Retrofit of Structures: Strength Reduction with Damping Enhancement

by

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ABSTRACT

A new procedure to retrofit existing structures subjected to seismic excitation is proposed. The main features of this procedure are to reduce maximum acceleration and associated forces in buildings subjected to seismic excitation by reducing their strength (weakening). The weakening retrofit, which is an opposite strategy to strengthening, is particularly suitable for buildings having overstressed components and foundation supports or having weak brittle components. However, by weakening the structure large deformations are expected. Supplemental damping devices however can control the deformations within desirable limits. The structure retrofitted with this strategy will have, therefore, a reduction in the acceleration response and a reduction in the deformations, depending on the amount of additional damping introduced in the structure. An illustration of the above strategy is presented here through an evaluation of the inelastic response of the structure through a spectral procedure, modified to fit structures with additional damping. The results are evaluated also with a more conventional dynamic nonlinear analysis. Both methods show that the retrofit solution is feasible and simplified techniques can be used for evaluation. A sensitivity analysis has also been carried out to evaluate the effectiveness of the retrofitting method in presence of uncertainties in the analysis, in the construction properties and in the ground motions through fragility analysis.

KEYWORDS: retrofit, strengthening, weakening, damping, inelastic spectral analysis, fragility.

1.0 INTRODUCTION

The retrofitting techniques intend to improve performance of structure, maintaining the response below acceptable thresholds, defined also as performance limit states. The structural response of inelastic buildings is measured in terms of displacements (deformations), although the accelerations (and stresses) are also important in order to avoid damages in the non-structural and contents of structures. components Performance based design strategy is usually concerned with prevention of structural damage although is very important to protect the contents and not-structural systems in particular in critical facilities such as hospitals, laboratories, advanced technology centers, where the "secondary" systems can be more expensive than the structure itself.

Therefore, in order to improve the performance of a building, both displacements and acceleration should be kept below acceptable limits. The most common procedures to improve the seismic performance of existing buildings are the following:

- *Strengthening* produced by adding (or by reinforcing) lateral elements, which lead to a reduction of deformations and displacements but lead to an increase in accelerations in the yielding structures.
- *Base isolations* change the dynamic properties of structures, reducing the seismic acceleration and drift but increasing the total displacement.
- *Supplemental Damping* devices reduce lateral displacements, but do not change substantially the amount of seismic acceleration in the inelastic structures.

The strengthening is the most intuitive strategy to

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improve the response of the building, and it is largely used currently. It can be easily applied to whole or parts of buildings to correct a weakness or not-homogeneous distribution of strength. Although it has positive benefits, it also changes the stiffness distribution, which might lead to damage in the non-strengthened parts. Strengthening of the whole structure is more invasive and more expensive.

Supplemental damping has a positive influence on structural response reducing deformations in inelastic structures and also accelerations in elastic structures. Damping devices are quite inexpensive and easy to insert in existing structures. Various damping devices - with different mechanical properties and dissipation characteristics - can be adopted (see Reinhorn et al, 1995 and Constantinou et al, 1998). Depending on the dampers chosen, stiffness and strength of the structure might increase in addition to damping characteristics, although using viscous dampers such stiffness and strength may be avoided.

This paper presents a new retrofitting method, aimed at reducing both displacements and accelerations. The retrofit procedure consists of:

- weakening the building by disconnecting frames or walls in the structure, to decrease its lateral strength. However, this reduction is often accompanied by increased displacements;
- adding damping devices to reduce and control the deformations and displacements.

Figure 1 shows the effects of each of the two steps of this technique, and their combination. In the figure the capacity of the structure has been represented by the bi-linear pushover curve describing approximately the response of the structure. In the first line of Figure 1 the effect of the strengthening and weakening of structures is shown. As a consequence of the weakening, the yield strength of the structure is reduced and a bigger displacement is required. The second line of Figure 1 shows the effect of damping, consisting in a reduction of the maximum demanded displacement, which switches along the inelastic branch of the pushover curve. The third line of Figure 1 shows the final result of the retrofitting procedure, providing a smaller demand both in acceleration and in displacements.

The "weakening retrofit" is easier to apply than other techniques, as the weakening of the structure can easily be obtained with simple changes in specific parts of the structure. (see practical details in last section of this paper). In this paper the effectiveness of the method and its feasibility are discussed. This method has some similarities with the base isolation method when used together with damping, since it reduces both the acceleration and the displacement.

