Optimization for Performance-based Seismic Retrofit of Existing Steel Moment Frames Using Connection Upgrade

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ABSTRACT: The seismic retrofit research for the connection vulnerability of the steel moment frames constructed before the 1994 Northridge earthquake has been conducted. The seismic retrofit schemes such as connection upgrade, damper, and buckling restrained braces have been developed for the brittle connection of the steel moment frames and applied to the existing buildings. Although the retrofitted steel moment frames satisfy the seismic performances, it cannot be said that these are economically reasonable and efficient seismic retrofit schemes because of the absence of obvious retrofit criteria. Therefore, this paper proposed the performance-based optimal seismic retrofit of the existing steel moment resisting frames using the genetic algorithm based on retrofit costs. Among the seismic retrofit schemes, the connection upgrade which changes the brittle behaviour of the existing connection to the ductile behaviour is selected in this paper. While satisfying the specific performance objective according to FEMA 356, the optimal seismic retrofit technique find the minimum numbers of the connection retrofit and their optimal locations using the optimization method is proposed. The nonlinear static analysis is performed based on the procedure represented in FEMA 356. The optimal seismic retrofit scheme of an example 3story-4bay steel moment frame is proposed using the proposed technique and studied the validity of that scheme.

1 INTRODUCTION

The steel moment resisting frame is the structural system which connects beam to column with rigid joints, the flexural stiffness and flexural strength of members of frame resist lateral forces. By virtue of their excellent ductility, the steel moment resisting frames have widely been used in intense seismic region. However, the abrupt brittle fracture of beam-column connection of the steel moment resisting frames was generated in 1994 Northridge earthquake, and it resulted in enormous damage. Since then, many researches with respect to connection brittle fracture of pre-Northridge steel moment resisting frame such as the experimental study and analytical modelling technique for connection of the steel moment resisting frames(Krawinkler 2000), the seismic performance evaluation for brittle connection of pre-Northridge steel moment resisting frame(Foutch 2002) and the modelling technique for various connection of the steel moment resisting frame(Lee 2010) have been conducted.

The research on the retrofit method for connection of pre-Northridge steel moment resisting frame(Roeder C 2000, AISC 1999) have also been carried out, and the realistic seismic retrofit method of connection(Hamburger 2000) have been represented. There were researches and/or cases(Liu 2009, Malley 2009) that proposed seismic retrofit scheme for the existing steel moment resisting frame and evaluated seismic performance based on developed seismic retrofit methods. These researches represented seismic retrofit schemes by connection upgrade, the addition of BRB(Buckling restrained brace) or viscous dampers, and the seismic performance of the existing building was improved through those schemes. However, the seismic retrofit schemes proposed in these researches have no any reasonable grounds and are possible that can be economically over-retrofit, though satisfying required seismic performance. Therefore, this paper proposes the optimal connection seismic retrofit scheme for the existing steel moment resisting frame based on the seismic retrofit cost. Using the optimization method such as Genetic Algorithm, the optimal seismic retrofit scheme that satisfies required seismic performance and find the minimum connection numbers for retrofit and their
locations is proposed.

2 SEISMIC RETROFIT

The cause of enormous damage that resulted from the Northridge earthquake was the abrupt brittle fracture of connection of the steel moment resisting frame. This doesn’t enable the buildings to show expected seismic performance. Figure 1 shows the connection fracture in the Northridge earthquake.

Figure 1 the connection fracture discovered in the Northridge earthquake (Roeder C. 2000)

Since then, SAC Joint Venture performed the test for moment connections occurring brittle fractures. Figure 2(a) shows the measured hysteretic behaviour of brittle connection. Through the hysteretic behaviour of brittle connection, connection fracture after yielding, strength degradation and pinching by unloading can be observed. The analytical model used in existing researches for depicting this hysteretic behaviour of brittle connection is such like Figure 2(b). The upper right quadrant represents response for positive moment and the abrupt fracture of bottom flange of beam connection. The considerable increase of strength and stiffness that follows plateau no change of strength and stiffness means the closure of crack of bottom flange. The lower left quadrant shows response for negative moment. That represents tension in top flange after completely closing of crack of bottom flange. The behaviour of this quadrant represents gradual loss of strength, reaching 0.04rad of rotation capacity and fracture in top flange.

