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Marcin Szyszka * and Paweł Sulik

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Experimental Testing and Numerical Modelling for Thermo-Mechanical Characterization of Masonry Materials: A Multi-Scale Approach

Marcin Szyszka [1],* and Paweł Sulik [2]

[1] Department of Building Engineering, Faculty of Civil Engineering, Wrocław University of Science and Technology, Wrocław, 50-370, Poland
[2] Fire Research Department, Building Research Institute, 00-611 Warsaw, Poland
* Correspondence: marcin.szyszka@pwr.edu.pl; Tel.: +48697353727

Abstract

The thermo-mechanical behavior of masonry materials is investigated through an integrated experimental testing and numerical modelling approach. The study focuses on the characterization of masonry under fire exposure, where coupled thermal and mechanical effects govern material response and failure mechanisms. A multi-scale framework is proposed to link physico-chemical transformations, material-level properties, and structural-scale behavior. The experimental component includes full-scale fire-resistance tests on load-bearing masonry walls, providing temperature evolution, deformation histories, and observed damage patterns. These results enable the identification of key mechanisms such as stiffness degradation, cracking, and the influence of thermal gradients on structural response. The experimental observations are used to support the development and calibration of numerical models capable of representing temperature-dependent behavior and strain-rate effects. In addition, non-destructive testing techniques are incorporated to relate internal damage to measurable diagnostic signals, enhancing material characterization and structural assessment. Although the present study is limited to structural-scale validation, the proposed approach demonstrates how combined experimental and numerical strategies can be used to develop consistent constitutive descriptions of masonry materials. The results contribute to improved understanding and modelling of engineering materials subjected to coupled thermo-mechanical loading.

Keywords: masonry; thermo-mechanical behavior; multi-scale analysis; experimental testing; numerical modelling; material characterization; non-destructive testing; failure mechanisms; constitutive modeling; fire exposure

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1. Introduction

Masonry remains one of the most widely used construction materials in the built environment, consisting of a heterogeneous composite of units (e.g., clay bricks) and mortar joints. Despite its long-standing application, its mechanical behavior under extreme conditions remains not yet fully understood, particularly under combined thermal and dynamic loading. This limitation is critical in fire scenarios, where elevated temperatures are frequently accompanied by additional mechanical actions such as impact from falling structural components or debris. Real fire-induced collapse events, including documented failures of frame-supported masonry structures subjected to extreme thermal exposure, further highlight the complexity of coupled thermo-mechanical interactions and progressive collapse mechanisms [32].

From a materials science perspective, masonry exhibits complex behavior due to its heterogeneous and brittle nature, characterized by anisotropy, tension–compression asymmetry, and strong dependence on confinement and stress state. The interaction between brick and mortar phases, as well as microstructural evolution under thermal exposure, significantly affects macroscopic performance. Previous studies have investigated masonry under elevated temperatures, highlighting degradation mechanisms, loss of stiffness, and reduction of strength [1–5,34–36,39]. Similarly, the response of masonry to dynamic and impact loading has been explored, demonstrating pronounced strain-rate sensitivity and complex failure modes [8–14,31,37,38].

However, these two aspects—thermal degradation and dynamic loading—have largely been studied independently. Only limited research addresses their combined effects, despite their practical relevance in post-fire structural response and progressive failure scenarios. Moreover, most available studies focus on specific material scales or isolated experimental techniques, which restrict the development of comprehensive constitutive descriptions [23–26,40].

Another key limitation lies in the insufficient integration of multi-scale experimental data. While microstructural characterization techniques such as X-ray diffraction, scanning electron microscopy, and micro-computed tomography provide insight into phase transformations and damage mechanisms [1–4,34–36], these observations are rarely systematically linked to macroscopic mechanical behavior. Similarly, non-destructive testing methods have shown potential for assessing damage in fire-affected structures [18–22], yet their correlation with residual mechanical properties remains incomplete.

In addition, numerical modeling approaches for masonry under extreme conditions remain fragmented. Although both continuum-based and particle-based techniques have been successfully applied in related contexts [23–26,40], their calibration and validation often rely on limited datasets and do not fully account for the coupling between temperature effects and strain-rate-dependent behavior.

A further limitation concerns the absence of a methodology that explicitly combines structural fire testing procedures with advanced characterization and model development. Existing fire-resistance testing standards define thermal boundary conditions, loading procedures, and acceptance criteria for wall elements [27–30], while Eurocode provisions describe the action of fire in structural design [33,41]. Material testing standards provide the basis for the characterization of mortar properties [42,43]. Recent studies also indicate that data-driven methods and machine learning may support the interpretation of non-destructive measurements and strength prediction [44,45], whereas full-field optical techniques such as high-temperature digital image correlation can enhance deformation monitoring under severe thermal exposure [46]. However, these tools have not yet been assembled into a unified framework tailored to masonry subjected to coupled thermo-mechanical loading.

