Failure modes and capacity evaluation of Ferro-cement laminated masonry infilled RC frame
Part 1: Identification of possible failure modes

Keywords
Masonry infill　Ferro-cement
Seismic strengthening　Infilled RC frame
Failure mode

〇Md. Shafiul Islam *1　Debasish Sen *2
Zasiah Tafheem *2　Hamood Alwashali*3
Matsutaro Seki *4　Masaki Maeda*5

1. Introduction

Strengthening of masonry infilled RC frame with ferro-cement (FC), as shown in Figure 1, is an economic and easy retrofitting way for developing countries. The current study is an ongoing research which mainly focusing on identification of possible failure mechanisms and capacity evaluation of FC laminated masonry infilled RC frame. Several researchers [1-5] conducted experimental investigation of FC laminated masonry infilled RC frames and found different failure modes. However, in most of the cases endeavor has not been taken to predict the lateral strength of the failure modes in previous experimental studies.

The objectives of this study are twofold. First objective is to identify possible failure modes of FC laminated masonry infilled RC frame based on past studies as well as current experimental investigation, and described in Part 1. The second objective is to propose and validate lateral strength evaluation methodology for all identified failure mechanisms and described in Part 2 of this study.

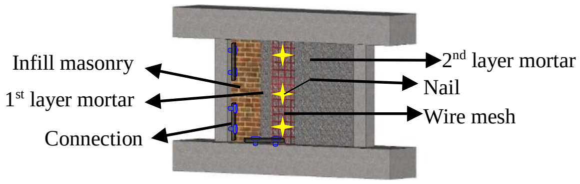


Figure 1: Schematic diagram of FC lamination on masonry infill

2. Failure modes investigation

Generally, FC laminated infill masonry has higher stiffness and strength, when compared to masonry infill only. Therefore, application of FC on masonry can change the overall failure mechanism of un-strengthened masonry infilled RC frame. Since the overall failure mode is not clear yet from past experiments [1-5], several experimental investigations [6-8] by the authors in wider scope research project SATREPS-TSUIB project, with one of the objectives is to clarify the seismic performance RC buildings with masonry infill and proposed feasible retrofit methods such as FC.

Table 1 Experimental investigation of FC laminated infilled frame

Reference		Specimen	Peak lateral resistance (kN)
SATREPS-TSUIB project	Hamood et al. [6]	IM-FC-1	538
		IM-FC-2	593
	Hamood et al.[7]	IM-FC-3	942
	Fatema et al. [8]	IM-FC-4	176
Past studies	Kaya et al. [1]	Sp-5	155
	Seki et al. [2]	S5-FM-FC	330
	Demirel et al. [3]	SMF	181
	Altin et al. [4]	Sp-4	191
	Zarnic and Tomazevic [5]	M4	389

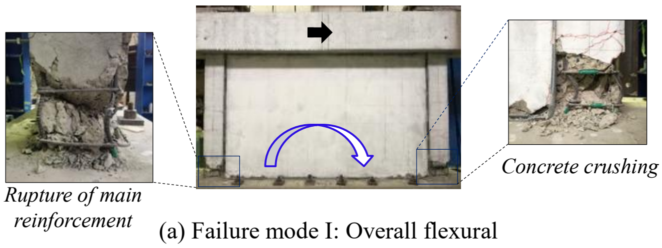
The observed failure modes of aforementioned studies in Table 1, are discussed as follows:

2.1 Failure mode based on SATREPS projects experimental investigation

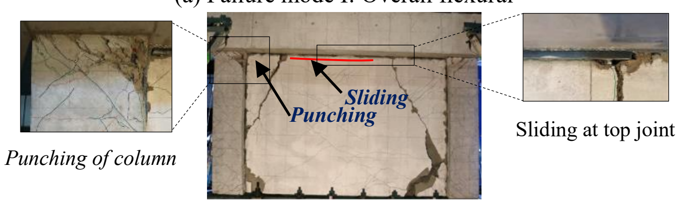
Four half scaled masonry infilled RC frames (IM-FC-1, IM-FC-2, IM-FC-3 and IM-FC-4). The detail material properties and experimental results of those specimens are discussed in authors another studies [6-8]. It was observed that specimen IM-FC-2 had overall flexure failure (rocking behavior) whereas IM-FC-3 and IM-FC-4 had punching shear failure of column, respectively. IM-FC-1 failed by mixed manner i.e. flexural rocking at lower story drift, and eventually failed by punching shear failure of column. The observed failures are discussed below with representative specimens.

Failure mode I: Overall flexural

Flexure failure mode is observed for the specimen IM-FC-2. At lower story drift, about 0.1%, longitudinal reinforcements in tension column experienced yielding following the formation of flexural crack at the bottom of tension column. Gradually the width of flexural crack increased up to 3mm. At peak resistance, at 0.4% story drift, concrete at the bottom of compression column started to crush and wire meshes at the bottom of the wall started to be ruptured. Finally, the main reinforcements of tension column ruptured, at 2% story drift, hence overall flexural failure (rocking) is confirmed. The lateral behavior and damages is shown in Figure 2(a).



(a) Failure mode I: Overall flexural



(b) Failure mode II: Column punching and sliding at top joint

Figure 2: Failure modes of specimens in SATREPS project.

