buildings

IMPACT FACTOR 3.1

CITESCORE 3.4

Haji Sadeghi, N., & Correia, M. (2025). Preventive Conservation of Vernacular Adobe Architecture at Seismic Risk: The Case Study of a World Heritage Historical City. Buildings, 15(1), 134. https://doi.org/10.3390/buildings15010134

Article

# Preventive Conservation of Vernacular Adobe Architecture at Seismic Risk: The Case Study of a World Heritage Historical City

Neda Haji Sadeghi, Hamed Azizi-Bondarabadi and Mariana Correia

Special Issue
Earthen Architecture: Challenges and Opportunities for the 21st Century

Edited by
Prof. Dr. Mariana Correia and Dr. Telma Ribeiro

MDPI

https://doi.org/10.3390/buildings15010134 *buildings*

MDPI

*Article*

# Preventive Conservation of Vernacular Adobe Architecture at Seismic Risk: The Case Study of a World Heritage Historical City

**Neda Haji Sadeghi [1,*], Hamed Azizi-Bondarabadi [2] and Mariana Correia [3]**

[1] Department of Art and Architecture, Yazd University, Yazd 8915818411, Iran
[2] Department of Civil Engineering, Yazd University, Yazd 8915818411, Iran; hamed.azizi@yazd.ac.ir
[3] CIAUD-UPT—Hub of CIAUD Research Center at UPT, Department of Architecture and Multimedia Gallaecia, UPT—Portucalense University, 4200-072 Porto, Portugal; marianacorreia@upt.pt
* Correspondence: neda.sadeghi@yazd.ac.ir

**Abstract:** Heritage is strengthened through proactive actions, known as preventive conservation, that are considered before earthquakes, rather than reactive actions addressed when the emergency situation occurs. Considering that there are several regions around the world with very active seismicity, conservation interventions should guarantee human safety and the improvement of the inhabitant's living conditions while keeping alive the earthen fabric and adobe buildings, thus preserving the lives of the residents but also preserving cultural heritage in the face of earthquakes. The main aim of this paper is to define a comprehensive conservation procedure addressing the preventive conservation of vernacular adobe vaulted houses in Yazd, an Iranian World Heritage property, since 2017. The fundamental phases of this procedure, which this paper's structure is based on, include introducing the case study and addressing the conservation objectives, the assessment of significance and value, the seismic criteria, the conservation strategies, seismic safety assessment, and decision-making on interventions. The comprehensive preventive conservation procedure presented in this paper was determined by relevant conservation criteria, which contributed to an adequate seismic-retrofitted intervention design. This conservation approach requires evaluation of the seismic performance and the buildings' safety, through which the decision regarding intervention could be made. Accordingly, this research also dealt with the seismic safety assessment of an adobe building through numerical research work performed using the software HiStrA Ver.2022.1.6. Based on the numerical results, decisions on the need and on the extent of intervention techniques were addressed. In addition, a comparative study was performed on different seismic strengthening techniques available in the literature to define fundamental conservation criteria. In this way, there are more chances for human lives to be preserved if an earthquake occurs.

**Keywords:** preventive conservation; vernacular; adobe heritage; earthen architecture; vaulted house; seismic safety; Yazd; cultural heritage preservation; HiStrA software Ver.2022.1.6

check for updates

Academic Editor: Antonio Formisano

Received: 18 November 2024
Revised: 26 December 2024
Accepted: 30 December 2024
Published: 4 January 2025

**Citation:** Haji Sadeghi, N.; Azizi-Bondarabadi, H.; Correia, M. Preventive Conservation of Vernacular Adobe Architecture at Seismic Risk: The Case Study of a World Heritage Historical City. *Buildings* **2025**, *15*, 134. https://doi.org/10.3390/buildings15010134



## 1. Introduction

Across the different continents, earthen heritage has always been present as part of human history. In spite of its evident cultural importance, worldwide, vernacular earthen architecture remains a fragile and vulnerable heritage that needs special attention and protection to survive, in particular as 15% to 17% of the world's population [1] lives in earthen dwellings. The number of earthen households around the world has been decreasing at a fast pace. Addressing preventive measures to avoid damage and degradation to these structures is crucial for the survival of this ancient heritage.

Earthen architecture has been an outstanding expression of human ingenuity throughout the centuries. Some of the oldest evidence of adobe architecture is from archeological sites such as Jericho (8300–7600 BCE) and Çatal Höyük in Anatolia (7500–6400 BCE) [1]. A wide and rich range of earthen typologies, techniques, and building cultures can be found around the world. This is the case of pueblos and adobe missions in the American southwest, pre-Columbian adobe Huacas in South America, and earthen pyramids in Central America. From northern Africa to the Iberian Peninsula, a high diversity of architectural heritage can be observed, from earthen Kasbahs, Ksours, and villages to rammed-earth military architecture. In sub-Saharan Africa, living heritage can be traced from modest dwellings and shrines to mosques and monumental palaces. In the Arab region, vernacular earthen architecture can be found in oasis parts of cultural landscapes, but also as skyscrapers in urban cities. Throughout Europe, earth was used to build farm buildings, churches, urban dwellings, and factories, but also bourgeois castles and powerful fortresses. Across Asia, a wide diversity of earthen techniques can still be found nowadays in places of worship, caravanserai, but also ancient archeological sites, historic urban villages, and desert cities along the Spice and Silk Roads.

Yazd, with its pristine earthen urban fabric, adobe wind-catchers, courtyards below ground level, historic houses, and communal qanats, remains an international reference for earthen architecture. The significance and value of Yazd as an adobe historic city contributed, in 1972 and 1976, respectively, to the city hosting the first and second 'International Symposiums on the Conservation of Mud Brick Monuments'. These events are known today as the first and second World Congresses on earthen architectural heritage. In 2003, Yazd hosted the 'Ninth International Conference on the Study and Conservation of Earthen Architecture'. Terra 2003 is known today as the 9th World Congress of Earthen Architectural Heritage organized under the aegis of ICOMOS-ISCEAH, the International Scientific Committee on Earthen Architectural Heritage from ICOMOS, the International Council on Monuments and Sites. Yazd is the only city in the world that has hosted the Earthen Architectural Heritage World Congress three times, which also demonstrates its special and unique character and importance.

Due to the relevance of Yazd's Outstanding Universal Value, in 2017, around 200 hectares of its earthen fabric were designated as a World Heritage property. Under the title 'Historic City of Yazd', this property was inscribed on the World Heritage List, under criterion (iii), for being an 'exceptionally elaborate construction system in earthen architecture and the adaptation of the ways of living to hostile environment for several millennia', and under criterion (v), for being an 'outstanding example of a traditional human settlement (...) in a desert environment (...) that results from the optimal use and clever management (. . .) [of the] qanat system and the use of earth (...)' [2]. Following the World Heritage assessment, and due to the potential risk to the property due to earthquakes [3], one of the World Heritage Committee recommendations was that research should be conducted regarding Yazd's risk-preparedness for seismic events.

This World Heritage property is a high visited tourist destination in Iran. Historical hotels and rehabilitated historical houses should be better prepared regarding preventive strengthening measures. That is why significant consideration should be given to implementing preventive conservation measures [4] by landowners and by ICHTO, the State Iranian Cultural Heritage Organization.

In order to determine an effective intervention plan for seismic retrofitting, and thereby to save the lives of residents and visitors, it is necessary to assess the seismic safety of built heritage before an earthquake occurs. This evaluation should also take into account the cultural and historical significance of the heritage. Hence, the main objective of this paper is to establish a comprehensive conservation procedure addressing the preventive conservation of historical adobe dwellings in Yazd, with a special focus on safety evaluation as a crucial step in the preventive conservation process. To this end, the seismic performance and structural safety of an adobe house, along with the impact of a suitable reinforcement methodology on its efficacy, are numerically assessed. It should be emphasized that this paper does not aim to investigate the current damage to adobe buildings in the historic fabric of Yazd and the applicable repair methods. The present research focuses on addressing preventive measures for adobe buildings that are in good condition and still in use.

## 2. Preventive Conservation

The notion of preventive conservation has been known about since the 19th century [5]. Notably, the process of identifying, evaluating, and controlling certain factors from interdisciplinary methods for the development of preventive conservation and maintenance techniques mostly originated inside the museum setting [6]. However, the notion of preventive conservation for built heritage was not extensively adopted until the 1970s, when it resurfaced after the recognition of the limited success and high expenses associated with conventional remedial conservation methods. This concept gained recognition as a distinct field in the early 1990s and underwent widespread dissemination, mostly due to the attempts of the International Center for the Study of the Preservation and Restoration of Cultural Property (ICCROM) [5]. ICCROM determined that preventive conservation should be defined as "The full range of actions designed to safeguard or to increase the life expectancy of a collection or an object." [7].

Nevertheless, the idea of preventive conservation has mostly been formulated within the framework of research on movable heritage. However, it seems that the notion remains equally applicable to built heritage [5]. This transition from collections to buildings involved various considerations on the matters concerning usage and the economic consequences of conservation, prompting studies to explore further aspects of community engagement and integrated political agendas [8,9]. Initiatives within the context of preventive conservation involve the establishment of a successful and methodical approach to recognize, assess, and manage the risks that impact all cultural assets. The objective of these activities is to mitigate these risks by assessing their level of influence on the consequences of degradation and implementing suitable strategies to prevent or, at the very least, decelerate their adverse impacts [10].

According to Ashurst [11], preventive conservation is a strategy that systematically seeks to guarantee the long-term physical preservation of historical structures. It is imperative for conservation professionals to acknowledge preventive conservation as the most efficient method for advancing the long-term preservation of cultural property [12].

It is significant to highlight that the strategies employed for the conservation of heritage in seismically active regions can be delineated into two distinct classifications: pre-earthquake conservation and post-earthquake conservation. The former is examined in the present study. The objectives of ICOMOS and ICCROM emphasize the need to establish a culture of prevention prior to an earthquake event. This approach is not only more cost-effective but also crucial, because reacting to emergencies after an earthquake may not always be efficient, particularly when the damage is irreversible [13]. The Lima Declaration [14] prescribed the establishment of a disaster mitigation culture and stressed the need for ICOMOS National Committees to enhance the essence of conservation charters, taking into account the mitigation of cultural heritage disasters in areas prone to earthquakes. In general, a thorough evaluation of the hazards that impact a site and its inhabitants and visitors is needed for the purpose of disaster prevention.

Concerning vernacular heritage, inadequate craftsmanship, insufficient financial support, a large number of buildings without maintenance, and the use of substandard materials require that measures be implemented to establish preventive conservation techniques and criteria. These are essential to safeguard this traditional architecture from various potential risks that may pose a threat in the future. Particular attention should be given to preventive conservation for earthen architectural heritage, as earth as the base raw material of the building is often inherently fragile and can degrade rapidly under certain conditions [5]. Analysis of earthquake-related casualties and losses in recent years indicates that seismic events can cause significant and devastating damage to buildings, particularly when built with fragile materials like adobe.

In 2001 and 2007, two earthquakes with a moment magnitude of around 8 affected various Peruvian regions and destroyed a vast number of adobe houses. In El Salvador, two earthquakes ($M_w$ of 7.7 and 6.6) caused severe damage and collapse in 200,000 adobe houses [15,16]. Blondet et al. [17] and Dowling [18] summarized the typical failure of adobe constructions due to earthquakes. Failures of adobe constructions (mainly dwellings) in different parts of the world (Iran and Pakistan, 2013; Turkey, Maden-(Elazığ), 2011; Peru, Pisco, 2007; San Simeon in California, 2003) were investigated by Tarque et al. [19] based on post-earthquake observations. Although there are different typologies of constructions in these areas, it seems that the type of building failure is common in all of them, basically being due to the low tensile strength of adobe masonry.

During earthquake events, the adobe material starts to fail at the zones of stress concentration, such as the corners of openings. Also, vertical cracks at the intersection of two orthogonal walls may appear. This is due to the absence of confinement elements that can guarantee a box behavior on each floor. If walls continue to break, then the most probable form of failure is due to the overturning of walls and the roof collapsing. The main reasons for the failure of adobe buildings can be summarized as the brittleness of adobe material, poor adhesion between mortar and adobe units, a lack of integrity (confinement elements) and weak connections between walls and roofs, a lack of bond beams, weak wall to floor connections, weak wall to wall connections, poor quality of the structural materials, poor workmanship during the construction, etc. [20,21].

The Alpine-Himalayan earthquake zone as one of the most earthquake-prone areas in the world and traverses the country of Iran. Over the course of the 20th century, Iran saw 20 significant earthquakes, resulting in the deaths of over 140,000 individuals, the demolition of a number of villages and cities, and substantial economic damages [22]. Recent seismic events that occurred in Tabas (1978), Bam (2003), and Dahoeieh-Zarand (2005) have shown that adobe buildings are inherently more vulnerable to seismic damage than other building types [23–25].

Notwithstanding its position in a region prone to earthquakes, Iran boasts a substantial collection of historical adobe buildings, especially in its central and southern regions. The historical city of Yazd, characterized by its significant adobe monumental and vernacular architecture, has a rich earthen legacy originating from ancient cultures and civilizations across several historical eras. The city's historical fabric is characterized by a large number of traditional vaulted adobe houses. A significant proportion of these houses remain in good condition and continue to be used on a daily basis.

Adobe vaults are often distinguished by the use of weak and fragile materials, excessive weight, and inadequate connections. As a result, their collapse is a significant contributor to human deaths, as was observed during the 2003 Bam earthquake [26–31]. Given the seismic risk in Yazd, characterized by a code-based peak ground acceleration of

0.25 g (return period of 475 years), together with the widely recognized high susceptibility of vaulted adobe houses to collapse during earthquakes, conservation efforts should prioritize a preventive approach regarding the irreversible collapse of these buildings during occurrences of exceptional seismic activity. The existence of a potential risk leads to a need to change conservation methodology components or to focus more specifically on some of these components. The methodology regarding the preventive conservation of historical adobe houses in Yazd presented in this paper includes different steps, such as documentation and studies; the definition of objectives; the assessment of significance and values; the definition of seismic safety and seismic intervention criteria; conservation strategies and the prioritization of case studies; decision-making on interventions; and seismic safety assessment.

## 3. Documentation and Studies

For the present paper, it was essential to examine Yazd's historic earthen fabric, its adobe architectural heritage, and its conservation practices. Additionally, it was also fundamentally important to assess the region's seismic activity and its protective regulations in that regard.

### *3.1. The City of Yazd and Its Seismicity*

Centrally situated in Iran, the city of Yazd serves as the administrative hub of Yazd province and is encompassed by expansive deserts characterized by a distinct climatic environment. Yazd, being the most arid city in Iran, has a hot desert summer climate with a maximum temperature of 45 °C, 12% relative humidity, and a high rate of evaporation; a cold winter with a minimum temperature of −14 °C; an average of 3188 sunny hours per year; and an estimated annual precipitation of 64 mm [32].

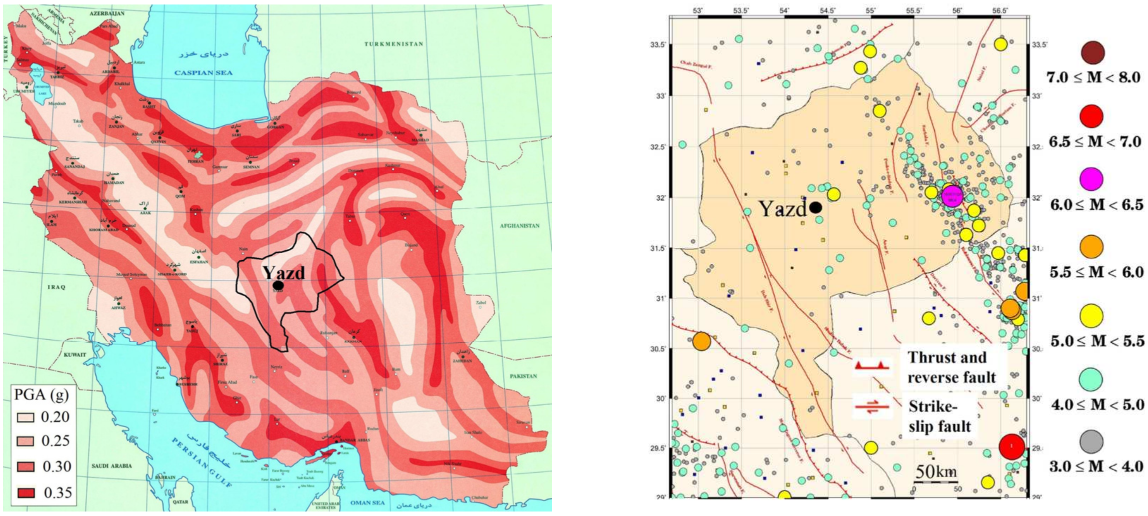
The combination of these natural conditions, together with the local abundance of high-quality soil suitable for constructing adobe units, has established adobe architecture as the prevailing building style in the historic fabric of Yazd (see Figure 1). The well-preserved adobe architecture of Yazd includes religious buildings, palaces, defensive fortifications, gardens, schools, and traditional dwellings that originated from different historical periods after the Islamic Era, namely from the 6th and 7th centuries and thereafter.

(**a**) (**b**)

**Figure 1.** Yazd's historic fabric: (**a**) general view; (**b**) view of residential buildings (source: M. Hoseini).

Based on the Iranian seismic design code (named hereafter Standard 2800) [33], the city of Yazd is prone to earthquakes, with a likely peak ground acceleration (PGA) of 0.25 g for a return period of 475 years (see Figure 2a). Furthermore, Ariamanesh [34] calculated its likely PGA as 0.27 g for a return period of 75 years. Asadi et al. [35] also calculated that Yazd has PGAs of 0.24 g for a return period of 475 and 0.35 g for a return period of

2475 years. Historically, Yazd province has been susceptible to seismic activity. Figure 2b illustrates the positions of earthquake epicenters and significant faults in the province and its surrounding regions.




(**a**) (**b**)

**Figure 2.** Earthquake hazard of Yazd province: (**a**) different seismic hazard zones of Iran [36]; (**b**) earthquake epicenters and main faults around the province [37].

The province saw nine significant historical earthquakes with an estimated magnitude greater than 4 before 1900 (see Table 1). The most significant ones took place in 1824, 1844, and 1853. However, there are no pertinent records documenting the extensive destruction they inflicted [35,38,39]. Since 1900, there have been thirteen earthquakes with a magnitude greater than 4.5 and an epicentral distance below 150 km from the city of Yazd, as presented in Table 1 [40]. No significant damage to structures was recorded in any of these events.

