INL/CON-10-20691
PREPRINT

Comparison of Nonlinear Model Results Using Modified Recorded and Synthetic Ground Motions

SMiRT 21

R. E. Spears
J. K. Wilkins

November 2011

COMPARISON OF NONLINEAR MODEL RESULTS USING MODIFIED RECORDED AND SYNTHETIC GROUND MOTIONS

R. E. Spears, J. K. Wilkins
Idaho National Laboratory, Idaho Falls, Idaho, USA-83415
E-mail of corresponding author: Robert.Spears@inl.gov

ABSTRACT

A study has been performed that compares results of nonlinear model runs using two sets of earthquake ground motion time histories that have been modified to fit the same design response spectrum. The time histories include applicable modified recorded earthquake ground motion time histories and synthetic ground motion time histories. The modified recorded earthquake ground motion time histories are modified from actual earthquake time history records that are selected based on consistent magnitude and distance. The synthetic ground motion time histories are generated using appropriate Fourier amplitudes, cumulative energy, and drift correction. All of the time history modification is performed using a similar algorithm to fit the design response spectrum. The study provides data to demonstrate that properly managed synthetic ground motion time histories are reasonable for use in nonlinear seismic analysis.

INTRODUCTION

Time history analysis is an important technique for structural seismic analysis especially when the evaluated structural response is nonlinear. For a typical site, design response spectra are established using code guidance (e.g. ASCE 4-98 [1]). To perform the time history analysis, time histories are established for a structure being evaluated with respect to the design response spectra. ASCE 43-05 [2], Section 2.4 makes the following statements with respect to these time histories:

> *Synthetic, recorded, or modified recorded earthquake ground motion time histories may be used for linear seismic analyses. Actual recorded earthquake ground motion or modified recorded ground motion shall be used for nonlinear seismic analyses. ... A modified recorded accelerogram is a time-history record of acceleration versus time that has been produced from an actual recorded earthquake time history. However, the Fourier amplitudes are scaled such that the resulting response spectrum envelops the target response spectrum…*

ASCE 43-05 [2], Section 2.4 also states that actual recoded earthquake ground motions are desirable for nonlinear analysis, but modified recorded ground motion are acceptable due to the potentially large number actual recoded earthquake ground motions needed to meet the response spectra requirements.

The study performed in this paper provides data to demonstrate that properly managed synthetic ground motion time histories are reasonable for use in nonlinear seismic analysis. The situation can exist where a seismic analysis group puts significant effort into establishing a representative set of directional acceleration time histories for a single earthquake event that is appropriate for a given site. If a structural analysis group then needs to perform nonlinear analysis on a structure at the site, it is desirable to have the flexibility of using synthetic ground motions for the additional required time histories. If synthetic ground motions are acceptable, then any number of additional time histories can be developed to support the nonlinear analysis using the initial set of directional acceleration time histories for reference. Also, no additional analysis effort is required from the seismic analysis group.

The study in this paper is performed as a hypothetical analysis on a hypothetical piping system experiencing earthquakes in a single horizontal direction. The first step in this study is to establish the hypothetical piping system (which represents a reasonable configuration for piping attached to a nuclear reactor). The second step in this study is to establish actual recorded earthquake ground motions from different earthquakes but having similar magnitude/distance pairs. Nine actual recorded earthquake ground motions are found which represents a significant number for comparison. The third step is to establish an appropriate design response spectrum and modify the nine actual recorded earthquake ground motions into modified recorded ground motions. The fourth step is to select a single modified recorded ground motion (as though it is the ground motion provided by a seismic analysis group) and develop nine synthetic ground motions based on it. The fifth step is to apply the acceleration time histories to the hypothetical piping system and compare the modified recorded ground motion results to the synthetic ground motion results. For comparison, three versions of the hypothetical piping model are run with all eighteen time histories. These include a linear model version (for information), a geometric nonlinear model version (where the springs only act in one direction), and a material nonlinear and geometric nonlinear model version (where plasticity is considered)

HYPOTHETICAL PIPING SYSTEM

The hypothetical piping system is shown in Fig. 1. It is made of linear beam elements in the straight sections and parabolic beam elements in the elbows. The wall thickness in the elbow and branch elements has been reduced to accommodate bending softening consistent with flexibility factors defined in the 2007 ASME Section III, Division 1, Subsection NB [3]. The beam material properties are representative of stainless steel and the densities of the various pipe sizes have been adjusted to account for water inside the pipes. There are also spring elements for the supports. The restraints on the model include fixed restraints at the termination points on the pipe and pinned restraints on the springs (which don't have rotational degrees of freedom).

