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Multi-Objective Optimization for Performance-based Seismic Retrofit using Connection Upgrade

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Abstract**—**The unanticipated brittle fracture of connection of the steel moment resisting frame (SMRF) occurred in 1994 the Northridge earthquake. Since then, the researches for the vulnerability of connection of the existing SMRF and for rehabilitation of those buildings were conducted. This paper suggests performance-based optimal seismic retrofit technique using connection upgrade. For optimal design, a multi-objective genetic algorithm(NSGA-II) is used. One of the two objective functions is to minimize initial cost and another objective function is to minimize lifetime seismic damages cost. The optimal algorithm proposed in this paper is performed satisfying specified performance objective based on FEMA 356. The nonlinear static analysis is performed for structural seismic performance evaluation. A numerical example of SAC benchmark SMRF is provided using the performance-based optimal seismic retrofit technique proposed in this paper

Keywords**—**connection upgrade, performace-based seismic design, seismic retrofit, multi-objective optimization

I. Introduction

In a steel moment resisting frame (SMRF), a structural system in which beams and columns are connected with rigid joint, the flexural stiffness and flexural strength of the frame members resist lateral force. This structural system has been widely used in strong earthquake regions for its excellent ductility capacity. However, the unanticipated brittle fracture of the connections of steel moment resisting frames occurred during the Northridge earthquake in 1994, which caused vast economic damage. Most of the fractures involved a fracture of the CJP weld connections, a fracture of the beam and column flange, or a fracture of the column web and panel zone. Since then, experimental studies have been conducted by SEAOC, ATC and CUREE on SMRF, analytical modeling methods, and appropriate retrofit methods [1]-[4]. As a result, a performance-based seismic retrofit technique was suggested. The SMRF seismic retrofit techniques based on a connection upgrade, a damper and a BRB were developed and applied to existing buildings [5]-[8]. However, although the SMRF retrofitted by the developed seismic retrofit technique could satisfy the seismic performance desired by the building owner, it may not be considered as an economically reasonable and efficient seismic retrofit scheme because the retrofitting is not based on definite criteria, including standards of cost. For this reason, Oh (2011) [9] developed an algorithm that satisfies the performance objectives, determines the optimum positions and minimizes the number of installations by means of a genetic algorithm (GA), which is an optimization technique, as well as a performance-based seismic design. However, the economic feasibility assessment has been limited to the initial cost, which corresponds to the number of installations. If the number of connection upgrades is increased, although the initial cost may be greater, the total economic cost may be reduced because better seismic performance decreases performance deterioration over time, damage by the occurrence of an earthquake. Hence, a reasonable economic feasibility assessment should take into account not only the initial installation cost but also life cycle cost (LCC) after retrofit.

Therefore, this study suggests a performance-based optimal seismic retrofit technique that considers the LCC after retrofitting. The performance-based optimal seismic retrofit technique introduced in this study consists of, out of many seismic retrofit techniques, a performance-based seismic retrofit technique that satisfies the specified performance objectives based on FEMA356 [10] through a connection upgrade that replaces the brittle connection behavior of the conventional SMRF with ductile connection behavior as well as an optimization technique that satisfies specified performance objectives with given constraints and obtains the Pareto solutions through NSGA-II (the Nondominated Sorting Genetic Algorithm-II) [11],which is a multi-objective GA, while employing the initial cost and LCC as objective functions.

II. Modeling of Connections Before and After Retrofitting

To utilize the technique suggested in this study, a nonlinear analysis of the connections of the SMRF should be carried out. The analytical modeling of the connections is important. Thus, among connection analysis modeling techniques, we employed the Krawinkler model (2000) [1], [13], as shown in Fig. 1, which is considered as the model closest to the actual behavior. The Krawinkler model, which is a nonlinear model including panel zones, directly models panel zones with eight rigid bodies and consists of the spring of panel zones and the spring of beam connections.