**Table 1.** Historical earthquakes that occurred near Yazd province [38] and the earthquakes that recently occurred near the city of Yazd [40].

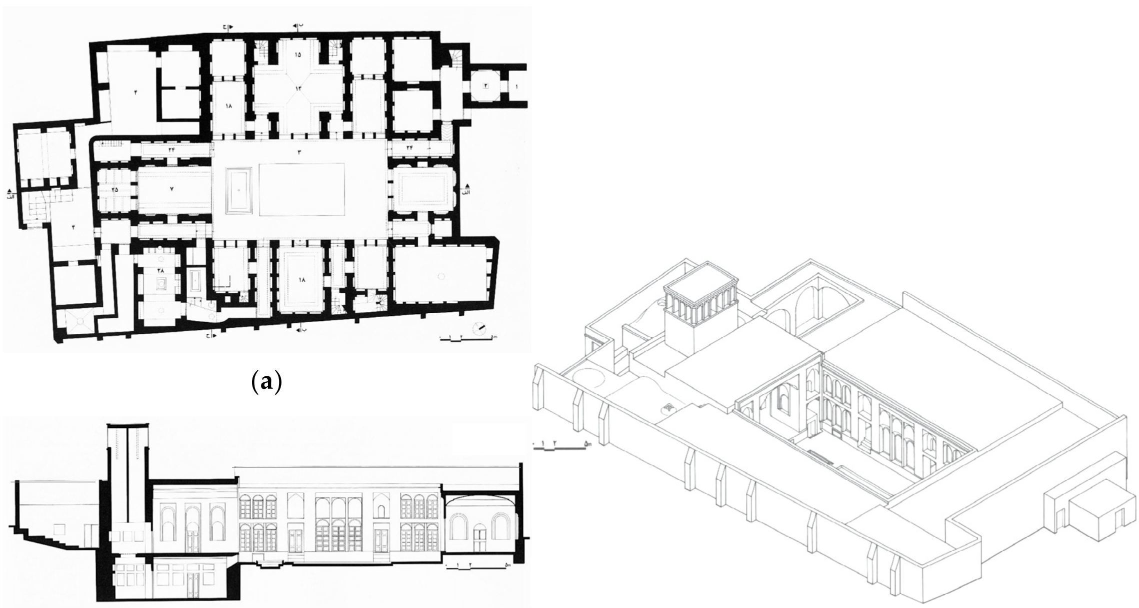
| Historical Earthquakes | | Recent Earthquakes | | |
|---|---|---|---|---|
| **Year** | **Magnitude ($M_s$)** | **Year** | **Magnitude** | **Epicentral Distance (km)** |
| 1344 | 5.7 | 1958 | 5.7 $M_w$ | 122 |
| 1459 | 6.6 | 1973 | 5 $M_b$ | 17 |
| 1591 | 5.9 | 1974 | 5.2 $M_b$ | 121 |
| 1752 | 5 | 1978 | 4.5 $M_b$ | 18 |
| 1765 | 4 | 1979 | 4.6 $M_b$ | 86 |
| 1784 | 4 | 1981 | 4.5 $M_b$ | 140 |
| 1824 | 6.4 | 1982 | 4.8 $M_b$ | 128 |
| 1844 | 6.4 | 1995 | 4.8 $M_b$ | 112 |
| 1853 | 6.5 | 2001 | 4.5 $M_b$ | 149 |
| | | 2005 | 4.5 $M_b$ | 56 |
| | | 2007 | 5 $M_w$ | 147 |
| | | 2012 | 4.5 $M_b$ | 64 |
| | | 2017 | 5 $M_b$ | 97 |

While Yazd is generally susceptible to nondestructive earthquakes of low to moderate intensity, the existence of eleven active faults in the city and its surrounding area (Figure 2b) indicates a significant seismic risk. This phenomenon emerges from a widely acknowledged seismologic theory, namely that devastating earthquakes are triggered by active faults following millennia of seismic inaction. This phenomenon pertains to two catastrophic seismic occurrences that took place in Iran, the 2003 Bam and 1978 Tabas earthquakes, both of which were also experienced in the city of Yazd. The existence of the oldest mosques in Tabas and in Arg-e-Bam dating back approximately 700 and 2000 years, respectively, prior to the occurrence of the earthquakes indicates that the absence of previous seismic events can lead to significant earthquakes characterized by extensively prolonged return periods [41,42].

### *3.2. Adobe Houses in Yazd*

A study conducted by Aqasafari et al. [43] revealed that in 2006, in the historic fabric of Yazd, there were almost 4200 adobe houses over 60 years old. The majority of them originate from the Qajar (1785–1925) and Pahlavi (1925–1979) eras, with just a small number surviving from the Safavid period (1501–1736) and older [44]. The vernacular architecture of Yazd's adobe structures has evolved over several centuries, as a direct response to the arid climatic conditions of the region. Each house is oriented towards a central courtyard containing a central pool and with gardens around its sides, which serves as the focal point for the living areas. Typically, the areas surrounding the courtyard are covered by a series of adobe barrel vaults, high solid earthen walls around the building constructed for the purpose of ensuring security and privacy and shielding against the sun and hot winds. This also comprises the only opening to the street, which is through the main entrance [45].

Yazd's vernacular adobe houses are commonly referred to as year-round houses due to the living areas surrounding the courtyard, to be used throughout the various seasons of the year [46]. A typical adobe house in Yazd is presented in Figure 3. It can be noted that, in addition to adobe masonry, Yazd's buildings also contain other materials, such as bricks (baked adobe), wooden components, floor tiles, gypsum, and earthen plaster, a mixture of clayish soil and straw.



(**a**) (**b**) (**c**)

**Figure 3.** Tehrani-ha house [47]: (**a**) plan view; (**b**) sectional elevation view; (**c**) perspective view.

### 3.3. Protection Policy and Conservation Activities in Yazd with Special Focus on Seismic Safety

The preservation and respect of cultural heritage may be ensured by formulating updated and protective regulations and legislation. However, there is a significant lack of conservation policies specifically addressing adobe architecture. Currently, there are no established regulations or criteria pertaining to the preservation of historical adobe architecture, both before and after the occurrence of an earthquake. This situation results in damage, devastation, or the loss of adobe heritage as a consequence of earthquakes, and a noticeable absence of inclination towards the restoration or the rebuilding of damaged adobe structures.

The Iranian codes for the seismic rehabilitation of existing buildings [48] and Standard 2800 [33] do not include adobe structures in the current construction codes. The absence of comprehensive legislation and laws in the field of conservation of adobe heritage in Yazd is evident, resulting in somewhat random conservation interventions. Moreover, Iran lacks a national regulation for the conservation of adobe heritage. The 2003 earthquake in Bam resulted in significant damage and destruction of several adobe structures in the citadel [49]. The newly restored or rebuilt buildings now only retain a limited number of architectural, cultural, and historical aspects of adobe heritage that existed previous to the catastrophe. In the case of Bam city, Victoria Kianpour [50] states that this occurred as a result of the urgency to accelerate reconstruction through the use of conventional building materials, concerns regarding the safety of adobe construction methods, and the absence of an established national building code or guidelines to support adobe construction.

Significant conservation efforts in the city of Yazd have been carried out under the oversight of ICHTO (Iranian Cultural Heritage, Handcrafts and Tourism Organization), keeping alive the World Heritage city earthen fabric and preserving its cultural heritage. Public or private organizations or individuals rent or purchase the aforementioned buildings for a new purpose, such as offices, institutes, museums, hotels, restaurants, and schools (see Figure 4). Over the past several decades, there has been an increasing inclination to convert some impressive examples of architecture into conventional hotels and restaurants catering to both domestic and foreign visitors. Nevertheless, there is concern regarding the alteration of the identity of the houses when introducing new functions and activities.

(**a**) (**b**)

**Figure 4.** Distinguished adobe houses in Yazd historic fabric: (**a**) Golshan house (hotel–restaurant); (**b**) Malek-o-Tojjar house (hotel–restaurant) (source: N. Haji Sadeghi).

The majority of conservation work in Yazd city has been carried out by masons who specialize in preserving and restoring historic adobe structures, under the guidance of architects or conservators. The conservation efforts described above did not take into account the enhancement of the seismic performance of these adobe dwellings, but rather focused on maintaining the visual integrity and preserving the original construction.

In the historic fabric of Yazd, the majority of recent conservation interventions in the adobe houses focused on immediate strategies to avoid collapse. Other conservation measures include removing debris, cleaning surfaces, renewing plaster, repairing damaged sections, restoring damaged parts, and rehabilitating traditional houses.

## 4. Conservation Objectives

Various goals are taken into consideration for the conservation and restoration of adobe projects in seismically vulnerable areas in the existing literature. These goals include the following:

- To improve the structural performance and safety of earthen buildings while minimizing the loss of historic fabric (project for the seismic retrofitting of historic earthen buildings in Peru) [51];
- To have minimal impact on the original building, but also to stabilize the ruins and make it safer for people (a project that is part of the "Getty Seismic Adobe Project to Historic Adobe Buildings") [52];
- To seismically stabilize the site and to develop a design that satisfies life safety and fabric preservation (a project at the Las Flores Adobe National Historic Landmark) [53];
- To protect the vernacular value in many of the villages in Peru (seismic risk management research project) [54];
- To minimize earthquake catastrophes and losses (research regarding a seismic retrofitting system in a historical adobe building) [52].

Significantly, the seismic upgrading of historic structures encompasses two separate and seemingly contradictory objectives. According to the Lima Declaration [14], the first priority for heritage protection in the face of catastrophes, such as earthquakes, is to save human lives. The presence of numerous heritage buildings at risk of collapse, used for housing, business, or tourism purposes ([14], Art 7), underscores the critical importance of prioritizing human life safety. The preservation of the integrity, authenticity, and historical features of built heritage must be prioritized as the subsequent objective in heritage conservation.

One of the primary objectives of addressing the preventive conservation of historical adobe houses in Yazd is to ensure the safety of a significant number of residents during earthquakes, considering the city's seismic risk levels. This need will be particularly crucial because of the limited availability of emergency services within a reasonable timeframe for a substantial portion of Yazd's historic city. This issue has emerged due to the compact urban structure of the historic fabric, characterized by narrow alleys and an organic layout of pathways (see Figure 5) [55], which increases the risk of catastrophe and fatalities during earthquakes.

The preservation of Yazd's earthen fabric and cultural heritage, which will protect the adobe houses during earthquakes, constitutes an additional goal for the conservation procedure. Furthermore, one of the primary goals during the strengthening process should be to ensure the conservation of the historical characteristics and integrity of the adobe buildings. Due to the World Heritage status of the property, it is not acceptable to enhance the safety of adobe buildings during earthquakes at the expense of damaging their historic fabric in the process of reinforcement.

Implementing suitable retrofitting methods and confirming their effectiveness using scientific methods, such as numerical modeling, can help to provide a systematic strategy and guidance for selecting suitable strengthening techniques. It is relevant, when defining the conservation process, to examine not only the architectural and structural elements but also other factors such as cultural, social, and economic concerns.

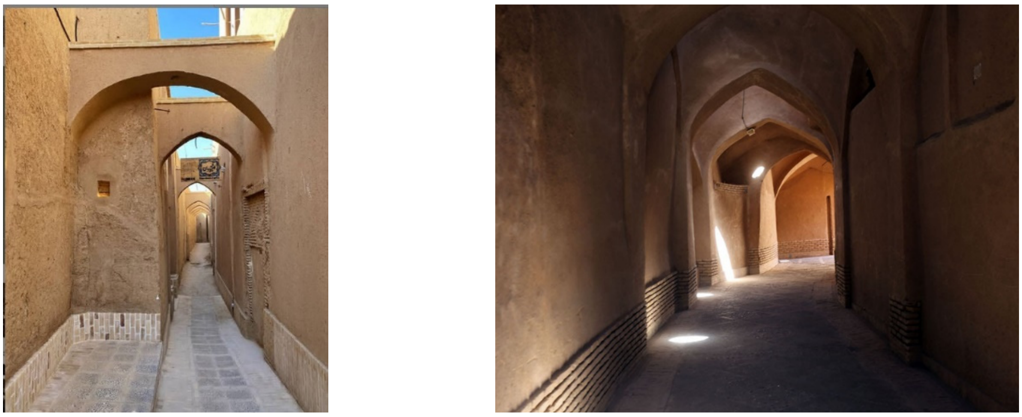


**Figure 5.** Narrow alleys and organic layout of pathways in the historic fabric of Yazd (source: N. Haji Sadeghi).

## 5. Evaluation of the Importance and the Conservation of Values

An analysis of the reasons why Yazd's earthen fabric is held in high regard for both current and future generations could enable the evaluation of its importance. Considering the significance of Yazd's historical fabric and how this significance might be increased through future use, interventions, preservation, and protection could be instrumental when addressing preventive conservation decision-making.

Historical houses in seismically prone areas are first and foremost valued as housing for current and future residents. What follows is an analysis of the earthen fabric's significance and the built heritage's value. Research investigations indicate that there is a significant number of historical adobe houses within the historic city of Yazd [43]. A substantial proportion of these adobe dwellings are currently inhabited. These ancient residences contribute to the overall fabric's liveliness and activity, preserving cultural individuality while also preventing cultural uniformity. Significantly, it can be stated that around the world, Yazd's earthen historic fabric is among one of the most extensive adobe urban sites in use, and in a good state of conservation. Its historical adobe architecture is erudite in its singularity, but vernacular in its origin [56]. The city is known for its traditional courtyard houses and well-designed urban landscape. The historical urban environment of Yazd is an indicator of the cultural, social, and religious configuration of the historical fabric. It is widely acknowledged that the city center skyline, which is particularly known for its minarets, wind-catchers, and domes, is a masterpiece and provides an exceptional view and visual integrity that can be seen from a great distance (see Figure 6).

**Figure 6.** Skyline of the historic fabric of Yazd (source: M. Correia ©ICHTO).

The techniques and the skills that are employed for the construction of vernacular adobe dwellings in Yazd's historic fabric constitute a remarkable architectural technology. The only local resources that are used to manufacture adobe units and mortar for the construction of walls and vaulted roofs are water and soil, which are obtained by excavating the earth to construct underground rooms of houses. The prevailing method used in the construction of adobe vaults and dome roofs in these dwellings is a refined and advanced roofing system, characterized by its construction without a framework.

Yazd's adobe vernacular architecture exemplifies the human ability to optimize the use of limited local resources in an effective way. Preserving this sustainable vernacular architecture and conducting in-depth studies on it may enhance the design of new buildings that ensure human comfort in challenging climatic conditions, and even further when facing climate change's stronger impacts in hot environments.

## 6. The Criteria for the Seismic Safety and Intervention

The diverse impacts of earthquakes on built heritage indicate that the characteristics of potential seismic events are critical parameters for establishing seismic criteria. Considering the seismicity of Yazd, the adobe houses should maintain their structural stability even during the most severe expected earthquakes. Some damages to structural and non-structural elements are allowable, only if these damages do not compromise the integrity of the entire structure. To this end, the structural capacity of adobe houses should be more than the seismic demand.

Preventive conservation interventions for vernacular adobe houses in Yazd must take into account the cultural, social, and historical value associated with these structures. Neglecting this value results in the erosion of people's identity and culture. The present and future functions of adobe buildings are critical for establishing seismic safety criteria. The majority of adobe structures within the historic fabric of Yazd have served as private residences. However, in recent decades, numerous adobe houses have been repurposed for various functions, including schools, institutes, hotels, and university departments (see Figures 4 and 7).

(**a**) (**b**)

**Figure 7.** New function of adobe houses in the city historic fabric: (**a**) Art and Architecture Department at Rasoulian house; (**b**) Rismanian house (Source: N. Haji Sadeghi).

It is necessary to establish seismic safety criteria for the preventive conservation of Yazd's historical adobe houses, considering the seismic activity in the area. Intervention measures for preventive conservation, in accordance with general conservation criteria and specific seismic safety criteria, should

- Ensure the safety of individuals (owner, user, visitor);

- Enhance the seismic resistance of buildings (reducing damages during minor or moderate earthquakes and minimizing structural damages during major earthquakes);
- Respect buildings' social, cultural, and historical value;
- Consider their current and future function;
- Create very limited alteration to the building's appearance;
- Minimize invasiveness in the original structure of adobe houses;
- Use traditional techniques and materials; when this is not possible, then a combination of traditional and modern techniques and materials should be considered (if their use do not affect the integrity of the building);
- Respect historical adobe houses' integrity and authenticity;
- Comply with original construction materials and techniques;
- Choose reversible materials with minimal impact on the adobe structure;
- Select economical materials (affordable materials for house owners);
- Consider the availability of materials and of technological competency in Yazd;
- Be durable in Yazd's climatic condition;
- Be easy to maintain and monitor.

These are a few recommendations to consider when addressing seismic safety criteria in preventive conservation.

## 7. Conservation Strategies and Prioritization of Case Studies

Considering the large number of vaulted adobe buildings existing in Yazd and the limited budget to address preventive proactive measures, it is essential and even critical, to prioritize the houses where conservation intervention will occur so that they are prepared if an earthquake strikes. There are some criteria that strongly influence the prioritization of adobe dwellings. This research focuses on the primary goal of the preventive conservation of adobe dwellings, which is to ensure the safety of people during an earthquake. The first parameter to consider is the number of residents in a house. The new use that can be allocated to a house can significantly impact its occupancy rate.

According to Standard 2800 [33], structures such as schools, mosques, theaters, and movie theaters, which can cause substantial loss of life when damaged, are classified as important buildings. When comparing the functions of adobe houses with those of the buildings in the specified categories, adobe houses serving as schools and universities, such as the Art and Architecture Department, emerge as the most significant structures due to the potential consequences of collapse and the associated loss of human life (see Figure 7a). To this end, for the current research, one of the buildings belonging to the Art and Architecture Department is considered as the case study for conducting seismic safety assessment (Section 9).

It is important to note that for many years, certain houses within the historic fabric of Yazd have hosted annual religious ceremonies on specific days. Most of these houses lack permanent residents, yet they attract hundreds of visitors on certain days (see Figure 7b). Consequently, prioritizing the preventive conservation of these buildings becomes essential. Furthermore, the classification of buildings in Eurocode 8 [57] and Standard 2800 [33] considers the social, cultural, and financial effects of building collapses.