フェローセメントにより補強した組積造壁を有する既存 RC 骨組の破壊モードと性能評価
その１　破壊モードの分類と性能評価

モハメド　シャフィウル　イスラム、デバシシュ　セン、ザシア　タフィーン、ハムッド　アルワシャリ、関松太郎、前田匡樹

Failure mode II: Column punching and sliding at top joint

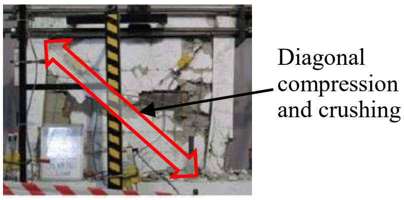
Column punching and top joint sliding failure were observed in specimen IM-FC-3. At lower drift, about 0.2%, parallel inclined cracks appeared on compression diagonal indicating the formation of diagonal strut. The strut cracked along compression diagonal at about 0.6% drift. Meanwhile, at 0.6% story drift, sliding also started at the top construction joint. The top joint sliding lead to the formation of shear cracks at the top of tension column on peak resistance at 0.8% drift. The main load transfer mechanism was sliding at top joint and punching shear failure column which is evident from close observation of shear cracks/damages at the top of column as shown in Figure 2 (b).

2.2 Failure mode based on past literature

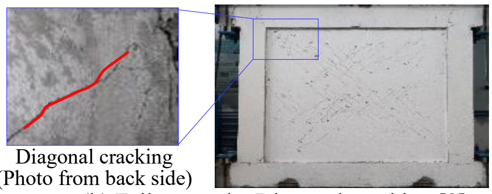
Two another types of failure modes are also observed in experimental observation by other researchers which are discussed below:

Failure mode III: Diagonal compression

Kaya et al. [1] investigated FC laminated masonry (hollow brick) infilled RC frame, designated as Sp-5, where crushing of compression diagonal was evident as shown in Figure 3(a). From the damage observation, it seems that the surrounding RC frame behaves in a similar way of masonry infilled RC frame i.e. hinge formation at the both ends of the columns.



(a) Failure mode: Diagonal compression [1]



(b) Failure mode: Diagonal cracking [2]

Figure 3: Failure modes of specimen from past literature

Failure mode IV: Diagonal cracking

Diagonal cracking of FC strengthened infill masonry is evident in experimental observation by Seki et al. [2] as shown in Figure 3(b). At maximum lateral resistance at 0.25% story drift was marked by the formation of diagonal crack on the FC strengthened masonry. At that stage, damage was concentrated at the bottom of columns and at the ends of the top beam.

3. Summary of possible failure mechanism

Based on the previous section, it evident that four distinct types of failure might happen for FC laminated masonry infilled RC frame. The expected damages of each constituent parts are described in Table 2. There are several parameters involved that might control the governing failure mechanisms. In brief, following observations are made from all of the experimental studies mentioned herein. If masonry is much stronger than surrounding frame, type I and II failure are more likely to occur where most of the damages concentrated in the RC frame. However, main reinforcement ratio of column and aspect ratio are also important to have flexural failure (I). In case of relatively weak infill masonry, failure mode III and IV can be expected, however, relatively weak masonry can also lead to punching failure of column as found in specimen IM-FC by Fatema et al. [8]. In this case there was no connection at the top construction joint where sliding is more likely to occur than diagonal compression or cracking of FC strengthened masonry. The overall failure tree of FC laminated masonry infilled RC frame is shown in Figure 4. The capacity evaluation of the above mentioned failure mechanisms are discussed in Part 2.

Table 2: Failure mechanisms RC laminated infilled wall

Failure modes	RC frame	Strengthened masonry	Top joint
I	• Tensile yielding of tension column	-	-
II	• Punching shear failure of tension column • Flexural or shear failure of compression column	-	Bond failure
III	• Flexural or shear failure of both columns	Crushing of diagonal strut	-
IV	• Flexural or shear failure of both columns	Major diagonal cracks	-

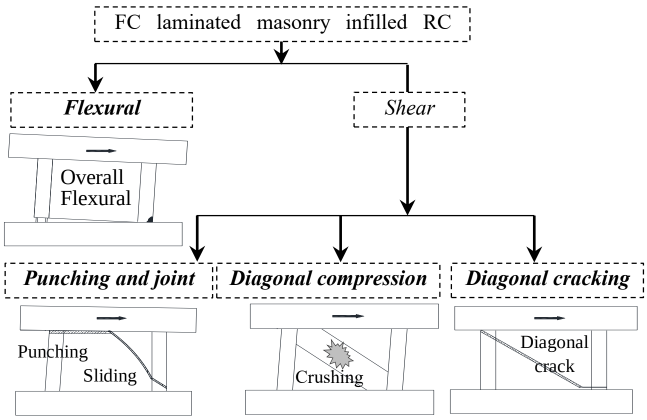


Figure 4: Possible failure modes

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1*東北大学大学院　学術研究員・博士（工学）
2*東北大学大学院　大学院生
3*東北大学大学院　助教・博士（工学）
4*建築研究所　特別客員研究員・工学博士
5*東北大学大学院　教授　・博士（工学）

1* Research Fellow, Grad. School of Eng., Tohoku University, Ph.D.
2* Graduate student, Grad. School of Eng., Tohoku University
3* Asst. Professor, Grad. School of Eng., Tohoku University, Ph.D.
4* Visiting Research Fellow, Building Research Institute, Dr.Eng
5* Professor, Grad. School of Eng., Tohoku University, Ph.D.