OPTIMUM RETROFIT OF A 3-STORY RC FRAME CONSIDERING NONLINEAR SSI

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ABSTRACT

New and existing structures should always satisfy the necessities of their contemporary codes. Continuous changes in design codes make it inevitable for existing structures to need to be rehabilitated every now and then so that they can fulfil the least expectable duty they are meant to. The expenses charged to perform a retrofit task may vary so vastly for one single project with a unique aim. Minimizing the costs while maintaining the outcomes is what most experts have been working on for decades. In this study, an optimization algorithm is employed to perform the retrofitting task in the most optimized manner. Soil-structure interaction (SSI) is assumed to exist in order to make the results as exact as possible. The required retrofitting material, CFRP in this case, has been found to be 74.4 square meters for the case including SSI and 98.4 for the case without this phenomenon. Costs are compared as well to make a judgement of whether or not SSI should be taken into account.

INTRODUCTION

Design codes of structures are changing persistently and with recent progressions in knowing true behaviour of structures against seismic and dynamic loads, existing structures seem to lack a lot when it comes to resist dynamic loads especially earthquakes. In this regard, parallel to new approaches to designing structures against these types of loadings, methods of retrofitting of existing structures continue to evolve so that structures in need of contrivances keep serving without being required to get totally rebuilt. Among several materials and methods of retrofitting structures, FRP's are finding their way to be more and more common as a result of their many distinguishing features. CFRP's specifically, whose effects are studied in this research, are getting popular among other types in Iran as a result of their relative reasonable price and good workability. To retrofit a structure, two main aims should be considered: First, satisfying new design codes necessities, and second having an eye on economical issues. The economical aspect of the problem induces the tendency of finding the minimum material needed to gain the optimum response.

Amoury& Ghobarah (2005) suggested that increasing the flexibility of the structure via shear deformations does not necessarily result in increased lateral deformations of the frame. To perform their surveys, they made use of GFRP and carried out pushover analyses to find the lateral displacement capacity of the frame.. 3-story reinforced-concrete (RC) frame shown schematically in Fig. 1 is assumed, whichneeds to be retrofitted so as to satisfy the requirements of new codes.

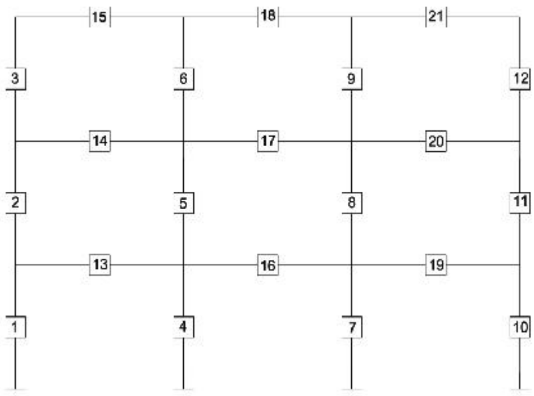


Figure 1.The 3-story 3-interval frame to be retrofitted

In the first stage, the structure is retrofitted to a level which leaves no shortage in carrying the loads caused by the pushover analysis, making it possible to meet all desired criteria. The Teaching-Learning Based Optimization (TLBO) algorithm, which is summarised in Fig. 2, is used to do the optimization of the needed retrofitting material i.e. CFRP.

