Strengthening of existing masonry structures: Concepts and structural behavior

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15.1 Introduction

Unreinforced masonry bearing wall construction, commonly termed URM, is one of the oldest construction types found worldwide. URM walls have been proven to be prone to failure during high or even moderate intensity earthquakes or high wind pressure; therefore, they represent a significant safety hazard. A causal breakdown of earthquake fatalities for the second half of the last century revealed that almost 60% of the lives lost were attributed to URM failures (Coburn and Spence, 2002). Moreover, structural decay due to aging or cumulative seismic-induced damage poses a direct threat to the preservation and safeguarding of historical structures that comprise an important part of many countries' cultural heritage. Thereby, there is a tremendous and urgent need for upgrading existing URM structures. In seismic areas, structures designed according to old seismic codes must meet upgraded performance levels demanded by current seismic design standards. In non-seismic areas, URM structures must be updated due to change of usage and/or the introduction of more stringent design requirements.

Numerous techniques have been developed aiming at increasing the strength and/or ductility of URM walls. These include the use of metallic or polymeric grid-reinforced surface coatings, shotcrete overlays, internal or external prestressing with steel ties, externally bonded fiber-reinforced polymers (FRP, such as epoxy-bonded strips or *in situ* impregnated fabrics) and near-surface mounted FRP reinforcement. FRP-based strengthening and/or seismic retrofitting techniques have been well-established in the civil engineering community due to the favorable properties offered by these materials. These include high strength and stiffness to weight ratio, corrosion resistance, ease and speed of application and minimal change in the geometry. Despite the many advantages associated with the use of FRP, the relevant strengthening techniques are not entirely problem-free. There are some drawbacks associated with the organic resins used to bind or impregnate the fibers. In addition, certain restrictions related to intervention strategies for historic masonry buildings (e.g., requirements for reversibility) may possibly inhibit FRP application.

One interesting solution to the above problems would be the replacement of organic binders with inorganic ones, for example, cement-based or hydraulic lime

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mortars. Bond conditions in mortar-based composites could be improved, and fiber–matrix interactions could be made tighter through the use of open-weaved fabrics instead of continuous fiber sheets. The resulting textile-based system, termed herein as textile-reinforced mortar (TRM) system, may be thought of as an alternative to the FRP-based system (Papanicolaou et al., 2007, 2008).

In this chapter, we aim to present (a) concepts for the strengthening of masonry structures with TRM and (b) key aspects of structural behavior. The following topics, also presented in Fyfe Europe SA and Triantafillou (2012), are covered:

- Brief description of materials and their properties.
- Intervention requirements and strengthening rationale.
- Aspects of structural modeling and retrofitting for seismic applications.
- Strengthening of masonry walls for out-of-plane or in-plane loads.
- Strengthening of curved masonry elements.
- Confinement of masonry columns.

15.2 Textile-reinforced mortar system

The TRM system may be considered as an alternative to FRP, which have already found their way into the field of strengthening and seismic retrofitting. With the aim of alleviating specific problems associated with the use of organic resins in FRP systems, the TRM system comprises an open weaved fabric made of long woven, knitted or even unwoven fiber rovings (e.g., glass, basalt, or carbon) in at least two (typically orthogonal) directions (Figure 15.1a), along with an inorganic mortar matrix (Triantafillou et al., 2006). The density, that is, the quantity of the spacing of rovings in

