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CRACK PATTERNS AND STRENGTHENING OF HISTORICAL UNREINFORCED MASONRY STRUCTURES

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Introduction

Recognizing possible crack patterns, discontinuities, **and brittle failure mechanisms in unreinforced masonry under seismic and gravitational forces enables effective retrofitting strategies**. A wide array of traditional and modern materials and strengthening techniques offer compatible, removable, and sustainable conservation options. Steel and timber tie-rods are commonly employed to support the horizontal thrust of arches, vaults, and roofs, and are particularly effective in connecting structural elements such as masonry walls and floors. Additionally, composite reinforcement systems utilizing carbon and glass fibers along with thin mortar layers can enhance tensile capacity, ultimate strength, and displacement to prevent brittle shear failures.

This study provides an overview of masonry structural diagnostics and compares traditional with advanced strengthening methods for walls, arches, vaults, and columns. It also presents **recent research on automated surface crack detection in unreinforced masonry (URM) walls, with an emphasis on machine learning and deep learning algorithms.**

Crack Patterns and Strengthening of Masonry Structures

Common crack locations and patterns observed in masonry buildings are: 1) in-plane diagonal or shear cracks; 2) out-of-plane partial or total collapse 3) cracking near openings; 4) separation between roof and walls or wall intersections; 5) cracking in arch and vault. The strength of URM walls subject to in-plane actions depends on several failure modes: joint sliding and diagonal tension, which are shear-controlled, and toe-crushing, which is flexure-controlled. Generally, rocking or sliding governs the response for URM columns with low vertical axial pressure and diagonal tension, and toe-crushing force-controlled actions are more frequent in high vertical axial stress.

Dynamical structural identification procedures are utilized to measure structure frequencies, oscillation modes, and dynamical features. Then different measurements are compared over time, enabling continuous monitoring of any damage development.

Another approach is employing Fracture Mechanics (FM), studying the structural integrity and behavior. In 1989, first, Bocca and Carpentieri [1] determined for the first time Fracture energy, GF, and the critical value of the stress-intensity factor, K_{IC}, for brick masonry specimens tested in bending with different notch depths, and the experimental results are compared with numerical simulations, obtained through a cohesive crack model developed originally for concrete. In 2022, Greco et al. [2] determined crack propagation analysis in masonry structures via an interelement cohesive fracture approach: assessment of mesh dependency issues. Several clear patterns were confirmed and detailed (figure 1), patterns similar to civil engineering approach experimental results [3].

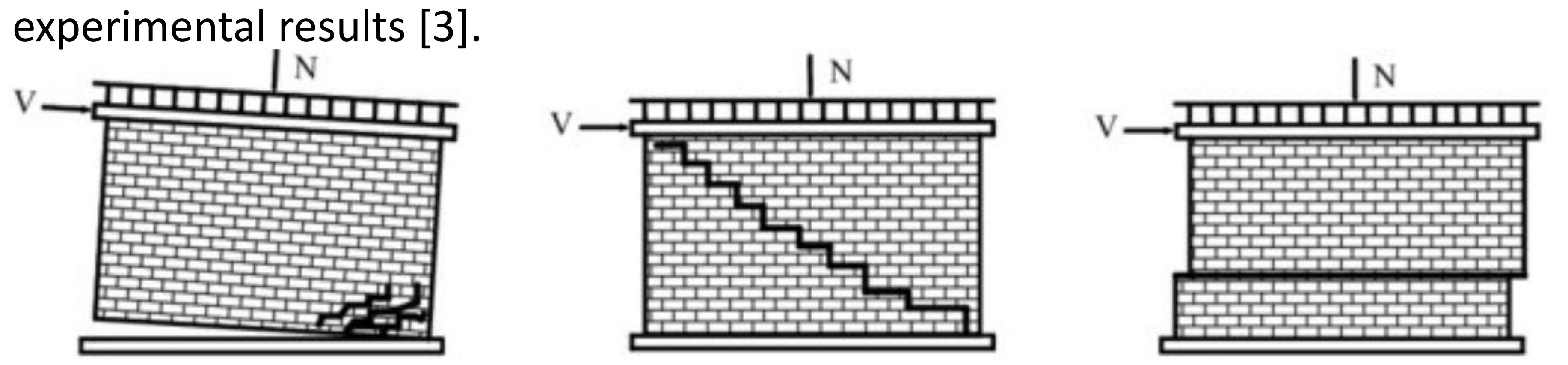

Figure 1. Crack patterns in UnReinforced Masonry (URM) walls **(a)** rocking failure; **(b)** diagonal cracking; **(c)** bed-joint sliding [3]

