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Emergency Response for Architectural Heritage in Seismic Areas: An Integrated Approach to Safety and Conservation

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Abstract: In 2015, hazard mitigation became a top priority on the international agenda, according to the United Nations Office for Disaster Risk Reduction. When it comes to architectural heritage, it is crucial to develop tools and site-specific response plans that can help the prompt and effective management of seismic events. The paper presents part of a research study carried out at the University of Parma, aimed at improving emergency strategies for the protection of cultural heritage damaged by earthquakes. Specifically, it analyses first aid and recovery reinforcements, with a specific focus on masonry churches affected by the 2012 quake in the Emilia Romagna region (Italy). The study highlights criticalities and good practices of a site-specific response. It shows that recovery with a sharp separation between emergency and reconstruction activities leads to wasted resources in terms of cost, material, and time. On the other hand, the most effective strategies for the conservation of architectural heritage in earthquake-prone areas have proved to be based on an integrated and shared approach, aimed at balancing safety, conservation, and economic issues. This leads to a broadening of the concept of emergency interventions and, more generally, of structural reinforcement in the field of architectural conservation.

Keywords: cultural heritage; historic masonry churches; post-earthquake damage assessment; emergency management; first aid intervention; seismic strengthening; architectural conservation

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1. Introduction

A wide range of historical built heritage is present in the Italian territory, which is characterized by a high seismic risk. As a matter of fact, earthquakes are the main cause of damage and loss of cultural heritage (CH), possibly erasing centuries of cultural development gains and resulting in huge economic costs for post-earthquake reconstruction [1–3].

In the emergency context, it is interesting to note that communities prioritise the protection of cultural assets, including historic buildings, as symbols of resilience. This is because CH provides a sense of continuity and identity that helps local communities overcome the trauma of destruction and displacement. It is also a valuable resource for sustainable social and economic development. Therefore, strengthening the capacity to protect CH from disasters goes hand in hand with strengthening the resilience of vulnerable communities, as stated in the Hyogo Framework for Action [4,5]. The ICCROM's statement "Culture cannot wait" underlines the importance of providing first aid to CH in emergencies to minimise risks and losses to vulnerable sites, buildings, and collections.

Since the 1980s, there has been a growing recognition of the importance of risk preparedness and preventive approaches for the protection of built heritage. As a result, policies and strategies for emergency responses have been progressively implemented at both international and national levels. Global intergovernmental organizations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Council on Monuments and Sites (ICOMOS), and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) have promoted charters and declarations outlining the principles for CH risk protection, as well as practical tools, guidelines, and training activities aimed at strengthening management and operational skills for the protection of tangible and intangible CH against sudden-onset disasters [6–10]. General strategies proposed at the global level need a site-specific application; at the time of the seismic event, it is crucial to have updated emergency plans that clearly identify any pre-existing risk factors that could increase damage to local CH, as well as emergency responders and operational procedures for the protection of historic buildings. To this aim, the United Nations Federal Emergency Management Agency (FEMA) encourages CH institutions to develop site-specific emergency plans for use in the event of a disaster or emergency, and provides expert guidance and practical long-term planning assistance to communities through non-profit networks such as the Heritage Emergency National Task Force [11]. Moreover, having an integrated approach to emergencies is also crucial. The recent PROCULTHER project, promoted by ICCROM, highlights the importance of including CH protection in disaster risk management processes to coordinate the specific objectives and agendas of heritage recovery with wider post-event recovery of the affected area, thus optimising resources [12].

In the Italian context, specific studies and research on emergency interventions began in the second half of the 20th century, encouraged by a growing concern about the lack of scientific knowledge needed to face the extensive damage to CH caused by the most significant earthquakes [13,14]. Since then, tools have been developed for on-site damage assessment [15–17] and for the design and realization of emergency stabilisation works [18–20]. Today, the Italian management model for seismic emergency responses is well recognised and used as an example internationally.

However, the recent earthquakes have highlighted some critical issues [21]. For example, in the 2012 Emilia seismic event, technicians were not trained to deal with the seismic damage as the Emilia region was only classified as a seismic area in 2003 [22]. Therefore, professionals and institutions with little specific or direct experience in large-scale emergency response were called upon to assess the damage and urgently design and implement safety measures in damaged buildings [23].

On-site damage and risk assessment for CH was carried out using inventory sheets for churches (Model A-DC) and palaces (Model B-DP) [15]. Their use during the Emilia earthquake revealed some critical points. In general, it appeared that the assessment was strongly influenced by the expertise of the technicians. Moreover, the accuracy of the interpretation of the collapse mechanisms was affected by the lack of information on the construction history and the techniques of the specific architecture. In addition, the standardised approach of the inventory sheets raised difficulties in highlighting the differences in the level of damage when it occurred in similar structural elements with the same collapse mechanism. Difficulties were also experienced when assessing complex buildings that did not conform to traditional structural schemes [24]. In fact, damage to architectural typologies other than churches and palaces did not have a suitable assessment tool.

Safety and stabilisation measures were then taken according to this damage assessment with the main purpose of immediate public safety (i.e., preventing collapses and ensuring humanitarian assistance). In the case of safety measures on listed buildings, the authorization of the superintendency was mandatory. Professionals were also required to prove that the urgent provisional works proposed were the most cost-effective solution [25].