Buildings in which damage would result in the loss of national heritage are extremely important when assessing the effects of collapse. These encompass cultural institutions, museums, libraries, and other locations where critical national documents and significant artifacts are conserved. In the historic fabric of Yazd, few buildings exist in such conditions; thus, it is essential to protect these dwellings in order for them to be able to withstand earthquakes. Residential buildings, offices, and hotels are subsequently considered. Given the implications of building failures, these structures possess moderate significance relative to those previously mentioned. The prevalence of adobe houses serving as residential buildings necessitates the establishment of effective parameters to prioritize intervention measures. The historical characteristics of adobe houses are a primary factor contributing to their significance. Furthermore, adobe houses exhibiting notable architectural or structural features should be prioritized for protection against earthquakes.

It is important to recognize that adobe houses within the historic fabric of Yazd are not standalone structures; rather, they are integrated components of a larger building complex. The safety of individual houses affects the safety of neighboring structures. Identifying vulnerable houses and reinforcing them improves the seismic safety of the entire complex. The challenges associated with rescue operations during an earthquake contribute to an increase in disaster impacts and fatalities. The location of buildings may serve as a significant factor in the prioritization of seismic strengthening measures. To assess the challenges of rescue operations in the historical fabric, it is essential to consider various parameters, including the proximity of the houses to emergency facilities, the width of adjacent roads, and the distance of the houses from urban open spaces [58].

The aforementioned parameters facilitate the prioritization of adobe houses and their classification into various levels according to the effects of their collapse. Each level comprises several adobe houses, and it is evident that the house with the most vulnerable structure to earthquakes should be prioritized for strengthening. To identify houses with the highest seismic vulnerability, more accurate safety assessment methods must be developed.

## 8. Decision-Making Intervention

The evaluation of the safety of adobe dwellings requires the analysis and interpretation of data obtained from their seismic safety assessment. Based on safety assessment results, a conclusion is drawn regarding the need for intervention approaches. The review of literature and field observations regarding recent earthquakes in regions with adobe architecture reveals that the vulnerability of such buildings is due to the insufficient compressive and shear strengths, extremely low tensile strength, and inadequate stiffness of adobe materials and structures. The unexpected failure of adobe structures and the dissemination of suffocating dust during their collapse are the primary contributors to significant human casualties [59]. Therefore, employing an appropriate retrofitting system to prevent or delay their collapse may be effective in mitigating earthquake disasters. This section considers intervention techniques aimed at the seismic retrofitting of adobe constructions.

Arya [60] introduced a set of intervention techniques and design recommendations derived from traditional methods for non-engineered masonry construction in seismic zones. Research conducted at the Getty Seismic Adobe Project (GSAP) has identified two primary retrofitting design concepts for adobe buildings: strength-based and stability-based. These concepts address elastic performance and post-elastic behavior, respectively. The former set of retrofitting techniques seeks to postpone crack formation by enhancing the capacity of adobe masonry or components within the elastic range. Stability-based retrofitting techniques prioritize enhancing the structural ductility of a building's post-elastic limit, which is deemed more critical than the structural performance prior to crack formation. These two retrofitting strategies may complement each other [14,61,62]. Michiels [61] and Haji Sadeghi [63] reviewed various seismic retrofitting techniques applicable to historical adobe buildings across each aforementioned group.

Despite the demonstration of vulnerability in adobe vaults during previous earthquakes, there is a shortage of experimental studies regarding the seismic behavior of vaulted adobe structures in the literature. Research focusing on specific intervention techniques for adobe vaults is also limited. In Peru, two vaulted adobe models—one unreinforced and the other fully reinforced with a polymer mesh—were subjected to simulated seismic tests.

The results indicated that the unreinforced adobe vault exhibited significant vulnerability, whereas the fully reinforced vault demonstrated satisfactory performance [64]. Sathiparan and Meguro [59] assessed the seismic performance of vaulted adobe house models utilizing both PP-band mesh and tie-bars. In order to evaluate the seismic behavior of vaulted adobe houses in Yazd, an experimental assessment of a typical adobe vault, strengthened with a textile-reinforced mortar (TRM)-based compatible composite, was conducted [65].

Various techniques were applied in conservation projects for adobe vaulted buildings across several cities in Iran, including Yazd, Bam, Kashan, and Isfahan. The techniques include the use of steel tie-rods in adobe vaults, PVC mesh covered with Kahgel [66], palm mesh and palm ropes covered with earth and straw mortar [67], fiberglass mesh and clay–straw mortar applied to both sides of the vaults [67,68], plastic mesh covered with industrial gypsum and clay mortar [69], and steel mesh covered with gypsum and straw mortar.

When selecting appropriate methods for preventive conservation intervention, there is first a need to establish conservation criteria and the principles of intervention. This is why seismic criteria for adobe houses are established and incorporated in Section 6. The final decision regarding an appropriate intervention technique for vaulted adobe houses involves selecting relevant techniques and evaluating their compliance with established seismic intervention criteria. The results are presented in Table 2.

**Table 2.** Assessment of intervention techniques for adobe buildings to determine seismic criteria.

| **Intervention Techniques** | **Minimally Invasive and Minimal Intervention** | **Respecting Authenticity** | **Compatible With Original Techniques** | **Compatible With Original Materials** | **Reversible** | **Durable** | **Having an Affordable Price** | **Availability of Materials and Feasibility of Techniques** | **Having Easy Maintenance Techniques** | **Monitorable** | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Timber bond beam | | | • | | • | | | • | • | | |
| Reinforced concrete bond beam | | | | | | | • | | • | | |
| Wooden tie beam | • | | | | • | • | | • | • | • | • |
| Steel tie rods | | | | | | • | • | • | • | • | • |
| Steel or nylon rods and straps | | | | | | | • | | | • | • |
| Steel mesh with cement plaster | | | • | | | | • | • | • | | |
| Geogrid mesh and earth plaster | • | | • | • | | • | • | • | • | • | • |
| Impregnated natural fiber mesh and earth plaster | • | | • | • | | • | • | • | • | • | • |

The symbol "•" indicates the compliance of the presented intervention techniques with seismic criteria.

All of the aforementioned intervention strategies enhance the seismic performance of adobe constructions. However, they also improve the structural behavior of adobe constructions at various scales. The two final intervention strategies shown in the table above demonstrate a higher level of adherence to the specified seismic criteria compared to the other techniques. The physical and mechanical characteristics of various mesh types presented in several studies [63,70–74] have shown that geogrid mesh is superior to impregnated natural fiber mesh for retrofitting adobe structures.

In addition to being compatible with adobe construction, natural fibers have certain limitations including moisture absorption leading to swelling and lower durability compared to geogrid mesh. Natural fibers are also more susceptibility to termite attack, and have inadequate fire resistance. Prior to the application of natural fibers in adobe construction, it was common practice to impregnate the fibers with a resin, such as epoxy or polyester resin. Impregnated natural fibers currently lack complete eco-friendliness. Meanwhile, natural fibers are also more costly than a geogrid mesh, particularly in arid towns like Yazd. Consequently, a geogrid mesh with earthen plaster is selected as the proposed intervention technique for the vaulted adobe house studied in this paper in the event of a need for seismic retrofitting. A numerical or experimental analysis should be used to validate and show the effectiveness of the suggested intervention strategy.

The selection of intervention strategies for each adobe structure is determined by the findings of the research on its historical and architectural characteristics, as well as the evaluation of its seismic structural properties. Therefore, it is necessary to establish a specific intervention plan for each adobe house. When dealing with exceptional structures that serve as monuments in the historical fabric, it is also relevant to establish specific criteria for seismic intervention and to choose suitable intervention techniques.

## 9. Seismic Safety Assessment

For built heritage in areas prone to earthquakes, safety assessment should ascertain whether the building is in a state that needs the implementation of a seismic retrofitting project and define the needed treatment measures. Within the preventive conservation procedure proposed in this study, safety assessment plays a key role. This phase includes several technical aspects, which require the phase presentation in more detail. Therefore, the objective of this section is to present a step-by-step numerical method for the seismic safety assessment of adobe vaulted houses in Yazd considering the principles of performance-based earthquake engineering as well as the conservation criteria. To this end, this section adopts a case study structure to which the method is applied. The method can be considered as a model for informed decision-making in the seismic preventive conservation of Yazd adobe vaulted houses in the future.

Strict structural analysis of any of the old vaulted adobe houses in Yazd is lacking, and the behavior, stability, and safety of these structures that face potential damage during earthquakes remain largely unknown. Generally, in the case of adobe structures, performed seismic studies have mostly focused on surveying their behavior under seismic events [18,27,75,76] and on the mechanical behavior of adobe units and prisms [77–79], adobe walls [15,80–82], and scaled adobe constructions with wooden pitched or flat roofs [83–86]. Despite the documented susceptibility of adobe vaults to earthquakes in the past, there is a scarcity of research in the literature regarding the seismic performance of vaulted adobe structures. The fact is that experimental studies on the seismic performance of adobe vaults are limited in the published literature [59,64,65].

Research performed by Kuwata, Takada, and Bastami [87] determined the natural period of a collapsed adobe vaulted structure in Bam, Iran, following the March 2003 earthquake. Moreover, the building's seismic response was examined including the discrete element approach. A limited number of field survey studies have also been conducted on the performance of vaulted adobe structures during the Bam earthquake [26,29]. Regarding the seismic performance of vaulted adobe houses in Yazd, Haji Sadeghi et al. [88] employed a numerical method to assess their structural integrity. Furthermore, Haji Sadeghi et al. [65] conducted an experimental evaluation of a traditional adobe vault in both reinforced and unreinforced states.

Considering the limited data on the structural analysis and performance of historical adobe buildings in Yazd, this section evaluates the structural performance and seismic safety of a case study structure, creating its numerical model in the software HiStrA Ver.2022.1.6 and performing several seismic analyses. The need to implement a strengthening technique, and its effectiveness on the structure's behavior is also evaluated.

Since the vulnerability assessment of historic adobe buildings is beyond the scope of the Iranian legal documentation (see Section 3.3), this section adopts the Italian guideline for reducing earthquake risk for cultural heritage buildings [89] (named hereafter DPCM11) and the Italian seismic code [90] (named hereafter NTC18). DPCM11 is one of the few available references which not only relies on the ISCARSAH recommendations [91] but also introduces specific numerical and analytical approaches for the seismic analysis and assessment of historical buildings. The approaches and procedures proposed in DPCM11 are general and can be applied to any historical building around the world, although local guidelines, if any, take precedence.

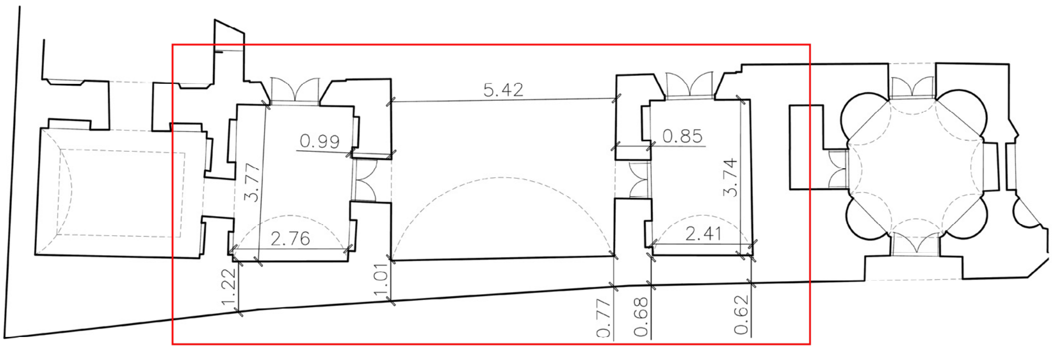
## 9.1. Description of the Case Study

As stated in Section 7, some adobe houses within Yazd's historic fabric now have new uses, such as schools, universities, and hotels, making earthquake-induced human casualties more significant than under their residential roles. Due to the importance of such houses in the disaster risk management of the city's historic fabric, the adopted case study addresses the building that hosts the Department of Art and Architecture of Yazd University, located in the heart of the fabric-nominated core zone. The department, with more than 500 students and staff members, is a historic complex including several connected houses (Figure 8a) dating back to the Qajar period (about 200 years ago). The case study, which is highlighted by the red line in Figure 8a, corresponds to the "Talar" space of one of these houses. In general, "Talar" is a dominant space in most of the Yazd traditional houses, comprising a three-sided room covered with a large-span barrel vault. Usually, it is supported by adjacent vaults with a shorter span. The Talar space may experience the most damage when an earthquake occurs, due to its large span with respect to the other vaults of a house.

The case study structure bordered by a red line in Figure 8b consists of a main barrel vault with a span and rise of 5.40 m and 1.70 m, respectively, and two adjacent vaults presenting a lower span and rise of 2.80 m, 0.90 m and 2.40 m, 0.80 m, respectively (see Figure 8b for other dimensions of vaults and walls). All the vaults under study have a thickness of 0.25 m in the form of a segmental shape, which is very common in Yazd historic houses. All of the walls maintain a constant thickness throughout their height except for the longitudinal continuous wall that presents a thickness linearly increasing up to 0.40 m at the top level.

This Talar space was chosen among several similar spaces in the department complex due to its simple form, consisting of a main central vault and two one-story adjacent smaller vaults (for more information about the Talar geometry types, see [88]), as well as its boundary conditions. The latter refers to the condition observed in the end section of the case study, which makes its numerical simulation possible without modeling the adjacent parts of the structure. As shown in Figure 8, the selected Talar space is surrounded by a dome and a perpendicular vault on the right and left sides, respectively. It was assumed that the existing dome and vault provide stiff boundary conditions on each side of the studied structure, as assumed in [88]. This can be simulated in the numerical model by considering supports at the end sections of the studied structure, namely on the exterior side of the ended transversal walls (see Section 9.2). However, to better simulate the real out-of-plane behavior of these walls as well as the rigidity of the supports, the supports were reproduced by three thick walls at the exterior side of each of the ended transversal walls (see Section 9.2).

(**a**)




(**b**)

(**c**)

**Figure 8.** The adopted case study structure: (**a**) position in the Department of Art and Architecture, shown by a blue line; (**b**) the structure borderline, shown by a red line, and dimensions; (**c**) the structure exterior view.

*9.2. Numerical Simulation*

Among the various structural component models available in the literature, a discrete macroelement model implemented in the software HiStrA Ver.2022.1.6 (Historical Structural Analyses) [92] was adopted in this paper. The link-based scheme for this macroelement was first introduced by Caliò et al. [93]. Subsequently, Pantò et al. [94] improved the macroelement to create a three-dimensional (3D) or spatial macroelement, incorporating seven degrees of freedom to represent six rigid body motions and one in-plane shear deformability. The 3D macroelement reproduces the main in-plane and out-of-plane mechanisms of unreinforced masonry structures.

The macroelement consists of four rigid plates connected by hinges, along with a single diagonal nonlinear link that rules the in-plane shear-diagonal failure mode (Figure 9a). Four two-dimensional interface elements located around the main element implement a specific set of nonlinear links to simulate the other possible mechanisms. The bi-flexural and axial mechanisms are controlled by a discretized matrix of transversal links. Two extra links placed along the thickness of the interface elements enable the out-of-plane sliding and torsion movements of masonry panels. The in-plane shear-sliding mechanism is governed by the single nonlinear link along the length of the interface elements [95]. The validity of the macroelement to model masonry infill panels [96], walls [94], and entire buildings [97–99] has been confirmed with respect to the available experimental and numerical results.

This simplified modeling method is capable of simulating curved masonry structures by irregular spatial macroelements (see Figure 9b) [95]. The curved masonry structures are discretized considering two different sets of grids composed of curved lines. The first and second sets of grids (red and blue lines in Figure 9c, respectively) are defined by means of horizontal planes along the structure height and vertical planes rotating around a fixed axis, respectively. This method, which has been validated in previous comparative research (e.g., [100]), has been used to model domes [101] and complex vaults [102]. Hence, such a spatial macroelement was adopted for the numerical simulation of the vaulted structure studied in this paper.

The macroelement method is also able to model externally bonded composite layers for the strengthening of masonry elements, as reported in [104,105]. As shown in Figure 9d, this reinforcement is simulated by incorporating zero-thickness rigid flat elements that are partially or completely connected to one of the macroelement surfaces by means of two-dimensional interface elements. The interface elements consist of a two-dimensional grid of transversal nonlinear links and a series of sliding nonlinear links to model the flexural detachment and the shear debonding (delamination) of reinforcement, respectively. Meanwhile, a specific one-dimensional interface element consisting of a discrete linear distribution of nonlinear links is used to simulate the connection between the rigid flat elements (reinforcement) [105]. The modeling method has been validated by Pantò et al. [106] and by Cannizzaro et al. [107] regarding the experimental results.

To replicate the global behavior of the case study structure, the entire structure was idealized in the HiStrA software Ver.2022.1.6 through a 3D numerical model. Figure 10 shows the computational model of the structure. In the numerical model, the actual dimensions (Section 9.1) and the construction details of the structure were considered.