Figure 2 Measured(a) and model(b) of moment-rotation behaviour of fracture connection(Foutch 2002)

The connection seismic retrofit is carried out by taking ductile behaviour instead of brittle fracture behaviour. FEMA351(Hamburger R.O. 2000)and AISC/NIST Design Guide 12(AISC 1999) represent pre-qualified connection upgrades WBH(Welded Bottom Haunch), WTBH(Welded Top and Bottom Haunch), WCPF(Welded Cover Plate Flange) and proprietary connection upgrades BB(Bolted Bracket), SW(Slotted Web Connection), SP(the SidePlate Connection) for the steel moment resisting frame. Figure 3(a) shows one of the connection upgrade detail which is haunch retrofit and Figure 3(b)
shows the hysteretic behaviour of this.

Figure 3 (a) Haunch detail and (b) Hysteretic curve for retrofit connection by haunch(Chi 2006)

The ductile connection in highly seismic hazard regions is defined as 0.03rad of plastic rotation capacity without significant strength degradation and 0.05rad of plastic rotation capacity without completely strength degradation(AISC 1997). After the bottom flange fracture occurs in 0.03rad of plastic rotation, the strength of connection decreases to 20% of original strength. The hysteretic model of connection such as Figure 4 is used to depict hysteretic behaviour of these ductile connections. This model has 0.04rad of plastic rotation capacity without the strength degradation and reaches 0.05rad of plastic rotation with the strength degradation of about 20% of original strength.

Figure 4 model of moment-rotation behaviour of ductile connection(Lee 2010)

3 THE OPTIMAL SEISMIC RETROFIT

This paper focuses on connection upgrade for the pre-Northridge steel moment resisting frame. The purpose of this paper is to find seismic retrofit scheme that minimizes seismic retrofit costs while satisfying seismic performance the building owner wants through the connection retrofit. In this paper, the seismic performance is determined by inter-story drift ratio. The retrofit for the part of building connection is taken in order to satisfy the hoped-for seismic performance. The retrofitted locations and numbers are determined through the optimization method. The seismic retrofit costs through connection retrofit mean the numbers of retrofitted connections which are determined by the optimization method. The optimal seismic retrofit scheme is proposed by finding retrofitted locations using GA algorithm one of the optimization methods.

3.1 The connection model

The hysteretic behaviour of the pre-Northridge steel moment resisting frame connection showing brittle fracture such as Figure 2(b) is used for the model of pre-connection retrofit. This model has the behaviour of abrupt brittle fracture in 0.01rad of rotation and reaches 0.04rad of rotation without the degradation of strength and stiffness and with 20%(Hamburger R.O. 2000) of strength of original strength after brittle fracture. The hysteretic behaviour of ductile connection such as Figure 4 is applied to the model of post-connection retrofit. The ductile model reaches 0.04rad of rotation without strength degradation and has 25% strength of original strength after fracture in 0.04rad of rotation. The
yielding moment meaning maximum strength in the hysteretic behaviour of connection is determined by beam-column connection used in the existing buildings.

3.2 Formulation

The purpose of this paper is to find the minimum retrofit costs with satisfying performance. So, the objective function is set by the minimization of connection retrofit costs. This means that the minimization of the numbers of connections which are retrofitted to ductile connections from the existing brittle connections, as in eq.(1). The design variables are whether connections are retrofitted. The constraint function is set not to exceed the allowable inter-story drift ratio of corresponding performance objective, as in eq.(2).

\[
\min \sum_{i=1}^{n} X_i
\]

\[DV. \ X_i = 0 \text{ for existing connections} \]

\[X_i = 1 \text{ for retrofitted connections} \]

\[s.t. \ \frac{\Delta}{\Delta_a} < 1 \]

where,

\(X_i\) is whether the i-th connection is retrofitted or remains

\(\Delta\) and \(\Delta_a\) are the maximum and allowable inter-story drift ratio, respectively

3.3 The optimal seismic retrofit method

The optimal seismic retrofit method consists of the step to model performances of pre-connection retrofit and post-connection retrofit for the existing steel moment resisting frame and the step for the application of optimization method. First, the hysteretic behaviour of connections for the existing steel moment resisting frame must be identified. The hysteretic behaviour of each connection are found through the existing test data or newly conducted test. The retrofit method for connection retrofit is also selected and the hysteretic behaviours of each connection for selected retrofit method are obtained. The hysteretic behaviours of pre-connection retrofit and post-connection retrofit become retrofit data base which connections, design variable, can select in the optimization procedure.

