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Citation for published version (APA):
Türkmen, S., de Vries, B. T., Wijte, S. N. M., & Ingham, J. M. (2021). Out-of-plane behaviour of clay brick masonry walls retrofitted with flexible deep mounted CFRP strips and additional single-sided FRCM overlay. Structures, 33, 2459-2474. https://doi.org/10.1016/j.istruc.2021.05.061

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DOI:
10.1016/j.istruc.2021.05.061

Document status and date:
Published: 01/10/2021

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
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Out-of-plane behaviour of clay brick masonry walls retrofitted with flexible deep mounted CFRP strips and additional single-sided FRCM overlay

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ARTICLE INFO

Keywords:
CFRP
Masonry
Reinforcement
FRCM
Seismic

ABSTRACT

The deep mounting of CFRP strips to masonry using a flexible adhesive was developed as a minimally-invasive and cost-effective out-of-plane seismic retrofitting technique for unreinforced masonry (URM) buildings. Previous experiments on one-way spanning full-scale walls confirmed the significant added value for out-of-plane lateral resistance and displacement capacity for the Flexible Deep Mounted (FDM) CFRP strips retrofitted walls with respect to unreinforced masonry. This out-of-plane performance could be further enhanced by the addition of a single-sided Fabric Reinforced Cementitious Matrix (FRCM) overlay to FDM CFRP strips retrofitted walls. The purpose of the current experimental campaign was primarily to investigate the out-of-plane performance of one-way spanning walls retrofitted with both FDM CFRP strip and a single-sided FRCM overlay. The results of the experiments confirmed the significant added value for out-of-plane lateral resistance of walls with the proposed retrofit combination with respect to the URM and solely FDM CFRP retrofitted walls. A cross section analysis using non-linear and linear material models for the used components was proposed. The model provided an overestimation of the lateral moment capacity for walls that were solely retrofitted with FDM CFRP strips for high mid-span displacement. For walls that were additionally reinforced with a single-sided FRCM overlay, the model provided a good approximation of both the internal moment versus curvature and the lateral moment versus mid span displacement relationships.

1. Background

Due to its high strength to weight ratio, high strength to stiffness ratio, resistance to chemicals and immunity to corrosion, fibre reinforced polymers (FRP) are gaining global popularity as seismic retrofit material for masonry structures. Large disadvantages associated with conventional strengthening systems with traditional building materials (i.e. steel frames and reinforced concrete jacketing), such as labor intensive, the addition of considerable mass to the existing structure, and an alteration of the aesthetics of a building, do not apply to FRP. Traditionally FRP sheets or plates are externally bonded (EB) to the masonry with an epoxy resin to increase both the wall strength and ductility. Over the last decade the near surface mounted (NSM) technique has been raised as a promising alternative, where FRP strips or rods are placed in a layer of epoxy in pre-cut vertical grooves in the wall. Although the NSM FRP method cannot be used in concrete elements for which the cover depth is low De Lorenzis and Teng [10], D’Antino and Pisani [8], near surface mounting offers several advantages over EB FRP such as higher strain at debonding and therefore more efficient use of the FRP, reduced aesthetic impact, reduced installation time, less exposure to accidental impacts and vandalism, and superior protection from fire and environmental influences [19,18,11]. Both the EB and NSM techniques, however, require double-sided application to strengthen walls for both lateral (out-of-plane) loading directions. In case of strengthening of load-bearing inner leaves of cavity walls, this would require both temporary rehousing of building occupants as well as the removal of the façade of the building, which is a costly operation.

The deep mounted technique was accordingly developed where deeper grooves are cut in the masonry, after which FRP strips are installed in the center of the wall [24]. The FRP strips therefore offer additional out-of-plane flexural capacity to the wall for both out-of-plane loading directions whilst only installing the reinforcement from
one side of the wall, leading to cost-effective retrofitting Türkmen et al. [23,24]. This retrofitting technique, named flexible deep mounted (FDM) CFRP strengthening, makes use of a flexible adhesive (Young’s modulus < 40 N/mm²) to attach the CFRP strip to the masonry substrate. Stiff epoxies used in traditional strengthening systems have significantly higher Young’s moduli (>2000 N/mm²). Pull-tests performed by Türkmen et al. [25] have shown that a flexible-adhesive system leads to higher interfacial fracture energy, increased wall displacement capacity arising from higher local slip capacity and larger slip capacity at damage initiation and thus leading to increased wall displacement capacity at the onset of irreversible damage to the retrofit. In an extensive experimental campaign on FDM CFRP strip retrofitted masonry walls, full-scale wall specimens were subjected high-speed cyclic loading conditions using a novel, cyclic bending test setup Türkmen et al. [25]. Experimental results confirmed the significant increase in the out-of-plane lateral resistance and deformation capacity for the FDM CFRP strip retrofitted specimens with respect to the unreinforced masonry (URM) specimens. The lateral moment resistance and the corresponding mean mid-span displacement increased with 130% and roughly a factor 90 respectively given axial load, due to the installation of two FDM CFRP strips.

For walls subjected to critical in-plane loading, the application of solely the FDM CFRP strips retrofit is insufficient to increase the in-plane load resistance. Diagonal compression tests on masonry panels showed that the installation of an FDM CFRP strip retrofit had no significant effect on the in-plane shear strength for the selected test conditions (Türkmen et al., 2019a). The FDM CFRP strip retrofit was combined with a single-sided FRCM overlay to form a hybrid retrofit (Fig. 1) in order to enhance the strength and pseudoductility of masonry for in-plane loading conditions. This hybrid retrofit was subjected to static-cyclic in-plane shear tests (Türkmen, de Vries, Wijte, & Vermeltfoort, 2019b) and diagonal compression tests (Türkmen et al., 2019a), proving the effectiveness of the single-sided FRCM overlay to enhance the in-plane shear strength and pseudoductility.