However, the Emilian experience proved that economic, conservation, and safety issues are difficult to balance in the context of emergencies. Sometimes structural issues need to be prioritised over conservative ones, especially where decorative and fresco elements are concerned. For example, composite confinement may hamper the definitive repair of artistic works, since it could damage the surfaces or prevent the reconstruction of original paintings until the complete safety of the structures is guaranteed and the temporary elements are removed. This is the case of the Church of Sant'Anna in Reno Centese (FE, Italy), where a spritz-beton confinement and FRP reinforcement were used to stabilise the collapsing bell tower. This cost-effective (around 10,000 euros) and structurally efficient solution was attested as the only one that could prevent the demolition of the dangerous slender structure [26]. However, it was quite invasive in terms of the preservation of the original fair-faced masonry. In fact, special care had to be taken to minimise damage to the masonry substrate during the removal of the safety measures. After the final reinforcement, the bell tower was plastered over and lost its original appearance. Conservation problems can also arise where emergency measures are not taken for economic reasons. This is the case of the Church of Sant'Egidio Abate in Cavezzo (MO, Italy), the roof of which collapsed during the earthquake. For lack of a temporary covering, the interior of the church has been exposed to the weather and pigeons for years, leading to progressive deterioration. This approach, although initially cost-effective, resulted in higher costs during the final intervention. Decay removal and surface restoration cost slightly less than the safety measures. The opposite approach was taken in the case of the Church of San Luca Evangelista in Medolla (MO, Italy), which also partially collapsed during the earthquake. A massive metal structure was erected as a temporary cover (Figure 1). This emergency measure protected the interior spaces and improved the conservation of the building. Nevertheless, it proved to be very expensive and completely disconnected from the final restoration work. In fact, the temporary structure (which cost around 770,000 euros) will have to be completely removed and replaced with other temporary works to allow the final restoration to take place.

Figure 1. Church of San Luca Evangelista in Medolla (MO, Italy). Expansive metal structure to urgently secure and protect the partially collapsed masonry church. Photo credits: MiC.

These examples suggest that if a balance between economic, safety, and conservation issues is not achieved, approaches to CH could result in a recovery process made up of disjointed actions, leading to wasted resources and a loss of value and significance. These examples are not intended to be representative of Italian seismic emergency management practices, which is recognised internationally as being one of the most effective [27]. Indeed, the emergency response in Emilia Romagna was able to face criticalities by creating an effective network based on a unified management approach. Particularly significant in the emergency phase was the creation of both the "Commission for the Securing of Slender Buildings" to define guidelines for the stabilisation of bell towers instead of demolishing them [28], and the "Validation Group" to speed up the cost assessment of seismic damage with homogeneous procedures [29]. In the reconstruction phase, the creation of the "Regional Agency for Reconstruction" to coordinate the reconstruction of Public Buildings and Cultural Heritage, and the "Joint Commission" for the approval of reconstruction projects with common and shared opinions after joint examination of economic, structural, and conservation aspects is noteworthy [30].

In the wider framework of risk reduction research, the Emilia Romagna Regional Agency for Reconstruction fostered collaboration with universities to analyse and optimize seismic response management. For example, three research projects funded by Emilia Romagna region were carried out at the Universities of Ferrara and Parma, with the aim of analysing the recurring collapse mechanisms of fortresses, cemeteries, and theatres and defining specific on-site damage assessment inventory sheets [31–33]. Furthermore, seismic damage and emergency interventions on masonry churches affected by the 2012 earthquake have been investigated with specific research [34].

The present paper deals with the further developments in such research on security and stabilization actions in masonry churches. In particular, all the Emilian masonry churches damaged by the 2012 earthquake have been considered, with the aim of identifying and sharing examples of good practice and broadening the perception of first aid and, more generally, structural reinforcement in the field of architectural conservation.

The manuscript is structured as follows. Section 2 deals with the selection of case studies and description of the methodology employed for the critical analysis. The results of this analysis, that is the selection of best practices for a knowledge-based approach to first aid and an integrated approach to recovery, are described in Section 3. Moreover, Section 4 deals with visible strengthening interventions and discussions about the balance between structural and formal issues of reinforcement in order to widen the concept of temporary to permanent stabilization. Finally, the conclusions are summarized in Section 5, highlighting the essential need to develop a joint approach (that takes into account operational, structural, conservation, and economic issues) in order to enhance effective strategies for sustainable recovery and protection of CH in earthquake-prone areas.

2. The Case of 2012 Emilia Earthquake

This section describes the selection of case studies and the methodology used for the critical analysis of first aid to churches.

Recalling the well-known analogy between the fields of medicine and architectural conservation, first aid can be defined as "*the immediate and interdependent actions taken to stabilise and reduce risks to endangered cultural heritage during and after an emergency*" [8] (p. 10). Specifically, first aid activities consist of three steps: situation analysis, on-site damage and risk assessment, and security and stabilization actions. This research focuses on the security and stabilization actions undertaken in an emergency and analyses them with reference to definitive retrofitting. Retrofitting is intended to be a reinforcement intervention carried out in the final phase of recovery to upgrade the existing structures and make them more resistant and resilient to the damaging effects of seismic hazards. In this context, strengthening interventions, which improve buildings' structural performance, and structural repairs, which replace damaged load-bearing elements, are considered.

This research paid particular attention to religious buildings, the seismic safety of which is increasingly becoming a priority objective at a national level [35]. Moreover, this architectural typology has been identified as being one of the most vulnerable to seismic actions, as demonstrated by previous earthquakes [36]. As a matter of fact, in the case of the 2012 earthquake, despite the enormous destruction caused to the Emilian CH (which highlighted the seismic vulnerability of the region), churches suffered the most damage. This is in terms of both the percentage of damaged buildings in relation to the total number of buildings affected by the event, and the severity of the damage. Furthermore, emergency interventions on churches were the most expensive [28].

2.1. Selection of Case Studies

Among the 529 damaged religious buildings, several structures were secured by emergency stabilisation works. A preliminary analysis considered 125 case studies whose emergency interventions were authorised by the "*Commissario Delegato*" between August 2012 and October 2016. Works carried out by the fire brigade as a matter of extreme urgency and small works carried out privately were not included the documentation. For each case, data on costs and techniques of emergency and definitive interventions were collected and compared. A detailed description of this analysis can be found in [29].

To further the investigation, 20 historical churches were selected among the above-mentioned cases, as shown in Table 1. The sample extends within the area affected by the seismic event, in the provinces of Bologna, Ferrara, Modena, and Reggio Emilia. Some churches were selected as being representative (positively or negatively) from a technical, conservative, or economic point of view, according to the suggestions of the reconstruction agency. Some others were selected on the basis of the economic analysis, taking into account interventions that were particularly outside the average cost of reconstruction. Finally, some case studies were selected at random to increase the statistical significance of the sample.

