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SEISMIC PERFORMANCE ASSESSMENT OF STEEL-FRAME BUILDINGS UTILIZING SPECTRAL MATCHING

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Abstract

This paper discusses the seismic performance assessment of a 4-story and an 8-story steel-frame building using the FEMA P-695 Far Field ground motion set. The response using the original set of ground motions was compared to the response using ground motions spectral matched to the FEMA P-695 SDC D_{max} target response spectrum using an interactive computational tool. Seismic collapse safety was predicted using nonlinear response history analysis using FEMA P-695 methodology where the ground motion set was incrementally scaled with respect to the target response spectrum. The probability of building damage and downtime, as a function of ground motion intensity, was predicted using nonlinear response history analysis using the FEMA P-58 framework and sub-set of the FEMA P-695 Far Field ground motions, where the building response was correlated to structural and non-structural damage via Monte Carlo simulation. The comparisons showed that, for the buildings examined, spectral matching the FEMA P-695 Far Field ground motions had a significant effect on seismic collapse safety and performance predictions. The median collapse margin ratio was similar for both the original and spectral matched motions, but the dispersion was significantly reduced using spectral matching and led to increased collapse safety (reduced probability of collapse) and to reduced estimates of repair costs and downtime.

Keywords: spectral matching; collapse analysis; performance assessment; steel-frame structures

1. Introduction

Evaluating the inelastic seismic performance of buildings often requires nonlinear response history analyses. Selection and modification of a set of ground motions (ground acceleration records) to be used in the analyses may be accomplished several ways [1], but in many regions of the world, appropriate acceleration records for a particular location, in terms of fault mechanism, magnitude, and distance from source-to-site, are typically sparse. As a consequence, synthetic ground motion records are used, or actual ground motion records (so-called "seed" ground motions) are modified (spectral matched) by adjusting the frequency content, the duration, and the amplitude of the original ground motion to "match" a target response spectrum that is appropriate for the location. For design purposes, the ASCE 7 elastic response spectrum [2,3] may be selected as the target spectrum. Yet, the impact of spectral matched ground motions on the nonlinear response and predicted seismic performance is not well understood.

Spectral matching requires fewer ground motions to obtain mean values of structural response, due to the reduced variability in the structural response, but it is not clear whether the spectral matched mean values (such as collapse-intensity spectral accelerations) are conservative or not conservative relative to the mean values based on the original seed ground motions [1]. The disparity in response is not a surprise, however, when it is realized that spectral matching is intended to match a target frequency content while at the same time preserving the non-stationary character of the original ground motion. Thus, aside from the degree to which modified motions "match" a target spectrum, the conclusions from previous studies are most likely a reflection of the different structures and different ground motion sets under consideration.

Spectral matching using the FEMA P-695 Far Field ground motions [4] are of particular importance because they are currently used in the United States to predict seismic collapse safety and response modification factors of buildings. In a previous study [5] the FEMA P-695 Far-Field ground motions were spectral matched to the ASCE 7-10 elastic response spectrum corresponding to the highest spectral accelerations (S_{DS} = 1.0 g, S_{D1} = 0.6 g) for Seismic Design Category (SDC) D (referred to herein as SDC D_{max}). In that study, the spectral matching was done using wavelets and a Broyden updating algorithm [6]. Although the modified ground motions were well-matched to the target spectrum within a wide range (T_0 = 0.2 S_{D1}/S_{DS}, to 3 seconds), the modified ground motions in that study contained a high degree of mismatch outside those bounds. As a consequence, for the non-ductile and ductile steel moment-frame buildings examined in that study, spectral matching sometimes led to increased dispersion in the structural response.

This study focuses on the effect of spectral matching using the FEMA P-695 Far Field ground motions on the predicted seismic performance of a 4-story and an 8-story ductile steel moment-frame building. In contrast to the previous study, spectral matching was done using an interactive computational tool called the *Spectrum Match Toolkit* [7]. Available at no cost, the *Spectrum Match Toolkit* internally utilizes the well-known *RSPMatch09* spectral matching program [8], but greatly simplifies its usage by providing a graphical user interface developed within the MATLAB programming environment [10] in order to allow the user to quickly select ground motions, the target response spectrum, and to generate modified ground motions. The *Spectrum Match Toolkit* also allows the user to choose ground motions from a predefined subset of the PEER NGA database, to perform spectrum matching according to the linear response history requirements of the 2015 NEHRP provisions [11], ASCE 7-16 [3], or according to user-defined requirements.