Even though numerous contributions on out-of-plane loaded and FRCM strengthened walls are available in the literature [3–6,7,9,12,27], the behaviour of the hybrid retrofitted masonry (FDM CFRP strips and single-sided FRCM overlay) when subjected out-of-plane loading conditions remain unknown. In this paper, the out-of-plane behavior of hybrid retrofitted masonry walls is characterized by means of three bending tests on full-scale walls. Both unreinforced masonry wall specimens as well as specimens strengthened with the proposed combined retrofit system were subjected to reversed-cyclic out-of-plane bending. Moreover, this study proposes a mechanical model for predicting the out-of-plane bending behaviour of strengthened walls. Finally, the validity of the model is checked by comparing the experimental outcomes with the model predictions. The research presented in this paper is an extension of the experimental campaign presented in Türkmen et al. [25].

2. Experimental program

2.1. Materials and characterization

The properties of the clay brick, mortar and masonry used for building the specimens, and the flexible adhesive, CFRP strip and
polymers modified mortar used for retrofitting the specimens were reported in §2.1 of the previous work of the authors Türkmen et al. [25]. The bi-directional CFRP mesh, with a fibre weight density of 1.79 g/cm³ and about 3 mm width per thread, had a square aperture dimension of approximately 20 × 20 mm². The theoretical cross section of the carbon fibre for design was 44 mm² per meter width. The Young’s modulus and roving strength for the CFRP mesh were reported as 230 kN/mm² and 1700 N/mm² respectively (Valeri, Ruiz & Muttoni, 2018). The mechanical properties of the FRCM system were previously determined by means of tensile coupon tests by Türkmen et al. [22], following the test procedure specified in AC434.13 (2013). The mean cracking stress and pre-cracked Young’s modulus of the FRCM coupons were found to be 4.23 N/mm² and 27,680 N/mm². The mean ultimate stress of the CFRP mesh and the FRCM cracked modulus (using the cross-sectional area of the mesh) following the tensile coupon tests were found to be 1682 N/mm² and 70,920 N/mm² respectively. More mechanical properties of this FRCM system, including the results of double lap shear tests and four-point bending experiments can be found in Türkmen et al. [22].

2.2. Constructing the specimens

The wall specimens for the quasi-static reversed-cyclic out-of-plane bending tests were constructed in the Structures Laboratory of the Technical University of Eindhoven. The foundation for specimens was formed by a steel plate on which a layer of bricks was glued with high-performance epoxy. A total of nine specimens with a height of 2750, a length of 965 mm and a thickness of 95 mm were constructed in running masonry. Finally, the specimens were left to cure for at least 28 days in the laboratory environment prior to testing. A schematic overview of the reinforced specimens is provided in Fig. 3.

2.3. Test setup and test procedure

The reversed cyclic out-of-plane bending tests were performed at the Structures Laboratory of Eindhoven University of Technology. The four point-bending test setup used for the cyclic testing is explained and illustrated in detail in Türkmen et al. [25]. A photo and schematic overview of the test setup used in this experimental campaign is provided in Figs. 4 and 5 and respectively. The vertical load was applied on top of the specimen using dead weight in the form of a steel beam, which simulated a stiff slab boundary condition. All specimens were burdened with a load of approx. 0.05 N/mm² (vertical compressive force of 4.8 kN), similar to the loads maintained during a previous experimental campaign by the authors Türkmen et al. [25] and a testing program for the seismic characterization of Dutch masonry walls [16]. Axial stress levels in the order of magnitude of 0.1 N/mm² or less are common for walls on the top floor of the masonry houses in the Groningen region. These walls in particular are prone to out-of-plane failure, mainly due to the limited overburden load.
Each wall was tested in displacement control, with cycles of increasing amplitude. Each cycle was composed by two runs, a run being the time needed to apply the maximum positive and negative target displacement starting and ending at zero displacement (Messali et al., 2020), as illustrated in Fig. 6. The loading procedure consisted of two stages. The target displacement initially increased with increments of 2.5 mm after each completed cycle, with an actuator speed of 2.0 mm/s. This protocol (Stage I) continued until a target displacement of 27.5 mm. Starting from a target displacement of 30 mm (Stage II), the target displacement increment was increased to 5 mm. The actuator speed during Stage II was initially set to 40 mm/s. However, due to the limitation of the electric actuator the test malfunctioned multiple times during the testing of specimen FRCM-1. Therefore all other FRCM specimens were tested using an actuator speed of 5 mm/s. The main reason why a loading phase with a lower loading speed (Stage I) was implemented for the strengthened specimens, was to prevent the initiation of dynamic effects for the smaller displacement amplitudes. The loading speed for all wall specimens, during both test stages is provided in Table 1. The draw-wire sensor located at mid-height of the specimens (DWS,3) was used to determine the loading speed at mid-height of the specimens.

2.4. Processing the measurements

To determine the relationship between stress in the CFRP strips and the moment, the measurements from the draw-wire sensors, the load cells and the strain gauges were processed. Processing was done by using a simplified mechanical representation of the wall, as provided in Fig. 7. This data processing procedure is explained in detail in paragraph 2.5 of Türkmen et al. [25].

The global force – mid-span displacement behaviour is illustrated in Fig. 8. The parameters presented in Fig. 8 are the lateral resistance ($P_{max}$), the corresponding moment ($M_{max}$) and mid-span displacement ($\delta_{WS,3,ma}$), the lateral load at the end of the test($F_{u}$), the corresponding moment ($M_{u}$) and mid-span displacement ($\delta_{WS,3,u}$). From the force–displacement ($F – \delta_{WS,3}$) relationship per half run, the initial stiffness ($k_{ini}$) was determined. A half run was defined as the loading path in either the push or pull direction. The initial stiffness of the wall, $k_{ini}$, was taken as the slope of the $F – \delta_{WS,3}$ loading branch within the displacement range $\delta_{WS,3} = [-2.5 \text{mm}, 2.5 \text{mm}]$. The value of the slope was calculated by fitting a linear regression through the data points. The
backbone curve (target displacements and corresponding forces) and one complete run ($\delta_3 = 0 \rightarrow \Delta_i \rightarrow \Delta_i \rightarrow 0$) are provided by a thick solid line and slim black lines respectively in Fig. 8.

