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Research Article

Seismic Protection of Museum Objects: Comparative Analysis of International Seismic Codes

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Abstract This study conducts a systematic comparative analysis of nine principal international seismic codes, focusing on their provisions for non-structural elements and their adequacy for protecting museum artifacts housed within buildings. While these standards share a consistent force-based framework for general non-structural components, they rarely address the distinct vulnerabilities of museum objects, such as low fragility thresholds, irreplaceability, and conservation constraints that often prohibit invasive anchoring. The results indicate that, although fundamental parameters (e.g., component weight and spectral acceleration) are universally included, advanced modifying factors, such as response reduction, resonance, and strength-related terms, are incorporated in only a limited number of codes, with overall parameter coverage ranging from 4 to 11. Even in the most parameter-rich formulations, the added complexity primarily refines inertial force scaling rather than governing artifact-specific stability mechanisms, including sliding, rocking, and overturning. The findings demonstrate that current seismic codes provide limited reliability for protecting museum objects when applied without adaptation. This research highlights the need for mechanism-aware extensions to existing code frameworks. It provides a foundation for the development of museum-specific seismic provisions to safeguard irreplaceable cultural heritage from earthquake hazards.

Keywords: Artifacts, Museum Objects, Non-Structural Elements, Risk Mitigation, Seismic Standards.

1. INTRODUCTION

Earthquakes rank among the most destructive natural phenomena, having claimed countless lives throughout history and inflicting substantial cultural and infrastructural damage. In this context, a nation's cultural and historical heritage, including the vast collections housed in museums, faces particularly acute vulnerabilities, necessitating proactive measures to mitigate seismic risks. Museums, which serve as critical centers of cultural and educational enrichment, play a pivotal role in preserving and disseminating a society's identity[1]. However, even lower-magnitude earthquakes can wreak havoc on unreinforced items within these institutions, highlighting the urgency of protecting museum collections with the same level of attention given to the structural integrity of the buildings themselves.

Numerous studies have examined the seismic response of museum objects and other non-structural components, often focusing on specialized supports, vibration isolation systems, or local site conditions[2]. Although these investigations have contributed to understanding the complexities of artifact protection, a comprehensive comparative analysis of how different national and international seismic codes address museum-specific needs remains relatively scarce. For instance, while some standards do offer guidelines for non-structural elements, these provisions are typically generalized to objects such as ceilings, partitions, or mechanical systems, rather than the delicate, heterogeneous artifacts found in museums. Moreover, there is a lack of holistic frameworks that integrate structural, curatorial, and conservation considerations for museum objects, leading to potential gaps in the practical implementation of protective measures. Consequently, questions persist regarding the adaptability and effectiveness of existing standards across diverse collections and contexts, underscoring the necessity for further research. Filling this gap by scrutinizing multiple leading seismic codes can illuminate best practices and inform future revisions, ultimately enhancing the resilience of museum collections worldwide. This study directly addresses this critical research gap through a systematic comparative analysis of nine leading international seismic codes, with a specific focus on evaluating and enhancing their adequacy for protecting fragile and irreplaceable museum artifacts.

Despite recent advances in recognizing the importance of non-structural elements, museums housing irreplaceable heritage objects rarely receive specific attention in these codes, leaving their collections without specialized guidelines[3]. Consequently, conventional building codes alone are insufficient to safeguard fragile, earthquake-vulnerable collections.

In the literature, the nonlinear behavior and seismic performance of reinforced concrete structural systems have been extensively studied. Comparative studies using TBDY 2018 and ASCE 41-17 have illustrated the effects of different nonlinear analysis procedures on structural response[4]. Investigations of shear wall systems with coupling beams have highlighted the influence of connection detailing on overall performance under seismic loads[5]. Furthermore, the impact of design parameters and site-specific conditions on structural behavior has been examined in previous research[6]. While these studies primarily focus on structural systems, the insights regarding nonlinear response and performance-based evaluation provide a valuable foundation for assessing the seismic behavior of complex building components, including nonstructural elements.

This paper aims to address the aforementioned gap by conducting a systematic comparative analysis of nine major seismic standards, spanning Türkiye, Italy, Mexico, Iran, China, Canada, the European Union, the United States, and New Zealand, with a particular focus on safeguarding museum collections. The primary objectives of this study are:

i. To compare the provisions for non-structural elements across the nine selected codes,
ii. To identify strengths, limitations, and gaps in their applicability to museum artifacts,
iii. To propose directions for future code adaptations that better address the unique vulnerabilities and conservation needs of cultural heritage objects.

By examining how each standard incorporates provisions for non-structural elements, this study underscores specific strengths, limitations, and opportunities for enhancement in the context of museum artifacts. The scope of the research encompasses both the technical dimensions of seismic protection and the broader curatorial and conservation considerations essential to preserving objects of cultural and historical significance. This holistic approach represents an innovative contribution, bridging the existing divide between generalized guidelines for non-structural components and the specialized requirements of valuable, delicate artifacts. Ultimately, the insights from this comparative framework are intended to inform future revisions to seismic codes and elevate global standards for the protection of museum collections.

In this paper, Section 2 outlines the adopted methodology and analysis criteria. Section 3 presents an overview of the selected seismic codes, and Section 4 provides a comparative evaluation of these codes with respect to museum object protection. Finally, Section 5 discusses key findings and implications with recommendations for future code development.

2. METHODOLOGY

The primary objective of this study is to evaluate the extent to which seismic provisions for non-structural elements, as specified in various international codes, adequately protect museum objects. Accordingly, a structured, descriptive, and analytical comparison of nine major seismic standards is undertaken. This section delineates the study's scope, the methodology for data collection, the analytical framework adopted, and the strategy for identifying potential gaps within existing regulatory frameworks.