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First, the spring that determines the stiffness and strength of panel zones are modeled in terms of trilinear behavior by the sum of the column webs and flange elements, as shown in Fig. 2. Equation (1)~(4) is the formula for the curve. The three other edges of the panel zone were considered as hinges.

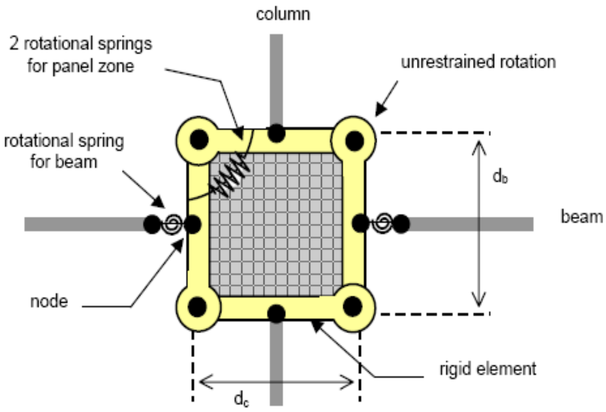

Fig.1 The Krawinkler Model (2000)

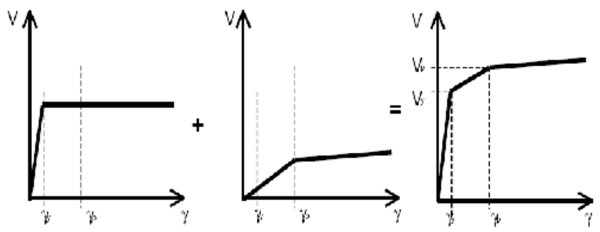

Fig. 2 Panel Zone Modeling

$$\gamma_y = \frac{F_y}{\sqrt{3}G} \tag{1}$$

$$\gamma_P = 4\gamma_y \tag{2}$$

$$V_y = 0.55 F_y d_c t \tag{3}$$

$$V_p = V_y\left(1 + \frac{3b_c t_{cf}^2}{d_b d_c t}\right) \tag{4}$$

Here, F_y denotes the panel zone yield strength, G is the shear modulus, γ_y is the yield distortion, γ_p denotes the full plastic distortion, d_c represents the width of the column flange, t is the thickness of the column flange, d_b is the width of the beam flange, and t_{cf} denotes the thickness of the beam flange.

The spring of the beam-column connections should be modeled in relation to the connection behavior before and after retrofitting, which is the most important factor in the techniques suggested in this study. For the hysteretic behavior of the connections before retrofitting, we applied the pre-Northridge SMRF connection hysteretic behavior in which early brittle fracture occurs. SAC joint venture performed experiments on the hysteretic behavior of the connections. Fig. 3 shows the hysteretic behavior of the brittle connections as measured in the experiments [12]. The positive moment region shows that the stiffness and strength sharply decrease at the small rotation angle as a consequence of the brittle connection fracture and the pinching effect. Fig. 4 shows the hysteretic model that was used to describe the hysteretic behavior of brittle connections in previous studies, which well explains the experimental behavior of the brittle connections [12].

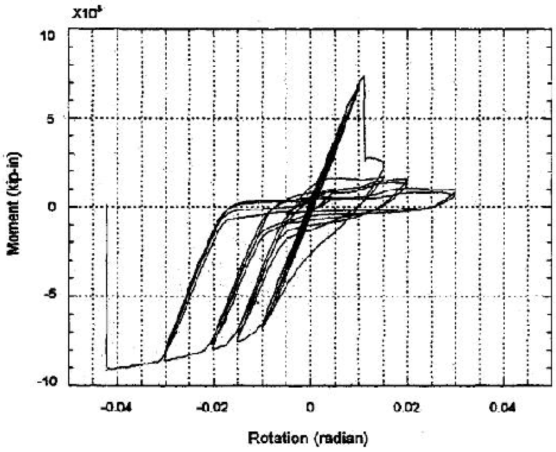

Fig. 3 Measured moment-rotation behavior of pre-Northridge buildings(Foutch et al. 2002)