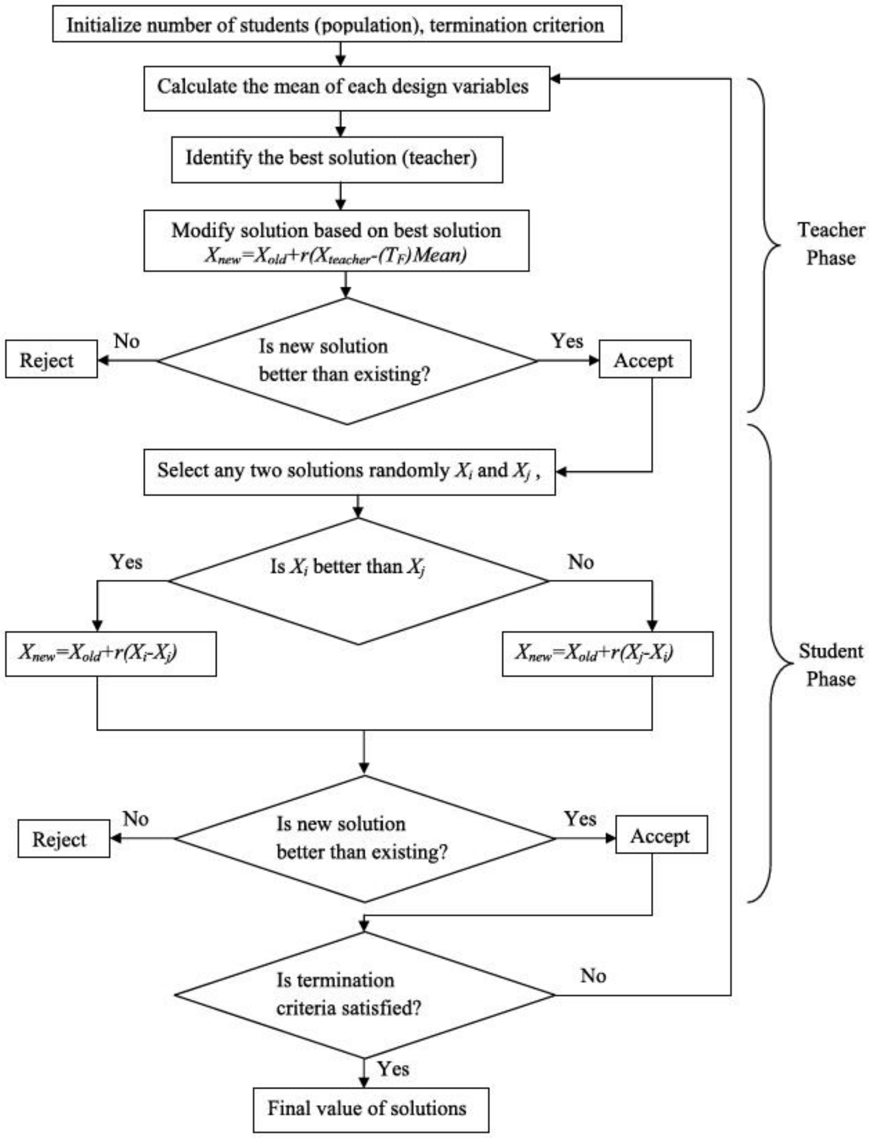


Figure 2.Flow chart of the TLBO algorithm (after Rao et al., 2011)

Figure 3 illustrates the pushover curve along with its bilinear representation.

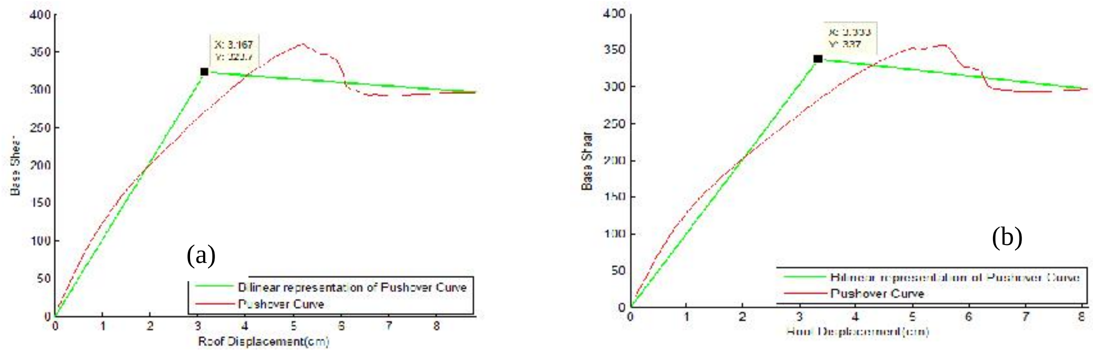


Figure 3.Bilinear representation of pushover curvebefore retrofitting(a) no SSI, (b) nonlinear SSI

The target displacement to be met for all states of the structure is yielded from Eq. (1):

$$S_t = C_0 C_1 C_2 S_a \frac{T_e^2}{4\pi^2} g \tag{1}$$

Table 1 shows suitable values for parameters in Eq. (1), based on the last revision of the Iranian Code of Retrofitting of Existing Structures no.360.

