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Dimensioning the flexural strengthening of concrete slabs with textile reinforced mortar – literature data evaluation

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Abstract

When strengthening reinforced concrete slabs with textile reinforced mortars (TRM), the “correct” consideration of the global bond behaviour between textile and cementitious matrix is identified as the main challenge in determining the most appropriate global analytical model. The first model evaluated here is based on classical assumptions for structural concrete design. The second model, as another extreme assumption, is completely neglecting textile bond in the cracked zone, thus assuming it as unbonded, end-anchored, external reinforcement. The third model is based on the simplifying assumption of the textile reinforcement being only significantly activated when the internal steel reinforcement is yielding. Analytical results from these approaches are compared to a database containing more than 130 test results reported in literature, and are statistically evaluated.

Keywords: textile reinforced mortar (TRM); flexural strengthening; concrete slabs; analytical model; dimensioning; textile bond; literature data base.

1 Introduction

Numerous experimental studies were conducted lately on flexural strengthening of reinforced concrete elements with textile reinforced mortars (TRM). This promising construction material, being created by embedding one or more layers of uni- or bi-axial glass, carbon or PBO textile meshes in a cementitious matrix, presents promising value not only in new construction elements but also in strengthening of existing.

The strengthening of concrete elements with TRM implies a relatively simple procedure. First, the existing concrete is mechanically treated to remove the superficial cement layer and to expose the aggregates inside (roughening). Before applying the first layer of shotcrete, the surface is wetted to help creating good bond between the

mortar and the concrete support. Afterwards, the textile reinforcement is applied in one or multiple layers with shotcrete layers in-between. A finishing mortar layer is added to enclose the textile reinforcement in this cementitious matrix.

Because this strengthening technology offers a highly reliable bond between the concrete support and the mortar, the failure at this interface is not prone to appear and the governing failure emerges at the interface between textile and mortar.

Given the small thickness of TRM and its capacity of being applied on large surfaces, the use of this method is very suitable for the strengthening of concrete slabs. As retrofitting nowadays presents significant challenges in order to bring old structures to meet new needs of serviceability and

ultimate strength, TRM becomes a promising option in engineers' toolbox.

In order to dimension TRM layers for flexural strengthening of concrete slabs, one needs to have guidelines that help in the structural design process. Thus, a theoretical model that sufficiently accurately describes the behaviour of the composite element is necessary.

Analytical approaches in use nowadays are often deduced from experimental results and rely on (semi-)empirical models that consider TRM as a whole reinforcement, without detailed appreciation of its internal bond behavior.

2 Literature database

A total of more than 130 experimental results from tests on reinforced concrete elements (i.e. one-way slabs, beams) strengthened with TRM [1-13] was collected from literature and added to a database that contains more than 50 distinct parameters for each experiment. Among them, there are parameters describing the test setup (i.e. 3- or 4-point bending, spans, shear spans), geometric properties (i.e. sectional dimensions, static height for steel reinforcement and textile), material properties for concrete, mortar, textile and steel (i.e. elastic moduli, compression and tensile strengths), and the flexural testing results (i.e. failure type, maximum load, ultimate deflection).

Some assumptions were made in cases where data was incomplete or missing, like in the case of concrete elastic modulus. In other cases, calculations were performed, based on existing data, to determine parameters such as concrete tensile strength, hardening modulus of steel reinforcement or ultimate bending moment.

After gathering this considerable amount of data, the next step was to compare theoretical models to the experimental data in order to evaluate the suitability of different analytical models.

3 Analytical models

Three different analytical models were considered to find the most suitable consideration of bond behaviour of TRM-retrofitted concrete slabs.

All the take into account the hardening capacity of the steel reinforcement after yielding. The behaviour model for the textile reinforcement is linear-elastic until failure, Fig. 1.

