Innovative Retrofitting of Masonry Structures

Elena Vasquez, Liam Chen
Massachusetts Institute of Technology, Cambridge, USA

***Abstract*—**Various retrofit techniques for reinforced concrete frame with infill wall have been steadily developed. Among those techniques, strengthening methodology based on diagonal FRP strips (FRP bracings) has numerous advantages such as feasibility of implementing without interrupting the building under operation, reduction of cost and time, and easy application. Considering the safety of structure and retrofit cost, the most appropriate retrofit solution is needed. Thus, the objective of this study is to suggest pareto-optimal solution for existing building using FRP bracings. To find pareto-optimal solution analysis, NSGA-II is applied. Moreover, the seismic performance of retrofit building is evaluated. The example building is 5-storey, 3-bay RC frames with infill wall. Nonlinear static pushover analyses are performed with FEMA 356. The criterion of performance evaluation is inter-story drift ratio at the performance level IO, LS, CP. Optimal retrofit solutions is obtained for 32 individuals and 200 generations. Through the proposed optimal solutions, we confirm the improvement of seismic performance of the example building.

***Keywords*—**Retrofit, FRP bracings, reinforced concrete frame with infill wall, seismic performance evaluation, NSGA-II.

I. Introduction

EXISTING reinforced concrete (RC) buildings with infill wall designed based on pre-1970s codes are vulnerable to earthquake ground motion since seismic design code was not established in that time. To resolve this problem, various seismic retrofit methods for pre-1970s RC structures with infill wall have been studied. However, conventional retrofit methods such as adding shear wall are difficult to apply and increase the weight of the structure. As a compression strut, infill wall resists lateral force such as earthquake load. If an irregular seismic wave occurs

efficiency. Furthermore, it is possible to apply to the occupied

continuously, infill wall will be separated from RC frame in the corner region and involves the failure. Therefore, fiber-reinforced polymer (FRP) was proposed as a new retrofit method [1], [2]. It is a remarkable composite material having a high tensile strength

performance of retrofit building.

II. The Simplified Model of Strut and Tie

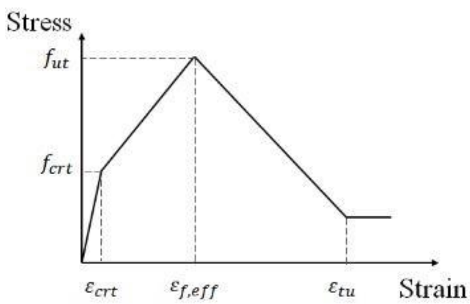
In [7], they defined diagonal compression strut and tension tie as infill wall and FRP retrofit. Fig. 1 shows the behavior of the strengthened strut model and the tie model for the relationship between stress and strain.

and buildings without any interruption. If FRP is used for retrofit method, many pre-1970s RC structures can be reinforced in a short time. Then building collapse can be prevented by increase of strength and deformation capacity of the elements. Erduran of Middle East Technical University (METU) obtained the results of improved performance by using the diagonal CFRP and anchors [3]. Binici et al. proposed a simplified analytical model for retrofit method of diagonal CFRP based on experimental results of METU [4]. Two diagonal braces will be named as FRP bracings in this study and El-Sokkary et al. also used this expression [5].

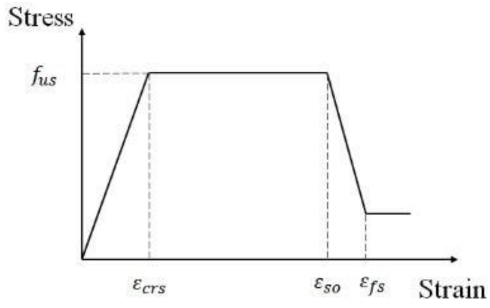
To maximize the advantages of FRP materials, the appropriate location and amounts of retrofit are needed. If the location and amounts of retrofit are 'solution', we can consider various solutions that can satisfy each performance level of the structure. However, in the case of large building, the number of solutions will increase dramatically. In seismic retrofit, the minimization of amounts of retrofit materials and the maximization of seismic performance are important factors. Since increase of retrofit materials without any limit is not proper, finding the most appropriate way which satisfies various purposes is needed. We use the non-dominated sorting genetic algorithm-II (NSGA-II). NSGA-II produces pareto-optimal solution through repetition of individual selection/crossover/mutation and crowding distance calculation. Pareto-optimal solution provides various retrofit cases as much as the number of individual. If a target can be expressed as genetic information and evaluation function is set, application of NSGA-II is possible [6].