The analysis of the structure for the different steps of the retrofitting procedure (original structure, weakened structure, weakened and damped structure) has been made through a spectral response approach. Such an analytical procedure, proposed by Reinhorn (1997) and Ramirez et al, (2000), for low damped structures, has been specifically adapted in this work to be applied to highly damped structures. The proposed method leads to a simplified and effective evaluation of the structural response of damped structure under seismic excitation. Such method allows a quick evaluation of such complex retrofit.

The proposed retrofitting method has been applied to a case study in order to show the response of the structure for each step of the procedure.

2.0 EXAMPLE APPLICATION

In order to illustrate the retrofitting technique, a 5stories steel frame structure of a hospital in Southern California (shown in Figure 2) is analyzed in this paper. The hospital was damaged in Northridge 1994 earthquake although its strength was larger than 60% of its weight. Large accelerations induced strong forces in connections and damaged much of the interior of the building.

The analysis has been performed on the longitudinal model of the structure. The structure in the longitudinal direction consists in four frames: two moment resisting frames (along axis lines 2 and 4) and two secondary frames having shear connections. In Figure 2b the typical longitudinal frame is shown. Figure 2c shows the typical weakened longitudinal frame. The weakening is obtained by replacing the fixed rigid connections with semi-rigid connections allowing high rotations

in the moment resistant frames. Figure 2d, finally, shows the longitudinal frame after the introduction of the damping devices. Linear viscous diagonal braces are introduced in all longitudinal frames of the structure. Two different types of dampers have been considered, C = 0.5 kN/mm/sec, and C = 1.5 kN/mm/sec, in order to obtain two different critical damping levels in the structure ($\beta_{\text{eff}} \approx 15\%$, $\beta_{\text{eff}} \approx 32\%$).

3.0 GROUND MOTIONS

In order to perform the evaluations, three hazards levels were considered: 10% in 50 years, 5% in 50 years and 2% in 50 years corresponding to PGA of 0.50 g, 0.63 g and 0.77g, respectively. The seismic excitation is derived according to FEMA 356 [7] and with the information provided by NSHMP (National Seismic Hazard Mapping Program) for the hospital's location. A set of twenty ground motions both real and simulated, whose characteristics are listed in Table 1, has been assumed to perform the nonlinear dynamic analysis. Such ground motions have been selected because their mean spectrum approaches that provided by FEMA 356 for a probability of occurrence of 2% in 50 years. Figure 3 shows the spectra of the 20 ground motions constituting the set.

4.0 EVALUATION OF BUILDING

The seismic response of the case study building has been evaluated by performing both spectral analysis and a nonlinear dynamic analysis. IDARC2D program (Valles et al, 1996) was used for both analyses. The elements (beams and columns) in the structure have been represented through bilinear moment-curvature relationships, and a yield surface including M-N interaction. The ultimate curvature was set equal to 50 times the yield curvature, and the post-elastic stiffness was set equal to 1% to the elastic stiffness.

4.1. Spectral Evaluation of Response

The case study response obtained using the spectral evaluation, as shown in Figure 4 clearly indicates that the response of the weakened structure is characterized by reduced acceleration demands and increased displacement demands. Figure 4 shows also numerically the trend of the

main quantities representing the structural response, i.e. the maximum displacement, the maximum interstory drift along the building height, the base shear and the R-factor (indicating the inelastic response of the structure). When a moderate additional viscous damping is introduced (C=0.5 kN/mm/sec), a reduction in the displacement can be observed, while the acceleration does not change. As can be seen from Figure 4, the slightly damped structure has maximum displacement and the interstory drift very close to the ones of the original When a more substantial viscous structure. damping is introduced in the structure (C=1.5 kN/ mm/sec) the displacements and interstory drifts are much smaller than the one found for the original structure. The reduction in displacement and interstory drift, therefore, strongly depend on the amount of damping provided in the structure.

4.2. Comparison to "pseudo-inelastic" analysis

As a note, the results are compared with the ones provided by the "pseudo-inelastic" spectral analysis of damped structures, as proposed by Ramirez et al (2000). The method proposed herein is more direct and does not require iterations. The comparison between the two procedures is shown in Figure 5. The results provided by the two procedures show the same trend for both moderate and high damping.