Table 1. Emilian masonry churches considered in the study.

Name	Location	Damage Index
Collegiata di Santa Maria Maggiore	Pieve di Cento (BO)	0.30
Chiesa di San Lorenzo Martire	Casumaro di Cento (FE)	0.35
Ex-Chiesa di San Lorenzo	Cento (FE)	0.21
Chiesa di San Filippo Neri	Cento (FE)	0.34
Chiesa di Sant'Anna	Reno Centese (FE)	0.20
Chiesa di San Michele Arcangelo	Bomporto (MO)	0.38
Oratorio di San Rocco	Bomporto (MO)	0.20
Chiesa di San Nicolò da Bari	Bomporto (MO)	0.26
Chiesa di Sant'Egidio Abate	Cavezzo (MO)	0.58
Chiesa della Beata Vergine del Rosario	Finale Emilia (MO)	0.54
Chiesa di San Bartolomeo	Finale Emilia (MO)	0.44
Chiesa di San Luca Evangelista	Medolla (MO)	0.70
Chiesa dei Santi Senesio e Teopompo	Medolla (MO)	0.46
Oratorio della Beata Vergine della Porta	Mirandola (MO)	0.53
Chiesa di San Francesco d'Assisi	Mirandola (MO)	0.85
Chiesa del Gesù	Mirandola (MO)	0.50
Chiesa di San Michele Arcangelo	Novi di Modena (MO)	0.55
Chiesa di Santa Caterina d'Alessandria	Novi di Modena (MO)	0.62
Chiesa di Santa Maria Annunciata	Reggiolo (RE)	0.36
Chiesa di Santa Maria Assunta	Reggiolo (RE)	0.50

2.2. Methodology

For each case study, documents were examined in the archives of the Regional Agency for Reconstruction, the "*Soprintendenza Archeologica Belle Arti e Paesaggio per la città metropolitana di Bologna e le province di Modena, Reggio e Ferrara*" and the Civil Protection Agency. With regards to damage assessment, the inventory sheet for churches (Model A-DC), photographic documentation, and the economic assessment drawn up by the Validation Group were consulted. In addition, with regard to safety measures, the "Emergency Provision Form (Annex 3)", reports, tables, and metric calculations were analysed. Finally, with regards to the final reinforcement, reports, tables, and metric calculations from both the preliminary and the executive project, as well as the corresponding opinions of the Joint Commission, were consulted. Specifically, the emergency interventions and the final seismic improvements were analysed in relation to the macro element, its collapse mechanisms, and the level of the damage.

A comparative analysis of the aforementioned data highlighted some recurring practices that, although implemented because of safety needs and economic priorities, represent possible weaknesses in the overall recovery strategy [37]. For example, it was observed that securing actions were mainly undertaken on structural elements that endangered public safety and accessibility. The urgent stabilisation of internal vaults and walls far from the main roads were often neglected and deferred to the final restoration, even in cases where there were higher levels of damage. This led to the potential further collapse of unsecured architectural elements. Not only does this mean a loss of cultural value, but it also creates debris that slows down the recovery process as it needs to be carefully removed and stored. Furthermore, in the event of a roof collapse, internal spaces are not protected by temporary covers; exposed to external weathering and decay for a long time, more invasive and expensive restoration work are then required. In general, a divergence between the level of damage and the techniques used in interventions was noted. In order to overcome such criticalities, a methodology for assessing the most effective securing techniques according to the level of damage, site conditions, and the value of the endangered architecture was proposed in [37]. The aim is to support first responders with a shared procedure to select the emergency measures specific to each case, taking into account the economic advantages, technical effectiveness, conservation requirements, and operational needs.

The above analysis allowed the critical identification of relevant examples of optimisation in emergency stabilisation, which are intended to advance the academic debate and serve as a guide to good practice.

3. Results: Identification of Effective Emergency Strategies

The major seismic events of the 20th century demonstrated that emergency actions have significant impacts on the long-term rehabilitation of the affected area and its community. Therefore, first aid measures play a strategic role in the recovery process of the architectural heritage. For this reason, actions set up immediately after the disaster should be interrelated with the following phases in order to progressively restore damaged architecture [38].

The following examples illustrate emergency interventions that not only prevent damage from worsening, but also allow a knowledge-based approach to definitive retrofitting and an integrated approach to recovery, taking into account safety and conservation issues.

3.1. Emergency Strategies for a Knowledge-Based Approach to CH Recovery

Nowadays, preventive strategies, defined by national and international codes and guidelines for CH protection against seismic risk [39–41], are aimed at reducing vulnerability by means of a knowledge-based approach. This approach entails an in-depth knowledge of the current state the building and, in the specific case, of the factors influencing its seismic behavior (i.e., construction materials and features, maintenance status, previous seismic reinforcement, etc.), in order to define respectful and effective interventions [42–45]. However, in the sudden onset of an earthquake, an in-depth knowledge of the structure could be difficult to achieve due to the large number of damaged buildings requiring safety measures in a very short time. Analysis using the On-Site Damage Assessment Inventory Sheet for Churches (Model A-DC), carried out during the 2012 Emilia earthquake, highlights the importance of collecting as much information as possible during the initial inspections. Indeed, damage assessment is crucial in order to set up both congruent funds for reconstruction and better plans for the following phases of the recovery process, optimizing resources in terms of the intervention strategies, timings, and costs.

