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Mechanics and durability of textile reinforced mortars: a review of recent advances and open issues

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Abstract

Application of textile-reinforced mortars (TRMs) for strengthening of existing masonry structures have received a growing attention in recent years. An extensive effort, both experimental and computational, has been devoted during the last 10 years for understanding the performance of these composites and their effectiveness in improving the performance of existing masonry structures. Nevertheless, several aspects regarding the durability and mechanics of these composites still remain unknown and need to be addressed in future studies. This letter is a short review with an effort on highlighting those aspects considering both experimental and numerical modelling approaches.

Keywords: : Textile reinforced mortars; TRM; FRCM; FRM; Masonry; Mechanics; Durability; Experimental mechanics; Computational modelling

1 Introduction

Application of textile reinforced mortars (TRMs) for externally bonded reinforcement of existing concrete and masonry structures has recently received a growing attention. The better physical, mechanical and hygrothermal compatibility of TRMs with masonry and concrete, compared to that of conventional fibre reinforced polymers [1–4] has made these composites the preferred choice for strengthening of those structures.

TRMs (also referred as FRCM or FRM in the literature), that originate from Textile Reinforced Concrete (TRC) [5], are composite materials consisting of continuous fabrics embedded in an inorganic matrix. For application to masonry structures, the most commonly used fabric types are steel, glass, basalt, polyparaphenylene benzobisoxazole (PBO). Sisal, flex and hemp have also been used in some cases. These fabrics are available in a wide range of mechanical properties and geometrical forms (including unidirectional / bidirectional / multidirectional, variable grid spacing, woven / welded / nonwoven / knitted, coated/uncoated fabrics, etc.). The matrix is either a cementitious (suitable for application to new masonry or concrete components or infills with high mechanical properties) or a lime-based mortar (including hydraulic limes, pozzolanic lime mortars, mixed cement-lime mortars, lime mortars mixed with short fibers, etc. preferred for weak and historical structures) [6]. This wide range of available fiber and mortar types allows design of composite materials with a large spectrum of mechanical properties, but at the same time makes development of unified predictive and design models a challenging task. When applied to masonry, as these composites are usually manufactured and applied on site following a wet layup procedure, the role of workmanship and onsite curing conditions on the final performance of the strengthening system becomes critically important and need to be considered in the design procedures.

While an extensive effort has been made by researchers, manufacturers and stakeholders in understanding of these composites and of the role of different parameters affecting their performance, there is still a lack of fundamental understanding of the mechanics and durability of these composites in the field acting as one of the barriers against their widespread use and application. The lack of sufficient laboratory and field data on the short- and long-term performance, standard in-situ and laboratory testing procedures, adequate constitutive laws for numerical simulations and techniques for quality and health monitoring of structures strengthened with these composites are among the current gaps in this field. This letter is a short review with an effort on highlighting these gaps considering both experimental and numerical modelling approaches.

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2 Mechanics of TRMs and TRM-strengthened masonry

The main characteristic of the TRM/TRC composites is their high strength and pseudo-ductile response. The tensile response of these composites, which can be described with the aim of the ACK theory [7], consists of three main stages [4,8–11], see Fig. 1(a): stage I: a linear stage which continues until first macro crack occurs in the mortar; stage II: the crack development stage in which several cracks are formed in the matrix; and stage III: a final linear stage in which no more cracks are formed, the cracks are widened with the increment of the load and all the applied load is resisted by the textile reinforcement. The behaviour in the stage I is mainly influenced by the modulus and strength of the mortar; in stage II by the textile-to-mortar bond behaviour, and in stage III by the effective modulus of the fabric. As a general rule, a high strength composite with a pseudo ductile response (that is preferred when seismic strengthening of components is of concern) should be composed of a reinforcement fabric with an elastic modulus several orders of magnitude higher than that of the mortar, and a bond strength equal to or slightly higher than the mortar tensile strength. A bond strength that is much larger than the mortar tensile strength leads to a TRM composites with linear elastic behaviour until failure (the crack development stage will not occur), while a bond strength that is much smaller than the mortar tensile strength leads to a tension softening response after the first mortar macro cracking.

