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METHODS FOR DETERMINING MASONRY COMPRESSIVE STRENGTH: FROM EXPERIMENTS TO AI APPROACHES

Summary: The compressive strength of masonry walls represents one of the key mechanical characteristics of masonry structures. Its determination goes beyond a simple consideration of the properties of individual materials and depends on the complex interaction between masonry units, mortar, assembly geometry, and loading conditions. This paper presents a systematization and analysis of methods for determining the compressive strength of masonry walls, including experimental, empirical–analytical, and numerical–mechanical approaches, with particular emphasis on contemporary methods based on artificial intelligence and hybrid models. The advantages and limitations of each group of methods are discussed, with a focus on their predictive capability and physical foundation. Special attention is given to the transition from traditional empirical relationships toward integrated multiscale and data-driven approaches, which provide a basis for improving research procedures and developing modern computational models for masonry structures.

Keywords: masonry compressive strength, experimental methods, numerical methods, artificial intelligence, hybrid approache

METODE ODREĐIVANJA ČVRSTOĆE ZIDANIH ZIDOVA PRI PRITISKU: OD EKSPERIMENTA DO AI PRISTUPA

Rezime: Čvrstoća zida pri pritisku predstavlja jednu od ključnih mehaničkih karakteristika zidanih konstrukcija, pri čemu njeno određivanje prevazilazi jednostavno razmatranje svojstava pojedinačnih materijala i zavisi od složene interakcije elemenata za zidanje, maltera, geometrije sklopa i uslova opterećenja. U radu je izvršena sistematizacija i analiza metoda za određivanje čvrstoće zida pri pritisku, uključujući eksperimentalne, empirijsko-analitičke i numeričko-mehaničke metode, uz poseban osvrt na savremene pristupe zasnovane na veštačkoj inteligenciji i hibridnim modelima. Razmatraju se prednosti i ograničenja svake grupe metoda, sa fokusom na njihovu prediktivnu sposobnost i fizičku utemeljenost. Poseban akcenat stavljen je na trend prelaska sa tradicionalnih empirijskih relacija ka integrisanim višeskalnim i data-driven pristupima, čime se stvara osnova za unapređenje istraživačkih procedura i razvoj savremenih proračunskih modela zidanih konstrukcija.

Ključne reči: čvrstoća pri pritisku zidanih zidova, eksperimentalne metode, numeričke metode, metode veštačke inteligencije, hibridni pristupi

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1. INTRODUCTION

Masonry structures are among the oldest and most widely used construction systems, with significant application in both historical and modern buildings [1]. Their behavior under load is largely determined by the mechanical characteristics of the wall as a complex composite material, where compressive strength plays a central role in assessing structural capacity, reliability, and safety. Unlike homogeneous materials, the compressive strength of masonry walls cannot be treated as a property of individual components, but emerges from the complex interaction of masonry units, mortar, joint geometry, and loading conditions.

The most direct approach to defining wall compressive strength is based on experimental testing of masonry prisms or panels under laboratory conditions [1]. Due to practical limitations of experimental methods, empirical and semi-empirical relations have been developed, while numerical-mechanical approaches based on the finite element method (FEM) allow physically grounded simulations of wall behavior. Recent advances in computing power and the availability of extensive data sets have enabled the application of artificial intelligence (AI) methods, whereas hybrid approaches combine experimental results, numerical simulations, and AI models to overcome the limitations of individual methods.

The aim of this paper is to provide a systematic overview and comparative analysis of methods for determining the compressive strength of masonry walls, with particular emphasis on their theoretical foundations, input parameters, advantages, and limitations. Special attention is given to the evolution of methodologies from classical experimental and empirical approaches toward modern numerical, AI-based, and hybrid models, and to their relevance for both research and engineering practice in the field of masonry construction.

2. METHODS FOR DETERMINING THE COMPRESSIVE STRENGTH OF MASONRY WALLS

The compressive strength of a masonry wall represents an effective mechanical property that describes its behavior under compressive load and defines the threshold at which global wall failure occurs. Unlike homogeneous construction materials, whose strength can be directly linked to the properties of the constituent material, wall compressive strength emerges from the composite interaction of masonry units, mortar, assembly geometry, and loading conditions [2]. Over time, multiple methodologically distinct approaches have been developed to determine this property, depending on theoretical foundations, input data, and the procedure for obtaining results.

The evolution of wall compressive strength assessment follows the development of experimental techniques and computational methods (Figure 1). Since the mid-20th century, standardized laboratory testing of masonry prisms has been the dominant approach, providing a reference for quantifying the mechanical behavior of masonry elements. While experimentally derived results are physically relevant, they are often limited by high costs, sample size restrictions, and incomplete representation of real wall variability.