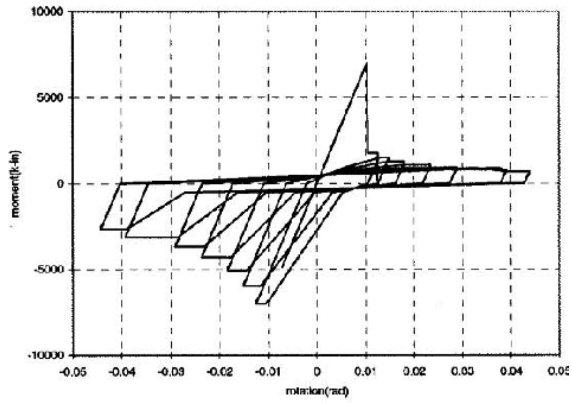

Fig. 4 Model of moment-rotation behavior of pre-Northridge connection(Foutch er al.2002)

Connection seismic retrofitting is performed by making the hysteretic behavior of the connections show early brittle fracture ductile. Since the Northridge earthquake, many studies have developed various retrofit connections that do not show early brittle fracture but have sufficient ductile ability for conventional SMRF connections at which a sudden brittle fracture may occur. Hambuger(2000) [14]suggested the specifications and design methods of various connections whose plastic rotation capacity and ductile capacity were improved when compared to those of pre-Northridge connections, in addition to the post-Northridge WUF-B.

FEMA351 [15] and AISC/NIST Design Guide 12 [16] suggested the pre-qualified connection upgrades and the patented connection upgrades known as WBH (Welded Bottom Haunch), WTBH (Welded Top and Bottom Haunch), WCPF (Welded Cover Plate Flange), BB (Bolted Bracket), SW (Slotted Web Connection) and SP (the Side Plate Connection) for SMRF. Experiments were performed on the hysteretic behavior of the retrofit connections. These results are shown in Fig. 5 [17]. No sudden brittle fracture pattern was found owing to the retrofitting, and the behavior was ductile. To describe the hysteretic behavior of the ductile connections, we used the connection hysteretic model shown in Fig. 6[18]. This model showed hysteretic behavior in which the connection had a plastic rotation capacity of 0.04rad without a decrease in the strength, reaching a plastic rotation of 0.05rad after connection fracture with an initial strength decrease of about 20%.

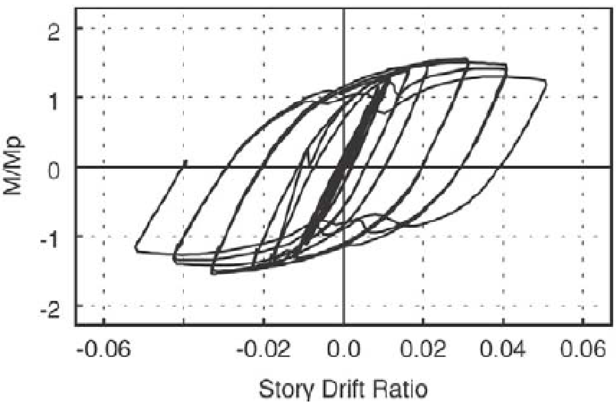

Fig. 5 The hysteretic curve of haunch-retrofit connections(Chi 2006)

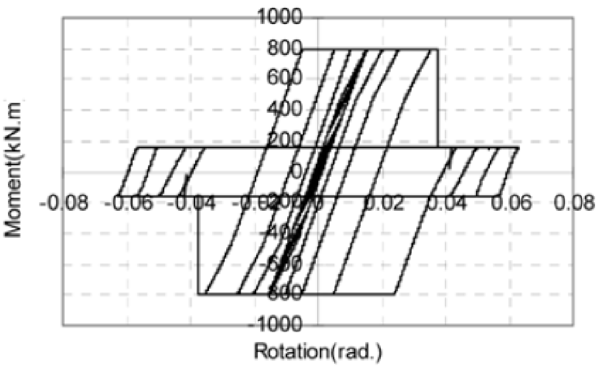

Fig. 6 Model of moment-rotation behavior of ductile connection (Lee 2010)