The non-linear seismic analysis program, opensees, is used to perform non-linear static analysis for each retrofit scheme in the optimization procedure. Two times pushover analysis is performed to perform the algorithm for one population of one generation. The first analysis is for obtaining target displacement, and the second analysis is for obtaining maximum inter-story drift ratio through loading to target displacement. The target displacement is obtained by displacement coefficient method proposed by FEMA356(ASCE 2000). The algorithm used in the performance-based optimal seismic retrofit method is the simple genetic algorithm(Deb 2001). Based on Standard Parameter Setting proposed by the existing study(DE Jong 1975), the values of parameters are determined, for example the crossover probability is 60%, the mutation probability is 3%, etc.

4 APPLICATION

This paper applies the optimal seismic retrofit method to SAC Benchmark 3-story example, proposes the optimal seismic retrofit scheme, and evaluates the performance for retrofit scheme proposed. This paper assumes the example structure locates LA in the U.S.(latitude : 33.93°, longitude : -118.40°) and the ground class is D(Stiff Soil). Figure 5 shows that structure which is the 3-story 4-bay steel moment resisting frame with rigid connection. The first three bays are moment resisting frames and the fourth bay is simple beam-column joint. Please refer to the details(Shan Shi 1997) for the structural design of
The design variables for the optimal seismic retrofit are beam ends connection of the first three bays, total 18 connections, and Figure 5 represents those variables. The hysteretic behaviors of the retrofit data base that each connection which is the design variables can select, pre-retrofit (brittle connection) and post-retrofit (ductile connection), are applied the model method for connection referred in 3.1.

This paper performs the optimal seismic retrofit method with respect to the performance objective \( P \) which is collapse prevention performance level for very rare(2%/50yr) seismic earthquake demands proposed in FEMA 273(BSSC 1997).

As a result of performing the optimal seismic retrofit method, the solution converges like Figure 6, the value of the objective function for the optimal solution is 2. That means the seismic performance can be satisfied through retrofitting two connections of 18 connections. The two optimal connection locations for retrofit are represented as number 9 and 12 connection in Figure 5. The evaluation for seismic performance of structure applied proposed optimal solution is conducted. Figure 7 shows pushover curves obtained by performing non-linear static analysis for pre-retrofit and post-retrofit structure. It is verified that the dissipated energy of building somewhat increases by retrofit.
Figure 7 Pushover curves for existing and optimal retrofit models

Figure 8 shows inter-story drift ratios for pre-retrofit and post-retrofit obtained by non-linear static analysis. The existing building which has pre-retrofit connections doesn’t satisfy allowable inter-story drift ratio (BSSC 1997), 5%, corresponding building collapse prevention level. After performing the optimal seismic retrofit method, as a result of application for the optimal seismic retrofit scheme, it is verified that the maximum inter-story drift ratio of building satisfies allowable inter-story drift ratio represented in the criteria.

Figure 8 Inter-story drift ratios for existing and optimal retrofit models

5 CONCLUSION

In this paper, the performance-based optimal seismic retrofit method for the steel moment resisting frame using connection upgrade is proposed. The optimal seismic scheme satisfying corresponding performance objective with the minimum retrofit cost is represented. As a seismic retrofit method, the method of changing brittle fracture connection of the existing building to ductile connection is selected. Using GA algorithm which is one of the optimization methods, the optimal seismic retrofit scheme searching the minimum numbers of the connection retrofit and their locations is proposed.

The method suggested in this paper is verified through the example of 3-story steel moment resisting frame with pre-Northridge connection. The optimal seismic retrofit method is conducted with respect to the performance objective P which is collapse prevention performance level for very rare (2%/50yr)
seismic earthquake demands proposed in FEMA 273(BSSC 1997). The minimum numbers of connection retrofit and their locations are searched through the GA algorithm, it is shown that the optimal solution satisfies performance objective.

This paper does not consider non-linear dynamic behaviour and is limited to 3-story example. The model for beam-column connection in this paper does not reflect the effect of panel zone. So, it needs an additional study to consider those limitations.

6 ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST)(No. 2010-0027246).

7 REFERENCE


Federal Emergency Management Agency.