This paper is composed of four parts.

1) Introduce the simplified analytical model [7] to show the behavior of the compression strut and FRP bracings.
2) Set objective functions and constraint conditions.
3) Generate an existing building based on OpenSees simulation platform proposed by [8] and apply NSGA-II.
4) Propose pareto-optimal solution and analysis the seismic



(a)



(b)

Fig. 1 Stress-Strain curve of model: (a) Tie model for FRP bracings; (b) Strut model for strengthened infill walls

FRP bracings are bonded on infill wall. To prevent the premature debonding, anchors are used. In Fig. 1 (a), the behavior of tie model for FRP bracings is shown. The cracking strength and the tensile strength of the tie are (1) and (2), respectively:

$$f_{crt} = \frac{V_{crt}}{w_f (t_f + t_p + t_{in})} \quad (1)$$

$$f_{ut} = \varepsilon_{f,eff} \cdot t_f \cdot E_f / t_{tie} \quad (2)$$

w_f and t_f are the width and thickness of FRP bracings. t_p and t_{in} are defined as the thickness of brick and plaster. V_{crt} can be calculated from the tensile strength of plaster and thickness of FRP bracings. As shown Fig. 1 (a), ε_{crt} is the cracking strain of plaster. It can be obtained through many uniaxial tension tests. $\varepsilon_{f,eff}$ means the effective strain where the anchor failure or desorption of FRP is occurred. According to [9], it is 0.002. ε_{tu} indicates the strain of the complete failure of FRP.

Fig. 1 (b) shows the relationship between stress and strain of the strengthened compression strut.

$$f_{us} = \frac{\min(f_{mv}L, 250 f_{mc})}{w_s} \quad (3)$$

f_{us} is the ultimate strength of strut. It can be determined based on the failure mode of infill wall. f_{mv} indicates the shear strength of the mortar or plaster. According to [10], it can be obtained by the compressive stress and parameters for initial shear strength of masonry under zero compressive stress. L is the width of the infill wall and f_{mc} is the uniaxial compressive strength of plaster. The ultimate strength is calculated by failure mode of infill wall. w_s is the effective width of the strut and is proposed by [11]. ε_{so} is the deformation capacity of infill wall.

While deformation capacity is determined at ultimate strength for the unreinforced infill wall, the reinforced infill wall is defined as twice effective strain based on many experimental test. Failure strain of the compression strut, ε_{fs}, is 0.01 before the reinforcement and three times the effective strain for after the reinforcement [7], [11].

III. Objective Functions and Constraint Conditions

Optimal solutions for the multi-objective functions can be calculated by taking the constraint conditions. Two objective functions are considered in this study. The first objective function is minimization of the total amounts of FRP bracings. To reduce the number of variables, the thickness of FRP is only used as variable in this function. The second objective function is the minimization of coefficient of variation (COV) for inter-story drift ratio. This function is to prevent the story collapse and a need of this is proposed from various study [12].

Three constraint conditions are applied to calculate the optimal solutions. First condition is the ratio of the maximum inter story drift to allowable inter story drift. If this ratio is high, it means dangerous state and the penalty is granted. This study refer to FEMA 356 [13]. IO level, LS level and CP level are considered. Second is prevention of building collapse. To reduce the damage on human life, precondition that performance point cannot exceed the collapse point is granted. Third condition is the constraint for the rotational deformation capacity of column and beam. Lateral force and axial force lead to the rotational deformation at structural frame. Since plastic hinge or failure of elements can be occurred, damage of structural elements should be minimized. Thus, to induce the elastic behavior of structural elements, third condition is necessary.

IV. Modeling

Fig. 2 is an example building which is composed of 5-storey, 3-bay RC frames with infill wall [5], [14]. This building is constructed before 1970s. Since it is based on earlier codes, non-ductile behavior can be occurred. Therefore, brittle failure or story collapse of structure can occur and retrofit of example building is performed.

