Appendix B - Verification of OpenSees

B.1 Introduction

In order to put OpenSees to use for the purposes of nonlinear dynamic analysis, a rigorous set of verifications must first be performed to establish baseline behavior and to verify new material properties. Because OpenSees is a new program, there is relatively little experience in using it for nonlinear dynamic analysis and no library of relevant reference files for such complex requirements. OpenSees must be verified before complex analyses are pursued to ensure that the program is providing accurate results and to verify modeling practices for structural behavior. The models used for verification serve the purpose of proving program accuracy as well as practice for achieving desired dynamic structural behavior. Verification of OpenSees is important because it ensures that the results will be dependable and valid in more complex analyses.

Understanding how to correctly model structural systems is important to attain the desired behaviors in a new program for future analyses. Such behavior ranges from linear material behavior to more complex issues like damping and nonlinear materials. These structural properties are independently analyzed in the verification models to achieve a complete understanding of dynamic modeling in OpenSees. The results are compared to identical models run under the programs Nonlin version 7.0 (2002) and Drain-2DX (2003). Once the behavior of standard dynamic properties is understood with an analysis package, applying the software to new and more advanced applications becomes possible. In this chapter, OpenSees is first verified for the standard material and dynamic properties, and later verified for newly added hyperelastic material properties.

Various programs have been chosen for verification versus OpenSees. Nonlin has been chosen for the verification of baseline structural behavior due to the simplicity of the program and the proven accuracy. Nonlin has a dependable set of verified models ranging from simple SDOF (single degree of freedom) systems to more complex models with energy dissipation devices. These models have been verified as being accurate versus Drain 2Dx and are trusted benchmarks for these analyses.

MathCAD (2001) has been chosen for verification of the new hyperelastic material properties programmed into the OpenSees framework. Since a hyperelastic material is not readily available for comparison in another analysis program, a Newmark algorithm created from scratch is used in MathCAD to analyze the material behavior on a step-by-step basis. Drain-2DX is chosen for comparison of the acceleration values given by OpenSees for establishment of force equilibrium. Drain is chosen due to the simplicity of the models and due to the accuracy of the program.

B.2 Baseline Verification Models

An initial set of seven models has been established to verify the baseline structural behavior in OpenSees versus Nonlin. The models consist of one and two degree of freedom systems with varying dynamic characteristics. Increasing levels of complexity are added as the models progress, including regional damping, device damping, yielding behavior, bilinear hysteretic behavior, and P-Delta effects. The response histories for each model are created using the Imperial Valley 1 ground motion for displacement, velocity, and acceleration.

The first model set used for verification involves the analysis of a single degree of freedom (SDOF) portal frame with 3.59% critical damping. The model was established in OpenSees using rigid beam-column elements pinned at each connection. The lateral stiffness is represented using a zero-length spring element at the hinges with material properties assigned to it that represent the desired bilinear material behavior in a rotational direction. The lateral stiffness of the frame is directly input into Nonlin, while it must be back-calculated and input as material properties in OpenSees. The chosen material for lateral stiffness develops a purely bilinear hysteretic behavior for each frame. The model is shown in Figure B.1

The damping is modeled using a truss element with artificially low stiffness, and assigning to it a stiffness-proportional Rayleigh damping factor that is calculated from the desired percent of critical damping. The mass of the structure is divided and concentrated at the two corners of the structure. This model is verified for a bilinear lateral stiffness with hardening, as well as for an elastic-perfectly plastic case with and without P-Delta effects. The response histories computed by OpenSees for displacement, velocity, and acceleration all match those given by Nonlin. The correlations for the dynamic behavior between OpenSees and Nonlin for the first model set are given in Figure B.2. For the sake of detail, the results are shown for the first 5 seconds of system response. Only a small amount of difference (0.5%) is shown between the results from the two programs at the maximum displacement points in the response history.

