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New Frontiers of Composites Applications in Heritage Buildings: Repair of Exposed Masonry of St. Nicola Church in Pisa

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Abstract: The upgrading and repair of masonry structures, which constitute a great part of built heritage, involve intricate aspects, in fact, the choice of the most suitable intervention technique is strongly dependent on its compatibility with superior preservation requirements. At present, beside more traditional approaches, many composite-based techniques are available, but, there are cases, such as exposed masonry, which are much more complicated to treat, since, to safeguard the original aspect, any intervention on the surface is precluded. In this paper, an innovative repair technique is discussed. The proposed method, highly adaptable and suitable for general application, is based on the insertion of a composite fabric into the mortar joints of the exposed masonry, partly relying on the indent repair technique traditionally used for the repair of masonry structures. Due to the peculiarities of the approach, the feasibility and efficiency of the solution cannot be demonstrated through application in the testing laboratory or on reduced samples, it was, therefore, necessary to identify a relevant case study for a field testing. After careful evaluation, duly considering the risks from the esthetic point of view, the proposed solution was implemented to repair the exposed masonry of the main façade and of the rear façade of the medieval San Nicola Church in Pisa, which is an outstanding example of the Pisan-Romanesque style. Thanks to a careful definition of the operational phases and to skilled workmanship, the solution was easily implemented in the year 2005, fully safeguarding the aesthetics of the façades, so demonstrating its feasibility. However, this successful outcome was only a first proof of the validity of the experiment, which also needed, for complete validation, the assessment of its efficiency over time. Only recently, after more than 15 years, it has been possible to ascertain that the intervention is still effective, because the crack patterns are stabilized and no reopening of the crack has occurred in the meantime, so achieving full confirmation.

Keywords: composite; FRP; fiber fabric; exposed masonry; heritage buildings; restoration; repair; strengthening

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1. Introduction

The assessment, decision making and planning of interventions on existing constructions is a modern engineering and architectural challenge, where intricate architectural and structural aspects often combine with the significance and the need for conservation of the historical, artistic, social, and economic values of the built environment and other relevant objects of cultural heritage. Dealing with existing constructions requires not only the implementation of sophisticated analysis and survey methods, but also the definition of intervention strategies, duly respecting the nature and the distinctive features of the construction itself. Owing to the fact that historical constructions have often been designed and built according to empirical rules, architectural canons, or simplified mechanical methods, and that the first structural codes date back to the end of 19th century, the assessment of the built environment cannot be approached directly by adopting the point of view of current codes, which are the result of modern achievements and improved knowledge about material properties, and theoretical models, also taking advantage of the availability of refined analysis tools. For this reason, minimum reliability levels accepted for the verifications of existing structures, and for their upgrading and repair, are commonly lower than the ones required in the structural codes for new structures, like Eurocode EN1990:2002 [1], and ISO2394:2015 [2]. Moreover, since the level of acceptance of such a reduced reliability is a function of significance, and the heritage value of the construction and of its content, the methodological approach, duly considering the reversibility and the compatibility of the interventions, is the result of a reasonable balance between the, often opposite, needs of consolidation and preservation. Evidently, the exigences of preservation are more and more predominant as soon as the significance of the construction becomes apparent; with this aim, several recommendations and standards have been issued. Focusing on built cultural heritage, particularly relevant are the standards of the European Standardization Committee (CEN) EN15898:2019 [3], EN16096:2012 [4], EN16853:2017 [5], the ICOMOS (International Council on Monuments and Sites) Charter [6–8] and the pertinent Guidelines of ICOMOS International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage (I.S.C.A.R.S.H.A.) [9], the standard of the International Organization for Standardization (ISO) ISO13822:2010 [10], and ISO12491:1997 [11], from which several national recommendations originate. It must be remarked that the main references about the conservation and restoration of monuments and sites, the Venice Charter 1964 [6], has been considerably supplemented and improved over time, till the Victoria Falls Charter [7,8]: an exhaustive review is provided by the ICOMOS in [9]. Because dealing with historical heritage is a complex interdisciplinary problem that can be tackled from different perspectives, recently, considerable efforts have been made to properly define the boundaries of the different disciplines and to find a common language for the interchange, storage, retrieval and updating of information [12], also in view of an increasingly massive usage of the Heritage-Building Information Modeling (H-BIM) [13,14].

The general procedure to be followed for the assessment of an existing structure is summarized in Annex B of the ISO13822 [11], where it is sketched how the current state of the considered structure and the resistance of its materials should be ascertained. The first step of the procedure is a preliminary assessment, duly considering the available historical documents, experimental in situ or reference test results, inspection, and survey reports, and other written or iconographic documentation. The outcomes of this preliminary assessment will indicate the eventual need of a detailed assessment, and finally the nature and type of interventions to be envisaged, if necessary. Clearly, during the procedure several key aspects should be considered, such as the definition of the mechanical properties of the existing materials [15–17], recognition of previous interventions, identification of peculiar building techniques or architectural canons adopted, chronology of the building phases, modifications of the structural scheme over time, and so on. Since, as already said, in heritage structures preservation exigencies are predominant, the procedure should be suitably modified. With this aim, additional considerations and provisions are given in the Annex H of ISO13822 [10], but, in the author's opinion, it is possible to propose here an improved version of the flowchart, illustrated in Figure 1, where peculiar aspects of heritage structures are highlighted, and the opportunity of developing appropriate H-BIM models is duly considered.

Specific examples of the application of the aforesaid procedure to historical structures are discussed in [18–22], also considering the effects of uncertainties [23,24], while extensive discussions about the evaluation of the statistical properties of the mechanical properties of building materials are reported in [25–27], where special methods are proposed to derive the main statistical parameters of the relevant mechanical properties of building materials of existing constructions, based on objective, blind, cluster analyses of available databases of in situ, and laboratory test results, assuming suitable probabilistic mixture models. The rationale of these special methods is that the mechanical properties of the building materials of coeval structures, characterized by similar typology, location, workmanship, and structural scheme, are described by comparable statistical parameters.

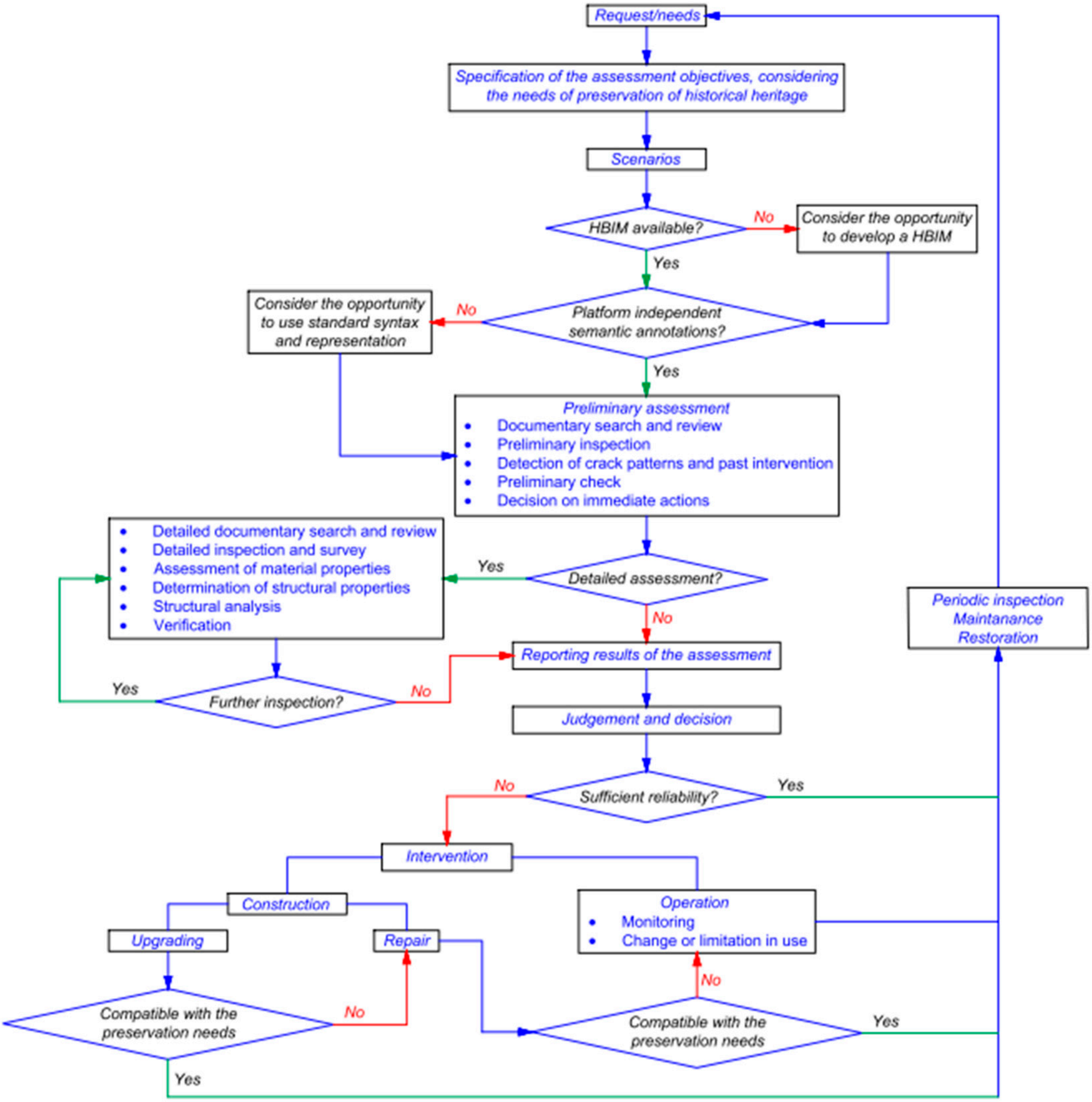


Figure 1. Flowchart illustrating the assessment procedure of heritage structures.