The textile-to-mortar bond behaviour is the most critical and complex mechanism and is influenced by several factors including the mechanical properties of the fabric and the mortar (strength and elastic modulus), the geometrical properties of the fabric (e.g. configuration, texture, surface properties, etc.), and the chemical compatibility between the fabric and mortar.

It is also worth mentioning that the stiffness of the fabric is also influenced by the manufacturing technique used for production of the fabrics and yarns and is usually in the range of 0.25 to 0.7 in common textiles used for manufacturing TRC/TRMs [12].

When TRC/TRMs are used for strengthening of existing structural components, the TRM-to-substrate bond behaviour and the hygro-thermo-mechanical compatibility of its matrix with the substrate becomes important as well [1], see Fig. 1(b). For this reason, the TRM composites used for strengthening of old or weak masonry structures are usually made of lime-based mortars or weak cement mixes, the TRM composites used for strengthening of new masonry or concrete structures are usually made of higher strength cementitious matrices.

For any newly developed TRM system, a fundamental understanding of these mechanisms, the interaction between them, and of how they are affected by manufacturing, curing and service conditions, are critical for appropriate selection and design of TRMs for strengthening purposes.

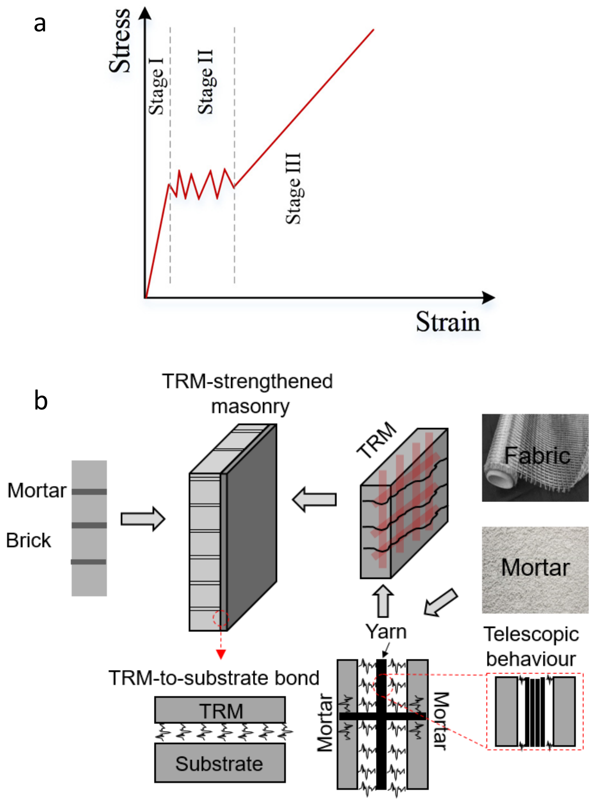

Figure 1. (a) Mechanics of TRM-strengthened masonry; (b) typical tensile response of TRMs.

This requires development of a consistent multi-scale mechanical testing framework, see Fig. 2, which allows establishing the material-structure performance correlations and allows development of constitutive laws needed for numerical simulations at different scales. At the micro-scale, a combination of standard materials testing methodologies (to characterize the mechanical, hygral and thermal properties of fibre, fabric and mortar) with fabric/yarn pull-out tests (for evaluation of the yarn-to-mortar and textile-to-mortar bond behaviour) are needed. Combination of these test methods with microstructural physical and chemical test methods allow further understanding of the bonding mechanism in the TRM system under investigation and development of innovative approaches for enhancing it (e.g. application of coating or surface modification technologies for enhancing the bond [13,14]). At the composite scale (TRM level), tensile, flexural and shear tests are essential for understanding the nonlinear response and cracking behaviour of these composites under different loading conditions and for validation/development of macro-scale damage models. TRM-to-substrate bond tests are also needed for evaluation of the governing failure mode and the bond strength of the whole strengthened system and of the ability of the TRM-to-substrate bond to fully transfer stresses from the substrate to the strengthening system. At the structural scale, the effectiveness of this strengthening technique in enhancing the capacity and nonlinear response of structural components can be evaluated by performing conventional static or dynamic tests on structural components or buildings.

