Evaluation of Seismic Performance and Design of AAC Building Systems

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Abstract

To achieve sustainability and resilience in construction, the demand for lightweight, high-strength panel systems with rapid and simple installation, as well as enhanced thermal insulation and acoustic performance, is increasing. Autoclaved aerated concrete (AAC), first developed in Sweden, has since been widely adopted across industrialized nations, particularly in the construction sector. Key advantages of AAC include its lightweight properties, effectiveness in reducing seismic forces, ease of installation, low thermal conductivity, fire resistance, and sound insulation. Its application significantly contributes to optimizing fuel and energy consumption, while its high compressive strength renders it a desirable material in contemporary construction practices. Given the growing demand for housing, the continued use of traditional materials and construction methods in Iran is increasingly inadequate. This study develops a design and implementation framework for a gravity-resisting and lateral load-bearing structural system using AAC elements, including reinforced blocks and panels. The proposed structural system adheres to internationally recognized building codes while incorporating Iranian seismic regulations. The design of floors and roofs employs reinforced AAC roof panels and a hybrid system combining AAC roof blocks with in-situ reinforced concrete. These elements were modeled based on sound engineering principles and evaluated through structural analysis software to compare performance outcomes. The findings indicate the influence of floor count, floor height, and building layout on the overall seismic behavior of the structure. The probability of exceeding thresholds of minor, moderate, and severe damage was analyzed under varying conditions. Specifically: (1) A comparison between one-story and two-story structures reveals reductions in the probability of exceeding partial, moderate, and severe damage thresholds by 59.7%, 94.5%, 99.3%, and 99.8%, respectively. (2) In comparing two-story and three-story structures, the respective reductions were 55.7%, 93.2%, 99.0%, and 99.7%.

Keywords: *autoclaved aerated concrete (AAC), compressive strength, damage probability thresholds, thermal conductivity, steel reinforcement, structural design methods.*

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1. Introduction

Assembled prefabricated construction technology offers significant advantages in improving construction efficiency, structural quality, and environmental performance, while simultaneously reducing labor demands, construction costs, and energy consumption [1]. In this context, a novel prefabricated panel-wall system is introduced, which utilizes a specialized mortar at the manufacturing stage to bond autoclaved aerated concrete (AAC) splicing panels into integrated wall elements. These prefabricated walls, reinforced for structural use, are transported to construction sites and combined with cast-in-place components such as columns and ring beams to form a unified structural system. This integration of AAC materials and prefabricated assembly combines key benefits including low weight, high compressive strength, thermal insulation, sound attenuation, fire resistance, and environmental sustainability. When properly designed, these systems offer not only ease of construction but also reliable seismic performance [2].

AAC was first developed in Sweden in 1924 and has since gained widespread use across industrialized nations, particularly in the construction sector [3]. Its benefits include reduced seismic load due to its low mass, ease of implementation, thermal efficiency, and fire resistance. These attributes make AAC highly effective in optimizing energy consumption and enhancing structural resilience [4]. Despite its introduction in Iran several years ago, AAC has yet to achieve widespread adoption among mass housing developers and construction professionals. A key challenge remains the lack of technical familiarity and limited promotion of its benefits. In response, this article seeks to compile relevant technical data on AAC, highlight its advantages, and compare it with similar construction materials to increase awareness among engineers, architects, and policy-makers [5].

This study first situates AAC among other lightweight construction materials, followed by an examination of its global production trends and technological evolution. It then evaluates the current status of AAC production and application in Iran. Classified as a second-category lightweight concrete, AAC is produced in both reinforced and unreinforced forms, with unreinforced types constituting approximately 80% of total output [6]. In 2011, combined production in Europe and Russia reached 24 million cubic meters. Although reliable statistics for China are unavailable, estimates suggest production levels of around 10 million cubic meters. Major producers also include Japan, South Korea, the United States, as well as countries in the Middle East, Africa, and Central Asia. For example, Japan produced 2.5 million cubic meters of AAC in 1992, predominantly in the form of slabs and reinforced panels. Global demand was estimated at 100 million cubic meters in 2011, with annual production increasing by 5 million cubic meters [7]. In contrast, Iran's practical production capacity stood at approximately 500,000 cubic meters in 2019, revealing a substantial gap in domestic supply and potential [8].

With Iran's construction industry facing increased demand for rapid, efficient, and sustainable building solutions, the application of AAC as a new construction method is becoming increasingly vital. AAC is a lightweight, porous concrete primarily composed of silica-based materials, cement, lime, and aluminum powder. It was originally developed to combine the advantages of wood—such as thermal insulation, workability, and lightness—while eliminating drawbacks like flammability and biological degradation [9].

The material's porous structure, which results from the chemical reaction between cement, lime, and aluminum powder, endows AAC with excellent thermal insulation and a favorable strength-to-weight ratio compared to conventional concrete. Due to its low weight and non-structural strength characteristics, one of the primary uses of AAC is in lightweight partition walls [10].

