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Performance-Based Methodology for Seismic Design and Evaluation of Bridges

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ABSTRACT

Numerous methods have been proposed for the seismic-resistant design of buildings, with performance-based design being one of the most promising approaches. This method integrates various previous techniques, offering a comprehensive framework. However, regrettably, there has been inadequate attention given to adapting this method for bridge applications in codes. It is evident that a similar effort, akin to what has been accomplished for buildings, is also necessary for bridges. By scrutinizing the design methods outlined in various codes and identifying their weaknesses, it is possible to achieve suitable results for the performance-based design of bridges. This research aims to develop a performance-based design method specifically tailored for bridges, thereby familiarizing engineers with the performance levels of bridges. The goal is to enhance the seismic resilience of bridges by providing a robust and adaptable design framework that aligns with the evolving needs of modern infrastructure.

Keywords:

Seismic Resilience, Bridge Engineering, Disaster Recovery.

1. Introduction

Performance-based design (PBD) has emerged as a transformative approach in structural engineering, offering enhanced flexibility and precision in achieving desired performance objectives. Initially developed for buildings, PBD focuses on addressing specific performance levels under various loading scenarios, such as seismic events, while optimizing safety, functionality, and cost-effectiveness. Over the past two decades, this methodology has gained significant traction in the design of buildings, where it has been extensively studied and applied to ensure resilience against natural disasters like earthquakes and windstorms [1]. However, the application of PBD to bridge structures remains relatively underexplored despite their critical role in infrastructure networks. Table 1 summarizes the key differences between code-based and performance-based design for buildings.

Table 1. Key Differences between Code-Based Design and Performance-Based Design in Buildings

Feature	Existing Seismic Design	Performance-Based Seismic Design
Design Approach	Prescriptive	Project-Specific
Design Performance Level	Life Safety	From Collapse Prevention to Immediate Occupancy
Design Methods	Simplified Dynamic Methods	Dependent on Required Performance Level
Damage Considerations	Structural Only	Structural and Non-Structural
Stakeholders in Design	Structural Engineer	Structural Engineer, Architect, Owner, Contractor

Bridges differ fundamentally from buildings in terms of structural behavior, load distribution, and design requirements. These differences necessitate tailored PBD approaches to address unique challenges such as dynamic loading from traffic, environmental effects, and seismic forces. Recent advancements in materials like ultra-high-performance concrete (UHPC) and fiber-reinforced polymers (FRPs), as well as innovative monitoring techniques such as Structural Health Monitoring (SHM), have further emphasized the need for performance-based methodologies specifically adapted for bridges [2]. This paper aims to compare PBD methods applied to buildings and bridges, highlighting their similarities and differences while exploring opportunities for cross-disciplinary knowledge transfer. By analyzing recent developments in PBD frameworks and their applications to both structural types, this study seeks to bridge the gap between theory and practice. The findings will contribute to advancing the state-of-the-art in PBD for bridges, ensuring safer and more resilient infrastructure.

2. PBD for Bridges

In recent years, valuable research has been conducted in the field of performance-based design in bridges. The beginning of this field of research in bridges can be considered after 2000. Chandler and Lam (2001) and Moehle and Deierlein (2004) demonstrate the progression of PBD from a conceptual framework to a more refined and practical approach in earthquake engineering[1][2]. In Chandler and Lam (2001), PBD is presented as a multi-disciplinary approach, integrating various aspects of engineering, including structural, geotechnical, and risk assessment[1]. Later, several papers focus specifically on the application of PBD to bridge design and assessment, highlighting the importance of this approach in critical infrastructure[3][4][5][6]. The review by Zhang and Alam provides a comprehensive global overview of PBD in bridge engineering, critically examining past practices and future directions[7]. Recent papers introduce machine learning and other advanced computational methods to enhance PBD methodologies [9]. The reviewed papers demonstrate the significant progress made in performance-based design for earthquake engineering, particularly in bridge design. The field has evolved from conceptual frameworks to sophisticated methodologies incorporating advanced computational techniques. Future research directions may include further integration of artificial intelligence, real-time monitoring, and adaptive design strategies in PBD [10-14].