5.0 SENSITIVITY OF RETROFIT

One of the most important aspects in retrofitting is the sensitivity in the estimation and evaluation of the mechanical properties of the existing building and of the retrofit components. In the current case, a correct and reliable analysis of the structure to retrofit is extremely important in deciding the amount of weakening and the amount of additional damping devices. It is also important to evaluate the uncertainties in the response quantities, to assure that the retrofit will be effective and will not be overcome by the variability of response due to uncertainties. This evaluation was developed using a probabilistic approach, which implies the development of a fragility analysis (Barron-Corverra, 2000).

Fragility curves are functions that represent the conditional probability that a given structure's

response to various seismic excitations exceeds performance limit states. Theoretically fragility represents the probability that the response R of a specific structure (or family of structures) exceeds a given threshold r_{lim} , associated with a given limit state, conditional on earthquake intensity parameter *I*. In mathematical form this is a conditional probability (Reinhorn, 2001):

$$Fragility = P\left\{R \ge r_{\rm lim} / I\right\}$$
(1)

where: *R* is response parameter (deformation, force, velocity, etc.), r_{lim} is response threshold parameter that is correlated with damage, I = earthquake intensity (represented by either return period, or PGA, or Modified Mercalli Intensities, etc.). This definition can be extended to N-dimensional parameters where the number of parameters to be checked is *N*. So the general definition can be written in the following form:

$$Fragility = \bigcup_{i=1}^{N} P\left\{R_i \ge r_{i \lim}/I\right\}$$
(2)

where the union indicates the aggregation of the conditional probabilities for multiple parameters with multiple threshold limits.

If the case is reduced to bi-dimensional case considering for instance displacements and accelerations of a story building the fragility can be written in the following form:

$$Fragility = P\left\{\Delta \ge D_{\lim} \cup Z \ge A_{\lim} / I\right\}$$
(3)

where: Δ is a random variable representing the displacement response, Z is the random variable representing the acceleration response, D_{lim} is the displacement threshold and A_{lim} is the acceleration threshold.

5.1. Approximation of sensitivity of retrofit

In this section a simple and quick evaluation of the sensitivity of the retrofitting method is performed by considering, both uncertain capacity and demands and by characterizing them with approximated statistical distributions. The effectiveness of the weakening has been evaluated by comparing the reduction in the acceleration demand with the effects of some uncertainties affecting the modeling assumptions. The effectiveness of damping has been evaluated by comparing the reduction in the spectral demand (consequentially, displacements) due to damping considering the scatter in the spectral demand due to uncertainty in the seismic input.

5.2. Variations in structural capacity

The evaluation of the capacity of the structure is related to all the uncertainties affecting the mechanical properties of the structure and the assumption about modeling. In this section, the effects of uncertainty in some modeling assumptions, listed below, are shown as an example of the confidence intervals for the capacity.

The capacity of the joint to transfer bending moment. Only two of the four frames constituting the longitudinal structure of the case study building (see Figure 2) are moment resistant frames (MRF), and the other two frames (frame lines No 3 and No 4) have semi rigid shear connection. The shearconnected frames are often assumed to have no flexural strength, although they can sustain large moments through an axial force couple involving the reinforced concrete slab and web tab connections. The most proper model to represent such connections would be a spring, whose effectiveness depends on the proper characterization of stiffness and strength. In order to bracket the capacity of the structure for the real MRF number, the two limit conditions (2MRF, 4MRF) have been considered, and the pushover curves are shown in Figure 8a both for the original and for the weakened structures. As can be observed, in this case the contribution of the secondary frames is not very relevant, having flexible and week semi rigid connections.

The modeling of the joint panel zone (JPZ). In the structural analyses, the contribution of the JPZ is often omitted, and the element of the building are characterized through their "node-to-node" length. The effective length of the joint panel zone depends on the detailed realization of the node itself, and it can relevantly affect the estimated capacity of the structure. Figure 8b shows the capacity of the original and of the weakened structure for the two limit assumptions: JPZ = 0 and JPZ = height of the element.

The horizontal load pattern in the nonlinear static analysis. The horizontal load pattern along the height can affect the calculated capacity of the building. Figure 8c shows, the two capacity spectra for the original and the weakened structures derived from two limiting distributions: a triangular distribution and a constant distribution along the building height. The horizontal load pattern does not seem to affect very much the spectral capacity, as shown in Figure 8c.