### 3. Test results and discussion

The test results are summarized in Table 2, with the following nine measured or derived parameters:

- Lateral strength ($P_{\text{max}}$), the corresponding moment ($M_{\text{max}}$) and mid-span displacement ($\delta_{3,\text{max}}$),
- Lateral load at the end of the test ($F_u$), the corresponding moment ($M_u$) and mid-span displacement ($\delta_{3,u}$),
- Maximum stress in both the left ($\sigma_{p,\text{max},L}$) and right ($\sigma_{p,\text{max},R}$) CFRP strip, together with the tensile utilization ($\Phi_p$), determined with respect to the tensile strength of 2880 N/mm$^2$.

All parameters (some represented in Fig. 9) are presented as absolute values for both the positive and negative displacement direction, and will be covered in the following sections.

#### 3.1. Lateral moment - displacement

The global mid-span lateral moment-displacement diagrams for the tested specimens, are shown in Fig. 9. The light grey lines represent the individual cycles, whereas the thick black lines highlight the backbone curve. The solid dark grey lines represent the first cycle with 50 mm target displacement. The cycle with FRM failure is highlighted by the dotted thick grey lines. It should be noted that the top graphs in Fig. 9 represent the pre-failure cycles, whereas the graphs at the bottom row represent the post-failure cycles. It should be noted the backbone curve covers the envelope curves up to and including the failure cycle. The
post-failure behaviour has no relevance for the practical applicability of the seismic retrofit system as CFRP mesh rupture was considered as retrofit failure.

The backbone curves of the lateral moment - mid span displacement for all FRCM specimens are shown together in Fig. 10, together with the backbone curves for URM and solely FDM CFRP retrofitted specimens (coded STRIP) obtained from the experimental campaign by Türkmen et al. [26]. First aspect observed from Fig. 10 was the difference between the mid span displacements $\delta_{DWS,3}$ corresponding to the maximum lateral moment resistance. No significant differences were found between the maximum lateral moment resistances of the FRCM specimens for both the push (mean 3.96 kNm) and pull direction (mean 7.67 kNm). The mid-span displacement corresponding to the maximum lateral moment resistance was higher for specimen FRCM-1 when compared to specimens FRCM-2–3. This was predominantly caused by the debonding failure mechanism of FRCM-1, as no significant difference was observed for the push direction of the FRCM specimens until $\delta_{3,max} \approx 100$ mm.

Compared to the URM and STRIP specimens, the single-sided FRCM overlay not only provides significant added value in terms of lateral moment – mid span displacement capacity on the pull side, but also for the push side as shown in Fig. 11. The mean lateral moment resistance of the URM specimen as obtained by Türkmen et al. [26] was 0.78 kNm. With the specimens in the current experiment campaign, the mean lateral moment resistance was increased with 408% and 883% for the FRCM side under compression and tension respectively. For the mean displacement $\delta_{3,max}$ corresponding to the lateral moment resistance, this was increased with 4380% from 2.1 mm (URM) to 94.2 mm (FRCM-2–3). The average lateral moment resistance of FDM CFRP retrofitted walls was found to be 1.82 kNm by Türkmen et al. [26], meaning the addition of a single-sided FRCM overlay to form a combination of retrofit measures provides a significant surplus in lateral moment resistance.

The mean lateral resistance of the STRIP specimens corresponding to a mid-span displacement target of ~ 100 mm was 1.6 kNm. The presence of the 15 mm thick FRCM layer in the compressed area of the cross-section during push cycles (FRCM overlay in compression) resulted in failure.
The simplified hairline crack (grey lines) and full crack patterns (black lines) for the FRCM side of the tested specimens are provided in Fig. 11. The fully cracked FRCM layer of specimen FRCM-2 is provided in Fig. 12. In fixed–fixed cases, the rocking mechanism develops after cracking at the wall top, usually the weakest section due to the lower axial load, followed by cracking at the bottom and finally at the wall mid-height [20]. Since in the no bond was present between the (gypsum capped) top of the specimens and the beam exerting the vertical load, the first full crack developed at the bottommost mortar bed joint.

At the start of the loading process, the lateral load was primarily resisted by the cementitious matrix until cracking. Afterwards the matrix undergoes a multi cracking process resulting in transfer of stresses from the matrix to the mesh. This is accompanied with some debonding at the mesh–matrix interface Mininno [17]. Eventually, all specimens failed due to CFRP mesh rupture (Fig. 13). The location of these ruptures were approximately at the bed joints between the 26th – 27th, 18th – 19th and 30th and 31st brick layers (counted from the top) for FRCM-1, FRCM-2 and FRCM-3 respectively.

Looking at the differences in crack pattern between the specimens, the most remarkable was the difference in the number of hairline cracks between FRCM-1 and FRCM-2–3. Specimen FRCM-1 showed approximately 2 times more hair-line cracks over the height of specimens compared to FRCM-2–3. Additionally, the hairline cracks of FRCM-1 also reached more towards the top and bottom of the specimen. These differences were attributed to the FRCM debonding failure mechanism which was observed for the FRCM-1 specimen, as shown in Fig. 14. This failure mechanism was caused by the faulty installation, as was mentioned before, of the CFRP mesh within the cementitious matrix for specimen FRCM-1.