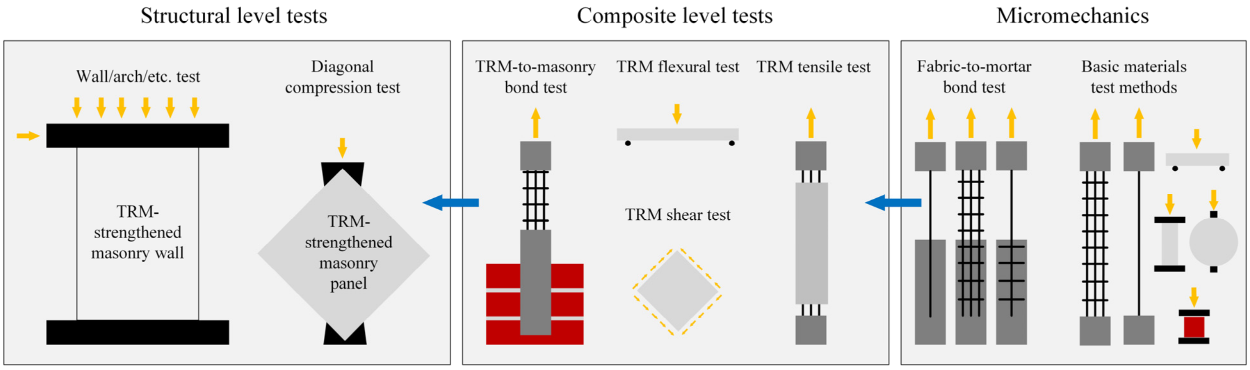

Figure 2. Experimental testing and constitutive modeling of TRM and TRM-strengthened masonry.

3 Discussion on experimental testing activities

Experimental evaluation of the mechanical response of TRMs and TRM-strengthened masonry have been the subject of several studies during the last 10 years. With large variety of available TRM and masonry types, further comprehensive experimental studies are still needed for fundamentally understand the performance of these composites, for development of strategies to enhance their performance and for development of guidelines/codes for durable and resilient deign of these composites for externally bonded reinforcement of masonry structures.

Most of the existing studies have been focused on the used of steel, glass, basalt, PBO (and to some extent natural fibres such as sisal or hemp) embedded in a cementitious or a lime-based matrix. The tests are usually performed at the composite level (TRM level) or at the structural level (TRM-strengthened masonry). These include direct tensile tests on TRM composites (and to some extent flexural tests), see e.g. [2–4,6], TRM-to-substrate bond behaviour, see e.g. [2–4,6], diagonal compression tests on TRM-strengthened masonry, see e.g. [15,16], or static cyclic (and in very few cases dynamic tests) on TRM-strengthened masonry structures, see e.g. [17–19]. Meanwhile, micromechanics of TRMs, i.e. the textile-to-mortar bond behaviour, and the parameters affecting that, remain poorly addressed and understood, see e.g. [1,20,21].

Even at the composite and structural level, there is a clear lack of standard experimental test methods and procedures for evaluating the performance of these composites. As these composites are usually applied to existing masonry structures following a wet layup procedure, the workmanship, application procedure, surface condition before application and curing conditions can have a significant influence on their mechanical response in the field. The laboratory experimental tests, however, are usually performed under controlled environmental conditions.

These considerations indicate the need for finding answers to the following questions with respect to these materials: what is the relation between the laboratory obtained experimental results and field performance (ignoring the role of environmental conditions)? How environmental field conditions affect the performance of these composites and the whole strengthened structure and how this can be simulated in laboratory? What are the most suitable test setups at each level from which the obtained experimental results are representative as the real performance of the material and what are the most suitable test setups from which suitable constitutive laws needed for numerical models can be extracted? What are the test procedures and considerations that need to be followed and reported so that the data obtained from different laboratories can be compared? Considering that many TRM types used for strengthening of masonry structures are made of a family of lime-based mortars, at what age the laboratory tests need to be performed to ensure the results are representative of the long-term performance of the strengthening system and considering the variety of available lime-based mortars, can we propose a unique testing age which ensures a similar curing age for comparison of the results from different test setups?