The advantages of AAC blocks include fire resistance, the absence of toxic gas emissions during combustion, excellent thermal performance without the need for additional insulation, and enhanced acoustic performance. These blocks also contribute to faster construction and reduced material usage for facades and structural mass. AAC has been successfully used in mass housing developments in countries such as the United Arab Emirates, Turkey, and China over the past two decades, serving as a model for innovative, resilient, and sustainable building technologies [11].

The aim of this study is to evaluate the structural and seismic performance of assembled AAC panel-wall systems, with a focus on their applicability and potential for widespread use in Iran's contemporary construction industry.

2. Methodology

This study establishes a comprehensive set of criteria for the design and implementation of a gravity-resisting and lateral load-bearing structural system composed of autoclaved aerated concrete (AAC) products, including reinforced blocks and panels. The framework is developed in alignment with internationally recognized standards and tailored to meet the specific requirements of Iran's seismic design codes. Particular attention is given to the structural design of floors and roofs, which utilize reinforced AAC roof panels either independently or in combination with AAC roof blocks and in-situ cast reinforced concrete. These hybrid roof systems are supported by steel reinforcements to ensure proper load transfer and resilience. Structural strategies are developed to ensure coherence in the seismic behavior of the roof and its interaction with supporting elements, focusing on effective load path continuity and inter-component compatibility under seismic forces.

The vertical load-bearing system is designed to support both dead and live gravity loads, while the lateral force-resisting system is engineered to counteract seismic and wind-induced forces. These systems are primarily composed of AAC reinforced wall panels and AAC blocks, integrated to form structural walls. The overall integrity and robustness of the building system are maintained through the use of horizontal and vertical ties or equivalent reinforcing elements that unify the structural components and enhance seismic resistance. The design process considers a range of variables influencing structural behavior, including the seismic and geotechnical characteristics of the site, the total height and number of floors, architectural layout, vertical cross-sectional configuration, dimensions and placement of openings, minimum wall thickness requirements, and minimum wall area ratios in both horizontal and vertical extensions based on story count. In addition, the mechanical properties and detailing of reinforcing ties and panels, as well as other effective construction parameters, are thoroughly addressed.

To assess the structural performance of AAC-based systems, a detailed software model is developed for the design and analysis of buildings incorporating reinforced AAC blocks and panels. This model facilitates the evaluation of both static and dynamic structural responses and complies with architectural requirements and diverse geotechnical and seismic conditions. The modeling process involves the selection of representative building types, specifically one-story and two-story configurations, which serve as the basis for validating design criteria and assessing performance under varying design assumptions.

For each prototype building, appropriate construction plans are developed by considering a variety of architectural and structural variables. These include plan dimensions, story heights, lengths of unrestrained wall segments, number of stories, wall density, layout symmetry, strength and dimensions of ties, resistance grades of AAC materials, and roof system types such as block-beam or two-way slab systems. Suitable structural analysis software is then selected to perform the modeling and evaluation process. Model elements are constructed to accurately simulate the behavior of all structural components, including reinforced AAC panels, AAC blocks, jointing mortars, integrated walls, roof systems, horizontal and vertical ties, reinforcing components, and the foundation system.

A detailed geometric model of each building is generated, incorporating different reinforcement strategies such as configurations without vertical ties, with vertical ties only, with horizontal bars in combination with vertical ties, and with flat-truss bed-joint reinforcements. Both static and dynamic analyses are conducted in linear and nonlinear formats under the combined effects of gravity and seismic loads, consistent with Iran's seismic regulations. Specifically, nonlinear static (pushover) analysis and incremental dynamic analysis (IDA) are performed using validated mechanical parameters derived from prior experimental studies and code-based data. The results from these nonlinear evaluations provide insights into the performance characteristics of AAC masonry elements, enabling a robust assessment of structural behavior.

The software-based analyses enable detailed evaluation of the modeled structures, allowing for the identification of strengths and weaknesses in the AAC-based systems. The findings are used to refine the design parameters and adjust the initial criteria iteratively, ensuring the accuracy and relevance of the structural model. This cyclical process—linking the theoretical framework with practical modeling outcomes—is repeated until reliable and optimized design solutions are achieved.

Finally, the methodology includes the development of practical guidelines for modeling, analysis, and structural design using AAC products. These guidelines culminate in the production of detailed construction drawings and design documents for each modeled building, thereby providing a foundation for real-world implementation. Through this process, the study seeks to validate the use of AAC systems under seismic conditions and propose optimized, regulation-compliant structural designs suitable for contemporary construction needs in Iran.

3. Findings and Results

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 88%, 50% and 24%, respectively.