A traditional restoration includes using steel ties at different levels to rehabilitate the wall's connections. strengthening scheme contribution depends on fiber tensile capacity and anchorage length. The connection between the substrate and reinforcing system is enhanced by ap-plying specific connectors inserted inside the masonry before the mortar's final covering layer is implemented. The bed joint reinforcement is typically used to improve the wall shear capacity. Moreover, the composite materials are applied to both wall sides, covering the entire surface or vertical/horizontal discrete strips with transverse connectors for multi-leaf/wythe walls.

Another possible option is grout injection. In this approach, masonry cracks are filled through a proper pattern of drilled holes to enhance the continuity of wythe (multi-leaf) wall sections [60].

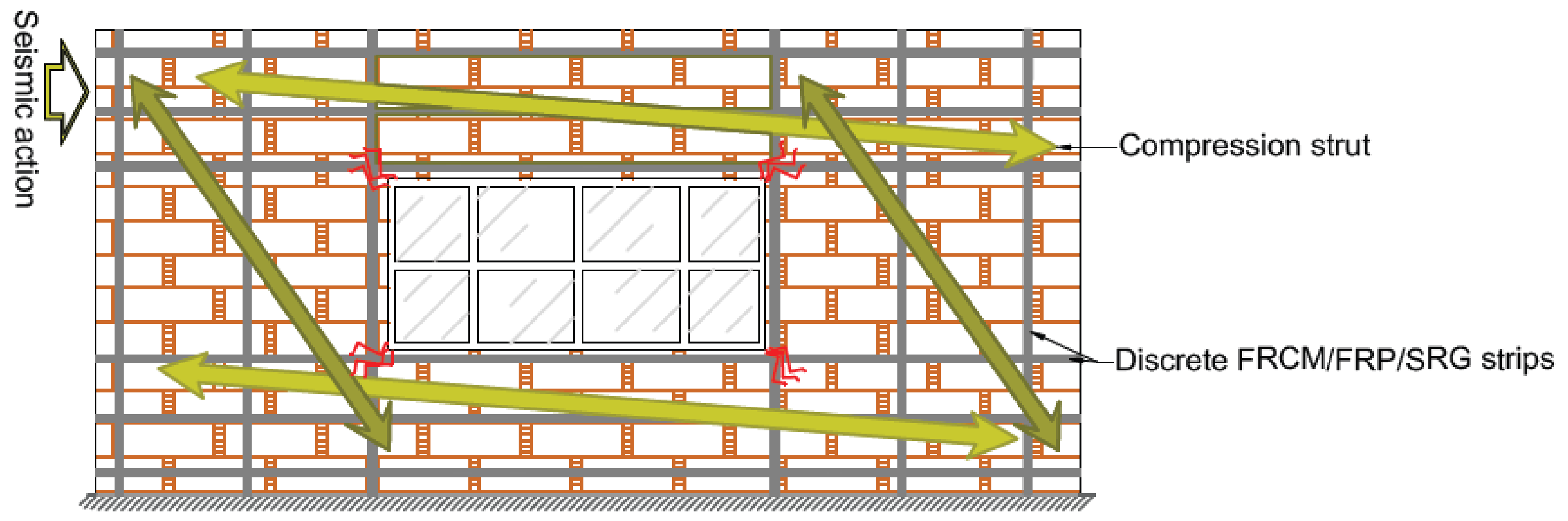

Figure 2. Strut-and-tie-model for the in-plane reinforcement of masonry walls with opening.