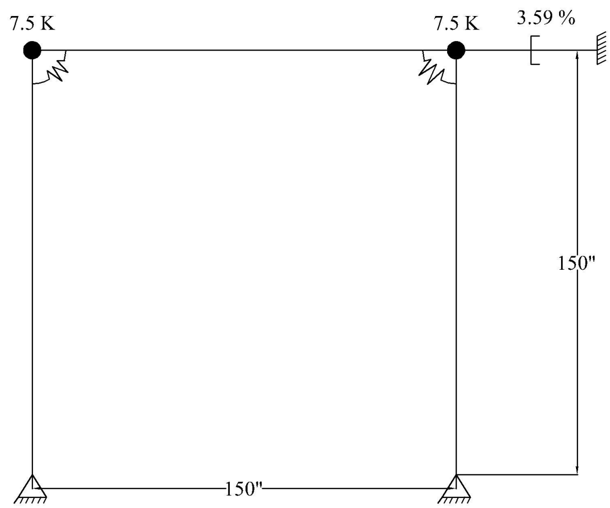

Figure B.1 – SDOF Portal Frame for First Model Set Verification

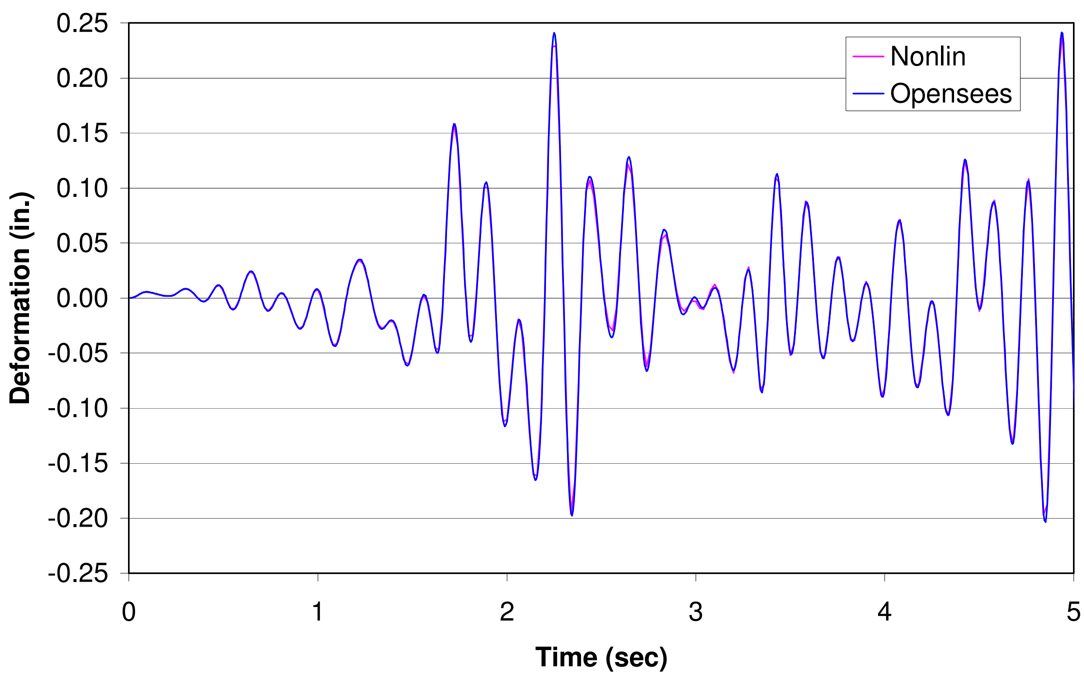

Figure B.2 –Displacement Response History for Model Set 1

The next set of models increases the complexity of the system by adding a chevron brace to the center of the portal frame. Due to the chosen strength of the frame, this is the first model to exhibit structural yielding. Elastic perfectly plastic behavior is assigned to the lateral stiffness for the frame. Accurately modeling yielding behavior is especially important for nonlinear dynamic analysis, so special attention was paid to match the values given by both Nonlin and Drain. The model used for the second set of verifications is shown in Figure B.3.

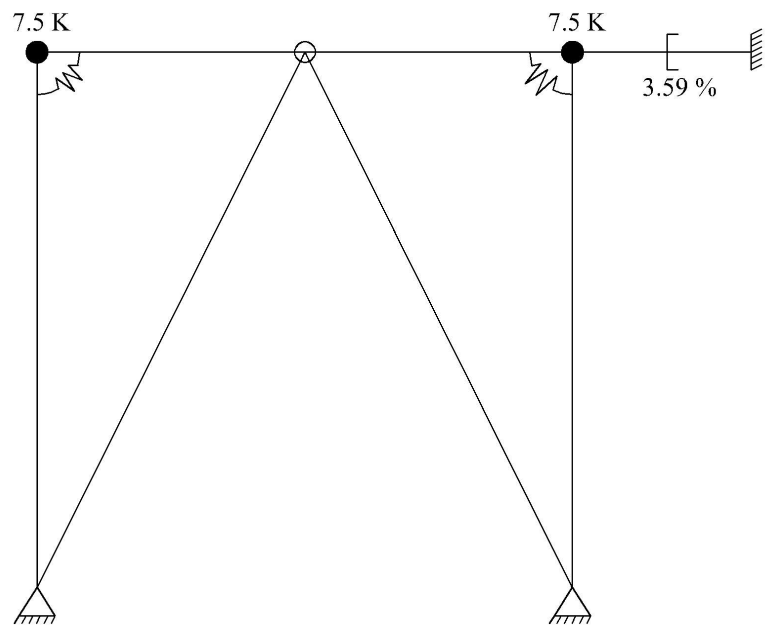

Figure B.3 – SDOF Portal Frame for Second Model Set Verification

This setup was analyzed with and without P-Delta effects, and the results show that the structural responses generated under OpenSees match reasonably well to those given by both Nonlin and Drain 2DX for structural yielding of an elastically, perfectly plastic system. The correlations for the dynamic behavior between OpenSees and Nonlin for the second model set are given in Figure B.4.