- The results of a 1-story structure with a regular plan and medium floor height

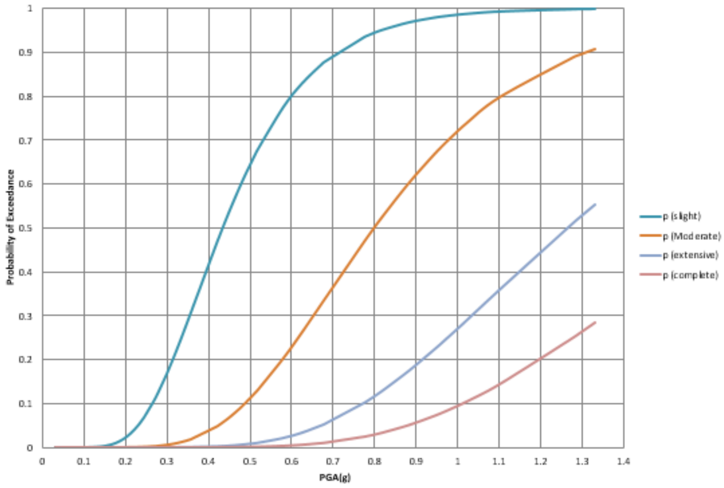

Figure 1. Fragility curve of the structure 1

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 90%, 55% and 28%, respectively.

- The results of a 1-story structure with a regular plan and high floor height

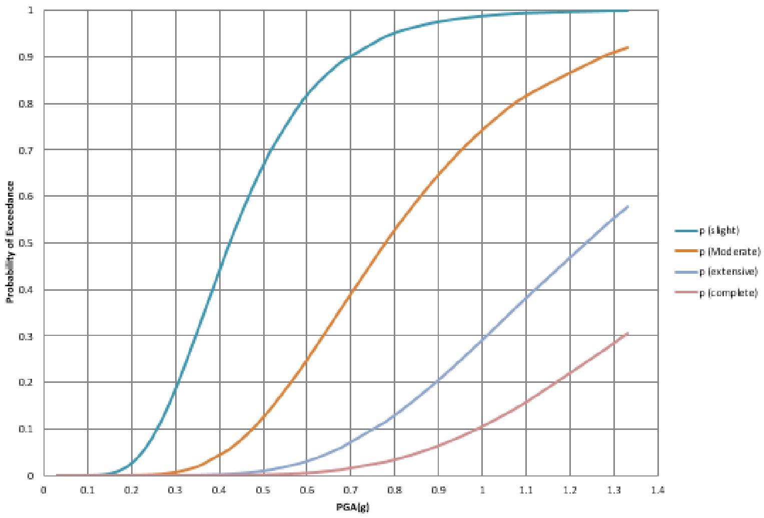

Figure 2. Fragility curve of the structure 2

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 92%, 58% and 30%, respectively.

- The results of a 1-story structure with an irregular plan and a short floor height

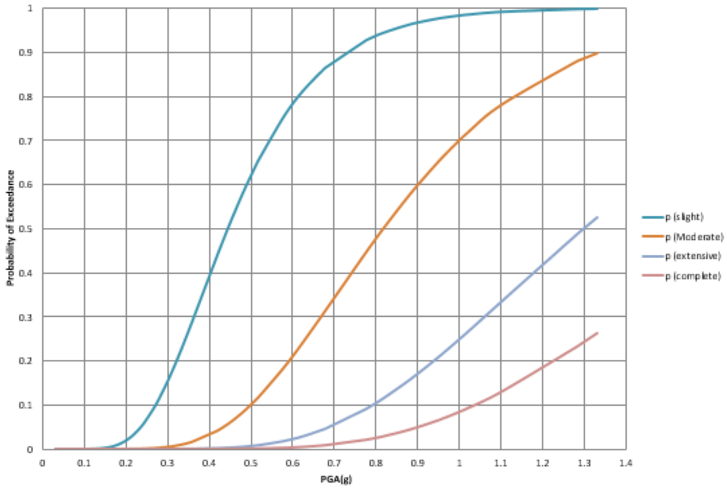

Figure 3. Fragility curve of the structure 3

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 90%, 52% and 25%, respectively.

- The results of a 1-story structure with an irregular plan and medium floor height

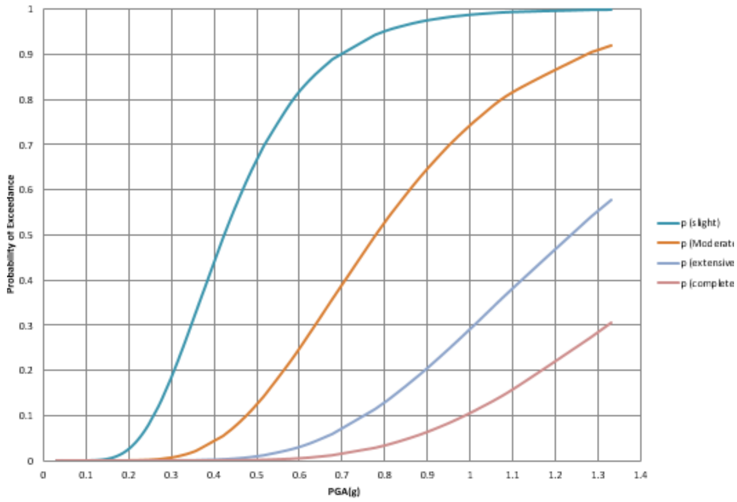

Figure 4. Fragility curve of the structure 4

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 92%, 57% and 30%, respectively.