Seismic collapse safety was then predicted using the FEMA P-695 methodology. Seismic performance in terms of repair costs and downtime was predicted using the FEMA P-58 framework [9] and a sub-set of the FEMA P-695 Far Field ground motion set (using both original ground motions and spectral matched ground motions) linearly scaled to three levels of ground motion intensity: 20%, 67% and 100% of the Maximum Considered (MCE) ground motions.

2. Spectral Matching

The FEMA P-695 Far-Field ground motions were spectral matched to the SDC D_{max} response spectrum. The modified ground motions were verified to exhibit realistic physical behavior by visually comparing the acceleration, velocity, and approximate energy content ("Arias Intensity") in the time domain.

For example, Fig. 1 shows a comparison of the original and modified acceleration, velocity, and displacement histories for the 1990 Manjil, Iran Abbar record (FEMA P-695 Far Field ground motion ID No. 15, component No. 1). The acceleration history shows a significant addition of high-frequency content in the modified ground motion, which is a typical product of spectral matching. The modified ground motion also has much stronger velocity pulses compared to the original seed ground motion. Lastly, the modified ground motion was physically realistic in that it has no residual velocity, realistic residual displacement, and similar energy content compared to the original record, in terms of the Arias Intensity.

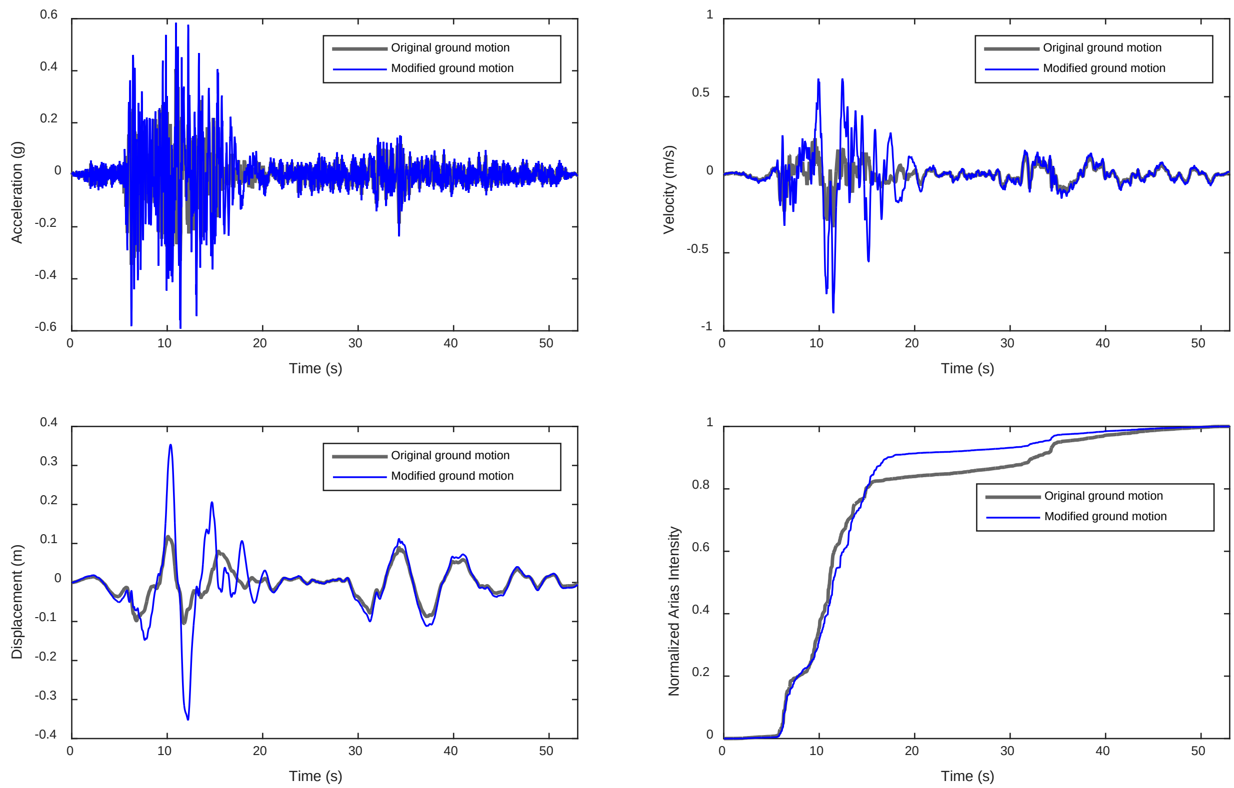


Fig. 1 – Ground motion characteristics for the 1990 Manjil, Iran Abbar record (FEMA P-695 Far Field ground motion ID No. 15, component No. 1).

