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COMPREHENSIVE FINITE ELEMENT SIMULATION OF THE FLEXIBLE WOOD DIAPHRAGMS

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Abstract

Unreinforced masonry (URM) buildings with flexible wood floors and roofs are known as one of the most seismically vulnerable building types in the world. These types of buildings accounts for major portion of the existing buildings in some countries like Mexico, Italy, Indonesia, Australia, and some portions of United States. The horizontal wood diaphragms of these buildings are intended to transfer inertial in-plane lateral forces to the vertical load resisting elements of the building (e.g. URM shear walls). However, failure of connections between the wood diaphragms and masonry walls and also flexibility of the diaphragm itself were identified as the major source of damage in URM buildings during the past earthquakes.

In this research, a methodology for the modelling of flexible wood diaphragms is discussed using the LS-DYNA software. For doing so, elastic elements with the corresponding section properties are used to represent joists and planks. Planks are connected to the joists through the nails, which their hysteretic behavior are modeled using the nonlinear discrete beam elements. Methodology presented in this study is validated with the full scale experimental study performed at Texas A&M University. Also, the methodology further validated for various retrofitted scenarios with the experimental data. Finally, the modelling approach is extended to a typical full 3D two-story URM building that contains flexible wood floor and roof. In this building model, the nonlinear 4-node fully-integrated shell elements with previously validated embedded masonry material are used to capture the extent of damage in the URM walls. Also, the effect of retrofit options on the overall seismic performance of the building is investigated.

This study aims to propose a novel analysis approach to better understand the behavior of flexible and retrofitted wood floor diaphragms. Also, this research facilitates the necessary analytical tools to study the integrated models of URM buildings with flexible wood floors.

Keywords: Timber diaphragm; Finite element analysis; Unreinforced masonry

1. Introduction

Unreinforced masonry (URM) buildings with flexible wood floors and roofs are known as one of the most seismically vulnerable building types in the world. These types of buildings accounts for major portion of the existing buildings in some countries like Mexico, Italy, Indonesia, Australia, and some portions of United States. The horizontal wood diaphragms of these buildings are intended to transfer inertial in-plane lateral forces to the vertical load resisting elements of the building (e.g. URM shear walls). However, failure of connections between the wood diaphragms and masonry walls and also the flexibility of the diaphragm itself were identified as the major sources of damage in URM buildings during the past earthquakes.

The numerical modelling of flexible wood diaphragms is a key component in the seismic assessment the unreinforced masonry (URM) buildings in regions of moderate to high seismicity. Extensive research has been conducted by various researchers related to wood diaphragms started as early as 1930's. However, until 1970's, most of this research focused on determining experimental values of maximum strength, stiffness or deflections of diaphragms with different sheathing pattern and materials. Most test results concluded that, in general, the behaviour of wood diaphragms was highly nonlinear and that nonlinearity was mainly due to the connection between boards and joists [1][10][6]. Since the 1970's, several numerical models of different levels of complexity were produced and implemented in non-commercial software. Most of these numerical methods employ simplified modelling technique such as equivalent 2D element with reduced modulus of elasticity or equivalent single degree of freedom mass/spring system to represent the flexibility and the nonlinearity in the diaphragm [5][3]. Some more complex modelling techniques were implemented by Aleman et al. [1] where diaphragm planks were modelled using quad elastic isotropic elements, joists were simulated using elastic beam elements, and nails were replicated using zero length springs in two perpendicular directions. Also equivalent nonlinear rotational spring at the intersection of the planks and the joists were suggested. The uniaxial material SAWS, developed by Folz and Filiatrault [4] was utilized to simulate the nonlinear force-displacement relationship of the springs. However, the implementation of these complex numerical modelling methods is very limited due to high computational cost of adding large number of DOFs in the conventional structural analysis finite element software.

In this research, a methodology for the modelling of flexible wood diaphragms is discussed using the LS-DYNA [7] software. Methodology presented in this study is validated with the full scale experimental study performed at Texas A&M University [9]. Also, the methodology further validated for various retrofitted scenarios with the experimental data. Finally, the modelling approach is extended to a typical full 3D two-story URM building that contains flexible wood floor and roof. In this building model, the nonlinear 4-node fully-integrated shell elements with previously validated embedded masonry material are used to capture the extent of damage in the URM walls. Also, the effect of retrofit options on the overall seismic performance of the building is investigated.