3.1 Textile-to-mortar bond behaviour

Although testing and modelling of the textile-to-mortar bond behaviour in cementitious matrices have been the subject of several studies for decades, see e.g. [22–27], the existing literature on the bond behaviour of TRM composites that are of interest for strengthening of masonry structures is very limited, (see e.g. [1,20,21] for a steel and a glass-based TRM).

Pull-out tests are the most common test method used for characterization of the bond behaviour in fibres embedded in different matrices [28]. These tests can be performed following a single-sided [29–31] or a double-sided [32,33] configuration. Naturally, each configuration has its own advantages and disadvantages. While the specimen and test setup preparation are more straightforward in single-sided tests, the boundary conditions are more realistic in a double-sided testing scheme. The variability of the experimental results are also smaller in a single-sided testing scheme [8]. Comparison between the experimental results obtained from different tests setups should be done with special care, as due to the differences in the boundary conditions and stress distribution between these two test methods, the peak load and toughness of the samples tested under a double-sided testing scheme are higher than the samples tested under a single-sided testing scheme [20,21,26].

The main output of the pull-out tests are force-slip curves which with the aim of analytical or numerical models can be used for extraction of the bond-slip laws. The main challenge, in this process, is ensuring the uniqueness of the obtained bond-slip laws. This requires accurate measurement of the fibre slip (at both loaded and free ends of the sample) and the strain/stress distribution of the fibre along its embedded length. However, due to the complexity of measurement of the fibre slip at the free end or lack of equipment for measurement of strain distribution along the embedded length, only the fibre slip at the loaded end has been measured and reported in the existing studies [20,21,34].

As mentioned before, the existing literature on pull-out response of TRM composites used for strengthening of masonry structures is still very limited. Recent studies have shown the important role of fabric configuration (unidirectional/bidirectional), loading rate (in the quasi static range), embedded length and mortar age (at the time of testing) on the pull-out response and bond behaviour of a limited number of existing commercial TRM types [20,21,34]. While there is a need for future studies on other TRM types, the unaddressed role of textile chemical/physical properties, configuration and texture (type of connection at the junctions, grid spacing, etc.), surface properties (surface roughness, type of coating), fabric inclination with respect to the crack surface, mortar chemical/physical properties, mortar curing conditions, loading rate and regime (high load rates, cyclic loads, sustained loads), environmental conditions and processing method on the bond behaviour of different TRM systems also need to be investigated. These studies are essential for development of durable, resilient and high performance TRM composites for strengthening applications.

3.2 TRM-to-substrate bond behaviour

The TRM-to-masonry bond tests have been extensively used for characterization of the bond performance in TRM-strengthened components [1–3,6]. A large variety of single-lap and double-lap shear test setups have been used and proposed by different authors. The round robin tests performed in the framework of RILEM TC 250-CSM are probably the most notable and comprehensive experimental database available in this field [2–4]. The results produced as the output of this activity showed a large variability of the bond strength, failure mode and force-slip curves between similar specimens tested in different test setups as well as between similar specimens tested under similar test setups but in different laboratories. This observation shows the critical need for standardization of the processing, manufacturing and testing methodologies for qualification and evaluation of the TRM-to-substrate bond performance.

TRM-to-substrate bond tests provide useful information on the ability of the strengthening system in transferring stresses from the substrate to the reinforcement (although tests are usually performed in a vice versa manner). In some studies, the results obtained from these are used for extraction of the fabric-to-mortar bond laws as well. However, it should be noted that the force-slip curves (and consequently the bond-slip laws extracted from them) obtained from TRM-to-substrate bond tests are significantly different than the ones obtained from fabric-to-mortar pull-out tests [21] and therefore the obtained results cannot be directly considered as the fabric-to-mortar bond response. This is due to the differences in the boundary conditions, active failure mechanisms and stress distribution in the specimens tested under these two test configurations [21]. Clearly, when the objective is extraction of the fabric-to-mortar bond-slip laws, the pull-out tests should be considered as the preferred testing methodology.