3. Building Model

The steel moment frame buildings developed in the ATC-76 project [12] were used as a basis for the buildings modeled in this study. The 4-story and 8-story building plan consisted of 20-ft bays, 15-ft first story height and 13-ft upper story height. Gravity columns were considered pinned at the base and spliced 4 ft above the third and sixth floors. The columns were oriented with the strong axis in the same direction as the moment frames. The ductile moment frames used reduced beam section (RBS) connections and were designed for SDC D_{max}.

The building models were developed using *OpenSees* [13] finite element software. Framing members were modeled using linear elastic elements and zero-length nonlinear springs to simulate the formation of plastic hinges in beams at the location of the reduced beam section, plastic hinges at the top or bottom of columns, and shear yielding of the column panel zone. Gravity framing was explicitly represented and column splices were idealized as pinned connections. Large displacements (second-order, P-Δ effects) were incorporated using the "co-rotational" approach. Inherent damping not explicitly modelled through component hysteresis was taken as 2% and incorporated in the analysis using mass and initial-stiffness proportional damping applied to all elements except the nonlinear springs. The building model is described in detail in [14].

3. Collapse Safety

Seismic collapse safety of the buildings was predicted using the FEMA P-695 methodology. This consisted of a sequence of gravity load analysis, frequency (period-determination) analysis, nonlinear pushover analyses (one analysis to estimate axial loads in columns, followed by one analysis that accounted for axial load interaction and which was used to calculate period-based ductility), and nonlinear dynamic response history analyses that were incrementally scaled in intensity, with respect to the target response spectrum for SDC D_{max}, until collapse.

The original ground motions were normalized by their peak ground velocities, as required by FEMA P-695, and then collectively scaled upward relative to the median response spectra for a given level of ground motion intensity. In this procedure, the spectral matched ground motions were not velocity normalized (which would undo the spectral matching), and the computed fundamental period of vibration was used for referencing spectral accelerations and for scaling. Incremental dynamic analyses (IDA) results are shown in Fig. 2 for the 4-story building and in Fig. 3 for the 8-story building. The top plots show the response spectra, the middle plots show IDA curves, and the bottom plots show the measured collapse points and collapse fragility curves.