Although out of the scope of the paper, it must be underlined that a relevant issue in the structural analysis of historical masonry structures is the recognition of recurrent relevant elements and associated collapse mechanisms, which are studied adopting static or dynamic approaches, often in the framework of rigid body mechanics. The kinematic analysis is a typical static approach [28,29], while the rocking analysis is a typical dynamic approach [28,29]. In the kinematic analysis, energy dissipation, which is generally disregarded, can be considered hypothesizing suitable frictional forces between the crack surfaces [30]. In contrast, the rocking analysis allows the energy dissipation due to impacts to be considered, by means of suitable coefficients of restitution, which can be derived using kinematic, kinetic or energetic approaches [31], which are equivalent only in the case when the impact is frictionless [32]. For the rocking analysis, an energetic coefficient of restitution can be defined as a function of the block slenderness [33], but in some cases it leads to unrealistic results [34].

Looking at the flowchart in Figure 1, it is evident that, in the case of insufficient reliability, interventions are necessary. Obviously, since for heritage structures demolition is not an option, two main options of intervention can be considered for them:

- construction, or
- operation.

In turn, construction may consist of upgrading, or of a less invasive repair, while operation may result in monitoring, and change, or limitation in use. Upgrading and repair are possible only if compatible with the preservation needs; if not, the sole remaining option is operation. It must be remarked that compatibility between construction and preservation is an intricate issue [35–37], strongly influencing the choice of the intervention technique, since alternative solutions can be characterized by different degrees of harmonization with the preservation requirements.

Over the years many solutions have been proposed for the upgrading and repair of existing structures, spanning from the most traditional techniques and materials to the most modern and innovative ones, making use of composite materials, which are increasingly adopted not only for masonry structures, but also for reinforced concrete structures [38,39], even including some unconventional coupling [40,41].

Focusing on upgrading and repair techniques for masonry structures, which constitute a great part of built heritage, many solutions making use of composite materials have been proposed over the years: these techniques, summarized in [42–46], are mainly based on the introduction of composite strengthening elements, in the form of bars, sheets, ribbons and plates, but other interesting applications can be envisaged, adopting other modern materials, such as fiber reinforced cementitious matrix (FRCM) [47,48]. In parallel with the development of the abovementioned techniques, ad hoc studies have been carried out, aiming to develop suitable theoretical mechanical models, as well as to assess the experimental behavior of the recurrent repaired and strengthened elements: masonry walls and columns [49–57], arches [58], vaults [59–61] and dome vaults, which are the bases of modern guidelines such as those developed by the Italian Research Council (CNR) [62], also in view of the development of a dedicated second generation Eurocode part [63,64], in the framework of the M515 Mandate from the European Commission to CEN [65,66].

As already remarked, when dealing with historical buildings the identification of the most appropriate repair technique cannot ignore the superior exigence of preservation [67,68] and the intricately related issues. Some typical examples of strengthening intervention using composite are reported in Figures 2–5, where different phases of the repair for bohemian vaults with lunettes (Figure 2), cross vault (Figure 3), dome vault (Figure 4), partly collapsed ribbed barrel vault (Figure 5) are illustrated. Of course, the application of composite reinforcements can also be addressed to stabilize nonstructural or secondary elements; for example, in Figure 6, a possible composite application is illustrated for the avoidance of overturning of partition walls, which can be a relevant issue in seismic areas.


(a) (b) (c) (d)

Figure 2. Composite strengthening of bohemian vaults with lunettes: (**a**) before the intervention; (**b**) application of composite strips; (**c**) detail of the composite reinforcement; (**d**) detail of the completed intervention.

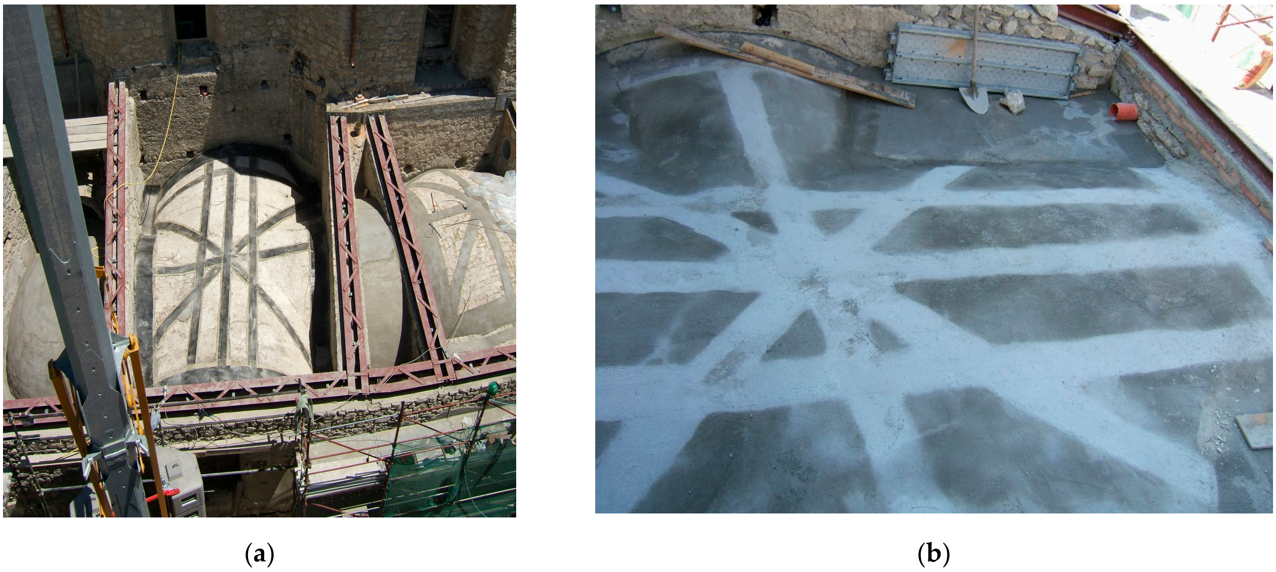
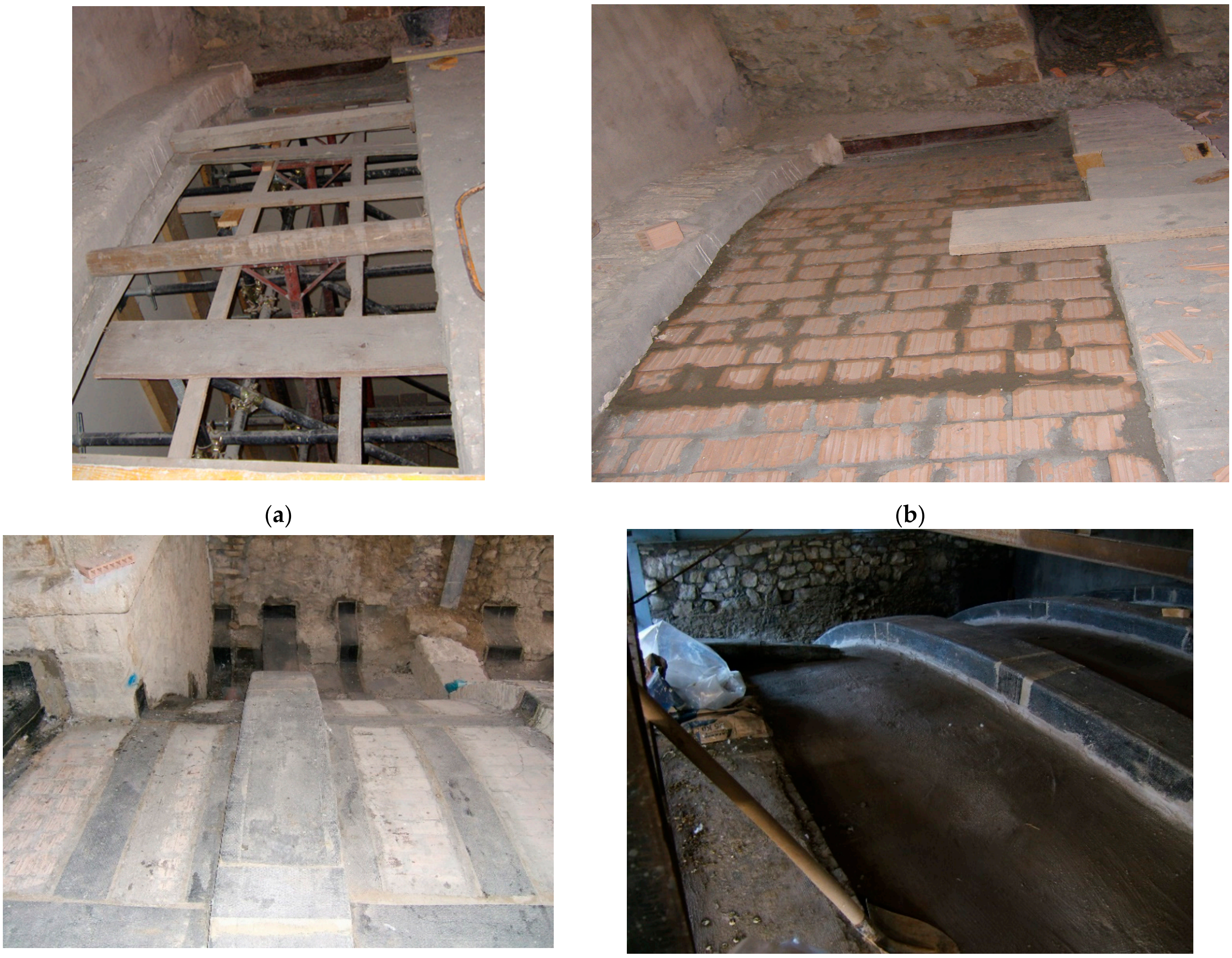

(a) (b)

Figure 3. Composite strengthening of a cross vault: (**a**) detail of the composite reinforcement; (**b**) detail of the completed intervention.