3. Code Requirements for Bridges

The AASHTO code incorporates analysis, design, and construction requirements to minimize the vulnerability of bridges to earthquakes. Ground motions are determined based on a low probability of exceedance during the bridge's service life. According to the code, bridges designed according to its provisions may be damaged in an earthquake, but the probability of collapse is low. The basic concept of AASHTO's seismic design is "life safety," although the code emphasizes the performance of important bridges after an earthquake. The fundamental principles of AASHTO's seismic design are as follows:

- Under minor to moderate earthquakes, the bridge should behave elastically, with no significant damage to structural components.
- Under severe earthquakes, the bridge should not collapse. Damage should be easily identifiable and repairable.

The AASHTO code classifies bridges into three categories based on importance: critical bridges, essential bridges, and other bridges

Table 2. Damage Descriptions of Structures in Earthquakes (SEAOC 1995).

Damage Index	Damage Range	Damage State
9-10	Full Serviceability	No damage. Uninterrupted service. Negligible structural and non-structural damage.
7-8	Serviceability	Most functions and services are available immediately after the earthquake. Minor repairs may require temporary disruption of non-essential services. Minor damage. The structure is usable immediately after the earthquake. Non-essential services may be interrupted.
5-6	Life Safety	Moderate damage. Selected components are not destroyed. Life safety is preserved; the structure is damaged but remains stable.
3-4	Near Collapse	Collapse of the structure is prevented; non-structural components may collapse. Severe structural damage, but no collapse; non-structural components collapse.
1-2	Collapse	Complete or partial collapse of the structural system. Complete collapse of the structure.

The importance of a bridge is determined by societal and defense needs [15-17]. Essential bridges are those that must be able to support emergency and security services immediately after an earthquake. Critical bridges must be able to carry their design traffic after an earthquake. After very severe earthquakes (2500-year return period), these bridges must be capable of handling emergency services traffic [18-22].

The Japanese seismic design code for bridges underwent significant changes after the 1995 Kobe earthquake. This code divides bridges into two categories:

- Standard bridges (Type A)
- Important bridges (Type B)

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Both groups must behave elastically underground motions with a high probability of occurrence, and their damage should be minimal. In areas with a low probability of earthquakes, important bridges may sustain minor damage, and standard bridges must not collapse [23].

Table 3. Performance Objectives for Different Structures

Performance level				earthquake
Near collapse	Life Safety	operational	Fully operational	
un-accepted performance for new buildings		a		Frequent(43-years return period)
			b	Occasional (72-years return period)
			c	Rare(475-years return period)

Ground motions used in analyses are divided into two categories:
- Group I: Ground motions at the boundaries of plates with a magnitude of approximately 8.
- Group II: Ground motions within plates with a magnitude of approximately 7 to 7.2.

This code approaches performance-based design due to its use of two design earthquakes.
In the Iranian code for seismic design of highway and railway bridges, bridges are designed and constructed in such a way that they do not lose their stability during an earthquake and that casualties and financial losses are minimized. According to this code, bridges can withstand minor and moderate earthquakes without significant damage and severe earthquakes without collapsing [24-26]. This code classifies bridges into three categories based on importance:
- Bridges of high importance: Bridges on main roads and freeways, and bridges providing access to vital industries and military installations.
- Bridges of medium importance: Bridges on primary roads and providing access to other industries and military installations that are not in the first category.
- Bridges of low importance: Bridges on secondary rural roads.

The importance factors for these bridges are 1.2, 1, and 0.8, respectively.
This review shows that in general, the following shortcomings are observed in these codes:
- In the force-based design method, a seismic force reduction factor is used in the design. This reduction factor is due to ductility, but such ductility does not exist in bridge design.
- Revising the definition of earthquake performance (response spectrum) and earthquake effect levels in the codes seems necessary.
- Seismic design is based on only one earthquake (except in Japan).
- The seismic performance of bridges should be considered in the bridge's shape design, but in these codes, seismic design is performed after the bridge design.
- Bridges that require specific requirements (arch bridges, etc.) are neglected in these codes.