- The results of a 1-story structure with an irregular plan and high floor height

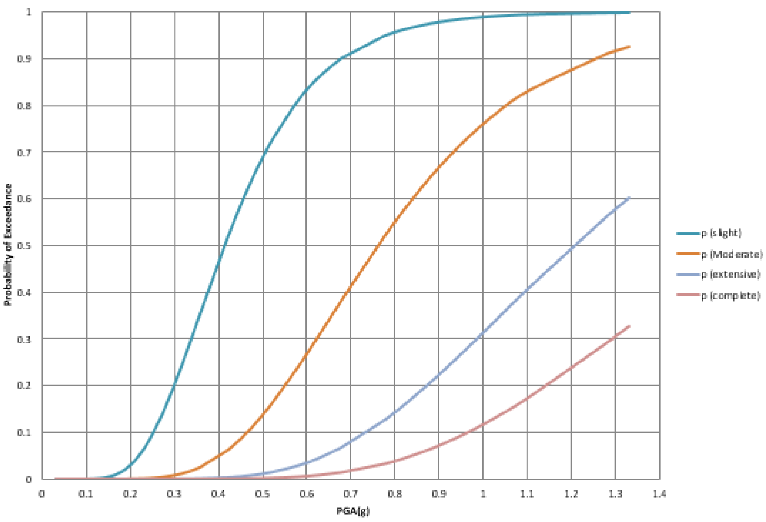

Figure 5. Fragility curve of the structure 5

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 93%, 60% and 32%, respectively.

- The results of a 2-story structure with a regular plan and a short floor height

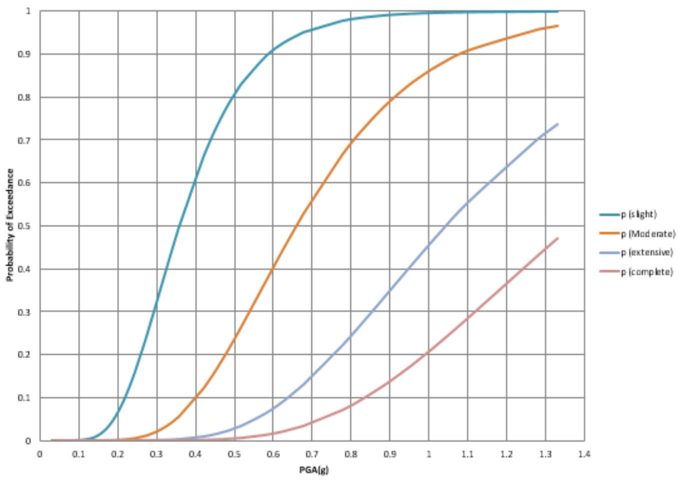

Figure 6. Fragility curve of the structure 6

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 96%, 72% and 48%, respectively.

- The results of a 2-story structure with a regular plan and an average floor height

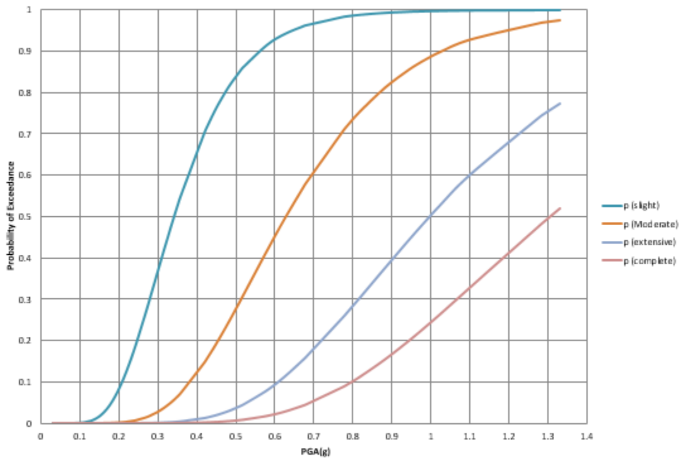

Figure 7. Fragility curve of the structure 7

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 97%, 78% and 52%, respectively.

- The results of a 2-story structure with a regular plan and high floor height

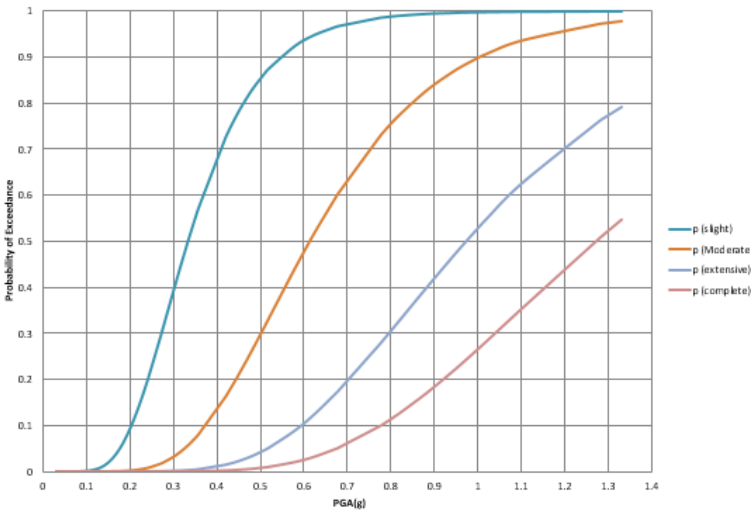

Figure 8. Fragility curve of the structure 8

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 98%, 79% and 55%, respectively.