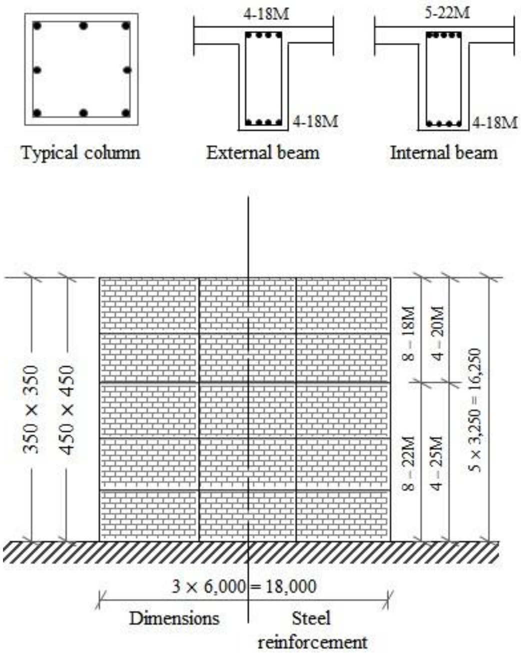


Fig. 2 Example building

TABLE I
PROPERTIES OF MATERIALS

Material	Compressive strength (MPa)	Yield strength (MPa)	Tensile strength (MPa)	Elastic modulus (MPa)
Concrete		-	-	20,000
Steel	-		-	200,000
Infill unit	10.5	-	-	7,000
FRP	-	-	3,430	230,000

Modeling is based on OpenSees simulation platform proposed by [8]. Fig. 2 and Table I provide the dimensions and properties of materials. Unclear material properties in reference is assumed using [4], [9]. Thickness of wall is fixed as 400 mm [9] and a type of FRP is carbon fiber-reinforced polymer (CFRP). To exhibit the inelastic behavior of elements, lumped plasticity model, composed of nonlinear flexure rotation spring to both ends of elastic element, is used. Only compression strut is applied to unreinforced infill wall. Strut-tie model is applied to retrofit infill wall. Nonlinear static pushover analysis with Newton-Raphson algorithm is performed by using the generated modeling. The performance evaluation of modeling is implemented assuming that example structure is in Los Angeles, United States, and applied displacement coefficient method (DCM). Immediate Occupancy (IO), Life safety (LS), Collapse Prevention (CP) performance level are considered.

V. SIMULATION AND RESULT

Fig. 2 provides the result of the nonlinear static pushover analysis for unreinforced modeling. In IO and CP level, this model exceeds the criteria of allowable inter-story drift ratio. Especially, first and second story show the high inter-story drift ratio in Table II. Moreover, the coefficient of variation for inter-story drift ratio is higher than 1.0 in CP level. As shown in Fig. 3, damage of elements is shown as various shapes. The shape of a star and circle represent the crack and plastic hinge of element. The shape of a wave is the failure of strut. By Fig. 3, we can particularly find the damages of elements from first to second story. These results indicate that when earthquake ground motion is occurred and that the structure can be in danger and story collapse may be occurred. Thus, retrofit for this modeling is needed.

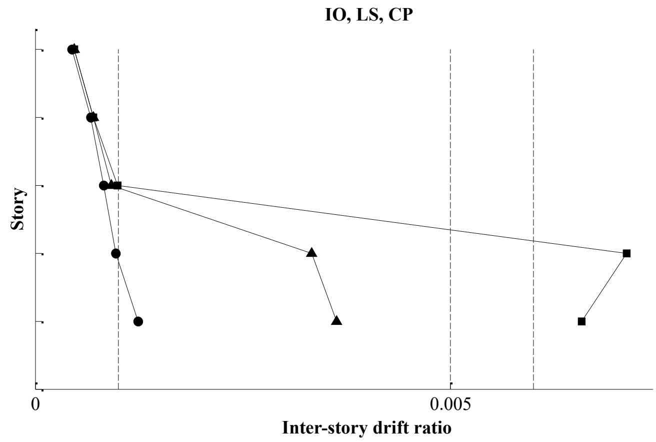


Fig. 2 Example building

TABLE II
RESULT OF PERFORMANCE EVALUATION

Story				4	5	Acceptance criteria	COV
IO (%)	0.12	0.10	0.08	0.06	0.04	0.1	0.3633
LS (%)	0.36	0.33	0.09	0.07	0.04	0.50	0.8496
CP (%)	0.65	0.71	0.09	0.07	0.04	0.60	1.0612