5.3. Variation in the structural seismic demand

The seismic demand is one of the most uncertain quantities involved in the evaluation of the structural response under seismic excitation, being the magnitude of the ground motion as well as its content in frequency and its duration very difficult to predict. Such parameters are usually assumed statistically, and they are characterized by a relevant distribution. The set of ground motions assumed in the current dynamic analysis, plotted in Figure 3, is an example of the order of magnitude of the scattering in the seismic input. The evaluation of the effect of the uncertainty in the seismic input is performed, by analyzing the response of the structure under the spectra assumed to be bound by mean plus and minus one standard deviation:

Max spectrum = Mean spectrum + std. dev (4)a Min spectrum = Mean spectrum - std. dev (4)b

The variations of the undamped and highly (β_{eff} = 30%) damped spectra are shown in Figure 9. The response of the structure for the assumed set of ground motions has been evaluated by spectral capacity analysis, and the comparison between the inelastic spectral displacements due to the ground motion uncertainty and due to added damping is shown in Table 2. The scattering in the displacements obtained due to uncertainty in ground motions is very relevant, especially when the undamped spectra are considered (74%). The scattering due to damped spectra, despite being not negligible, is much smaller (22%). The reduction in displacements due to damping evaluated on the mean spectrum is approximately 36%, bigger that the scattering in the damped spectra. From this simple analysis we can conclude that, despite the uncertainties in the ground motions, the damping is an effective solution to reduce displacements.

5.4. Sensitivity of fragility

The influence of uncertainties can be expressed by the fragility curves which consider the capacity, the demands and the limit states. Fragility curves can be used for decisions to strengthen buildings that are at high risk of being damaged and for this purpose it is necessary to know the effects of different structural parameters such as strength, stiffness, and damping on fragility.

The fragility curves due to weakening plotted in Figure 11 show some sensitivity to the location of the response (fist and fourth stories being more sensitive), however the weakening does not affect substantially the fragility.

The current study of the damping enhancements show that the fragility of exceeding the Imminent Damage State and the Moderate Damage State show a considerable reduction of fragility when damping is added as seen in Figure 12 for three different levels of damping ratios [5%, 15% and 25%]. This is also in agreement with fragility sensitivity studied by Barron, 2000 and Reinhorn and Barron, 2001. However this reduction is not proportional; the reduction is more significant for low values of damping ratio [15%] than for higher values of damping ratio [25%].

Considering uncertainties in the estimates of performance limit states (v=1) shown in Figure 12 the trends of improvement of fragilities with added damping are maintained as compared with those neglecting those uncertainties (v=0). However, neglecting the uncertainties it may lead to unconservative fragility curves, in particular at the lower earthquake intensities..

6.0 PRATICAL DETAILS

The structural "weakening" can be obtained by releasing selected connections in the structure. The properties of the modified connections depend on the materials and the construction practices used in the building. Figure 13 shows some possible alternatives of the "weakening" for some structures with different characteristics and materials.

In steel moment resistant frames, the weakening can be obtained by releasing the bolts, removing the complete joint penetration welds, and removing the slab around the columns (see Figure 18a). In steel braced frames, the weakening can be simply obtained by removing braces themselves (see Figure 13b), being usually the braces the strongest components of these structures.

In RC frames the weakening can be obtained by cutting the bottom bars of the reinforcement, as it is shown in Figure 13c or Some top bars could also be cut, without compromising the resistance of the structure to vertical loads (negative moment at the joints). Alternatively, the beam-column connection's strength can be reduced by reducing the moment capacity of the column, cutting some of the vertical bars above and below the joint.

Shear wall structures can be weakened by removing, or disconnecting them from the structure, some of the walls (see Figure 13d).

Although weakening can be achieved in any type of buildings, it is particularly suitable to steel (framed and braced) buildings, which are usually much stronger than necessary.

7.0 REMARKS AND CONCLUSIONS

In this paper a new retrofitting procedure for building subjected to seismic excitation is proposed, consisting in weakening the structure and adding additional damping devices. The procedure modifies both accelerations and displacements, thus improving the structural performance of structures subjected to seismic excitation. The weakening of the structure alone, it has the effect of decreasing the inelastic acceleration and the base shear response, however, it increases the ductility demand. Enhancing the structural damping alone, it produces a strong reduction in the ductility demand, without much change in the seismic acceleration. The new procedure reduces both quantities depending on the amount of strength reduction and amount of added damping. The benefits of the retrofitting procedure, introduced for a general case, are been shown in detail on a case study. The easy applicability of the proposed retrofitting technique is also discussed in the paper, and some details are shown for buildings of different material and geometrical features.