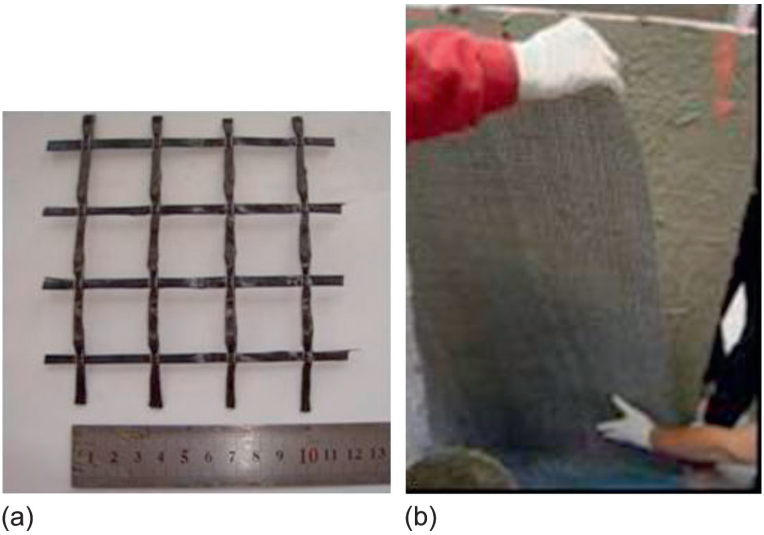

Figure 15.1 (a) Bidirectional textile and (b) application on masonry specimen.

each direction can be controlled independently. Thus, this affects the mechanical characteristics of the open weaved fabric and the degree of penetration of the mortar matrix through the woven mesh.

The TRM system is applied similarly to FRP. The walls are first ground at locations where materials are protruding (e.g., irregular blocks or mortar at joints) and brushed clean. Then, dust and any loose particles are removed (e.g., with air pressure). Finally, a standard wet lay-up procedure follows to bond the textile layers on the surface of the masonry wall. The procedure involves application of the mortar on the (dampened) wall surface, subsequent application of the textile by hand (Figure 15.1b) and roller pressure. The mortar is also applied in between layers and on top of the last textile layer. Application of the mortar is made in a few millimeter (e.g., 3–4 mm) thick layers using a smooth metal trowel. The textile is pressed slightly into the mortar, which protrudes through the perforations between fiber rovings.

15.3 Mechanical properties

In the TRM system, fibers provide tensile load capacity and stiffness, while the matrix ensures sharing of the load among fibers and protects the fibers from the environment. The composite action between the open weaved fabrics and mortars is achieved through a mechanical interlock of mortar at fabric perforations. This is also achieved through some impregnation of fibers near the surface of the rovings, in case the fabrics are not coated (dry fibers). As a consequence, bond conditions between fibers and matrix are not perfect and the development of relative slip is possible.

The result of debonding at the fiber–matrix interface is that TRM, unlike FRP, does not behave as a linear elastic material. Its response in uniaxial tension parallel to a principal fiber direction (illustrated in Figure 15.2) is characterized by an initial linear elastic part (uncracked matrix), followed by a branch associated with extensive cracking in the mortar (stage IIa). When this cracking is stabilized, the fibers are tensioned and carry the load until they debond, pullout and eventually rupture.

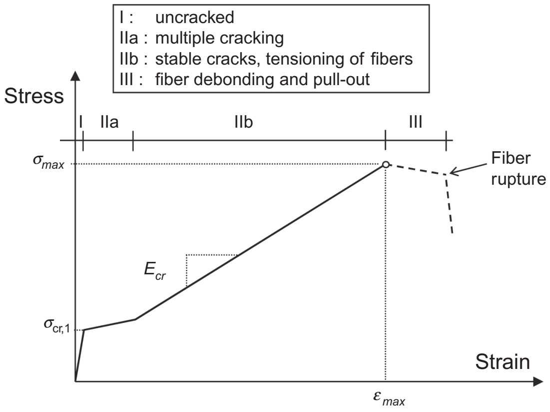

Figure 15.2 Idealized stress–strain curve in uniaxial tension parallel to a principal fiber direction.

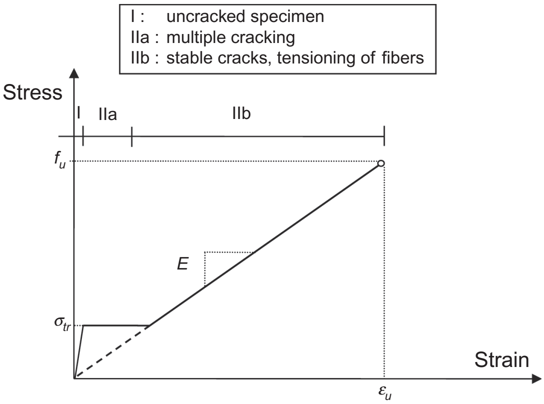

Figure 15.3 Simplified stress–strain curve.