2.1. Scope and Rationale

This study analyzes nine internationally recognized seismic codes originating from Türkiye, Italy, Mexico, Iran, China, Canada, the European Union, the United States, and New Zealand. These codes have been selected for their broad applicability and relevance to regions with a high concentration of museums.

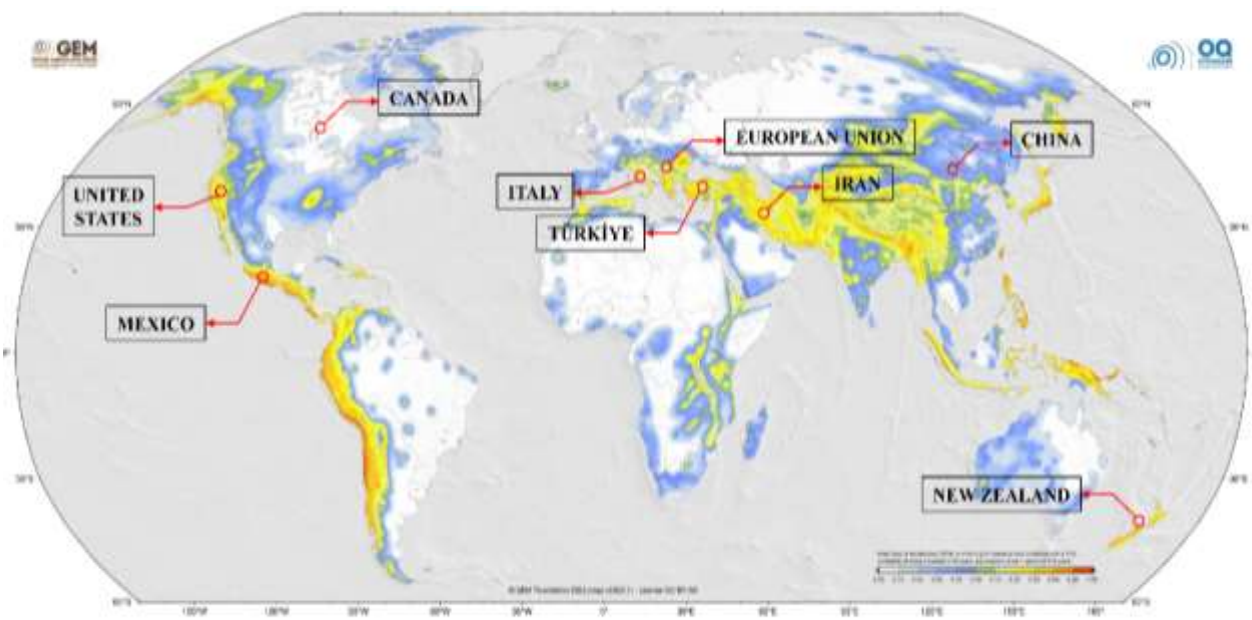

Figure1. Global Seismic Hazard Map, Selected countries for this study are highlighted [7]

Specifically, the chosen countries/regions represent a combination of high seismic hazard levels (as classified by the Global Seismic Hazard Map of the GEM Foundation, version 2023.1) and the presence of major museum institutions with significant collections of vulnerable artifacts (e.g., Smithsonian in the USA, Louvre in France/EU, Topkapi and Archaeological Museum in Türkiye, National Museum of Anthropology in Mexico, and the Forbidden City in China).

Figure 1 illustrates the Global Seismic Hazard Map (GEM Foundation, 2023.1), depicting Peak Ground Acceleration (PGA) with a 10% probability of exceedance in 50 years on reference rock conditions. The selected countries/regions are highlighted, indicating their locations in high- to very-high seismic hazard zones. Moreover, these nine codes are among the most widely referenced and applied international standards in the seismic design literature and practice, covering diverse regulatory approaches, from force-based (e.g., ASCE 7, Eurocode 8) to performance-based. This selection ensures a representative global perspective on non-structural element provisions while maintaining focus on regions where seismic risk to cultural heritage is a documented concern.

The analysis focuses on the formulas and parameters used to calculate seismic forces on non-structural components, with particular emphasis on their adequacy in safeguarding museum objects, which are often fragile and of substantial cultural significance. Rather than performing an in-depth engineering assessment of each code, the study adopts a comparative methodology to identify both shared elements and deficiencies in the treatment of parameters relevant to the seismic protection of museum artifacts.

The dataset consists of the most recent publicly available editions of the selected seismic codes. From each document, relevant sections, clauses, and formulas concerning non-structural elements commonly designated as “components” or “non-structural components” are systematically extracted. These provisions are then organized into a comparative table to enable direct cross-referencing among the codes and to clearly identify the presence or absence of specific seismic design parameters.

2.2. Analytical Framework

In response to the central research question, whether current seismic provisions for non-structural elements adequately address the specific protection requirements of museum objects, a descriptive and analytical review is conducted, focusing on three critical dimensions.

i. The formulas utilized in each code for calculating seismic forces on non-structural components are examined, with particular attention to governing parameters such as mass, height, response modification factors, and any applicable special coefficients.
ii. The extent to which the codes differentiate between varying degrees of fragility or value among non-structural elements is assessed.
iii. The degree to which the codes explicitly address the protection of sensitive, high-value, or irreplaceable items, such as museum artifacts, is evaluated.