- The results of a 2-story structure with an irregular plan and a short floor height

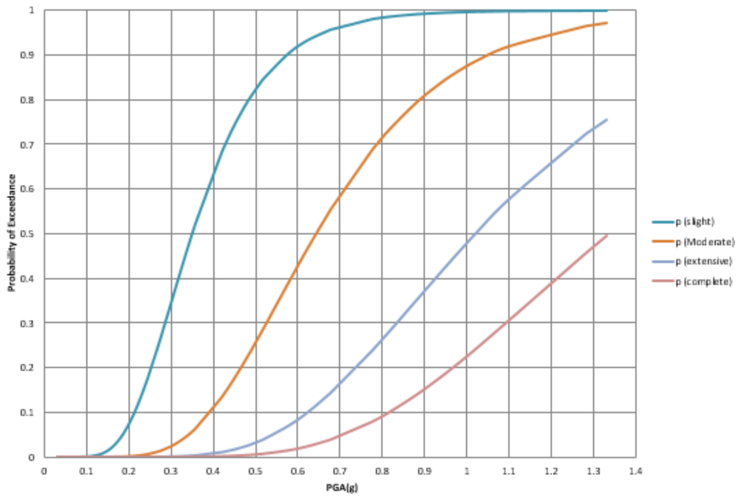

Figure 9. Fragility curve of the structure 9

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 97%, 73% and 50%, respectively.

- The results of a 2-story structure with an irregular plan and medium floor height

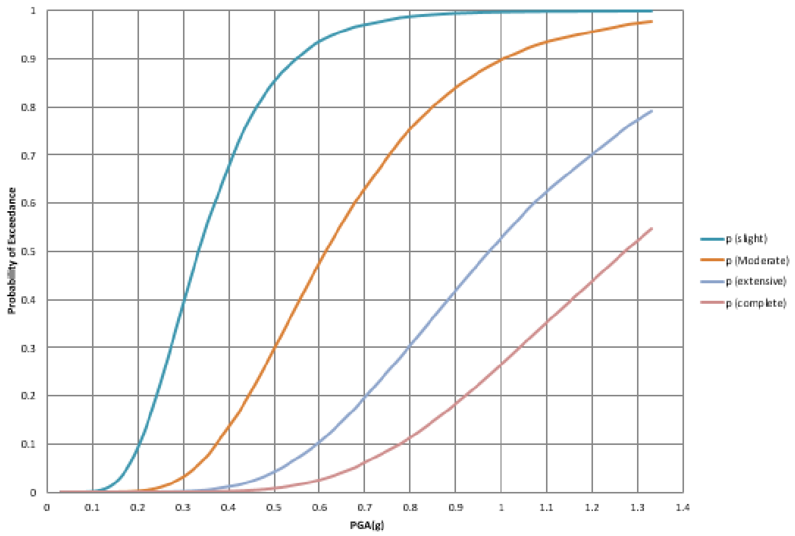

Figure 10. Fragility curve of the structure 10

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 98%, 80% and 55%, respectively.

- The results of a 2-story structure with an irregular plan and high floor height

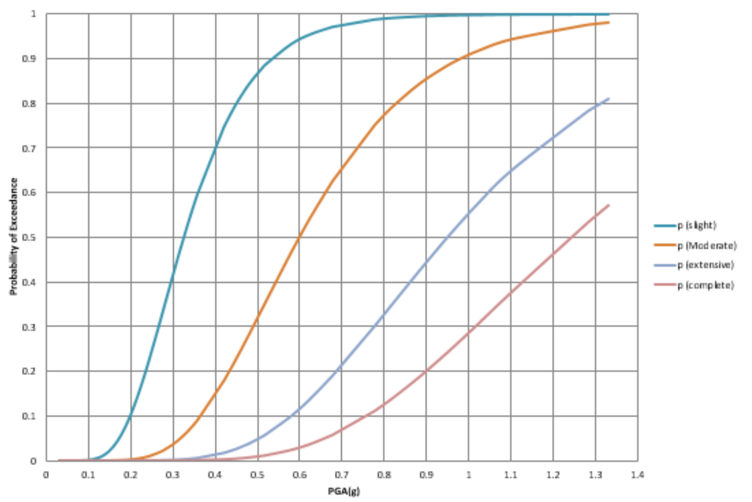

Figure 11. Fragility curve of the structure 11

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 99%, 81% and 57%, respectively.