It can be assumed that the "multiple cracking" branch (IIa) can be represented by a horizontal line, because of its small slope (even zero in some cases). Thereby, the stress–strain behavior can be further simplified, as shown in Figure 15.3.

Values of practical interest on the simplified stress–strain curve are the ultimate tensile strength (f_u), the maximum elongation at ultimate (ε_u), the transition zone tensile stress (σ_{tr}) and the tensile modulus (E). Such values are obtained on the basis of experimental investigations.

15.4 Intervention requirements and strengthening rationale

The primary objective of strengthening with TRM is to increase the strength of masonry elements, as well as the overall capacity of a masonry structure. TRM in the form of externally applied jackets should be located primarily in areas where tensile stresses are to be carried and should not be relied upon to carry compressive stresses, due to possible local instability.

If TRM strengthening concerns historical structures, a critical evaluation and proper selection of the system should be made with respect to standards for preservation and evaluation. The adopted solution, then, shall guarantee compatibility, durability, and reversibility.

For the appropriateness of the TRM system for a specific application, the engineer should evaluate the existing structure to establish its existing capacity, identify deficiencies and their causes, and determine the condition of the masonry substrate. The evaluation should include a field inspection, review of relevant documents, and a structural analysis. The TRM system application can be employed for the following reasons: flexural and shear strengthening to resist tensile stresses within a structural member or between adjoining members; connection between members (e.g., connections between orthogonal walls or vault and wall ties); floor stiffening; crack width limitation;

confinement; and axial capacity enhancement of columns. Hence, the TRM system application may be aimed at increasing the capacity of walls, arches, or vaults; wrapping of columns to increase compressive strength and ductility; reducing thrust forces in thrusting structures; transforming non-structural members into structural members by increasing their stiffness and strength; strengthening and stiffening horizontal non-thrusting structures; and wrapping buildings at floor and roof locations.

TRM can be applied to structural members that have suitable mechanical properties. If the masonry is damaged, cracked, etc., it should first be repaired with appropriate techniques (e.g., grout injection) to ensure a proper sharing of loads between TRM and masonry.

For masonry structures subjected to cyclic loads (e.g., seismic or thermal variations), the bond between masonry and TRM may degrade during the structure's lifetime. In such cases, it is advisable to properly anchor the TRM to the masonry using anchors.

15.5 Structural modeling

The performance of a TRM system can be assessed on the basis of a structural idealization representing the behavior of the structure for the expected future use. Internal forces in the masonry can be determined using methods of structural analysis (e.g., frame models and finite element analysis). In particular, the structure can be modeled as either linear elastic, or through proven nonlinear models capable of simulating the inelastic behavior and the negligible tensile strength of masonry.

Simplified methods can also be used to describe the behavior of the structure. For instance, assuming that tensile stresses are directly carried by the TRM, stresses may be determined by adopting a simplified stress field that satisfies the equilibrium conditions, but not necessarily strain compatibility. This method may be realized for in-plane loaded masonry structures through the well-known strut-and-tie modeling (e.g., Krevaikas and Triantafillou, 2005). According to this procedure, the engineer calls upon experience and intuition to draw load paths through the structure in the form of a truss. The truss is analyzed for the design loads and proportioned according to the applicable code and/or to other rules of practice. Truss elements in tension (ties) indicate regions where TRM strips should be placed; masonry itself constitutes the struts. The dimensioning of the TRM is achieved based on the calculated tensile force in each tie and the design value of the force in the strengthening system. In this exercise, the engineer may be aided by knowledge of the magnitude and directions of principal stresses, obtained by a linear elastic plane stress finite element analysis of the structural element under the design loads. The struts and ties of the model may then be drawn collinear to the principal stress resultants.