On the basis of these previous studies, we performed the modeling of the beam-column connections before and after retrofitting. The structural analysis software used for the optimal seismic retrofit technique is Opensees, a type of nonlinear earthquake analysis software. To describe the hysteretic behavior of beam-column connections in Opensees, a zero-length element should be placed at the position where the panel zone and the beam come into contact with each other, as shown in Figure 1, so that the behavior of the given connection may be represented through the element. The model material of the connection element is the hysteretic material provided by Opensees. The hysteresis of the brittle behavior before the connection upgrade as well as the ductile behavior after the retrofit are expressed using the material model. Thus, using the material model used in previous studies and Opensees, we described the hysteretic behavior of the pre-Northridge SMRF connections while showing early brittle fracture in the modeling of the connections before retrofitting. In the model, a sudden brittle fracture occurred at the rotation of 0.01rad, and 20% of the initial strength was maintained up to 0.04rad after the brittle fracture without a decrease in the stiffness and strength. The hysteretic behavior of a ductile connection was applied to the modeling of the connection after retrofitting. The ductile connections were set up to reach the rotation of 0.04 rad without a decrease in the strength and to ensure 25% of the initial strength following the fracture at 0.04 rad. The yield moment value, indicating the maximum strength in the connection behavior, was to be determined by the beam-column connections used in existing buildings.

III. Performance-based Optimal Seismic Retrofit Technique

This study focused on the retrofitting of the connections in the pre-Northridge SMRF. The purpose of this study is to suggest a seismic retrofit scheme that ensures sufficient seismic performance to accomplish the stated performance objectives through a connection upgrade while minimizing the initial cost and LCC. The seismic performance is assessed on the basis of the inter-story drift ratio. Building connections are partly retrofitted in order to satisfy the desired level of seismic performance. The position and number of connections to be retrofitted are determined by an optimization technique. We used NSGA-II, a multi-objective GA which utilizes a heuristic optimization technique.

A. Performance-based Seismic Retrofit

The performance-based seismic retrofit technique used in this study conformed to the procedures of FEMA356, as in the case of a performance-based seismic design. In a summary of the procedures, the performance objective is first determined. Then, a nonlinear static analysis is performed to a sufficient displacement to obtain the objective displacement. The objective displacement is calculated using the pushover curve for the control node and with (5), as shown below. A nonlinear static analysis is performed once again to objective displacement to obtain the maximum inter-story drift ratio, which is a seismic performance index, after which it is compared to the performance objective standards.

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \qquad (5)$$

Refer to FEMA356 for the performance objectives and the details about the equation above.

B. Formulation for The Optimal Seismic Retrofit Technique

In this study, we employ NSGA-II, which is a multi-objective GA, as the optimization algorithm for the performance-based seismic retrofit technique. The design variables are whether connections are retrofitted at the position of beam-column connections to be retrofitted.

In this study, the seismic performance objective desired by the building owner is set as the constraint functions in the performance-based seismic retrofit technique. As mentioned above, seismic performance is assessed on the basis of the inter-story drift ratio. The constraint is that the maximum inter-story drift ratio of the structure should not exceed the allowable inter-story drift ratio desired by the building owner.

The first objective function is the initial cost generated by the connection upgrade. In general, the seismic retrofit cost through a SMRF connection upgrade is calculated as the number of retrofitted connections multiplied by the retrofitting cost of one connection. Hence, the initial cost of the connection seismic retrofit in this study is considered as the number of retrofitted connections, and minimizing the number of retrofitted connections is equal to minimizing the initial cost.