To address these challenges, this study proposes a multi-scale experimental–numerical methodology for the characterization of masonry materials under coupled thermo-mechanical loading. The proposed framework integrates physico-chemical characterization, mechanical testing under varying loading regimes, and numerical modeling within a unified approach. The methodology is designed to ensure consistency across material, meso-, and structural scales, enabling the identification and calibration of constitutive models for masonry under extreme conditions. By linking microstructural evolution, mechanical response, and modeling strategies, the proposed approach provides a comprehensive basis for understanding and predicting the behavior of brittle composite materials.

2. Limitations of Existing Approaches

Despite the substantial body of research on masonry materials, current approaches remain fragmented in characterizing their behavior under extreme conditions. Existing studies can generally be grouped into investigations of high-temperature effects, dynamic or impact loading, and numerical modeling. However, these research directions are typically developed independently, which limits their applicability to realistic scenarios involving coupled actions.

2.1. Separation of Thermal and Dynamic Effects

A large number of studies have focused on the influence of elevated temperatures on masonry materials, demonstrating reductions in strength and stiffness as well as significant microstructural changes such as dehydration, phase transformation, and crack development [1–5,34–36,39]. These investigations provide a detailed understanding of thermally induced degradation mechanisms at both material and structural levels.

In parallel, the dynamic behavior of masonry has been investigated under impact loading, blast conditions, and moderate strain-rate regimes. These studies show that masonry exhibits pronounced rate sensitivity and complex failure modes that differ from those observed under quasi-static loading [8–14,31,37,38]. Additional research has extended this perspective to combined hazard scenarios, including seismic and fire loading, as well as energy-based damage assessment methods [15–17].

However, these two research areas are rarely connected. The interaction between temperature-induced degradation and rate-dependent mechanical behavior remains insufficiently explored. This gap is particularly relevant for realistic structural scenarios, where fire exposure may be followed by dynamic actions such as falling debris or progressive collapse mechanisms. As a result, current knowledge does not adequately describe how thermal damage modifies dynamic response or how strain-rate effects evolve in degraded materials.

2.2. Lack of Multi-Scale Integration

Masonry is inherently a multi-phase and multi-scale material system, in which macroscopic behavior emerges from interactions among constituents, interfaces, and evolving microstructure. Although individual scales have been extensively studied, systematic integration across scales remains limited.

At the micro- and meso-levels, advanced characterization techniques have been used to investigate temperature-induced transformations and damage mechanisms, including phase changes, pore evolution, and microcracking [1–4,34–36]. Experimental studies on masonry units and small-scale assemblies further demonstrate that these microstructural changes directly influence stiffness degradation and strength loss [5,39].

At the structural level, full-scale investigations provide insight into global response under fire exposure and combined loading conditions [39]. However, these studies are typically conducted independently of detailed material characterization, limiting their ability to explain the underlying mechanisms governing observed behavior.

Similarly, dynamic investigations are often restricted to specific specimen scales and do not establish consistent links between material behavior and structural response [8–14]. Consequently, existing research lacks a hierarchical experimental framework that connects microstructural transformations, material-level properties, and structural-scale performance. Although multi-scale modeling approaches have been proposed in related contexts [40], their application to masonry under coupled thermo-mechanical loading remains limited.

2.3. Limited Correlation Between NDT and Mechanical Properties

Non-destructive testing techniques, such as ultrasonic pulse velocity, impact-echo, and electroacoustic methods, have demonstrated potential for assessing damage in masonry and concrete structures exposed to fire [18–22]. These techniques are particularly attractive for post-fire diagnostics and structural health monitoring.

However, their application remains largely qualitative or semi-empirical. The relationship between measured signals and residual mechanical properties is not yet sufficiently established, particularly under coupled thermal and mechanical loading conditions. Moreover, validation of NDT results against detailed internal damage characterization is still limited.

Recent developments suggest that data-driven approaches and machine learning techniques may enhance the interpretation of NDT data and improve strength prediction [44,45]. Nevertheless, these methods remain insufficiently integrated with experimental observations and are rarely applied within a consistent multi-scale framework.

2.4. Fragmented Modeling Strategies

Numerical modeling of masonry under extreme conditions has been addressed using both continuum-based approaches, such as the finite element method, and discrete or particle-based techniques [23–26,40]. These methods have proven effective in simulating specific phenomena, including thermal degradation and impact-induced failure.

However, current modeling strategies are often developed using limited experimental data and are rarely validated across multiple scales. As a result, their predictive capability remains constrained. In addition, the selection between different modeling paradigms is typically not supported by systematic comparison or integration within a unified framework.

2.5. Absence of a Unified Methodological Framework

The limitations outlined above indicate the absence of a comprehensive methodology that integrates experimental and modeling approaches across scales. While fire testing standards define boundary conditions and performance criteria for structural elements [27–30], and Eurocode provisions describe fire actions in structural design [33,41], these components are not combined with advanced experimental techniques and modeling strategies into a single coherent framework.

Material testing standards provide procedures for the characterization of mortar properties [42,43], while high-resolution measurement techniques, such as digital image correlation, enable full-field deformation and crack monitoring under thermal loading [46]. In addition, recent developments in machine learning offer new opportunities for interpreting experimental data and enhancing predictive capabilities [44,45].