The use of simplified stress fields should be carefully chosen, because a statically admissible stress field could have already caused structural collapse due to the brittle nature of the masonry system. In the case of structures with regular or repetitive parts, substructures may be identified that allow for a rapid evaluation of the global behavior of the strengthened structure. Similarly, simplified models may be adopted for verifications of local failure mechanisms, provided that their use is properly justified.

As described in Chapter 16 safety verifications at the ultimate limit state are done easily at the member level, implying that internal forces and moments are compared to the respective resistances. Such forces and moments may be obtained directly through proper analysis methods, or indirectly by integrating stresses obtained by finite element analysis.

15.6 Design of retrofitting for seismic applications

Seismic retrofitting with the TRM system is typically aimed at total or partial strengthening, replacing or rebuilding of structural members and modifying the overall structural behavior by connecting different structural members. The type and size of selected TRM systems shall take into account the following:

- Poor connections between floors/roof and vertical walls shall be improved.
- Connections in walls ending on masonry T-junctions or masonry edges may need improvement.
- Floors effectively connected to vertical walls may have to be properly stiffened in their plane to be able to transfer horizontal forces to the vertical walls parallel to the earthquake direction. They also shall provide restraint to the movement of vertical walls perpendicular to the earthquake direction.
- TRM strengthened members where local ductility is enhanced are always recommended. Moreover, local TRM strengthening shall not reduce the overall ductility of the structure.
- Weak members, for which strengthening is not appropriate or possible, shall be eliminated.
- In the case of strongly irregular buildings, it may not be possible to improve structural behavior substantially by TRM strengthening. In such cases, TRM may be used for few structural members, to ensure a minimum regularity to the structure.

The TRM-based retrofitting strategy follows the principle of increasing the capacity of under-designed members. It does this with the aim of achieving, at the same time, a greater structural regularity and the elimination of possible local collapse of masonry walls or structural components. To avoid seismic vulnerability, care should be taken to ensure that the TRM will not decrease the overall ductility of the structure. Particular care should be taken to interventions aiming at joining vertical columns to avoid the formation of hinges in arches and vaults. The increase of hinge ductility of both columns and vaults is of crucial importance.

15.7 Strengthening of masonry walls for out-of-plane loads

Out-of-plane collapse of masonry walls is one of the most frequent failure mechanisms. Such a mechanism is primarily the result of seismic actions (inertia forces) and secondarily of horizontal forces originated by the presence of arches and vaults.

Out-of-plane collapse can develop as *overturning*, *vertical flexural failure* or *horizontal flexural failure*.

Collapse by overturning (Figure 15.4a) may occur by the formation of a hinge at the bottom of walls neither connected to the orthogonal walls, nor restrained at their top. This mechanism depends on several factors, including the boundary conditions and the slenderness of the wall.

A possible retrofitting solution may involve the use of TRM applied to the top part of the masonry and properly anchored into the orthogonal walls, e.g., in the form of an embracing "belt" (Figure 15.4b). In this case, resistance to overturning is provided by the horizontal fibers of the TRM System. Particular care should be taken in the rounding of masonry corners to avoid stress concentrations in the fibers.

Masonry walls restrained at both top and bottom regions and subjected to horizontal loading may fail due to flexure with formation of three hinges at the top, bottom and in between (Figure 15.5a). Vertical flexural failure may occur in high masonry walls and/or walls restrained far apart from orthogonal walls. In the case of seismic loads, masonry walls loaded from opposite sides by floors located at different heights are

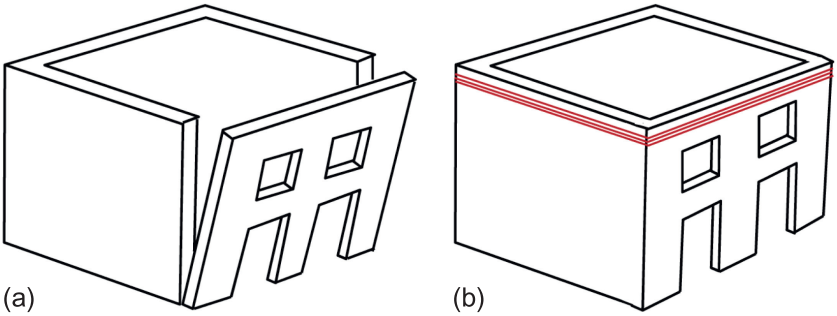

Figure 15.4 (a) Collapse by overturning and (b) application of embracing belt.