To facilitate this analysis, a comparative matrix is constructed to systematically display the presence or absence of relevant parameters across the nine seismic codes. The matrix is organized according to factors known to influence the seismic response of non-structural components, including the component's mass or weight, vertical placement within the structure (e.g., height-related factors), amplification or design coefficients, attachment or anchorage methods, and provisions for dynamic amplification near the structure’s fundamental frequency. This comparative framework enables the identification of parameters consistently addressed across multiple codes, as well as those inconsistently referenced or potentially omitted.

2.3. Gap Analysis

Building upon the comparative matrix, a gap analysis is conducted to directly address the central research question: Do current seismic code provisions adequately account for the specific protection needs of museum objects, or are critical considerations insufficiently addressed? This analysis comprises three principal components. Parameters particularly relevant to museum artifacts, such as conservation requirements, the need for specialized bracing or anchorage systems, and the application of more stringent performance thresholds, are identified and flagged when they are absent from the code texts or addressed with insufficient specificity.

The analysis highlights inconsistencies among codes in the treatment of non-structural elements, including variations in safety factors and divergent criteria for detailed anchorage. These discrepancies may bear significant consequences for the adequate seismic protection of culturally and historically valuable objects. Finally, although this study does not advance comprehensive revisions to existing codes, it identifies potential areas for enhancement in future code development. The recommendations are intended to inform code-writing bodies and relevant stakeholders, thereby fostering revisions that better reflect the specialized requirements of seismic protection for museum objects.

2.4. Limitations of the Study

This methodology focuses on the non-structural seismic provisions in the main text of each selected code, while operating under several defined constraints. Supplementary documents are excluded from in-depth analysis. Commentaries, appendices, and auxiliary guidelines are not systematically reviewed; consequently, certain clarifications or nuanced interpretations found in these materials may not be represented in the present findings.

The study does not incorporate external validation. It excludes interviews with subject-matter experts, museum professionals, or code authors, and does not utilize case studies of museum damage resulting from past seismic events. Accordingly, the analysis is based exclusively on the codified content of the seismic standards under review.

The study applies to a selective geographic scope. Although the chosen seismic codes reflect a diverse range of seismically active regions with substantial museum collections, excluding other global contexts may limit the generalizability of some observations.

Despite these limitations, the methodology provides a systematic framework for assessing whether existing seismic codes adequately address the distinct vulnerabilities of museum objects. By identifying both shared parameters and critical omissions, the study contributes to ongoing refinement of seismic code development, particularly by promoting more resilient and culturally sensitive protective strategies.

3. OVERVIEW OF THE SELECTED SEISMIC CODES

An overview of the selected seismic codes was undertaken to assess whether the non-structural provisions in these codes effectively account for the distinct requirements of museum objects. The review focuses on two primary considerations: 1) the definitions of non-structural elements as specified by each regulation. 2) the equations or formulas employed to calculate the seismic forces acting on these components.

3.1. Definitions of Non-Structural Elements

Seismic codes typically define non-structural elements as components that do not contribute to the building's primary load-resisting system, encompassing a broad range of items such as architectural finishes, partitions, ceilings, mechanical equipment, and general contents. This generalized approach, summarized in Table 1, often groups museum artifacts into vague categories such as “components,” “parts,” or “contents,” without explicitly acknowledging their unique characteristics. For instance, in codes such as TBEC 2018 (Türkiye), Standard No 2800 (Iran), and ASCE/SEI 7-22 (United States), definitions emphasize independence from the structural system and potential safety risks from damage. Still, they fail to differentiate between routine elements (e.g., lighting fixtures) and irreplaceable cultural artifacts, which may be highly fragile and require non-invasive protection methods.

A comparative review of the definitions presented in Table 1 reveals a strong convergence toward generalized categorization across the selected international seismic codes. In most regulations, non-structural elements are treated as a homogeneous group, with museum objects implicitly subsumed under broad terms such as components, parts, or contents. This implicit inclusion occurs without any explicit differentiation based on fragility, irreplaceability, material heterogeneity, or cultural significance. As a result, artifacts of exceptional historical or artistic value are, at the definitional level, placed on equal footing with routine architectural or mechanical elements such as suspended ceilings or service equipment.

Table 1. Definitions of Non-Structural Elements in Selected Seismic Codes

Seismic Code	Abbreviation	Country	Terminology for Non-Structural Elements
Turkish Building Seismic Code [8]	TBEC 2018	Türkiye	• Elements are attached to the structural system but act independently • Damage to these elements can threaten safety, harm the structure, and impair building functionality
Iranian Code of Practice for Seismic Resistant Design of Buildings [9]	Standard No. 2800	Iran	• Elements that are attached to the primary structure • Not involved in resisting seismic loads
National Building Code [10]	NBC 2020	Canada	• The items listed in Table 4.1.8.18 of the code
Seismic Building Code for Mexico [11]	Mexico 2023-09-16 NTC-SISMO	Mexico	• Contents and non-structural elements are not part of the structural system and are vulnerable to seismic displacement • Their failure can lead to significant economic, functional, or operational losses, highlighting the need for proper consideration in seismic design
Technical Standards for Construction [12]	NTC 2018	Italy	• Components whose stiffness, strength, and mass do not significantly influence the structural response • Highly important for safety and the protection of human lives
Code for Seismic Design of Buildings [13]	GB 50011-2010	China	• Nonstructural components of buildings, including architectural, mechanical, and electrical components permanently attached to structures themselves
Eurocode 8 [14]	Eurocode 8	Europe	• Non-structural element, architectural, mechanical, or electrical element, system, and component which, whether due to lack of strength or to the way it is connected to the structure, is not considered in the seismic design as a load-carrying element
Minimum Design Loads and Associated Criteria for Buildings and Other Structures [15]	ASCE/SEI 7-22	United States	• Components that are in or supported by a structure • Components that are outside of a structure and are permanently connected to the mechanical or electrical systems • Components that are part of the egress system of a structure
Structural Design Actions Part 5: Earthquake actions – New Zealand [16]	NZS 1170-5:2004	New Zealand	• The items listed in Table 8.1 of the code

From an analytical perspective, this definitional generalization has important implications. Definitions form the conceptual foundation for the application of seismic demand equations, importance factors, and detailing requirements. When museum artifacts are not explicitly distinguished within the regulatory language, they inherit design assumptions that are implicitly tailored to replaceable, standardized, and often damage-tolerant components. Consequently, the unique constraints associated with museum objects—such as conservation ethics, reversibility of interventions, and intolerance to even minor damage—are not reflected at the earliest stage of code-based seismic decision-making.