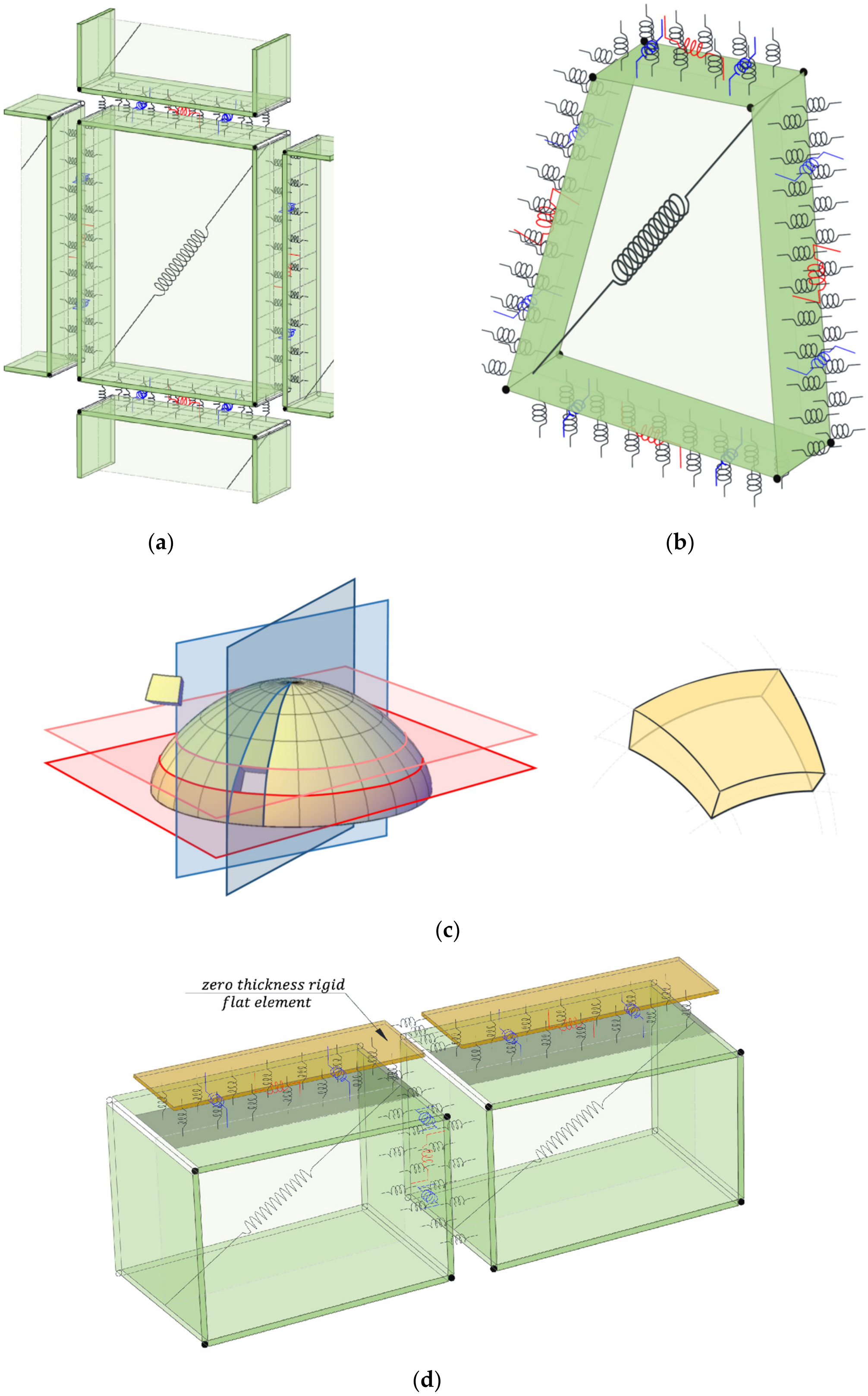



**Figure 9.** The adopted modeling method: (**a**) the regular and (**b**) irregular 3D macroelements for modeling masonry elements; (**c**) the discretization procedure of curved masonry structures; (**d**) the zero-thickness element for modeling reinforcing layers [103] (blue, red, and black springs represent different nonlinear links used in the macroelement).

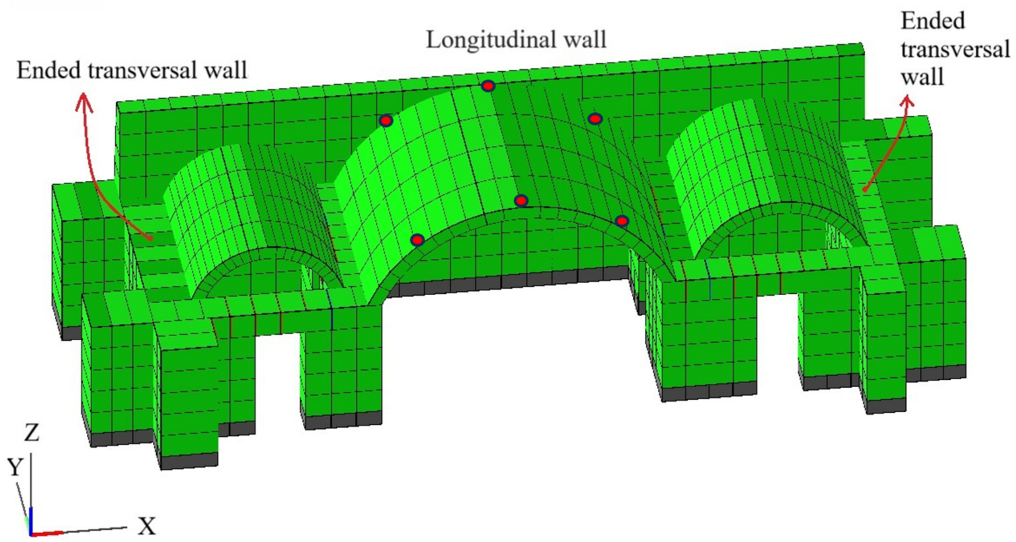



**Figure 10.** The computational model of the case study structure in HiStrA Ver.2022.1.6 (red dots represent the considered control nodes in the pushover analyses).

The building has no visible structural damage due to soil settlement, gravity loads, and environmental actions, resulting in a much simpler model without the need to simulate any existing cracks. The construction method of the structure, particularly the connections between its various parts (such as walls and vaults), could potentially lead to out-of-plane failures under seismic action, as observed for similar buildings during past earthquakes [108]. This is in agreement with the ability of the adopted 3D macroelement to simulate all types of failure modes of masonry structures.

Conducting in situ nondestructive tests to derive the mechanical properties of materials used in a historical building is a widely accepted and standard material assessment methodology. However, conducting such tests is outside the objective of this study. On the other hand, there are no ad hoc in situ studies to determine the mechanical properties of the case study structure. Therefore, they were adopted from the available experimental results in the literature. The entire building, including all the walls and vaults, are entirely made of adobe units and mud mortar for bed and head joints. There are several experimental research works about the mechanical properties of adobe masonry, including those addressed in [109] from different regions around the world. However, due to dependency of adobe mechanical properties on the local soil type, the local production procedure, and the difference between old and new material, this paper makes reference to an experimental study performed on local and old adobe material.

To the best of the authors' knowledge, Eslami et al. [79] conducted the only experimental research that addressed the mechanical properties of traditional adobe units and mud mortar used in Yazd. They sampled a number of adobe units from a 100-year historical building in Yazd to conduct the relevant material characterization tests.

They determined the mechanical properties of masonry prisms by sampling a number of adobe units from a historic building that is roughly the same age as the case study structure in this paper. Therefore, the relevant properties for the entire building model, which are listed in Table 3, were adopted from the above-mentioned study. For performing seismic analyses, it should be noted that the strengths were divided by the confidence safety factor mentioned in NTC18 [90] and assigned to the lowest level of structural knowledge (LC1), namely SF = 1.35.

**Table 3.** Mechanical properties of the masonry material adopted in the numerical model [79].

| Density (kg/m$^3$) | Compressive Strength (MPa) | Modulus of Elasticity (MPa) | Tensile Strength (MPa) | Shear Strength (MPa) |
|---|---|---|---|---|
| 1745 | 1.12 | 214 | 0.1 | 0.057 |

In the vernacular adobe architecture of Yazd, there is a traditional method consisting of spandrel walls and vaults, which is applied to vaulted adobe roofs/floors to flatten their extrados without adding to their weight. Such extremely thin adobe walls and short-span vaults, known as "Konou", are built usually upon the vault's transversal direction. The structure under study uses such details at its roof level. In the numerical model, Konou's weight was considered and applied as a vertical load. Furthermore, the live load determined by NTC18 [90] was applied, taking into account the fact that the roof is only accessible for maintenance purposes. The seismic weight of the entire structure was estimated to be about 2286 kN.

### 9.3. Seismic Analysis

Pushover analysis, a nonlinear iterative analysis method that subjects the structure to incremental static lateral loading until it reaches a predefined analysis target, was considered to evaluate the global seismic behavior of the structure. The analysis produces a nonlinear force–displacement curve (capacity curve), where the base shear force and the structure's top displacement, respectively, represent the force and displacement. For this study, the N2 method [110] was used as a common nonlinear static procedure (NSP) for evaluating the seismic safety of historic buildings within the performance-based seismic assessment framework (e.g., [111–114]).

The main limitation of the conventional NSPs, such as the N2 method, is that they assume that the dominant translational mode captures the structure's dynamic behavior. Irregular masonry structures without box behavior typically exhibit a dynamic response with predominant torsional or local modes, making the application of the N2 method impossible. On the other hand, the extended N2 method [115], a non-conventional NSP designed to account for higher mode effects in pushover analysis, is suitable for masonry structures exhibiting box behavior and rigid diaphragms [116]. When applied to masonry structures with flexible diaphragms, some other procedures, such as adaptive pushover analysis [117] and modal pushover analysis [118], do not demonstrate significant improvements in the capacity curve and failure mechanisms [119,120].

When exposed to multidirectional real earthquakes, irregular structures exhibit a tridimensional complex response. A 3D building model's nonlinear dynamic analysis can accurately represent the real dynamic response by simultaneously adopting the two horizontal components of seismic ground motions. None of the NSPs mentioned above can accurately reproduce this complex behavior because they only look at incremental lateral loading in the structure's main directions, such as the longitudinal and transversal directions. This is especially true for irregular masonry buildings without box behavior, where the structural elements are vulnerable to local damage and failure mechanisms [121].

Hence, this study employed the multi-directional pushover analysis (MDPA) method, first proposed and applied to an irregular historic masonry palace in [122]. The main approach of the method involves performing individual pushover analyses in different directions with respect to the structure's plan, for which a mass proportional lateral load pattern is assumed. This is achieved to capture various failure mechanisms of irregular masonry structures, both in plan and elevation, which are roofed by flexible diaphragms and lack box behavior. For the structure's seismic performance assessment, the N2 method is applied to the MDPA method results. When applied to another historic masonry building, Kalkbrenner et al. [121] verified the approach, comparing pushover analysis results with those from nonlinear dynamic analysis in terms of damage patterns and capacity curve. Furthermore, the method adopted in this study was previously used by Chácara et al. [123] for seismic vulnerability assessment of a masonry mockup tested in a laboratory, for which the out-of-plane failure mechanism was predominant during the test.

In order to capture effectively all the collapse mechanisms and torsion effects around the structure, eight pushover analyses were carried out, changing the loading direction with an angular step of 45°. Four analyses were conducted along the main directions of the structure, which are typically considered for regular structures: positive X (P0), negative X (P180), positive Y (P90), and negative Y (P180) (refer to Figure 8b for the X and Y directions). We refer to the other analysis directions as P45, P135, P225, and P315 based on their angle to the positive x direction.

The arc-length control and the modified Newton–Raphson method were used to solve the numerical problem during the nonlinear analysis. Each pushover analysis was run until reaching structural collapse. It was assumed that the capacity curve's collapse criterion corresponds to a displacement that either causes a drop of at least 20% in the structure base shear [90,124] or a numerical divergence due to large deformations of structural members during the analysis. For each pushover analysis performed in this study, the gravitational loading was first applied to the model, and then increasing the horizontal loading imposed the model according to a mass proportional loading distribution.

This model considers the distribution of structural masses as well as additional masses due to gravity loading in their actual locations. As reported in [122,123] for masonry structures with higher mode effects, a set of 50 control points, which represent the mass distribution within the entire structure, were determined to govern the complex out-of-plane behavior of the structure. Some control points were considered at the approximate locations in which the plastic hinges are formed in the vaults under cyclic lateral loading in the X direction. Others were at the vaults' impost and the walls' middle height. A mass was allocated to each control point based on the structure's volume of influence. Within the N2 method, the corresponding mass distribution of the adopted control points was used to idealize the entire structure as a nonlinear single-degree-of-freedom (SDOF) system (see Section 9.4).

In general, for masonry structures with rigid diaphragms well connected to the walls, the center of mass of the top floor level is usually considered the control node to represent the structure's displacement in the capacity curve. However, selecting an appropriate control node for irregular masonry buildings with flexible diaphragms, like the one in this study, presents a challenge [120,125]. Several references, including [125,126], report that the solution to this challenge is to consider different control nodes to capture the response of the most critical structural elements during the analysis. Therefore, six points located at the middle vault's top level, which present the largest out-of-plane displacements, were selected among the set of control points. The displacement of each of the selected control points was monitored throughout the pushover analyses. The average value of the displacements was employed to provide the analysis's capacity curve, as reported in [121].

Figure 11 shows the capacity curves obtained from pushover analysis of the studied structure along different directions. The significant difference between the obtained capacity curves in terms of displacement and base shear force indicate the sensitivity of the structure's seismic behavior to the loading direction, arising from its irregular configuration and its lack of box-type behavior. This confirms the adoption of the MDPA method to govern the complex seismic response of the case study structure. Figure 12 depicts the results of analyses along the positive X and Y directions in terms of damage pattern. The formation of four plastic hinges in the vaults' transversal sections primarily governs the damage pattern in the X direction (Figure 12a). This implies that the in-plane action of the vaults is more effective than the out-of-plane action of the transversal walls (the walls along the Y direction) in resisting the X direction's imposing loads. The vault span has two hinges on each side, with additional hinges located at the vault's imposts. This failure mode is common for vaulted structures under asymmetric lateral loading. In the Y direction, the out-of-plane overturning of the longitudinal back wall due to insufficient connections between the wall and vaults is predominant (Figure 12b). The failure modes in both directions have been observed during past earthquakes—in particular, the 2003 earthquake that occurred in the city of Bam, characterized by its adobe vaulted buildings (Figure 13) (for more information, see [108]).

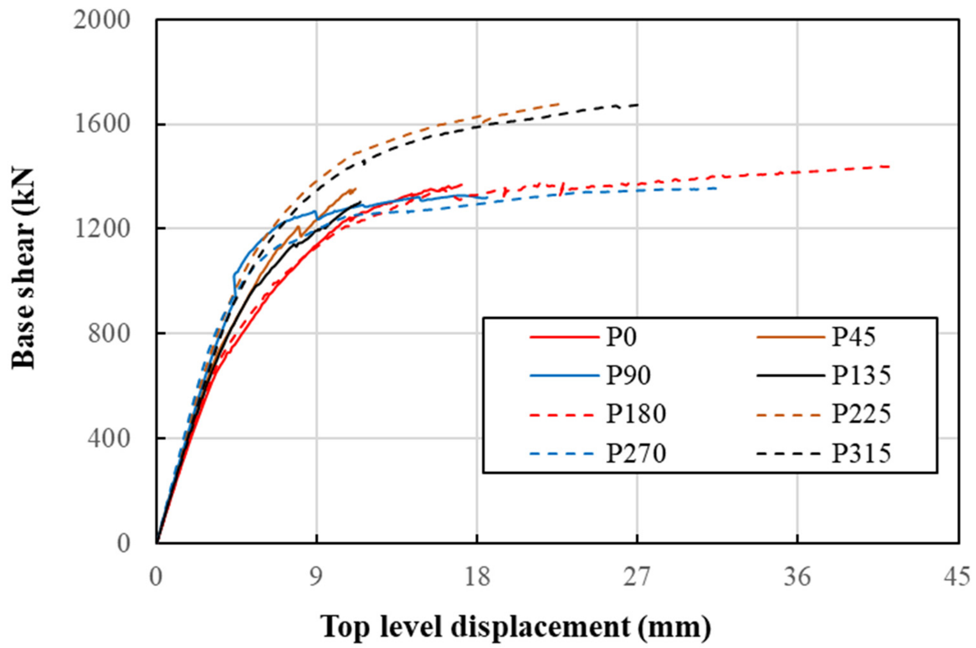
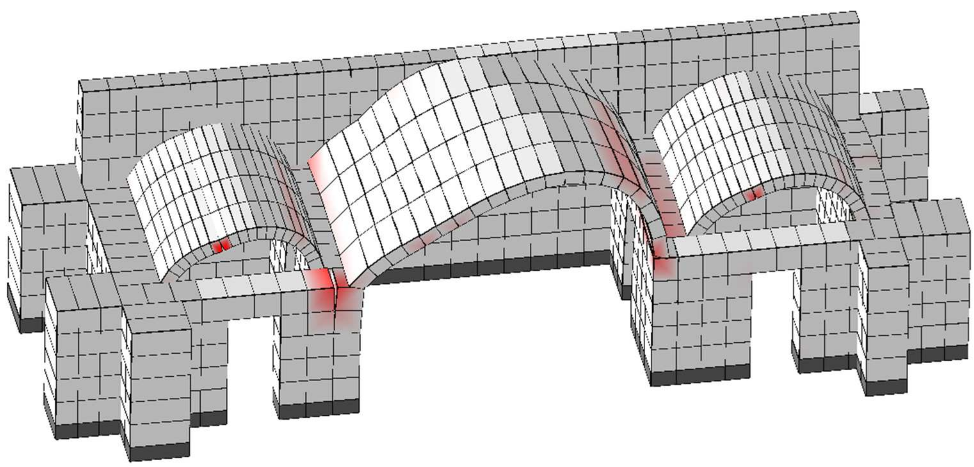
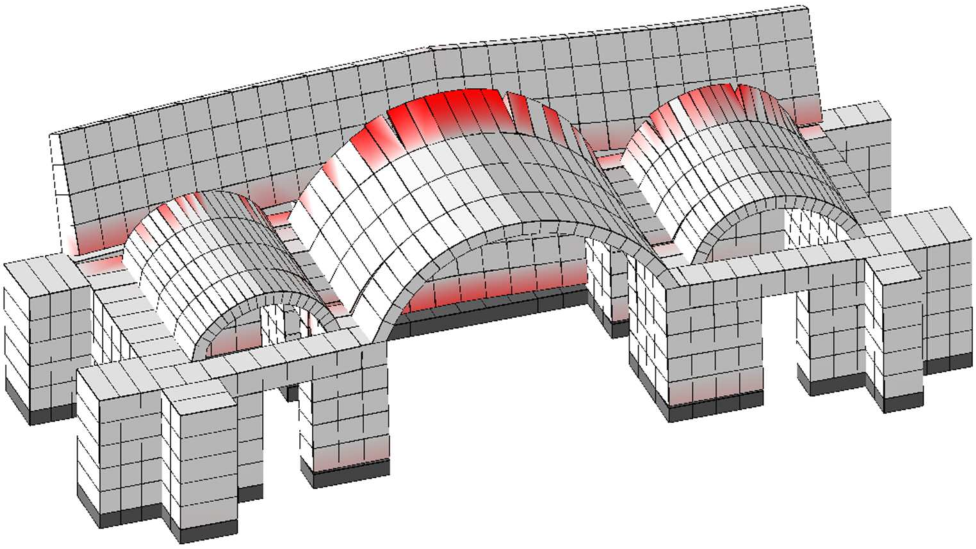



**Figure 11.** The pushover-obtained capacity curves of the unretrofitted structure in different analysis directions.



(**a**)

**Figure 12.** *Cont*.



(**b**)

**Figure 12.** Damage (red-color contour of plastic strain) to the unretrofitted structure resulting from (**a**) the positive X-direction and (**b**) the positive Y-direction pushover analyses.