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

Figure 4. Composite strengthening of a dome vault: (**a**) detail of the composite reinforcement; (**b**) detail of the completed intervention.



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

(**c**) (**d**)

Figure 5. Composite strengthening of a partly collapsed ribbed barrel vault: (**a**) detail of the collapsed part; (**b**) reconstruction of the collapsed part; (**c**) detail of composite reinforcement; (**d**) detail of the completed intervention.

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

Figure 6. Composite intervention to avoid overturning of partition walls: (**a**) application of the composite reinforcement; (**b**) detail of the completed intervention.

However, there are cases which are much more complicated to treat, where, to safeguard the original aspect, any intervention on the surface is precluded. A particularly relevant case is exposed masonry. In this case, a typical intervention technique, originally proposed around 20 years ago, is the so-called bed-joints structural repointing, consisting in the insertion in the bed-joints of steel bars duly anchored at their ends, or of narrow rigid composite plates. These narrow composite plates can be obtained including steel or composite bars in a suitable polymeric matrix [69] or can directly be fiber-reinforced polymer (FRP) plates [70]. The operational sequence of these two repointing techniques, which are described in detail in References [69,70], can be summarized as follows:

1. preparation of the composite strip of the given length,
2. removal of the mortar of the bed joints near the external surface,
3. insertion of the strip, (...),
4. injection of the resin to fill the joint and glue the strip to the masonry.

Obviously, the field of application of these repointing techniques is rather limited: in fact, on the one hand the rigid strips can be applied only in the cases where the masonry courses are regular, on the other, their length is limited and not easily adaptable to conform with the various, and sometime unforeseen, situations that can occur in real applications. In addition, the limited insertion depth involves delicate bonding problems. Aiming to overcome all these issues, around the 2000s, the author developed an alternative strengthening technique, based on the insertion of composite fabrics into the mortar joints, partly resorting to the indent repair technique, which is an ancient and traditional solution for the repair of masonry structures.

Evidemtly, the solution, described in the following section, which is highly adaptable and suitable for general application, required some experimental validations. Unfortunately, for its peculiarities, the feasibility of the solution cannot be demonstrated through application in a testing laboratory or on reduced samples. For that reason, it was necessary to identify a relevant case study for a field testing of the feasibility and the effectiveness of the proposed technique. In fact, after a careful evaluation, in the year 2005, the solution was implemented to repair the main façade and the rear façade of the San Nicola Church in Pisa. The intervention is described in detail in Section 3. Although rather pioneering, thanks to skilled workmanship, the solution was easily implemented, fully safeguarding the aesthetics of the façades, so demonstrating its feasibility. However, for a complete validation of the proposed technique, its effectiveness over time also needed to be ascertained.

Today, after more than 15 years, and considering the present condition of the St. Nicola Church, there is more convincing evidence supporting the validity of the method.

2. The Proposed Strengthening and Repair Technique of Exposed Masonry

The innovative solution illustrated in the following was inspired by the classical indent technique, traditionally used to substitute damaged or weak parts of masonry structures or to make more effective the connections between adjacent walls. Examples of applications of this technique are shown in Figures 7 and 8, concerning the strengthening of a parastas, and of an uncoursed rubble masonry wall, respectively.


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

Figure 7. Application of the indention technique to the strengthening of a parastas: (**a**) during the intervention; (**b**) at the end of the intervention.

Figure 8. Application of the indentation technique: strengthening of uncoursed rubble masonry wall.

The basic idea is that, using the indent technique. it would be possible to easily insert FRP reinforcements in the regular mortar joints of the masonry. The main feature of the method is that the FRP reinforcement is obtained in situ, starting from rolls of textile fabrics of fibers, which are unrolled and duly impregnated with polymers, as soon as the indentation repair process proceeds.

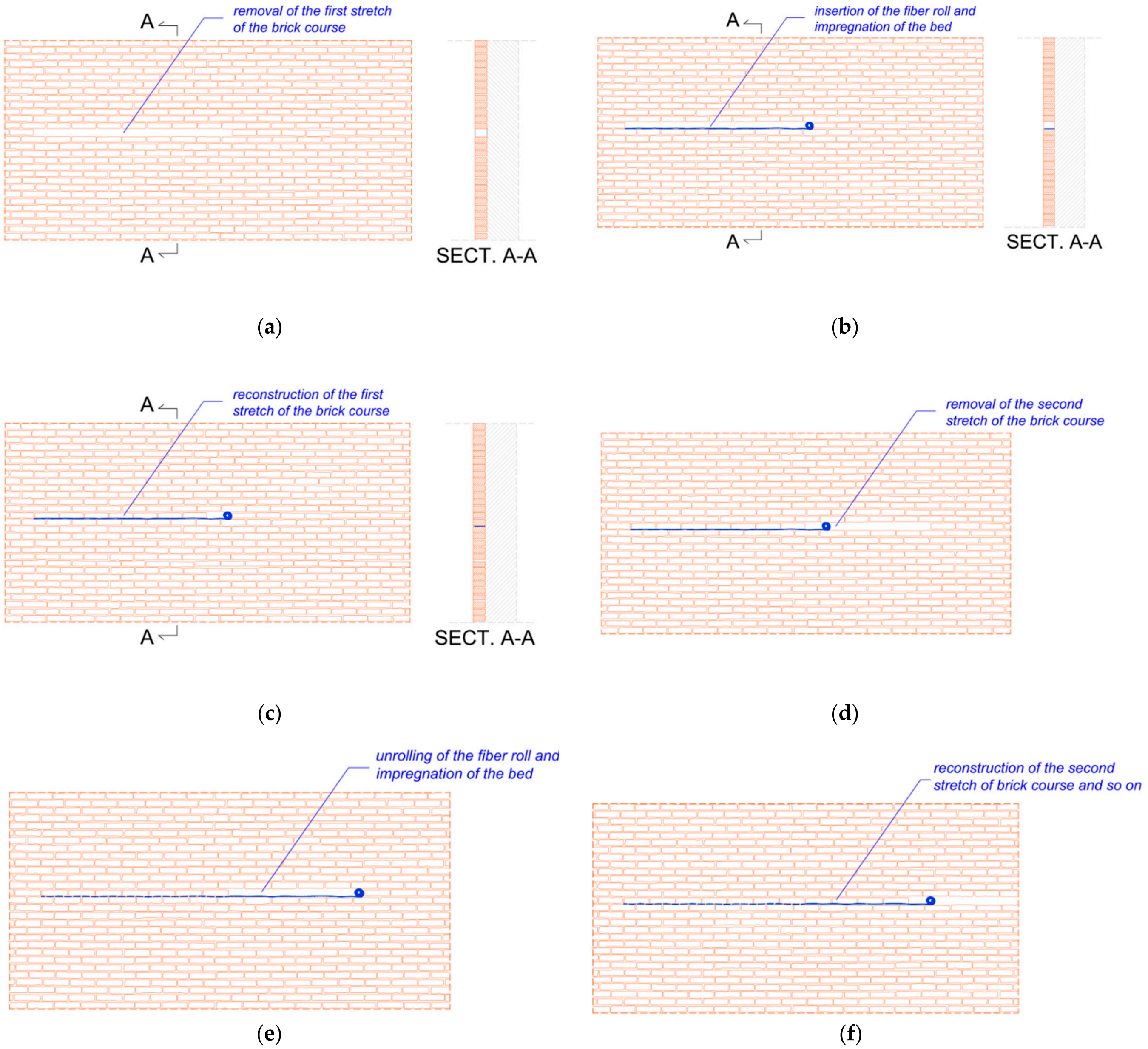
Referring to the exposed brick masonry, the main operational steps of the methods, summarized in Figure 9, are:

1. identification of the position of the brick masonry course of interest for the intervention,
2. preparation of a fiber strip of adequate length: the roll is formed starting from a fabric of the appropriate fiber: namely, aramid, carbon, glass, etc.; the width of the fabric should be a suitable multiple of the final width of the strip, in such a way that, folding the fabric one or more times or by superimposing more than one fabric, the desired thickness, and cross section area, is obtained,
3. rolling up of the fiber strip,
4. starting of the indent: careful removal of the first stretch of the brick course (Figure 9a), and cleaning of the so obtained recess,
5. application, using a spatula or a paintbrush, of low viscosity polymeric resin, for example, epoxy resin, insertion and partial unrolling of the fiber roll and its impregnation with the resin (Figure 9b),
6. waiting until the resin is suitably cured, typically 24 h;
7. reconstruction of the stretch of the brick course: reinsertion of the bricks and renovation of mortar joints (Figure 9c), using a mortar having a composition similar to the historical one, for example, a lime mortar,
8. removal of the second stretch of the bridge course (Figure 9d),
9. unrolling and impregnation of the fiber roll, as in step 5 (Figure 9e),
10. reconstruction of the stretch and renovation of mortar joints, as in step 6, and so on until the total extension of the course is completed (Figure 9f).