Despite these advances, these tools are typically applied independently and are not systematically integrated into a unified methodology. Consequently, the development of robust and transferable constitutive descriptions for masonry under coupled thermo-mechanical loading remains limited, motivating the approach proposed in this study.

3. Proposed Methodology

3.1. Conceptual Framework

This study proposes a multi-scale experimental–numerical methodology for the characterization of masonry materials subjected to coupled thermo-mechanical loading. The framework is designed to integrate physicochemical characterization, mechanical testing under varying loading regimes, and numerical modeling into a unified, hierarchical structure.

The methodology is based on three fundamental principles: consistency across scales, representation of coupled loading effects, and integration of experimental observations with numerical modeling. These principles ensure that observations obtained at the micro-, material-, and structural levels can be systematically linked and used to identify and validate constitutive models.

The overall workflow progresses from material characterization to model validation, establishing a consistent pathway for describing masonry behavior under extreme conditions. The structure of the methodology is illustrated in Figure 1.

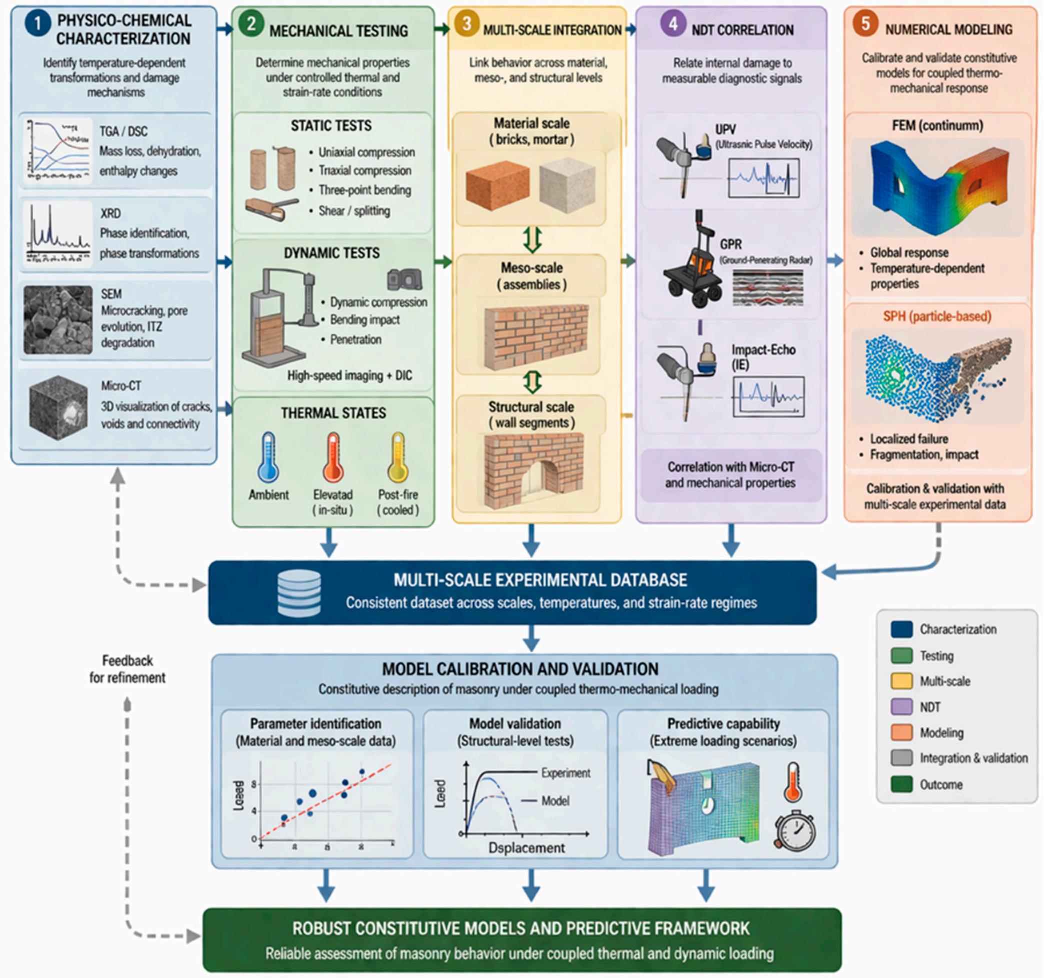

Figure 1. Proposed methodological workflow for the multi-scale characterization of masonry under coupled thermo-mechanical loading.

3.2. Physico-Chemical Characterization

The first stage of the methodology focuses on identifying temperature-dependent transformations in masonry constituents. This step provides essential input for subsequent mechanical testing and modeling.

The characterization includes thermogravimetric analysis and differential scanning calorimetry to quantify mass loss and thermal effects; X-ray diffraction to identify mineral phases and phase transformations; scanning electron microscopy to investigate microcracking and pore evolution; and X-ray micro-computed tomography to obtain three-dimensional information on internal damage. These techniques have been widely applied to investigate thermally induced degradation in masonry materials [1–5,34–36].