Looking at the damage to the masonry on the as-built side of the specimens, multiple bed joint cracks over the height of the wall were observed, ranging from 14 to 17 in total, mainly concentrated at the constant lateral moment area. This was in line with the damage observed by Türkmen et al. [26] for walls retrofitted with solely FDM CFRP. Some local crushing of the mortar was also observed on the as-built side of the specimens. After the CFRP mesh rupture, increased crushing of the cementitious matrix was observed for the post-failure push cycles.

3.3. Stresses in the CFRP strip

Using the equations presented in paragraph 2.5, the tensile stress distribution of the CFRP strips were determined. The stress distribution in both the left (dashed lines) and right (solid lines) CFRP strips are shown in Fig. 15 for all the FRCM specimens, at various target displacements during the pull cycles (FRCM under tension). The same stress

![Fig. 9. Moment–mid span displacement plots of STRIP-1 (A), STRIP-2 (B) and STRIP-3 (C).](image-url)
In overall, the reached stress levels over the CFRP strip between the push and pull cycles differed significantly, for both the pre-failure and post-failure stages. The stress in the CFRP strips at ~ 50 mm mid-span displacement (diamond marked lines) was significantly lower for the pull cycles than for the push cycles. The overall mean stress values following from the middle two strain gauges at ~ 50 mm mid-span displacement was 161 N/mm\(^2\) and 642 N/mm\(^2\) respectively. For the displacement corresponding to the pre-failure cycle, the difference of the CFRP strip stresses remained significant between the pull (336 N/mm\(^2\)) and push cycles (1107 N/mm\(^2\)). A difference in CFRP strip stresses was also observed between FRCM-1 and FRCM-2–3 at the pull side of the pre-failure cycle. The overall mean stress values following from the middle two strain gauges were 434 N/mm\(^2\) and 287 N/mm\(^2\) respectively when the target displacement was reached. This difference in CFRP stress was attributed to the difference of the mid-span displacement levels corresponding to the pre-failure cycles, which was ~ 130 mm for FRCM-1 and ~ 93 mm for FRCM-2–3.

Looking at the post-failure (CFRP mesh rupture) cycles, tensile stress distribution of the CFRP strips for the FRCM-1 specimens is similar for the push and pull cycles. Looking at the CFRP stress difference between the push and pull cycles for the FRCM-2–3 specimens on the other hand, a significant difference in stress distribution was observed. Whereas the
push cycles continued to show a parabolic stress distribution of the height, the pull cycles had a more bilinear shape, with lower peak values near the height position of the full FCRM crack. Comparing the push cycle of FRCM-1 with FRCM-2–3, the CFRP strip stresses are significantly lower for the FRCM-1 specimen. This was attributed to the debonding failure mechanism of specimen FRCM-1, where due to the local detachment of the FRCM layer, the effective lever arm (and thus the CFRP stresses) between the compressed zone and the CFRP strips decreased.

4. Cross-Section analysis

The experimental out-of-plane experiment results described in the previous chapter have demonstrated the effectiveness of the proposed retrofit scheme within the current study: flexible deep mounted (FDM) CFRP strips on brick masonry, combined with a single-sided Fabric Reinforced Cementitious Matrix (FRCM) layer. This chapter will focus on the development of a non-linear model using a cross-section analysis.

4.1. Material model

The masonry, cement matrix, CFRP mesh and the CFRP strip are considered as separate interacting components with an own stress–strain relation. The stress–strain relations are summarized in Fig. 17. It should be stated that the tensile and compression side of the masonry and cementitious matrix as shown in Fig. 17 are disproportionate for illustrative purposes.

The idealized stress–strain curve for masonry under compression and tension is determined using Eq. (1), where:

\[ \frac{\sigma}{f_m} = \frac{\varepsilon}{\varepsilon_{mc}} \]

- \( E_m \) is the Young’s modulus of masonry;
- \( f_{mc} \) is the compressive strength of masonry; \( \varepsilon_{mc} \) the corresponding strain determined with Eq. (2);
- \( \varepsilon_{mc} \) is the strain corresponding to 0.9\( f_{mc} \) in the descending part. At this point the stress–strain curve shifts from parabolic to linear descending relation.
- 0.2\( f_{mc} \) is the maximum residual compressive stress and corresponding failure strain (\( \varepsilon_{m,cr} \)). The failure strain determined as \( \varepsilon_{m,cr} = 2.75\varepsilon_{m,cm} \) for mortar with lime content [14].
- \( f_{mt} \) is the tensile strength of the masonry. The role of this parameter is usually neglected for FRCM retrofitted masonry. The tensile strength of the masonry is included in the current study in terms of consistency with the cross-sectional analysis presented in Appendix A of Türkmen et al. [26]. For design purposes it is suggested to follow common practice and available literature, and neglect the role of the masonry tensile strength. Neglecting the low masonry tensile strength will not lead to significant different results for the out-of-plane load–displacement behavior of the retrofitted masonry wall.
- \( G_{I} \) is the mode I fracture energy of the masonry;
- \( w \) is the crack width. The relation between the crack width and the strain is determined with the sum of the height of a single bed joint and the height of a single brick, as presented in Eq. (3);
- \( \gamma_{t} \) is the factor representing tension softening.
\[
\sigma_m(e) = \begin{cases} 
  f_m, & \text{if } e > \frac{f_m}{E_m} \\
  E_m e, & \text{if } 0 > e \leq \frac{f_m}{E_m} \\
  f_m \left(0.9 - 0.7 \frac{e - \epsilon_{m,cp}}{\epsilon_{m,cm} - \epsilon_{m,scp}}\right), & \text{if } \epsilon_{m,cm} < e \leq \epsilon_{m,scp} \\
  0.2f_m, & \text{otherwise} 
\end{cases}
\]

\[
\epsilon_{m,cm} = \frac{2f_{m,c}}{E_m} 
\]

\[
w = e (b_{brick} + b_{bedjoint})
\]

The Young’s modulus and the compressive strength of the masonry were determined as 3,350 N/mm\(^2\) and 8 N/mm\(^2\) respectively with the companion tests. The flexural strength of masonry obtained was 0.375N/mm\(^2\). Generally a factor 1.5 is assumed between the average tensile bond strength and the flexural strength [28]. The tensile strength of the masonry was thus assumed at 0.25 N/mm\(^2\). For the fracture energy, values in the range 4.2–11.5 N/m were reported by Vermeltfoort & van der Pluijm [29] for masonry typologies that are similar to the

Fig. 17. Idealized stress–strain relations for masonry under compression and tension, CFRP under tension, cementitious matrix under compression and tension, and the embedded CFRP mesh under tension.