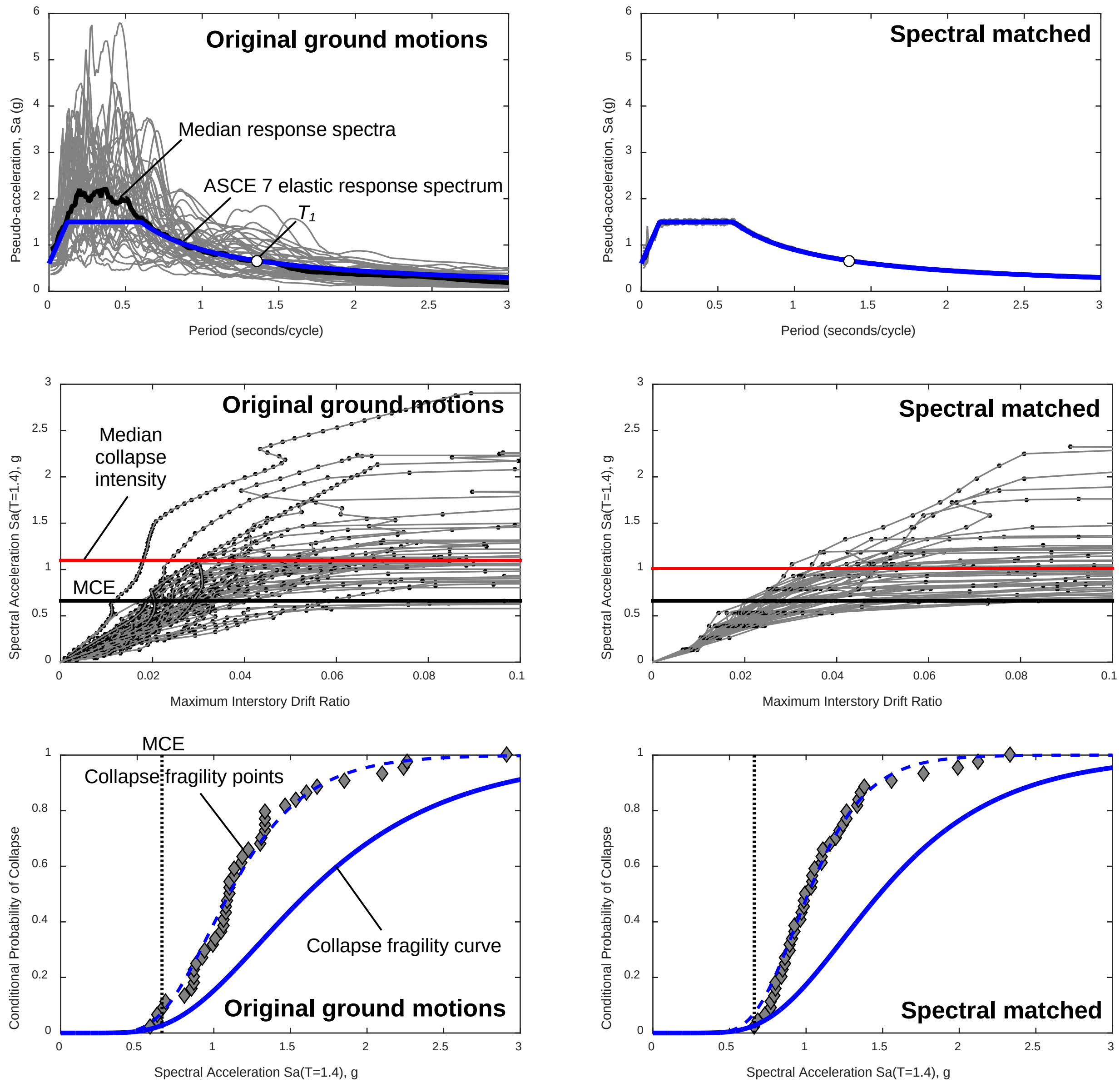


Fig. 2 – Incremental dynamic analyses (IDA) results for the 4-story building

A seismic collapse fragility curve was determined by fitting individual collapse points (spectral acceleration at the reference period and corresponding probability of collapse for a one scaled ground motion record) assuming a lognormal cumulative distribution function.

The median collapse spectral acceleration was adjusted (increased) to account for the change in spectral shape that corresponds to high-intensity ground motions. The adjustment was based on the period-based ductility determined in the nonlinear pushover analysis, and the total dispersion, β_{Total} in collapse capacity was calculated using Eq. (1).

$$\beta_{Total} = \sqrt{\beta_{RTR}{}^2 + \beta_{DR}{}^2 + \beta_{TD}{}^2 + \beta_{MDL}{}^2} \tag{1}$$

The β_{RTR} in Eq. (1) was taken as the measured record-to-record dispersion in the nonlinear seismic response history analyses to emulate the aleatoric uncertainty in strong ground motions. Epistemic uncertainty was incorporated by assigning dispersion due to design β_{DR}= 0.1, test data β_{TD}= 0.2, and modeling uncertainty β_{MDL}= 0.2 based the rubric defined in FEMA P-695.