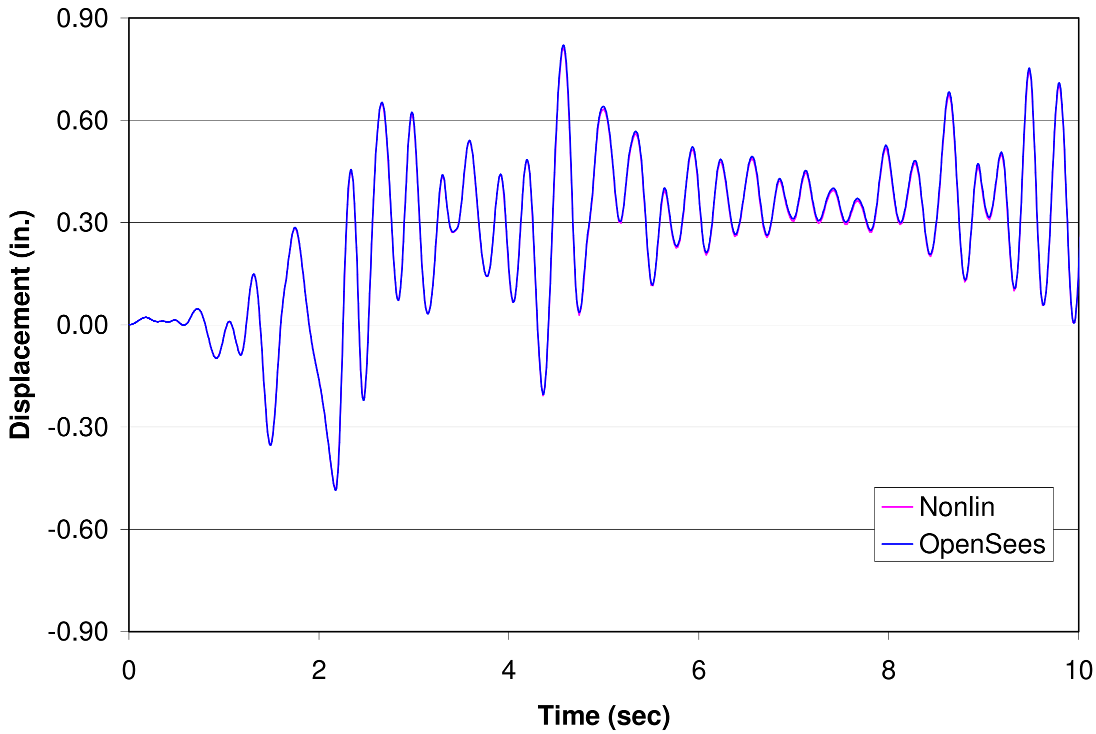

Figure B.4 –Displacement Response History for Model Set 2

The final set of models includes a damping device along with the damping inherent to the external frame. This device is attached from the apex of the chevron bracing to the corner node of the portal frame, and effectively adds a second internal degree of freedom and damping source to the system. The frame for the third set of models is shown in Figure B.5.

The damping device is given a damping coefficient, a bilinear component of lateral stiffness, and mass. The bilinear stiffness of the device introduces the effects of device yielding to the model set. The damping for the device is modeled using a parallel material combination of a bilinear stiffness material and a viscous material for damping. The lateral stiffness of the frame and chevron bracing remain unchanged, and this system was analyzed with and without P-Delta effects. The behavior correlation between OpenSees and Nonlin for this set of models is given in Figure B.6.