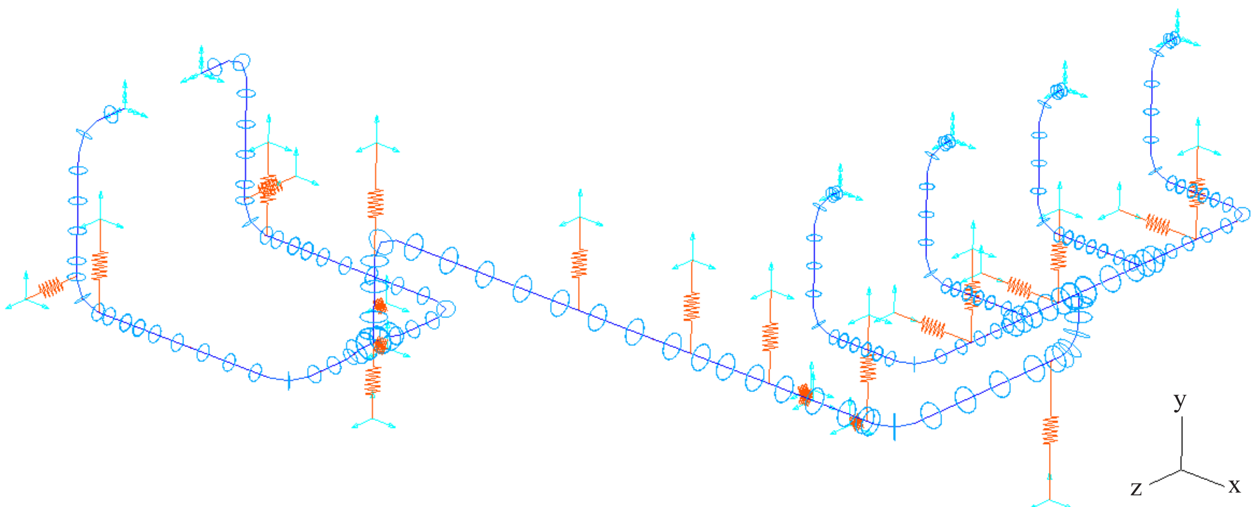


Fig. 1: Hypothetical piping system

The first plot in Fig. 2 shows the cumulative effective mass ratio of the model in the z-direction (identified in Fig. 1). This is the direction that the acceleration time histories are applied to the model (and gravity is also applied to the model in the negative y-direction). To accommodate nonlinearity, the model is run as a direct time history analysis. Consequently, Rayleigh damping is used to approximate a 5% modal damping. The second plot (in Fig. 2) shows the Rayleigh damping curve used (shown as a solid red curve) and a 5% damping curve (shown as a dotted blue curve). The third plot (in Fig. 2) shows how the response spectrum differs between that for the Rayleigh damping curve (shown as a solid red curve) and that for a 5% modal damping curve (shown as a dotted blue curve). (The time history for the response spectra example is the modified recorded ground motion used to generate the synthetic ground motions discussed later.)

The first plot in Fig. 2 shows that the first significant natural frequency of the model occurs at a frequency of 3.8 Hz. This corresponds to one point where the Rayleigh damping curve is equal to 5%. The other point where the Rayleigh damping curve is equal to 5% is at 6.9 Hz. This creates a situation where a good agreement is achieved between the Rayleigh damped and 5% modal damped response spectra from about 3 Hz to 100 Hz. Another observation that can be made with the first plot in Fig. 2 is that 14 mode shapes and a little more than 70% of the model mass are represented at frequencies in the range of 2.5 Hz to 10 Hz.

The same mesh and acceleration time histories are used for all of the model runs. These include linear model runs, geometric nonlinear model runs, and material nonlinear and geometric nonlinear model runs. The geometric nonlinear model runs differ from the linear models only in the spring definitions. For the geometric nonlinear model runs, the vertical springs above the piping only act in tension. Also in the geometric nonlinear model runs, the vertical spring below the piping and the horizontal springs only act in compression. The material and geometric nonlinear model runs differ from the geometric nonlinear models only in the plasticity definitions.

For model runs that are material and geometric nonlinear, the piping has a true yield stress of 25 ksi and a true ultimate stress of 91 ksi at a true plastic strain of 0.259 in/in. Kinematic hardening is used for the plasticity.

Abaqus/Standard [4] software is used to perform the model runs. Stress/strain data is output at 0.005 second intervals during a model run and Abaqus/Standard is used to find maximum stress/strain for a given model run. Combination of results from multiple model runs and resulting stress plot generation is performed with subroutines in Mathcad [5] software.