(**a**)

(**b**)

**Figure 13.** Real damage to adobe vaults during the 2003 Bam earthquake: (**a**) the in-plane failure mode and formation of plastic hinges [59] and (**b**) the out-of-plane failure mode and overturning of the vault's back walls [17].

### *9.4. Seismic Safety Assessment of the Unretrofitted Structure*

DPCM11 [89], which respects the conservation principles of built heritage such as those recommended in ISCARSAH [91], proposes three levels of EL1, EL2, and EL3 for seismic vulnerability assessment. The assessment at these levels requires progressively more complex seismic analysis. At the EL1 level, a static linear analysis of the structure is conducted using simple models based on limited geometric and mechanical parameters, primarily obtained from qualitative visual inspections, to determine the corresponding collapse acceleration. The EL2-level assessment examines macroelements in one or more sections of the structure and uses kinematic analyses to investigate the potential activation of various collapse mechanisms. At level EL3, the whole structure is analyzed globally using a suitable numerical modeling method, such as finite element modeling, and different static and dynamic analyses that are linear and nonlinear. Moreover, the EL3 level requires applying a performance-based seismic assessment method to the entire structure.

This section evaluates the seismic performance of the studied structure using the MDPA capacity curves, adhering to the EL3 level of DPCM11 [89]. To achieve this, a seismic assessment objective, which is the desired performance level against a specific earthquake hazard, is defined. Next, the N2 method is applied to each direction's capacity curve to assess its compliance with the relevant performance criterion. A detailed description of the procedure and the obtained results are presented in the following.

The N2 method involves identifying a structure's inelastic displacement response, known as the target displacement, by intersecting the idealized bilinear SDOF capacity curve with the inelastic demand spectrum for the given earthquake. For this method to work, the multi-degree-of-freedom (MDOF) structure capacity curve needs to be reduced to the equivalent nonlinear SDOF system response. Each point of the SDOF capacity curve, also known as the base shear ($F^*$)–displacement ($d^*$) curve, is obtained as follows:

$$F^* = \frac{F_b}{\Gamma} \tag{1}$$

$$d^* = \frac{d_n}{\Gamma} \tag{2}$$

where $d_n$ and $F_b$ are the displacements and the base shear forces of the MDOF structure resulting from the pushover analysis, respectively. $\Gamma$ is the modal participation factor, which is given by:

$$\Gamma = \frac{\sum m_i \Phi_i}{\sum m_i \Phi_i^2} \tag{3}$$

where $m^*$ is the equivalent mass of the SDOF system, while $m_i$ is the mass of node $i$ in a MDOF masonry structure. $\Phi_i$ corresponds to the displacement of the same node within an assumed normalized displacement vector $\Phi$. The shape vector $\Phi$ must be normalized so that the displacement at the structure's highest level equals one [110].

The MDPA method used in this study takes into account various analysis directions for which determining the corresponding main translational mode from a modal analysis is not straightforward. This makes it impossible to assume the fundamental mode shape as the vector $\Phi$. For this reason, the shape vector $\Phi$ was approximately estimated proportionally to the mass and height of each of the fifty control points, as suggested in NTC18 [90] and used in [122,123]. In all of the analysis directions, this simplified procedure resulted in constant values of 1.58 and 199 tons for the modal participation factor and the equivalent mass of the SDOF system, respectively.

In the N2 method, the SDOF capacity curve is then idealized into a bilinear elastoplastic curve by finding the stiffness $k^*$ and making the areas (dissipation energies) under both curves equal up to the collapse capacity displacement $d^*_u$ (Figure 14), as explained in NTC18 [90]. The target displacement of the equivalent SDOF system ($d^*_t$) is obtained by applying a coefficient greater than one $C = \mu_R / R$ to the system's elastic demand displacement $d^*_{et}$, where the behavior factor $R$ represents the ratio between $d^*_{et}$ and $d^*_y$ (the yield displacement of the SDOF system, as shown in Figure 14). For a given $R$, the ductility demand $\mu_R$ can be calculated using Equation (4) (for $T_c$, see Figure 14), which was developed by Guerrini et al. [127] for short-period masonry structures.

$$\mu_R = \left[ \frac{(R-1)^{2.1}}{\left(\frac{T^*}{0.055} + 0.7\right)\left(\frac{T^*}{T_C}\right)^{2.3}} + R \right] \tag{4}$$

where $T^*$ is the period of the equivalent SDOF system, which can be obtained using the system's yield shear force ($F^*_y$) as $T^* = 2\pi\sqrt{\frac{m^* d^*_y}{F^*_y}}$. Table 4 presents the results of the N2 method applied to the studied structure. In Table 4, $d_t$ is the target displacement of the MDOF structure obtained as $d_t = \Gamma \cdot d^*_t$.

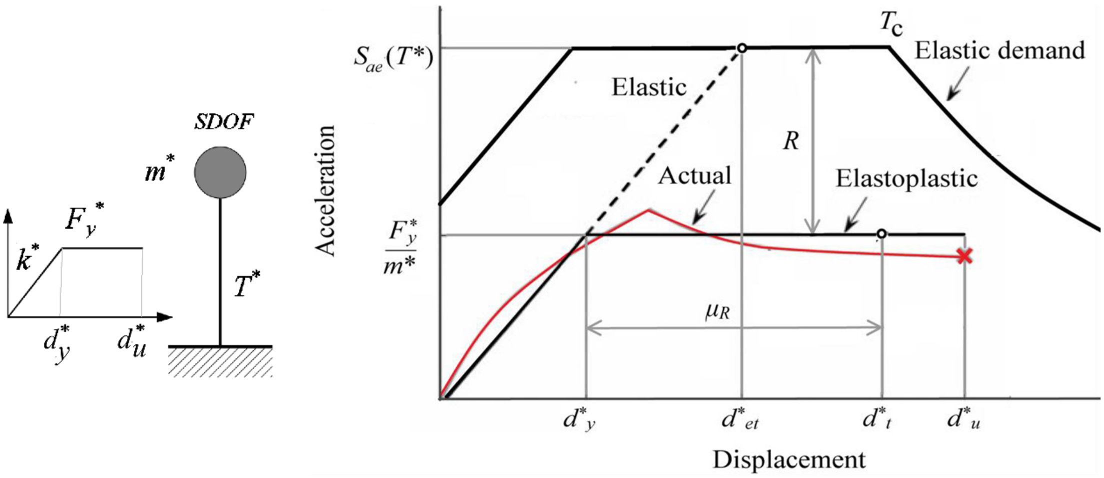



**Figure 14.** The procedure of the N2 method to determine the target displacement of short-period structures (adapted from [128]) (the red curve represents the actual capacity curve of a SDOF structure).

**Table 4.** The N2 method results of the unretrofitted structure obtained for different analysis directions.

| Analysis Name | $d^*_y$ (mm) | $F^*_y$ (kN) | $T^*$ (s) | $k^*$ | $d^*_u$ (mm) | $\mu$ [1] | $\mu_R$ | $d_t$ (mm) |
|---|---|---|---|---|---|---|---|---|
| P0 | 5.6 | 837.6 | 0.229 | 149.8 | 10.8 | 1.93 | 2.26 | 20.0 |
| P45 | 4.2 | 791.1 | 0.205 | 186.8 | 7.1 | 1.69 | 3.05 | 20.4 |
| P90 | 3.6 | 806.4 | 0.186 | 226.3 | 11.7 | 3.25 | 3.33 | 18.7 |
| P135 | 4.1 | 759.7 | 0.205 | 186.4 | 7.2 | 1.76 | 3.45 | 22.2 |
| P180 | 5.8 | 867.1 | 0.230 | 148.5 | 26.1 | 4.5 | 2.06 | 19.0 |
| P225 | 5.3 | 1005.1 | 0.203 | 190.6 | 14.3 | 2.70 | 1.55 | 12.9 |
| P270 | 3.9 | 816.8 | 0.192 | 211.6 | 20.1 | 5.15 | 3.03 | 18.5 |
| P315 | 5.6 | 999.8 | 0.210 | 179.0 | 17.4 | 3.11 | 1.55 | 13.6 |

[1] $\mu$ represents the capacity ductility of the SDOF structure as the ratio between the ultimate and yield displacements.

Once the target displacement of the equivalent SDOF structure is obtained, its seismic vulnerability can be assessed based on different criteria. As stated in Section 4, built heritage located in earthquake-prone areas should meet the life safety performance level. According to DPCM11 [83], the displacement capacity for this performance level ($d_{SLV}$) is given as $d_{SLV}$ = 0.75$d^*_u$. This guideline defines the corresponding earthquake demand as one that has a 10% exceedance probability of occurrence over the structure's useful life. The return period of this earthquake ($T_{R,SLV}$) is 475 years, given a useful life of 50 years. For the city of Yazd, the PGA value corresponding to this hazard level ($a_{g,SLV}$) is equal to 0.24 g, as determined in [35].

In addition to the displacement-based criterion $f_{d,SLV}$ (Equation (5)), two other criteria are presented as capacity-to-demand ratios based on the acceleration response ($f_{d,SLV}$) and the earthquake return period ($I_{S,SLV}$) according to Equations (6) and (7), respectively.

$$f_{d,SLV} = \frac{d_{SLV}}{d_t^*} \quad (5)$$

$$f_{a,SLV} = \frac{a_{SLV}}{a_{g,SLV}} \quad (6)$$

$$I_{S,SLV} = \frac{T_{SLV}}{T_{R,SLV}} \quad (7)$$

where $a_{SLV}$ is the PGA value for an earthquake that causes the displacement capacity ($d_{SLV}$) and demand ($d^*_t$) corresponding to the life safety performance level to be equal, i.e., $d^*_t \mid_{PGA = aSLV} = d_{SLV}$. Also, TSLV is the earthquake's return period, with the PGA equal to $a_{SLV}$. $T_{SLV}$ can be calculated from a probabilistic seismic hazard analysis such as that performed by Asadi et al. [35] for the city of Yazd (Figure 15a).

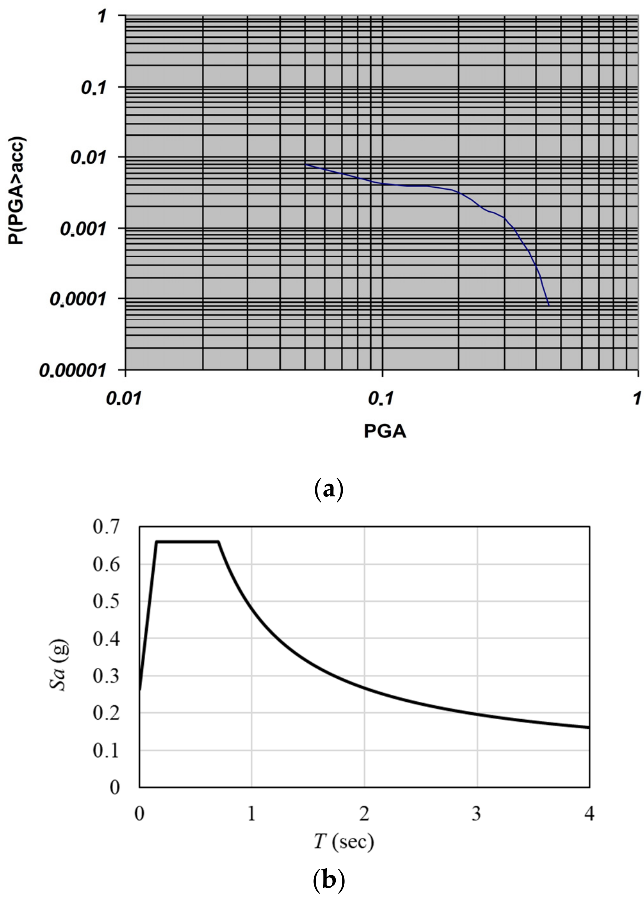



**Figure 15.** The earthquake demand employed in this study: (**a**) the seismic hazard curve of the city of Yazd [35]; (**b**) the elastic spectrum adopted for the N2 method [33].

The main difference between the $I_{S,SLV}$ and $f_{a,SLV}$ factors is that $I_{S,SLV}$ also considers the local site conditions and the earthquake history of the area under study. The minimum value of these three factors (S.F.) can be conservatively considered as the structure safety factor, which implies safeguarding the lives of the structure's inhabitants against the given earthquake when it exceeds one.

In this study, the elastic acceleration design spectrum defined by Standard 2800 [33] for soil type III, which is moderately stiff and has an average shear wave velocity between 175 and 375 m/s at a depth of 30 m, was used when applying the N2 method. Figure 15b shows the elastic spectrum obtained for PGA = 0.24 g.

Table 5 shows the safety factors obtained for different analysis directions. The results indicate that the studied structure does not comply with the requirements of the life safety performance level and needs to be strengthened with an effective method.

**Table 5.** The safety factors of the unretrofitted structure calculated for different analysis directions.

| Analysis Name | $d^*_t$ (mm) | $d_{SLV}$ (mm) | $a_{SLV}$ (g) | $T_{SLV}$ (year) | $f_{d,SLV}$ | $f_{a,SLV}$ | $I_{S,SLV}$ | S.F. |
|---|---|---|---|---|---|---|---|---|
| P0 | 12.7 | 8.1 | 0.199 | 313 | 0.64 | 0.83 | 0.66 | 0.64 |
| P45 | 12.9 | 5.3 | 0.172 | 274 | 0.41 | 0.72 | 0.58 | 0.41 |
| P90 | 11.9 | 8.8 | 0.219 | 377 | 0.74 | 0.91 | 0.79 | 0.74 |
| P135 | 14.1 | 5.4 | 0.170 | 274 | 0.39 | 0.71 | 0.58 | 0.39 |
| P180 | 12 | 19.6 | 0.288 | 662 | 1.63 | 1.20 | 1.39 | 1.20 |
| P225 | 8.2 | 10.7 | 0.265 | 598 | 1.31 | 1.10 | 1.26 | 1.10 |
| P270 | 11.7 | 15.1 | 0.259 | 578 | 1.29 | 1.08 | 1.22 | 1.08 |
| P315 | 8.6 | 13.0 | 0.280 | 645 | 1.51 | 1.17 | 1.36 | 1.17 |

### *9.5. Seismic Safety Assessment of the Retrofitted Model*

This section evaluates numerically the effectiveness of a mesh-based strengthening technique, as already concluded previously. It is important to improve the seismic performance of the studied structure in order to meet the life safety criteria. The strengthening technique includes using a bonded TRM on the exterior side of the building's walls and vaults. The TRM layer is composed of a fiberglass mesh embedded in earth-based mortar. There are detailed micro-modeling approaches in the literature for simulating the TRM reinforcement on curved masonry substrates, such as the finite element model proposed in [129]. However, such numerical models are not applicable in this study in which a specific macroelement is used for masonry modeling. In this paper, the TRM layer was numerically simulated, modeling the reinforcement element in HiStrA Ver.2022.1.6 (see Section 9.2), while considering the elastic and bond-slip behavior of the TRM layer. The bond-slip behavior of masonry specimens externally reinforced by TRM has been addressed by a number of experimental and numerical research works (e.g., those addressed in [73]). However, a very limited number of research contributions for the bond-slip behavior of the TRM layer composed of a fiber glass mesh embedded in earthen mortar can be found in the literature (e.g., [130,131]). Hence, the relevant material properties of TRM (Table 6) were adopted from the experimental campaign performed by Romanazzi et al. [130] and the analytical work by the same authors [132]. The mesh is very similar to that used in the experimental campaign performed by Haji Sadeghi et al. [65] on adobe vaults. In Table 6, Ef and ft are the tensile module and the ultimate tensile strength of the fiberglass mesh, while the initial shear stiffness of the matrix ks, the ultimate debonding stress τf, the fracture energy Gs, and the friction factor μs characterize the TRM's bond-slip behavior.

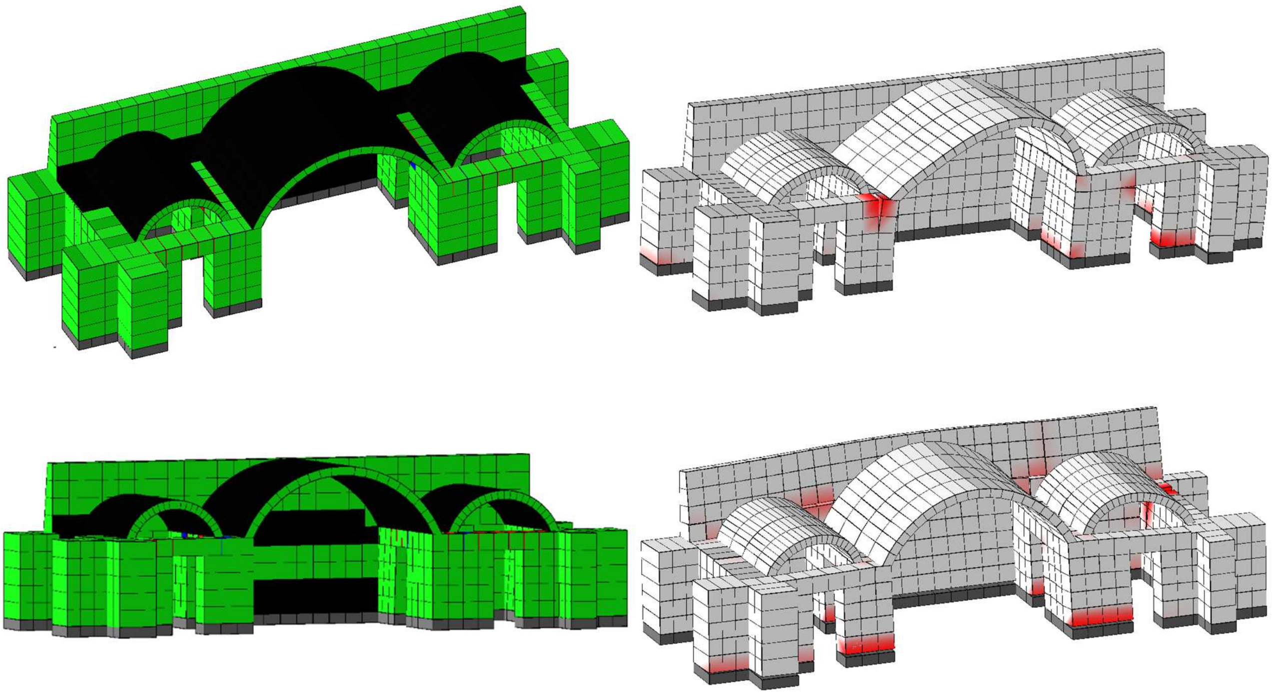
**Table 6.** Mechanical properties of reinforcing TRM adopted in the numerical model [132].

| Tensile | | Bond-Slip | | | |
|---|---|---|---|---|---|
| $E_f$ (GPa) | $f_t$ (MPa) | $k_s$ (N/mm$^3$) | $\tau_f$ (MPa) | $G_s$ (N/mm) | $\mu_s$ (-) |
| 32 | 626 | 3.75 | 0.45 | 0.55 | 0 |

There exist several techniques for implementing meshes on adobe structures. Meshes can be constructed on either one or both sides of adobe components, such as walls and vaults. Furthermore, mesh can be employed to enclose the entire structure or just the crucial portions of the building. Concerning the second scenario, it is necessary to ascertain the desired extent of the surface(s) that should be covered with mesh in order to ensure sufficient resistance against a given earthquake-induced loading. Respecting the minimum intervention principle, a step-by-step procedure was followed to determine the desired layout for TRM. For this, only the critical analysis directions along which the structure could not comply with the criteria corresponding to the life safety performance level (i.e., P0, P45, P90, and P135) were considered.