- The results of a 3-story structure with a regular plan and a short floor height

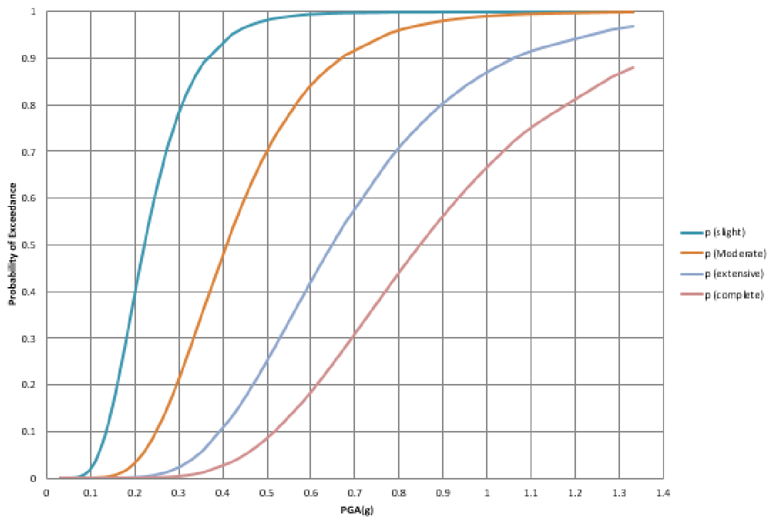

Figure 12. Fragility curve of the structure 12

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 97% and 88%, respectively.

- The results of a 3-story structure with a regular plan and average floor height

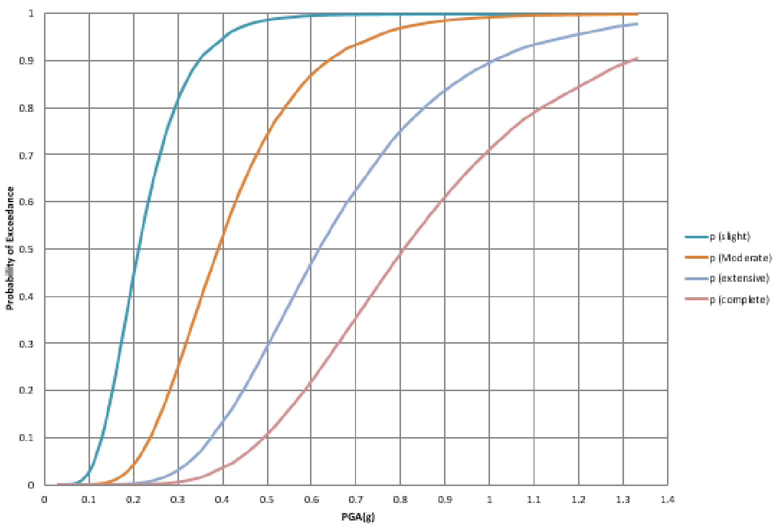

Figure 13. Fragility curve of the structure 13

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 98% and 90%, respectively.

- The results of a 3-story structure with a regular plan and high floor height

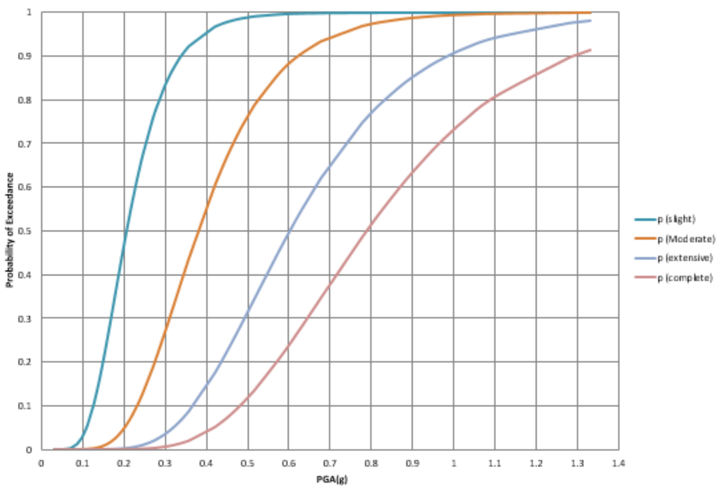

Figure 14. Fragility curve of the structure 14

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 99% and 91%, respectively.