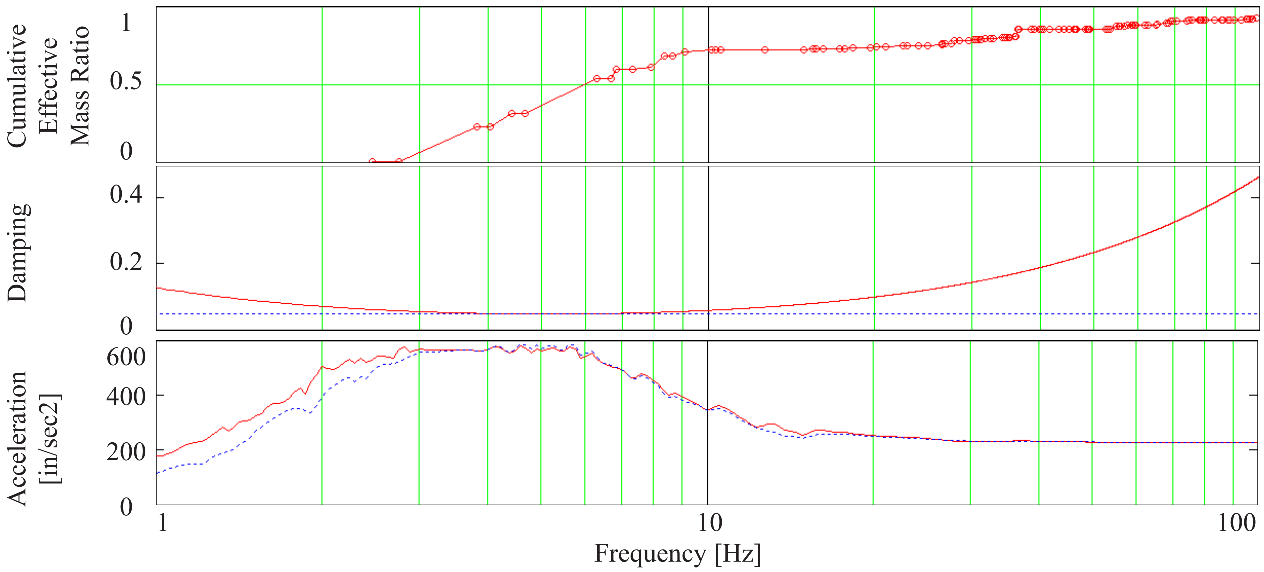


Fig. 2: Cumulative effective mass ratio, damping, and response spectrum

ACTUAL RECORDED EARTHQUAKE GROUND MOTIONS

Nine time histories were downloaded from the online PEER database. The records were gathered from the 1999 Duzce event, the 1974 Hollister event, the 1979 Imperial Valley event, the 1999 Kocaeli event, the 1980 Livermore event, the 1984 Morgan Hill event, the 1966 Parkfield event, the 1987 Superstition Hills event and the 1981 Westmoreland event. An attempt was made to gather records with similar characteristics, such as soil type, distance to rupture, and fault mechanism. As such, these records were all generated by a strike slip fault mechanism, each record was collected on a USGS class C soil (180-360 meter/second shear wave velocity to a depth of 30 meters) and each record was located no greater than 20 kilometers from the fault rupture. The range of PGA for the records was 0.822 to 0.154 g. The range of PGV was 10.3 to 62.1 cm/second (4.05 to 24.4 inches/second). The range of PGD was 1.25 to 17.61 cm (0.49 to 6.94 inches). Only one record from any given seismic event was collected. Because of this requirement, the range of behaviors observed in the time histories is wide. Nevertheless, this group is still broadly representative of the activity that can be expected near a strike slip fault on class C soils. The most powerful record is from the 1999 Duzce, Turkey earthquake and its PGA is 0.822 g. The weakest earthquake is from the Livermore earthquake of 1980 and its PGA is 0.154 g.

DESIGN RESPONSE SPECTRUM AND MODIFIED ACTUAL RECORDED EARTHQUAKE GROUND MOTIONS

The design response spectrum for this study is developed considering the nine actual recorded time histories and considering that the motion needs to be strong enough to develop material nonlinearity. To produce a reasonable design response spectrum, the actual recorded ground motions response spectra are scaled to make their cumulative energy values similar. The design response spectrum is then drawn such that, at any frequency, only one actual recorded ground motion response spectrum is not enveloped. This design response spectrum is then scaled up to ensure significant plasticity in the hypothetical piping model. While this is not a rigorously developed design response spectrum for a given site, it represents a reasonable hypothetical site-specific design response spectrum where the nine actual recorded ground motions are relevant.