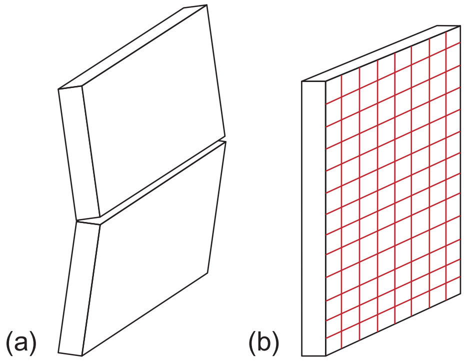

Figure 15.5 (a) Vertical flexural failure and (b) strengthening by TRM.

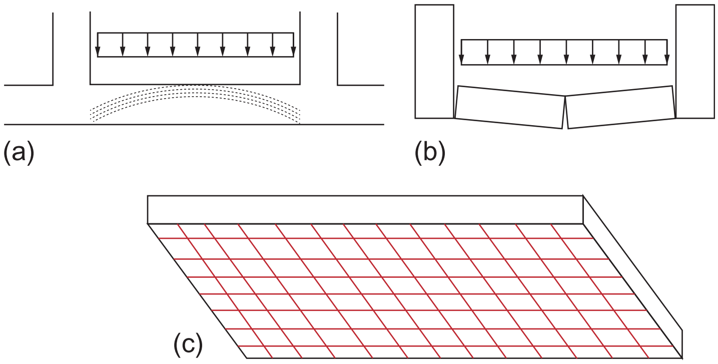

Figure 15.6 (a) Arching effect, (b) collapse due to horizontal flexure, and (c) strengthening by TRM.

particularly sensitive to vertical flexural collapse mechanisms. Such walls may be strengthened with TRM on the tension side, with effective fibers being those running in the vertical direction (Figure 15.5b).

Masonry walls restrained at the bottom, as well as firmly connected with (vertical) transverse walls, behave in a way analogous to three-side supported "slabs." They resist horizontal forces by an arching effect of the top strip (Figure 15.6a). Masonry walls restrained at the bottom, but not firmly connected with transverse walls, may collapse as illustrated in Figure 15.6b. Such walls may be strengthened with TRM on the tension side. The effective fibers are those running in the horizontal direction (Figure 15.6c).

TRM-based strengthening of masonry walls subjected to out-of-plane cyclic loads has been studied experimentally by Papanicolaou et al. (2008). In this study, it was shown that TRM overlays provide an extremely high gain in strength and deformation capacity, comparable—if not higher—to that provided by equivalent FRP systems.

15.8 Strengthening of masonry walls for in-plane loads

In-plane failure of masonry walls is also a frequent failure mechanism, as a result of seismic actions parallel to the walls. Typical actions include *combined bending and axial load* and *shear force*. Special attention in this regard should be given to *lintels and tie areas*.

Masonry walls subjected to combined bending and axial load are column-type members, which can be strengthened with TRM containing vertical fibers as close as practically possible to the most highly stressed areas (see Figure 15.7a for cyclic in-plane bending). Quite often, strengthening for in-plane bending may be combined with that for other cases, hence full coverage of the wall may be selected (Figure 15.7b). The strengthening system should be adequately anchored to the end parts (top and bottom) of the masonry wall.