Despite this prevailing generality, Table 1 also highlights subtle but meaningful differences in how specific codes frame non-structural elements. Notably, the Mexican seismic code (NTC-SISMO) extends its definition beyond mere structural non-participation to explicitly recognize vulnerability to seismic displacement and the potential for significant economic, functional, or operational losses following failure. Although still not museum-specific, this multidimensional framing aligns more closely with the risk profile of museum artifacts, where functional disruption, loss of cultural value, and post-event operability are critical considerations. Such definitional nuance suggests an implicit recognition that not all non-structural elements carry equivalent consequences when damaged.

Other codes emphasize safety-related consequences in their definitions, particularly with respect to life safety and building functionality (e.g., TBEC 2018 and NTC 2018). While these perspectives are essential from a regulatory standpoint, they remain insufficient for protecting irreplaceable cultural assets. The absence of explicit references to object fragility, value, or conservation sensitivity indicates that museum artifacts are not conceptually prioritized as a distinct category within current seismic code taxonomies.

Overall, the comparative analysis of definitions demonstrates that existing seismic codes provide a necessary but limited conceptual framework for non-structural elements. While adequate for distinguishing structural from non-structural components, the prevailing definitional approaches do not capture the behavioral complexity or societal value of museum objects. This definitional gap constitutes a foundational limitation that propagates through subsequent stages of seismic force formulation and design provisions, as explored in the following sections. Recognizing this limitation is therefore essential for evaluating the adaptation potential of existing codes and for informing future developments aimed at artifact-sensitive seismic protection strategies.

3.2. Seismic Force Formulations

Most codes feature a formula that multiplies an element's mass by a representative floor acceleration (or spectral acceleration) and include additional coefficients for component importance and dynamic amplification. Table 2 summarizes major parameters from each code's non-structural seismic demand equation. Although the notations differ, the underlying principles tend to be similar. Also, Table 2 compiles the horizontal seismic force equations for non-structural elements as prescribed by nine principal seismic codes. While the mathematical expressions vary in form and notation, most follow a standard structure based on parameters such as the component's weight, height within the building, spectral acceleration, and modification factors related to importance or flexibility. This comparative overview provides a technical foundation for evaluating the extent to which these formulations address the specific vulnerabilities of museum objects, which will be further analyzed in Section 4.

Table 2. Overview of Horizontal Seismic Force Equations for Non-Structural Elements

Seismic Code	Country	Horizontal Seismic Force Equation	Eq. No.
TBEC 2018	Türkiye	$F_{ie} = m_e A_{ie} B_e / R_e$	(1)
Standard No. 2800	Iran	$V_{pu} = (0{,}4 a_p A(1+S) I_p W_p / R_{pu}) \cdot (1 + 2Z/H)$	(2)
NBC 2020	Canada	$V_P = 0{,}3S(0{,}2) I_E S_P W_P$	(3)
NTC-SISMO	Mexico	$F_C = a_i \Omega_a W_c$	(4)
NTC 2018	Italy	$F_a = (S_a \cdot W_a)/q_a$	(5)
GB 50011-2010	China	$F = \gamma \eta \xi_1 \xi_2 \alpha_{max} G$	(6)
Eurocode 8	Europe	$F_a = S_a \cdot W_a \cdot \gamma_a / q_a$	(7)
ASCE/SEI 7-22	United States	$F_p = 0{,}3 S_{DS} I_p W_p [H_f / R_\mu][C_{AR}/R_{po}]$	(8)
NZS 1170-5:2004	New Zealand	$F_{ph} = C_p(T_p) C_{ph} R_p W_p$	(9)

4. COMPARATIVE ANALYSIS

To evaluate the adequacy of current seismic code provisions for protecting museum objects, a structured comparative analysis was conducted. The comparative analysis presented in this section aims to bridge the gap between seismic code formulations and the specific protective needs of museum artifacts. By systematically examining the constituent parameters of seismic force equations across nine international codes, the study seeks to identify commonalities, omissions, and potential weaknesses. This structured evaluation provides a foundation for determining whether existing code-based approaches offer adequate safeguards for fragile, high-value non-structural elements, particularly those in museum environments. Table 3-6 presents an overview of horizontal seismic force calculation parameters for non-structural elements.