To produce modified actual recorded ground motions, the method described in Spears [6] is used. The primary modification technique in this method is based on scaling the Fourier amplitudes to modify the response spectrum to better match the design response spectrum. There are also less significant low energy modifications performed to improve the response spectra match. Fig. 3 shows the resulting design response spectrum (center blue dotted curve) and nine modified actual recorded ground motion response spectra (red solid curves). (The upper and lower blue dotted curves represent the acceptable error bands as defined in ASCE 43-05 [2], Section 2.4.) Fig. 4 shows acceleration and displacement time histories for the nine modified recorded ground motions.

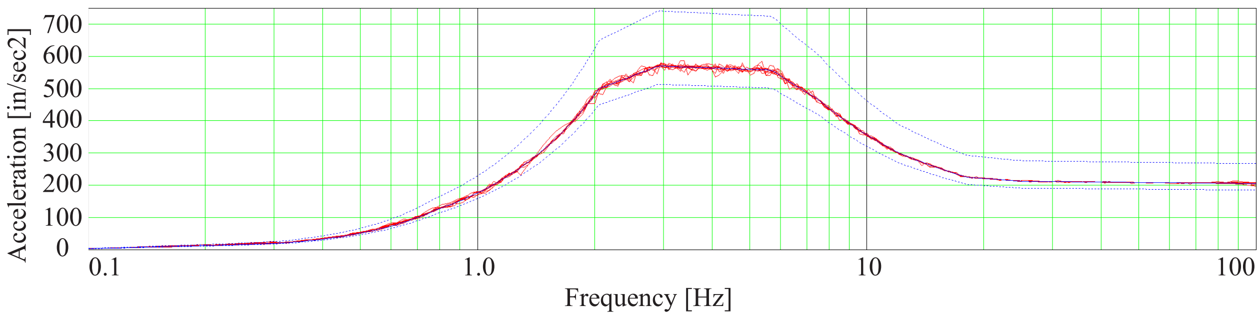


Fig. 3: Design response spectrum and response spectra for the nine modified recorded ground motions

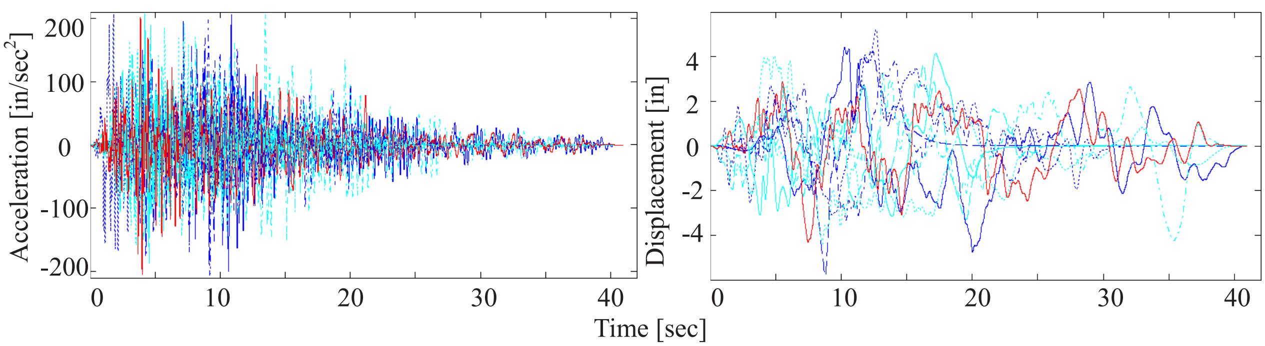


Fig. 4: Acceleration and displacement time histories for the nine modified recorded ground motions

SINGLE MODIFIED RECORDED GROUND MOTION AND SYNTHETIC GROUND MOTIONS

To generate synthetic ground motions, a single modified recorded ground motion is selected (as though it is the ground motion provided by a seismic analysis group). The selected modified recorded ground motion for this study is the solid red curve from Fig. 4. This is a somewhat arbitrary selection as any of these modified recorded ground motions should be appropriate. The selected modified recorded ground motion is the fifth time history to reach 50% of its maximum cumulative energy in time. It is the fourth longest record and it has the second highest total cumulative energy.

To develop the nine synthetic ground motions, a process similar to that described by Spears [7] is used. Initially, Fourier transform amplitudes and acceleration time history amplitudes (averaged over half second intervals) are established. This is shown in Fig. 5 where the red curves are the Fourier transform amplitudes and acceleration time history for the selected modified recorded ground motion. The blue curves in Fig. 5 are the established amplitudes. (The Fourier transform amplitudes are not average so the blue curve is on the red curve.)