Moreover, once the emergency is over, the design of the final reinforcement requires a deep understanding of the building's condition throughout the on-site investigations. In some cases, however, stabilisation measures may prevent a proper assessment of the current state of the building. In cases of stabilisation with wooden planking and composite confinement, the damaged surfaces are hidden and prevent the survey of crack patterns and material conditions. In such cases, it is crucial to fully document the state of damage before installing the confinement layers. Figure 2 shows the example of the Church of Jesus in Mirandola (MO, Italy). The 2012 earthquake caused the detachment of the masonry outer layer in the transept. In this case, before the wooden confinement was installed, the cracks were documented manually in a specific report. Today, technology-based monitoring and documentation tools (e.g., 3D laser scanning for reconstruction and drones for aerial photography) can assist in the collection of data during an emergency. Geomatic techniques offer support to the operational fieldwork of rapid mapping strategies in sudden emergency contexts, solving the problem of inaccessible areas. Recent studies have addressed innovative assessment methods for a rapid preliminary survey, for example unmanned aerial vehicles (UAVs) equipped with cameras for aerial survey, ZEB1 portable light detection and ranging (LiDAR) mapping implemented into handle tools with simultaneous localisation and mapping (SLAM) algorithms [46], computer vision combined with augmented reality [47], and machine learning for damage detection [48–50].

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

Figure 2. Transept of the Church of Jesus in Mirandola (MO, Italy). Crack pattern documentation (**a**) realized before the installation of the wooden confinement (**b**). Photo credits: Comune di Mirandola Provincia di Modena, Allegato 3 Scheda opera provvisionale urgente.

Moreover, to investigate the state of conservation of a building, safety and accessibility are needed. Urgent stabilization can help approaches to the building if correctly set up in the emergency. To this regard, Figure 3 shows two different interventions with stabilisation measures against overturning mechanisms using scaffolding. The scaffolding in the Church of San Francesco d'Assisi in Mirandola in Mirandola (MO, Italy) is made up of multiple layers to support shoring of the façade (Figure 3a). In the Church of Beata Vergine del Rosario in Finale Emilia (MO, Italy), the single-layer scaffolding is instead set up as a hooping element, connected laterally to metal pillars with their own foundations (Figure 3b). Although the technology is similar, the first example does not account for accessibility requirements, while the second allows easy access to both external and internal spaces.

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

Figure 3. Structural scaffoldings in (**a**) Church of San Francesco d'Assisi in Mirandola (MO, Italy) and (**b**) Church of Beata Vergine del Rosario in Finale Emilia (MO, Italy). Photo credits: (**a**) MiC, (**b**) Google maps, 2016.

Structural scaffolding can also be used to carry out on-site inspections and diagnostics from a short distance away. This was the case in the Church of Santa Maria Assunta in Reggiolo (RE, Italy), where the structural scaffolding was installed in the emergency phase to support the damaged vaults (Figure 4). For further optimisation it was also used for the final rehabilitation, avoiding the need to replace it with new temporary supports which would have resulted in higher costs and wasted materials. This was made possible with an awareness in the design of the structural scaffolding from the outset; engineered in accordance with the operational and safety requirements of the future building site, constant maintenance and minor adjustments ensured efficiency throughout the entire recovery process.

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

Figure 4. Church of Santa Maria Assunta in Reggiolo (RE, Italy): (**a**) Emergency scaffoldings to support the damaged vaults; (**b**) In situ inspection for executive design, using emergency scaffoldings. Photo credits: L. Ferrari, 2017.

Although technically effective, this security technology can be quite expensive. However, for an installation period of more than eighteen months (data updated to 2012), purchasing rather than renting improves the efficiency of this solution from an economic point of view [51]. In the latter case, for example, the purchase of the scaffolding (at a cost of around 150,000 euros) proved to be the most cost-effective solution, not only because of the long installation time and its reuse during the final retrofitting, but also because it was installed inside the church (and therefore protected from decay) and sold to the contractor carrying out the final restoration work, reducing the actual cost by 25%.

3.2. Emergency Strategies for a Integrated Approach to CH Recovery

At the beginning of the 20th century, the development of international and collective awareness of the significance of cultural heritage (CH) and its role in society has given rise to a theoretical framework made of rules, principles and agreements for the protection and conservation of architectural assets. Although the importance of strengthening historic buildings against possible external threats has been recognised since the Athens Charter (1931), emergency interventions were not specifically addressed until the 1990s, when a renewed interest in reducing the risk of natural disasters arose at an international level [52].

At the beginning of the 21st century, the ICOMOS Charter (ISCARSAH Principles) considered urgent safeguard measures, recognising the specific nature of this type of intervention in relation to emergency conditions. Specifically, the "do no harm" principle is stated as follows: "*No action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in cases where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g., after seismic damages); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way*" [41] (Section 1: "General Criteria"). In line with the international principle, the Italian Code for Cultural Heritage also states that, in cases of extreme urgency, provisional interventions that are essential to prevent damage to the architectural heritage may be carried out. The national code also requires immediate notification to the superintendence and the immediate submission of project documents on the definitive interventions for approval according to the regular authorisation procedure [53] (Article 27).

The 2011 guidelines for seismic risk assessment and reduction of cultural heritage take up the ISCARSAH principle and emphasise that safeguarding interventions should not be concerned with formal integration into the fabric, but should aim to minimise irreversible changes to the assets [39] (paragraph 6.1). Moreover, in compliance with the Italian Technical Code, securing interventions designed for a shorter nominal life and lower load combinations are allowed [40] (paragraph 2.4).

Therefore, the theoretical framework of heritage conservation conceives first aid securing as an exception, a temporary technical tool that needs to be free from the usual principles and procedures. Due to sudden damages and the different timing and priorities in an emergency context, the protection of architectural heritage cannot be pursued as in ordinary conditions, where it would be a progressive activity carried out through conservation plans and restoration projects for maintenance and rehabilitation, as outlined by the Krakow Charter in 2000. Safeguarding interventions are only required to meet a single condition in terms of the impact on the assets, (i.e., the "do no harm" principle) [8] (p. 14). According to this approach, first aid is autonomous and separate from the conservation process.