Table 3: Overview of Horizontal Seismic Force Calculation Parameters for Non-Structural Elements

Seismic Code	Country	Horizontal Seismic Force	Constant Coefficient	Spectral Acceleration	Component Importance Factor
TBEC 2018	Türkiye	F_{ie}	-	A_{ie}	-
Standard No. 2800	Iran	V_{pu}	0.4	A(1+S)	I_P
NBC 2020	Canada	V_P	0.3	S(0.2)	-
NTC-SISMO	Mexico	F_C	-	a_i	-
NTC 2018	Italy	F_a	-	S_a	-
GB 50011-2010	China	F	-	α_{max}	γ
Eurocode 8	Europe	F_a	-	$\alpha \cdot S$	γ_a
ASCE/SEI 7-22	United States	F_p	0.4	S_{DS}	I_P
NZS 1170-5:2004	New Zealand	F_{ph}	-	$C_p(T_p)$	R_p

Table 4: Overview of Horizontal Seismic Force Calculation Parameters for Non-Structural Elements

Seismic Code	Structure Importance Factor	Component Weight	Effect of Height	Response Modification Factor	Overstrength Factor
TBEC 2018	I	m_e	-	R	-
Standard No. 2800	-	W_p	z/H	R_{pu}	-
NBC 2020	I_E	W_p	A_x	R_p	A_r
NTC-SISMO	-	W_c	-	-	-
NTC 2018	-	Wa	-	q_a	-
GB 50011-2010	-	G	ξ_2	-	-
Eurocode 8	-	W_a	z/H	q_a	-
ASCE/SEI 7-22	I_e	W_p	H_f	R	Ω_0
NZS 1170-5:2004	-	W_p	-	C_{ph}	-

Table 5: Overview of Horizontal Seismic Force Calculation Parameters for Non-Structural Elements

Seismic Code	Component Resonance Ductility Factor	Component Strength Factor	Fundamental Vibration Period of the Element	Fundamental Vibration Period of the Building
TBEC 2018	-	-	-	T_p
Standard No. 2800	a_p	-	-	-
NBC 2020	-	-	-	-
NTC-SISMO	Q'_c	-	r_T	T_1
NTC 2018	-	-	-	-
GB 50011-2010	ξ_1	-	-	-
Eurocode 8	-	-	T_a	T_1
ASCE/SEI 7-22	C_{AR}	R_{po}	-	-
NZS 1170-5:2004	-	-	-	T_p

Table 6: Overview of Horizontal Seismic Force Calculation Parameters for Non-Structural Elements

Seismic Code	Component Factor	Story Displacement	Damping Factor	Type Factor
TBEC 2018	-	u_i	-	-
Standard No. 2800	-	-	-	-
NBC 2020	C_p	-	-	-
NTC-SISMO	-	-	β_c	-
NTC 2018	-	-	-	-
GB 50011-2010	-	-	-	η
Eurocode 8	-	-	-	-
ASCE/SEI 7-22	-	-	-	-
NZS 1170-5:2004	-	-	-	-

4.1. Evaluation of Seismic Force Parameters Across Codes

The core of the seismic protection problem for museum artifacts lies in a profound "Engineering Disconnect." While seismic codes have evolved to ensure the structural survival of buildings (Life Safety), they remain fundamentally primitive in their approach to the "preservation" of brittle, high-value contents. This section deepens the first dimension of the analytical framework defined in Section 2.2 by critically evaluating the governing parameters embedded in the horizontal seismic force formulations for non-structural elements (NSEs).

The evaluation of seismic force parameters for non-structural elements, as delineated in the analytical framework's first dimension, is anchored in the empirical data from Tables 3-6 and the synthesized matrix in Table 7. This section undertakes a rigorous comparative dissection of these parameters, encompassing mass, height, response modification factors, and special coefficients to unpack their similarities and differences. The critique is structured to illuminate the core issue: a pervasive misalignment between general non-structural provisions and the specialized vulnerabilities of cultural heritage, culminating in a call for paradigm shifts in code development.

Table 7: Comparative Summary Matrix of Key Parameters for Horizontal Seismic Force Calculation on Non-Structural Element

Parameters	TBEC 2018	Standard No. 2800	NBC 2020	NTC-SISMO	NTC 2018	GB 50011-2010	Eurocode 8	ASCE/SEI 7-22	NZS 1170-5:2004
Horizontal Seismic Force	✓	✓	✓	✓	✓	✓	✓	✓	✓
Constant Coefficient	-	✓	✓	-	-	-	-	✓	-
Spectral Acceleration	✓	✓	✓	✓	✓	✓	✓	✓	✓
Component Importance Factor	-	✓	-	-	-	✓	✓	✓	✓
Structure Importance Factor	✓	-	✓	-	-	-	-	✓	-
Component Weight	✓	✓	✓	✓	✓	✓	✓	✓	✓
Effect of Height	-	✓	✓	-	-	✓	✓	✓	-
Response Modification Factor	✓	✓	✓	-	✓	-	✓	✓	✓
Overstrength Factor	-	-	✓	-	-	-	-	✓	-
Component Resonance Ductility Factor	-	✓	-	✓	-	✓	-	✓	-
Component Strength Factor	-	-	-	-	-	-	-	✓	-
Fundamental Vibration Period of the Element	-	-	-	✓	-	-	✓	-	-
Fundamental Vibration Period of the Building	✓	-	-	✓	-	-	✓	-	✓
Component Factor	-	-	✓	-	-	-	-	-	-
Story Displacement	✓	-	-	-	-	-	-	-	-
Damping Factor	-	-	-	✓	-	-	-	-	-
Type Factor	-	-	-	-	-	✓	-	-	-
Number of Parameters Covered	**7**	**8**	**9**	**7**	**4**	**7**	**8**	**11**	**6**

Commencing with similarities, the data in Table 3 demonstrate that foundational elements such as horizontal seismic force and spectral acceleration are ubiquitous (100% coverage in Table 7), with component weight featured in nearly all codes (Table 4). This congruence signifies an entrenched global adherence to force-based methodologies, in which inertial forces are idealized as $Fp \approx Wp \times A$. Analytically, this uniformity establishes a standardized safety threshold, ostensibly efficient for broad application across seismic zones.