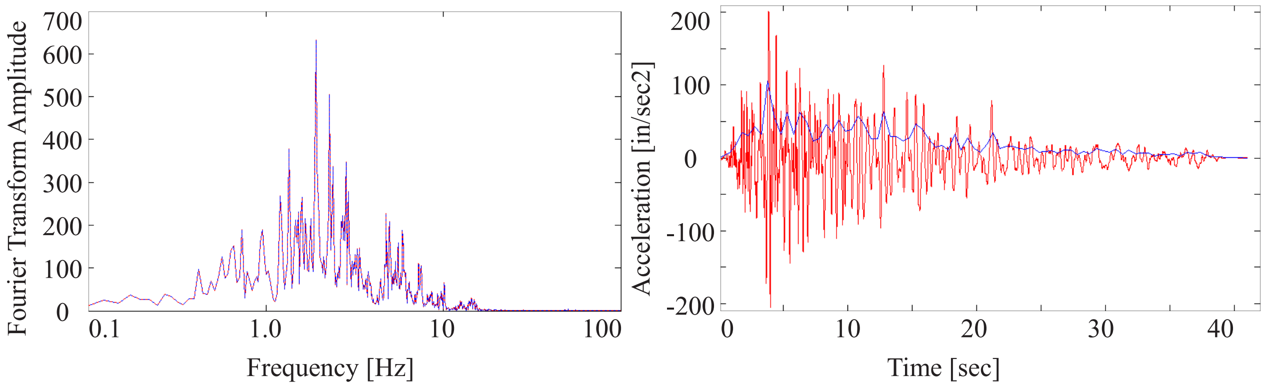


Fig. 5: Fourier transform amplitudes and acceleration time averaging

Next, random phasing is assigned to the Fourier transform amplitudes and the inverse transform is taken to produce each acceleration time history (with the desired frequency content). The averaged acceleration time history amplitudes are then used to shape each acceleration time history (giving it an appropriately shaped cumulative energy versus time). It is also scaled to achieve the appropriate total cumulative energy. Finally, the acceleration time history is drift corrected and given a reasonable displacement time history. For this study, this is performed in five steps. First, the Fourier transform is taken on the displacement time history (produced by twice integrating the selected modified recorded ground motion). Second, random phasing is assigned to the displacement Fourier transform amplitudes and the inverse transform is taken to produce a new displacement time history (with the right frequency content). Third, the start and end of the of the displacement time history are smoothly transitioned to zero. This occurs at times outside the 5% to 95% region of the cumulative energy relative to the total cumulative energy for the selected modified recorded acceleration ground motion. Fourth, the acceleration time history is modified with low frequency (< 0.5 Hz) corrections such that, when integrated twice, its displacement time history is similar to the developed displacement time history. Fifth, cosmetic corrections are made to the start and end of the acceleration time history (also outside the 5% to 95% region of the cumulative energy relative to the total cumulative energy) to ensure it starts and ends at zero.

This process is repeated nine times and the resulting time histories are modified further to achieve a good match with the design response spectrum. This modification is performed using the same techniques as used to produce the modified actual recorded ground motions except only the low energy modifications are applied. (The portion based on scaling the Fourier amplitudes tends to significantly alter the total cumulative energy and the desired total cumulative energy has already been achieved at this point in the process.) The resulting modified time histories are the synthetic ground motions. Fig. 6 shows acceleration and displacement time histories for the nine synthetic ground motions. The correlation coefficient between any two of the synthetic ground motions shown in Fig. 6 is less than 0.3 (as required by ASCE 43-05 [2], Section 2.4).

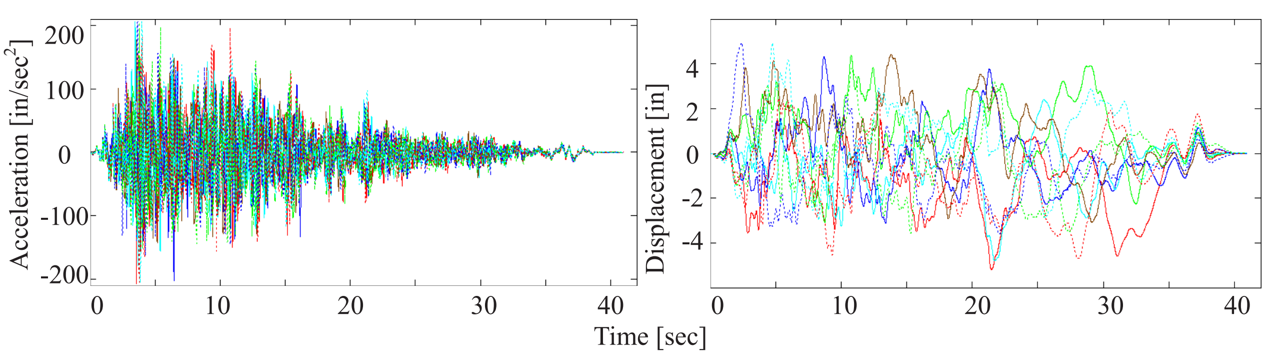


Fig. 6: Acceleration and displacement time histories for the nine synthetic ground motions

Fig. 7 shows the resulting nine modified actual recorded ground motion response spectra (red solid curves) and the design response spectrum (center blue dotted curve). (The upper and lower blue dotted curves represent the acceptable error bands as defined in ASCE 43-05 [2], Section 2.4.)