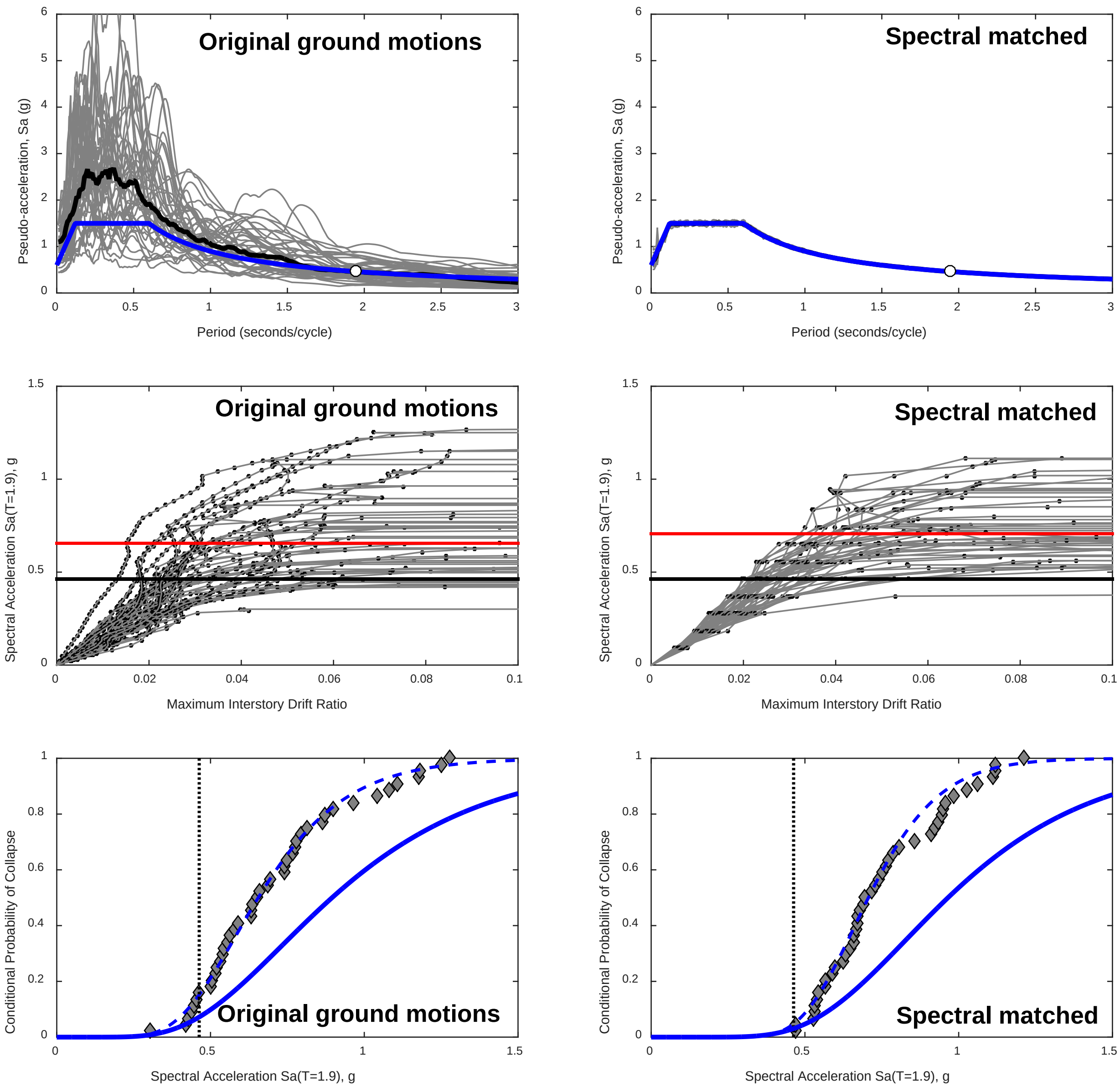


Fig. 3 – Incremental dynamic analyses (IDA) results for the 8-story building

Table 1 summarizes the collapse safety results. The median collapse margin ratio (CMR) was calculated by dividing the median spectral acceleration at collapse (for the collective set of ground motions) by the MCE-level spectral acceleration. The CMR was adjusted (ACMR) for period elongation and strong ground motion for long-periods using the Spectral Shape Factor (SSF) defined in FEMA P-695, based on period-based ductility determined in the nonlinear static pushover analysis. The probability of collapse given MCE-level ground motions, $P_{c|MCE}$ was calculated based on the ACMR and the total dispersion calculated in Eq. (1).

Spectral matching decreased the dispersion in structural response (β_{RTR}) for both the 4-story and 8-story buildings and decreased the dispersion across the full range of ground motion intensities. For the 4-story building, spectral matching decreased the median collapse intensity in terms of spectral acceleration (CMR) by 8%. By contrast, for the 8-story building the median collapse intensity was higher for spectral matched motions by 9%. Spectral matching usually led to less severe structural response, but not always (see Fig. 4, for example). Interestingly, the collapse safety of both the 4-story and 8-story buildings was predicted to be higher for spectral matched motions. The increase in predicted collapse safety is probably attributable to that fact that for design basis earthquake (DBE) ground motions and for maximum considered earthquake (MCE) ground motions, a change in the dispersion leads to a larger impact, compared to a change in the median collapse intensity. Thus, even though the modified ground motions led to results for the 8-story building that indicated a smaller margin of safety, the conditional probability of building collapse (given MCE ground motions) was lowered for both buildings using the modified ground motions compared to the original ground motions. Moreover, both buildings met the ASCE 7 requirement of a conditional collapse probability less than or equal to 10%.