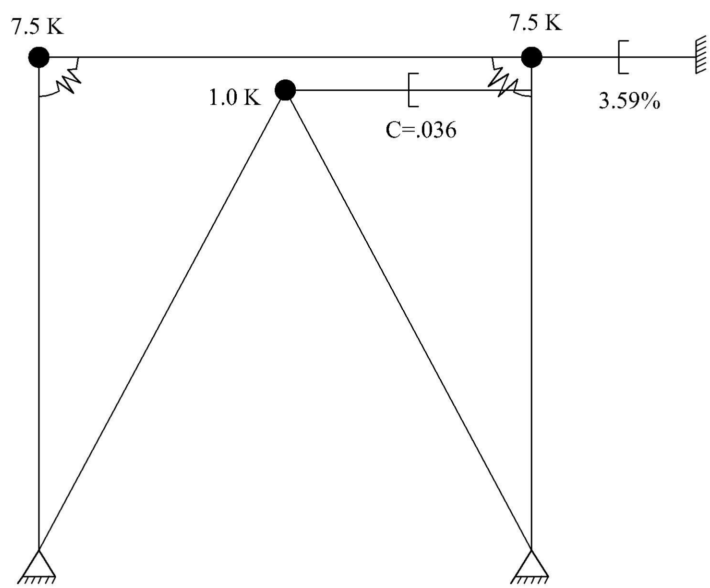

Figure B.5 – Portal Frame for Third Model Set Verification

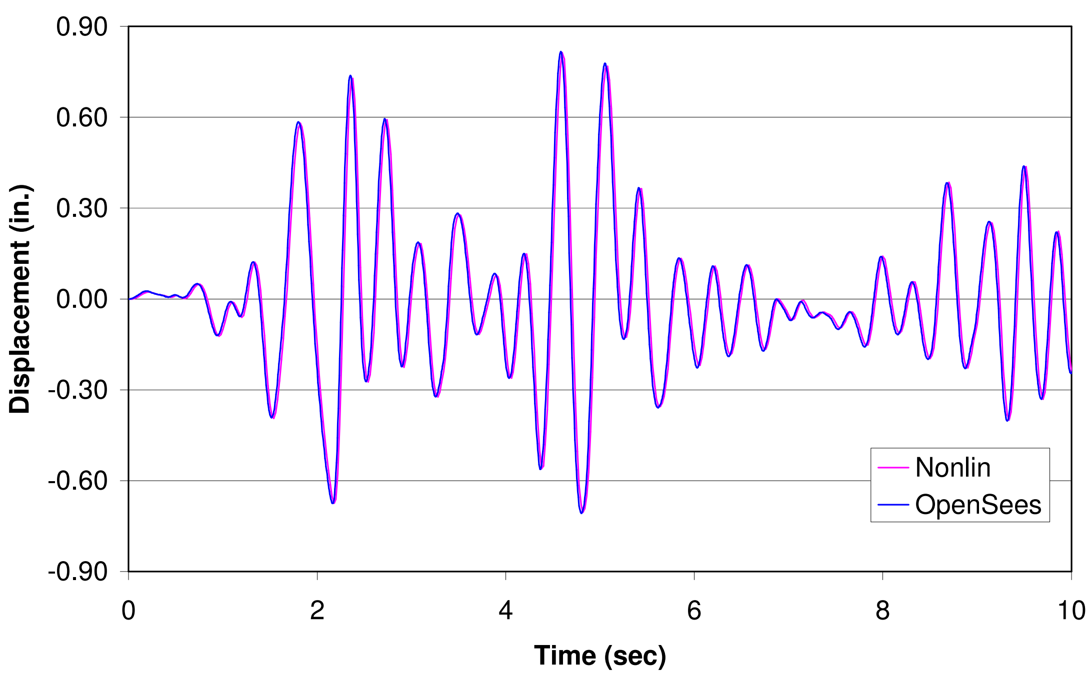

Figure B.6 – Displacement Response History for Third Model Set

The inclusion of P-delta effects is important for accurate modeling of structural systems subjected to a ground motion. Each model setup was considered with and without P-Delta effects in OpenSees and compared to the same results in Nonlin. These effects can be instituted in OpenSees by selecting the type of geometric transformation designed for this purpose, or by directly inputting the geometric stiffness into the material behavior related to the lateral stiffness of the frame. Both methods give the same results when compared to Nonlin.

B.2.1 Baseline Troubleshooting

The bilinear behavior in OpenSees requires verification before the model sets were analyzed. Multiple materials are available that can be used to model material properties such as hardening, pinching, degrading stiffness, and hysteretic behavior. For the purposes of these verifications, a purely bilinear behavior is required for the lateral stiffness behavior of the system to match the behavior of the Nonlin models. Bilinear hysteretic behavior is most accurately given by the Steel01 material in OpenSees for modeling a purely bilinear hysteretic behavior. Other materials introduce different values for pinching and change in modulus upon repeated loading and unloading cycles, which may be helpful for the hysteretic characteristics of other systems. The hysteretic behavior of the Steel01 material as modeled by Opensees is shown in Figure B.7.

The models require special attention at various points during the verification in order for the dynamic behavior to match the Nonlin models. Ensuring that the analysis setup is identical between the two programs is of primary importance. The same integrator, algorithm, and time step are required to avoid mathematical deviation. A Newmark integrator is used with the constant average acceleration factor to solve for the response of the system. Next, special attention must be given to the OpenSees model to ensure that the dynamic properties are the same as in the Nonlin model. The structural period of vibration is found to be influenced by the exact placement of mass. Once all of the dynamic characteristics are taken into account and the same analysis is performed, the results are found to correlate for the model sets.

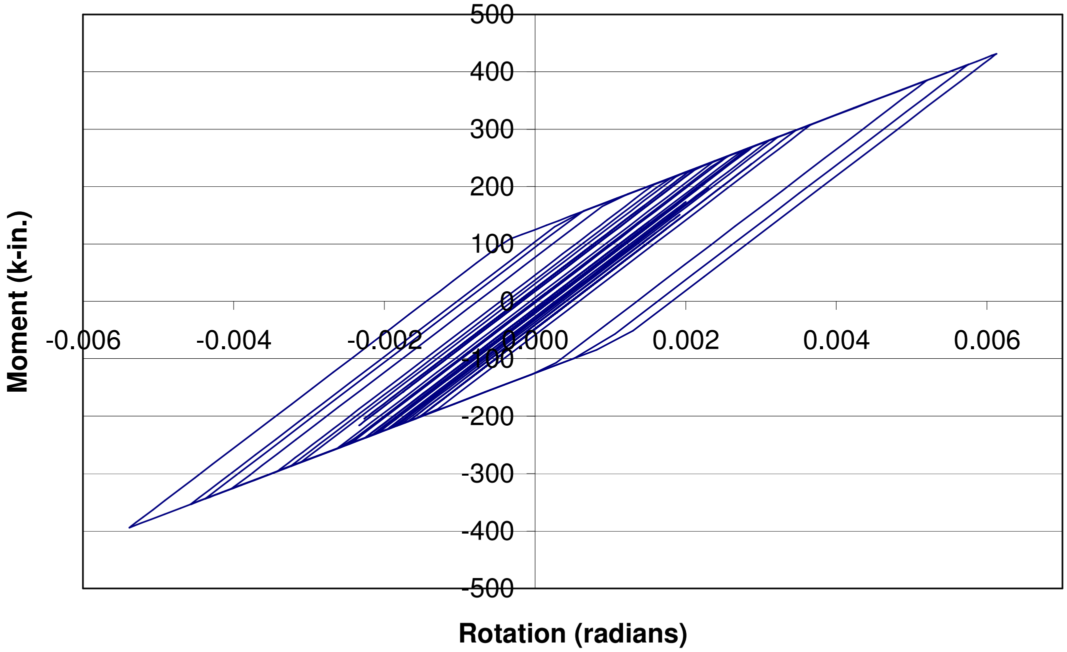

Figure B.7 – Steel01 Hysteretic Behavior

System damping is found to be most consistently modeled as stiffness-proportional Rayleigh damping coefficients rather than mass-proportional coefficients. This is due to the comparative ease of use for the stiffness calculations, and due to the sensitivity of Opensees to the exact placement of mass on dynamic system properties. Rayleigh proportional factors for mass and stiffness can be back-calculated from the viscous damping coefficient, and then assigned to a member with preset stiffness properties. Also, a parallel material may be formed from viscous and uniaxial materials to give the same damping effects. For the device in the final model set, both methods of damping were installed for comparative purposes to observe the effects when device yielding occurs. Both methods for modeling damping were found to give the same results.