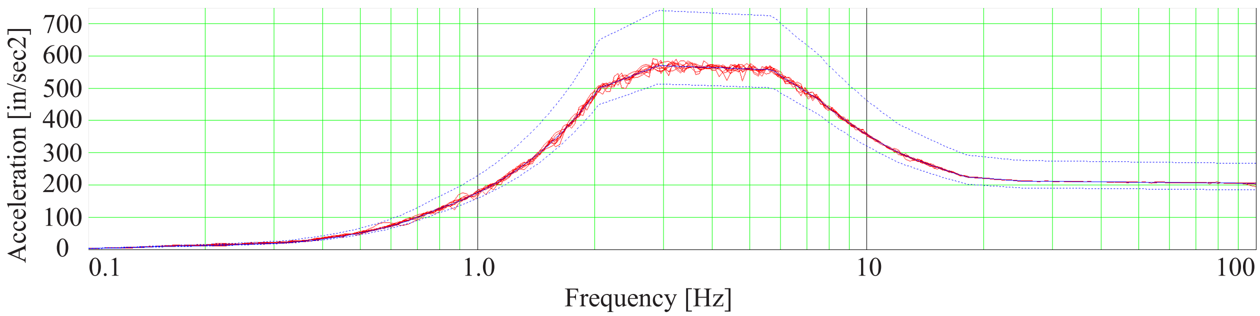
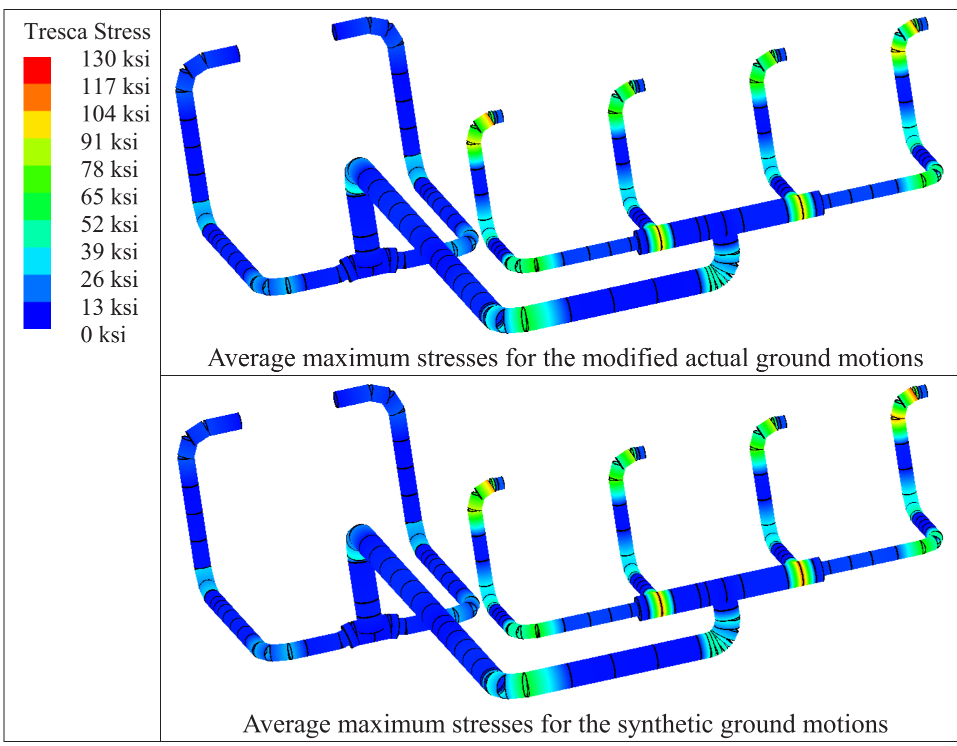


Fig. 7: Design response spectrum and response spectra for the nine synthetic ground motions

MODIFIED RECORDED GROUND MOTION AND SYNTHETIC GROUND MOTION RESULTS

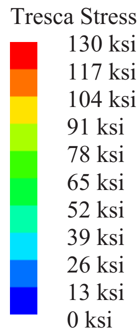
The Tresca stress results of the modified actual ground motions and synthetic ground motions are summarized in Fig. 8 – 10. These figures show linear model results, geometric nonlinear results, and material and geometric nonlinear model results respectively. To evaluate results, maximum nodal results are found for each model run. Using these maximum results, the highest, average, and lowest nodal results are found for each group of nine model runs. Fig. 8 – 10 only show plotted results for the average maximum stresses, but the maximum stress value for each case is listed on the right side of the figures.

