INVESTIGATION OF THE LATERAL CAPACITY OF FERRO-CEMENT RETROFITTED INFILLED MASONRY IN RC FRAME AND SIMPLIFIED PREDICTION APPROACH

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1. Introduction

Strengthening of existing RC buildings refers to inclusion of new structural element(s) and/or capacity upgradation of existing structural elements. The former includes insertion of steel bracing; concrete shear walls in existing RC frame, while the latter refers to jacketing of RC beam/columns. These methods are effective, however, labor intensive and expensive for developing countries. In developing countries, several seismically vulnerable buildings, i.e. not properly designed for seismic load, are required to be strengthened to withstand future seismic incidents. The usual structural system is RC frame which contain brick masonry as partition. Utilization of the existing masonry panel as structural elements would be an economically viable solution to strengthen the existing RC buildings. Some attempts have been taken to utilize masonry infill with connection with RC frame to strengthen RC buildings1). Strengthening of infilled masonry with the aid of Ferro-cement (FC), External Cementitious composite (cement mixture with low volume of fibers) or Textile Reinforced mortar are possible candidates. Among them Ferro-cement lamination on masonry is comparatively easy to apply at field and low cost. In general, Ferro-cement retrofitting of masonry refers to the application of an initial mortar layer on masonry wall which is followed by the placement of steel wire mesh and a second mortar layer. However, application of one-layer mortar after mounting wire mesh on masonry wall is also common, as illustrated in Fig. 1 (a). It is to be noted that Ferro-cement in this study can also be called as jacketing technique. Some anchorages, i.e. nailing of

Ferro-cement is a composite material, which could be easily utilized as a strengthening material for infilled masonry panel from the perspective of workmanship and economy. In this study, the effect of several parameters on shear capacity of Ferro-cement has been compiled from previous experimental test data. A simplified proposal to estimate expected lateral capacity of Ferro-cement lamination is presented.

Fig. 1: a) Details of Ferro-cement (Seki et al. 2018) and b) Dowel bar connection with RC frame and nailing with masonry

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several parameters on the shear capacity of FC lamination attached on infilled masonry panel based on thorough review of experimental studies in literature. Second, to propose a simplified approach to predict the lateral capacity of the Ferro-cement lamination mounted on infilled masonry wall.

2. Acquisition of Previous Experimental Data

A few studies have been conducted on Ferro-cement retrofitting of infilled masonry wall. In this study, experimental results of some half scaled masonry infilled RC frames, with and without Ferro-cement retrofitting, have been acquired from literature. All the studied FC retrofitted masonry walls contains square wire mesh on solid or hollow bricks. The details of all specimens are shown in Table 1. The lateral contribution of Ferro-cement layer has been determined from experimental data as the differences in lateral capacity of FC laminated infilled masonry surrounded by RC frame ($P_2$) and masonry infilled RC frame ($P_1$) as illustrated in Fig. 2. The shear stress on FC lamination, $\tau_{fc}$, has been determined using Eq. 1.

\[
\text{Shear stress on Ferro-cement, } \tau_{fc} = \frac{P_2-P_1}{n_sL_t}
\]

where, $L$, $t$, and $n_s$ refer to the length, thickness, and number of Ferro-cement retrofitted surfaces.

Fig. 2: Lateral load determination on FC layer

3. Effect of Different Parameters

Ferro-cement retrofitted infilled masonry works as a composite section. Therefore, characteristics of constituent materials as well as anchorage system, which is used to connect Ferro-cement lamination to masonry wall/RC frame, might have influences on the shear capacity. However, the connection of wire mesh to masonry wall has not been investigated in this study because of the lacking of detail properties of connection in the acquired past data. In this section, the effects of several parameters on shear capacity of FC lamination are discussed using previously acquired test results.

3.1 Horizontal Mesh Reinforcement

Wire mesh in Ferro-cement contains horizontal and vertical mesh reinforcement, as shown in Fig. 3. The lateral force will be mostly carried by the horizontal mesh reinforcement assuming similar behavior of shear wall. In shear wall, lateral/transverse reinforcement takes much shear forces than the vertical reinforcement. The computed in-plane shear stress developed on Ferro-cement laminate is presented in Fig. 4 as a function of total horizontal steel area ($A_{hs}$) normalized by horizontal masonry infill area ($A_{mas}$). Shear stress varies (0.1~3 MPa) with in the range of mesh reinforcement ratio shown in Fig. 4. Even for same mesh content, there is a variation of shear stress that might be attributed to different kinds of connection used in the studied literature. For example, in the study by Zarnic and Tomazevic (1985), two specimens without and with connection between FC layer and RC frame, namely M3 and M4, showed 0.11 and 0.78 MPa shear strength, respectively, even though having same mesh reinforcement ratio (0.2%). The effect of connection will be discussed in the following subsection. Due to this large variation of shear strength with mesh reinforcement, it is difficult to conclude a clear correlation within the scope of this study. However, if all the parameters, except mesh ratio, were same there might be a relation between mesh content and shear strength of FC layer.