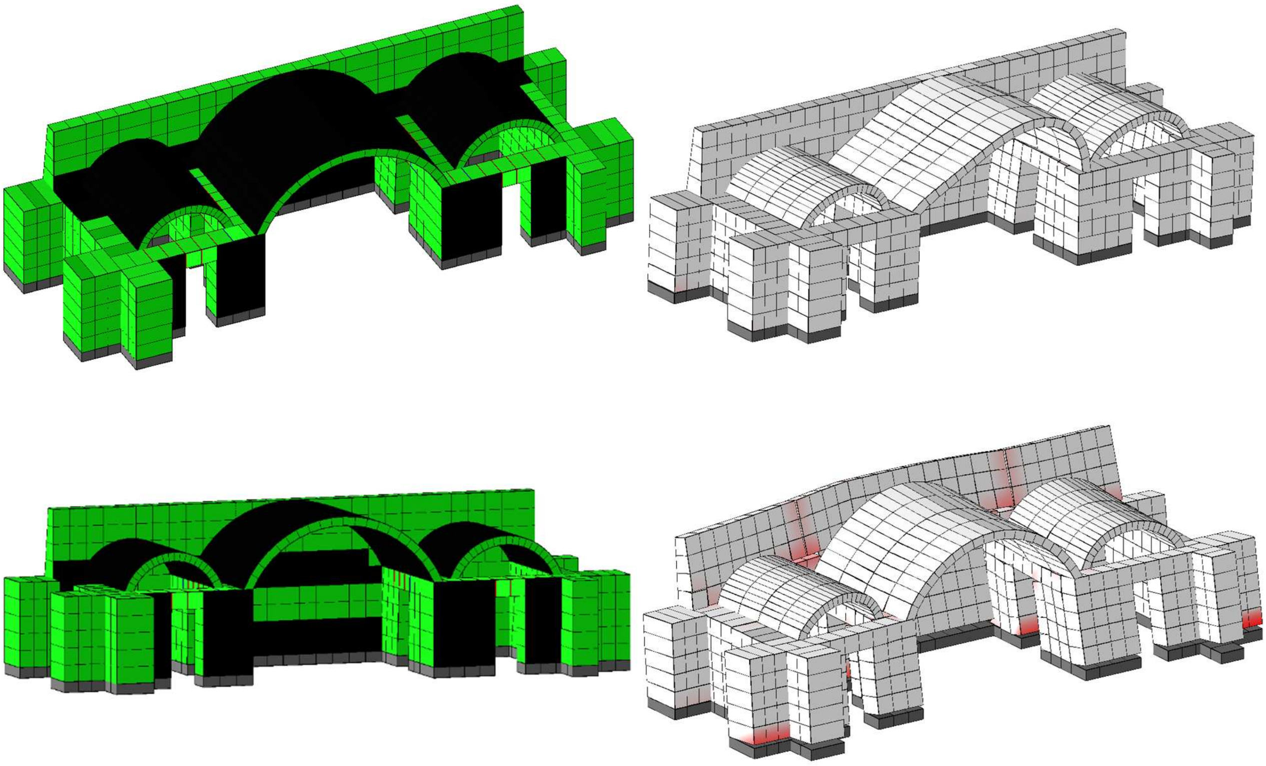
Within the adopted procedure, first, an initial layout was assumed based on the damaged parts of the unretrofitted structure. This indicates that the procedure intends to find a reinforcing layout by which the main failure modes of the unretrofitted structure are prevented. Next, the assumed layout was examined to determine whether the structure met the acceptance criteria. Otherwise, the proposed retrofitting layout was changed considering the damaged parts of the retrofitted structure. This procedure was repeated until the criteria were satisfied for all the considered analysis directions.

For instance, Figures 16a and 17a show the retrofitting layouts considered in the two last steps of the procedure before the final step. Concerning the first step, the results of the analyses along the positive X and Y directions (Figure 16b) show that the retrofitting layout considered in this step could significantly improve the damage conditions of the unretrofitted structure, in particular the damage observed in the barrel vaults (see Figure 12 for comparison). However, some serious in-plane damages in the structure's front walls and the overturning of the longitudinal back wall are still observed in the X and Y directions, respectively (see Figure 16b). For this reason, the front walls were retrofitted in the next step (Figure 17a. The results show that this retrofitting layout could effectively prevent the front walls' damage under the positive X direction analysis (Figure 17b). However, the out-of-plane overturning of the longitudinal back wall still happens due to its insufficient connection with the vaults. Hence, it was decided to add a TRM layer along the longitudinal back wall to prevent the out-of-plane failure mode in the final step.



(a) (b)

**Figure 16.** The case study structure retrofitted with the TRM layers (black surfaces) in the first step of the retrofitting procedure before the final one: (**a**) the computational model in different views; (**b**) damage (red-color contour of plastic strain) of the retrofitted structure resulting from the positive X direction (**top**) and the positive Y-direction (**bottom**) pushover analyses.



(**a**) (**b**)

**Figure 17.** The case study structure retrofitted with the TRM layers (black surfaces) in the second step of the retrofitting procedure before the final one: (**a**) the computational model in different views; (**b**) damage (red-color contour of plastic strain) of the retrofitted structure resulting from the positive X direction (**top**) and the positive Y-direction (**bottom**) pushover analyses.

As a result, the layout depicted in Figure 18 was obtained. The damage patterns of the retrofitted structure resulting from the analyses in the positive X and Y directions and corresponding to the ultimate capacity displacement of the unretrofitted structure are shown in Figure 19. Comparing Figures 12 and 19, the effectiveness of the adopted retrofitting technique in preventing the main in-plane and out-of-plane failure modes of the studied structure is observed. As shown in Figure 19, the retrofitted structure exhibits no serious damage in the X direction, while only minor damage to the base of some piers is observed in the Y direction. The pushover-obtained capacity curves were obtained as shown in Figure 20. The methods used for the seismic analysis and safety assessment of the retrofitted structure were similar to the unretrofitted model. As a result, the N2 method parameters and the safety factors for the critical analysis directions were obtained as reported in Tables 7 and 8, respectively. Figure 20 and Table 7 demonstrate that the retrofitting technique is capable of improving all the capacity parameters including initial stiffness, shear strength, and ductility, in particular in the X direction where both interior and exterior sides of the vaults have been retrofitted.

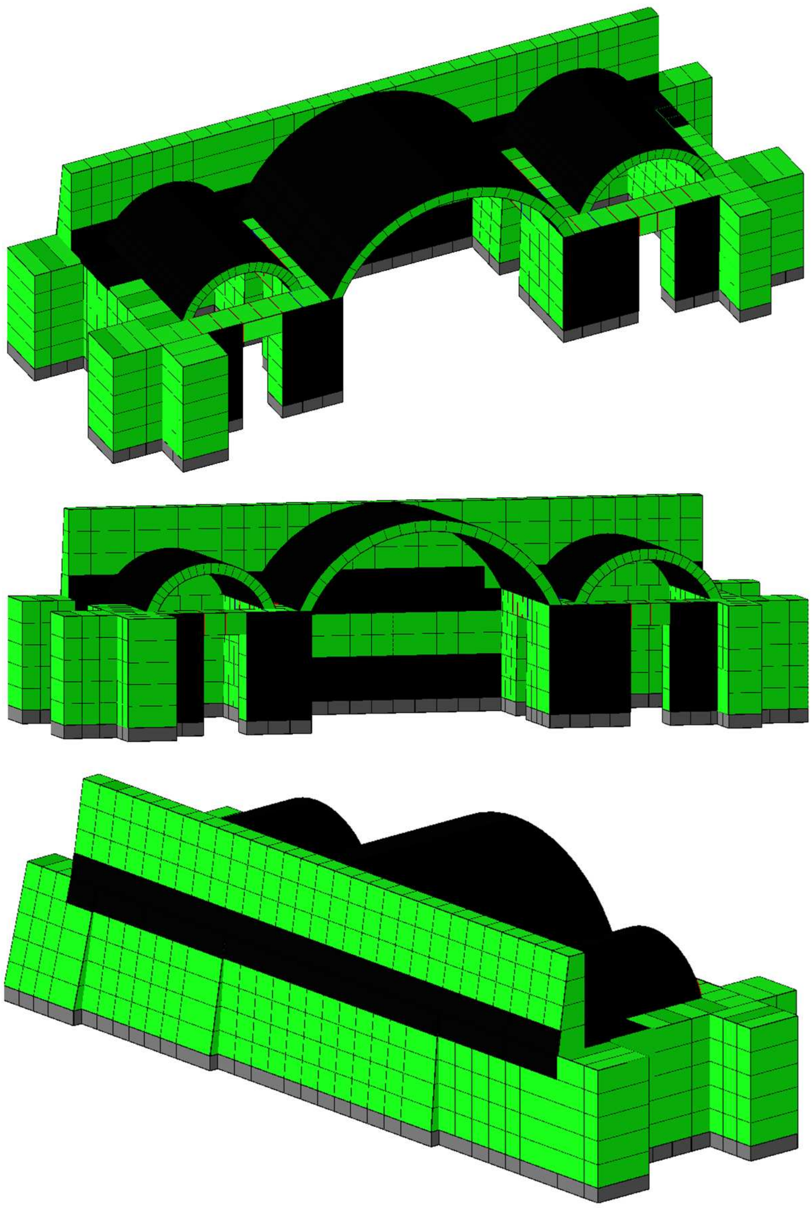


**Figure 18.** The computational model of the case study structure retrofitted with the final TRM layers (black surfaces) in different views.

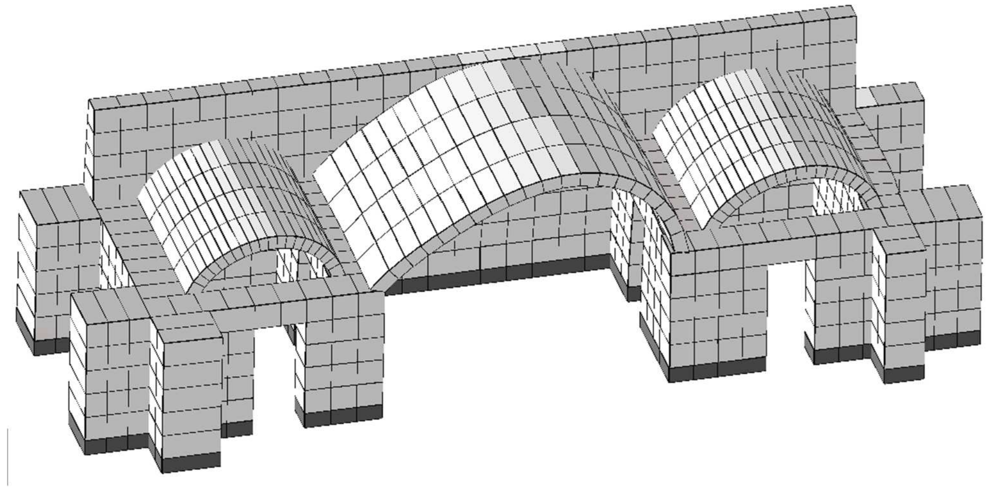
**Table 7.** The N2 method results of the retrofitted structure obtained for the critical analysis directions.

| Analysis Name | $d^*_y$ (mm) | $F^*_y$ (kN) | $T^*$ (s) | $k^*$ | $d^*_u$ (mm) | $\mu$ | $\mu_R$ | $d_t$ (mm) |
|---|---|---|---|---|---|---|---|---|
| P0 | 7.6 | 1250.8 (49%) | 0.218 | 165.4 (10%) | 26.7 (147%) | 3.51 (82%) | 1.03 | 12.3 |
| P45 | 6.3 | 1285 (62%) | 0.196 | 204.1 (9%) | 11.2 (58%) | 1.78 (5%) | 1.00 | 10.0 |
| P90 | 3.2 | 1057.9 (31%) | 0.155 | 326.3 (44%) | 14.8 (26%) | 4.63 (42%) | 1.58 | 8.1 |
| P135 | 4.8 | 1107.6 (46%) | 0.185 | 228.9 (23%) | 11.8 (64%) | 2.46 (40%) | 1.28 | 9.8 |

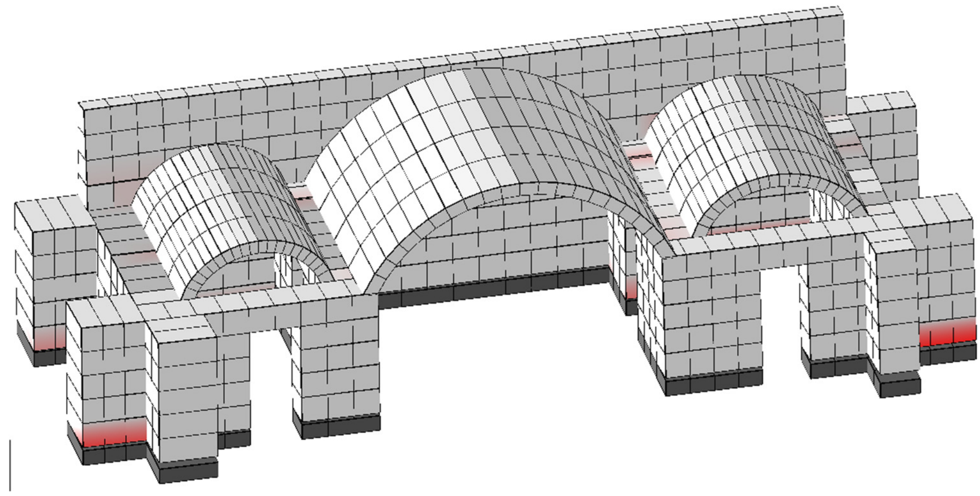
(The numbers in parentheses represent the percentage increase in the parameter with respect to the unretrofitted condition).

**Table 8.** The safety factors of the retrofitted structure calculated for the critical analysis directions.

| Analysis Name | $d^*_t$ (mm) | $d_{SLV}$ (mm) | $a_{SLV}$ (g) | $T_{SLV}$ (year) | $f_{d,SLV}$ | $f_{a,SLV}$ | $I_{S,SLV}$ | *S.F.* |
|---|---|---|---|---|---|---|---|---|
| P0 | 7.8 | 20.0 | 0.372 | 2083 | 2.57 | 1.55 | 4.39 | 2.57 |
| P45 | 6.3 | 8.4 | 0.287 | 662 | 1.34 | 1.20 | 1.39 | 1.20 |
| P90 | 5.1 | 11.1 | 0.292 | 689 | 2.17 | 1.22 | 1.45 | 1.22 |
| P135 | 6.2 | 8.8 | 0.274 | 617 | 1.43 | 1.14 | 1.30 | 1.14 |



(**a**)



(**b**)

**Figure 19.** Damage (red-color contour of plastic strain) of the structure retrofitted with the final layout resulting from (**a**) the positive X-direction and (**b**) the positive Y-direction pushover analyses.

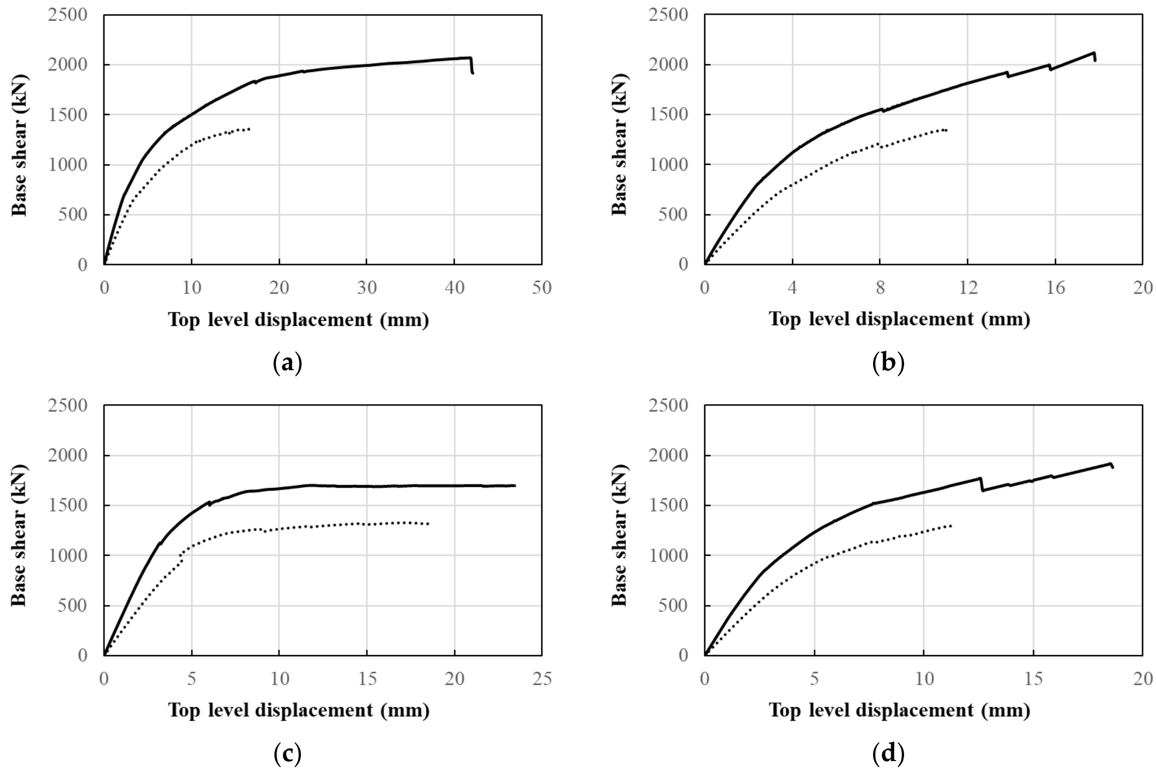



**Figure 20.** Capacity curves of the unretrofitted (dotted line) and retrofitted (continues line) structures obtained from (**a**) P0; (**b**) P45; (**c**) P90; and (**d**) P135 analyses.