During the 1970s and 1980s, the focus shifted toward empirical and semi-empirical formulations, correlating component properties with wall strength. Advances in computational mechanics during the late 1980s and 1990s promoted numerical approaches, particularly the finite element method (FEM), which defines wall strength implicitly through global failure simulations [3]. From the 2010s onward, the expansion of data sets and increased computational power facilitated machine learning applications, where wall strength is treated as a nonlinear functional relationship between input parameters and structural response [4]. The current state-of-the-art involves hybrid approaches, integrating experimental data, numerical simulations, and AI models within a single framework.

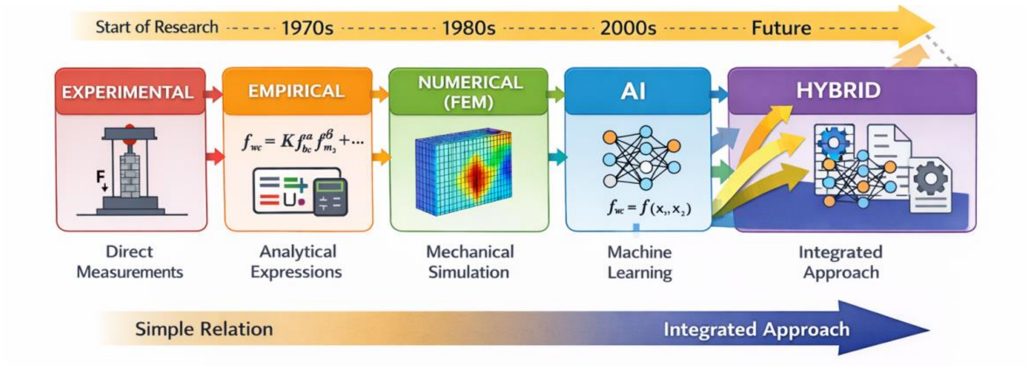

Figure 1: Evolution of methods for masonry compressive strength

Historical development indicates that compressive strength is not a universal material property but a methodology-dependent quantity. Understanding these differences is essential for the correct interpretation and reliable application of results in the analysis and design of masonry structures.

1.1. EXPERIMENTAL METHODS

Experimental methods remain the reference approach, directly determining compressive strength through laboratory testing of masonry prisms or panels under uniaxial compression. Strength is defined as the maximum stress achieved at failure, providing directly interpretable results [5]. On the basis of these measurements, mean and characteristic values necessary for structural design and verification are derived.

The compressive strength is explicitly defined through standardized procedures, and can be expressed by the formula: (1).

$$f_{wc} = \frac{F_{max}}{A} \tag{1}$$

Where: F_{max} is the maximum compressive force, and A is the effective cross-sectional area of the wall.

Major international standards cover these procedures, including Eurocode 6 [6] (EN 1052 [7]), TMS 402/602 with ASTM C1314 [8,9], CSA S304 [10], AS 3700 [11], and RILEM recommendations [12]. While the testing philosophy is generally consistent, differences exist in sample geometry, statistical processing, and the role of indirect methods.

Modern codes use masonry prisms as reference specimens, yet they differ in the directness of experimental input. Eurocode 6 relies on indirect, analytically calibrated expressions, American and Canadian standards combine empirical relations with normative values, while the Australian–New Zealand AS 3700 emphasizes a test-based methodology. RILEM guidelines provide flexibility regarding specimen geometry, slenderness, and number of layers, but due to their research-oriented nature, do not prescribe a single procedure.

Table 1 summarizes the main differences between international standards in terms of testing philosophy and implementation. Despite variations, all approaches rely on experimental data, which remain essential for model calibration. However, high costs and limited generalizability justify the development of numerical and data-driven methods.

1.2. EMPIRICAL–ANALYTICAL AND SEMI-EMPIRICAL METHODS

Empirical–analytical methods define masonry compressive strength through calculation formulas derived from regression analysis of experimental data [1]. These expressions, integrated into leading design codes such as Eurocode 6 and MSJC, express wall strength as a function of component characteristics (masonry units, mortar) and element geometry, enabling straightforward engineering application and clear physical interpretation. However, their applicability is limited to experimentally verified ranges and does not fully capture wall heterogeneity, local damage mechanisms, or complex stress states.