2. Analytical model for timber diaphragm

To investigate the effect of weak flexible timber diaphragm and the effect of diaphragm strengthening with structural plywood LS-DYNA was used. LS-DYNA® [7] is a versatile three-dimensional non-linear finite element analysis program, owned and developed by Livermore Software Technology Corporation (LSTC), capable of computationally intensive time-domain multi-physics simulation. Although initially conceived for modelling short-duration events such as impact and blast in the military and mechanical engineering arenas, the program has been extensively developed to cover a very wide range of applications that today include civil engineering structures, soils and soil-structure interaction, and loading by earthquake or long-duration events such as movements due to construction.

A particular advantage of LS-DYNA is its speed of computation (using the explicit integration technique) for very large and complex models, which might contain elements numbered in the millions. Typically, LS-DYNA is run on multiple processor clusters, using the distributed memory method coupled with a Message Passing Interface communications protocol (MPI). This allows efficient use of large numbers of processors working in parallel.

2.1. Nail Modeling in LS-DYNA

In this study, the nails were modeled as nonlinear beam elements using MAT-HYSTERETIC-BEAM element which requires defining the shear force versus plastic strain backbone curve for the nail. The shear strength can be dependent on the axial force. The biaxial bending-axial interaction curve can be also defined.

The behavior of the nail depends on many factors including the properties of the side members, nail size and material, etc. Due to the very wide range of nail connection assemblies and the complex interaction of nails and wood, simple analytical models that can be used for obtaining the nail behavior for different configurations is very limited. As a matter of fact, the nail behavior used in a specific connection-which is required for an accurate modeling of the connection-most of the times, should be determined from experiments. McLain [8] developed a procedure for predicting the load-slip curves of laterally loaded nailed wood joints as shown below:

$$V_n = A\log_{10}(1 + Be_n) \quad (1)$$

where:
V_n = Lateral load, kN
A, B = Empirically-derived constants, kN and mm^{-1}, respectively
e_n = Interlayer slip, mm (relative displacement of joint members)
The backbone curve for modeling the shear force versus interlayer slip displacement of the nail is shown in Figure 1.

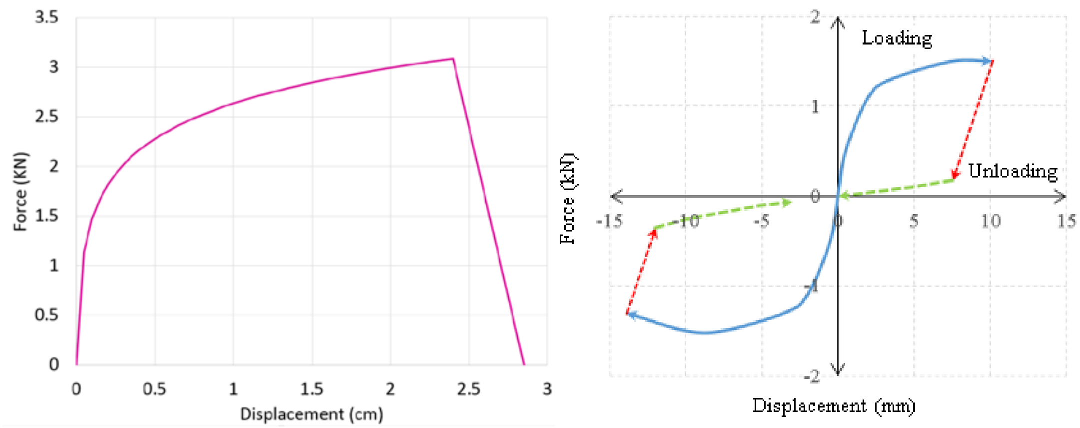


Figure 1 Force-displacement backbone and unloading curves for nails

The MAT_HYSTERETIC_BEAM material model requires the user to input the usual properties such as the mass density, Young's modulus, and Poisson's ratio. These properties can be used to control the critical timestep of the element and, in combination with the section properties, can be used to calibrate the elastic stiffness of the beam. Additional properties to be defined are the isotropic hardening type, shear force – plastic strain curve, and optionally the pinching factor. These parameters are used to control (shear) yielding and hysteretic shear behaviour of the beam element.

2.1. Timber Diaphragm Modeling in LS-DYNA

The modelling approach for timber diaphragms is based on the assumption that the fastener connections are the primary source of nonlinearity in the response of timber diaphragms with nailed connections. Sheathing, framing, and bridging elements are assumed to behave linear elastic. This assumption is consistent with the results from laboratory tests and those in the literature.