In this study, the main direction of the fiber glass mesh is parallel to the X or Y directions. However, it is possible to use the mesh with a different orientation, such as a 45° angle from the X and Y directions. On the other hand, pushover analyses were conducted in different directions. In general, it is expected to obtain a more effective response when the analysis load direction is parallel to the mesh main direction. For instance, if a 45°-oriented mesh is used for retrofitting the vaults, the results under P45, P135, and P225 may be more desirable than those obtained in this study. However, due to the absence of pullout tests for oriented meshes embedded in earthen mortar in the literature, this subject was not studied in the current paper.

## 10. Conclusions

Iran, one of the Middle East's largest countries, is recognized as one of the most seismically active regions worldwide. Historical earthquakes in Iran, particularly the devastating Bam earthquake in 2003, have illustrated the significant vulnerability of traditional vaulted adobe structures to seismic forces. This paper studies the vernacular vaulted adobe houses within the historic fabric of Yazd, addressing their seismic vulnerability. To mitigate the potential loss of lives and the irreversible damage to the studied adobe dwellings caused by future earthquakes, it is necessary to establish a comprehensive preventive conservation program. The main goal of the current paper is to define the methodology of intervention in preventive conservation through a case study building, focusing on the conservation objective, significance and conservation value assessment, seismic safety and intervention criteria, safety assessment, and the proposed conservation strategy and techniques.

It is worth noting that all of the aforementioned conservation phases play an important role in the decision-making process when considering an intervention. Based on the studies performed, ensuring the life safety of inhabitants during earthquakes was considered as the first objective, which would be achieved through the preventive conservation of adobe houses in the historic fabric of Yazd. The assessment of the seismic performance and safety of built heritage in earthquake-prone regions is a crucial step in the preventive conservation process. Therefore, the main emphasis of this paper has been on evaluating the performance and safety of a selected adobe house under seismic events through a numerical research work. To this end, one of the adobe structures in the Art and Architecture Department of Yazd University was chosen as the case study in this work, based on the potential consequences of its collapse, involving the loss of many human lives.

The seismic safety of the case study structure was evaluated, creating its numerical model in the software HiStrA Ver.2022.1.6 and performing several seismic analyses. The obtained safety factors showed that the structure needs to be retrofitted. A TRM layer composed of a fiber glass mesh embedded in earthen mortar was adopted for retrofitting the structure. Next, different retrofitting layouts were numerically examined to find the layout with the maximum structural effectiveness and minimum intervention.

Despite the seismic vulnerability of vaulted adobe architecture in Iran, the research on this topic is still very limited in the literature. This also emerges from the fact that there is a lack of research regarding this roofing type in vernacular adobe houses around the world. This paper can be considered as one of the first steps toward developing a comprehensive methodology for the pre-earthquake conservation of such adobe vaulted architecture. These findings also respond to the World Heritage Committee recommendations following the approval of Yazd on the World Heritage List in 2017. In addition, considering the lack of literature in the research area, these outcomes can be used to provide guidelines for the preventive conservation of adobe architecture when faced with earthquakes.

Future earthquakes in regions with a vaulted adobe architecture, such as city of Yazd, may lead to damage and failure of this kind of historical adobe heritage. Consequently, safeguarding these historical adobe structures not only ensures the safety of individuals but also preserves this unique form of vernacular architecture for future generations.

**Author Contributions:** Conceptualization, N.H.S. and H.A.-B.; methodology, N.H.S. and H.A.-B.; software, H.A.-B.; validation, H.A.-B.; formal analysis, H.A.-B.; investigation, N.H.S.; resources, N.H.S.; data curation, H.A.-B.; writing—original draft preparation, N.H.S. and H.A.-B.; writing—review and editing, M.C.; visualization, N.H.S.; supervision, N.H.S.; project administration, N.H.S.; funding acquisition, M.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in this study are included in the article material. Further inquiries can be directed to the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Correia, M. *Conservation in Earthen Heritage Assessment and Significance of Failure, Criteria, Conservation Theory, and Strategies*; Cambridge Scholars Publishing: Cambridge, UK, 2016.
2. World Heritage Centre. UNESCO—World Heritage Convention Platform. Historic City of Yazd. Available online: https://whc.unesco.org/en/list/1544/ (accessed on 22 December 2024).
3. UNESCO World Heritage Centre. Decision: 41 COM 8B.18. Historic City of Yazd (Islamic Republic of Iran). Available online: http://whc.unesco.org/en/decisions/6890 (accessed on 22 December 2024).
4. FEMA. Incremental Seismic Rehabilitation of Hotel and Motel Buildings (FEMA 400). In *Risk Management Series*; Krimgold, F., Hattis, D., Green, M., Eds.; Federal Emergency Management Agency (FEMA): San Francisco, CA, USA, 2005.
5. Joffroy, T. Preventive conservation: A concept suited to the conservation of earthen architectural heritage? In *Terra 2012–12th SIACOT Proceedings, 11th International Conference on the Study and Conservation of Earthen Architectural Heritage, and 12th Iberian-American Seminar on Earthen Architecture and Construction*; Correia, M., Jerome, P., Blondet, M., Achenza, M., Eds.; ARGUMENTUM: Lima, Peru, 2016; pp. 255–260.
6. Lucchi, E. Review of preventive conservation in museum buildings. *J. Cult. Herit.* **2018**, *29*, 180–193. [CrossRef]

7. de Guichen, G. Preventive conservation: A mere fad or far-reaching change? *Mus. Int.* **1999**, *51*, 4–6. [CrossRef]
8. Della Torre, S. Planned preventive conservation and the structural performances of buildings. In *Structural Analysis of Historical Constructions—Anamnesis, Diagnosis, Therapy, Controls*; Van Balen, K., Verstrynge, E., Eds.; Taylor & Francis Group: Boca Raton, FL, USA, 2016.
9. Van Balen, K. Preventive conservation of historic buildings. *Restor. Build. Monum.* **2015**, *21*, 99–104. [CrossRef]
10. Gutiérrez-Carrillo, M.L.; Bestue Cardiel, I.; Molero Melgarejo, E.; Marcos Cobaleda, M. Pathologic and risk analysis of the Lojuela Castle (Granada-Spain): Methodology and preventive conservation for medieval earthen fortifications. *Appl. Sci.* **2020**, *10*, 6491. [CrossRef]
11. Ashurst, J. *Conservation of Ruins*; Routledge: London, UK, 2007.
12. AIC (American Institute for Conservation of Historic and Artistic Works). Code of Ethics and Guidelines for Practice. Available online: http://www.conservation-us.org/about-us/core-documents/code-of-ethics-and-guidelines-for-practice (accessed on 22 December 2024).
13. UNESCO/ICCROM/ICOMOS/IUCN. *Managing Disaster Risks for World Heritage*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2010.
14. ICOMOS. *Lima Declaration for Disaster Risk Management of Cultural Heritage*; ICOMOS: Paris, France, 2010.
15. Figueiredo, A.; Varum, H.; Costa, A.; Silveira, D.; Oliveira, C. Seismic retrofitting solution of an adobe masonry wall. *Mater. Struct.* **2013**, *46*, 203–219. [CrossRef]
16. Blondet, M.; Villa Garcia, G.; Brzev, S. *Construcciones de adobe resistentes a los terremotos: Tutor*; Earthquake Engineering Research Institute (EERI): Oakland, CA, USA, 2003.
17. Blondet, M.; Vargas, J.; Tarque, N.; Iwaki, C. Seismic resistant earthen construction: The contemporary experience at the Pontificia Universidad Católica del Perú. *Inf. De La Construcción* **2011**, *63*, 41–50. [CrossRef]
18. Dowling, D. Adobe housing in El Salvador: Earthquake performance and seismic improvement. In *Natural Hazards in El Salvador*; Rose, W.I., Bommer, J.B., López, D.L., Carr, M.J., Major, J.J., Eds.; Geological Society of America: Boulder, CO, USA, 2004.
19. Tarque, N.; Sayın, E.; Rafi, M.M.; Tolles, E.L. Behaviour of adobe construction in recent earthquakes. In *Structural Characterization and Seismic Retrofitting of Adobe Constructions: Experimental and Numerical Developments*; Varum, H., Parisi, F., Tarque, N., Silveira, D., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 15–33.
20. Varum, H.; Parisi, F.; Tarque, N.; Silveira, D. *Structural Characterization and Seismic Retrofitting of Adobe Constructions: Experimental and Numerical Developments*; Springer: Cham, Switzerland, 2021.
21. Rafi, M.M.; Varum, H. Seismic performance of adobe construction. *Sustain. Resilient Infrastruct.* **2017**, *2*, 8–21. [CrossRef]
22. Appeal, U.F. *Bam Earthquake of 26 December 2003. Islamic Republic of Iran. Relief, Recover and Immediate Rehabilitation*; United Nations: Rome, Italy, 2004; p. 7.
23. Jafarzade, F. Civil engineering features of damage on June 20, 1990 Manjil- Rudbar earthquake, Iran. In Proceedings of the Earthquake Engineering, Tenth World Conference Balkema, Rotterdam, The Netherland, 19–24 July 1992; pp. 99–102.
24. Berberian, M. Tabas-e-Golshan (Iran) catastrophic earthquake of 16 September 1978; a preliminary field report. *Disasters* **1979**, *2*, 207–219. [CrossRef] [PubMed]
25. Lotfalipour, M.; Dehghan-Banadaki, A.; Bakhshi, A.; Ghannad, M.A. Dynamic Characteristics of Rural Adobe Houses in Iran Using Ambient Vibration Measurements. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008.
26. Mahdi, T. Performance of traditional arches and domes in recent Iranian earthquakes. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004.
27. Maheri, M.R.; Naeim, F.; Mehrain, M. Performance of Adobe Residential Buildings in the 2003 Bam, Iran, Earthquake. *Earthq. Spectra* **2005**, *21*, 337–344. [CrossRef]
28. Minke, G. *Building with Earth: Design and Technology of a Sustainable Architecture*; Birkhäuser: Basel, Switzerland, 2006.
29. Maïni, S. *The French Contribution to the Reconstruction of Bam and Its Citadel: Diagnosis of Damages to Vaulted Structures Arg-e Bam and Bam town, Iran*; International Center for Earth Construction, School of Architecture of Grenoble: Grenoble, France, 2004.
30. Zahrai, S.M.; Heidarzadeh, M. Seismic Performance of Existing Buildings During the 2003 Bam Earthquake. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004.
31. Ashtiany, M. *Preliminary Observations on the Bam, Iran, Earthquake of 26 December 2003*; Earthquake Engineering Research Institute (EERI): Oakland, CA, USA, 2004.
32. Ayatollahi, S.M.H. The Passive Solar of Yazd: Reflections and Performance Evaluation after 10 Years Use. *Am. Trans. Eng. Appl. Sci.* **2012**, *1*, 379–392.
33. BHRC. *Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No. 2800)*; Fourth Revision; Building and Housing Research Center: Tehran, Iran, 2015. (In Persian)
34. Ariamanesh, M. *Zoning of Earthquake Hazards, Faults, Landslides and Potential Hazards to the Municipal Gas Network and Related Facilities in Yazd City*; National Iranian Gas Company: Yazd, Iran, 2017. (In Persian)

35. Asadi, A.; Neshat, S.; Barkhordari, K. Seismic hazard assessment and determination of maximum design base acceleration of Yazd. *J. Rehabil. Civ. Eng.* **2014**, *2*, 1–8. [CrossRef]
36. IIEES. International Institute of Earthquake Engineering and Seismology. Available online: http://www.iiees.ac.ir/en/ (accessed on 22 December 2024).
37. Dezvareh, M.; Naserieh, S.; Rouhi, A.; Boroumand, B. *Seismicity Maps of the Provinces of Iran (1900–2016)*; Institute of Geophysics, University of Tehran: Tehran, Iran, 2017.
38. Ambraseys, N.N.; Melville, C.P. *A History of Persian Earthquakes*; Cambridge University Press: Cambridge, UK, 2005.
39. ICHHTO. *Nomination of Historic City of Yazd for Inscription on the World Heritage List*; UNESCO, World Heritage Convention: Tehran, Iran, 2016.
40. USGS. Search Earthquake Catalog. Available online: https://earthquake.usgs.gov/earthquakes/search (accessed on 22 December 2024).
41. Nadim, F.; Moghtaderi-Zadeh, M.; Lindholm, C.; Andresen, A.; Remseth, S.; Bolourchi, M.J.; Mokhtari, M.; Tvedt, E. The Bam earthquake of 26 December 2003. *Bull. Earthq. Eng.* **2004**, *2*, 119–153. [CrossRef]
42. Mohajer-Ashjai, A.; Nowroozi, A.A. The Tabas Earthquake of September 16, 1978 in east-central Iran: A preliminary field report. *Geophys. Res. Lett.* **1979**, *6*, 689–692. [CrossRef]
43. Aqasafari, A.; Amiri, H.; Danesh, J.; Beheshtian, M.J. The quantitative and qualitative characteristics of housing in the historical texture of the Yazd city (1976–2006). *J. Stud. Iran. Islam. City* **2011**, *2*, 67–82.
44. Abouei, R. Conservation of Badgirs and Qanats in Yazd, Central Iran. In Proceedings of the 23th Conference on Passive and Low Energy Architecture, Geneve, Switzerland, 6–8 September 2006.
45. Memarian, G. *Statics of Vaulted Structures in Islamic Architecture of Iran*; Elm-o-Sanat University Press: Tehran, Iran, 1988.
46. Noghsan-Mohammadi, M.R. A Quest in Urban Morphology: An Analytical Approach in Formation and Transformation of a Traditional City: With Special Reference to Case of Yazd, Iran. Doctoral Dissertation, University of Sheffield, Sheffield, UK, 2001.
47. Haji-Qassemi, K. *Ganjnameh: Cyclopaedia of Iranian Islamic Architecture. Volume 14. Yazd Houses*; Shahid Beheshti University: Tehran, Iran, 1996.
48. MPO. *Instruction for Seismic Rehabilitation of Existing Buildings*; No. 360; Management and Planning Organization of Iran: Tehran, Iran, 2007.
49. Correia, M.; Jing, F. *Report on the Joint World Heritage Centre/ICOMOS Reactive Monitoring Mission to the World Heritage Property of Bam and Its Cultural Landscape (Islamic Republic of Iran), 16–22 October 2011*; UNESCO: Paris, France, 2012; p. 56.
50. Jha, A.K.; Barenstein, J.D.; Phelps, P.M.; Pittet, D.; Sena, S. *Safer Homes, Stronger Communities: A Handbook for Reconstructing After Natural Disasters*; World Bank Publications: Washington, DC, USA, 2010.
51. Cancino, C.; Lardinois, S.; D'Ayala, D.; Ferreira, C.F.; Quinn, N.; Torrealva, D.; Vicente, E. Seismic retrofitting of historic earthen buildings—A Project of the Earthen Architecture Initiative, The Getty Conservation Institute. In *UNESCO International Colloquium on the Conservation of World Heritage Earthen Architecture*; United Nations Educational, Scientific and Cultural Organization: Paris, France, 2012.
52. Tolles, E.L. Seismic Retrofit Applications of Getty Seismic Adobe Project Technology to Historic Adobe Buildings. In *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*; Hardy, M., Cancino, C., Ostergren, G., Eds.; Getty Conservation Institute: Los Angeles, CA, USA, 2006; pp. 159–164.
53. Barrow, J.M.; Porter, D.; Farneth, S.; Tolles, E.L. *Evolving Methodology in Seismic Retrofit: Stabilizing the Las Flores Adobe*; Getty Conservation Institute: Los Angeles, CA, USA, 2009; Volume 18, pp. 165–173.
54. Vargas-Neumann, J.; Rodríguez-Larraín, S.; Robles, T.M.; Onnis, S. Vernacular heritage seismic risk management—Ongoing educational project. In *Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development*; Correia, M., Carlos, G.D., Rocha, S., Eds.; Taylor & Francis Group: London, UK, 2014.
55. Khalili, M.; Moradi, G.; Rahimi, A. Assessing the existing context and proposed plan of Yazd historical texture from the point of access to emergency services using network analysis. *Urban-Reg. Stud. Res.* **2012**, *4*, 63–80.
56. Crocker, E.; Araoz, G. Toward a Comprehensive Taxonomy of Earthen Architecture. In Proceedings of the Terra 2008: The 10th International Conference on the Study and Conservation of Earthen Architectural Heritage, Bamako, Mali, 1–5 February 2008; Rainer, L., Rivera, A.B., Gandreau, D., Eds.; Getty Conservation Institute: Los Angeles, CA, USA, 2008.
57. CEN. *Eurocode 8: Design of Structures for Earthquake Resistance—Part 1: General Rules, Seismic Actions and Rules for Buildings*; CEN: Brussels, Belgium, 2004.
58. Saeedy, S.; Shamsipour, A.K.; Fallah, S.; Saeedy, S. Evaluation of Relief and Rescue Operations in Historic Regions (Case of Study: Fahadan District in Yazd City, Iran). *Urban Plan. Des. Res. (UPDR)* **2013**, *1*, 50.
59. Sathiparan, N.; Meguro, K. Strengthening of adobe houses with arch roofs using tie-bars and polypropylene band mesh. *Constr. Build. Mater.* **2015**, *82*, 360–375. [CrossRef]
60. Arya, A.S. Non-engineered construction in developing countries -An approach toward earthquake risk prediction. *Bull. N. Z. Soc. Earthq. Eng.* **2000**, *33*, 187–208.