Table 1: Comparison of Masonry Standards

Standard / System	Reference Test	Strength Determination	Geometry & Slenderness Control	Alternative to Lab Test	Design Philosophy	Role of Experiments	Key Advantage	Key Limitation
Eurocode 6 (EN 1996-1-1)	EN 1052-1 (EN 772 / EN 1052)	Indirect; prism-based	Strict control; h/t ≤ 5; element-adapted geometry	Empirical relations	Conservative, code-strict	Basis for defining design values	Standardized, reliable	Limited parameters; indirect approach
TMS 402/602 (ACI 530/ASCE 5)	ASTM C1314	Direct prism testing or “ unit strength method”	Flexible slenderness; correction factors	Yes – unit strength method	Practical, operational	Direct design method	Simple, practical	Relies on typical values
CSA S304	CSA prism test	Experimental; mean & characteristic strength	Slenderness corrected by factors; less restrictive than EC6	Limited	Combined (empirical & code)	Design & verification	Balanced safety & flexibility	Still experiment-dependent
AS 3700	AS 3700 prism tes	Direct measurement of maximum compressive strength	Clearly defined geometry; controlled conditions	Practically none	Experimentally based	Crucial for strength determination	High physical realism	High cost; testing required
RILEM Recommendations	RILEM TC recommendations	Scientific-empirical approach; wide parameter set	Geometry & slenderness explicitly analyzed	Multiple analytical expressions	Scientific-research	Theoretical & methodological code basis	Broad theoretical flexibility	Non-mandatory

Two dominant types of analytical relations are commonly identified. The first group consists of linear-type functions, defining wall strength as a weighted combination of unit compressive strength (f_{bc}) and mortar strength (f_{mc}), with coefficients (α,β) depending on material and assembly geometry. While suitable for quick engineering estimates, they neglect complex interactions among components under real conditions:

$$f_{wc} = \alpha f_{bc} + \beta f_{mc} \tag{2}$$

The second group includes power-law (stepwise) functions, which establish a nonlinear dependence of wall strength on its components. These models are easier to calibrate against experimental data and, due to alignment with Eurocode 6 principles, more accurately reflect real structural behavior, making them widely adopted in research and engineering practice [13,14]:

$$f_{wc} = K f_{bc}^{\alpha} f_{mc}^{\beta} \tag{3}$$

Where K, α, and β are empirical coefficients defined by the standard based on statistical analysis of experimental data.

Semi-empirical extensions refine basic relations by introducing additional parameters, such as the mortar volume fraction (ξ), enabling finer calibration and a more detailed description of wall mechanics:

$$f_{wc} = \xi \left[\left(\frac{2}{3} \sqrt{f_{bc}} - \alpha \right) + \beta f_{mc} \right] \tag{4}$$

Despite their simplicity and broad adoption, these formulas remain dependent on material properties and geometry, and neglect several influential factors. Wall slenderness, aspect ratios, horizontal and vertical joint thicknesses, complex triaxial stress states, and the behavior of the interface between units and mortar (ITZ) are often not considered. These limitations highlight the need for advanced numerical models and the application of soft-computing and AI-based methods.

1.3. NUMERICAL–MECHANICAL METHODS (FEM)

With the development of computational mechanics, masonry compressive strength can be interpreted through numerical–mechanical approaches based on the finite element method (FEM) [15]. These methods allow physically grounded but indirect determination of wall strength using macro-, micro-, and simplified micromodels, differing in discretization level and strength definition. This approach enables detailed analysis of stress–strain states and the interaction between units and mortar:

$$\sigma = D(\varepsilon)\varepsilon \tag{5}$$

Where: σ and ε are the stress and strain vectors, while D represents the nonlinear material matrix.

Three levels of modeling are commonly applied. Macro-models treat the wall as a homogenized continuum, efficient for global analyses but unable to capture local failure mechanisms or contributions of individual components. Compressive strength is determined indirectly from the maximum axial force and the gross cross-sectional area.

In contrast, micro-models represent the most detailed approach, modeling masonry units, mortar, and interfaces as separate nonlinear constituents. Wall strength emerges from the global failure of the prism, driven by material interaction and the development of cracks and damage [16]. While highly accurate physically and realistic in failure description, their application is limited by high computational cost.

Simplified micromodels offer a compromise: elements are modeled as elastic or elastic–plastic continua, while nonlinearity and degradation are concentrated in interface elements. Compressive strength is taken as the maximum system response in the analysis. This approach provides a favorable balance between realism and efficiency, suitable for parametric studies and variant analysis.