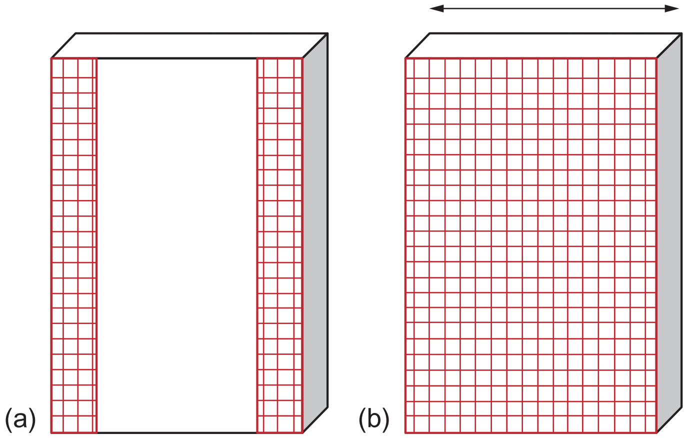

Figure 15.7 TRM strengthening of masonry walls subjected to in-plane combined bending and axial load: (a) placement of fibers in the highly stressed areas and (b) full coverage of the wall.

In-plane shear failure in masonry is typical in shear wall—type elements. Strengthening can be provided by applying TRM jackets on the wall sides (as shown in Figure 15.7b) so that a "truss" mechanism may be activated (analogous to the way a shear is carried by reinforced concrete members). Jacketing may be two-sided (preferably), or even one-sided, if interventions on both sides are not permitted, or if they are not practically possible.

The areas connecting different wall bays within a masonry panel are named tie areas (Figure 15.8). Their role is (a) to restrain the adjoining (vertical) walls to assume deformed shapes compatible with the applied horizontal load and (b) to support the masonry wall above openings. The former generates shear and flexural stresses and is significant in the case of seismic loading; whereas the latter is played by lintels located above openings (Figure 15.8).

As a result of vertical loads, the following effects in the areas above openings are displayed: (a) the part of the masonry wall above the opening cannot carry its own

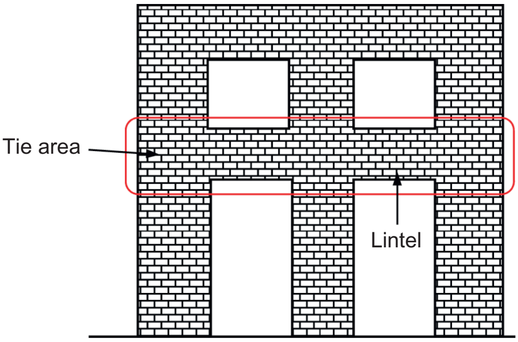

Figure 15.8 Lintels and tie areas.

weight and is supported by a lintel functioning as a beam; (b) when the wall bays surrounding the openings are slender, so as not to withstand horizontal loads due to the presence of the opening itself, the lintel provides adequate strength to carry the tensile stresses and ensure the overall equilibrium of the wall.

Lintels may be realized using structural elements having both axial and flexural capacity; alternatively, they may have only axial capacity. In the former case lintels function as beams and carry tension to ensure the overall equilibrium of the wall. In the latter, support to the wall above the opening is ensured by formation of a reinforced masonry member located just above the opening. Tensile stresses in this member are carried by the TRM strengthening system, which is applied preferably on the bottom face of the lintel. In this case, equilibrium conditions are probably reached after the masonry wall above the strengthened member has developed substantial deformations. To ensure proper functioning of lintels formed through strengthening, the TRM should be properly anchored into the adjacent masonry walls (as in Figure 15.9a).

Tie areas strengthened with TRM should be verified for bending moment, shear force and axial force (if any) acting at the connection with vertical masonry walls. Strengthening may be carried out by installing externally or internally (ideally both) horizontal TRM tapes. Flexural strengthening requires horizontal fibers and is better achieved by placing TRM at upper and lower regions of the ties. Shear strengthening, on the other hand, requires mainly vertical fibers covering the full height of the ties. Hence, a TRM jacket with full coverage of the tie (Figure 15.9b) would serve all functions. Moreover, if the jacket is external and continuous, it also may function as external wrapping of the masonry structure.

TRM-based strengthening of masonry walls subjected to in-plane cyclic loads has been studied experimentally by Papanicolaou et al. (2007). In this study, it was shown that TRM overlays provide an extremely high gain in strength and deformation capacity, comparable—if not higher—to that provided by equivalent FRP systems.