A simple sensitivity analysis has also been performed to prove the consistency of both the retrofitting method and the spectral analysis in regard to the most common uncertainties affecting the evaluation of the structural response. The reduction in accelerations due to weakening has been compared with the effects, on accelerations, of modeling uncertainties affecting the capacity of the system, and it resulted to be not significantly changed. The reduction in displacements due to damping has been compared with the effects of uncertainties in ground motions characteristics on the spectral demand. The scattering due to uncertainty in ground motions resulted to be not negligible, despite the efficiency of damping in reduce displacements is not compromised by such uncertainty, being their effects in damped structure much smaller than not in undamped ones.

The proposed spectral procedure has been tested by comparing the obtained results with the ones provided by a nonlinear dynamic analysis, and it proved to be effective, both for low and high damping. The proposed spectral procedure is a low time-consuming procedure, and it can be use in place of the nonlinear dynamic analysis in order to evaluate the response of the structure, also in the case of highly damped structures.

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EQ	Description	Earthquake		Time Step	PGA
code	Description	Magnitude	Factor	(sec)	(g)
la21	fn 1995 Kobe	6.9	1.15	0.020	1.28
la22	fp 1995 Kobe	6.9	1.15	0.020	0.92
la23	fn 1989 Loma Prieta	7.0	0.82	0.010	0.42
la24	fp 1989 Loma Prieta	7.0	0.82	0.010	0.47
la25	fn 1994 Northridge	6.7	1.29	0.005	0.87
la26	fp 1994 Northridge	6.7	1.29	0.005	0.94
la27	fn 1994 Northridge	6.7	1.61	0.020	0.93
la28	fp 1994 Northridge	6.7	1.61	0.020	1.33
la29	fn 1974 Tabas	7.4	1.08	0.020	0.81
la30	fp 1974 Tabas	7.4	1.08	0.020	0.99
la31	fn Elysian Park (simulated)	7.1	1.43	0.010	1.30
la32	fp Elysian Park (simulated)	7.1	1.43	0.010	1.19
la33	fn Elysian Park (simulated)	7.1	0.97	0.010	0.78
la34	fp Elysian Park (simulated)	7.1	0.97	0.010	0.68
la35	fn Elysian Park (simulated)	7.1	1.10	0.010	0.99
la36	fp Elysian Park (simulated)	7.1	1.10	0.010	1.10
la37	Fn Palos Verdes (simulated)	7.1	0.90	0.020	0.71
la38	fp Palos Verdes (simulated)	7.1	0.90	0.020	0.78
la39	fn Palos Verdes (simulated)	7.1	0.88	0.020	0.50
la40	fp Palos Verdes (simulated)	7.1	0.88	0.020	0.63

TABLE 1: GROUND MOTION DATA (SPECTRAL INFO)

	Inelastic Spectral Displacements (mm)		Variation from Mean		Range of Variation		Variability due to
	Undamped	Damped	Undamped	Damped	Undamped	Damped	damping
	structure	structure	structure	structure	structure	structure	
Mean-st.dv.	215	202	-36%	-18%			6%
Mean	334	246	0%	0%	74%	22%	36%
Mean+st.dv	462	256	38%	4%			80%

TABLE 2 – VARIABILITY OF RESPONSE DUE TO GROUND MOTIONS AND DAMPING



Figure 1: Main steps of the proposed retrofit strategy



Figure 2: Typical plan and longitudinal frame of the study case



Figure 3: The Selected Set of Ground Motions









0.70

PGA (g)

0.80

0.60



0.50



Figure 5: - Comparison between the proposed "inelastic" procedure and the "pseudo-inelastic"



Figure 6: Comparison of Nonlinear Dynamic Analysis and Spectral Analysis



Figure 7: Scatter of response of original and changed structure for all ground motions



C. LOAD PATTERN

Figure 8: Capacity Variations Obtained by Varying Modeling Assumptions



Figure 9: Scattering in the structural seismic demand (considering damping)



Figure 10: Response distribution (concentric circles) versus acceleration-displacement limit states



Figure 11: Fragility curves at story levels.



Figure 12: Sensitivity of "damping" fragility to uncertainty of limit states



a. Steel Moment Frames

b. Steel Braced Frames



c. RC Moment Frame



Figure 13: Suggested structural modifications for Weakening