Obviously, if the total extension of the course exceeds the length of a single fiber roll, an additional fiber roll can be incorporated, provided that it overlaps the previously inserted one by not less than 500 mm. In this way, it is possible to obtain reinforced mortar joints of unlimited length, overcoming the limitations of the usual repointing techniques, but this is only one of the distinctive features of the method. Actually, in addition to its adaptability and economy, the proposed technique sensibly reduces the sensitiveness of the composite reinforcement to debonding phenomena, which is a typical issue for strengthening interventions, when using composite materials. It must be stressed that, providing tensile resistance to the masonry, the reinforcement can be limited to a part of the wall thickness, maintaining its effectiveness: this feature is particularly relevant when intervention on both faces of the masonry is prohibited by preservation needs, as in a case where one face is decorated or painted, or relevant masterpieces prevent the accessibility of the face. Moreover, in the framework of the proposed approach, the tying effect assured by the composite strips is scarcely influenced by their initial shape, since, even if initially bent, the composite strips, which are restrained by the surrounding masonry, cannot straighten up. However, in view of the practical application of this technique, and considering potential risks from the esthetic point of view, other key aspects needed to be duly studied:

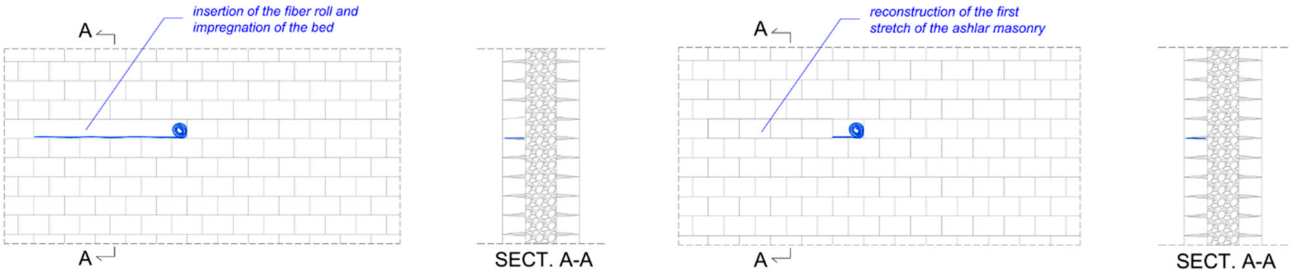
- extension to other types of exposed masonry,
- feasibility in real cases,
- appearance of the exposed masonry at the end of the intervention,
- effectiveness over time.

Regarding the first key aspect, it must be highlighted that, in principle, due to its peculiarities, the method can be easily extended: in fact, it can be applied in general, provided that minor modifications are introduced, as a function of the masonry type under consideration. Some relevant examples are given in Figures 10 and 11, for ashlar masonry, and rubble uncoursed masonry, respectively, where they are indicated the needed relevant deviations from the general method. In the case of ashlar masonry, even fine tooled, the strips can be inserted again in the mortar joints (Figure 10a), considering that usually the square-cut stones are transversally wedge shaped (Figure 10b) to allow not only the necessary adjustments in the construction phase, but also the substitution of the stones during maintenance. In addition, in the case of rubble uncoursed masonry, a rough dressing of the bed joint before the unrolling and impregnation of the fiber roll (Figure 11a) could be very helpful to regularize the final shape of the composite strip, limiting stress concentrations.



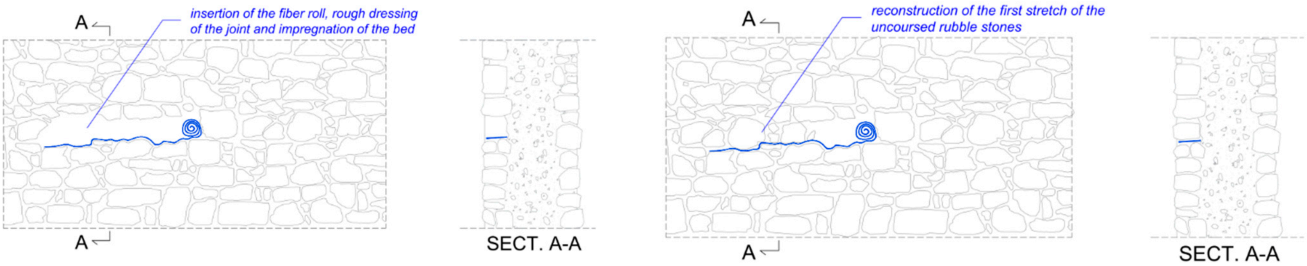
(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 9. Phases of the proposed intervention: (**a**) removal of the first stretch of brick course; (**b**) unrolling and impregnation of the fiber roll; (**c**) reconstruction of the first stretch of the brick course; (**d**) removal of the second stretch of brick course; (**e**) unrolling and impregnation of the fiber roll; (**f**) reconstruction of the second stretch of the brick course.



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

Figure 10. Relevant modifications of the proposed intervention for ashlar masonry: (**a**) unrolling and impregnation of the fiber roll; (**b**) reconstruction of the stretch of the ashlar course.



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

Figure 11. Relevant modifications of the proposed intervention for rubble uncoursed masonry: (**a**) unrolling and impregnation of the fiber roll and rough dressing of the bed; (**b**) reconstruction of the stretch of the ashlar course.

Answering the other key aspects, however, requires experimental evidence. As anticipated, due to its intrinsic nature, the feasibility and the efficacy of the technique can be tested and validated only in the field, evaluating the results after a long enough time interval. After a careful examination of all the pros and cons, it was decided that the occasion for testing the method was the restoration and repair of the St. Nicola Church, in Pisa. Since the church presented a relevant crack pattern in the exposed brick masonry of the façades, the method appeared particularly eligible in order to bridge and prevent the reopening of the cracks. This relevant case-study is illustrated and discussed in the following Section.

3. The Case Study: The Restoration of St. Nicola Church in Pisa

The proposed technique was experimentally applied in the year 2005, as described in the following.

3.1. St. Nicola Church

The St. Nicola Church, located in the historical center of Pisa, not far from the Arno River, is a remarkable example of the Pisan Romanesque architectural style, which is the subject of huge literature (see, for example, [71–78]). The Church belongs to an ancient building complex, including the leaning bell tower and the Augustinian monastery, bounded to the west by St. Maria Street, to the south by St. Nicola Street and to the east by the Carrara Place. The main façade and the rear façade face St. Maria Street and Carrara Place, respectively.

The leaning bell-tower (Figure 12), 35.5 m high, and inclined around 1°13′, and considered a masterpiece of the Pisan Romanesque style, is characterized by a complex architectural organization, with the cross section varying along the height: actually, the cross section starts as ribbed circular, with eight external ribs, at the base, to become octagonal at higher orders, and finally hexagonal at the level of the belfry, and of the roof.

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

Figure 12. The bell tower of the St. Nicola Church in Pisa: (**a**) the bell tower from St. Maria Street; (**b**) the belfry.

The first mention of the Church dates back to the year 1097, but significant enlargements, in some cases attributed to Giovanni Pisano, were promoted between 1297 and 1313 by the Augustinian fathers. Important modifications were introduced around the 1700s, consisting of the construction of the eight side chapels and of the longitudinal barrel vault covering the central nave. This solid brick barrel vault, around 120 mm thick, is stiffened by masonry arches, spaced at around 2.4 m. The actual configuration was finally achieved in 1828, with the execution of the two remaining lateral chapels, beside the main entrance.

The thrust of the barrel vault is sustained by buttresses supported by the transverse walls of the south chapels, coming up from the mono-pitched roof of the south side, as illustrated in Figure 13.

Figure 13. The south wall of St. Nicola Church.

3.2. Crack Patterns and Diagnosis of the Causes

To recognize the active failure mechanisms and to assess the suitability of the proposed method, a preliminary study was carried out. The outcome of the study was the identification of three main families of cracks, originated by two different failure mechanisms.

A first crack pattern, summarized in Figure 14, affected the longitudinal barrel vault of the nave and its stiffening arches. This crack pattern denoted the exemplary and classical vault mechanism, characterized by three longitudinal Pol Abraham's hinged cracks [79,80]: A central one at the intrados of the crown (Figure 15a) and two lateral ones, nearly symmetric, at the extrados of the vault haunches (Figure 15b).

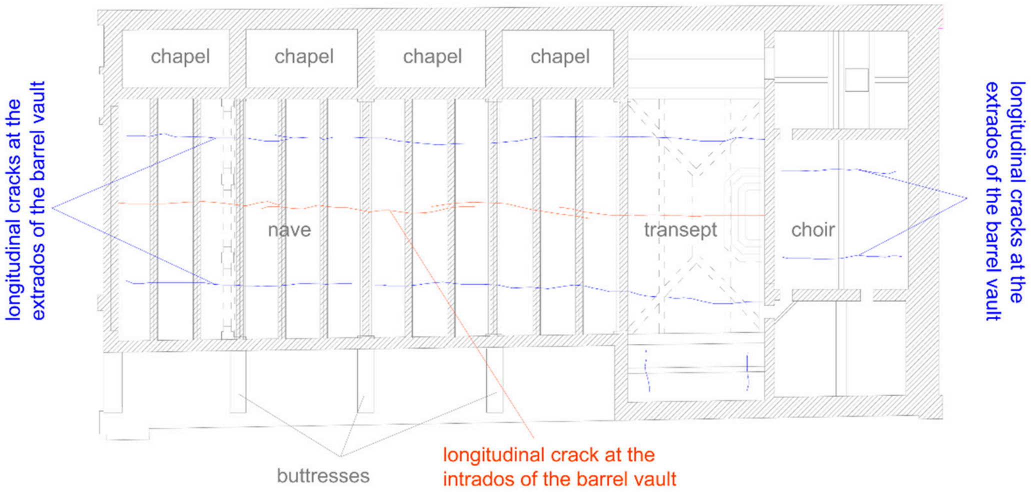


Figure 14. Crack pattern of the longitudinal barrel vault of the nave.


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

Figure 15. Longitudinal hinged cracks of the barrel vault of the nave: (**a**) longitudinal crack at the intrados; (**b**) longitudinal crack at the extrados of the barrel vault haunches.

A second, clearly visible, family of vertical cracks, summarized in the diagrams of Figure 16a,b, was detected on the main façade (Figure 17) and on the rear façade (Figure 18). A common feature of these cracks, mainly concentrated near the rose windows on the main façade, and in the neighborhood of the second window on the rear façade, was the width increasing with the height.


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

Figure 16. Graphic representation of the crack pattern on the façades: (**a**) main façade; (**b**) rear façade.