The second objective function is the LCC occured after retrofit. In this study, we set the LCC to occur after retrofitting as the expected failure cost caused by earthquakes during the life cycle after retrofit, as in (6), according to the method suggested by Wen and Kang (2000)[19] .

$$E[C(t,X)] = \frac{\nu}{\lambda}(1-e^{-\lambda t})\sum_{j=1}^{K} C_j P_j \tag{6}$$

Here, K is the number of seismic damage states considered, C_j is the cost function of the j th seismic damage state, P_j denotes the probability of the j th damage state to occur, t is the service life of a new structure or remaining life of a retrofitted structure, λ represents the annual monetary discount rate and ν is an annual occurrence rate of major seismic events modeled by a Poisson process. As in (7) C_j, the cost incurred during the j th damage state, includes six types of cost: the damage cost, the loss of contents, the relocation cost, the economic loss, the cost of injury and the cost of human fatalities.

$$C_j = C_j^{dam} + C_j^{con} + C_j^{rel} + C_j^{eco} + C_j^{inj} + C_j^{fat} \tag{7}$$

Refer to Kang and Wen (2000)[19] regarding the method of calculating the expected failure cost and the details about the cost functions.

IV. Application

The developed performance-based optimal seismic retrofit technique is applied to a three-story SAC benchmark to suggest the optimal seismic retrofit scheme for existing structures and to assess the structural seismic performance when the suggested technique is applied to an existing building. The structure is a three-story four-span SMRF as shown in Fig. 7. For details of the structural design of this example, please refer to Shi (1997) [20].

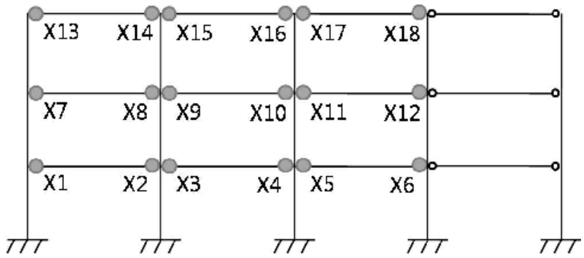

Fig. 7 Elevation diagram of 3-story example and the positions where retrofitting is possible

A. Review of whether or not to perform seismic retrofitting

Before applying the performance-based optimal seismic retrofit technique suggested in this study, we review whether or not the seismic performance of the three-story model in the example satisfies the seismic performance objectives. All of the connections at both ends of the first three spans, which are a part of the SMRF, follow the pre-Northridge connection model, in which early brittle fracture occurs. The method suggested in Section II is applied to this hysteretic modeling of connection. The seismic performance of the model is reviewed for performance objective P, which is collapse prevention (CP) under very rare earthquake risk. The seismic performance of the structure is assessed on the basis of the inter-story drift ratio, and the allowable inter-story drift ratio corresponding to CP is 5%. With respect to performance objective P, the maximum inter-story drift ratio is 5.27%, which exceeds the allowable inter-story drift ratio of 5% suggested by FEMA 356 as shown Fig. 8. Thus, a seismic retrofit was necessary.

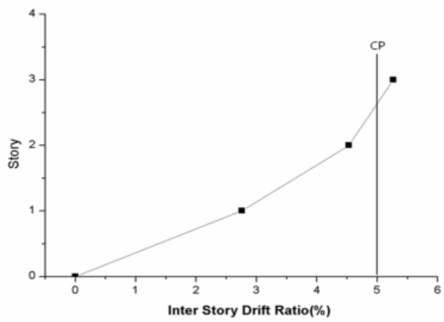

Fig. 8 Inter-story drift ratio before retrofitting

B. Implementation of the performance-based optimal seismic retrofit technique

In the performance-based optimal seismic retrofit technique suggested in this study, the seismic retrofit is carried out by means of a connection upgrade. The connections to be assessed as to whether or not they require retrofitting, which are the design variables, are the connections at both ends of the first three spans of the SMRF shown in Fig. 7. There are 18 design variables in total, and each connection is numbered (X1-X18). The connection hysteretic modeling method described in Section II is applied to the hysteresis before retrofitting (brittle connections) and after retrofitting (ductile connections), as shown in Fig. 9. This represents the database applicable to each connection as the design variables.