The combined use of these methods enables a comprehensive description of microstructural evolution under thermal loading, forming a direct link between physico-chemical processes and macroscopic mechanical behavior.

3.3. Mechanical Testing Framework

The second stage establishes a structured experimental program to determine the mechanical response of masonry materials under varying loading conditions.

3.3.1. Static Testing

Static tests are used to determine baseline mechanical properties, including compressive strength, tensile capacity, and fracture behavior. The experimental program includes uniaxial compression, triaxial compression under varying confinement, bending tests, and shear-compression tests. These procedures are consistent with established testing methodologies for masonry materials and mortar characterization [42,43].

The results of static testing provide fundamental parameters for constitutive modeling and serve as a reference for assessing the influence of thermal and dynamic effects.

3.3.2. Dynamic Testing

Dynamic behavior is investigated using impact-based loading systems that cover moderate strain-rate regimes relevant to structural scenarios such as falling debris or localized failure. The experimental program includes dynamic compression tests, bending impact tests, and penetration tests using different impactor geometries.

High-speed imaging combined with digital image correlation is employed to capture full-field deformation and crack propagation [46]. Previous studies have demonstrated that strain-rate effects significantly influence failure mechanisms and load-bearing capacity in masonry and similar brittle materials [8–14,31,37,38].

This stage enables characterization of rate-dependent behavior and provides data for developing constitutive models that account for dynamic effects.

3.3.3. Thermal Loading Conditions

Mechanical tests are conducted under controlled thermal conditions, including ambient temperature, elevated temperature during heating, and post-fire conditions after cooling. These conditions are selected to capture the influence of temperature history on material behavior.

Thermal exposure is defined in accordance with standard fire curves and testing procedures used in structural fire engineering [27–30], while the definition of fire actions follows Eurocode provisions [33,41]. This ensures consistency between material-level experiments and structural-scale conditions.

3.4. Multi-Scale Experimental Strategy

A key component of the proposed methodology is the hierarchical progression across scales, ensuring consistency between different levels of observation.

At the material scale, individual bricks and mortar specimens are tested to determine fundamental properties. At the meso-scale, composite assemblies are investigated to capture interactions between units and mortar. At the structural scale, larger masonry elements or wall segments are analyzed to obtain global response characteristics.

This multi-scale strategy enables the identification of scale-dependent behavior and provides a comprehensive dataset for model development. It also facilitates the linkage between microstructural transformations and macroscopic mechanical response.

3.5. Non-Destructive Testing Integration

Non-destructive testing techniques are incorporated to establish relationships between internal damage and measurable diagnostic signals. The methodology includes ultrasonic pulse velocity, ground-penetrating radar, and impact-echo methods [18–22].

Measurements are performed across different scales and correlated with internal damage observed through microstructural characterization. In addition, recent developments in data-driven approaches offer opportunities to improve the interpretation of NDT results and to link them to residual mechanical properties [44,45].

This integration enhances the methodology's diagnostic capability and supports both experimental analysis and potential-field applications.

3.6. Numerical Modeling Framework

The final stage integrates experimental findings into a numerical modeling framework for constitutive description and predictive analysis.

Two complementary approaches are considered: continuum-based modeling using the finite element method and particle-based methods such as smoothed particle hydrodynamics [23–26,40]. These approaches enable the simulation of both global structural response and localized failure processes.

Model calibration is performed using experimental data obtained at different scales, incorporating temperature-dependent material properties, strain-rate effects, and observed failure mechanisms. The use of complementary modeling techniques improves the robustness and predictive capability of the proposed framework.

3.7. Methodological Workflow

The proposed methodology is structured as a sequential and interrelated process that integrates experimental characterization and numerical modeling within a unified framework. The process begins with physico-chemical characterization, followed by mechanical testing under controlled thermal and loading conditions. The experimental program is extended through a multi-scale strategy, ensuring consistency between observations at different levels.

Non-destructive testing techniques are used to establish relationships between internal damage and measurable signals, while numerical modeling enables the calibration and validation of constitutive descriptions. The overall structure and interrelation of these stages are illustrated in Figure 1.

The framework integrates physicochemical characterization, mechanical testing, multiscale experimental analysis, nondestructive diagnostics, and numerical modeling into a unified approach. Physico-chemical techniques (TGA/DSC, XRD, SEM, and micro-CT) are employed to identify temperature-dependent transformations and microstructural evolution. Mechanical behavior is investigated through static and dynamic testing under controlled thermal conditions, enabling the characterization of strength, stiffness, and strain-rate effects.

A hierarchical multi-scale strategy is adopted to ensure consistency between material, meso-, and structural levels. Non-destructive testing methods (e.g., ultrasonic pulse velocity, ground-penetrating radar, and impact-echo) are used to establish correlations between internal damage and measurable diagnostic signals. The resulting experimental data are integrated into a multi-scale database that serves as the basis for calibrating and validating numerical models using complementary approaches (finite element method and smoothed particle hydrodynamics).