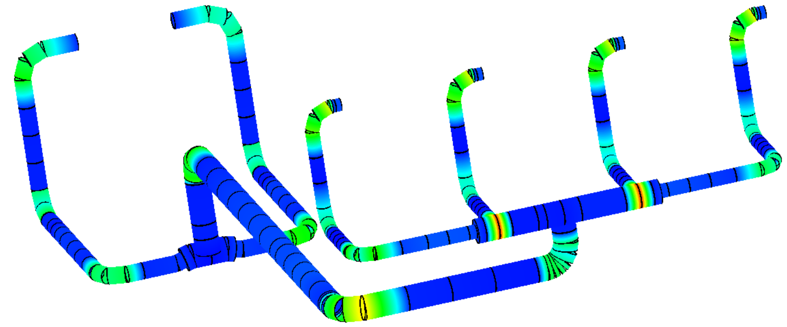


Maximum stress	[ksi]
For the highest maximum stresses results	134
For the average maximum stresses results (shown to left)	114
For the lowest maximum stresses results	89.5

Maximum stress	[ksi]
For the highest maximum stresses results	139
For the average maximum stresses results (shown to left)	123
For the lowest maximum stresses results	113

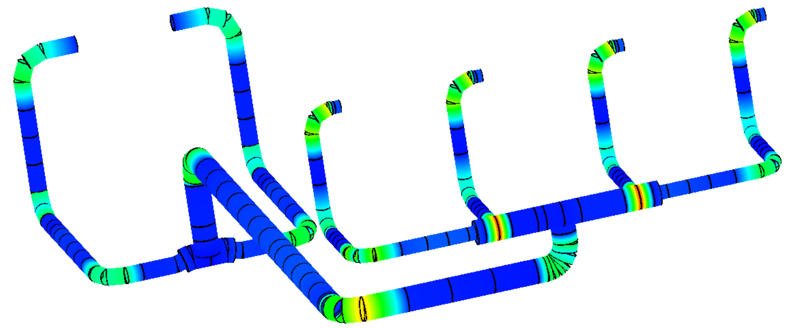
Fig. 8: Linear model Tresca stress results





Average maximum stresses for the modified actual ground motions

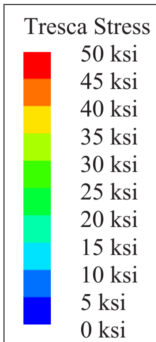
Maximum stress	[ksi]
For the highest maximum stresses results	180
For the average maximum stresses results (shown to left)	128
For the lowest maximum stresses results	93.4

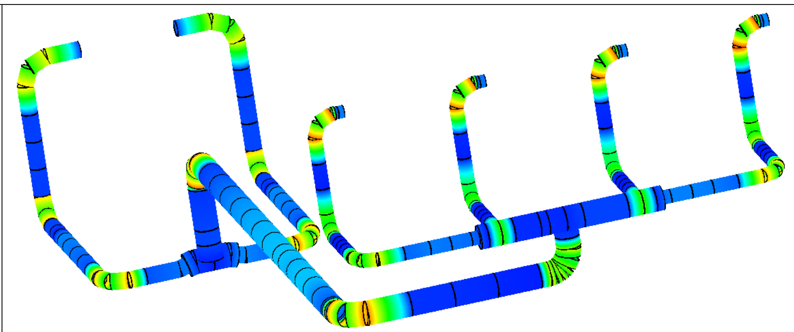


Average maximum stresses for the synthetic ground motions

Maximum stress	[ksi]
For the highest maximum stresses results	174
For the average maximum stresses results (shown to left)	130
For the lowest maximum stresses results	103

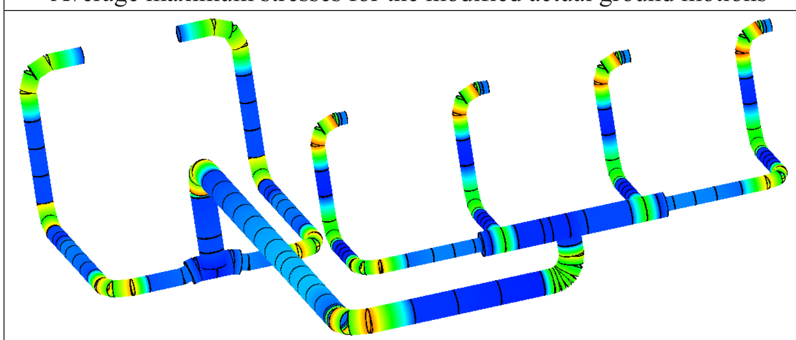
Fig. 9: Geometric nonlinear model Tresca stress results