To extend the performance-based design method for bridges, defining three performance levels seems necessary and sufficient:
1. In operation without reduced traffic volume
2. In operation with minor damage
3. Near collapse

Compared to buildings, bridges have very few non-structural components [27-32]. Therefore, a performance level related to non-structural components is not defined for them. For example, the electrical and mechanical installations of bridges are not as important to the bridge's service as they are in buildings.

The ATC-18 (1997) code defines two earthquake levels for seismic design:

- Service Level Earthquake: An earthquake with a 50-30% probability of being exceeded during the bridge's service life. The return period of the earthquake depends on the selected probability of exceedance and the bridge's service life [33-35].
- Life Safety Level Earthquake: Has a 10% probability of being exceeded during the bridge's service life.

This code defines two performance levels for bridges:

- Immediate Occupancy Level: The bridge can handle its normal traffic immediately after the earthquake, and repairs are completed a few hours (maximum 24 hours) after the earthquake.
- Limited Operation Level: Repairs take a maximum of 3 days. The bridge's service is disrupted, and only essential traffic can pass. After the critical situation ends (a few months after the earthquake), the bridge requires major repairs [36-40].

The ATC-32 code defines the following three damage levels:

- Minimal Damage: This damage occurs in the elastic response. Damage is limited to small flexural cracks in the concrete, and no permanent deformation occurs.
- Repairable Damage: This damage occurs in the inelastic response [41-45]. Cracking in the concrete, yielding of reinforcing steel, and minor spalling of concrete are likely. These damages can be restored to the pre-earthquake condition without replacing new components. Repairs should not require closing the route [46-48]. At this damage level, permanent deformations are small.
- Significant Damage: Cracking of concrete, yielding of reinforcing steel, and major spalling and disintegration of concrete occur in this state. Repairs require closing the route. Permanent deformation is large, and partial or complete replacement of components is necessary.

In this code, bridges are divided into two categories: important and ordinary. However, these terms are not precisely defined. In general, an important bridge connects two sections of a major road and is necessary for emergency services after an earthquake. An ordinary bridge does not play an important role in emergency traffic.

If a third category called "critical bridges" is added to these two categories, the definition is complete. This method of categorization seems necessary to define the characteristics of each group. In this way, bridges are divided into three categories [similar to the classification of buildings according to SEAOC2000]. These three categories are:

- Critical Bridges: Include bridges connecting major highways and essential buildings and facilities such as hospitals, police, fire departments, communication centers, etc. Just as these buildings are essential for post-earthquake services, the bridges connecting these sections are also necessary for the useful function of these sections. Therefore, the importance of these bridges depends on the importance of the buildings they connect. It should be noted that bridges that provide access to special facilities such as water or electricity are also critical [49-53].
- Important Bridges: Bridges that are economically or historically important. Some of these bridges may not play an important role in transportation, but due to the cost and problems of their reconstruction, they are placed in this category.
- Ordinary Bridges: Bridges that do not play an important role in emergency traffic.

ATC18 states that at the limited service level, bridge repairs should be completed within three days at the most. Obviously, this period is very short for bridge repair, and it seems impossible to carry out repairs in this period. It has recently been suggested that damage identification should take

three days. Perhaps the intention of specifying this time was to emphasize reducing delays in repair. Of course, damage identification and repair can be done simultaneously.
In addition to the above, the suitability of the site in terms of soil type and hazard potential should be considered when locating and determining the form of the bridge or when determining seismic strengthening requirements.
The expected location of damage after an earthquake should be specified in columns (piers), abutments, foundations, abutments, and retaining walls for the performance levels of uninterrupted service, limited service, and collapse prevention.

Table 4. Performance Objectives in Bridges.