Table 1.Needed parameters to calculate target displacement (Iranian Code of Retrofitting of Existing Structures no.360)

	δ_t (cm)	S_a	C_2	C_1	C_0	T_i	C_m	V_y(KN)
Primary structure (no SSI)	8.00	0.72	1.015	1.07	1.30	0.533	0.90	337
Primary structure (SSI)	8.70	0.70	1.012	1.06	1.30	0.570	0.90	334
Retrofitted structure (no SSI)	7.40	0.72	1.0003	1.01	1.30	0.533	0.90	748
Retrofitted structure (SSI)	8.30	0.70	1.002	1.02	1.30	0.570	0.90	559

Studies are done once more considering nonlinear soil-structure interaction using the UCD soil model in which the foundation is supposed to be placed on springs reaching softened constants under bigger strains than a threshold. Fig. 4 illustrates this state for a single footing schematically. All modelling and the programming are done in the OpenSees software environment.

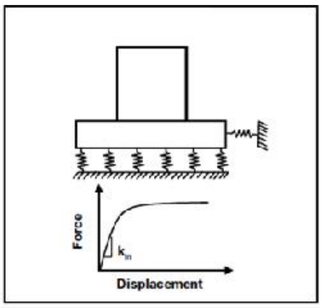


Figure 4. Behaviour of footing on UCD soil (after Raychowdhury and Hutchimson, 2008)

In order to account for the softening of the soil in high strains which cause the nonlinearity, the UCD[1] soil model is implemented. To use this model in the present solution scheme, conventional fundamentals of shallow foundations bearing capacity have been used as in Eq. (2) (Terzaghi, 1943):

$$q_{ult} = cN_c F_{cs} F_{cd} F_{ci} + \gamma D_f N_q F_{qs} F_{qd} F_{qi} + 0.5\gamma B N_\gamma F_{\gamma s} F_{\gamma d} F_{\gamma i} \tag{2}$$

whereq_{ult} is the ultimate bearing capacity for unit area of the footing; c is the cohesion of the underlying soil of the foundation in case cohesive; B dimension of the foundation and N_c, N_q and N_r are bearing capacity factors. F_{cs},F_{cd} and $F_{ci}$are supposed shape, F_{qs}, $F_{qd}$and F_{qi}depth and F_{rs}, F_{rd} and F_{ri}, inclination factors in each section of the equation. The lateral bearing capacity is calculated as the total resisting force on the embedded side of the footing, as in Eq.(3):

1. University of California Davis

$$p_{ult} = 0.5\,\text{¥}\,K_p D_f^2 \tag{3}$$

in which p_{ult} is the soil passive pressure in unit area and K_p is the passive lateral pressure coefficient based on Coulomb (1776).
Mechanical properties of structural materials are presented in Tables 2 and 3.

Table 2. Mechanical properties of concrete for non-linear structural behaviour

Mechanical Properties	Characteristic Strength (kPa)	Strain in Maximum Strength	Crushing Strength (kPa)	Strain before Crushing	Tension Strength (kPa)
Core Concrete	24×10^3	0.0024	5.6×10^3	0.015	0
Cover Concrete	21×10^3	0.002	5×10^3	0.005	0

Table 3. Mechanical properties of steel for non-linear structural behaviour

Mechanical Properties	Yield Stress (kPa)	Initial Modulus of Elasticity (kPa)	Strain Hardening Ratio
Reinforcing Steel	420×10^3	2×10^8	0.01

Soil properties, based on which underlying springs are derived are shown in Table 4.

Table 4. Values of soil mechanical properties

Mass Density (ton/m3)	Reference Shear Modulus (kPa)	Reference Bulk Modulus (kPa)	Friction Angle	Phase Transformation Angle	Peak Shear Strain	Reference Pressure (kPa)	Pressure Dependence Coefficient (d)	Porosity (e)
1.9	7.5×10^4	2.0×10^5	33	27	0.1	80	0.5	0.7

Figure 5 illustrates rotations of the elements with and without SSI.