Fig. 18. (a) Comparison of the compression stress–strain relationship of the material model (dotted line) with the measurements obtained from the compression tests on masonry prisms (black lines). (b) Comparison of the normalized (towards their peak) compression stress–strain relationship of the material model (dotted line) with the normalized stress-strain curve domain reported by Jafari et al. [13] (grey area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
masonry used in this research. Comparing the compression stress–strain relation of the material model with the measurements obtained from the compression tests on masonry prisms, both shown in Fig. 18, it was observed that the proposed material model and parameters provide a good approximation of the experimentally determined compression behaviour until the peak strength. No comparison could be made for the post-peak region due to lack of experimental data. Due to lack of experimental data for the post-peak region within the current study, a compression tests on masonry prisms, both shown in Fig. 18, it was observed that the post-peak stress–strain relationship following from compression as reported by Jafari, Rots, Esposito and Messali [13], it was observed that the post-peak stress-strain relationship following from the proposed material model was within the boundaries of the obtained stress–strain curves for masonry by Jafari et al. [13].

The stress–strain relation of the embedded CFRP strips are provided in Eq. (4). The Young’s modulus and tensile strength of the CFRP strips were determined by Türkmen et al. (2020) as 198,000 N/mm² and 2,880 N/mm².

\[ \sigma_p(e) = E_c e \]  

(4)

The stress–strain relation of the cementitious matrix and the embedded CFRP mesh are provided in Eqs. (5) and (6) respectively, where \( E_{CM} \) and \( E_{mesh,cm} \) are the Young’s moduli of the cementitious matrix and the embedded CFRP mesh respectively.

\[
\sigma_{cm}(e) = \begin{cases} 
0 & e < \frac{f_{CM,c}}{E_{CM}} \\
E_{CM} \cdot \frac{f_{CM,c}}{E_{CM}} & \frac{f_{CM,c}}{E_{CM}} \leq e \leq \frac{f_{CM,m}}{E_{CM}} \\
\varphi E_{CM} & \frac{f_{CM,m}}{E_{CM}} < e \leq \frac{f_{FRCM,m}}{E_{CM}} \\
0 & e > \frac{f_{FRCM,m}}{E_{CM}} 
\end{cases}
\]  

(5)

\[
\sigma_{mesh}(e) = \begin{cases} 
0 & e < 0 \\
E_{mesh,cm} \cdot \frac{f_{mesh,cm}}{E_{mesh,cm}} & 0 \leq e \leq \frac{f_{FRCM,m}}{E_{mesh,cm}} \\
0 & e > \frac{f_{FRCM,m}}{E_{mesh,cm}} 
\end{cases}
\]  

(6)

Where the factor \( \varphi \), used to describe the post-peak behaviour of the cementitious matrix using tension softening, is determined using Eq. (7). The Young’s moduli of the cementitious matrix and the embedded CFRP mesh are obtained following Eqs. (8) and (9) respectively, where \( f_{mesh,cm} \) is the roving strength of the CFRP mesh and \( f_{CM} \) is the tensile strength of the cementitious matrix as determined by Türkmen et al. [22]. The factor \( \alpha \) defines the shape of the tension softening curve, where \( \alpha = 0 \) represents a linear declining tension softening curve. An overview of the material parameters for the non-linear model if provided in Table 3.

\[ \varphi = \left( \frac{f_{FRCM,m} - \varphi}{f_{FRCM,m} - f_{CM,c}} \right)^{1-\alpha} \]  

(7)

\[ E_{CM} = f_{CM} \]  

(8)

\[ E_{mesh,cm} = f_{mesh,cm} \]  

(9)

### 4.2. FDM CFRP retrofitted walls

The rectangular cross section of the FDM CFRP retrofitted specimens as tested by Türkmen et al. [26] is provided in Fig. 19. The lined area represents the compressed zone of the cross section. Two CFRP strips are present at position \( z = 0 \), which result in a combined tensile force of \( F_p \). The net force in the masonry is the sum of the masonry tensile force \( (F_{m,t}) \) and the masonry compression force \( (F_{m,c}) \). It is assumed that the strain profile is linear, and the CFRP strips are perfectly bonded without any slip. The strain distribution over height \( z \) is obtained using Eq. (10), where \( \epsilon_A \) and \( \epsilon_B \) are the maximum compressive and tensile strain respectively for the masonry.

\[ \epsilon(z) = \frac{z}{t_w} (\epsilon_A + \epsilon_B) + (\epsilon_B - \epsilon_A) \frac{z}{t_w} \]  

(10)

For the maximum strain on compressed side (A), a corresponding maximum tensile strain of the masonry (B) was determined where the condition as provided in Eq. (11) was met. This was the condition in which the tensile forces (CFRP strip, masonry) and compressive forces in the masonry were in balance. The moment curvature relation at mid-height is assumed to be representative for the full wall. The axial load \( (V) \) on a specimens and the weight \( (W) \) of a specimens were 4.8 kN and 4.7 kN respectively.

\[ F_m + F_p + V + \frac{W}{2} = 0 \]  

(11)