The timber diaphragms are idealised as an assemblage of elastic beams and, in case of timber panel sheeting, shell elements. The floorboards or panels are connected to the timber joists by non-linear beam elements that represent the hysteretic behaviour of the nailed connections. The non-linear beam elements are modelled at the correct geometric location for a realistic prediction (Figure 2). This is true especially for timber plank diaphragms where the rotational stiffness of each nail couple prevents bending in the floorboards providing in-plane stiffness to the diaphragm. For timber plank diaphragms nodal rigid bodies are used to create the offset between the beam element at the centreline of the floor plank and the non-linear beam element at the location of the nailed connection.

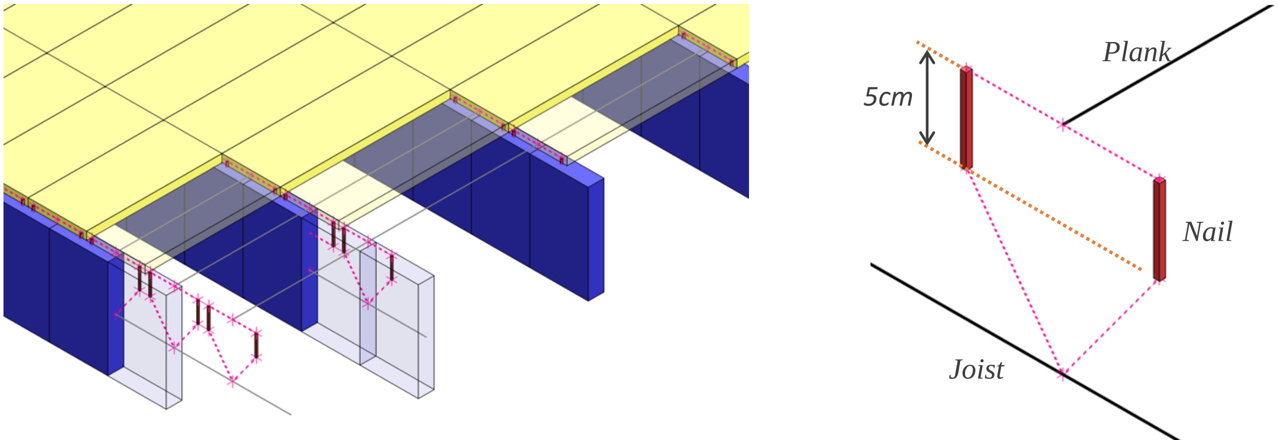


Figure 2 Timber diaphragm modeling

3. Test description

Peralta et al [9] performed displacement-controlled quasi-static reversed cyclic tests on existing and rehabilitated floor and roof wood diaphragms under in-plane lateral loads. Two experimental specimens were chosen for the validation study in this paper:

1. A square edged single straight sheathed diaphragm (MAE-2) designed to represent a typical roof diaphragm in pre-1950's URM buildings (Figure 3)
2. The retrofitted diaphragm with an unblocked plywood overlay (MAE-2B) designed for improving the diaphragm's in-plane lateral stiffness.