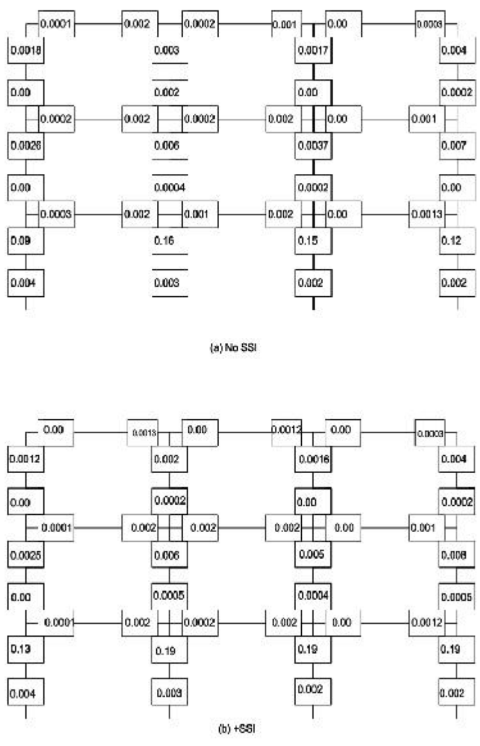
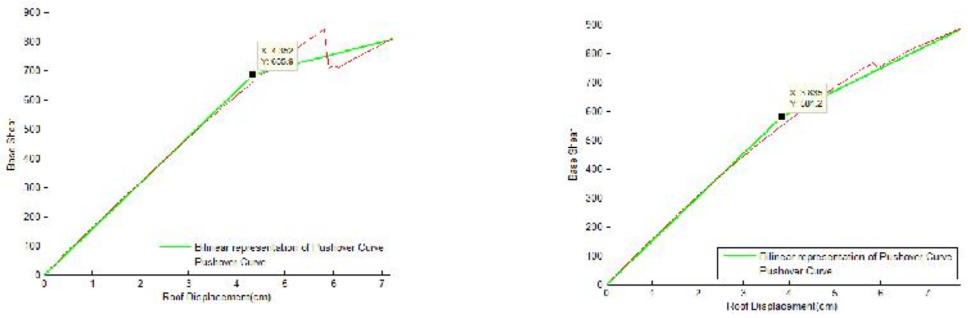


Figure 5.Rotations of the elements before retrofitting (a) no SSI, (b) nonlinear SSI

After retrofitting the structure, pushover curves and their bilinear estimations are drawn as shown in Fig. 6.



(a) (b)

Figure 6.Bilinear representation of pushover curve for retrofitted structure (a) no SSI, (b) nonlinear SSI

Table 5 represents the number of CFRP layers needed to retrofit the frame considering the nonlinear SSI as well.

Table 5.Number of CFRP layers needed

Element number	Pushover (no SSI)	Pushover (SSI)
1	3	3
2	1	3
3	1	1
4	3	3
5	1	2
6	-	-
7	3	3
8	1	2
9	-	-
10	3	3
11	1	3
12	1	1

Rotations of the elements which may eventually lead to the formation of plastic hinges wil reach a controlled measure after the frame is retrofitted. Fig. 7 illustrates the amounts of these rotations for the retrofitted frame. Finally, base shears for the primary structure and the retrofitted one are depicted in Fig. 8 for the sake of comparison.

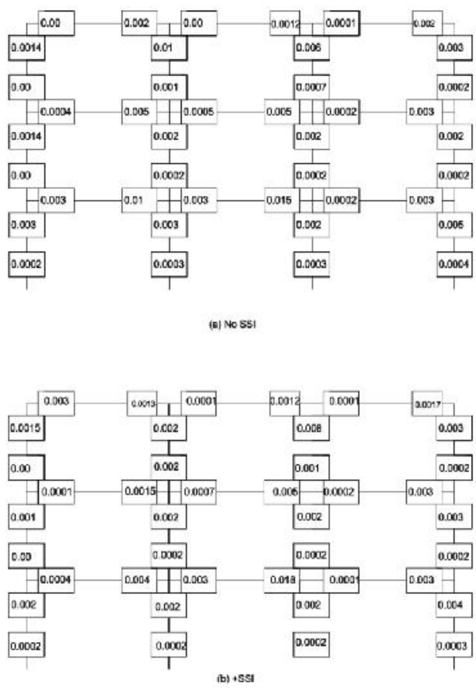


Figure 7.Rotations of the elements after retrofitting (a) no SSI, (b) nonlinear SSI