In FEM, wall compressive strength is not expressed explicitly but is generated as the global response of the numerical model at failure. The validity of simulations depends on discretization level (macro, meso, or micro) and the proper selection of constitutive laws—Mohr–Coulomb and Drucker–Prager for macro-models, or damage–plasticity and cohesive laws for detailed approaches [16]. FEM results are inherently case-dependent, influenced by material properties, joint geometry, and mesh density. No universal function exists for all masonry types; careful calibration of constitutive models against experimental data is essential, as results rely directly on chosen parameters and modeling assumptions.

1.4. AI-BASED METHODS

Advances in computing and the availability of large data sets have enabled the application of artificial intelligence (AI) for predicting masonry wall compressive strength. AI models, including neural networks and advanced regression algorithms, learn complex nonlinear relationships directly from experimental data. While accurate, they do not define strength via analytical expressions or constitutive laws, but as an approximating function output, limiting physical interpretability and binding predictions to the training domain [17]:

$$f_{wc} = F(X) \tag{6}$$

Where: X is the set of input parameters, and F is the function learned from the data.

The model's form is implicitly defined by network weights and applies only within the training data domain. Advantages include capturing complex nonlinearities and high predictive accuracy, while limitations are reduced interpretability and dependence on input data quality.

Commonly used AI approaches for masonry strength prediction include artificial neural networks (ANNs), particularly multilayer perceptrons, due to their capacity to model nonlinear interactions between material and geometric parameters [4,18]. ANFIS models combine fuzzy logic with adaptive learning for better interpretability and efficiency on smaller datasets, though with slightly lower accuracy. Support vector machines (SVM) offer stable generalization but limited scalability for heterogeneous data. Ensemble and hybrid AI approaches, e.g., ANN+GA, ANN+PSO, or ANFIS with optimization, enhance precision and stability but increase computational demand.

AI models define wall compressive strength as an implicitly learned function connecting material and geometric parameters with structural response. Inputs are often laboratory data from EC6 and ASTM-standard prism tests, ensuring physical relevance but limited sample numbers. Data can also be generated via FEM "virtual experiments," expanding datasets but introducing dependence on constitutive models and failure criteria [19].

1.5. HYBRID METHODS

Hybrid approaches integrate experimental testing, numerical simulations, and AI models to overcome limitations of individual methods. In this framework, AI models can be guided by fundamental mechanical principles to ensure physically consistent predictions, while FEM simulations enrich datasets where experimental results are limited. Combining explicit mechanical relations with implicitly learned dependencies improves model robustness and extends the applicability domain [20].

Hybrid methods do not constitute a separate fifth method but systematically combine two or more approaches to increase accuracy, broaden applicability, and reduce experimental cost.

Unlike “pure” methods, they act as a bridge. Compressive strength is defined contextually, with the model output reflecting both physical knowledge and data. Common combinations include experiment + empirical analysis, experiment + FEM, FEM + AI, experiment + AI, or empirical + AI.

Classical engineering hybrids (experiment + empirical) calibrate predefined analytical relations and provide physically interpretable results. Experiment + FEM enables virtual expansion of experimental datasets. Advanced approaches, such as FEM + AI, use FEM to generate large datasets for AI to learn surrogate models for rapid predictions. Experiment + AI trains directly on laboratory data for high accuracy, while empirical + AI represents physics-guided AI where analytical expressions serve as inputs and AI corrects model errors. Hybrid methods thus bridge experimental, analytical, and numerical approaches, combining their strengths while mitigating individual weaknesses, yet remaining dependent on the quality and context of input data.

3. ANALYSIS OF METHODS FOR DETERMINING MASONRY WALL COMPRESSIVE STRENGTH

A systematic comparison of methods for determining masonry wall compressive strength is presented in Table 2, providing an overview of their theoretical foundations, input parameters, and methodology for generating results. The classification includes experimental, empirical–semi-empirical, numerical–mechanical (FEM) approaches, as well as AI-based models and hybrid solutions. The analysis considers criteria such as the definition of strength, type of input data, functional relationships, and the key advantages and limitations of each method. This structure allows for a clear distinction between directly measured quantities, analytical functions, numerical simulation outputs, and implicit data-driven relations, providing an objective framework for selecting an appropriate research approach.

The comparative analysis in Table 2 highlights that methods for determining wall compressive strength differ significantly not only in how results are obtained but also in the underlying concept of this mechanical property. Common to all methods is the recognition that wall compressive strength is not a universal quantity and depends on material type, geometry, and application domain. Experimental and empirical methods are highly physically grounded but limited in flexibility and cost, treating strength as an explicitly defined or directly measured quantity. Numerical and AI-based approaches enable detailed simulations but require computational resources and precise calibration, introducing the concept of strength as an implicit or emergent outcome of a complex mechanical or data-driven process. Hybrid methods combine the best characteristics of these approaches, balancing accuracy, physical relevance, and reduced cost, while remaining dependent on the quality of input data and modeling assumptions.