The proposed workflow enables the development of constitutive models that capture the coupled effects of temperature and dynamic loading, providing a comprehensive and transferable framework for analyzing masonry materials under extreme conditions.

4. Theoretical Basis

4.1. Thermo-Mechanical Behavior of Masonry as a Brittle Composite

Masonry is a heterogeneous composite material composed of units and mortar joints, whose mechanical response is governed by the interaction between its constituents and the properties of the interfacial transition zone. From a mechanical standpoint, masonry exhibits quasi-brittle behavior characterized by limited tensile strength, pronounced cracking, and strong dependence on confinement and stress state. The asymmetry between compressive and tensile strength, together with sensitivity to hydrostatic pressure, distinguishes masonry from homogeneous materials and necessitates dedicated constitutive descriptions [34–36].

The macroscopic response of masonry arises from mechanisms operating at smaller scales, including microcrack initiation and propagation, frictional sliding along interfaces, and progressive damage accumulation. These processes are strongly influenced by material heterogeneity, the internal geometry of masonry units, and the distribution of defects within both brick and mortar phases.

4.2. Temperature-Dependent Material Degradation

Exposure to elevated temperatures induces a series of physico-chemical transformations that significantly affect the mechanical properties of masonry constituents. These transformations include dehydration of hydrates, decomposition of binding phases, thermal expansion mismatch between components, and the development of microcracking. Experimental studies have consistently shown that these processes lead to a reduction in stiffness and strength, as well as changes in failure modes [1–5,34–36].

The degradation is not uniform across the material system. Differences in thermal properties between brick and mortar, combined with the evolution of the interfacial transition zone, result in localized damage and stress redistribution. Consequently, temperature-induced changes at the microstructural level directly influence load transfer mechanisms and the macroscopic response of masonry elements.

4.3. Strain-Rate Effects and Dynamic Response

The mechanical behavior of masonry is also influenced by the rate of loading. Under dynamic conditions, materials typically exhibit strain-rate sensitivity, which may result in apparent increases in strength and modifications of failure patterns. In masonry, this response is further complicated by the composite nature of the material and the interactions among its constituents.

Experimental investigations have demonstrated that dynamic loading conditions, including impact and moderate strain-rate compression, lead to distinct fracture mechanisms and energy dissipation processes compared with quasi-static loading [8–14,31,37,38]. These differences are associated with inertia effects, delayed crack propagation, and changes in the relative contribution of tensile cracking and compressive crushing.

4.4. Coupled Thermo-Mechanical Effects

In realistic scenarios, thermal and mechanical actions act simultaneously or sequentially, leading to coupled thermo-mechanical behavior. Temperature-induced degradation modifies stiffness, strength, and fracture energy, which in turn affects the response of masonry to subsequent or concurrent mechanical loading. Conversely, mechanical loading may accelerate the evolution of damage in thermally weakened materials.

The interaction between temperature effects and strain-rate-dependent behavior involves multiple mechanisms, including temperature-dependent softening, changes in fracture properties, and shifts in failure modes. These mechanisms are inherently interdependent and cannot be adequately described using uncoupled approaches. As a result, predicting masonry behavior under combined loading requires experimental data obtained under controlled thermal and mechanical conditions, as well as constitutive models that capture their interaction.

4.5. Implications for Constitutive Modeling

The complexity of masonry behavior under coupled thermo-mechanical loading necessitates the development of advanced constitutive models that incorporate temperature-dependent material properties, strain-rate sensitivity, and damage evolution. In addition, such models must ensure consistency across scales by linking microstructural transformations with macroscopic response.

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Continuum-based approaches provide an effective framework for capturing global structural behavior, while particle-based methods offer advantages in representing localized failure and fragmentation processes [23–26,40]. However, the reliability of these approaches depends on calibration against comprehensive experimental datasets.

The methodology proposed in this study provides a structured pathway for such calibration by integrating physico-chemical characterization, mechanical testing, and multi-scale observations. This integration enables the development of constitutive descriptions that are physically grounded and applicable to complex loading scenarios involving coupled thermo-mechanical effects.

5. Structural-Scale Experimental Component of the Proposed Methodology

5.1. Description of the Experimental Case

The experimental dataset considered in this study is derived from full-scale fire-resistance tests conducted on load-bearing masonry walls constructed from ceramic hollow units. The tested specimen had dimensions of approximately 3000 mm in width, 3500 mm in height, and 270 mm in thickness, and was subjected to a vertical load of approximately 750–790 kN, corresponding to a high level of utilization of its load-bearing capacity.

The applied masonry units had a length of 373 mm and a width of 250 mm. The minimum thickness of the external walls was 8 mm, while the internal webs were 5 mm thick. The geometry of the units is shown in Figure 2.