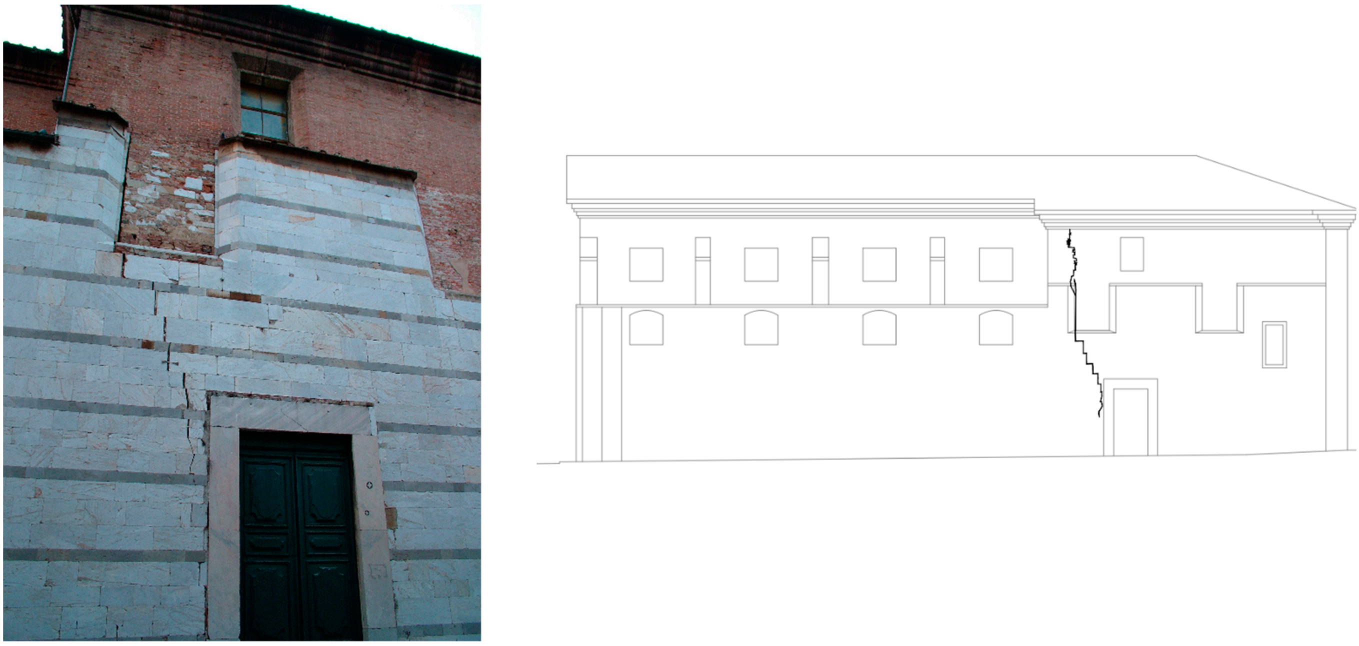

(**a**) (**b**)

Figure 17. The crack pattern on the main façade: (**a**) general view; (**b**) detail.

The crack patterns just described are both coherent with a unique failure mechanism: the relative horizontal displacement of the vault abutments, caused by the horizontal thrust, and by the resulting out-of-plane rotation of the longitudinal walls, barely restrained by the main façade, and by the rear façade. The origins of this failure mechanism seem quite remote; in fact, several stone stripes have been detected on the main façade straddling the cracks (see Figure 17b). The presumable rationale of the insertions of these narrow stones was stitching the cracks, but, the stone stripes also having cracked, the results were clearly unsatisfactory.

The third detected crack pattern was a significant vertical crack on the south façade, located at the connection between the nave and the transept, whose opening increased with the height (Figure 19). This crack was originated by a second failure mechanism, initiated in fairly remote times: a settlement of the foundation of the corner between the main façade and the south façade, further emphasized by the construction, in the 19th century of the arched passage connecting the Church with the Royal Palace. Nevertheless, after a suitable analysis of the evolution of the crack over time, it was concluded that the settlement was no longer active, and that specific strengthening interventions of the foundation were unnecessary. For these reasons, the interventions were mainly concentrated on the façades.

Figure 18. General view of the crack pattern on the rear façade.



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

Figure 19. The crack pattern on the south façade: (**a**) detail; (**b**) graphical representation.

3.3. Repair and Restoration Intereventions on the Church Façades

Repair and restoration interventions on the church façades pursued the twofold objective of bridging the main cracks, thus preventing their further opening, and of increasing the efficiency and tensile strength not only of the masonry joints, but also of the connections between the adjacent façades. Moreover, to minimize their sensitivity to differential vertical displacements, interventions with negligible bending stiffness in the vertical plane were preferred.

With these objectives, three different types of major interventions were envisaged, indicated as type A, type B, and type C intervention, respectively:

- the scope of the type A intervention was to strengthen the edge joist of the main façade, also contributing, together with the type C intervention, to restore the connection with the transverse walls,
- the objective of type B intervention, based on the innovative method described in Section 2, was to efficiently bridge the cracks in the exposed masonry, preventing their reopening, also demonstrating the feasibility of the method itself,
- finally, the objective of the type C intervention was to provide an efficient connection at the top of the south façade and of the rear façade. The type C intervention was based on the application at the top of the wall of a horizontal steel plate, centered in the wall plane, duly connected with the wall itself. Considering that this kind of intervention is rather common, further details are omitted.

3.3.1. Type A Intervention

Type A intervention is summarized in Figure 20. It combines a composite steel-FRP strip, strengthening the edge joist at the top of the gable of the main façade (Figure 21a), with a composite steel-FRP horizontal tie, placed on the inner side of the gable, above the extrados of the barrel vault, covering the nave.

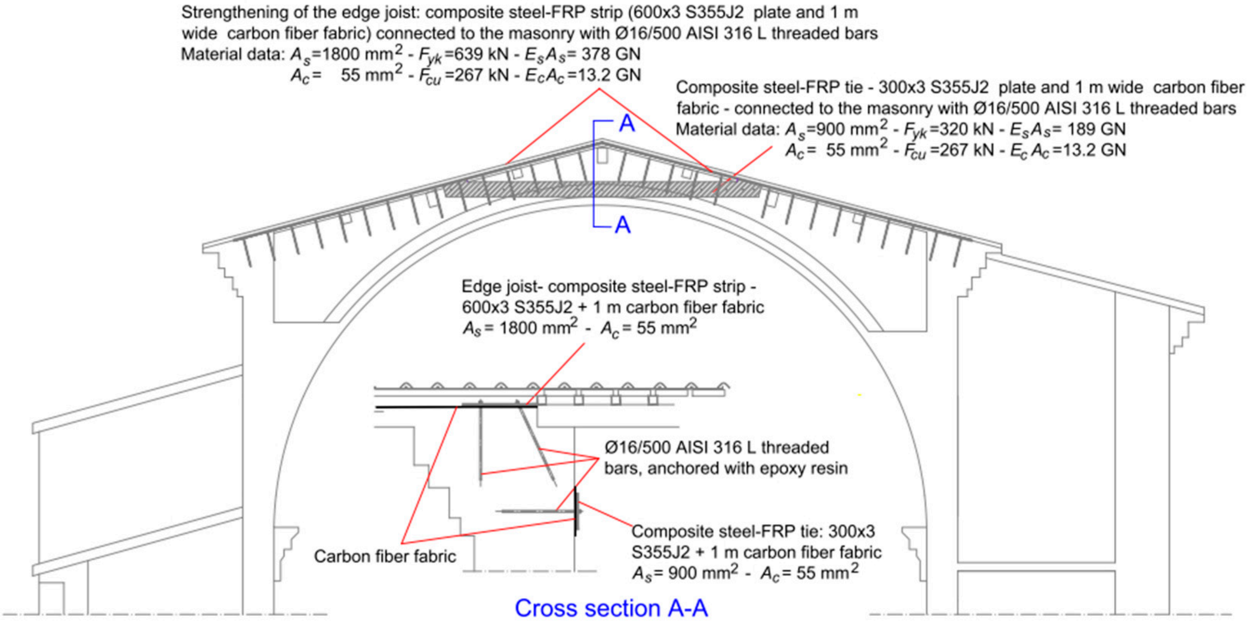


Figure 20. Main façade: strengthening of the edge joist at the top of the gable: type A intervention.


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

Figure 21. Phases of type A intervention: (**a**) edge joist before the intervention; (**b**) fixing of the carbon-fiber fabric; (**c**) upper steel plate; (**d**) glass-fiber net interposition for electrical insulation.

The composite steel-FRP strip was obtained superimposing to a 1000 mm wide bidirectional carbon-fiber fabric, weighing around 2.0 N/m^2, duly fixed to the properly dressed edge joist by means of low viscosity epoxy resin (Figure 21b), a S355J2 grade steel plate, 600 mm wide and 3 mm thick, connected to the masonry by means of threaded stainless steel bars, AISI 316L grade, 16 mm diameter (Figure 21c), so also preventing the debonding of the composite reinforcement. A thin glass-fiber net, interposed between composite and steel, aimed to avoid any contact between carbon and steel, guaranteeing the electrical insulation (Figure 21d). The relevant mechanical properties of the carbon-fiber fabrics were:

- Elastic modulus: $E_c \approx 240$ GPa,
- Effective area: $A_c \approx 55$ mm^2/m,
- Tensile strength: $f_{cu} \approx 4850$ MPa.

The operational steps of the intervention can be summarized as follows:

- cleaning of the masonry surface, removing all weak and loose parts, as well as any cause that would potentially reduce the adhesion of the reinforcement,
- preparation of the top surface and its dressing by means of fine mortar,

- insertion of the connecting bars,
- application of low viscosity resin,
- addition of a bidirectional carbon-fiber fabric, and its impregnation with the low viscosity resin,
- addition of the insulating glass-fiber net,
- application of the steel plate,
- zinc coating of the steel plate.

The composite FRP-steel tie, composed of a composite strip, about 335 mm wide, and a S355J2 steel plate 300 mm wide and 3 mm thick, was obtained and connected similarly to the top composite strip (Figure 22), but the carbon fiber strip was obtained by folding the fabric to one third and two thirds of its width.