The net force in the masonry, and the tensile forces in the CFRP strips were derived from Eqs. (12) and (13) respectively. The moment and curvature were determined with Eqs. (14) and (15) respectively.

\[ F_m = \int_-\frac{t_m}{t_w} \sigma_m(\epsilon(z)) l_z dz \]  

(12)

\[ F_p = E_t \cdot \epsilon(z = 0) \cdot b_t \cdot t_{p,n} \]  

(13)

\[ M = \int_-\frac{t_m}{t_w} \sigma_m(\epsilon(z)) l_z dz \]  

(14)

\[ \kappa = \frac{\epsilon_B - \epsilon_A}{t_w} \]  

(15)

With the material parameters as provided in Table 3, the moment–curvature relation following from the model was obtained for \( V = 4.8 \) kN. This is shown with a black dotted line in Fig. 20 and

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*Fig. 19. Cross section analysis of the FDM CFRP retrofitted specimens tested by Türkmen et al. [26].*
Fig. 20. Internal moment-curvature relation following from the cross-section analysis with the moment-curvature relations for the constant lateral moment zone for FDM CFRP retrofitted specimens [26].

compared to the moment–curvature relations of the constant moment zone \((3/8h_w \leq x \leq 5/8h_w)\) for FDM CFRP retrofitted specimens (grey dots), obtained by Türkmên et al. [26]. After the first crack occurred in the model, there was a slight decline in the moment resistance, which was not consistent with the experimental findings. Furthermore, for curvatures higher than \(1.5 \times 10^{-4}\), the moment resistance following from the model was overestimated. This overestimation became stronger for higher curvatures. The moment – CFRP stress relation following from the model, as shown in Fig. 21, provided a good approximation of the experimental results.

Using the non-linear material models and the cross section analysis, the moment-displacement relation was determined and compared with the experiments. This was done in Fig. 22 for both the 4 line loads and 2 line loads configuration when testing FDM CFRP retrofitted walls [26]. With the initial set of parameters (set 1, as shown in Table 4), the first major difference with the non-linear model and the experiments was observed for the moment resistance at the end of the elastic branch of the envelope. This kink in the moment-displacement curve following the model, the kink being the first significant difference in stiffness of the envelope curve, was initiated at a moment resistance that was lower than found with the experiments. Increasing the fracture energy \(G_t\) to 11.5 N/m (parameter set 2), the moment-displacement following the model fitted better with the experimentally obtained moment-displacement correlations for low displacement values (\(\delta_{mid} \leq 5\text{mm}\)). This improved fit was also observed for the moment–curvature relation and moment CFRP stress relation as shown in Figs. 20 and 21 respectively. Looking at the moment versus mid span displacement plots, it was observed that the model provides an underestimation of the moment resistance for \(\delta_{mid} \leq 120\text{mm}\). For higher values for mid span displacement, the moment resistance following from the beam model proved an overestimation. Reducing the compressive strength and Young’s modulus of masonry to 6 N/mm² and 2500 N/mm² respectively (keeping \(\varepsilon_{m,cn}\) constant), which represents parameter set 3, did not result in an improved fit.

The model was also run with an axial load of 20 kN, and compared with the experimental results of the FDM CFRP retrofitted wall that was tested with the same axial load by Türkmên et al. [26]. For axial load \(V = 20\text{ kN}\), no significant difference was observed between the outcomes following the three different parameter sets (Fig. 23). The moment-displacement relation following parameters set 2 provided the best fit with the experimental results. It should be noted that the calculations for the model were force based, so no results were obtained after the maximum moment was reached.

For low axial loads it was concluded that the cross-section analysis provided a decent estimation of the moment resistance until \(\delta_{mid} \leq 120\text{mm}\). The over estimation of the moment after \(\delta_{mid} \approx 120\text{mm}\) was attributed to the “plane sections remain plane” assumption not being valid for higher mid-span displacement values. Another possible reason was that for the non-linear model the slip of the CFRP laminates with respect to the flexible adhesive was neglected. By means of direct pull-out experiments on masonry prisms with flexible adhesive bonded CFRP strips, Türkmên et al. (2020) reported free end slips around 2 mm for anchorage lengths of 1 m. For higher mid-span displacements, the slip of the CFRP laminates could become significant with respect to the elongation of the CFRP. The revised engineering model proposed by Türkmên et al. [26] provided a significantly better approximation of the experimental results.

4.3. FDM CFRP and single-sided FRCM overlay retrofitted walls

The rectangular cross section of the FDM CFRP and single-sided FRCM overlay retrofitted specimens is provided in Fig. 24. In addition to the cross section analysis presented in the previous paragraph, the FRCM layer is included. The FRCM layer is modelled using two components, the embedded CFRP mesh (dotted line) and the reinforced mortar (dense lined area). It is assumed that the strain profile is linear, and the CFRP strips, CFRP mesh and reinforced mortar are perfectly bonded without any slip until CFRP mesh reinforcement occurs.

The strain distribution over height \(z\) was obtained using Eq. (10). For the maximum strain on compressed side (\(\varepsilon_A\)), a corresponding maximum tensile strain of the masonry (\(\varepsilon_B\)) was determined where the condition as provided in Eq. (16) was met. This was the condition in which the tensile forces (CFRP strip, CFRP mesh, cementitious matrix, masonry) and compressive forces in the masonry were in balance. The moment curvature relation at mid-height was again assumed to be representative for the full wall.

\[
F_n + F_t + F_{cm} + F_{mesh} + V + \sum \frac{W}{2} = 0 \tag{16}
\]

The net force in the masonry, and the tensile forces in the CFRP strips were obtained from Eqs. (12) and (13) respectively. The tensile forces in the embedded CFRP mesh and the cementitious matrix were determined in accordance with Eqs. (17) and (18) respectively.
\[ F_{\text{CM}} = \int_{z}^{\frac{L}{2}} \sigma_{\text{CM}}(\epsilon(z)) l_{w} dz \]  
\[ F_{\text{mesh}} = \epsilon(z) E_{\text{mesh}} A_{\text{mesh}} \]  