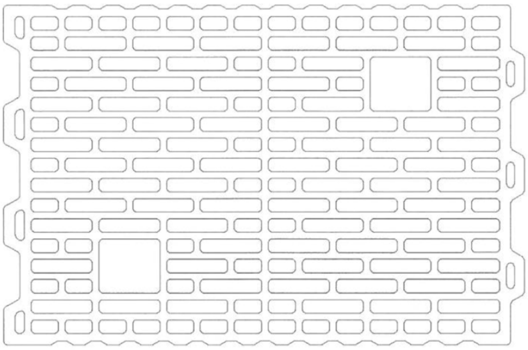

Figure 2. Geometry and cross-section of the hollow masonry units used in the tests.

The fire exposure and loading conditions were defined in accordance with standard fire-resistance testing procedures [27–30] and structural fire design provisions [33,41].

5.2. Geometry and Measurement Layout

The geometry of the tested wall and the distribution of measurement points are presented in Figure 3. The instrumentation system included thermocouples placed on the unexposed surface and within the wall thickness, as well as displacement sensors used to measure both vertical shortening and horizontal deflections.

At measurement points 1–5, average temperatures were recorded, while points 6–9 captured maximum temperatures. Horizontal displacements were measured at points A, B, and F, whereas vertical displacements were recorded at points C, D, and E.

The adopted measurement configuration provides spatially distributed data, enabling the analysis of both thermal gradients and deformation patterns at the structural scale.

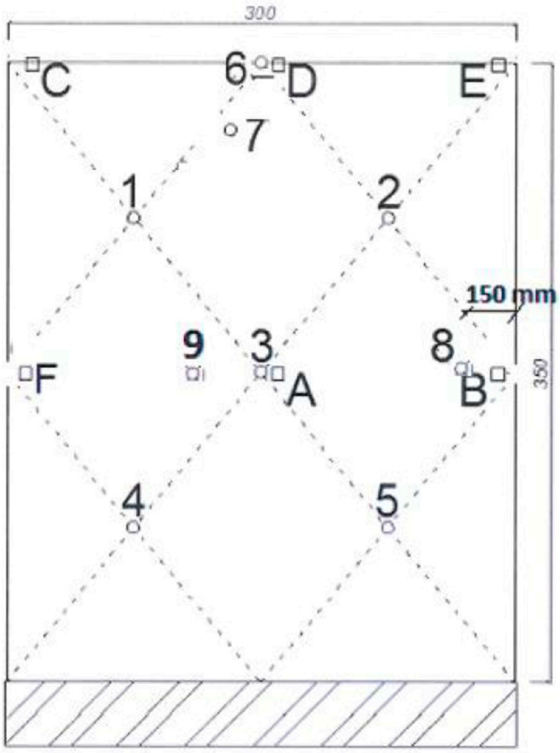

Figure 3. Measurement layout showing thermocouple locations and displacement sensors.

5.3. Thermal Response

The thermal loading followed a standard fire curve, as shown in Figure 4, which presents both the furnace temperature and selected temperature measurements within the specimen. The temperature evolution is characterized by rapid heating during the initial phase, followed by a gradual increase to exceed 1000°C, consistent with standard fire-exposure conditions [27–30]. The recorded temperature distribution indicates the development of significant thermal gradients across the wall thickness, reflecting the low thermal conductivity of masonry and the influence of internal voids within the units.

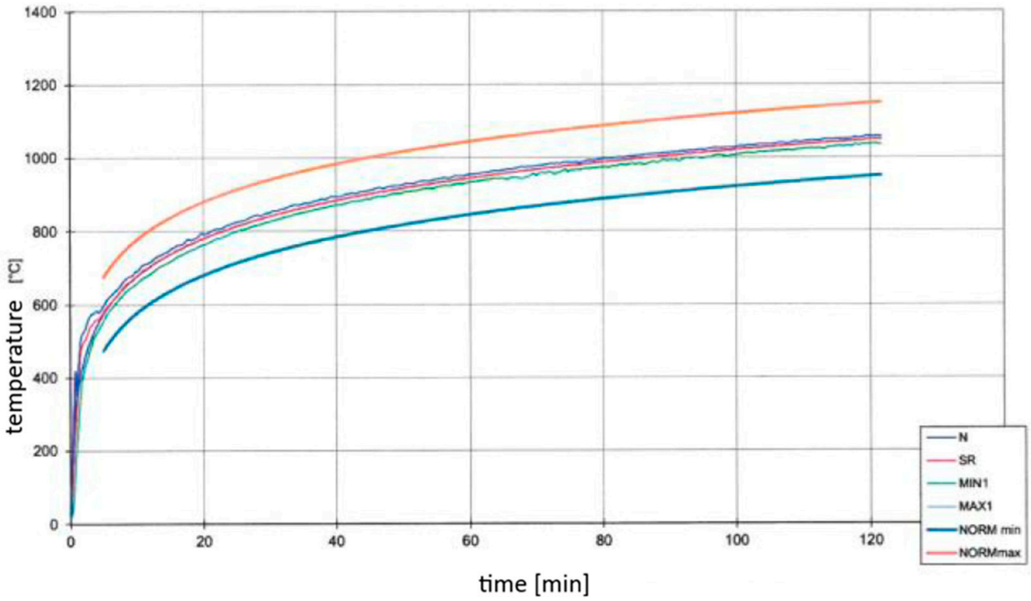

Figure 4. Temperature evolution during the fire test, including furnace temperature and selected measurement points.