Table 1 – Summary of Predicted Building Safety

Ground Motions	**Median CMR**	**ACMR**	$\boldsymbol{\beta_{RTR}}$	$\boldsymbol{\beta_{Total}}$	$\mathbf{P_{c\|MCE}}$
4-story building					
Original	1.66	2.43	0.35	0.46	2.8%
Spectral Matched	1.53	2.24	0.29	0.42	2.7%
8-story building					
Original	1.41	1.93	0.34	0.45	7.2%
Spectral Matched	1.53	2.08	0.25	0.39	3.1%

4. Repair Costs and Downtime

Seismic performance in terms of repair costs and downtime was predicted using the FEMA P-58 framework and a sub-set of ground motions (listed in Table 2) that were selected from the FEMA P-695 Far Field ground motion set. The original ground motion sub-set (left plot in Fig. 4) was normalized using the *FEMA P-695 Toolkit* [15]. As in the collapse safety analyses, the spectral matched ground motion sub-set (right plot in Fig. 4) was not velocity normalized. The sub-set was then scaled to the intensity level of interest: (1) a serviceability-level intensity, defined as 20% of the MCE, which roughly corresponds to a 72-year mean recurrence interval for the western United States [16]; (2) a DBE-level intensity, which corresponds to 67% of the MCE for design using ASCE 7; and (3) an MCE-level intensity.

As was observed in the collapse safety assessment, spectral matching generally led to less severe structural response compared to the original ground motions, but not always (see Fig. 2). To illustrate a ground motion record and building where spectral matching was more severe, the nonlinear story drift response history for the ABBAR--L record is shown in Fig. 5 for the 4-story building. The difference in response is negligible at the serviceability-level ground motion intensity, but significant at the DBE and MCE level intensities.

Table 2 – Ground Motion Sub-Set used to Predict Seismic Performance

P-695 ID	Record Name	Earthquake	Magnitude
1	Beverly Hills - Mulhol	1994 Northridge	6.7
2	Canyon Country-WLC USC	1994 Northridge	6.7
11	Yermo Fire Station CDMG	1992 Landers	7.3
15	Abbar BHRC	1990 Manjil, Iran	7.4
17	Poe Road (temp)	1987 Superstition Hills	6.5
18	Rio Dell Overpass	1992 Cape Mendocino	7
21	LA - Hollywood	1971 San Fernando	6.6

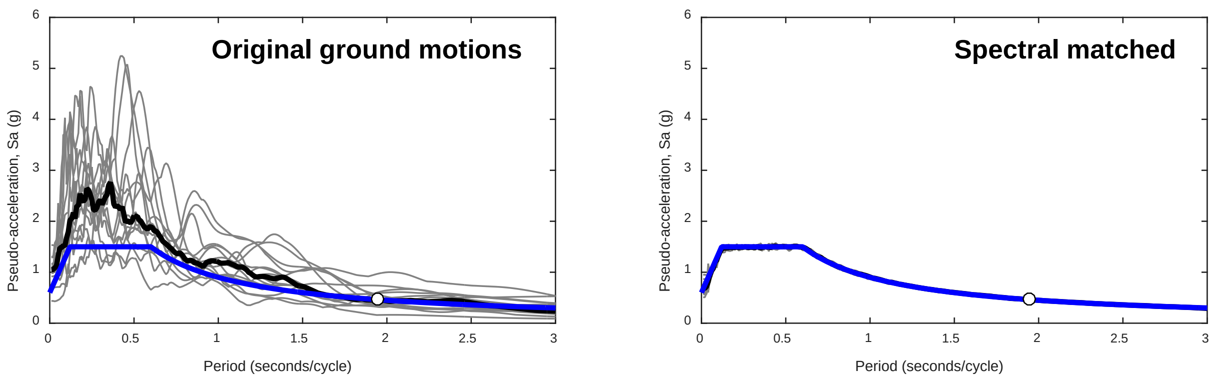
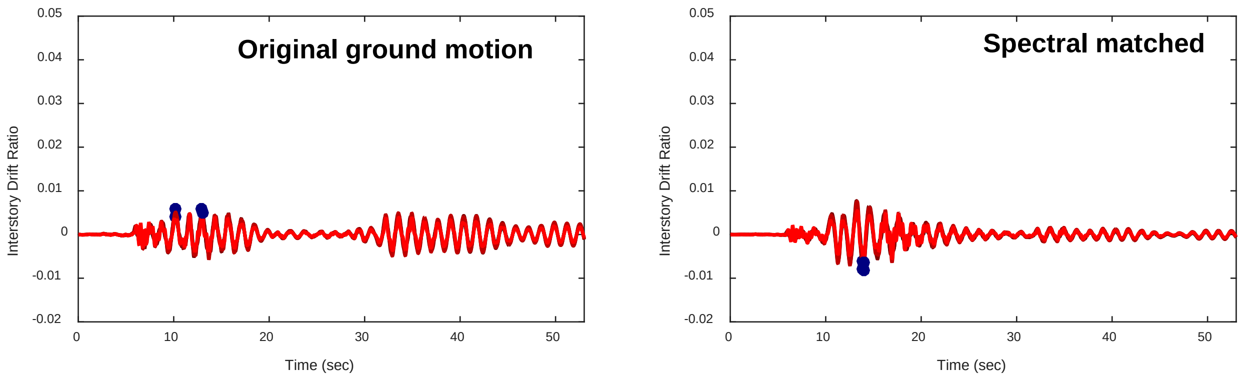