61. Michiels, T.L.G. Seismic Retrofitting Techniques for Historic Adobe Buildings. *Int. J. Archit. Herit.* **2015**, *9*, 1059–1068. [CrossRef]
62. Tolles, E.L.; Kimbro, E.E.; Ginell, W.S. *Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures*; Getty Conservation Institute: Los Angeles, CA, USA, 2003.
63. Haji Sadeghi, N. Conservation and Safety Assessment of Vaulted Adobe Architecture in Yazd, Iran. Ph.D. Thesis, University of Minho, Braga, Portugal, 2018.
64. Torrealva, D.; Vargas-Neumann, J.; Blondet, M. Earthquake resistant design criteria and testing of adobe buildings at Pontificia Universidad Catolica del Peru. In *Proceedings of the Getty Seismic Adobe Project 2006 Colloquium*; Hardy, M., Cancino, C., Ostergram, G., Eds.; Getty Conservation Institute: Los Angeles, CA, USA, 2006; pp. 3–10.
65. Haji Sadeghi, N.; Oliveira, D.V.; Silva, R.A.; Mendes, N.; Correia, M.; Azizi-Bondarabadi, H. Experimental characterization of adobe vaults strengthened with a TRM-based compatible composite. *Constr. Build. Mater.* **2021**, *271*, 121568. [CrossRef]
66. CRAterre. *Conservation and Disaster Risk Reduction in Ardakan—Tabayi House Experience*; CRAterre-ENSAG/Hamyaran/Ardakan Municipality/Ardakan District/with the support of the European Union; CRAterre: Grenoble, France, 2010.
67. Rouhi, J. Lesson Learned from New Technical Interventions Applied in the Tekiyeh of Bam Citadel. In Proceedings of the 4th National and 2nd International Conference on Applied Research in Civil Engineering, Architecture and Urban Management, Tehran, Iran, 27–29 December 2016.
68. Rouhi, J.; Aveta, A.; Marino, B.G. A Comparative Analysis (SWOT) of Technical Intervention Plans Carried Out in Sistani House and Payambar Mosque of Bam Citadel. *Mediterr. J. Soc. Sci.* **2017**, *8*, 431. [CrossRef]
69. Zamanifard, A. Seismic Consolidation of Rural Adobe Building (Case Study: Tabas Isfahak Historical Village). *J. Hous. Rural Environ.* **2019**, *38*, 123–136.
70. Jesus Barroso, C.A. Reforço Sísmico Inovador de Construção de Taipa. Master's Thesis, University of Minho, Guimaraes, Portugal, 2017.
71. Panchal, A.P.; Patel, C.D. Experimental study on seismic behavior of adobe masonry with hemp fibre ropes. *Int. J. Adv. Res. Innov. Ideas Educ.* **2023**, *9*, 4497–4502.
72. Cassese, P.; Fenu, L.; Asprone, D.; Occhiuzzi, A.; Parisi, F. Experimental study on the in-plane response of adobe masonry wallets strengthened with textile reinforced matrix systems. In Proceedings of the the 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Athens, Greece, 28–30 June 2021; pp. 1322–1332.
73. Boem, I. Masonry elements strengthened with TRM: A review of experimental, design and numerical methods. *Buildings* **2022**, *12*, 1307. [CrossRef]
74. Ferrara, G.; Caggegi, C.; Martinelli, E.; Gabor, A. Shear capacity of masonry walls externally strengthened using Flax-TRM composite systems: Experimental tests and comparative assessment. *Constr. Build. Mater.* **2020**, *261*, 120490. [CrossRef]
75. Tolles, E.L.; Webster, F.A.; Crosby, A.; Kimbro, E.E. *Survey of Damage to Historic Adobe Buildings After the January 1994 Northridge Earthquake*; Getty Conservation Institute: Los Angeles, CA, USA, 1996.
76. Blondet, M.; Vargas-Neumann, J.; Tarque, N. Observed behaviour of earthen structures during the Pisco (Peru) earthquake of august 15, 2007. In Proceedings of the 14th World Conference on Earthquake Engineering, Beijing, China, 12–17 October 2008.
77. Silveira, D.; Varum, H.; Costa, A.; Martins, T.; Pereira, H.; Almeida, J. Mechanical properties of adobe bricks in ancient constructions. *Constr. Build. Mater.* **2012**, *28*, 36–44. [CrossRef]
78. Silveira, D.; Varum, H.; Costa, A. Influence of the testing procedures in the mechanical characterization of adobe bricks. *Constr. Build. Mater.* **2013**, *40*, 719–728. [CrossRef]
79. Eslami, A.; Ronagh, H.R.; Mahini, S.S.; Morshed, R. Experimental investigation and nonlinear FE analysis of historical masonry buildings—A case study. *Constr. Build. Mater.* **2012**, *35*, 251–260. [CrossRef]
80. Bossio, S.; Blondet, M.; Rihal, S. Seismic Behavior and Shaking Direction Influence on Adobe Wall Structures Reinforced with Geogrid. *Earthq. Spectra* **2013**, *29*, 59–84. [CrossRef]
81. Varum, H.; Tarque, N.; Silveira, D.; Camata, G.; Lobo, B.; Blondet, M.; Figueiredo, A.; Rafi, M.M.; Oliveira, C.; Costa, A. Structural Behaviour and Retrofitting of Adobe Masonry Buildings. In *Structural Rehabilitation of Old Buildings*; Costa, A., Guedes, J.M., Varum, H., Eds.; Building Pathology and Rehabilitation; Springer: Berlin/Heidelberg, Germany, 2014; Volume 2, pp. 37–75.
82. Meybodian, H.; Eslami, A.; Morshed, R. Sustainable lateral strengthening of traditional adobe walls using natural reinforcements. *Constr. Build. Mater.* **2020**, *260*, 119892. [CrossRef]
83. Illampas, R. Experimental and Computational Investigation of the Structural Response of Adobe Structures. Ph.D. Thesis, University of Cyprus, Nicosia, Cyprus, 2013.
84. Tarque, N. Numerical Modelling of the Seismic Behaviour of Adobe Buildings. Ph.D. Thesis, Università degli Studi di Pavia, Pavia, Italy, 2011.
85. Tolles, E.L.; Kimbro, E.E.; Webster, F.A.; Ginell, W.S. *Seismic Stabilization of Historic Adobe Structures*; Getty Conservation Institute: Los Angeles, CA, USA, 2000.

86. Blondet, M.; Vargas-Neumann, J.; Velásquez, J.; Tarque, N. Experimental study of synthetic mesh reinforcement of historical adobe buildings. In *Structural Analysis of Historical Constructions, New Delhi 2006*; Lourenço, P.B., Roca, P., Modena, C., Agrawal, S., Eds.; Macmillan India: New Delhi, India, 2006.
87. Kuwata, Y.; Takada, S.; Bastami, M. Building damage and human casualties during the Bam-Iran earthquake. *Asian J. Civ. Eng. (Build. Hous.)* **2005**, *6*, 1–19.
88. Haji Sadeghi, N.; Oliveira, D.V.; Correia, M.; Azizi-Bondarabadi, H.; Orduña, A. Seismic performance of historical vaulted adobe constructions: A numerical case study from Yazd, Iran. *Int. J. Archit. Herit.* **2018**, *12*, 879–897. [CrossRef]
89. PCM. *DPCM 2011: Direttiva del Presidente del Consiglio dei Ministri per valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni, G.U. n. 47 G.U. n. 47 ed.*; (In Italian). PCM: El Segundo, CA, USA, 2011.
90. MIT. *NTC 2018: D.M. del Ministero delle Infrastrutture e dei Trasporti del 17/01/2018. Aggiornamento delle Norme Tecniche per le Costruzioni (in Italian)*; MIT: Cambridge, MA, USA, 2018.
91. ICOMOS/ISCARSAH. *Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage*; ICOMOS: Paris, France, 2003.
92. Gruppo Sismica, s.r.l. *HiStrA (Historical Structure Analysis) Arches and Vaults, ver.2022.1.6*; Gruppo Sismica s.r.l.: Catania, Italy, 2022.
93. Caliò, I.; Marletta, M.; Pantò, B. A new discrete element model for the evaluation of the seismic behaviour of unreinforced masonry buildings. *Eng. Struct.* **2012**, *40*, 327–338. [CrossRef]
94. Pantò, B.; Cannizzaro, F.; Caliò, I.; Lourenço, P.B. Numerical and experimental validation of a 3D macro-model for the in-plane and out-of-plane behavior of unreinforced masonry walls. *Int. J. Archit. Herit.* **2017**, *11*, 946–964. [CrossRef]
95. Caddemi, S.; Caliò, I.; Cannizzaro, F.; Pantò, B. New frontiers on seismic modeling of masonry structures. *Front. Built Environ.* **2017**, *3*, 39. [CrossRef]
96. Pantò, B.; Silva, L.; Vasconcelos, G.; Lourenço, P.B. Macro-modelling approach for assessment of out-of-plane behavior of brick masonry infill walls. *Eng. Struct.* **2019**, *181*, 529–549. [CrossRef]
97. Castellazzi, G.; Pantò, B.; Occhipinti, G.; Talledo, D.A.; Berto, L.; Camata, G. A comparative study on a complex URM building: Part II—Issues on modelling and seismic analysis through continuum and discrete-macroelement models. *Bull. Earthq. Eng.* **2022**, *20*, 2159–2185. [CrossRef]
98. Maio, R.; Ferreira, T.M.; Estêvão, J.M.C.; Pantò, B.; Caliò, I.; Vicente, R. Seismic performance-based assessment of urban cultural heritage assets through different macroelement approaches. *J. Build. Eng.* **2020**, *29*, 101083. [CrossRef]
99. Pantò, B.; Cannizzaro, F.; Caddemi, S.; Caliò, I. 3D macro-element modelling approach for seismic assessment of historical masonry churches. *Adv. Eng. Softw.* **2016**, *97*, 40–59. [CrossRef]
100. Cannizzaro, F.; Pantò, B.; Caddemi, S.; Caliò, I. A Discrete Macro-Element Method (DMEM) for the nonlinear structural assessment of masonry arches. *Eng. Struct.* **2018**, *168*, 243–256. [CrossRef]
101. Cannizzaro, F.; Liuzzo, M.; Margani, G.; Pantò, B. An interdisciplinary approach for the geometric, constructive, and structural assessment of historical masonry domes with application to the 'Badia di Sant'Agata' in Catania, Sicily. *Int. J. Archit. Herit.* **2024**, *18*, 1033–1058. [CrossRef]
102. Chácara, C.; Pantò, B.; Cannizzaro, F.; Rapicavoli, D.; Caliò, I. Numerical simulation of the response of an unreinforced brick-masonry cross vault subjected to seismic loading. *Int. J. Archit. Herit.* **2023**, 1–21. [CrossRef]
103. Chácara, C. Macro-Element Nonlinear Dynamic Analysis for the Assessment of the Seismic Vulnerability of Masonry Structures. Ph.D. Thesis, University of Minho, Guimaraes, Portugal, 2018.
104. Caddemi, S.; Caliò, I.; Cannizzaro, F.; Lourenço, P.B.; Pantò, B. FRP-reinforced masonry structures: Numerical modelling by means of a new discrete element approach. In Proceedings of the 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Rhodes Island, Greece, 15–17 June 2017.
105. Pantò, B.; Cannizzaro, F.; Caddemi, S.; Caliò, I.; Chácara, C.; Lourenço, P.B. Nonlinear modelling of curved masonry structures after seismic retrofit through FRP reinforcing. *Buildings* **2017**, *7*, 79. [CrossRef]
106. Pantò, B.; Malena, M.; de Felice, G. A macro-modelling approach for arches strengthened with externally bonded inorganic matrix composites. *Structures* **2021**, *33*, 4299–4312. [CrossRef]
107. Cannizzaro, F.; Pantò, B.; Caddemi, S.; Caliò, I. Discrete modelling of externally bonded composite layers on masonry structures. *Compos. Struct.* **2023**, *315*, 116937. [CrossRef]
108. Azizi-Bondarabadi, H.; Haji Sadeghi, N. Local seismic culture in Iranian vernacular architecture: Evidence from Yazd earthen architecture. *Built Herit.* **2022**, *6*, 5. [CrossRef]
109. Sánchez, A.; Varum, H.; Martins, T.; Fernández, J. Mechanical properties of adobe masonry for the rehabilitation of buildings. *Constr. Build. Mater.* **2022**, *333*, 127330. [CrossRef]
110. Fajfar, P. A nonlinear analysis method for performance-based seismic design. *Earthq. Spectra* **2000**, *16*, 573–592. [CrossRef]
111. D'Ayala, D.; Ansal, A. Non linear push over assessment of heritage buildings in Istanbul to define seismic risk. *Bull. Earthq. Eng.* **2012**, *10*, 285–306. [CrossRef]

112. D'Ayala, D.; Meslem, A.; Vamvatsikos, D.; Porter, K.; Rossetto, T. *Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings*; GEM Foundation: Pavia, Italy, 2015.
113. Giordano, E.; Clementi, F.; Nespeca, A.; Lenci, S. Damage assessment by numerical modeling of Sant'Agostino's sanctuary in Offida during the central Italy 2016–2017 seismic sequence. *Front. Built Environ.* **2019**, *4*, 87. [CrossRef]
114. Torelli, G.; D'Ayala, D.; Betti, M.; Bartoli, G. Analytical and numerical seismic assessment of heritage masonry towers. *Bull. Earthq. Eng.* **2020**, *18*, 969–1008. [CrossRef]
115. Kreslin, M.; Fajfar, P. The extended N2 method considering higher mode effects in both plan and elevation. *Bull. Earthq. Eng.* **2012**, *10*, 695–715. [CrossRef]
116. Azizi-Bondarabadi, H.; Mendes, N.; Lourenço, P.B. Higher mode effects in pushover analysis of irregular masonry buildings. *J. Earthq. Eng.* **2019**, *25*, 1459–1493. [CrossRef]
117. Gupta, B.; Kunnath, S.K. Adaptive spectra-based pushover procedure for seismic evaluation of structures. *Earthq. Spectra* **2000**, *16*, 367–392. [CrossRef]
118. Chopra, A.K.; Goel, R.K. A modal pushover analysis procedure to estimate seismic demands for unsymmetric-plan buildings. *Earthq. Eng. Struct. Dyn.* **2004**, *33*, 903–927. [CrossRef]
119. Lourenço, P.B.; Mendes, N.; Ramos, L.F.; Oliveira, D.V. Analysis of Masonry Structures Without Box Behavior. *Int. J. Archit. Herit.* **2011**, *5*, 369–382. [CrossRef]
120. Nakamura, Y.; Derakhshan, H.; Griffith, M.C.; Magenes, G.; Sheikh, A.H. Applicability of nonlinear static procedures for low-rise unreinforced masonry buildings with flexible diaphragms. *Eng. Struct.* **2017**, *137*, 1–18. [CrossRef]
121. Kalkbrenner, P.; Pelà, L.; Sandoval, C. Multi directional pushover analysis of irregular masonry buildings without box behavior. *Eng. Struct.* **2019**, *201*, 109534. [CrossRef]
122. Cannizzaro, F.; Pantò, B.; Lepidi, M.; Caddemi, S.; Caliò, I. Multi-directional seismic assessment of historical masonry buildings by means of macro-element modelling: Application to a building damaged during the L'Aquila earthquake (Italy). *Buildings* **2017**, *7*, 106. [CrossRef]
123. Chácara, C.; Cannizzaro, F.; Pantò, B.; Caliò, I.; Lourenço, P.B. Seismic vulnerability of URM structures based on a Discrete Macro-Element Modeling (DMEM) approach. *Eng. Struct.* **2019**, *201*, 109715. [CrossRef]
124. *EN 1998-3*; Eurocode 8: Design of Structures for Earthquake Resistance—Part 3: Assessment and Retrofitting of Buildings. CEN: Brussels, Belgium, 2005.
125. Lagomarsino, S.; Camilletti, D.; Cattari, S.; Marino, S. Seismic assessment of existing irregular masonry buildings by nonlinear static and dynamic analyses. In *Recent Advances in Earthquake Engineering in Europe: 16th European Conference on Earthquake Engineering-Thessaloniki 2018*; Pitilakis, K., Ed.; Springer International Publishing: Cham, Switzerland, 2018; pp. 123–151.
126. Pelà, L.; Aprile, A.; Benedetti, A. Seismic assessment of masonry arch bridges. *Eng. Struct.* **2009**, *31*, 1777–1788. [CrossRef]
127. Guerrini, G.; Graziotti, F.; Penna, A.; Magenes, G. Improved evaluation of inelastic displacement demands for short-period masonry structures. *Earthq. Eng. Struct. Dyn.* **2017**, *46*, 1411–1430. [CrossRef]
128. Azizi-Bondarabadi, H. Analytical and Empirical Seismic Fragility Analysis of Irregular URM Buildings with Box Behavior. Ph.D. Thesis, University of Minho, Guimaraes, Portugal, 2018.
129. Scacco, J.; Milani, G.; Lourenço, P.B. A micro-modeling approach for the prediction of TRM bond performance on curved masonry substrates. *Compos. Struct.* **2021**, *256*, 113065. [CrossRef]
130. Romanazzi, A.; Oliveira, D.V.; Silva, R.A. Experimental investigation on the bond behavior of a compatible TRM-based solution for rammed earth heritage. *Int. J. Archit. Herit.* **2019**, *13*, 1042–1060. [CrossRef]
131. Han, W.; Wu, F.; Zhao, Y.; Wang, H.; Chu, S. Experimental study on bond behavior of gass textile mesh in earth-based matrix. *Materials* **2023**, *16*, 1161. [CrossRef]
132. Romanazzi, A.; Oliveira, D.V.; Silva, R.A. An analytical bond stress-slip model for a TRM composite compatible with rammed earth. *Constr. Build. Mater.* **2021**, *310*, 125228. [CrossRef]