Performance level			earthquake
Collapse prevention	Limited service	Immediate Service	
Uninterrupted Operation for new bridges			Frequent(43-years return period)
a			Occasional (72-years return period)
	b c		Rare(475-years return period)
			Very rare(970 -years return period)

Damage from past earthquakes to bridges can be used as an example of the performance levels required for bridge design. Concrete members such as abutments are subject to cracking and spalling in mild to moderate earthquakes, and significant substructure displacement occurs in more severe earthquakes. During an earthquake, foundation movement due to soil liquefaction can affect foundations, abutments, and retaining walls. The destruction of steel abutments that have shown sufficient resistance to earthquakes in the laboratory is also a problem, even in moderate earthquakes. The reason for this can be attributed to the uneven distribution of force in the abutment. Although insufficient shear reinforcement has been identified as a source of failure, a careful evaluation of other building defects should be performed. For example, the failure may be due to a design flaw due to a sudden change in the stiffness of the bridge structure. This has been observed in some bridges in the Kobe earthquake. These defects are not easily detectable. For this reason, the problem is mistakenly diagnosed as insufficient shear reinforcement. Although most of the bridge's components are structural components, there are several non-structural factors that can greatly affect the bridge's performance after an earthquake. For example, movable bridges, such as bascule and suspension bridges, require a power source to adjust their opening and closing capabilities. If the bridge is open at the time of the earthquake and the power source fails, preventing the bridge span from moving, the bridge may no longer be usable, even if no structural damage has occurred in the bridge itself. For bridges that carry mass transit lines, the failure of electrical components may disrupt the bridge's function and make it impossible to use the bridge for transportation. Depending on the size and route of the bridge, the failure of the bridge lighting may limit its use to daytime.
In addition to the non-structural components of the bridges themselves, some non-structural components are dependent on the bridge's transportation. Power, telephone, and water lines may be transmitted by the bridge. In some cases, these facilities are only transferred to the site via the

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bridge, and bridge failure results in the disruption of these facilities. The critical situation after an earthquake depends entirely on the availability of these facilities to save lives.

4. Proposed Performance Design Methods for Bridges

The current method of bridge design is force-based design. ATC18 suggests that displacement-based design be performed for each service and safety performance level. However, longitudinal reinforcement and shear keys are better designed using the force method. In contrast, evaluating the ductility and movement of abutments using the displacement method gives accurate results.
Performing this two-level method provides a better understanding of the overall performance of the bridge. For important bridges (bridges that are not in the ordinary category), a nonlinear static analysis must be performed. ATC18 recommends that pushover analysis be used for displacement-based performance design. This analysis obtains the nonlinear response of the structure. This method provides very accurate and detailed information about the structure's response, taking into account irregularities, nonlinear behavior, and modal interaction (longitudinal-transverse). However, the uncertainty due to modeling and the earthquake considered must be taken into account. With the method mentioned for seismic design, design for other critical forces should be based on performance. Specific forces that may be of concern in bridges are impacts from pieces of ice or floods. Floren (1998) discussed the impact conditions in performance-based design. These forces may occur simultaneously with an earthquake. By specifying the required design level of the bridge, taking into account the protection system against collisions, the desired design can be achieved. Preventing damage, safety, and risk reduction are more important than economic issues. The performance-based design method has not yet been incorporated into bridge codes. This method requires initial attention to the suitability of the site and the shape of the bridge and specifying the potential for interaction with the earthquake. The performance function is determined according to engineering principles, private issues, and public needs. The bridge can be designed for uninterrupted use, limited use, and prevention of collapse under the effect of a tolerable earthquake with a return of 43 years to a rare earthquake (with a return of 970 years). In a logical design, we must specify the accuracy of the performance level. Finally, quality assurance is possible during construction and with good maintenance and inspection of the bridge. With this design method, the complete design of the bridge is obtained, along with its social functions.
The flow chart of the seismic design of a bridge based on performance is shown in Figure (5-2). Different design methods have been proposed depending on the importance of the bridge and the desired design level. This method includes force resistance, displacement, and energy methods. The force resistance method has been used in the design of existing bridges.
In the force resistance method, the earthquake forces are obtained by the equations given in the code, and the structural members are designed in such a way that they have sufficient resistance against these forces. The displacement-based design method involves limiting the relative displacement of the story and the deformation of the bridge, taking into account the damping characteristics of the structure. The energy-based design method equates the total input energy (applied earthquake forces) with the elastic energy capacity of the structure and the damping capacity. Therefore, the damage potential of the structure depends on its ability to dampen the input energy during the plastic cyclic response. The proposed energy and displacement methods are still under development and have not yet been widely used by engineers.