This is not a trivial similarity; it is the defining assumption of current code practice. In effect, the codes assume that the "problem" of protecting non-structural elements is primarily a matter of estimating an equivalent horizontal inertial force and ensuring that attachments, supports, or components can resist it.

Table 7 provides a concise summary matrix of the presence or absence of critical parameters across the nine seismic codes. This visualization highlights that ASCE/SEI 7-22 (United States) offers the most comprehensive set of parameters (11 out of the listed ones). At the same time, codes like NTC 2018 (Italy) are more limited, potentially affecting their adaptability for protecting delicate museum artifacts.

Among the reviewed standards, the equation in ASCE/SEI 7-22 (United States) is the most comprehensive. This equation integrates a wide array of influencing variables, as shown in Table 2, Eq. (8). The formulation begins with a force constant (0.3), multiplied by the design spectral acceleration S_{DS}, the component importance factor I_p, and the component weight W_p. Its further accounts for the height amplification of the component through H_f, as well as energy dissipation capacity via the ductility reduction factor R_μ. Additionally, two highly specialized parameters, component amplification ratio C_{AR} and component strength factor R_{po}, are introduced, reflecting the response characteristics of the object in relation to the structure's motion and the inherent strength capacity of the component, respectively.

No other code simultaneously incorporates this breadth of variables. For instance, Euro-code 8 considers spectral acceleration, component importance, and height-related amplification, but lacks explicit inclusion of ductility, overstrength, or component resonance. Similarly, the Mexican code (NTC-SISMO) includes a simplified equation focused on acceleration and weight but omits modifiers for structural hierarchy or response characteristics. The Canadian NBC 2020 and New Zealand NZS 1170.5 equations include only basic parameters, such as weight and site acceleration, offering limited adaptability for sensitive or high-risk components, such as museum artifacts.

The equation from ASCE/SEI 7-22 further distinguishes itself by incorporating response modification factors (R) and overstrength capacity (Ω_0), enabling a more nuanced assessment of the expected force reduction due to system behavior. Even though museum objects themselves do not exhibit ductile behavior in the conventional sense, the inclusion of such modifiers in the base formulation permits engineers to adjust inputs when modeling particularly delicate or non-anchored artifacts.

In conclusion, the ASCE/SEI 7-22 formulation demonstrates the highest level of parametric integration among the codes examined, offering a versatile framework for engineers aiming to refine seismic protection strategies for museum artifacts. However, its effectiveness for this purpose depends heavily on the user's ability to interpret and adapt its parameters to reflect the unique characteristics of heritage collections, an issue explored further in the next section through a comparison with prior research findings.

For conventional engineered components, pipes, mechanical units, partitions, and ceilings, this model is defensible mainly because damage is frequently linked to exceeded anchorage capacity or excessive inertial demand transmitted through connections. For museum artifacts, however, the dominant vulnerability is often not connection failure or material yielding, but loss of stability (sliding, rocking, impact, overturning). These are mechanism-driven responses governed by contact conditions and geometry. Therefore, the cross-code similarity documented in Table 7 should be interpreted as evidence of a shared regulatory paradigm that is well-calibrated for engineered NSEs but only indirectly transferable to museum objects. Therefore, international harmonization at the inertial-force level does not imply museum adequacy; it means a common starting point that may systematically omit the governing physics of artifact response.

While the inertial core is consistent, the codes diverge in how they tune the inertial estimate. The matrices (Tables 3–6) show three main classes of divergence:

- Importance and consequence scaling (component and/or structural importance factors)
- Spatial amplification (height-related modifiers)
- Behavior/strength modifiers (response modification factors, overstrength, and component-related response terms)

These differences unquestionably matter: they can raise or reduce the predicted force for the same object. Yet they do not change the underlying logic: the codes still operate within a force-based representation of demand. Even parameter-rich formulations remain, fundamentally, refined ways of estimating a force, not ways of predicting which stability mechanisms are triggered. In other words, code-to-code differences are primarily differences in how inertial demand is amplified or reduced, not differences in whether sliding/rocking/overturning is explicitly controlled.

4.2. Comparison with Parameters Identified in Literature

Beyond the provisions outlined in seismic design codes, a substantial body of literature has addressed the dynamic behavior of museum artifacts through analytical, experimental, and observational studies. These investigations have identified a range of parameters that significantly influence the seismic response of free-standing or loosely anchored objects in museum environments. These parameters are often absent or underrepresented in standard code-based formulations.

Experimental and analytical studies on the seismic response of museum objects consistently demonstrate that these artifacts exhibit highly nonlinear, mode-dependent dynamic behavior under underground excitation. As illustrated in Figure 2, such objects may respond through a range of mechanisms, including sticking[17], sliding[17, 18], rocking[17, 19], sliding-rocking[17], overturning[20], and in rare cases, free-flight[17, 21]. The transition from static equilibrium to dynamic motion is a critical threshold; once crossed, the object's response type directly determines the set of parameters governing its seismic performance.

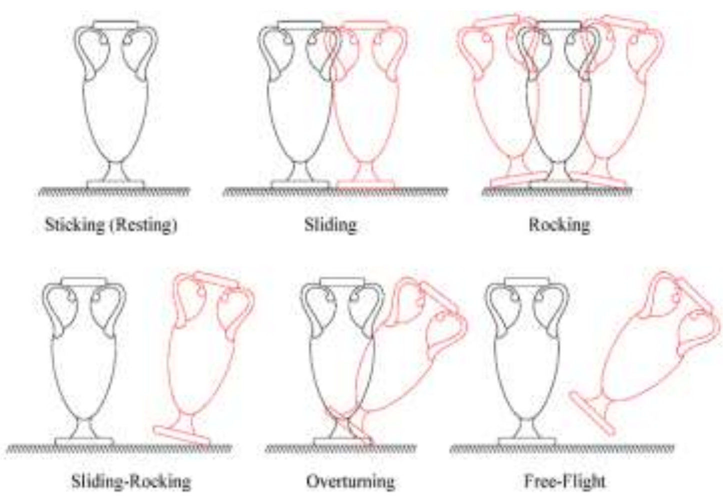

Figure 2. Failure mechanisms for artifacts under base excitations[2].