5.4. Mechanical Response

The mechanical response of the wall is illustrated in Figure 5 and Figure 6, showing the evolution of horizontal displacements and vertical elongation during fire exposure.

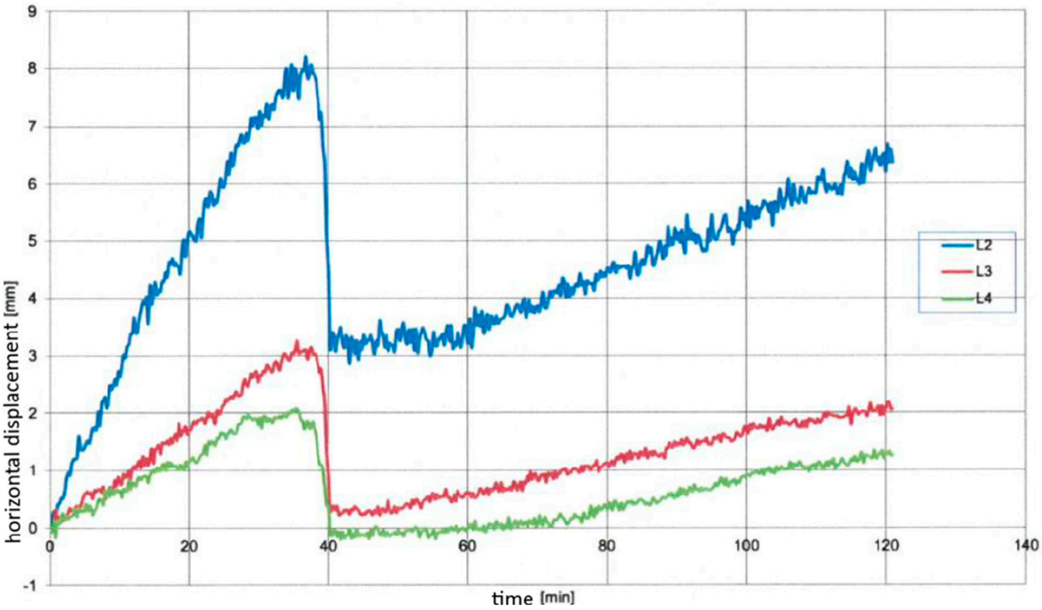

Figure 5. Horizontal displacements.

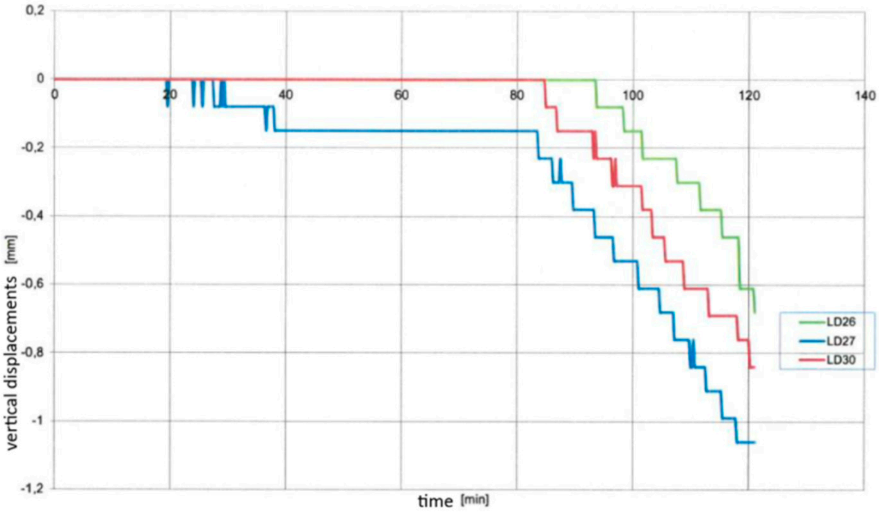

Figure 6. Vertical displacements.

The results indicate and underline nonlinear deformation evolution, increasing displacement rates at later stages, and coupling between thermal effects and mechanical degradation.

5.5. Damage Evolution and Failure Mechanisms

The progression of damage during the test is primarily on the inner side of the specimen, namely the heated side. This situation is clearly illustrated in Figure 7, which shows the unheated and heated sides of the wall after the test.

The observed damage includes the formation of vertical cracks, detachment of plaster layers, and progressive degradation of masonry units. Particular attention should be given to the influence of unit geometry, as the global load-bearing capacity was significantly affected by the spalling and local failure of perforated units.

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Figure 7. Post-test state – unheated side of the wall (on the left) and the heated side of the wall (on the right).

These observations indicate that structural response is strongly governed by local mechanisms related to unit configuration and internal geometry. Consequently, full-scale tests alone provide only a partial understanding of the underlying processes, as they do not directly capture the evolution of damage at lower scales.