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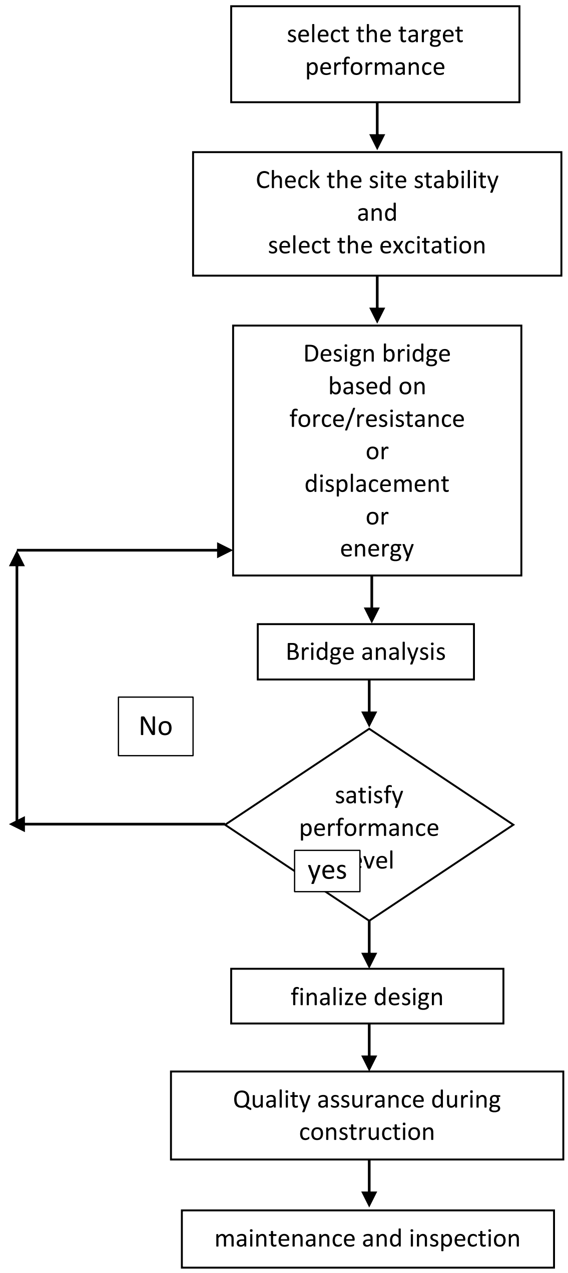

Figure 1. proposed flowchart of Bridge Performance-Based Design

5. Conclusion

This research compares performance-based design (PBD) methodologies applied to buildings and bridges, addressing the lag in PBD adoption within bridge engineering. While building design has extensively embraced PBD, bridge design predominantly relies on force-based methods, which this study argues are inadequate for ensuring optimal seismic resilience. A critical analysis of current codes, including AASHTO, Japanese, and Iranian standards, reveals shortcomings in seismic force reduction factors, reliance on single-earthquake design scenarios (excluding Japan), and the

separation of seismic considerations from initial design phases. The study emphasizes the need for incorporating seismic performance directly into the conceptual bridge design. These codes also frequently lack specific guidelines for unique bridge types like arch bridges.
This study proposes a framework centered on three performance levels: uninterrupted service, usability with minor damage, and near collapse. This classification acknowledges the limited non-structural components in bridges compared to buildings, focusing instead on structural integrity. The research incorporates the earthquake levels defined in ATC-18 (service and safety) and damage levels from ATC-32, advocating for a three-tiered bridge categorization (critical, important, ordinary) to better align design objectives with societal needs. The methodology underscores integrating site suitability, soil considerations, and hazard potential early in the design and strengthening processes. It suggests explicitly defining expected damage locations in structural elements for each performance level, drawing lessons from past earthquakes. The research promotes a hybrid force-based and displacement-based design approach and the adoption of nonlinear static analysis (pushover analysis). This work aims to guide the implementation of PBD principles in bridge engineering, leading to safer, more reliable, and socially responsible infrastructure.

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