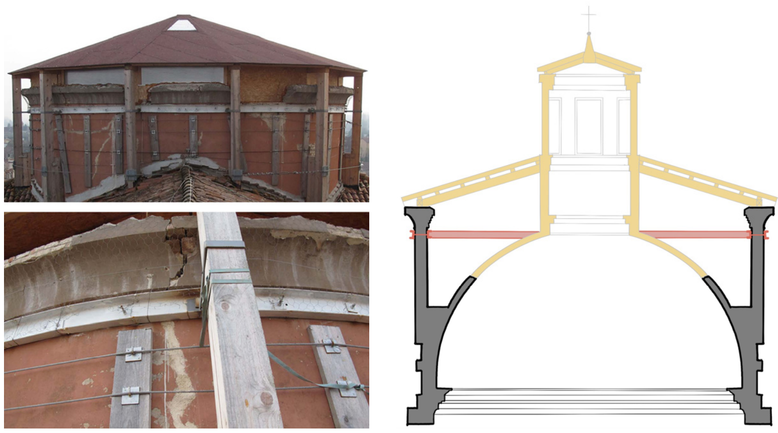
However, as the aim is the same as in conservation, the possibility of integrating securing measures into the final restoration work should be considered. In early 2000, Dolce suggested that the most effective provisional works, especially from an economic point of view, are those which can be integrated into the final intervention [20] (p. 6). The guidelines for seismic risk assessment and reduction of cultural heritage also highlight the possibility of considering temporary works as a definitive solution thanks to their intrinsic reversibility, which is an interesting feature from a conservation point of view [39] (paragraph 6.3). Such an integrated approach is of particular interest because of its positive impact on cost-effectiveness and conservation. To this aim, the selection of stabilisation measures should consider the possibility of reusing them in the final retrofitting operation [54] (p. 22).

However, this application is not always possible and requires a careful evaluation of the specific case. In this regard, the example of the Church of Jesus in Mirandola (MO, Italy), damaged by the 2012 Emilia earthquake, is worth mentioning. After the emergency interventions that secured the external parts, further safeguarding measures were needed to access the internal spaces for the assessment of the state of conservation to be finalized with the executive design. During the authorization process of these stabilization works, the Ministry of Culture required a specific document taking into account the temporary nature of safeguarding measures [55]. For each emergency action, different strategies and solutions were considered in relation to the realistic needs and, above all, the possibilities of reuse in the following phases. The aim of such a preliminary assessment is to demonstrate that the adopted solution is the most effective and that, where possible, reusable and definitive interventions are preferred to temporary ones. For example, the new tie-rods installed in the central nave during the emergency (against overturning mechanisms), originally set up to be temporary, were modified to be permanent. Traditional pole anchorages (*bolzone* in Italian) were used to permanently integrate the new anchors with the existing ones. This was actually a requirement of the superintendency, to reduce the impact of the definitive works on the masonry. Moreover, different solutions for the temporary cover have been considered. Although the safety conditions did not allow for the realisation of a permanent roofing, the covering structure was set up to create a walking surface to carry out restoration work both on the roof and inside the church. Moreover, a structural scaffolding needed to be installed inside to stabilize the perimetral walls. To this regard, the possibility of using the scaffolding installed in the emergency phase to carry out the final work was also verified in the document, taking into account the safety of the workers and the economic advantage of purchasing then reselling the scaffolding. The document cited is thus an example of integrated approach to recovery, where urgent interventions are designed in view of their impact on future restoration works.

This way, emergency stabilisation becomes the first step in the restoration of damaged architecture [56,57]. Therefore, the challenge is to reconcile urgent interventions with the conservation principles of authenticity and recognisability, as well as reversibility and compatibility, so the emergency stabilisation can be permanently integrated into the existing building.

To this regard, certain stabilisation measures are more suitable than others. For instance, tie-rods can be easily converted into a permanent reinforcement with minor modifications, such as replacing the anchorages and/or re-tightening [20] (p. 2). However, to ensure definitive strengthening, it is crucial to properly design and localize these elements during the previous emergency phase, not only to meet the structural requirements, but also to respect the formal architectural scheme and decorations. There are other examples in the literature of temporary interventions that have become permanent. This is the case in the safety works carried out at Castello Visconteo in Trezzo sull'Adda (MI, Italy), where an isolated slender wall was in danger of overturning [58]. Considering the historical value of the site, the securing measures were designed to allow access for visitors and to enhance the significance of the archaeological ruins. The provisional stabilisation, consisting of inclined metal strands anchored to the masonry and to the ground, was designed to be reversible and non-invasive. To this end, the connections to the wall were made through the scaffolding holes, thus avoiding any further damage to the masonry. The repetition of the same modular elements also helped the integration with the context, creating a sense of order. Initially designed to be temporary, the reinforcement was then left in place permanently thanks to the possibility of re-tightening the strands. However, if the permanence of the intervention had been assumed from the outset, further optimization could have been achieved, such as with the use of stainless steel.

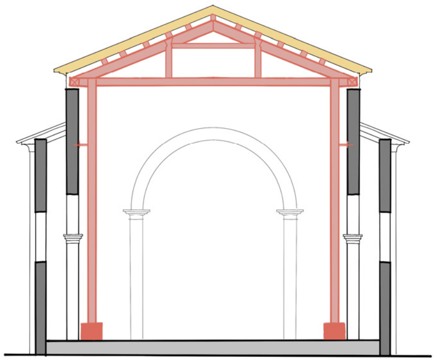
The Emilia experience also provides some examples of emergency interventions that found a permanent place in the final restoration. The case of the Church of Santa Maria Maggiore in Pieve di Cento (BO, Italy) is an interesting example of the contribution of emergency measures to the final recovery. Its lantern and part of the dome collapsed in the 2012 earthquake, and the tambour was severely damaged [59]. The tambour was first hooped with metal cables, then a glass fibre-reinforced plaster was applied to confine the masonry, and a C-shaped metal profile (UPN) was added to encircle the upper part, supporting a temporary cover to protect the interior spaces (Figure 5a). These urgent interventions were then incorporated into the final restoration design and became a permanent reinforcement (Figure 5b). Therefore, hooping with metal profiles or composite materials, a commonly used technique for emergency securing, can be suitable for permanent interventions. To this end, materials and localization must be designed for the long-term.