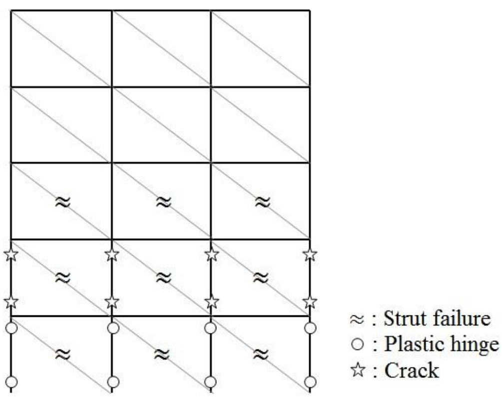
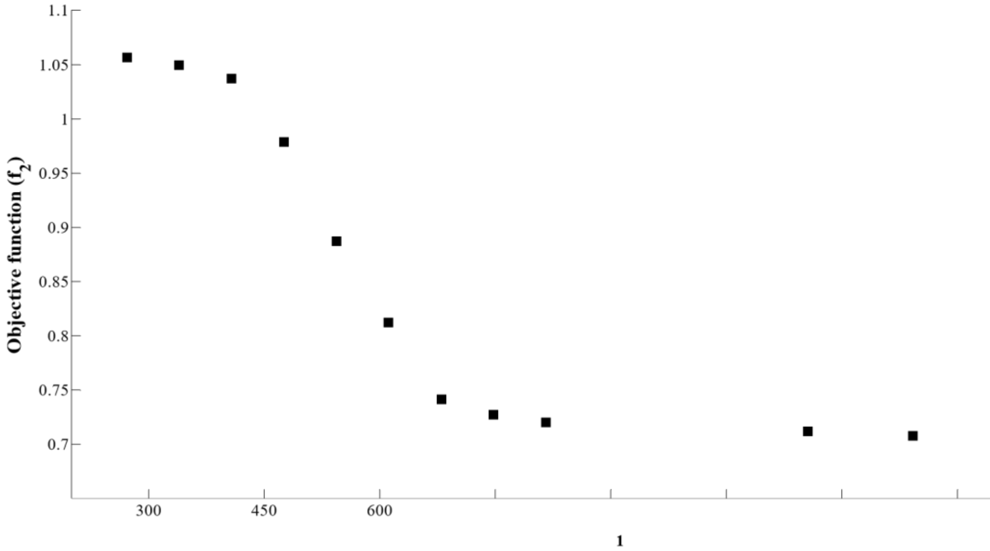
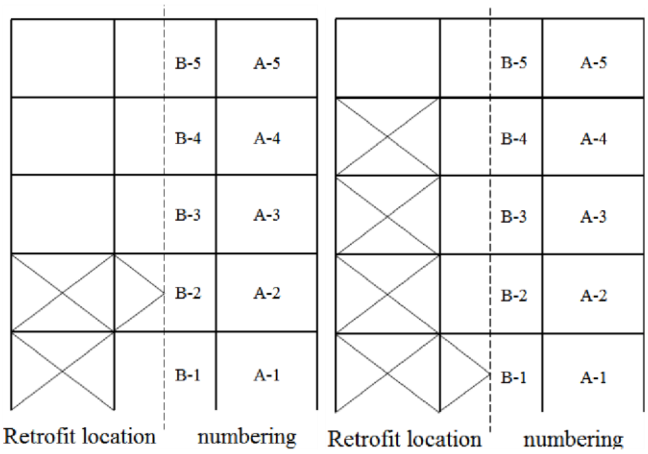


Fig. 3 Damage assessment of elements

To simulate NSGA-II, users should set the parameters such as population size, generation, design variables. In this study, population size and max generation are 32 and 200, respectively. The number of design variables is 10. The range of FRP sheets is from 0 to 10 and the thickness of one sheet of FRP is 0.17mm [15]. The amount of FRP for each location is determined randomly.

Fig. 4 plots the pareto-optimal solution for two objective functions. While the minimum retrofit amounts are 272 mm^2 and COV is 1.06, the maximum amounts are 1292 mm^2 and COV is 0.71. From these results, the inverse relationship between quantity and coefficient of variation is obtained.





(a) (b)

Fig. 5 Retrofit locations of the retrofit schemes (a) The minimum quantity (b) The maximum quantity

TABLE III
THE NUMBER OF FRP SHEETS FOR EACH LOCATION

Numbering		A-1	A-2	A-3	A-4	A-5
The number of FRP sheets	Min retrofit	1	1	0	0	0
	Max retrofit	5	5	1	6	0
Numbering		B-1	B-2	B-3	B-4	B-5
The number of FRP sheets	Min retrofit	0	1	0	0	0
	Max retrofit	2	0	0	0	0

nine locations in both Figs. 5 (a) and (b) require the retrofit. The Table III provides details of the retrofit quantity for each location. The figure in the Table III means the number of FRP sheets. According to the Table III, 5 sheets and 36 sheets are needed for the minimum and maximum retrofit.