Fig. 4 – Response spectrum of ground motion sub-set used to predict seismic performance

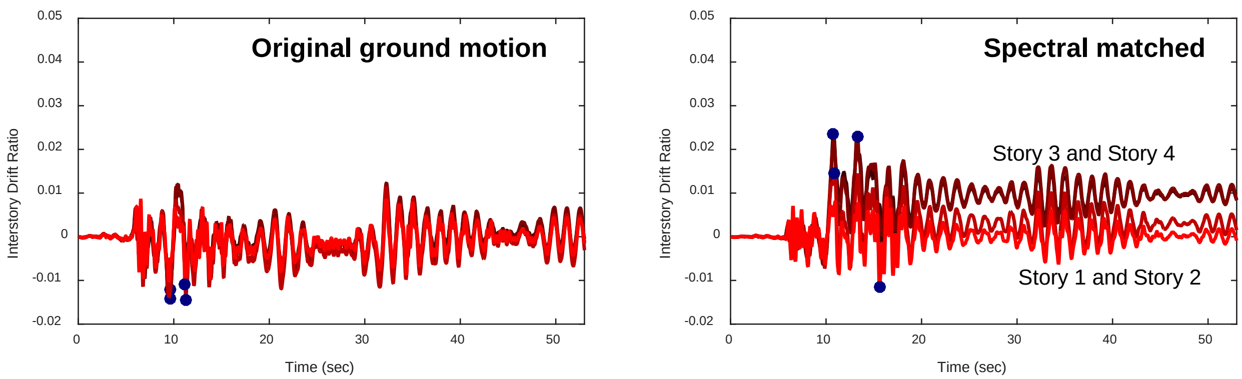
The repair cost, repair time, and likelihood of unsafe placards was predicted using in the FEMA P-58 software *PACT* using 200 Monte Carlo simulations to correlate interstory drifts, floor accelerations, and roof accelerations to structural and non-structural damage. Structural components, for example, consisted of beam connections, column splices, and base plates. Non-structural components included a variety of items, ranging from mechanical, electrical, and plumbing (MEP) equipment to exterior cladding and partition walls. The quantities of components in the buildings were estimated using the FEMA P-58 spreadsheet tools. The *PACT* model is described in [5].

The median predicted performance is summarized in Table 3. Repair cost is shown as a percentage of the total cost of replacing the building, estimated at 230 dollars/sf for the core and shell and 537 dollars/sf for tenant improvements. The repair cost data in *PACT* was adjusted to reflect 2013 national average commercial construction costs in the United States. Repair time was estimated using typical construction schedules (392 days for the 4-story buildings, and 462 days for 8-story buildings) based on advice from practicing engineers. The maximum number of workers per square foot (used to calculate repair time) was one worker per 1,000 square feet (the default value in *PACT*). Although not directly quantified in Table 3, in this study "downtime" was defined as encompassing both the repair time and the probability of an unsafe placard ("red tag") being placed on the building, since both consequences could lead to operational downtime of the office building.

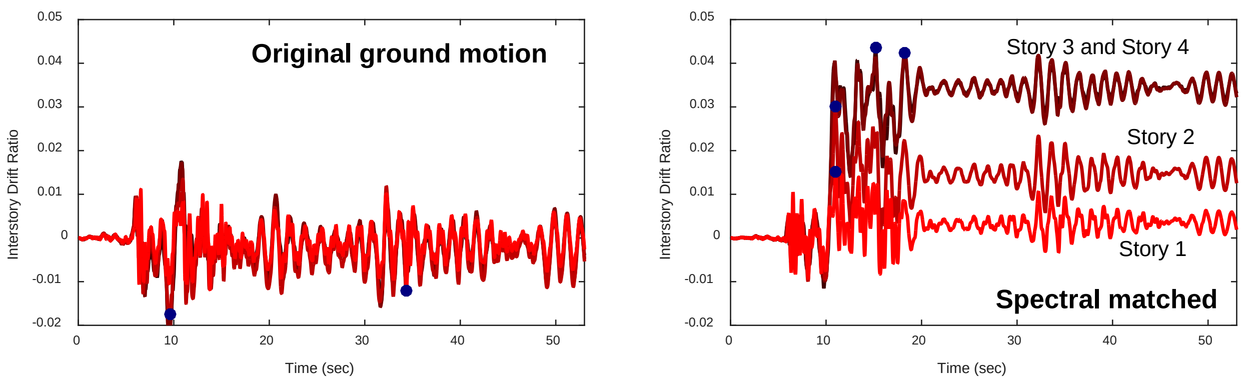
The contribution of structural and non-structural components to the predicted damages and cost depended on the individual scenario simulated in *PACT*, but generally speaking, the repair costs and associated repair time were dominated by damage to interior partition walls. Other significant contributors to damage included bolted shear tab connections for the gravity beams, and unanchored MEP equipment. As was observed in the collapse safety assessment, spectral matching generally led to less damage, but not always (Fig. 5 as a case in point).