Fig. 3: Free body diagram after diagonal cracking of FC layer

Fig. 4: Relationship of shear stress on FC with steel area

3.2 Connection with Frame and Masonry

The connection of Ferro-cement layer i.e. mesh reinforcement with the masonry wall and RC frame is important to avoid premature delamination of FC laminate. This parameter is overlooked in most of the studies reviewed in this study, except by Kaya et al. (2018) and Altin et al. (2010). Kaya et al. (2018), considered two specimens, designated as Sp-3 and Sp-4 with Ferro-cement having 230mm long dowel connection with RC frame with spacing of 300 and 150 mm, respectively. Another specimen, designated as Sp-5, was designed with mixed dowel spacing from 75~300 mm. The test results, as shown in Fig. 5(a), revealed that the Ferro-cement layer with less dowel anchor spacing, with RC
frame, can carry higher shear stress. It is to be noted that, all the above mentioned specimens contains same horizontal mesh reinforcement. Altin et al. (2010)\(^{26}\) experimentally found that the insertion of mesh reinforcement in surrounding RC frame, in specimen Sp-3, is more effective than that of the insertion of additional dowel bar (specimen Sp-2), as shown in Fig. 5(b). All these test results indicate that efficient utilization of shear capacity of Ferro-cement lamination can be secured by the usage of connection with RC frame, which actually improve the integrity of the retrofitted masonry.

3.3 Lamination Mortar Properties

In Ferro-cement retrofitting, a mortar layer of 10–40 mm thickness is being employed on one or both sides of infilled masonry. The compressive strength of mortar varies mostly within 1–15 MPa. Fig. 6 depicts the shear stress on Ferro-cement layer as a function of mortar compressive strength of Ferro-cement laminate (\(f_{\text{mort}}\)) normalized by masonry compressive strength (\(f_{\text{mas}}\)). Most of the points vary between 1–2 MPa, without showing any specific trend. Actually, Ferro-cement layer endures diagonal tensile stresses under lateral load same as on masonry infill. According to ACI 549\(^{25}\), tensile load carrying capacity of Ferro-cement does not depend on the lamination thickness because the mortar cracks before failure of composite section in tension which occurred in diagonal cracking. The independence of mortar thickness is also evident from Fig. 7, as there is no specific pattern with the change in thickness (t) of mortar layer normalized with the length (L) of Ferro-cement coating. In other words, the influence of the mortar properties is not conclusive from the tests studied from literature.

4. Proposal on Capacity Prediction of Ferro-cement

As discussed in earlier section, mesh reinforcement, mortar properties and connection with RC frame might have influence on the lateral force carried by Ferro-cement layer, however the influence of each parameter is not clear from literature. In this section, a simplified approach has been proposed to predict the lateral capacity of reinforced mortar considering amount of mesh reinforcement. The contribution of mortar has been ignored assuming mortar will be cracked diagonally before the yielding of reinforcement. In the capacity prediction, diagonal crack on the
masonry walls. However, for simplicity, Ferro-cement could be considered to have similar behaviour to reinforced masonry infill, therefore, studies for reinforced masonry are referred in this section. Assuming the same behavior for the Ferro-cement laminated masonry, an empirical reduction factor ($\omega$) has been imposed in Eq.2 to accommodate the less effectiveness of mesh reinforcement compared to contribution in RC shear wall. The less effectiveness might happen due to the less development length provided for reinforcements in masonry. Anderson and Priestley (1992)\textsuperscript{10}, observed that the strength of shear reinforcement in reinforced masonry wall is approximately half than that of in RC shear wall. Several building codes e.g. MSJC (2011)\textsuperscript{11}; CSA-S304 (2004)\textsuperscript{12} and NZS 4230 (2004)\textsuperscript{13} have also taken account less effectiveness of horizontal reinforcement for internally reinforced masonry. The range of the reduction factor varies in between 0.5~0.8. In this study, the empirical reduction factor has been assumed as 0.7 for Ferro-cement lamination.