(17)

(18)

The moment and curvature are determined with Eqs. (19) and (15) respectively.

\[ M = \int_{z}^{\frac{L}{2}} \sigma_{n}(\epsilon(z)) l_{n} dz + \int_{z}^{\frac{L}{2}} \sigma_{\text{CM}}(\epsilon(z)) l_{w} dz + \epsilon(z) E_{\text{mesh}} A_{\text{mesh}} \]  

(19)

With the material parameters as provided in Table 3, the moment-curvature relation following from the model was obtained using \( G_{\text{H}} = 11.5 \text{N/m} \). This is shown with a black dotted line in Fig. 25 and compared to the obtained internal moment-curvature relations of the constant moment zone (\( 3/8h_{w} \leq x \leq 5/8h_{w} \)) for specimens FRCM-2 and FRCM-3 (grey dots). Looking at the results for when the FRCM layer is under compression (black lines), there was a slight decline in the internal resistance after the first crack, which was not consistent with the experimental findings. This was also the case for the cross section analysis with no single-sided FRCM overlay. Looking at the results for when the FRCM layer is under tension (dotted black lines) the internal moment - curvature relations is slightly overestimated, whereas the internal moment – CFRP strip stress relation was underestimated. The lateral moment – CFRP stress relation, as shown in Fig. 26, provided a good approximation of the experimental results.

Using the same procedure as mentioned in Section 2.5, the non-linear material models and the cross section analysis, the lateral moment-displacement relation was determined and compared with the experiments. This is indicated in Fig. 27 with the dotted black line. Even though the level of maximum lateral moment resistance following from the model seemed in line with the experimental outcome, the corresponding mid-span displacement showed a significant deviation. The reason for this deviation was linked to the value maintained for the ultimate tensile strain of the FRCM. Türkmen et al. [22] reduced the initial ultimate tensile strain of the FRCM from \( \epsilon_{\text{FRCM, u}} = 1.91\% \) (obtained from tensile slab tests) to \( \epsilon_{\text{FRCM, u}} = 0.64\% \) to provide a better fit between the outcome of the cross-section analysis and the results from the four-point bend tests with FRCM retrofitted prisms. Increasing the value for the ultimate tensile strain of the FRCM with 30% from \( \epsilon_{\text{FRCM, u}} = 0.64\% \) to \( \epsilon_{\text{FRCM, u}} = 0.83\% \), resulted in an improved fit with the experimental values, as shown in both Figs. 25 and 26 in black solid lines. Looking at Fig. 26, given a value for internal moment, the model significantly overestimates the stress in the CFRP strips. The non-linear model assumed that the strain profile was linear, and the CFRP strips are

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**Table 4**

| Parameter set | \( E_{m} (\text{N/mm}^2) \) | \( f_{m} (\text{N/mm}^2) \) | \( G_{f I} (\text{N/m}) \) |
|---------------|-----------------|-----------------|-----------------|
| Parameter set 1 | 3350 | 8 | 4.2 |
| Parameter set 2 | 3350 | 8 | 11.5 |
| Parameter set 3 | 2500 | 6 | 11.5 |

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**Fig. 22.** Lateral moment-displacement relation following from the cross section analysis for specimens the FDM CFRP retrofitted specimens, tested with four line loads (left) and two line loads (right).

**Fig. 23.** Lateral moment-displacement relation following from the non-linear model for an axial load of 20 kN.
Fig. 24. Cross section analysis of FDM CFRP and single-sided FRCM overlay retrofitted specimens.

Fig. 25. Internal moment - curvature relation following from the cross-section analysis with the internal moment-curvature relations for the constant lateral moment zone for FRCM-2-3. Distinction between the FRCM overlay being under tension or compression.

Fig. 26. Internal moment - CFRP strip stress relation following from the cross-section analysis with the internal moment-CFRP strip stress relations for the constant lateral moment zone for FRCM-2-3. Distinction between the FRCM overlay being under tension or compression.

Fig. 27. Lateral moment-displacement relation following from the non-linear model compared with the experimental values for specimens FRCM2-3.

Fig. 28. Lateral moment-displacement relationship obtained using the nonlinear model, with neglected (dotted) and included (solid) FRCM in compression, compared with specimens FRCM2-3.
perfectly bonded without any slip. As mentioned for the cross-section analysis using only the FDM CFRP strips, the slip of FDM CFRP strips was not negligible. Even though the tensile stresses of the CFRP strips were overestimated, the limited effect of the CFRP strips on the internal moment capacity did not affect to overall prediction of the model.

The contribution of FRCM in compression was included. Meriggi, de Felice and De Santis [15] report that only in the case of composite reinforced mortar composites, which are 30–50 mm thick and whose spalling/buckling is prevented by the FRP connectors, the presence of the reinforcement on the compression side is accounted for by increasing the thickness of the wall cross section. Neglecting the contribution of FRCM in compression resulted in a significant deviation between the model outcome and the experimental result, as shown in Fig. 28. It is worth noting that up to a mid-span displacement of 100 mm, the dotted line had a reasonable fit with the moment-displacement relationship obtained for the STRIP-4 specimens. Based on these findings, the inclusion of the contribution of FRCM in compression is justified. It should be noted that the contribution of the FRCM overlay in compression is considered with its own material properties in the proposed cross section analysis, and not by increasing the thickness of the masonry as suggested by Meriggi et al. [15].