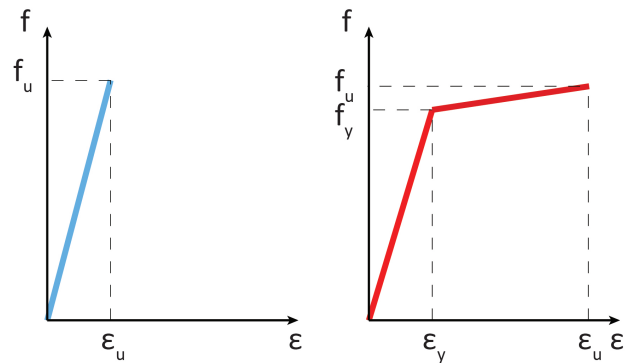


Figure 1. Constitutive laws for textile reinforcement model (left), and steel reinforcement (right)

3.1 Rigidly bonded textile

Here, classic reinforced concrete theory assumptions, such as plain sections remaining plain after deformation, rigid bond between concrete and reinforcement and no tension taken by the concrete, are considered.

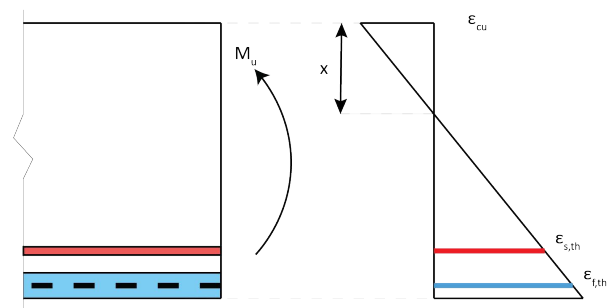


Figure 2. Strain compatibility with rigidly bonded reinforcements

Strain compatibility between concrete in compression, steel reinforcement and textile reinforcement in tension is straightforward, Fig. 2, and the sectional forces are determined accordingly. The calculations were performed at ULS, considering a maximum ultimate strain for the compressed concrete of 3‰.

Equilibrium for normal forces considers the tensile forces in the reinforcements and the compression force in the concrete, determined from strains. A solver is implemented to find the position x of the neutral axis which satisfies equilibrium. After

obtaining the lever arm of inner forces resulting from x , the moment capacity can be determined and compared to the experimental value.

Applying this approach to all experimental test results and analyzing the ratio between experimental and analytical moment capacity, Fig. 3, it can be found that this approach overestimates the experimental capacity of the strengthened slab by 18% on average, with a coefficient of variation of 30%, Table 1.

Table 1. Rigid bond model results

	M_{exp}/M_{theo}
AVG	0,85
COV	30%

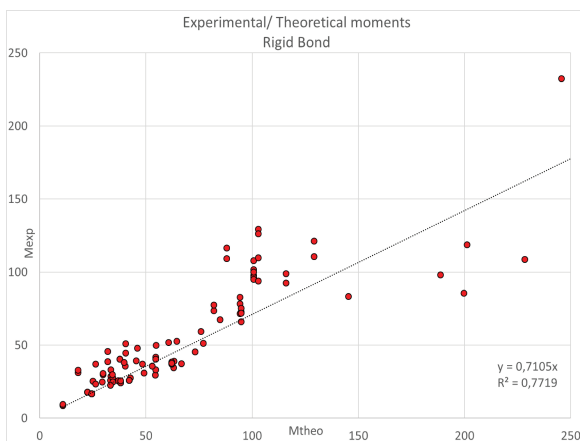


Figure 3. Comparison of M_{exp}/M_{theo} ratio for rigid bond model

3.2 Unbonded end-anchored textile

At the opposite extreme from the previous approach, this model completely neglects bond between textile and mortar in the cracked zone of the strengthened element. To determine the cracked length L_{cr} , Fig. 4, it is necessary to calculate the cracking moment and find its position in the moment diagram. The theoretical textile strain is computed using the ultimate deflection δ_u obtained in the experiment by calculating the total elongation ΔL of the textile fibres with a static height d_f from Eq. (1), considering a rigid body mechanism of a single span slab [2]:

$$\Delta L = \frac{4\delta_u}{L} \times (d_f - x) \quad (1)$$

Strain compatibility (i.e. plain sections remaining plain) is used only to determine the strain in the steel reinforcement, also applying the same assumption of 3‰ maximum concrete strain.