5.6. Role of the Dataset Within the Proposed Framework

The experimental results obtained from the full-scale fire tests represent the structural-scale component of the proposed multi-scale methodology and provide a consistent description of masonry behavior under coupled thermal and mechanical loading.

The combination of temperature measurements, displacement data, and visual observations enables the identification of key response characteristics, including the development of thermal gradients, progressive deformation, and damage evolution. These observations confirm the strong interaction between thermal degradation and mechanical response.

Within the proposed framework, structural-scale data define the boundary conditions and global response characteristics that numerical models must reproduce. At the same time, the observed deformation patterns and failure mechanisms provide indirect information about processes occurring at lower scales, such as microcracking and material degradation.

Although the dataset does not include direct measurements at the material or microstructural levels, it establishes a consistent reference for integrating additional experimental data and for validating multi-scale modeling approaches.

5.7. Limitations and Perspective

The presented implementation is limited to structural-scale observations and does not include direct physico-chemical characterization, material-scale testing, or dynamic loading conditions. As a result, the full multi-scale integration proposed in this study remains to be achieved.

Nevertheless, the results demonstrate the feasibility of incorporating structural-scale experimental data into a broader multi-scale framework. Future work will focus on extending the methodology by integrating microstructural characterization, rate-dependent testing, and advanced numerical modeling to achieve a comprehensive description of masonry behavior under coupled thermo-mechanical loading.

6. Discussion

The results presented in this study demonstrate the applicability of the proposed methodology for characterizing masonry under coupled thermo-mechanical loading, while also highlighting the challenges associated with its full implementation. The structural-scale experimental data provide a detailed description of the global response of masonry walls exposed to fire, including temperature evolution, deformation behavior, and damage development.

A key observation is the strong interaction between thermal gradients and mechanical response. The development of significant temperature differences across the wall thickness leads to non-uniform expansion, which induces bending, cracking, and progressive degradation of stiffness. The recorded displacement histories and observed damage patterns confirm that masonry behavior under fire conditions cannot be adequately described by considering thermal or mechanical effects independently. Instead, the response is governed by their coupling, which affects both deformation evolution and load-bearing capacity.

From a methodological perspective, the presented dataset illustrates the role of structural-scale experiments within a broader multi-scale framework. The measurements obtained during fire tests define global response characteristics that numerical models must reproduce. At the same time, the observed damage patterns indicate the presence of underlying mechanisms, such as microcracking and material degradation, which originate at lower scales but manifest at the structural level.

Compared with existing approaches, which typically focus on isolated aspects such as thermal degradation or dynamic loading, the proposed methodology emphasizes integrating experimental observations across scales. The combined use of temperature measurements, deformation data, and visual observations enables a more comprehensive description of masonry behavior and provides a consistent basis for model development and validation.

However, the current implementation remains limited to structural-scale observations and does not include direct physico-chemical characterization or material-scale testing. Consequently, the link between observed structural response and underlying microstructural processes is not explicitly quantified. In addition, although included in the conceptual framework, the influence of strain-rate effects and dynamic loading conditions is not addressed experimentally in the present study.

Despite these limitations, the results demonstrate that structural-scale data can be systematically incorporated into a multi-scale methodology. The integration of additional experimental and modeling components is expected to improve predictive capability. In particular, combining multi-scale experimental data with advanced numerical approaches will enable the development of constitutive models that capture temperature-dependent degradation and rate effects.

Overall, the study highlights the importance of adopting a multi-scale perspective for analyzing masonry under extreme conditions and demonstrates the potential of the proposed methodology as a structured basis for such an approach.

7. Conclusions

This study presented a multi-scale experimental–numerical methodology for the characterization of masonry materials subjected to coupled thermo-mechanical loading. The proposed framework integrates physicochemical characterization, mechanical testing, nondestructive evaluation, and numerical modeling into a unified approach, enabling a consistent description of material behavior across scales.

The structural-scale experimental results from full-scale fire tests demonstrate the methodology's capability to capture the global response of masonry walls under combined thermal and mechanical actions. The recorded temperature evolution, deformation histories, and observed damage patterns confirm the strong interaction between thermal gradients and mechanical behavior, underscoring the need to account for coupled effects in the analysis of masonry structures exposed to fire.

The results further indicate that structural-scale data provide essential information for defining boundary conditions, validating numerical models, and interpreting failure mechanisms. At the same time, they highlight the need to incorporate additional information from lower scales, including microstructural transformations and material-level properties, to achieve a comprehensive understanding of masonry behavior.

The current implementation is limited to the structural-scale component of the proposed framework and does not include direct physico-chemical characterization, material-scale testing, or dynamic loading conditions. Consequently, full multi-scale integration remains a subject for future work.

Future research will focus on extending the methodology by incorporating microstructural analysis, rate-dependent testing, and advanced numerical modeling. The integration of these components is expected to enable the development of constitutive models that accurately describe the coupled thermo-mechanical behavior of masonry under extreme conditions.

In summary, the proposed methodology provides a structured and transferable framework for analyzing masonry materials, contributing to a better understanding and modeling of their behavior under complex loading scenarios.

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