B.2.2 Baseline Findings

After taking special care to match each of the structural parameters identically between the two programs, the results are found to correlate for all of the measured response values. The same response histories are found from OpenSees for displacement, velocity, and acceleration for each of the models within 1% of accuracy versus Nonlin. Both techniques of modeling P-Delta behavior in OpenSees give the same results when compared to Nonlin. The only behavioral discrepancy occurs in the elastic, perfectly plastic models, where a large amount of residual displacement occurs. The OpenSees displacement response history shows a larger amount of residual displacement than the results from Nonlin (+17%). However, the OpenSees results show less residual displacement that the results for the same model analyzed under Drain 2DX (-7%). This deviation occurs due to the unpredictable nature of structures with plastic behavior combined with large residual displacements. The structure is very sensitive to errors when approaching the impending instability that gives the large amount of residual displacement. The OpenSees results still fall within an acceptable range between the two dependable analysis programs.

As a result of the verification of baseline structural behaviors, the important parameters in OpenSees are identified so that an accurate representation of structural behavior can be produced. The modeling parameters were systematically modified until the results matched, such as placement of mass and damping type. The capabilities of OpenSees have been established and are shown to be a promising tool for nonlinear dynamic analysis of structures. These results show the accuracy of this program, and structural parameters to be aware of as more complex nonlinear dynamic analyses are pursued with OpenSees.

B.3 Hyperelastic Element Verification

For OpenSees to be productive for the proposed study involving the nonlinear dynamic analysis of structures with hyperelastic devices, a new material property was programmed into the program code. The material was successfully compiled along with the existing OpenSees source code so that the analysis package is now a unique entity. This new material property allows for modeling of hyperelastic elements, or elements composed of materials with an elastic, nonlinear stress-strain response defined by a cubic polynomial. However, verification must be performed to ensure that the behavior of the new material is accurate. Once verified, this type of element is of particular interest as a structural device in seismic response because of the potential for increased structural predictability without the prohibitive increase in structural forces that commonly accompany many other structural devices.

B.3.1 Hyperelastic Behavior in OpenSees

The hyperelastic material behavior programmed into OpenSees requires validation before it can be applied to complex models. Specific programming considerations were accounted for in the creation of the material behavior inside of the OpenSees program framework. Hyperelastic elements were installed into an SDOF frame and verified versus MathLab routines and the previous study on hyperelastic behavior (Jin, 2003). Verifying the accuracy of this new material property is crucial in establishing a baseline for hyperelastic behavior.

The open-source nature of OpenSees allows users to make additions to the analysis package. To create a hyperelastic material property, two new files with the extensions ".cpp" and ".h" are created using the Microsoft Visual Studio.Net programming environment. An outline is given with the source code for guidance on creating all of the necessary parts within the new files. The new files simply need to be added to the appropriate material class folder inside the OpenSees code. The components of the new files describe the stress-strain behavior of the element on a per-step basis, such that the analysis portion of OpenSees knows exactly how to progress the material behavior between each time step of an analysis. Other files are modified within the program structure to recognize the new material files and to enable them to function properly within the program framework. Once all of the necessary files have been created and modified, the project can be re-compiled into a new executable to perform the new analysis capabilities.

An initial set of models was established in OpenSees for validation incorporating the new materials versus a hand-made Newmark routine in MathCAD. The behavior is required to be verified through hand-drawn calculations due to the newness of the OpenSees program and additions made to it. The MathCAD routine performs a step-by-step Newmark analysis of a nonlinear structure with iteration performed between time steps to reach force convergence. The codes are shown below for the nonlinear Newmark routine created in MathCad.

$$S(u) := \left| \begin{array}{l} q \leftarrow |u| \\ \text{Stiff} \leftarrow 3 \cdot a \cdot (0.82137 \cdot q)^2 + 2 \cdot b \cdot (0.82137 \cdot q) + c \\ \text{Stiff} \end{array} \right.$$