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

Figure 5. Church of Santa Maria Maggiore in Pieve di Cento (BO, Italy). (**a**) Emergency intervention: temporary covering and hooping with metal profile and steel cables; (**b**) definitive intervention: reconstruction of the collapsed part (in yellow) and retrofitting with the emergency hooping profile (in red). Photo credits: (**a**) MiC, (**b**) L. Ferrari, 2024.

Another interesting example is the Church of Santa Caterina d'Alessandria in Novi di Modena (MO, Italy) [60]. The seismic event caused the roof to collapse and the masonry walls to overturn. From the outset, the project aimed to restore the usability of the site by creating a welcoming situation, which is why it avoided the use of props that create a sense of precariousness. The first aid stabilization thus consisted of a stand-alone structure of timber trusses and piers fixed to the ground by external reinforced concrete plinths (Figure 6a). The wooden structure was stiffened by two wooden curbs connected to the masonry walls to prevent overturning (i.e., the lower curb was connected by a metal curb previously realised on the walls and the upper curb was connected by bars injected into the previously reinforced masonry). It was also configured to support both the temporary covering during the emergency phase and the permanent covering after the restoration work. Time and cost savings were achieved through the use of modular and standardised elements assembled using dry technology (Figure 6b). Lightweight and easy to handle on site, this technology accelerated the construction process and reduced the construction site costs. It could also be easily adapted to the different shapes of the historic architecture. This allowed the wooden frames to become a recognisable, permanent element that could be integrated into the restored building (eventually covered with suitable finishing), thus recovering some of the efforts made during the emergency phase. Finally, the project also appeared to be particularly respectful of the existing structure in that the original trusses, which were still capable of performing load-bearing functions, were not replaced, but rather consolidated with punctual interventions. It should be noted, however, that such an approach requires special conditions. In fact, the safety solutions described above were implemented after the end of the seismic crisis, following an initial phase of provisional stabilisation with shoring and hooping interventions carried out by the fire brigade teams.


(**a**)


(**b**)

Figure 6. Church of Santa Caterina d'Alessandria in Novi di Modena (MO, Italy). (**a**) Scheme of the emergency stabilization made of a permanent timber frame (in red) and temporary cover (in yellow) (**b**) Detail of materials and technology of the timber frame. Photo credits: (**a**) L. Ferrari, 2024, (**b**) MiC.

4. Discussion: Structural, Formal and Functional Issues of Seismic Reinforcement

The examples of emergency measures cited in Section 3 are in line with conservation principles and are therefore suitable to become permanent. Designed for temporary strengthening, they are reversible and respectful of the building (minimum intervention). The materials and structures were selected to be compatible with the historical masonry. Authenticity was also enhanced by the use of contemporary techniques and materials, as well as visible reinforcements that were formally integrated into the existing architecture.

However, visible reinforcement is not easily accepted in common practice. It is worth mentioning the case of the Arch of Spello (PG, Italy), damaged by the earthquake of 1997 (shear mechanism). The emergency intervention consisted of the installation of a slender metal support with an arched form, located at the intrados of the masonry arch (Figure 7a). Initially a provisional work, the intervention had the potential to remain in place permanently since it was in line with restoration principles of minimum intervention, reversibility, compatibility, authenticity and recognizability, as described by Doglioni in [61]. However, the final repair replaced the visible metal support with a traditional and invisible "stitch and unstitch" masonry restoration (Figure 7b).

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

Figure 7. Arch of Spello: (**a**) the metal safety support of the damaged arch; (**b**) on the right, the final repair work [61] (p. 152).

In the case of the 2012 earthquake, when it came to definitive interventions, traditional techniques were more widely accepted than innovative solutions that make the intervention visible. The approval documents drawn up by the Joint Commission to authorise reconstruction projects usually require hoops to be placed inside, tie-rods to be hidden above cornices or embedded into the masonry, and anchors to be covered with plaster or injected into the masonry even if they are less effective and more invasive. One of many examples is the Church of Santa Maria Assunta in Reggiolo (RE, Italy). The seismic strengthening of the bell tower was approved by the commission on the condition that the metal profiles were placed mainly inside the structure and therefore invisible from the outside. The visual impact of the external interventions was thus minimised; the hoops were required to be installed in correspondence with the existing eaves lines to hide them from below, the metal plate anchors also had to be hidden and their size had to be reduced. Otherwise, they had to be similar to the traditional pole anchorages.

Safety and conservation issues have been addressed since ancient times. Strengthening elements have always been used in construction to improve the stability of structures in case of earthquakes, either being inserted during construction or added afterwards to stem instabilities that have occurred in the meantime. In 20th century operational practice, technical and structural aspects were handled separately from formal and conservative aspects not only in "more general" restorations but also, and above all, in "more specific" consolidation, often considered "the engineering part of restoration" [61]. This attitude has had unsatisfactory outcomes; sometimes there is a clear prevalence of engineering aspects related to the safety of the structure, and other times formal aspects related to conservation prevail [62]. On the other hand, with regard to consolidation works, 20th century restoration culture has expressed itself, through the restoration charters, in an ambiguous manner, accepting the use of modern techniques and materials as long as they do not alter the appearance and character of the building. This requirement has justified the use of innovative technologies that allow invisible, but generally irreversible, incompatible, and not very durable reinforcements, effectively preserving the appearance but not the structure of the historic fabric.

In light of this tendency, studies developed since the 1980s have considered the humanistic assumptions of strengthening choices, bringing consolidation back into the disciplines of conservation [53] (article 29). Structural reinforcement is an essential to a restoration project, understood as part of an architectural project that satisfies the three Vitruvian components of *firmitas*, *utilitas*, and *venustas*. It must be conducted univocally and not in the dualism of knowledge that still exists between architects and engineers [63]. This is also reflected in the dialectic of visibility and invisibility, in which the former is now predominantly used, as it is more respectful of the existing material authenticity, more reversible, and easier to inspect. Contemporary aesthetic culture seems to have changed, softening the "disturbance" previously felt towards the technical parts and elements that serve the functionality of the architecture [64].

