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# State of research on shear strengthening of RC beams with FRCM composites

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## HIGHLIGHTS

- A database of RC beams strengthened in shear with FRCM composites is developed.
- FRCM composites provide increase in the shear strength of RC beams of 3%–195%.
- Possible internal-external transverse reinforcement interaction is observed.
- Different failure modes are observed depending on the strengthening configuration.
- Further work is needed to develop more accurate and reliable design models.

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## ABSTRACT

This paper summarizes the state of research on the topic of shear strengthening of RC beams using externally bonded FRCM composites. In the first part of this paper, a detailed bibliographical review of the literature on the shear strengthening of RC beams using FRCM composites is carried out, and a database of experimental tests is developed. Analysis of the database shows that FRCM composites are able to increase the shear strength of RC beams. The effectiveness of the strengthening system appears to be influenced by parameters including the wrapping configuration, matrix compressive strength relative to the concrete compressive strength, and axial rigidity of the fibers. Different failure modes have been reported, including fracture of the fibers, detachment of the FRCM jacket (with or without concrete attached), and slippage of the fibers through the mortar. A possible interaction between the internal transverse steel reinforcement and the FRCM system has also been observed. In the second part of this paper, four design models proposed to predict the contribution of the FRCM composite to the shear strength of RC beams are assessed using the database developed. Results show that the use of the properties of the FRCM composite in Models 3 and 4 instead of the fiber mechanical characteristics does not significantly increase the accuracy of the models. A simple formulation such as that proposed by Model 1, based on the bare fiber properties, is found to be more accurate for beams with or without composite detachment.



## 1. Introduction

Reinforced concrete (RC) structures are affected by external factors such as lack of maintenance, environmental conditions, or overloading that can cause deterioration and potentially diminish their structural performance. In addition, there is a growing need for upgrading existing structures in order to comply with requirements established in new design guidelines or to achieve an adequate level of performance due to the modification of expected loads caused by a change in use. The intervention of these structures requires the use of satisfactory rehabilitation and/or strengthening techniques that result in adequate behavior of the structure after the retrofitting process is carried out. Traditional techniques such as the increase of concrete section using concrete jackets or the use of externally bonded steel elements, which are common especially in developing countries, can often be

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considered as structurally acceptable but may not comply with modern requirements in which time- and cost-efficient interventions are usually required.

For this reason, externally-bonded fiber reinforced polymer (FRP) composites have become one of the most common intervention techniques for RC structures. Advantages of this technique include high stiffness-to-weight and strength-to-weight ratios, good fatigue characteristics, and ease of application. However, some limitations of this method, mainly related to the use of organic resins, have been pointed out [1]: (1) debonding of FRP from the concrete substrate; (2) poor behavior of epoxy resins at temperatures at or above the glass transition temperature; (3) relatively high cost of epoxy resins; (4) difficulty to apply onto wet surfaces or at low temperatures; (5) lack of vapor permeability; (6) incompatibly of epoxy resins with the substrate material; and (7) difficulty to conduct post-earthquake assessment of damage suffered by the structure. This suggests that the use of FRP might not be suitable for all applications, and new techniques that overcome some of these limitations are needed.

Composite materials that employ an inorganic cement-based matrix instead of an organic matrix allow for overcoming some of the limitations of FRP composites. Different names have been used in the literature to describe this type of composite depending on the matrix and fibers employed including textile reinforced concrete (TRC), textile reinforced mortar (TRM), fiber reinforced concrete (FRC), mineral based composites (MBC), and fiber reinforced cementitious matrix (FRCM). In this paper, the term FRCM is used to describe the aforementioned systems. FRCM composites exhibit significant heat resistance and vapor permeability and can be applied at low temperatures or onto wet surfaces [2]. The use of FRCM composites as a strengthening material for RC beams was first studied by [3–6], and their work can be considered as the starting point for the development of more recent research since their findings showed promising results. While research on the topic is still scarce, recent studies by [7–10], among others, have confirmed the effectiveness of this technique for flexural and shear strengthening and confinement of axially/eccentrically loaded RC elements.