$$F(u) := \left| \begin{array}{l} q \leftarrow |u| \\ \text{Force} \leftarrow \text{signum}(u) \cdot \left[a \cdot (0.82137 \cdot q)^3 + b \cdot (0.82137 \cdot q)^2 + c \cdot (0.82137 \cdot q) + d \right] \\ \text{Force} \end{array} \right.$$

```
Newmark(DTacc, DTan, β, γ, C, K, m, P) :=
  Npts ← (rows(P) − 1)
  Ninterp ← DTacc / DTan
  for v ∈ 0 .. Npts
    for b ∈ 0 .. 3
      U[v, b] ← 0.0
  Δt ← DTan
  cos ← 0.82137
  a ← (1/(β·Δt))·m + (γ/β)·C
  b ← (1/(2·β))·m + Δt·(γ/(2·β) − 1)·C
  KD ← (γ/(β·Δt))·C + (1/[β·(Δt)^2])·m
  for i ∈ 1 .. (Npts − 1)
    Uo ← U[[Ninterp·(i−1)], 1]
    Vo ← U[[Ninterp·(i−1)], 2]
    Ao ← U[[Ninterp·(i−1)], 3]
    ΔP ← (P[i] − P[i−1]) / Ninterp
    w ← 0
    for j ∈ 1 .. Ninterp
      Δp ← ΔP + a·Vo + b·Ao
      kT ← (cos^2)·(S(Uo)) + K + KD
      fs ← (cos)·(F(Uo)) + K·Uo
      Load ← fs + ΔP
      D ← Uo
      Y ← 1
      for x ∈ 1 .. Y
        ΔR[1] ← Δp
        ΔD ← ΔR[x] / ((cos^2)·(S(Uo)) + K + KD)
        Uo ← Uo + ΔD
        true ← cos·F(Uo) + (K)·Uo
        ΔR[x+1] ← Load − true
      Δu ← Uo − D
      Δv ← [ (γ/(β·Δt))·Δu − (γ/β)·Vo + Δt·(1 − γ/(2·β))·Ao ]
      Vo ← Vo + Δv
      Ao ← ((P[i] + j·ΔP) − C·Vo − cos·F(Uo) − K·Uo) / m
      U[[Ninterp·(i−1)+j], 0] ← DTan·[Ninterp·(i − 1) + j]
      U[[Ninterp·(i−1)+j], 1] ← Uo
      U[[Ninterp·(i−1)+j], 2] ← Vo
      U[[Ninterp·(i−1)+j], 3] ← Ao
  U
```

For the Newmark Routine, the Force and Stiffness routines are first established to reference the associated values at varying levels of displacement into the Newmark routine. The routines determine the force present in the system and the stiffness in the sytem based on the current system displacement (q), and based on the polynomial coefficients for the hyperelastic material (a, b, c, d). The Newmark Routine requires the establishment of many system parameters to perform the analysis. The first required parameters are the time step for the acceleration record (DTacc), and the time step desired for the analysis of the system (DTan). Next, the parameters beta (β) and gamma (γ) are required for the interpolation of the acceleration record (P). P is a column matrix of values containing the data points of a ground motion record. Next, the structural parameters for stiffness (K), viscous damping coefficient (C), and mass (m) are required. Once these are established, the routine will output a matrix of results for acceleration, velocity, and displacement of the SDOF system.

The nonlinear model analyzed under the Newmark routine consists of an SDOF system with elastic lateral stiffness and a hyperelastic element installed as a lateral brace. The behavior of the hyperelastic system was verified for eight equations created for the 2.5 ductility range within 2% accuracy. The eight equations are the same ones used in the previous study conducted on hyperelastic element behavior (Jin, 2003). The correlation established for the F3 element results are given in Figure 2.5.

After validating the material behavior using MathCAD, the models used in the original hyperelastic study by Changsun Jin (2003) were recreated in OpenSees for further comparison. The SDOF models consist of rigid beam and column elements pinned at each connection. The lateral stiffness of the structure is added through the use of zero length spring elements in the top corners of the structure. A viscous damper is connected to the top right corner of the structure with 5% of critical damping considered. The simplicity of this model aids in analyzing the behavior with the inclusion of hyperelastic elements, and in reproducing the behavior from the model in the original report. However, since the original computer models are not available, slight differences in modeling technique may introduce small differences between the model sets.