Average maximum stresses for the modified actual ground motions

Maximum stress	[ksi]
For the highest maximum stresses results	50.2
For the average maximum stresses results (shown to left)	46.7
For the lowest maximum stresses results	45.6



Average maximum stresses for the synthetic ground motions

Maximum stress	[ksi]
For the highest maximum stresses results	50.1
For the average maximum stresses results (shown to left)	47.3
For the lowest maximum stresses results	47.1

Fig. 10: Material and geometric nonlinear model Tresca stress results

There is significant plastic strain that occurs in the material and geometric nonlinear models. For the modified actual ground motion model runs, the highest maximum equivalent plastic strain is 0.129 in/in, the average maximum equivalent plastic strain is 0.085 in/in, and the lowest maximum equivalent plastic strain is 0.040 in/in. For the synthetic ground motion model runs, the highest maximum equivalent plastic strain is 0.125 in/in, the average maximum equivalent plastic strain is 0.114 in/in, and the lowest maximum equivalent plastic strain is 0.076 in/in. (As noted previously, the synthetic ground motions used in the study are developed using only low energy modifications to produce a response spectra match. This approach does not significantly alter the total cumulative energy. Repeating the study with the synthetic ground motions being developed including the Fourier amplitude scaling techniques increases total cumulative energy and maximum equivalent plastic strain values by about 50% while leaving the maximum stress values essentially unchanged.)

CONCLUSION

A study has been performed that compares results of nonlinear model runs using two sets of earthquake ground motion time histories that have been modified to fit the same design response spectrum. The time histories include modified recorded earthquake ground motion time histories modified from actual earthquake time history records and synthetic ground motion time histories using appropriate Fourier amplitudes, cumulative energy, and drift correction. The study shows results for a linear model (for information), for a geometric nonlinear model, and for a material nonlinear and geometric nonlinear model. All of the models show very good Tresca stress agreement relative to the stress plot pattern and maximum Tresca stress. Also, the model with material nonlinearity shows very good maximum equivalent plastic strain agreement. Consequently, this study provides data to demonstrate that properly managed synthetic ground motion time histories are reasonable for use in nonlinear seismic analysis.

ACKNOWLEDGEMENTS

Notwithstanding the terms and conditions included in the ASME copyright form (1903), the identified paper, material, or work was or will be authored by Battelle Energy Alliance, LLC (BEA) under Contract No. DE-AC07-05IDI45 17 with the U.S. Department of Energy. The United States Government retains, and the other entity or entities identified in this document, by accepting the identified paper, material, or work for publication acknowledges that the United States Government retains, a non-exclusive, paid-up, irrevocable, world-wide license to publish and reproduce the published form of the identified paper, material, or work or allow others to do so, for United States Government purposes. BEA does not make any expressed or implied representations or warranties with respect to fitness for use of the identified paper, material, or work and BEA does not indemnify the other entity or entities identified in this document or any third parties from any and all claims, damages, or attorney fees that may arise from the use, reproduction, or publication of such paper, material, or work. Any and all litigation involving entities rights and duties under this document will be brought in a court of competent jurisdiction in the state of the defendant's principal place of business identified in this document.

REFERENCES

[1] "ASCE 4-98, Seismic Analysis of Safety-Related Nuclear Structures and Commentary," *American Society of Civil Engineers*, 1998.
[2] "ASCE/SEI 43-05, Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities," *American Society of Civil Engineers*, 2005.
[3] "ASME Boiler & Pressure Vessel Code BPVC, Section III, Division 1 – Subsection NB," *American Society of Mechanic Engineers, ASME International*, 2007.
[4] ABAQUS Standard, Version 6.10-2, ABAQUS Inc., 2007.
[5] Mathcad 14.0, Parametric Technology Corporation, 2007.
[6] Spears, R. E., "Method for Generating Design Earthquake Time Histories with an Emphasis on Maintaining Phasing, PVP2010-25229," *Proceedings of PVP2010 ASME Pressure Vessels and Piping Division Conference*, July 2010.
[7] Spears, R. E., "Unique Method for Generating Design Earthquake Time History Seeds, PVP2008-61244," *Proceedings of PVP2008 ASME Pressure Vessels and Piping Division Conference*, July 2008.