Figs. 6 (a) and (b) show the inter-story drift ratio of retrofit models when the minimum and maximum retrofit is applied, respectively. Based on FEMA 356, the results are satisfied with the allowable inter-story drift ratio for two cases. Thus, we can confirm the effectiveness of FRP bracings analytically as

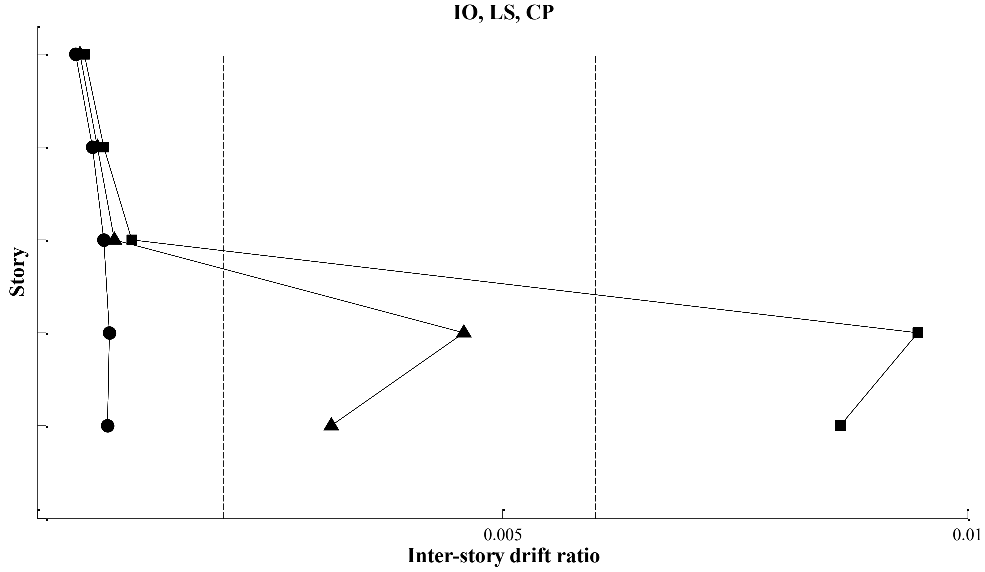
In this study, optimal retrofit design of reinforced concrete frame with infill wall using FRP materials was suggested and applied to a 5-story RC frame with infill wall. FRP bracings was used as retrofit method. Based on OpenSees simulation platform, modeling of the structure was implemented. To find the optimal solution for retrofit, NSGA-II was used. Objective functions were selected for the minimization of the total amounts of FRP bracings and coefficient of variation for inter-story drift ratio. NSGA-II provided the pareto-optimal solution and we found that the inverse relationship between the total amounts of FRPs and the coefficient of variation was obtained. All results were satisfied with the allowable inter-story drift ratio. Therefore, we could confirm the effectiveness of FRP bracings method.

750 900 1050 1200 1350
Objective function (f)

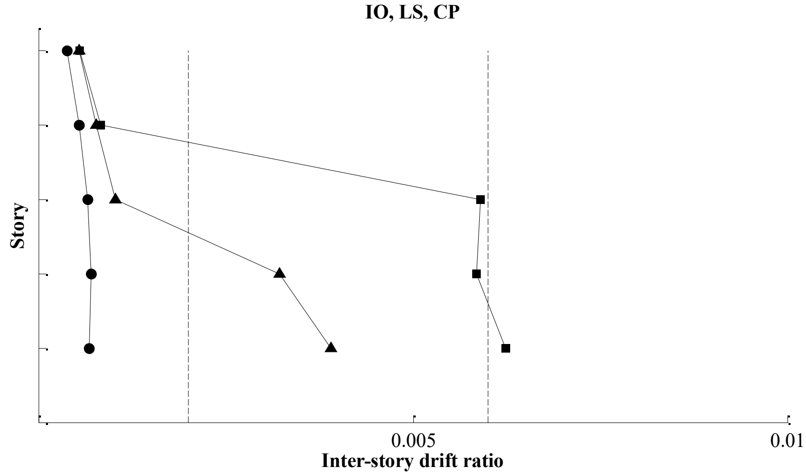
Fig. 4 Pareto-optimal solution

VI. CONCLUSION

Figs. 5 (a) and (b) provide the retrofit locations of the minimum and maximum retrofit scheme. X-shape in Fig. 5 represents that FRP bracings are needed. Five locations and



(a)



(b)

Fig. 6 Inter-story drift ratio of retrofit models (a) The minimum retrofit quantity (b) The maximum retrofit quantity

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