The RM wall in-plane flexural strength is correlated to the following governing fail-ure modes: 1) crushing the masonry in compression represented by stress block and neu-tral axis depth is calculated for the fabrics in tension and masonry in compression; 2) masonry substrate debonding, fabric-matrix interface debonding, fabric slippage inside the matrix, or tensile fabric rupture, which is masonry remains in the elastic range in compression. The externally bonded steel fabric is assumed to be elastoplastic, and the strain profile is calculated based on the plane-sections-remain-plane hypothesis. The stress and strain profile and failure modes are represented in Figure 3, almost the same as RC behavior. Applying FRP bars or strips on wall surfaces can avoid both in-plain and out-of-plain collapse mechanisms. The explanations for notations represented in Figure 3 are as follows: ε_m is the compressive strain of masonry, ε_f tensile strain of FRP/FRCM/SRG, εmu ultimate compressive strain of masonry, ε_{fd} design tensile strain of FRP/FRCM/SRG, E_f Stiffness (mean value) of FRP/FRCM/SRG provided by tensile tests and f_{mu} is the compressive strength of masonry.

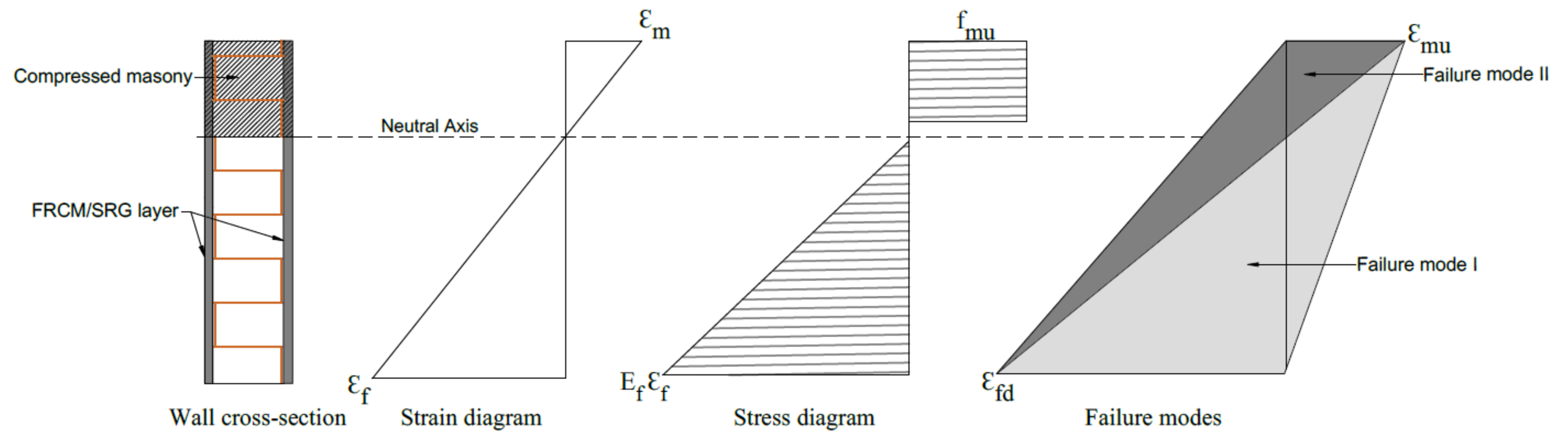

Figure 3. Cross-section of the wall, strain, stress profiles, and failure modes.

The FRCM/SRG qualification is established on a test procedure that provides data on material properties, force, and deformation limit states, including failure modes, according to specified test approaches. The qualification parameters should be representative only of the procedure that experienced the experimental tests and cannot be developed for diverse scenarios.

Conclusion

This study overviews typical crack patterns developed in masonry structural elements that may provide helpful information regarding the collapse mechanisms that allow for reliable retrofitting interventions. The application of traditional and modern techniques for repairing and strengthening masonry walls, arches, vaults, domes, and columns has been presented, e.g., externally bonded fabric-reinforced cementitious matrix (FRCM), steel-reinforced grout (SRG), and tie-rod systems. In addition, several research results in automatic surface crack detection for URM walls are presented, considering crack detection based on machine learning and deep learning algorithms.

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