Numerical–mechanical approaches allow physically grounded insight into the behavior of masonry assemblies and identification of local failure mechanisms, but they demand detailed modeling and high computational effort. In contrast, AI methods achieve high predictive accuracy for wall compressive strength, yet their application is limited to the domain of available data and they offer reduced interpretability. Hybrid methods, integrating experimental data, numerical simulations, and AI models, provide a modern response to the limitations of individual approaches. Their ability to combine physical consistency, extended applicability, and enhanced prediction robustness indicates significant potential for advancing methodologies in masonry structure assessment.

Table 2: Comparative Overview of Methods for Determining Masonry Wall Compressive Strength

Method	Basis	Strength Definition	Inputs	Advantages	Limitations	Common Features	Function / Result
Experimental	Testing	Direct measureme nt in	Wall prism, load, deformations	Realistic, standardized, reference method	Expensive and time-consuming; limited number of samples; local	Based on actual wall behavior; valid only for tested material	Direct value
Empirical / Semi-Empirical	Experiment	Analytical function based on material	Brick strength, mortar strength, geometry	Quick to apply; simple; physically interpretable	Does not capture all mechanical effects; material-specific; limited domain	Based on experimental data; uses wall as composite concept	Linear; Power-law
Numerical (FEM)	Mechanics	Global failure simulation	Constitutive laws (Mohr-Coulomb, Drucker-Prager, damage), geometry, load	Analyzes complex geometries, local effects, heterogeneity, masonry interfaces	Computationally expensive; depends on model choice and calibration; not universal; micromodels require high	Case-dependent; strength is output, not input; depends on material properties and wall	Implicit relation
Emergent / AI / Soft Computing	Input Data	Predicted strength based on learned functions from data	Predominantly experimental data, material parameters	Captures complex nonlinearities and interactions; high accuracy within data domain; fast predictions	Black-box nature; valid only within training domain; limited physical interpretability; depends on data quality and quantity; limited	Strength is model output, not physically defined; domain of validity limited	Implicit function
Hybrid Method	Combination	Combines 2+ approache: experiment, empirical, FEM (MKE),	Experimental data + numerical results (FEM) + material parameters	Improves accuracy and robustness; wider use; cuts test costs; balances physics and data-driven prediction.	Higher complexity; requires multi-layer calibration; still in development; depends on data quality and assumptions; not universally applicable	Combines advantages of individual methods; strength defined contextually; valid within input data domain	Combined explicit-implicit relation

Therefore, the table not only serves as a comparative overview of existing methods but also provides a foundation for understanding current trends in defining masonry wall compressive strength, reflecting a clear shift from simplified empirical expressions toward integrated, multi-scale models that correspond to the real complexity of masonry structures.

4. CONCLUSION

The systematic analysis of experimental, empirical, numerical, and AI-based models demonstrates that the compressive strength of masonry walls is not a simple material constant. Rather, it should be understood as an effective mechanical property of a complex masonry assembly, emerging from the nonlinear interaction between masonry units, mortar, geometry, and specific loading conditions.

Within the domain of construction materials, experimental methods continue to serve as the reference approach, essential for the calibration and validation of all other models. Laboratory tests provide direct insight into the actual behavior of the composite system, identifying local failure mechanisms and crack propagation. However, high costs and logistical constraints limit the representation of the full spectrum of material variability, motivating the development of analytical approximations.

Empirical and semi-empirical models, as reflected in contemporary standards such as Eurocode 6, offer an optimal balance between engineering practicality and physical grounding. Yet, their reliability decreases when applied to modern heterogeneous materials that fall outside the range of experimental data on which these expressions were originally based. In contrast, numerical–mechanical (FEM) approaches treat compressive strength as the result of global system failure, allowing detailed separation of contributions from individual components and interfaces. While scientifically rigorous, these models are highly sensitive to constitutive law parameters, often limiting their direct applicability in practice.

AI-based methods introduce a new perspective, treating compressive strength as a learned nonlinear function in a multidimensional parameter space. Despite their strong predictive capability, the “black-box” nature of these models necessitates caution in physical interpretation. Hybrid approaches, which integrate experimental results, numerical simulations, and AI models, currently appear as the most promising solution. Such integrated frameworks maintain mechanical consistency while significantly improving predictive accuracy, paving the way for the modernization of technical standards and the development of advanced computational procedures for masonry structures.

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