- The results of a 3-story structure with an irregular plan and a short floor height

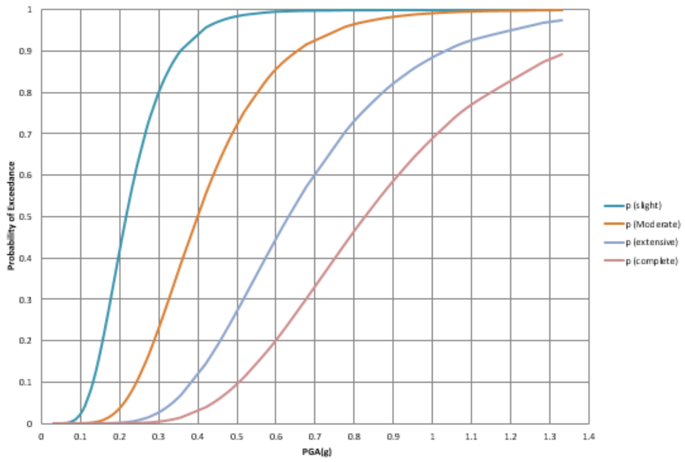

Figure 15. Fragility curve of the structure 15

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 98% and 89%, respectively.

- The results of a 3-story structure with an irregular plan and average floor height

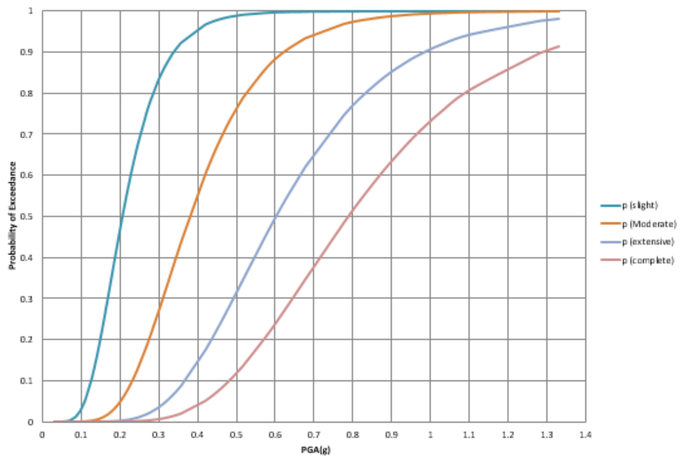

Figure 16. Fragility curve of the structure 16

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 99% and 91%, respectively.

- The results of a 3-story structure with an irregular plan and high floor height

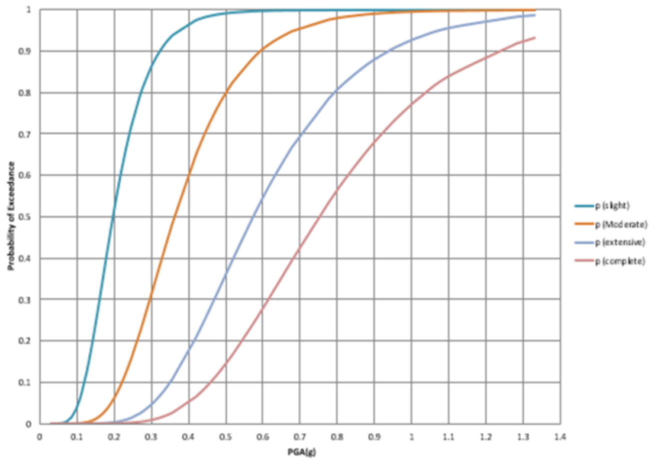

Figure 17. Fragility curve of the structure 17

According to the figure, the exceedance probability of structure from the threshold of slight, moderate, extensive and complete damage is calculated as 100%, 100%, 100% and 93%, respectively.

4. Discussion and Conclusion

The findings of this study demonstrated that the structural system composed of autoclaved aerated concrete (AAC) reinforced panels and blocks provides a reliable and efficient solution for both gravity-bearing and seismic load-bearing construction. The analysis revealed that as the number of stories increases, the vulnerability of the structure to seismic damage becomes more pronounced. For instance, the probability of passing damage thresholds was significantly lower in one-story structures than in two- or three-story configurations. This aligns with the general understanding that structural mass and height amplify seismic response and demands on structural integrity [4]. These results affirm the suitability of AAC systems in low-rise buildings, where their lightweight nature, high thermal performance, and simplified integration with prefabricated components can be fully leveraged.

The performance of the AAC-based systems under seismic loading scenarios was further validated through nonlinear static and dynamic analyses. The application of pushover and incremental dynamic analysis (IDA) confirmed that the AAC wall system exhibited consistent lateral stiffness and acceptable ductility levels within the code-prescribed limits. These findings support previous empirical research indicating that reinforced AAC elements, when properly tied horizontally and vertically, can achieve effective energy dissipation and prevent progressive collapse during seismic events [1]. Moreover, the inclusion of bed-joint reinforcements and integrated vertical ties contributed significantly to the structural coherence under dynamic stress conditions. This mirrors the outcomes of studies conducted on masonry wall systems subjected to lateral loading, which emphasized the critical role of reinforcement continuity in achieving resilience [3].