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

Figure 22. Composite steel-FRP tie: (**a**) carbon-fiber reinforcement; (**b**) steel plate.

The main characteristics of the edge joist composite steel-FRP strip can be summarized as follows:

- Steel part:

  Area: $A_s = 1800\ \text{mm}^2$,
  Yield strength: $F_{yk} = 639$ kN,
  Axial rigidity: $E_sA_s = 378$ GN,

- Carbon part:

  Area: $A_c = 55\ \text{mm}^2$,
  Ultimate strength: $F_{cu} = 267$ kN,
  Axial rigidity: $E_cA_c = 13.2$ GN;
  While the main characteristics of the composite steel-FRP strip were:

- Steel part:

  Area: $A_s = 900\ \text{mm}^2$,
  Yield strength: $F_{yk} = 320$ kN,
  Axial rigidity: $E_sA_s = 189$ GN,

- Carbon part:

  Area: $A_c = 55\ \text{mm}^2$,
  Ultimate strength: $F_{cu} = 267$ kN,
  Axial rigidity: $E_cA_c = 13.2$ GN.

3.3.2. Type B Intervention

One of the main objectives of the type B intervention was to validate the proposed repair technique, experimentally demonstrating its practical feasibility and effectiveness in a relevant heritage construction. As described in Section 2, this innovative technique is based on the insertion of continuous FRP strips in mortar layers, resorting to a suitable and ordered removal and reinsertion of bricks of a given course, according to the traditional indent repair technique. In the present case study, the extension of the brick course affected by a single step of the indent (removal and reinsertion of brick elements) was fixed around 2 m, adopting a maximum distance between a reinforced brick course and the nearest reinforced one of around 0.6 m. Owing to the presence of a relevant historical pipe organ on the rear of the façade, the intervention was limited to the exterior wall.

Carbon-fiber fabric, already described in the previous Subsection, and low viscosity epoxy resin were used to assemble the composite reinforcement. The four layer carbon fiber roll was obtained by repeatedly folding the 1.0 m wide strip of carbon-fiber fabric. The mechanical characteristics of the roll thus resulted:

- Area: $A_c = 55\ \text{mm}^2$,
- Ultimate strength: $F_{cu} = 267$ kN,
- Axial rigidity: $E_cA_c = 13.2$ GN.

Because the operational phases, illustrated in Figure 23, perfectly matched those described in Section 2, additional information is unnecessary.


(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 23. Relevant operational phases of the intervention: (**a**) removal of the first stretch of the brick course; (**b**) reconstruction of a stretch of the brick course, before unrolling the fiber roll; (**c**) unrolling and impregnation of fiber roll; (**d**) stretch of the brick course ready for reconstruction; (**e**) intervention in advanced stage; (**f**) intervention almost completed.

The strengthened brick courses of the façade and the lengths of the interventions are summarized in Figure 24.

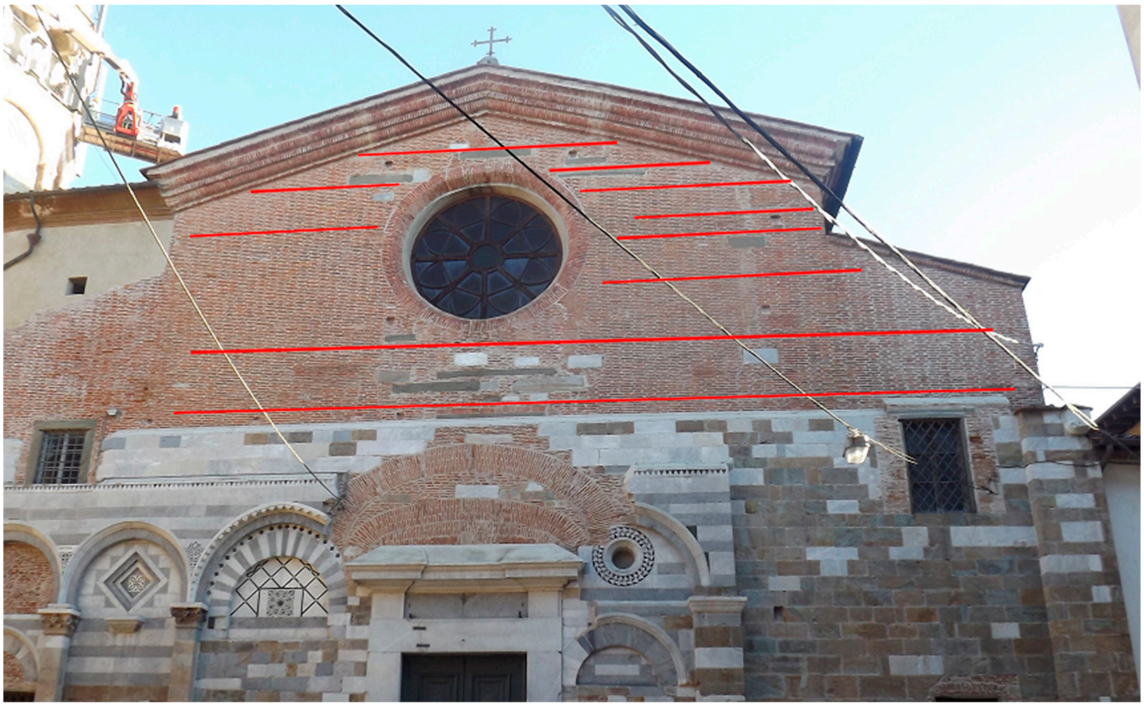


Figure 24. Strengthened brick courses of the main façade.

The intervention is providing tensile strength to the horizontal courses of the masonry. Considering that the wall width is 0.6 m, the influence area of each reinforcement is around 0.36 m^2: the equivalent tensile strength of the masonry is thus around 0.75 MPa, which is the information needed when homogeneous mechanical models are adopted to assess the masonry.

3.4. Discussions

Although extremely difficult, thanks to highly skilled workmanship, the intervention was very successful, fully safeguarding the aspect of the exposed masonry. However, this satisfactory outcome was only the first part of the experiment validation, in fact, to arrive at sounder conclusions a long enough period of observation was necessary. Now, after more than 15 years, sounder final conclusions can be drawn, based on the observation of the actual condition of the crack patterns, originally detected on the church façades, and described in Section 3.2.

To assess the crack evolution, in principle there are several methods, including the permanent installation of extensometers and deformometers on suitable measuring bases, also in view of continuous monitoring, remote sensors, laser scanning, radar measurements, traditional and digital photogrammetry, and so on. Due to their relative invasiveness, the need for monitoring of the whole width of the façade, the high economic costs. the difficulties in assuring stability of the signal over very long periods of time, the rapid obsolescence of electronic instrumentation and the relevant hardware, continuous monitoring by means of such kind of devices was excluded. As the precision of remote sensing techniques is on the order of millimeters, it was decided to adopt a periodic (every six months) topographical survey using high precision laser stations, monitoring the geometry of the edges between the main and the south façade, and the rear and the south façades, associated with careful visual inspections, also in view of possible implementation of the most appropriate remote sensing techniques.

At the end of the intervention, the deviations from the vertical line of relevant points of the edges between the main façade and the south façades, and the rear façade and the south façade were measured. The results are summarized in Table 1, where positive values indicate north−south displacements.

Table 1. Deviations from the vertical line of edges between the façades and the south façade—positive values indicate north−south displacements.

Edge	Point ID	H [m]	Deviation [mm]
between the main façade and the south façade	1	1.07	10.2
	2	2.70	25.7
	3	4.28	40.8
	4	8.43	80.3
	5	12.70	60.4
between the rear façade and the south façade	1	8.32	−20.3
	2	10.73	−26.2
	3	13.45	−32.8

Subsequent measurements over time showed very small variations, within the typical sensitivity of the instrumentation, so demonstrating that remote survey techniques were not suitable for the intended scope, since the movements, if any, were too small.

As a consequence, it was necessary to rely on accurate periodic visual inspections, in order to assess reopening of cracks, or formation of new cracks, which would exclude the activation of such phenomena.

The present situation is attested by the photographic documentation, taken at the end of June 2021, which is summarized in Figures 25 and 26, referring to the main façade, and in Figures 27 and 28, referring to the rear façade, and the south façade, respectively.

Figure 25. The actual aspect of the main façade—global view (June 2021).

Figure 26. The actual aspect of the main façade—detail (June 2021).

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

Figure 27. The actual aspect of the rear façade (June 2021): (**a**) global view; (**b**) detail.

Figure 28. The actual aspect of the south façade (June 2021).

Looking at the photos, it can be remarked that all the crack patterns have stabilized. In addition, till now,

- there is no evidence of the reopening of existing cracks, or of the formation of new cracks, on the exposed masonry of the main façade, as demonstrated in detail by the photo in Figure 26,
- the marble facing of the rear façade, reconstructed during the restoration works of 2005, is undamaged, while the crack pattern. previously evident in the neighborhood of the central window is no longer active (Figure 27b), and, finally,
- the vertical crack of the south façade is still closed, so confirming that the differential settlement, which originated it, is nearly inactive.

On the basis of these remarks, the feasibility and the effectiveness of the proposed intervention technique can be definitively validated.

4. Conclusions

An original reinforcement technique aiming to close and to bridge the cracks affecting exposed masonry, preventing at the same time their reopening and their further propagation, is presented in the paper. The solution, which overcomes the limitations of common repointing techniques, is based on the insertion of fiber fabrics in the mortar layers between adjacent masonry courses, which can be achieved resorting to the indent repair technique, which is a rather classical method for intervention on masonry structures. The main features of the proposed method are not only economy, high reversibility, and compatibility with the preservation needs, but also extreme flexibility, so that it can be easily adapted to unforeseen or nonstandard situations, which can occur during the execution. For these reasons, the solution is particularly suitable for the repair and restoration works on heritage buildings and constructions. Moreover, it can be applied, with small adjustments, to practically all kinds of exposed masonry, spanning from fine tooled ashlar masonry to uncoursed rubble masonry.