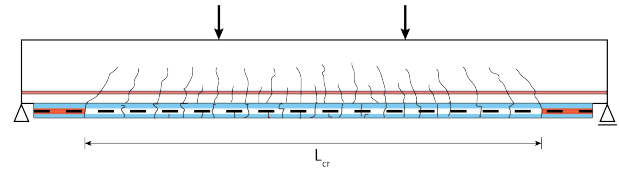


Figure 4. Unbonded length in cracked zone

A solver was applied to find the neutral axis position for having sectional equilibrium, resulting in associated tensile forces in the textile and steel reinforcement. The moment capacity is calculated with associated lever arms of reinforcements, and compared to the experimental moment.

Applying this model to the experimental data, Fig. 5, results in an average M_{exp}/M_{theo} ratio greater than 1, Table 2, implying that this approach underestimates the real capacity and thus, offers conservative results. The experimental data is 26% higher on average than the analytical results, with a further reduced COV of 24%.

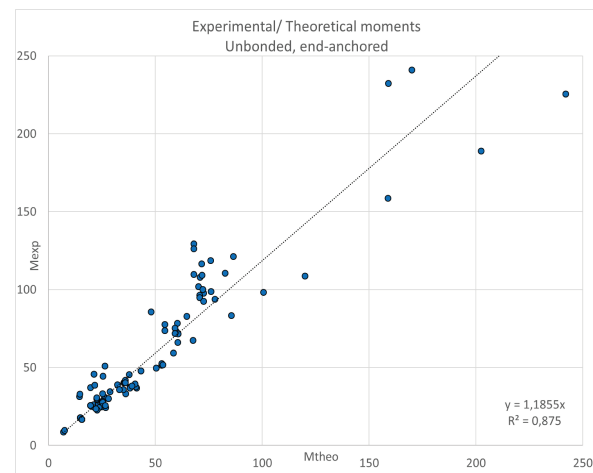


Figure 5. Comparison of M_{exp}/M_{theo} ratio for unbonded, end-anchored model

Table 2. Unbonded, end-anchored model results

	M_{exp}/M_{theo}
AVG	1,26
COV	24%

3.3 Unbonded textile, activated by steel yielding

This model is an intermediate approach between the rigid bond model (section 3.1) and the unbonded model (section 3.2) because the length where unbonded behaviour of the textile reinforcement is considered reduces to the length where steel reinforcement yields, Fig. 6. At the same time, it is based on the principles used in the second approach, i.e. considering the total textile elongation from global displacement compatibility to determine the textile strain. It can be described as a refinement of the unbonded model.

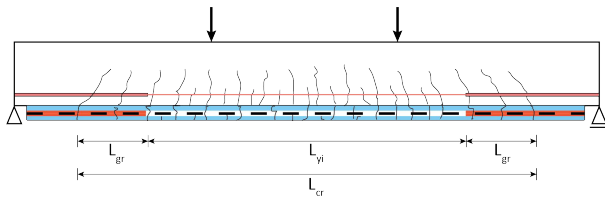


Figure 6. Unbonded length

By calculating a weighted overall static height for the textile and steel reinforcement and considering usual analysis assumptions of cracked reinforced concrete, it is possible to determine the neutral axis position in the elastic state which allows to find the yielding moment for the steel reinforcement. Determining the position of this moment in the moment diagram allows finding the length L_{yi} where the internal steel reinforcement is yielding and thus, the length where the textile is considered being activated.

The difference between the cracked length L_{cr} and the length L_{yi} with plasticised internal steel is the transition zone of a gradient length L_{gr} where the bond between textile reinforcement and mortar changes gradually from unbonded to sufficiently bonded.

The strain in the textile reinforcement is again calculated by dividing the total elongation ΔL from Eq. (1) by L_{yi} .

The same process as in the other two models presented above was used to determine the tensile force in the steel reinforcement by using strain compatibility with an ultimate concrete strain of $\epsilon_{cu} = 3\text{‰}$. By applying a solver to find the neutral axis position and sectional equilibrium, the sectional

moment capacity can be determined and compared to the experimental data.

The results show, Fig. 7, that this method is still underestimating the real capacity but only by 12% on average and with a somewhat higher COV of approx. 28%, Table 3.