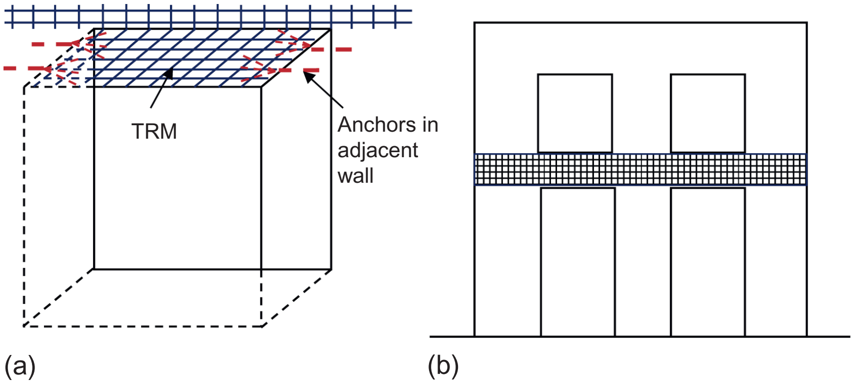

Figure 15.9 Strengthening of (a) lintel above an opening and (b) tie area.

15.9 Strengthening of curved masonry elements

Masonry elements with single curvature (arches, barrel vaults) or double curvature (domes) may fail due to the formation of "hinges" that correspond to a mechanism of collapse. Hinges form as a result of practically zero tensile strength and are located in the intrados or extrados, with eccentricity to the mid-plane of the structure (Figure 15.10a). As a result, the hinged section can only carry an axial force, which acts at an eccentricity equal to half the thickness of the masonry element.

TRM reinforcement delays the opening of cracks and formation of hinges on the opposite side with respect to the one where the TRM system is installed (Figure 15.10b). However, it should be remembered that this reinforcement is not effective in controlling crushing of the masonry or shear failure.

15.9.1 Arches

Arches may be of two types: (a) arch schemes, that is, arches resting on fixed or hinged supports; or (b) arch-pier schemes, which are frame-type structures, comprising arches resting on piers. Both schemes generally tend to collapse due to the formation of at least four hinges.

The collapse mechanism associated with the formation of four hinges may be prevented by bonding TRM to the extrados (Figure 15.10b) or the intrados (Figure 15.10c) of the masonry arch. If practically possible (this is rare), TRM should be applied to both the extrados and the intrados. However, access to the intrados is typically not possible, hence TRM should be applied to the extrados. This configuration also has the advantage that compressive stresses developing at the TRM-masonry interface (Figure 15.10b) improve bond conditions.

For arch–pier structures, the application of TRM to the extrados or intrados may not be sufficient to prevent relative displacement of the pier-arch connections. In such a case, it is preferable to act on the piers or set a tie rod between the pier–arch connections.

15.9.2 Barrel vaults

Barrel vaults have a single curvature; hence, their behavior is similar to that of arches. Strengthening with TRM may be applied to the extrados and/or the intrados. An advantage of the TRM system here is that fibers may also be activated in the

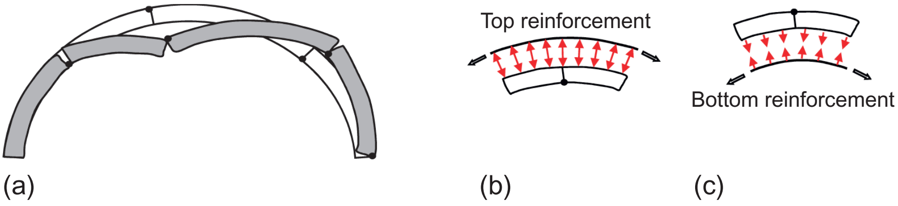

Figure 15.10 (a) Collapse mechanism in curved masonry element. Activation of fibers in (b) the extrados and (c) the intrados prevents the formation of hinges.

longitudinal direction (perpendicular to the plane of curvature), bridging the ideal arches forming the barrel vault. Such a mechanism is of particular importance in cases of horizontal loading. It is recommended to use bidirectional TRM with fibers in the longitudinal direction amounting to approximately 25% of those installed in the transverse direction.