Evidently, to fully validate the method an ad hoc experimental campaign was needed, aiming to assess not only the feasibility and effectiveness of the proposed solution, but also its performance over time. It must be remarked that, taking into account the peculiarities of the method, it is quite impossible to define specimens adequately representative of the real operational conditions, therefore, to assess the feasibility of the method it was necessary to identify a real heritage building, suitable for testing the solution. After a careful survey, and a deep critical analysis of the pros and cons, the St. Nicola Church in Pisa was selected as a particularly significant case study, and the proposed technique was adopted to repair the crack pattern of the exposed brick masonry of the main façade.

A first significant validation was obtained at the end of the intervention, demonstrating the practicability of the method, but for a full validation it was necessary to wait and see the effect over time. Only recently, after checking the actual condition of the Church, and remarking the intervention is still effective, has complete validation been possible.

5. Patents

The proposed method, although original, is not patented. It can be freely used, provided the source is acknowledged.

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References

1. European Committee for Standardization (CEN). *EN 1990 Eurocode—Basis of Structural Design*; CEN: Brussels, Belgium, 2002.
2. International Organization for Standardization (ISO). *ISO 2394 General Principles on Reliability for Structures*; ISO: Geneva, Switzerland, 2015.
3. European Committee for Standardization (CEN). *EN 15898 Conservation of Cultural Heritage—Main General Terms and Definitions*; CEN: Brussels, Belgium, 2019.
4. European Committee for Standardization (CEN). *EN 16096 Conservation of Cultural Property—Condition Survey and Report of Built Cultural Heritage*; CEN: Brussels, Belgium, 2012.
5. European Committee for Standardization (CEN). *EN 16853 Conservation of Cultural Heritage—Conservation Process—Decision Making, Planning and Implementation*; CEN: Brussels, Belgium, 2017.
6. International Council on Monuments and Sites (ICOMOS). *International Charter for the Conservation and Restoration of Monuments and Sites (The Venice Charter 1964)*; ICOMOS: Charenton-le-Pont, France, 1965. Available online: https://www.icomos.org/charters/venice_e.pdf (accessed on 26 June 2021).
7. International Council on Monuments and Sites (ICOMOS). *Charter—Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage, the ICOMOS 14th General Assembly in Victoria Falls, Zimbabwe, in 2003*; ICOMOS: Charenton-le-Pont, France, 2003. Available online: https://www.icomos.org/charters/structures_e.pdf (accessed on 26 June 2021).
8. ICOMOS International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage (I.S.C.A.R.S.H.A.). *Recommendations for the Analysis, Conservation and Structural Restoration of Architectural Heritage*; ICOMOS: Charenton-le-Pont, France, 2003. Available online: http://orcp.hustoj.com/wp-content/uploads/2016/04/Recommendations-ICOMOS.pdf (accessed on 26 June 2021).
9. International Council on Monuments and Sites (ICOMOS). *Monuments and Sites I—International Charters for Conservation and Restoration*, 2nd ed.; Petzet, M., Ed.; ICOMOS: Charenton-le-Pont, France, 2004. Available online: http://openarchive.icomos.org/id/eprint/431/1/Monuments_and_Sites_1_Charters.pdf (accessed on 26 June 2021).
10. International Organization for Standardization (ISO). *ISO 13822 Bases for Design of Structures—Assessment of Existing Structures*; ISO: Geneva, Switzerland, 2010.
11. International Organization for Standardization (ISO). *ISO 12491 Statistical Methods for Quality Control of Building Materials and Components*; ISO: Geneva, Switzerland, 1997.
12. International Organization for Standardization (ISO). *ISO 12491 Information and Documentation—A Reference Ontology for the Interchange of Cultural Heritage Information*; ISO: Geneva, Switzerland, 2014.
13. López, F.; Lerones, P.; Llamas, J.; Gómez-García-Bermejo, J.; Zalama, E. A Review of Heritage Building Information Modeling (H-BIM). *Multimodal Technol. Interact.* **2018**, *2*, 21. [CrossRef]
14. Croce, V.; Caroti, G.; De Luca, L.; Jacquot, K.; Piemonte, A.; Véron, P. From the Semantic Point Cloud to Heritage-Building Information Modeling: A Semiautomatic Approach Exploiting Machine Learning. *Remote Sens.* **2021**, *13*, 461. [CrossRef]
15. Corradi, M.; Borri, A.; Vignoli, A. Experimental study on the determination of strength of masonry walls. *Constr. Build. Mater.* **2003**, *17*, 325–337. [CrossRef]
16. Binda, L.; Saisi, A. Research on historic structures in seismic areas in Italy. *Prog. Struct. Eng. Mater.* **2005**, *7*, 71–85. [CrossRef]
17. Rovero, L.; Alecci, V.; Mechelli, J.; Tonietti, U.; De Stefano, M. Masonry walls with irregular texture of L'Aquila (Italy) seismic area: Validation of a method for the evaluation of masonry quality. *Mater. Struct.* **2016**, *49*, 2297–2314. [CrossRef]
18. Lagomarsino, S.; Podestà, S. Damage and vulnerability assessment of churches after the 2002 Molise, Italy, earthquake. *Earthq. Spectra* **2004**, *20*, 271–283. [CrossRef]
19. Croce, N.; Croce, P.; Pelusi, M.; Taccola, R. Rehabilitation and seismic upgrading of the masonry arch bridge over the Magra river in Villafranca. *Procedia Struct. Integr.* **2018**, *11*, 371–378. [CrossRef]
20. Beconcini, M.L.; Croce, P.; Marsili, F.; Muzzi, M.; Rosso, E. Probabilistic reliability assessment of a heritage structure under horizontal loads. *Probab. Eng. Mech.* **2016**, *45*, 198–211. [CrossRef]
21. Marsili, F.; Croce, P.; Friedman, N.; Formichi, P.; Landi, F. Seismic reliability assessment of a concrete water tank based on the Bayesian updating of the finite element model. *ASCE-ASME J. Risk Uncertain. Eng. Syst.* **2017**, *3*, 021004. [CrossRef]
22. Croce, P.; Landi, F.; Formichi, P. Probabilistic Seismic Assessment of Existing Masonry Buildings. *Buildings* **2019**, *9*, 237. [CrossRef]
23. Croce, P.; Marsili, F.; Klawonn, F.; Formichi, P.; Landi, F. Evaluation of statistical parameters of concrete strength from secondary experimental test data. *Constr. Build. Mater.* **2018**, *163*, 343–359. [CrossRef]
24. Croce, P.; Beconcini, M.L.; Formichi, P.; Landi, F.; Puccini, B.; Zotti, V. Bayesian Methodology for Probabilistic Description of Mechanical Parameters of Masonry Walls. *ASCE-ASME J. Risk Uncertain. Eng. Syst.* **2021**, *7*, 4021008. [CrossRef]
25. Croce, P.; Formichi, P.; Landi, F. Influence of Reinforcing Steel Corrosion on Life Cycle Reliability Assessment of Existing R.C. Buildings. *Buildings* **2020**, *10*, 99. [CrossRef]
26. Beconcini, M.L.; Croce, P.; Formichi, P.; Landi, F.; Puccini, B. Experimental Evaluation of Shear Behavior of Stone Masonry Wall. *Materials* **2021**, *14*, 2313. [CrossRef] [PubMed]
27. Croce, P.; Beconcini, M.L.; Formichi, P.; Landi, F.; Puccini, B.; Zotti, V. Evaluation of Partial Safety Factors for the Structural Assessment of Existing Masonry Buildings. In Proceedings of the 18th International Probabilistic Workshop, IPW2020, Guimarães, Portugal, 12–14 May 2021; Matos, J.C., Lourenço, P.B., Oliveira, D.V., Branco, J., Proske, D., Silva, R.A., Dousa, H.S., Eds.; Springer Nature Switzerland A.G.: Cham, Switzerland, 2021; pp. 341–352. [CrossRef]