In the NSGA-II algorithm, after the formation of the initial population, the retrofit position and the number of retrofits are determined for each of the individual. The connections that are retrofitted and those that are not have different hysteretic behavior models. A fitness evaluation is performed with respect to the two objective functions of the individual, and the rank is determined. If the ranks are identical, the one with a higher crowding distance is sent to the next generation to evolve through crossover and mutation in pursuit of solution diversity. Refer to Liu (2003)[21] and Wen and Kang (2000)[19] regarding the types of damage states and the cost function of the second objective function.

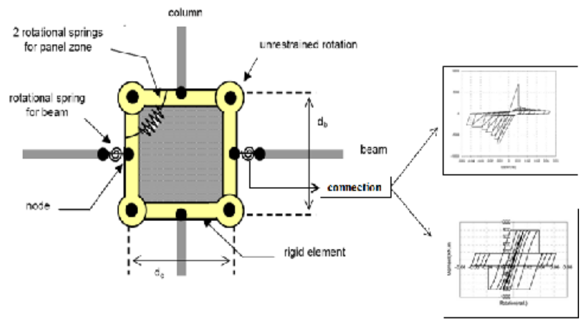

Fig. 9 Connection upgrade database

This study performs a multi-objective optimal seismic retrofit technique that satisfies the performance objective of CP (an allowable inter-story drift ratio of 5%) under very rare earthquake risk (2%/50yr) and that simultaneously minimizes the expected failure cost during the life cycle. The result shows that the Pareto solutions (non-dominated solutions) are obtained as shown in Fig. 10.

The six types of Pareto solutions shown in Figure 10 are the non-dominated solutions that can minimize the two objective functions, the number of retrofit connections (initial retrofit cost) and the expected failure cost after retrofitting, while satisfying the constraints. For example, a comparison of Non-Dominated Solutions 6 and 1 demonstrates that the initial number of installations was greater in Solution 6 than in Solution 1, which means that the initial cost is greater, whereas the expected failure cost after the retrofitting of the former is less than that of the latter, indicating that the two solutions are in a non-dominated relationship. It is up to the user to choose between the two. Hence, the algorithm proposed here is a more reasonable seismic retrofit technique in that it suggests various retrofit schemes despite the equal domination relation between the two objective functions.

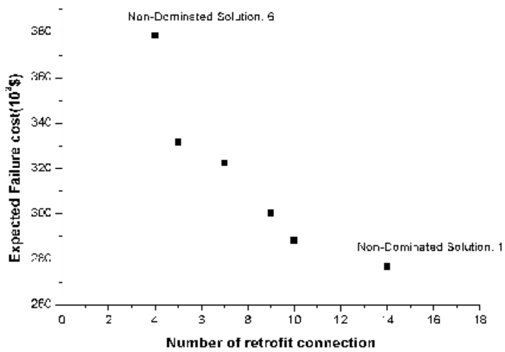

Fig. 10 Result of the algorithm implementation

V. Conclusion

In this study, we suggest an efficient and reasonable performance-based optimal retrofit technique that considers the initial number of installations (the initial installation cost) and the LCC after retrofitting using the multi-objective algorithm NSGA-II and apply it to a three-story SAC benchmark steel frame structure. The application of the algorithm enables the suggestion of various retrofit schemes having an equal domination relationship from which users can choose.

In this study, we take into account only a connection upgrade. The validity of the proposed algorithm needs to be verified with respect to various retrofit techniques, including the brace, BRB and damper techniques.

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