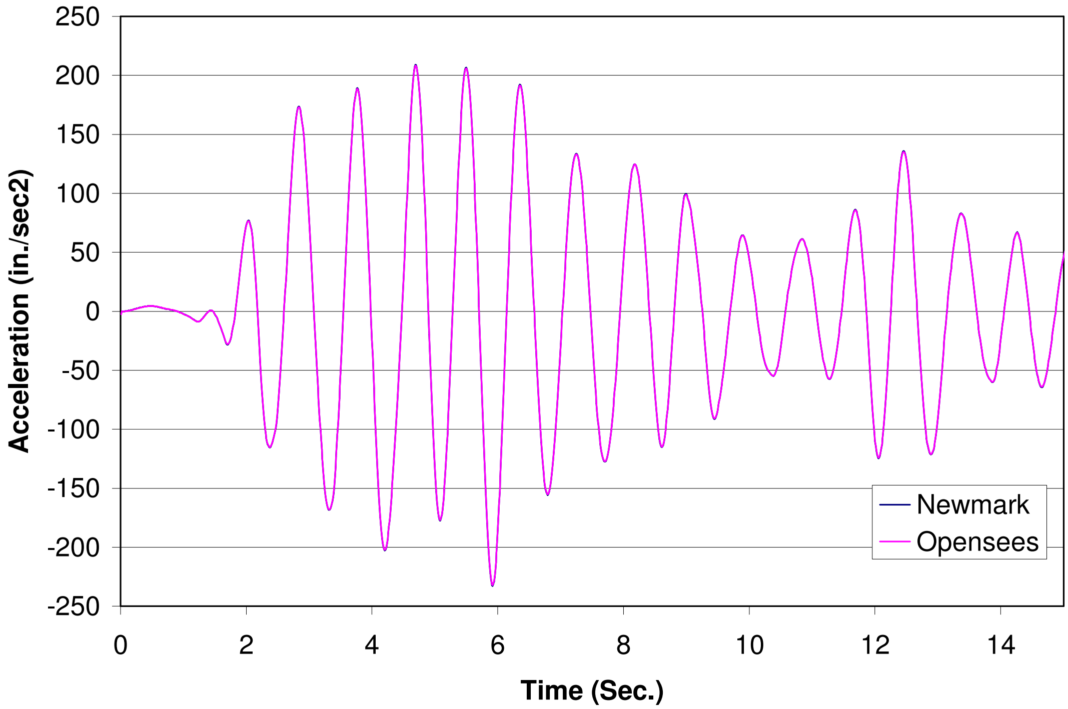

Figure B.8 – Acceleration Response History for Hyperelastic Verification

OpenSees was used to recreate the same IDA analyses performed in the original report on hyperelastic element behavior (Jin, 2003). To achieve this, each ductility range was input into OpenSees using the scripting language to create a switch. Instituting a switch allows OpenSees to analyze the same model under a variety of parameters without having to run each model individually. The results from each analysis are then post-processed using a variety of macro programs in Microsoft Excel. The macros are programmed to import the data from the OpenSees results files and create the IDA plots for maximum displacement and base shear. Also, routines have been established to trim an existing response history from a small analysis time step to a more course time step. This creates a response history that is easier to use in Excel and for data concurrency as will be discussed next regarding force equilibrium. A sample of the IDA results given by the macros using the OpenSees data is given in Figure B.9.

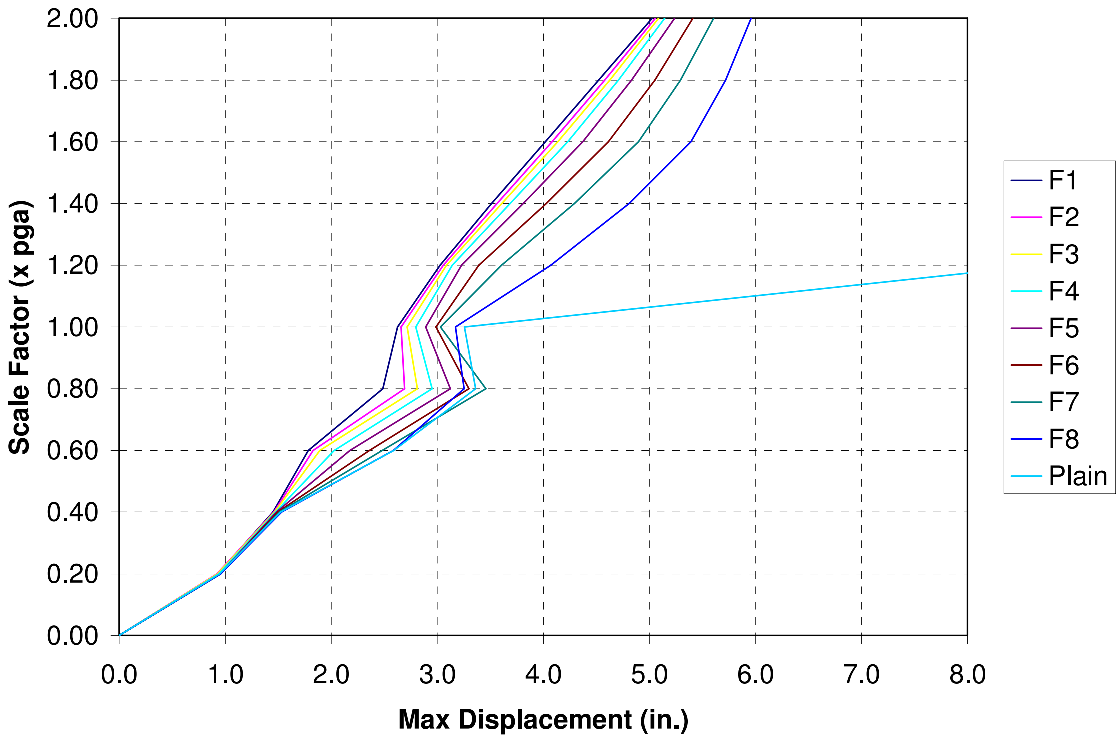

Figure B.9 – IDA Curves for Max. Displacement with Mu=4.0 Hyperelastic Devices

<u>B.3.2 Troubleshooting</u>

While running the models in OpenSees, reaching a converged solution became important due to the highly nonlinear behavior within the model. The solution algorithm chosen uses a modified Newton-Rhapson method to advance between time steps with the tangent stiffness from the previous time step. This method achieved a converged solution while other methods would not due to the nonlinear considerations.

Before the large amounts of IDA data could be processed, the baseline values for equilibrium of the structure had to be verified to avoid wasting lengthy processing times on faulty analyses. Since the hyperelastic material does not dissipate energy, the damper is the only source of energy loss. Thus, matching values should be found when the column shears are compared to the inertial forces of the structure (F=ma).

Force equilibrium within the system became a consideration when the element force response history did not correlate with the inertial force values calculated using the total acceleration response history. Essentially, equilibrium appeared to not be reached in the reported results from OpenSees. Upon investigation of the problem, the maximum base shear was found to not occur at the maximum recorded acceleration value. This is because relative acceleration is recorded in OpenSees, and total acceleration is needed. Therefore, the entire acceleration response history must be analyzed along with the ground motion history to get the maximum total acceleration of the structure.