4.4. Comparison with existing models

Two design guidelines have been recently developed, providing acceptance criteria and design provisions for externally bonded FRM systems for the strengthening of masonry structures: the Italian guideline CNE-DT 215 and the (at the time of writing not yet published) ACI RILEM joint committee guideline ACI 549 0L [2] – RILEM TC 250- CSM. These guidelines follow a yield design approach, in which the ultimate conditions for masonry in compression and FRCM in tension are represented in terms of maximum stresses. Meriggi et al. [15] report that there are still some crucial issues which need to be tackled, including the development of a simplified approach for the design of the FRCM reinforcement and the estimate of the deflection capacity. The same authors proposed an approach for the design and evaluation of the ultimate bending moment MR and of the corresponding displacement uR. This design approach, provided in Appendix B, was followed for a FRCM retrofitted wall with the same dimensions, axial load and CFRP mesh characteristics as the tested walls reported in this chapter. It should be noted that safety/design factors, characteristic values, the CFRP strips and second order effects were left out of the analysis. The outcome of the aforementioned approach was compared with the results obtained using the model proposed in the current study (Fig. 29). For the model, the parameters in Table 3 with \( \epsilon_{FRCM, 6} = 0.83\% \) and Table 4 (\( G_t = 11.5 N/m^2 \)) were used.

Both the estimation for the ultimate bending moment and the corresponding displacement were in agreement with the results of the proposed model. The approach proposed by Meriggi et al. [15] seems able to provide simple and well estimated values for both the ultimate bending moment and the corresponding displacement for the considered case.

5. Conclusions and future work

An experimental program was undertaken to assess the out-of-plane behaviour of one-way spanning full scale clay brick masonry walls retrofitted with flexible deep mounted (FDM) carbon fiber reinforced polymer (CFRP) strips and single-sided fabric reinforced cementitious matrix (FRCM) overlay. In the experimental testing program three full-scale masonry walls were tested with a four point-bending test setup. From the experimental campaign the following conclusions were drawn:

1) All specimens failed due to CFRP mesh rupture. For one specimen, where the CFRP mesh in the FRCM layer was installed incorrectly, FRM debonding was observed. This also resulted in 2 times more hair-line cracks over the height when compared to the other specimens.

2) For the displacement corresponding to the pre-failure cycle, the difference of the CFRP strip stresses remained significant between the pull (mean CFRP strip utilization 11.7%) and push cycles (mean 38.4%). This difference was caused due to the alternating compression zone between the FRCM layer and the masonry.

3) The mean lateral moment resistances of the FRCM specimens were found to be 3.96 kNm (FRCM under compression) and 7.67 kNm (FRCM under tension), significantly higher for the mean lateral moment resistances found for both URM (0.78 kNm) and FDM CFRP strips retrofitted specimens (1.82 kNm) tested by Türkmen et al. [26] under similar conditions. The addition of a single-sided FRCM overlay to form a combination of retrofit measures together with the FDM CFRP strips provides a significant surplus in terms of lateral moment resistance.

4) For the mean mid-span displacement corresponding to the maximum lateral resistance, an increase of 4380%, from 2.1 mm (URM) to 94.2 mm, was determined with respect to unreinforced specimens.

5) Strong linear relations were \( (R^2 \geq 0.95) \) were found for both the internal moment and the curvature, and the internal moment and the CFRP strip stress levels.

6) The contribution of the FRCM layer in compression was found to be significant for the lateral moment resistance, effectively resulting in an increased lever arm between the FDM CFRP strips and the resultant force of the compression zone when analysing the cross-section (over the height) of the wall.

The experimental out-of-plane experiments demonstrated the effectiveness of the proposed retrofit scheme within the current study. Another goal of this study was the development of a simple and practical applicable out-of-plane model for FDM CFRP and single-sided FRCM overlay retrofitted masonry walls. A cross section analysis using non-linear and linear material models for the used components was proposed. From the modelling efforts the following conclusions were drawn:

7) Initially looking at the validity of the cross-section analysis using non-linear material models, it was found for specimens solely retrofitted with FDM CFRP strips that the lateral moment capacity was overestimated after a mid-span displacement of \( \sim 120 \)
mm, when compared to the experimental results of Türkm en et al. [26]. The model assumed that the strain profile was linear, and the CFRP strips are perfectly bonded without any slip. From Türkm en et al. (2020a) it was found that the slip of FDM CFRP strips was not negligible, especially for higher CFRP stresses.

8) The revised engineering model using rigid blocks, as proposed by Türkm en et al. [26], provided a significantly better approximation of the experimental results for solely FDM CFRP strips retrofitted specimens, when compared to the proposed model in the current study.

9) The cross section analysis using non-linear and linear material models provided a good approximation of both the internal moment – curvature and the lateral moment – mid span displacement relation as obtained with the experiments. This was applicable for both directions: FRCM in tension and FRCM under compression. In contrast to existing literature, the inclusion of the contribution of FRCM in compression was justified.

10) Even though the tensile stresses of the CFRP strips were overestimated with respect to the internal moment, due to the slip of the embedded CFRP strips being non-negligible, the limited effect of the CFRP strips on the internal moment capacity did not affect to overall prediction of the model.

11) Both the ultimate bending moment and the corresponding displacement following from the proposed model showed good agreement with values obtained using similar models in literature.

As for the future work, Nonlinear Time History (NLTH) analyses will be performed on single degree of freedom (SDOF) systems, using the non-linear model and other findings from the current experimental campaign. This step is important for the analysis of the dynamic out-of-plane behaviour of FDM CFRP and single-sided FRCM overlay retrofitted clay brick masonry walls. Using these additional analyses the applicability of the combined retrofit seismic more active countries can be assessed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors wish to gratefully acknowledge the support by Quake-Shield, a joint venture between Royal Oosterhof Holman and SealteQ Group, in providing the funding and the materials. Additional appreciation for the technicians of the Structures Laboratory of Eindhoven University of Technology for their help in offering the authors with the resources in running the experimental program.

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