In general, the existing literature shows a sufficiently high TRM-to-mortar bond strength can be achieved in most TRM-masonry systems. In cases where the bond strength is not sufficient, masonry surface treatment (sandblasting, grinding, etc.) or use of connectors can be used. Again, further studies at this level are still needed including evaluation of the role of surface preparation (before TRM application), curing conditions, loading regime and reinforcement ratio.

3.3 TRM Mechanical behaviour

Direct tensile tests are the most common method used for evaluating the mechanical response of TRM composites [2–4]. Flexural tests have received less attention but are easier to perform. In-plane shear tests, critical for understanding the cracking and nonlinear behaviour of TRM composites, have not also received ant attention yet.

Tensile tests provide useful information on the global mechanical response of the strengthening system (deformation capacity, strength and crack spacing) and can also be used for validation of the bond-slip laws extracted from the pull-out tests [4,8–11]. Whether or not all the three typical stages of the tensile response, mentioned in section 2, are observed in the experimental results is dependent on the fabric properties, the mortar properties, the fabric-to-mortar bond properties [4,6,10,11]), test procedure and the test setup employed for performing the tests.

Direct tensile tests are particularly complex and require specific attention to the specimen's alignment in addition to the adequate gripping. The test setups commonly used [1–4,35,36] or proposed [37,38] for performing direct tensile tests are designed either to achieve the highest possible load-bearing capacity in the TRM composite under investigation (clamping-grip methods, bolted, wedge, pneumatic, etc.) or to achieve a load-bearing capacity that is sufficiently representative as what is observed in the field (e.g. clevis-grip method) [38]. In the clamping method, the pressure applied to the mortar at the clamping areas should be sufficiently high to avoid slippage of the fibres during the tests, but at the same time should not be too high to cause crushing of the mortar. A survey of the literature shows that in most experimental tests performed on lime-based TRMs this pressure was either not enough to avoid slippage or was too high and resulted in crushing of the mortar [2–4]. In the clevis method, on the other hand, the load is applied to the samples through shear stresses. However, the results are dependent on the length of the mortar through which these shear stresses are transferred to the samples (or in simple terms the length of the tabs). In both test setups, the load is transferred from the mortar to the fabric. This makes calculation of the fibre stresses needed for presentation of the tensile behaviour of the TRM system complicated especially when fibre slippage occurs in the clamping areas. To address these challenges, a tension stiffening tensile testing scheme was also introduced in [1] in which tensile loads are directly applied to the fabric left outside of the mortar at both ends of the sample. In this testing scheme: (i) the slippage of the fibers in the gripping area is completely avoided; (ii) the stresses applied to the fibers can be directly and accurately calculated; (iii) the load application is consistent with the pull-out tests (in both tests the load is applied to the fabric) and (iv) the results provide the average response of the embedded fabric which can be used for calculation of the tension stiffening effect of the fibers on the mortar and are directly comparable with tensile tests on dry fabrics.

The tensile tests performed on different TRM composites in the framework of the RILEM TC 250-CSM, again, showed a large variability of the tensile behavior between different labs as a result of different test setups and procedures followed. Despite existence of a relatively large experimental database on tensile response of TRM composites, the large variety of the available TRM systems indicates the need for further studies at this level. There is particularly a lack of understanding and systematic studies on the role of fabric configuration (e.g. how transverse fibers in bidirectional fabrics affect the tensile response), physical/chemical properties of the mortar and fabric, processing, curing and manufacturing procedures on mechanical response of these composites. Such information can be helpful in development of guidelines for design and application of TRM composites with expected mechanical response.

3.4 TRM-strengthened masonry mechanical behaviour

Diagonal compression tests on TRM-strengthened masonry panels, see e.g. [15,16], or in-plane and out-of-plane tests on TRM-strengthened walls or vaults, see e.g. [39–42], have been the main testing schemes used for evaluating the structural response of strengthened components. In general, TRM composites are observed to be effective in enhancing the performance of masonry at structural scale. Most of the existing literature consist of evaluation of the effectiveness of different TRM types (mostly glass and steel-based TRMs) in strengthening of undamaged or damaged (tuff, brick and rubble stone) masonry walls or panels, see e.g. [15,16,43,44]. Effectiveness of natural-based TRMs in enhancing the structural performance of masonry has also recently been the subject of few studies, see e.g. [45,46]. With the urgent need for lowering the carbon footprint of the constructions, it is expected that natural-based TRMs receive a more extensive attention, especially with focus on innovative ways to enhance the durability of these composites, in the coming years.