In this context, the current formulations prescribed in seismic codes appear insufficiently nuanced. As shown in Section 4.2, most codes adopt inertial-based equations that consider mass, spectral acceleration, and a limited set of modifying coefficients. However, these formulations largely neglect the object's response phase and support conditions, both of which are crucial for determining its actual dynamic behavior.

Recent literature emphasizes that the pre-seismic stability configuration of a museum object plays a pivotal role in both the magnitude of seismic force imparted and the resulting response[2]. For instance, objects with friction-based stability (e.g., unanchored artifacts resting on shelves) may transition into a sliding regime under relatively low acceleration. In such cases, the friction coefficient between the object and its support surface becomes a dominant parameter [22] yet this variable is absent in all code-based formulations reviewed in Table 2.

Alternatively, for artifacts that undergo rocking, a typical behavior among tall, slender, or pedestal-mounted objects, several geometric ratios govern response characteristics[23]. These include the slenderness ratio (base width to height), the geometric ratio (surface area to volume), the inertia ratio (moment of inertia distribution), the centroid ratio (distance of center of mass from base), and the volumetric ratio[24]. These parameters are well documented in physical modeling studies and numerical simulations, but are not reflected in the simplified seismic force equations of any existing regulations.

This misalignment reveals a structural gap in regulatory design: by abstracting all non-structural elements into a uniform category, the codes overlook the complexity and sensitivity of museum artifacts. The absence of critical parameters, such as friction, slenderness [25] The rocking angle and support interaction not only reduce predictive accuracy but also undermine the practical design of artifact protection measures.

In summary, while literature-based models offer a physically grounded and behaviorally accurate representation of museum artifact response under seismic excitation, their insights have not been systematically translated into code provisions. The comparison presented in this section underscores the need for a conceptual shift from purely force-based abstraction to a hybrid framework that complements code-scalable demand measures with stability and mechanism-oriented parameters. Such an approach is essential for bridging the gap between regulatory simplicity and the complex dynamic realities governing the seismic vulnerability of museum artifacts.

5. DISCUSSION

This discussion synthesizes the findings from the comparative analysis, critically examining the unique vulnerabilities of museum artifacts and the shortcomings of current seismic codes in addressing them. Building on the evaluation of force parameters (Section 4.1) and literature comparison (Section 4.2), it argues that while codes provide a foundational framework for non-structural elements, they fall short in accommodating the specialized needs of cultural heritage. Concrete recommendations for code improvements are proposed, followed by an expanded limitations section incorporating case studies of earthquake damage to museums. Finally, directions for future research are outlined to bridge these gaps.

5.1. Museum-Specific Vulnerabilities and the Limits of Current Code Logic

The comparative analysis presented in this study demonstrates that international seismic codes provide a coherent and internally consistent framework for the design of generic non-structural elements. However, when this framework is examined through the lens of museum object protection, fundamental conceptual limitations become apparent. Museum artifacts differ from conventional non-structural components not only in material fragility, but also in their irreplaceability, conservation constraints, and sensitivity to even minor damage. These characteristics introduce a consequence structure that current seismic codes are not calibrated to address.

Several of the reviewed codes incorporate component or structural importance factors (Tables 3 and 4), which in conventional non-structural element (NSE) design are intended to reflect life-safety considerations and the need for operational continuity. For museum artifacts, however, failure primarily entails irreversible cultural and historical loss rather than life-safety or operational disruption in the conventional sense. Existing importance factors, designed to address life-safety and operational continuity, are neither calibrated for nor capable of encoding the irreversible cultural loss associated with artifact damage. Moreover, their functional role within code formulations is limited to scaling inertial force demand, without guiding what constitutes acceptable performance for fragile and conservation-sensitive objects.

As a result, even where essential factors are present, they act as indirect and incomplete surrogates for museum value. The code can increase the calculated force demand. Still, it does not specify whether the design objective should be the prevention of first motion, the limitation of sliding displacement, the avoidance of rocking impacts, or the elimination of overturning risk. For artifacts that cannot be rigidly anchored due to conservation ethics, this absence of explicit performance definition becomes particularly problematic. In such cases, increasing force demand may not translate into meaningful risk reduction and may even encourage inappropriate or impractical interventions.

5.2. Parameter Richness versus Behavioral Relevance

The summary matrix in Table 7 may initially suggest that codes with more parameters offer more comprehensive protection. However, this interpretation is misleading when applied to museum artifacts. Parameter count alone is a misleading metric of adequacy for museum objects; the critical question is not how many parameters are included, but whether those parameters govern the actual failure mechanisms of artifacts.

The evidence from Tables 3–6 shows that the additional parameters introduced in more elaborate formulations primarily originate from a structural engineering paradigm. These include height-amplification terms, response-modification factors, overstrength coefficients, and resonance- or period-based adjustments. Such parameters refine inertial force estimation and are essential for engineered, anchored components. However, none of the reviewed codes explicitly incorporates parameters that control artifact stability, such as friction capacity at contact interfaces, geometric stability indices related to base dimensions and center-of-mass location, or constraints imposed by conservation requirements on anchorage and intervention.