5. Validation with Experimental Data
To validate the proposed capacity prediction approach, experimental capacity of several RC frames, infilled with FC retrofitted masonry, have been acquired from previous test data\textsuperscript{6}, as discussed in earlier section. At the same time, estimated lateral capacity of masonry infilled RC frame with FC has been estimated as a summation of experimental capacity of masonry infilled RC frame, and predicted capacity of FC laminate (Eq.2).

![Experimental vs. Estimated lateral capacity of masonry infilled RC frame with Ferro-cement](image)

Fig. 8: Experimental vs. Estimated lateral capacity of masonry infilled RC frame with Ferro-cement

Fig. 8 shows the experimental and estimated lateral capacities of several FC laminated masonry infilled RC frames. The proposed capacity prediction approach showed a fair prediction, where the average experimental to estimated capacity ratio is 0.96 and coefficient of variation is 0.2. In some cases, prediction overestimates the experimental capacity. This can be attributed to the lacking of connection between mesh reinforcement and masonry wall and/or surrounding RC frame which prevents the full development of Ferro-cement lamination strength.

6. Conclusion
In this study, the variation in shear stresses of Ferro-cement has been investigated with several parameters using experimental test data available in literature. The parameters investigated are: mesh reinforcement, mortar properties, and connections with RC frame. This is followed by a proposal of simplified approach to predict lateral capacity of externally reinforced mortar layer based on mesh reinforcement content. The simplified approach can predict the lateral capacity of Ferro-cement lamination with an average experimental to estimated capacity ratio of 0.96 with some dispersion with experimental result having coefficient of variation of 0.2.

However, the proposed simplified approach does not consider influence of mortar strength and connection because of the simplicity and lacking of connection details in literature. The influence of such parameters need further study to improve the proposed prediction approach and verify the reduction factor ($\omega$) In addition, failure of RC frame (e.g., shear failure) prior to failure of Ferro-cement might completely change expected seismic performance which needs further study.

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## Table 1: Details of RC Frame Specimens with Infilled Reinforced Mortar Retoolished Masonry

| RC Frame | Infill masonry | Perforation layer | Reinforcement | Section properties | Specimen name | Compressive strength of masonry | Lateral Capacity |
|-----------|----------------|-------------------|---------------|---------------------|---------------|-------------------------------|------------------|
|           |                |                   |               |                     |               |                               |                  |
|           |                |                   |               |                     |               |                               |                  |
|           |                |                   |               |                     |               |                               |                  |
|           |                |                   |               |                     |               |                               |                  |
|           |                |                   |               |                     |               |                               |                  |
|           |                |                   |               |                     |               |                               |                  |

### Column Longitudinal Concrete

| RC Frame | Compressive strength of masonry |
|-----------|---------------------------------|
| Specimen  | Membrane 150x150 250x250 |
|           | Membrane 150x100 200x200 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |
|           | Membrane 150x100 250x250 |
|           | Membrane 100x100 250x250 |
|           | Membrane 100x70 250x250 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |
|           | Membrane 150x100 250x250 |

### Longitudinal Reinforcement

| RC Frame | Longitudinal reinforcement |
|-----------|----------------------------|
| Specimen  | Membrane 150x150 250x250 |
|           | Membrane 150x100 200x200 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |
|           | Membrane 150x100 250x250 |
|           | Membrane 100x100 250x250 |
|           | Membrane 100x70 250x250 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |

### Connection with masonry and RC Frame

| RC Frame | Connection with masonry and RC Frame |
|-----------|-------------------------------------|
| Specimen  | Membrane 150x150 250x250 |
|           | Membrane 150x100 200x200 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |
|           | Membrane 150x100 250x250 |
|           | Membrane 100x100 250x250 |
|           | Membrane 100x70 250x250 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |

### Lateral Capacity

| RC Frame | Lateral Capacity |
|-----------|------------------|
| Specimen  | Membrane 150x150 250x250 |
|           | Membrane 150x100 200x200 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |
|           | Membrane 150x100 250x250 |
|           | Membrane 100x100 250x250 |
|           | Membrane 100x70 250x250 |
|           | Membrane 100x100 200x200 |
|           | Membrane 100x70 200x200 |

### Conclusion

- The coefficient of variation is 0.
- The average experimental to estimated capacity ratio is 0.9.
- Several experimental capacity of RC frames, infilled with masonry, is considered to have similar behaviour to reinforced masonry infill.
- Therefore, studies for reinforced masonry are referred in this section.

### Validation

To validate the proposed capacity prediction approach, the validation method of Calvi and Bolognini (2001) and Seki et al. (2018) is applied. The contribution in the development of new codes is also considered.

### Test Data

- Fig. 8: Experimental vs. Estimated lateral capacity of masonry

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