Examples of visible strengthening interventions that search for a balance between structural, functional, and formal issues are presented here. The case studies concern local reinforcements designed to address a specific vulnerability in historic buildings damaged by the earthquake. Even if such examples deal with definitive interventions, they are intended to be possible strategies for emergency measures designed to be both visible and permanent strengthening elements from the outset. The aim is to broaden the concept of seismic reinforcements into the conservation of historical buildings.

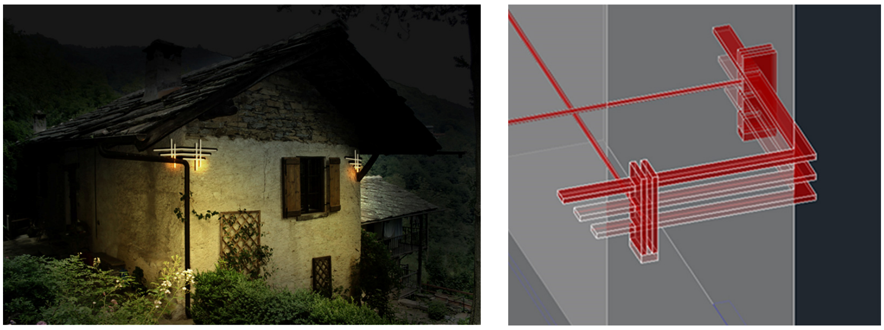
4.1. Tie-Rods: A Traditional Strengthening Integrated with Lighting

Over time, historical architectural manuals have recognised the essential structural function of tie-rods with visible anchors and condemned the practice of concealing them, which reduces their structural effectiveness. In the past, they have taken many forms and are usually optimised to resist horizontal action, or sometimes even enhanced with floral, animal, or geometric decorations [65].

An example of formal integration of visible anchors is presented in [66]. Specifically, Palazzo Costabili (Ferrara, Italy) was stabilised against seismic actions by new tie-rods. The pole anchors were designed to recall the shape of those already located in the building. This geometric proportion required the height of the central part to be increased in order to withstand current bending stresses. The tensioning system was also similar to the traditional one, even though the shapes were simplified to ensure recognizability. Authenticity was more evident in the anchors between the arches, which were designed with triangular plates to balance both technical efficiency and integration with the existing decoration.

The study also explored the possibility of associating lighting elements with tie-rods to improve the integration of the structural element into the architectural context. Specifically, a hoop system was required to prevent the overturning mechanism caused by the earthquake in the upper corner of the building, next to the main entrance (the museum's ticket office). Other functional elements were located on the same facades; the museum's banner, the video surveillance camera, and several lighting spots. The seismic reinforcement was therefore designed with the aim of integrating these separate elements into a unified system. The external tie-rods were made of an L-shaped steel profile to accommodate the linear LED lighting and connected at the corner by a steel plate that also served as the anchor base for the camera. The intervention, reversible and compatible with the masonry fabric, enhanced the visual impact of the functional elements on the façade.

Another example is the strengthening element designed for an alpine building, the perimetral walls of which were prone to overturning. Tie-rods were thus inserted in the upper part to ensure a box-like behaviour. External anchors along the staircase and entrance path were integrated with lighting to illuminate the walkway (Figure 8a). Such anchors consisted of modular vertical and horizontal steel elements, variable in number and size depending on the forces involved and the localisation on the wall (surface or corner). The tie rod was anchored between the two vertical profiles by means of a tensioning system and the LED lighting element was located under the vertical profile and along the horizontal ones (Figure 8b).



(a) (b)

Figure 8. Alpine building reinforced with tie-rods. The anchorage is composed of a modular element and light spots. Photo credits: L. Ferrari, 2017.

4.2. Structural Staircase to Strengthen Slender Structures

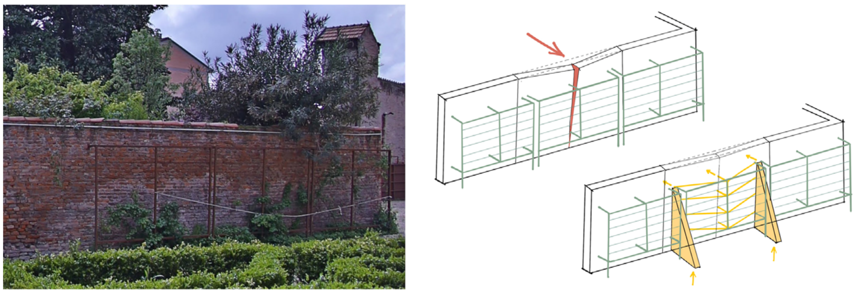
External hoops are particularly effective for slender structures (such as bell towers), both as an emergency measure and as a permanent seismic reinforcement. The same structural element can be located inside the structure and connected to the masonry by radial bars to strengthen the structure, as proposed by Jurina [67]. This structural element can be connected to vertical distribution elements such as stairs for inspection and periodic maintenance. This solution was used in the restoration of the Church of Santa Maria Assunta in Reggiolo (RE, Italy). The bell tower suffered significant damage during the 2012 earthquake, particularly in the octagonal drum of the belfry. The final reinforcement consisted of the construction of an internal metal structure made up of vertical posts connected by horizontal bars to internal and external horizontal plates. The existing wooden staircase located in the upper part of the bell tower was also severely damaged by the 2012 earthquake and was therefore replaced by a new metal staircase made up of a continuous stringer with shelf steps. These elements are connected to masonry walls by injected bars. The structural staircase thus defines an internal reinforcement that connects the shaft to the belfry and the perimeter walls (improving the box-like behaviour). This reinforcement structure was also used as a safety staircase during the restoration work, reducing the safety costs by eliminating the need for external scaffolding [68].