The modeling efforts highlighted the importance of architectural layout and wall-to-floor ratios in determining seismic performance. Structures with symmetric layouts and balanced wall distributions performed better in maintaining integrity under simulated earthquake forces. These insights are consistent with seismic design principles that advocate for uniformity in mass and stiffness distribution to avoid torsional irregularities and stress concentration [11]. Moreover, the importance of minimum wall thickness and adequate wall ratios in each elevation direction, as considered in the current modeling framework, reflects the seismic regulations followed globally for non-frame load-bearing systems [6]. By integrating these variables into the modeling process, this study offers a holistic approach to evaluating AAC structural systems in compliance with both international and national seismic standards.

Importantly, the results affirm that AAC structural walls can serve as viable lateral load-resisting elements, particularly when combined with effective tie mechanisms. The observed behaviors during nonlinear analyses confirm that such systems can withstand moderate to high seismic loads without critical failure, provided the wall elements are reinforced and detailed appropriately. This finding complements research in Turkey and East Asia, where AAC panel systems have been deployed in low- and mid-rise structures with demonstrated success in recent seismic events [7, 9]. The synergy between prefabrication and AAC technology enhances not only the structural reliability but also construction speed and quality control, a conclusion also drawn by studies evaluating modular construction systems in disaster-prone regions [5, 8].

Additionally, this study underscores the environmental and economic advantages of AAC construction, particularly in rapidly urbanizing contexts such as Iran. The thermal efficiency and fire-resistant characteristics of AAC reduce the need for supplemental insulation and safety measures, which can lower construction and operational costs over the building's life cycle. This observation is supported by the broader literature on energy-conscious building systems, which highlights AAC's contribution to passive design strategies and sustainability [2]. Furthermore, the lightweight nature of AAC simplifies handling and reduces the required foundation size, especially in single-story applications—an advantage particularly relevant for low-income housing development and reconstruction efforts in earthquake-affected areas [12].

The comparative modeling of different reinforcement scenarios also provided important practical insights. Buildings modeled with both horizontal and vertical reinforcements showed greater capacity to resist lateral forces and exhibited delayed damage progression during seismic simulations. These findings corroborate the conclusions of prior experimental studies that emphasized the importance of multi-directional reinforcement in non-frame wall systems [10]. Additionally, scenarios without vertical ties or unreinforced configurations resulted in early failure modes or drift exceedance under nonlinear incremental loading, echoing previous warnings against under-reinforced masonry systems [4]. Consequently, the study reinforces the necessity of integrated reinforcement strategies in AAC construction for it to qualify as a reliable seismic-resistant technology.

In terms of practical application, the software modeling and analysis approach used in this study presents a replicable framework for designing AAC-based systems in compliance with diverse architectural needs and regional seismic risks. The flexibility to accommodate different wall thicknesses, tie configurations, and structural layouts allows for adaptive use in both rural and urban contexts. This adaptability is aligned with recent calls for performance-based engineering approaches in earthquake-prone regions that prioritize resilience and efficiency in structural systems [1, 3]. Therefore, the structural design methodology proposed in this study contributes to a growing body of knowledge advocating for innovative, prefabricated solutions that balance structural performance, cost, and sustainability in modern construction.

One notable limitation of this study is its reliance on idealized modeling conditions and predefined material properties based on prior research and code recommendations. Although nonlinear analysis techniques such as pushover and IDA offer valuable insights into system behavior under seismic loading, they cannot fully replicate the complex interactions and degradation mechanisms that occur during real earthquakes. Factors such as workmanship variability, imperfect connections, long-term material deterioration, and unaccounted boundary conditions may influence actual performance in ways not captured by the model. Additionally, the focus on one- and two-story buildings, while practical for validation, limits the generalizability of the findings to mid- and high-rise structures. Future empirical testing and in-situ performance monitoring would further enhance the accuracy and applicability of the results.

Future research should consider expanding the study to include multi-story buildings and diverse soil-structure interaction conditions. Investigating the dynamic behavior of AAC wall systems with various roof systems, such as steel joists, composite decks, or cross-laminated timber panels, would also provide broader insights. Moreover, experimental validation of the modeled reinforcements—particularly under cyclic and post-yield loading—would help bridge the gap between theoretical performance and real-world applications. Studies incorporating variable environmental conditions such as humidity, temperature fluctuations, and freeze-thaw cycles would further enhance understanding of AAC durability in different climates. Finally, cross-national comparative studies involving countries with high seismic risk and active AAC use, such as Japan, Turkey, and China, would offer valuable benchmarks for policy and design development.

From a practical standpoint, the findings of this study highlight the need for greater integration of AAC-based prefabricated systems into Iran's national housing and construction strategy. The demonstrated seismic performance and construction advantages of AAC systems suggest that they can serve as effective alternatives to traditional brick or concrete masonry systems, especially in low-rise buildings and mass housing developments. Architects, engineers, and construction managers should be trained in the design and detailing of AAC structural systems to ensure proper implementation. Regulatory bodies and standard-setting agencies should also revise seismic design codes to explicitly accommodate AAC wall systems and reinforcement strategies, promoting wider adoption and investment in local AAC production facilities. Moreover, the integration of AAC systems into modular construction platforms could accelerate post-disaster reconstruction and sustainable urban development in seismic regions.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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