Consequently, parameter-rich formulations may yield more adjustable force estimates, but they do not necessarily produce more physically representative protection strategies for museum objects. On the contrary, increased complexity can introduce greater interpretive freedom, allowing different designers to arrive at widely varying force demands for the same artifact, without any guarantee that these demands correlate with the actual onset of sliding, rocking, or overturning. In this sense, complexity increases variability faster than it increases museum relevance, because the added sophistication targets force tuning rather than mechanism control.

5.3. Implications for Code Development and Concrete Recommendations

The findings of this study indicate that the primary limitation of current seismic codes is not the absence of isolated parameters, but the framing of the non-structural design problem itself. Existing regulations are formulated around force resistance, whereas the seismic vulnerability of museum artifacts is often governed by preservation of stability. Bridging this mismatch requires targeted amendments rather than wholesale restructuring of existing codes.

Several concrete pathways for code improvement emerge from this analysis:

- *Artifact-Specific Classification:* Seismic codes could introduce a distinct subclass of non-structural elements for museum artifacts, recognizing their unique vulnerability and conservation constraints. This classification would enable differentiated performance objectives without altering the core structure of existing codes.
- *Mechanism-Oriented Performance Criteria:* Rather than relying exclusively on force amplification through importance factors, codes could define artifact-specific performance limits tied to first motion, maximum allowable displacement, or rocking stability thresholds. Such criteria would directly address the dominant failure mechanisms observed in the literature.
- *Incorporation of Stability Parameters:* Simplified, code-compatible descriptors of stability, such as friction demand-to-capacity ratios, slenderness indices, or geometric stability checks, could be introduced as supplementary verification steps alongside force-based calculations.
- *Explicit Treatment of Conservation Constraints:* Codes could acknowledge situations where anchorage is limited or prohibited, and provide alternative guidance for mitigation strategies such as base isolation at the display level, controlled sliding interfaces, or reversible restraint systems.

These recommendations do not require abandoning force-based design but rather complement it with mechanism-aware provisions that reflect the physical behavior of artifacts.

5.4. Limitations of the Study

The conclusions of this study should be interpreted in light of several limitations. The analysis is intentionally restricted to the main body of each selected seismic code, excluding commentaries, appendices, and supplementary guidelines. As a result, certain clarifications or interpretive nuances present in auxiliary documents may not be reflected in the findings.

In addition, the absence of external validation, such as expert interviews or case studies of real earthquake damage to museums, represents a significant methodological limitation. While this decision ensures methodological consistency, it also limits the ability to directly correlate code provisions with observed artifact performance during past seismic events.

Finally, although the selected codes represent a geographically diverse set of seismically active regions with substantial museum inventories, the exclusion of other regulatory frameworks may constrain the generalizability of some observations.

5.5. Directions for Future Research

Future work should aim to address these limitations and extend the present findings in several directions. Empirical validation through documented case studies of museum damage in past earthquakes would provide critical insight into the practical effectiveness of current code-based approaches. Experimental and numerical studies that translate stability-governing parameters into simplified, design-ready metrics could further support code adaptation efforts.

Equally important is engagement with museum professionals, conservators, and regulatory stakeholders to ensure that proposed seismic provisions align with ethical conservation principles and practical operational constraints. Ultimately, the development of museum-specific seismic protection guidelines, whether as annexes to existing codes or as standalone documents, represents a promising pathway to reconcile regulatory frameworks with the unique demands of cultural heritage preservation.

6. CONCLUSION

This study evaluated whether the seismic provisions for non-structural elements in nine principal international codes adequately address the unique vulnerabilities of museum artifacts. Through a systematic examination of code-based force formulations and a comparative review of parameters identified in the literature, the results reveal a clear and persistent gap between regulatory assumptions and the dynamic response characteristics of museum objects under seismic excitation.

Although all reviewed codes incorporate fundamental inertial variables—such as component weight and floor-level spectral acceleration—they uniformly treat museum artifacts as generic non-structural elements, typically grouped with partitions, cladding, or mechanical equipment. None of the codes explicitly distinguishes fragile or high-value artifacts as a separate category, nor do they incorporate parameters that directly govern artifact-specific response mechanisms, including sliding, rocking, or overturning. Critical factors emphasized in experimental and analytical studies—such as frictional capacity, geometric slenderness, base contact conditions, and conservation-driven limitations on anchorage—remain absent from standard force-based formulations.

Among the examined standards, ASCE/SEI 7-22 provides the most elaborate formulation by incorporating multiple modifying factors related to component importance, height amplification, and response characteristics. Nevertheless, even this comparatively comprehensive approach remains fundamentally limited when applied to museum artifacts whose seismic behavior is controlled by stability, geometry, and conservation constraints rather than by inertial force magnitude alone.

The findings demonstrate that existing seismic codes, while generally effective for conventional non-structural safety, offer limited reliability in protecting cultural assets housed in museums. When applied without adaptation, the generalized nature of these provisions may result in either insufficient protection or overly conservative interventions, particularly for artifacts that cannot be rigidly anchored or modified for ethical conservation reasons.

Accordingly, this study underscores the need for targeted adaptations within seismic design frameworks to accommodate museum collections better. Such adaptations may include the introduction of artifact-specific classifications, the incorporation of simplified stability-oriented parameters, and the adoption of hybrid approaches that combine code-based force estimation with behavior-informed performance criteria. Bridging the gap between regulatory simplicity and the physical complexity of artifact response is essential to ensure that seismic risk mitigation strategies extend beyond life safety and structural integrity to encompass the preservation of irreplaceable cultural heritage.

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Authors’ Contributions

In this study, authors contributed equally to the study.

Competing Interests

The authors declare that they have no conflict of interest.

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