4.3. "Structural Furnishing" against Overturning and Share Mechanisms

The integration of structural elements and furniture offers other possibilities for integrating visible reinforcements.

Consider, for example, bracing elements, a common technique for strengthening masonry fabrics against earthquakes. Such reinforcements can be visually invasive but, if integrated with furniture, they can become part of the interior design of the building. This is the case of a restoration project developed within a Master's thesis at the University of Parma [69]. During the 2012 earthquake, the masonry walls of the Crevalcore Town Hall were found to be weak against horizontal forces. This was due to the fact that the original transversal walls on the ground floor had been transformed into columns as a result of post-construction structural modifications. The project [69] involved the insertion of a bracing element between the masonry columns to improve the stiffness of the structure against seismic actions. It also combined structural needs with re-functionalisation issues. An Internet cafè was created on the ground floor and the stiffening system was used to create a shelving structure for bottle racks and bookcases. Specifically, the metal structural cross was integrated with laminated wooden shelves which are mobile and flexible elements that can be adapted to specific functional needs.

Another example concerns the buttresses the in Palazzo Costabili used to prevent the overturning of part of the boundary wall. Buttresses have been used since ancient times to stabilise structures against horizontal earthquake action. When added after construction, buttresses can be invasive, requiring effective connections and adequate foundations. However, when integrated into the context, they can become distinctive architectural elements. In the Palazzo Costabili, the structural reinforcement was inspired by the furnishings in the courtyard [66], including a gazebo with perforated corten panels and a light metal structure to support the growth of vegetation, positioned adjacent to the overturning wall (Figure 9a). The buttress, designed with the same elements and material, was integrated into the latter, creating a single system of reinforcement and landscaping. Specifically, the buttress had been designed as an active reinforcement using a mechanism that connects it to the foundations and allows for active compression of the elements. In this way, an opposite force to the overturning action was applied to the wall (Figure 9b). However, due to the complexity of the site condition and the limited space available, the property preferred the more common technique of "stitch and unstitch" for the final intervention.



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

Figure 9. Palazzo Costabili in Ferrara (Italy). (**a**) Boundary wall with existing metal structure to support the growth of vegetation. (**b**) Boundary wall affected by overturning mechanism caused by the seismic action (in red) and reinforcement proposal for metal buttress integrated with existing support for vegetation (in yellow). Photo credits: (**a**) Google Maps, 2013; (**b**) L. Ferrari, 2017.

The above examples of interventions demonstrate that a visible strengthening element can respect the architectural value of the building and become a meaningful sign in the constructive history of the building, a witness to structural damage and an expression of contemporary architectural language. Structural elements can thus go beyond the limits of a technical tool and become a figurative element that expresses the authenticity of the restoration intervention. Becoming part of the conservation intervention of the fabric, the reinforcement is indeed subjected to these ethical implications. However, operational difficulties can hinder the application of such an approach. For example, the size and position of the elements must be both structurally efficient and compatible with the building. This can be difficult to achieve with the standard solutions given by manuals and codes, and requires a site-specific design. This can lead to increases in time and cost that are not in line with common practice. However, this goal can be met through an interdisciplinary approach and constructive dialogue between architects, engineers, professionals, and academics.

5. Conclusions

In the present paper, the seismic strengthening of architectural heritage sites has been analysed with the aim of identifying the strengths and weaknesses of emergency strategies and defining a "best practice" framework for the protection of cultural heritage (CH) in future seismic emergencies. In particular, the research focused on the safety and stabilisation of damaged churches, with specific reference to the 2012 Emilia earthquake.

In line with international and national codes and guidelines, knowledge-based and integrated approaches to first aid have been recognised as being fundamental to the effective and sustainable recovery of CH. Indeed, such an approach requires consideration of the impact of emergency measures on long-term recovery, and the planning of interventions that are effective from an economic, structural, and conservative point of view.

Best practices for a knowledge-based approach to seismic emergencies have been identified:

(a) Damage documentation should gather as much information as possible during the initial inspections. To this end, manual damage assessment can be enhanced by recent geomatic techniques, which allow inaccessible areas to be surveyed and improve the time and accuracy of the survey (e.g., CV-AR and AI for damage detection);
(b) Priority should be given to damage documentation when using securing techniques that conceal the surface (e.g., crack pattern and material surveys should be fully completed prior to stabilisation);
(c) Preference should be given to emergency stabilisation work that allows access to the exterior and interior of the building in order to document the state of conservation from a short distance (e.g., single-layer structural scaffolding rather than multi-layered, set up in accordance with safety requirements so that it can be used for in-depth on-site investigation during executive design).

Moreover, best practices for an integrated approach to long-term recovery have been identified:

(a) The authorisation procedure for securing interventions should require specific proof that stabilisation measures have been designed taking into account the possibility of reuse in the final retrofit (e.g., technical document with assessment of the temporary nature of emergency stabilisation);
(b) Preference should be given to emergency stabilisation that can be reused to carry out final restoration works (i.e., structural scaffoldings), or that can be included into the final retrofit with minor modifications (e.g., tie-rods with external anchors, metal hoops, and stand-alone covering structures). For this, localisation should be correctly selected from the outset and structural performances should be designed for long-term behaviour;
(c) In the case of emergency strengthening that is intended to become permanent, both traditional and innovative materials and techniques are appropriate, as long as they are non-invasive (minimum intervention), compatible, reversible, and, above all, authentic and recognisable (e.g., traditional tie-rods as well stainless-steel cables used against overturning, both of which are visible elements).
(d) Emergency interventions that will be permanently visible should be carefully integrated into the historic building, not only from a technical/structural point of view but also from a cultural/formal one. To this end, correlating the structural function with other functions (e.g., lighting, distribution, or furnishing) can help make a strengthening element a meaningful sign of the building's value.

The aforementioned "lessons learned" from previous seismic emergencies broaden the concept of urgent seismic strengthening; its purpose is not only the short-term stabilisation of CH sites, but also the optimisation of resources and the enhancement of knowledge and architectural significance.

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