These existing experimental data, generally, show the effectiveness of TRM composites in enhancing the strength and ductility of masonry walls without significantly changing their stiffness. With the variety of available TRM and masonry types, further investigations at this scale are still needed. It should also be noted that these observations are mostly taken from monotonic static tests performed on masonry panels or walls. Dynamic tests (specially shaking table tests) on walls or buildings, essential for understanding the response of these structures against seismic actions, are still scarce, see e.g. [18,47], and require further attention. Again, as in externally bonded reinforcement applications TRM composites are usually applied following a wet lay-up procedure, the workmanship, surface conditions and curing conditions can have a significant influence on their properties and their effectiveness in enhancing the behaviour of the existing structure. Most of the existing tests, however, are performed under controlled laboratory conditions. Development of a fundamental understanding of how these parameters can influence the mechanical response at structural scale and of the procedures that ensure achieving the expected functionality in the field are of critical importance. Novel quality and health monitoring techniques for early age monitoring the curing and hydration processes in the onsite applied TRM system can also be very helpful.

3.5 Durability

The existing literature on durability and long-term performance of TRC and TRM composites is very limited at the moment, see e.g. [48–55]. There is, therefore, a lack of clear understanding of the main deterioration mechanisms in each TRM system, of the long-term field or laboratory performance of these composites, and of standard accelerated aging test methods and setups for evaluating the durability of these composites. These gaps not only affects our ability to design durable TRM composites, but also influences development of design guidelines and codes for considering the role of aging in the performance of TRM composites.

Understanding the durability of TRM composites requires development of a multi-scale testing/modelling framework in which the deterioration mechanisms and stability of these systems is evaluated at each level separately (textile, matrix, textile-to-mortar bond and TRM-to-substrate bond) and at structural/system level as a whole (TRM composite or TRM-strengthened masonry). The challenge lies in designing tests setups with accurate boundary conditions and exposure levels that ensures a rate of deterioration at all levels that is representative of what occurs in the field.

Water attack, high temperatures, alkaline environment, exposure to salts and freeze-thaw actions seem to be the main concerns in environmental deterioration of TRM composites used for strengthening of masonry structures. Synergistic effect of mechanical and environmental loads can also be critical as mechanical stresses can lead to micro- and macro-cracking and consequently accelerating the deterioration processes. Obviously, the wide range of chemical/physical characteristics of the fabrics and matrices used for development of TRC and TRM composites indicates each system can be vulnerable to a different set of environmental conditions.

The recently initiated RILEM IMC committee (on Durability of Inorganic Matrix Composites used for Strengthening of Masonry Constructions) is expected to address some of these open issues and establish the basis for understanding of the durability of these systems. At the moment, with the lack of comprehensive studies and standard testing methodologies, it is difficult to draw conclusions on durability of TRM composites for each application or to develop guidelines for durable design of TRMs for strengthening of existing structures. Studies are needed to understand the deterioration mechanisms in each of the common TRM composites under the above mentioned environmental and mechanical conditions, to develop standard accelerated aging test methodologies and test setups, to develop remedial actions to enhance the durability of each system, to perform surveys on the field behaviour of these composites and establish lab-field correlations, and to develop health and quality monitoring techniques for evaluating their service performance.

4 Discussion on numerical modelling activities

A range of micro- and macro-modelling approaches have been used and proposed by different researchers for assessment or prediction of the mechanical response of TRM composites or TRM-strengthened structures, e.g. [56–59].