This paper summarizes the state of research on the topic of shear strengthening of RC beams using externally bonded FRCM composites with the goal of serving as a reference point for the development of future research. In the first part of this paper, a detailed bibliographical review of the literature on the shear strengthening of RC beams using FRCM composites is carried out. This review summarizes the major findings and points out main aspects that should be addressed in future research. In the second part of this paper, design models proposed to predict the contribution of the FRCM composite to the shear strength of RC beams, including the ACI 549.4R [11] expressions, are assessed using a database of experimental results collected and compiled by the authors.

## 2. Experimental database

Fifteen articles related to shear strengthening of RC beams using FRCM composites were found in the technical literature and are summarized in Table 1. From these articles, a database that includes the characteristics and results of experimental tests on the FRCM strengthened beams was developed and is presented in Table A1 in Appendix A. Eighty-nine strengthened beams are included in the database.

### *2.1. Evaluation of the database and distribution of data*

In order to evaluate the information collected in the database, the shear strength provided by the FRCM system ($V_{FRCM}$) is calculated by subtracting the shear strength of the corresponding control beam ($V_{CON}$) for each test. Although experimental specimens aimed to investigate the shear behavior of strengthened specimens are designed to attain shear failure, it is important to highlight that in some cases (seven tests, see Tables 1 and A1) the addition of the FRCM system changed the failure mode from a brittle shear failure to a more ductile flexural failure. Specimens that failed in flexure can be considered as a lower bound of the strengthening capacity, but the behavior of beams that failed in that fashion is not further discussed in this paper.

Figs. 1–3 present the variation of the ratio $V_{FRCM}/V_{CON}$ as a function of the main geometrical and mechanical properties of the strengthened beams and the FRCM system. The horizontal axis of each plot is subdivided in order to evaluate the number and percentage of tests in different ranges, and values of which are labelled along the top of each graph. The points are subdivided according to the type of failure: flexural or shear. Shear failure is divided according to the presence or absence of detachment of

**Table 1**
Summary of studies on shear strengthening of RC beams using externally bonded FRCM composites.

| Reference | Year | Beam cross-sectional shape[a] | Number of strengthened beams | Failure mode | | Strengthening configuration[d] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Flexure[b] | Shear[c] | SB | U[e] | | W |
| [9] | 2006 | R | 3 | 2 | 1 | | | | 3 |
| [10] | 2006 | R | 2 | | 2 | | | | 2 |
| [12] | 2008 | T | 9 | | 9 | | 9 | (6) | |
| [13] | 2009 | R | 7 | | 7 | 7 | | | |
| [1] | 2012 | R | 8 | | 8 | 8 | | | |
| [14] | 2013 | R | 6 | 2 | 4 | 2 | 4 | | |
| [15] | 2014 | R | 6 | | 6 | 3 | 3 | | |
| [16] | 2014 | R | 2 | | 2 | | 2 | (1) | |
| [17] | 2014 | T | 10 | | 10 | | 10 | (6) | |
| [18] | 2015 | R | 6 | | 6 | | 6 | | |
| [19] | 2015 | R | 8 | | 8 | 2 | 6 | | |
| [20] | 2015 | R | 7 | 2 | 5 | | 7 | | |
| [21] | 2015 | R | 8 | 1 | 7 | 3 | 3 | | 2 |
| [22] | 2015 | R | 1 | | 1 | | | | 1 |
| [23] | 2016 | R | 6 | | 6 | 6 | | | 1 |
| | | **Total** | 89 | 7 | 82 | 31 | 50 | (13) | 8 |

[a] R = Rectangular, T = T-beam.
[b] Yielding of longitudinal reinforcing steel bars followed by concrete crushing.
[c] Failure mode related to FRCM debonding, fiber rupture, diagonal tension, and/or yielding of internal stirrups.
[d] SB = Side bonded, U = U-wrapped, W = Fully wrapped.
[e] Number in parentheses indicates number of tests that include anchors.