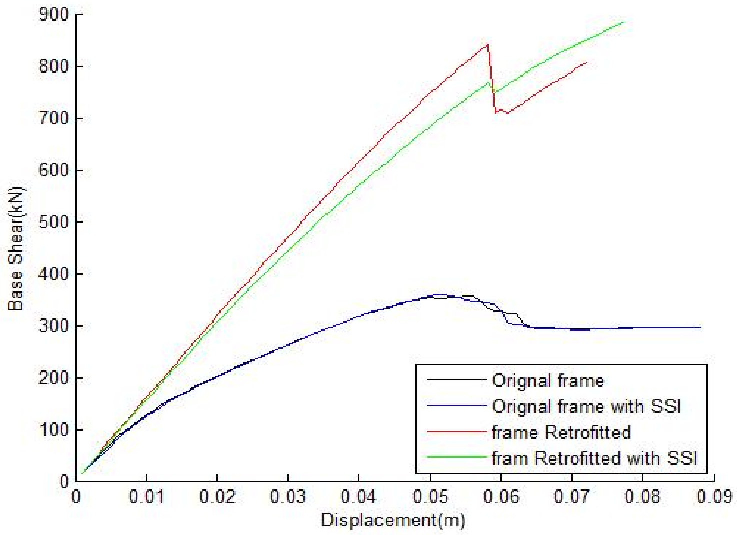


Figure 8.Base shears in the primary and retrofitted frames with and without nonlinear SSI

Recorded story drifts before and after the performance of retrofitting are illustrated in Fig. 9.

CONCLUSIONS

A 3-story frame was retrofitted in an optimum manner using the TLBO algorithm considering nonlinear SSI. Results suggest that the existence of nonlinear SSI may cause the destruction patterns to be different from when this phenomenon is not considered. This is while this consideration leads to lower expenses of rehabilitation. Table 6 summarizes retrofitting costs with and without considering SSI.

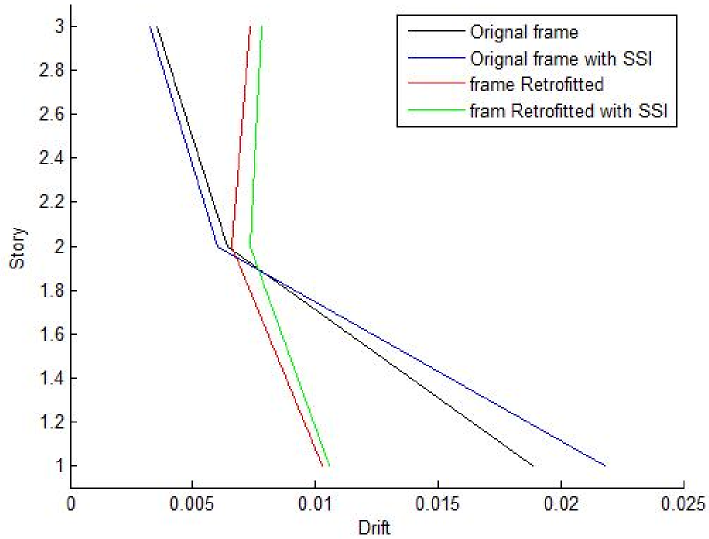


Figure 9.Peak story drifts in the primary and retrofitted structures with and without SSI

Table 6.Area and cost of CFRP required for optimal retrofitting of the frame

	CFRP area required to satisfy the considered retrofitting purpose (m^2)	Required CFRP cost (rials)
Pushover (no SSI)	74.4	111600000
Pushover (SSI)	98.4	147600000

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