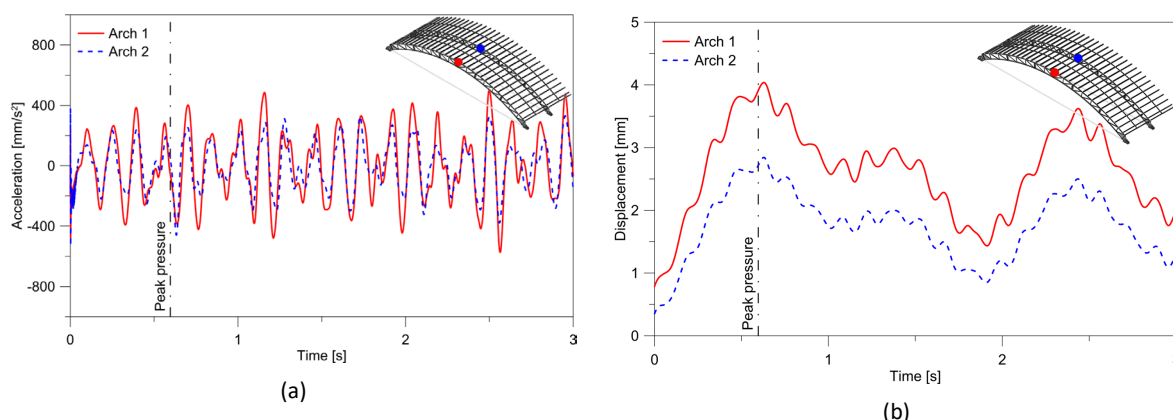


Fig. 9: Example of time history of (a) acceleration and (b) vertical displacement.

Table 2: FEM results.

	210 °N	222 °N	257 °N
Max vertical displacement [mm]	4.0	6.9	6.3
Max Von Mises stress [MPa]	132	221	196
Max horizontal displacement [mm]	3.4	5.0	4.6

8. Conclusions

The requalification of the Campo Marzio railway station provides a comprehensive case study on the structural use of glass in large-span transparent envelopes integrated within a historic context and exposed to extreme environmental actions. The project demonstrates how the reconstruction of a glass roof, inspired by an early-20th-century iron-and-glass archetype, can be successfully achieved through contemporary steel-and-glass technologies without compromising structural performance or architectural clarity.

From a structural standpoint, the adoption of lightweight reticular steel arches combined with differentiated support conditions proved effective in controlling global stiffness and accommodating thermal and deformation demands. The glass envelope was developed through a typological approach, identifying multiple glass configurations tailored to curvature, support conditions and functional requirements. Cold-bent laminated glass panels played a key role in achieving the desired geometry while maintaining visual continuity and material efficiency.

The modelling and verification strategy for the glass components highlighted the importance of explicitly accounting for imposed curvature, interlayer coupling variability and glass–structure interaction. The use of dedicated finite-element analyses, combined with simplified planar checks for control purposes, allowed serviceability and ultimate limit states to be assessed in a consistent and performance-oriented manner. Particular attention was paid to the extraction of fixing forces from the deformed configuration, ensuring compatibility between glass panels, connection systems and supporting steel members.

A major contribution of the study lies in the assessment of wind-induced dynamic effects on the glazed roof. The coupled CFD–FEM approach adopted for the Bora wind conditions enabled a realistic representation of both the spatial distribution and temporal evolution of wind pressures, including the combined action of external suction and internal pressure. The dynamic analyses confirmed a stable structural response, with limited displacements and no significant amplification phenomena, even under conservative assumptions regarding glass stiffness. These results validate the feasibility of large transparent envelopes in high-wind environments when appropriate modelling strategies and boundary conditions are adopted.

Overall, the Campo Marzio project demonstrates that the integration of architectural intent, advanced structural modelling and environmental analysis is essential for the successful realization of contemporary glass structures in heritage contexts. The methodologies discussed in this paper may serve as a reference for the design of future large-span steel-and-glass envelopes subjected to complex wind actions, reinforcing the role of glass as both a structural and expressive material in challenging architectural applications.



Fig. 10: Exterior views of the roof and of the main glazed façade during construction.

Acknowledgements

The authors would first like to acknowledge Fondazione FS Italiane for promoting the redevelopment of the historic Campo Marzio railway station. They also wish to thank the University of Trieste, Department of Engineering and Architecture, for the study on wind action and the dynamic response of the glazed roof, conducted in collaboration with SMStrutture. The authors are grateful to Architect Andrea Abatecola of PLAT Studio, who was responsible for the architectural design of the redevelopment project. Finally, they acknowledge the contributions of the entire design team, including PICHLER Projects, C.E.M.E.S. S.p.a., PLAT Studio, and SMStrutture.

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