15.9.3 Domes

Domes are double curvature vaults and exhibit both membrane-type and flexural-type stresses. In a dome subjected to vertical loads, membrane-type tension stresses develop along the dome parallels and may cause cracking along the meridians, especially near the connection with the supporting structure. In this case, application of TRM in a circular configuration around the lower part of the dome's perimeter (Figure 15.11) may help prevent the opening of cracks, as well as reduce the magnitude of the horizontal force acting on the supporting structure.

Flexural-type stresses are typically localized where the dome meets the supporting structure or at the edge of a skylight, if present. Such stresses may cause collapse of parts of the dome between meridian cracks. If the load carrying capacity of such parts is controlled by failure of the region connecting the dome to the supporting structure, then the dome may be strengthened by applying the TRM system in a circle around the lower part of the dome perimeter, as shown in Figure 15.11. This is done so that horizontal fibers may be activated. However, if the dome supporting structure does not develop any displacement, then the horizontal fibers are inactive; TRM should be applied along the dome meridians, implying that the vertical fibers of TRM will become effective. Special attention in TRM strengthening for flexural-type stresses should be given to debonding near the supporting structure, which may be controlled through the application of anchors.

15.10 Confinement of masonry columns

TRM confinement of masonry columns subjected to compression increases both ultimate load capacity and failure strain. It also may improve the column performance under the serviceability limit state. Confinement with TRM jacketing is typically achieved by wrapping the member along the perimeter (Figure 15.12).

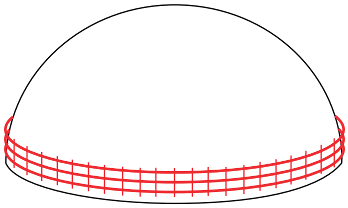

Figure 15.11 Strengthening at the lower part of a dome.

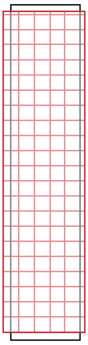

Figure 15.12 Masonry column wrapping.

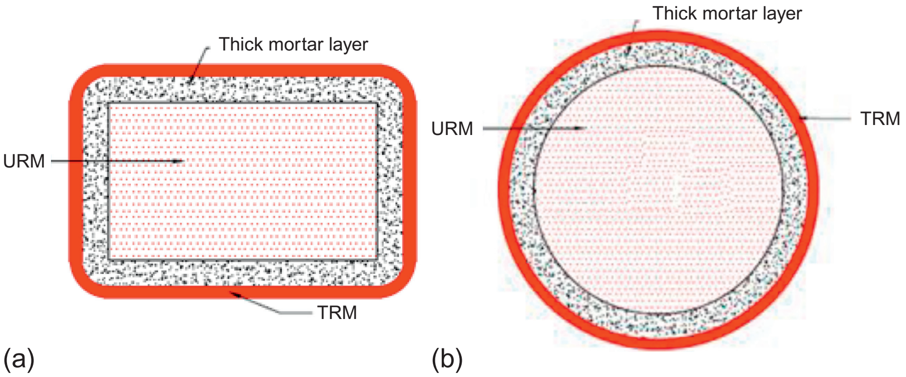

Figure 15.13 Confinement of (a) a rectangular masonry column and (b) a circular masonry column.

Finally, a possible configuration is the confined enlargement of the section by application of a thick mortar layer on the masonry. This should be done prior to the application of the TRM (Figure 15.13a and b).

15.11 Summary

In this chapter, the author presented concepts for strengthening of masonry structures with TRM, as well as key aspects of structural behavior. The following topics were covered: brief description of TRMs and their properties, with an emphasis on tensile behavior; intervention requirements and strengthening rationale; aspects of structural modeling and retrofitting for seismic applications; strengthening of masonry walls for out-of-plane or in-plane loads; strengthening of curved masonry elements, such as arches, barrel domes and vaults and confinement. It was shown that TRM is an effective and convenient solution in a variety of applications involving the retrofitting of unreinforced masonry walls.

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