28. Funari, M.F.; Mehrotra, A.; Lourenço, P.B. A Tool for the Rapid Seismic Assessment of Historic Masonry Structures Based on Limit Analysis Optimisation and Rocking Dynamics. *Appl. Sci.* **2021**, *11*, 942. [CrossRef]
29. Casapulla, C.; Giresini, L.; Lourenço, P.B. Rocking and kinematic approaches for rigid block analysis of masonry walls: State of the art and recent developments. *Buildings* **2017**, *7*, 69. [CrossRef]
30. Casapulla, C.; Argiento, L.U. In-plane frictional resistances in dry block masonry walls and rocking-sliding failure modes revisited and experimentally validated. *Compos. Part B Eng.* **2018**, *132*, 197–213. [CrossRef]
31. Croce, P. Nonlinear Dynamics of Swinging Clapper Bells under Arbitrary or Resonant Forcing Functions. *Appl. Sci.* **2020**, *10*, 5528. [CrossRef]
32. Stronge, W.J. Smooth dynamics of oblique impact with friction. *Int. J. Impact Eng.* **2013**, *51*, 36–49. [CrossRef]
33. Housner, G.W. The behavior of inverted pendulum structures during earthquakes. *Bull. Seismol. Soc. Am.* **1963**, *53*, 403–417. [CrossRef]
34. Giresini, L.; Taddei, F.; Solarino, F.; Mueller, G.; Croce, P. Influence of stiffness and damping parameters of passive seismic control devices in one-sided rocking of masonry walls. *J. Struct. Eng.* **2021**, accepted.
35. Forster, A.M. Building conservation philosophy for masonry repair: Part 1—"Ethics". *Struct. Surv.* **2010**, *28*, 91–107. [CrossRef]
36. Forster, A.M. Building conservation philosophy for masonry repair: Part 2—"Principles". *Struct. Surv.* **2010**, *28*, 165–188. [CrossRef]
37. Borri, A.; Corradi, M. Architectural Heritage: A Discussion on Conservation and Safety. *Heritage* **2019**, *2*, 41. [CrossRef]
38. Souza, R.A.d.; Trautwein, L.M.; Ferreira, M.d.P. Reinforced Concrete Corbel Strengthened Using Carbon Fiber Reinforced Polymer (CFRP) Sheets. *J. Compos. Sci.* **2019**, *3*, 26. [CrossRef]
39. Naser, M.Z.; Hawileh, R.A.; Abdalla, J. Modeling Strategies of Finite Element Simulation of Reinforced Concrete Beams Strengthened with FRP: A Review. *J. Compos. Sci.* **2021**, *5*, 19. [CrossRef]
40. Reda Taha, M.M.; Shrive, N.G. New Concrete Anchors for CFRP Post-Tensioning Tendons. Part I: State-of-the-art Review/Design. *ACI Struct. J.* **2003**, *100*, 86–95.
41. Reda Taha, M.M.; Shrive, N.G. New Concrete Anchors for CFRP Post-Tensioning Tendons. Part II: Development and Experimental Investigation. *ACI Struct. J.* **2003**, *100*, 96–104.
42. Babatunde, S.A. Review of strengthening techniques for masonry using fiber reinforced polymers. *Compos. Struct.* **2017**, *161*, 246–255. [CrossRef]
43. Corradi, M.; Borri, A.; Vignoli, A. Strengthening techniques tested on masonry structures struck by the Umbrian-Marche earthquake of 1997–1998. *Constr. Build. Mater.* **2002**, *16*, 229–239. [CrossRef]
44. Ferretti, E.; Pascale, G. Combined Strengthening Techniques to Improve the Out-of-Plane Performance of Masonry Walls. *Materials* **2019**, *12*, 1171. [CrossRef]
45. Nanni, A.; Tumialan, J.G. Fiber-Reinforced Composites for the Strengthening of Masonry Structures. *Struct. Eng. Int.* **2003**, *13*, 271–278. [CrossRef]
46. Krzywoń, R. Steel-Reinforced Polymers and Steel-Reinforced Composite Mortars for Structural Applications—An Overview. *J. Compos. Sci.* **2020**, *4*, 142. [CrossRef]
47. Aiello, M.A.; Cascardi, A.; Ombres, L.; Verre, S. Confinement of Masonry Columns with the FRCM-System: Theoretical and Experimental Investigation. *Infrastructures* **2020**, *5*, 101. [CrossRef]
48. Funari, M.F.; Verre, S. The Effectiveness of the DIC as a Measurement System in SRG Shear Strengthened Reinforced Concrete Beams. *Crystals* **2021**, *11*, 265. [CrossRef]
49. Ascione, L.; Feo, L.; Fraternali, F. Load carrying capacity of 2D FRP/strengthened masonry structures. *Compos. Part B* **2005**, *36*, 619–626. [CrossRef]
50. Micelli, F.; Di Ludovico, M.; Balsamo, A.; Manfredi, G. Mechanical behavior of FRP-confined masonry by testing of full-scale columns. *Mater. Struct.* **2014**, *47*, 2081–2100. [CrossRef]
51. Wiztani, J.; Zigler, R. Stress State Analysis and Failure Mechanisms of Masonry Columns Reinforced with FRP under Concentric Compressive Load. *Polymers* **2016**, *8*, 176. [CrossRef]
52. Prota, A.; Marcari, G.; Fabbrocino, G.; Manfredi, G.; Aldea, C. Experimental In-Plane Behavior of Tuff Masonry Strengthened with Cementitious Matrix–Grid Composites. *J. Comp. Constr.* **2006**, *10*, 223–233. [CrossRef]
53. Papanicolaou, C.G.; Triantafillou, T.C.; Papathanasiou, M.; Karlos, K. Textile Reinforced Mortar (TRM) versus FRP as Strengthening Material of URM Walls: Out-Of-Plane Cyclic Loading. *Mater. Struct.* **2008**, *41*, 143–157. [CrossRef]
54. Oliveira, D.V.; Silva, R.A.; Garbin, E.; Lourenço, P.B. Strengthening of three-leaf stone masonry walls: An experimental research. *Mater. Struct.* **2012**, *45*, 1259–1276. [CrossRef]
55. Gattesco, N.; Boem, I. Characterization tests of GFRM coating as a strengthening technique for masonry buildings. *Compos. Struct.* **2017**, *165*, 209–222. [CrossRef]
56. Fagone, M.; Ranocchiai, G. Experimental investigation on out-of-plane behavior of masonry panels strengthened with CFRP sheets. *Compos. Part B* **2018**, *150*, 14–26. [CrossRef]
57. Corradi, M.; Castori, G.; Sisti, R.; Borri, A.; Pesce, G.L. Repair of Block Masonry Panels with CFRP Sheets. *Materials* **2019**, *12*, 2363. [CrossRef]
58. Briccoli, B.S.; Rovero, L. Towards a methodology for estimating strength and collapse mechanism in masonry arches strengthened with fibre reinforced polymer applied on external surfaces. *Mater. Struct.* **2008**, *41*, 1291–1306. [CrossRef]

59. Baratta, A.; Corbi, O. Stress analysis of masonry vaults and static efficacy of FRP repairs. *Int. J. Solids Struct.* **2007**, *44*, 8028–8056. [CrossRef]
60. Garmendia, L.; Larrinaga, P.; San-Mateos, R.; San-José, J.T. Strengthening masonry vaults with organic and inorganic composites: An experimental approach. *Mater. Struct.* **2015**, *85*, 102–114.
61. Bednarz, Ł.; Drygała, I.; Dulińska, J.; Jasieńko, J. Study of Materials Behavior in a Monumental Vault Strengthened by a Carbon Net in a Mineral Matrix Subjected to Seismic Influence. *Appl. Sci.* **2021**, *11*, 1015. [CrossRef]
62. Italian National Research Council (CNR). *CNR/DT 200/R1/2013: Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures*; CNR: Rome, Italy, 2013. Available online: https://www.cnr.it/en/node/2636 (accessed on 26 June 2021).
63. Ascione, L.; Caron, J.; Godonou, P.; Van Ijselmuijden, K.; Knippers, J.; Mottram, T.; Oppe, M.; Sorensen, M.; Taby, J.; Tromp, L. *Prospect for New Guidance in the Design of FRP, JRC Report EUR 27666, JRC99714*; Publications Office of the European Union: Luxembourg, 2016. Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC99714 (accessed on 26 June 2021).
64. Gutiérrez, E.; Dimova, S.; Pinto, A. *Purpose and Justification for New Design Standards regarding the Use of Fibre-Reinforced Polimer Composites in Civil Engineering—Support to the Implementation, Harmonization and Further Development of the Eurocodes, JRC Report EUR 22864, JRC037836*; Publications Office of the European Union: Luxembourg, 2007. Available online: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC37836/eur%2022864%20en.pdf (accessed on 26 June 2021).
65. European Commission. *M/515 EN—Mandate for Amending Existing Eurocodes and Extending the Scope of Structural Eurocodes*; European Commission: Brussels, Belgium, 2012.
66. European Committee for Standardization (CEN). *CEN/TC250—Response to Mandate M/515—Towards a Second Generation of Eurocodes, CEN-TC250—N 993*; European Committee for Standardization: Brussels, Belgium, 2013.
67. Valluzzi, M.R. Strengthening of masonry structures with Fibre Reinforced Plastics: From modern conception to historical building preservation. In Proceedings of the Structural Analysis of Historic Construction: Preserving Safety and Significance, SAHC08, Bath, UK, 2−4 July 2008; D'Ayala, D., Fodde, E., Eds.; CRC Press: Boca Raton, FL, USA, 2008; pp. 33–45.
68. Valluzzi, M.R.; Modena, C.; de Felice, G. Current practice and open issues in strengthening historical buildings with composites. *Mater. Struct.* **2014**, *47*, 1971–1985. [CrossRef]
69. Valluzzi, M.R.; Binda, L.; Modena, C. Mechanical behavior of historic masonry structures strengthened by bed joints structural repointing. *Constr. Build. Mater.* **2004**, *19*, 63–73. [CrossRef]
70. Bosiljkov, V. Micro vs. Macro Reinforcement of Brickwork Masonry. *Mater. Struct.* **2006**, *39*, 235–245. [CrossRef]
71. Sanpaolesi, P. *Il Duomo di Pisa e L'architettura Romanica Toscana delle Origini*; Pacini Editore: Pisa, Italy, 1975. (In Italian)
72. Salmi, M. *L'architettura Romanica in Toscana*; Bestetti & Tumminelli: Milano, Italy, 1926. (In Italian)
73. Tigler, G. *Toscana Romanica*; Jaca Book: Milano, Italy, 2006. (In Italian)
74. Ragghianti, C.L. Architettura lucchese e architettura pisana. *Critica d'arte* **1949**, *28*, 168–172. (In Italian)
75. Coroneo, R. *Architettura Romanica dalla metà del Mille al primo '300*; Ilisso: Nuoro, Italy, 1993. (In Italian)
76. Willis, R. *Remarks on the Architecture of the Middle Ages (Especially of Italy)*; Cambridge University Press: Cambridge, UK, 1835.
77. Argan, G.C. *L'architettura Protoromanica, Preromanica e Cristiana*; Dedalo: Bari, Italy, 1978. (In Italian)
78. Argan, G.C. *L'architettura Italiana del '200 e '300*; Dedalo: Bari, Italy, 1978. (In Italian)
79. Abraham, P. *Viollet-le-Duc et le Rationalisme Medieval*; Vincent et Fréal: Paris, France, 1934. (In French)
80. Heyman, J. *The Stone Skeleton*; Cambridge University Press: Cambridge, UK, 1995.