Micro-modelling approaches, in which all the constituents of masonry (brick and mortar) and TRM composites (textile and mortar), and the interactions between them are modelled individually [46-47], allow detailed understanding of the mechanisms governing the nonlinear response of the component under investigation. These models can also be used for development of average macro-damage models for investigation of the mechanical response at structural scale as direct application of micro-modelling at structural scale can be computationally very expensive. On the other hand, utilization of such modelling strategies requires extensive knowledge on micro-mechanical properties of the constituents (including elastic and inelastic properties of brick, mortar, brick-mortar interface, fabric, TRM matrix, fabric-to-mortar interface and TRM-to-masonry substrate), which are not usually available.

Macro-modelling approaches, in which the masonry and the TRM are simulated as homogenous layers attached together (either by considering a perfect bond between masonry and TRM or by using interface elements between them to consider possible delamination at the interface) are more suitable for structural-scale simulations. Nevertheless, calibration of these models and the material parameters require extensive and costly experimental characterization tests for each case. Additionally, depending on the damage model used, a range of parameters that cannot be explicitly measured in the experimental tests are usually needed. Even in case of masonry, for which macro-modeling has been used for several years (e.g. [60,61]), the choice of those input parameters are still under discussion and simplified relations that can be used for obtaining those parameters from standard mechanical properties (such as compressive strength or elastic modulus) are missing. In case of TRMs, the standard smeared crack modelling approaches, available in most FE packages, are commonly used [57,59,62]. The lack of sufficient knowledge and experimental data on the nonlinear response of TRMs, specifically cracking and nonlinear response under complex loads (such as shear, or torsion) and tension stiffening effect of fabrics on mortar/concrete, however, are the major obstacles in validation of the smeared crack approaches.

Application of detailed or simplified homogenization approaches in which the average properties are obtained from micro-modeling simulations can help in overcoming this problem [63,64]. But, again, the reliability of the simulations is highly dependent on the versatility and availability of experimental data at micro-scale.

5 Conclusions

Application of textile reinforced mortars (TRMs) for externally bonded reinforcement of existing masonry and historical structures has recently received a growing attention. The variety of the available fabric and mortar types allows tuning of their properties and thus a fit-for-purpose design of these composites. At the same time, this makes development of unified application, design and qualification procedures for these composites challenging. An extensive effort has been devoted to understanding of these composites and of their effectiveness in seismic strengthening of existing masonry structures. Despite these efforts, several issues regarding their mechanical response and durability, field performance are still open and standard testing methodologies, numerical modelling approaches, or techniques for non-destructive testing and monitoring the health of structures strengthened with these composites are missing. A non-exhaustive list of the main challenges and open issues in this field, to date, are listed as follows:

- There is a need for development of consistent testing methodologies and procedures for evaluation of the mechanical response and durability of TRM composites at all scales for (a) obtaining experimental results that are representative of the filed response; and for (b) obtaining data which allow development of constitutive laws needed for numerical simulations. Considering the role of curing age, curing conditions and manufacturing process on the mechanics and durability of these composites, currently unaddressed, is also critical.
- With the large variety of available TRM and masonry types, the existing experimental results are still insufficient for fully understanding of the mechanical performance of these composites. Micromechanical test results (especially fabric-to-mortar bond tests), in particular, are the most scarce, but essential for understanding and predicting the mechanical performance of TRM composites and need to be comprehensively studied in future investigations. At the composite scale, in-plane shear tests and out-of-plane tests under complex boundary conditions, critical for in-depth understanding of the nonlinear response and cracking behaviour of these composites, are still missing. At the structural scale, performing dynamics tests on buildings or structural components strengthened with TRM composites need to be considered for understanding the actual effectiveness of these composites in protecting existing structures against seismic actions.
- Durability of TRM composites under different environmental conditions is still an open issue. There is a need for development of standard testing and

measurement methodologies for evaluating the durability of TRM composites at different scales. Long-term field performance is not available yet and consequently the actual deterioration mechanisms that can affect the performance of these composites in the field are not very well known.

- Development of non-destructive testing and health monitoring approaches for evaluating the quality/performance of TRM composites in the laboratory and in the field are also needed.
- Although a wide range of numerical and analytical models have been developed for simulating the nonlinear behaviour of TRM composites and TRM-strengthened masonry components so far, the lack of sufficient experimental data at different scales is the main obstacle against development of validated reliable numerical tools which consider all possible failure mechanism in these systems.

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