(a) Serviceability-level intensity (20% of the MCE)



(b) DBE-level intensity (67% of the MCE)



(c) MCE-level intensity

Fig. 5 – Nonlinear story drift response history for ABBAR--L record.
(Solid dots represent the maximum story drift.)

Spectral matching decreased the median expected repair cost, repair time, and the likelihood of the office building being shut down for safety reasons for both buildings at all levels of ground motion intensity, compared to the original seed ground motions. The predicted decrease in damage and downtime was directly caused by the decrease in dispersion in accelerations and story drift ratios from the structural analyses. The difference in predicted performance, however, was more pronounced for lower intensities of ground shaking. At the MCE level, for example, the difference in repair costs between original and modified ground motions was noticeable, but the difference in repair time and the possibility of unsafe placards was not significant.

Table 3 – Summary of Median Predicted Building Performance

Median Building Performance	**Ground motion intensity**					
	20% of MCE		**67% of MCE**		**100% of MCE**	
	Ground motion record					
	Original	**Spectral Matched**	**Original**	**Spectral Matched**	**Original**	**Spectral Matched**
4-story building						
Repair cost (US$)	1,300,000	1,078,000	3,353,846	2,455,556	5,375,000	4,544,444
Repair time (days)	63	49	206	142	334	303
P_{unsafe}	37%	19%	96%	92%	99%	98%
8-story building						
Repair cost (US$)	1,705,000	1,423,333	4,862,500	3,845,455	9,000,000	5,644,444
Repair time (days)	51	41	179	145	360	240
P_{unsafe}	12%	3%	89%	86%	100%	98%

5. Conclusions

Spectral matching the FEMA P-695 Far Field ground motions had a significant effect on seismic collapse safety and performance predictions. For the 8-story building, the probability of collapse predicted using spectral matched ground motions was half that predicted using the original ground motions. While the spectral matched motions sometimes resulted in lower collapse margin ratios and more severe structural response, the modified ground motions always decreased the dispersion in both the linear and the nonlinear response. Thus, the increase in predicted collapse safety was ascribed to observation that a change in the dispersion led to a larger impact compared to a change in the median collapse intensity, for DBE-level and MCE-level ground motions. This decrease in the response dispersion not only dominated the prediction of the probability of collapse, it also dominated the probability of building damage and downtime.

Spectral matching may be valid, therefore, for a FEMA P-695 collapse safety analysis that does not use the record-to-record dispersion from the IDA, and that instead uses a pre-defined value of dispersion (say, β_{RTR} = 0.4, for example). In such an approach using a pre-defined dispersion, the decreased dispersion caused by spectral matching simply does not enter the assessment. In fact, in terms of computational speed spectral matching may lead to a more efficient calculation of the median collapse margin ratio.

On the other hand, spectral matching for a FEMA P-58 analysis to evaluate seismic performance may not be conservative. The narrower dispersion in structural response associated with spectral matched ground motions compared to the original ground motions generally led to lower estimates of building damage, repair time, and to a smaller likelihood of the building being red tagged.

Further research is required to substantiate these two conclusions, especially with respect to a non-collapse performance assessment. The results discussed here were based on one sub-set extracted from the FEMA P-695 Far Field ground motions, and it is recognized that a different sub-set selection may lead to different conclusions. Similarly, it is important to recognize that the goal of this study was to establish whether spectrally matched FEMA P-695 Far Field ground motions are reliable to use in engineering practice for performance assessments, and other sets of ground motions (such as the FEMA P-695 Near Field ground motions set) are also beyond the scope of the current study. Finally, when compared with the results from a prior study of similar buildings, this study demonstrated the importance of maintaining a good match with the response spectrum over a wide range of structural response, especially in the high-frequency content band (periods less than T_0 = 0.2 S_{D1}/S_{DS}).

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