Table 3. Unbonded, yield-activated model results

	M_{exp}/M_{theo}
AVG	1,12
COV	28,5%

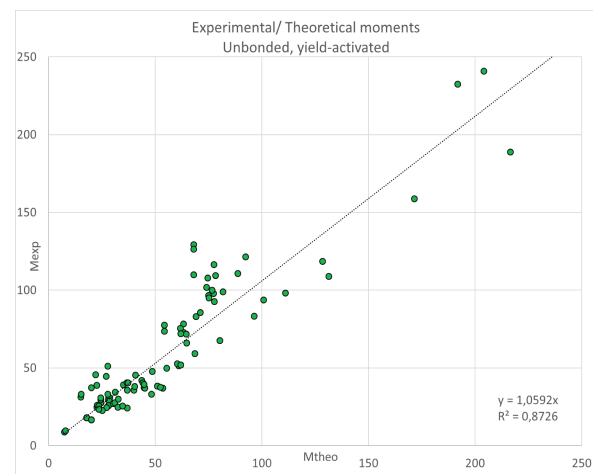


Figure 7. Comparison of M_{exp}/M_{theo} ratio for unbonded yield-activated model

4 Comparison and discussion

An intuitive analysis to compare the efficiency of the evaluated models can be performed by observing the differences between the trend lines of each model and the diagonal line representing equality between experimental and analytical results, Fig. 8. Moreover, the conservatism of a model can also be determined by the number of the points located above the diagonal, falling in the safe side, Table 4.

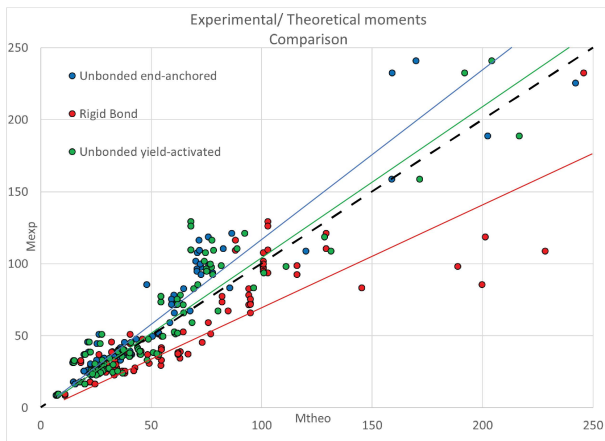


Figure 8. Models comparison

For the first model assuming rigid textile bond, a smaller amount of data is situated above the diagonal in comparison to the second model, where an unbonded textile behaviour is assumed over the cracked length of a specimen. For the model with unbonded yield-activated textile, the situation is more equilibrated in terms of data distribution between conservative and unsafe results.

Table 4. Data comparison

	Rigid bond model	Unbonded, end-anchored model	Unbonded, yield-activated model
Conservative results	20%	79%	58%
Average ratio M_{exp}/M_{theo} of unsafe results	0.74	0.96	0.86

5 Conclusions

The purpose of this literature data evaluation study was to identify a suitable, simple, yet conservative analytical model that allows to determine the sectional moment capacity of concrete slabs strengthened with textile reinforced mortar with sufficient accuracy. The efficiency of flexural strengthening with TRM majorly depends on the bond behaviour between textile and surrounding mortar, determining the attainable textile stresses at ultimate.

From the three models applied (rigidly bonded textile, end-anchored textile unbonded over

cracked length, or over steel yielding length, respectively), the model stands out that considers the strengthening textile being unbonded over the length with yielding internal steel reinforcement, offering the closest fit to the experimental data collected from literature. Statistically, this analytical approach provides a good level of accuracy, with an average underestimation of only 12% of the real capacity of more than 130 experimental results. Its reliability, being reflected by a coefficient of variation of less than 30%, is reasonable, given that textile bond primarily relies on mortar tensile strength.

Further work needs to be done to find a more accurate method that also takes into account the behaviour of the textile in the bond gradient zones, as well as bond influences in the cracked and yielding zones. These influences could explain the difference between experimental and analytical results. Another study should be conducted on finding a reliable calculation method to determine the ultimate deflection of a TRM strengthened concrete element, as it determines the textile strain at ultimate.

6 Acknowledgements

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