Further investigation discovered that the response history time step, concurrency of data points, and mathematical units were all factors related to accuracy in force equilibrium. Again, simple frame models were created in OpenSees and verified for force equilibrium using Drain-2DX. The OpenSees acceleration record matched the Drain relative acceleration. This verifies the data from OpenSees, and shows that the correct answers can be expected after the installation of hyperelastic elements.

After verifying the acceleration values, the focus turned to concurrency between the data points chosen to find total acceleration. The acceleration record was being trimmed along the correct time interval to achieve the same time record as the ground motion; however, a shift was necessary to get the correct data point occurring at the corresponding time step to the GM record. Otherwise, incorrect frequency content was being included from the total acceleration, and causing the two measures of system forces to differ slightly. Once the correct recorded values were trimmed along the correct time step, the correct total acceleration was obtained and the base shear records matched the calculated inertial forces. This same verification was performed on frames with hyperelastic elements, and the response history correlation is shown in Figure B.10.

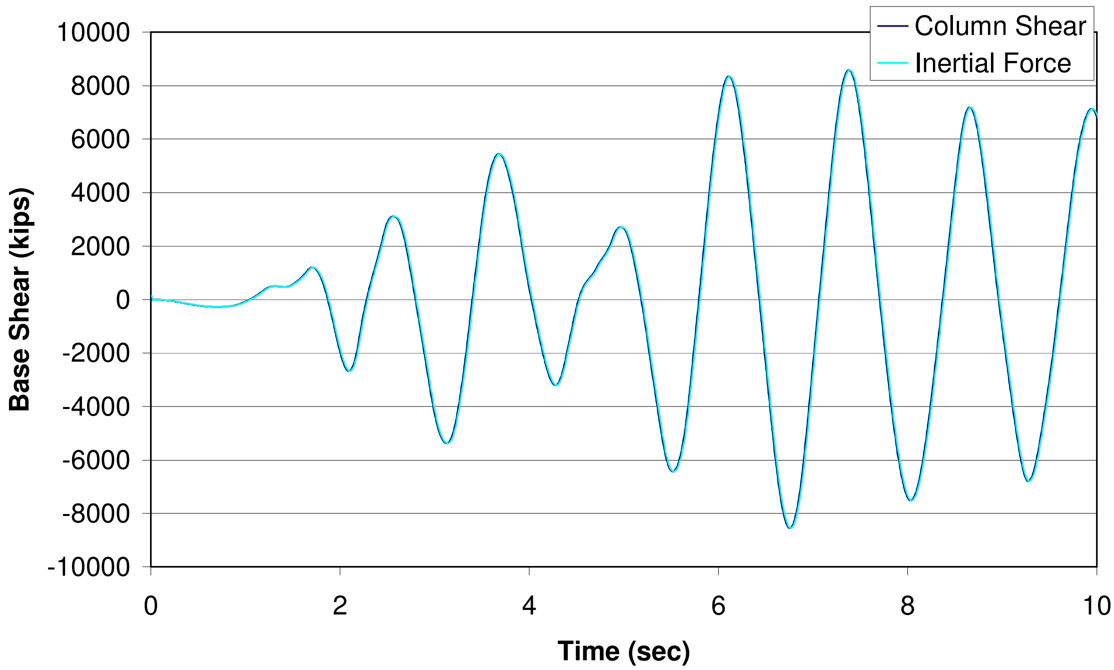

Figure B.10 – Base Shear Response History Verification

B.3.3 Hyperelastic Findings

From a numerical standpoint, the MathCAD results match the OpenSees results for hyperelastic behavior, and the OpenSees IDA data matches the curves given in the initial study on hyperelastic behavior. One minor difference occurs between the IDA curves from choosing the correct absolute maximum term for maximum and residual displacements. This results in more variance and irregularities in the IDA curves in Jin's report. Any small numerical differences can be contributed to the differences between analysis types used between the report and OpenSees. Regenerating an exact duplication of structural behavior is impossible between drastically different analysis packages, and the reported differences are insignificant in terms of overall behavior.

For the behavior of the hyperelastic material in OpenSees, it has been validated versus the Newmark routine and successfully compared to the previous report on hyperelastic behavior. Also, force equilibrium was verified for a system with hyperelastic bracing as another confirmation of accurate behavior. From the report, the same structural devices are verified for the best performance in structures subjected to higher levels of ground motion (> 0.25g) without attracting detrimental amounts of base shear. All of the applicable findings for the behavior of hyperelastic devices in nonlinear structures are verified as being accurate and relevant for future modeling concerns. Most importantly, the range of hyperelastic equations that gives the most desirable results can be confirmed and used for further analysis of more complex systems

B.4 Conclusions

The verification of baseline structural behavior shows that the nonlinear dynamic behavior of structures is accurately given by OpenSees analyses. Important modeling benchmarks have been established for creating the desired nonlinear dynamic behavior in OpenSees. The verification of the hyperelastic material behavior in OpenSees confirms that the newly programmed materials are accurate for the desired properties. Considering both sets of verification, the modeling of nonlinear structural yielding along with hyperelastic material behavior can be modeled together with accuracy. With these new and recently established material behaviors, new ground can be broken in the research of nonlinear dynamic behavior of structures.