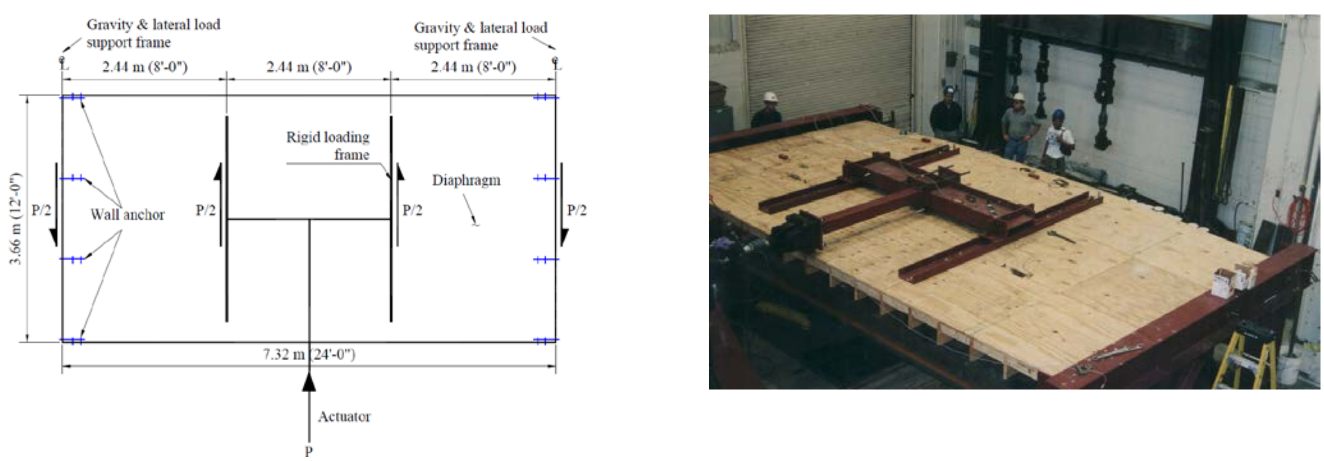
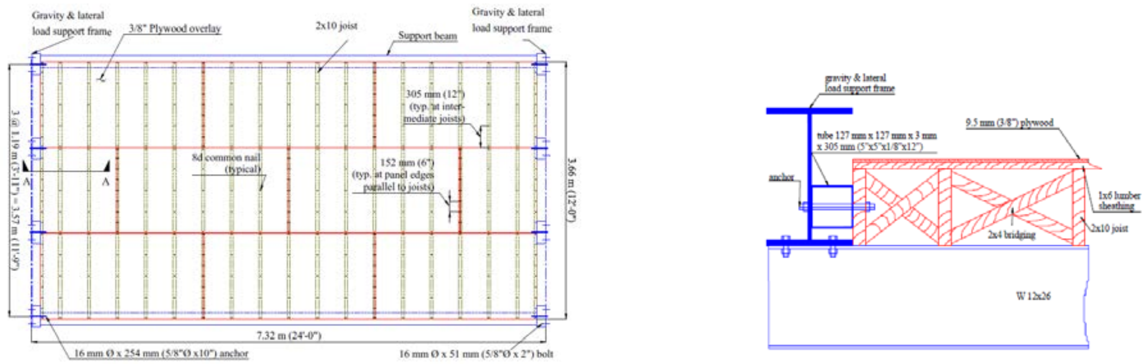


Figure 3 General diaphragm test setup [9]

Figure 4 shows details of the MAE-2B model and panel arrangements. Specimen MAE-2 is similar to MAE-2B without plywood overlay.



(a) (b)

Figure 4 MAE-2B test specimen: a) plan view details; b) connection details [9]

Southern Pine lumber was used for the solid wood elements. The material properties were determined from AF&PA (1997) and APA (1986) and are listed in Table 1.

Table 1 Material Properties [9]

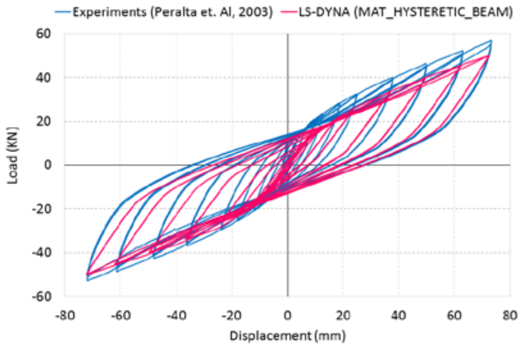
Property	Solid wood	Plywood
Young's Modulus, MPa (ksi)	12400 (1800)	1490 (216)
Poisson's Ratio	0.2	0.2
Specific Gravity	0.55	-

8d common nails were used with diameter of 3.33 mm and length of 6.35 cm.

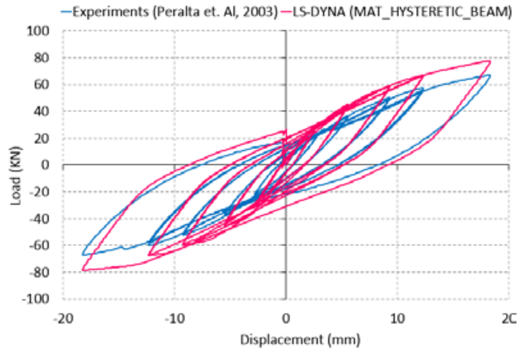
Displacement-controlled quasi-static reversed cyclic testing was performed on each diaphragm applying two cycles for each lateral displacement amplitude (a total of 10 displacement amplitudes with maximum value of 76.2 mm). These displacement amplitudes were determined to be appropriate for determining the elastic and inelastic lateral response of the diaphragm specimen.

4. Numerical and experimental results comparison

Figure 5 compares the predicted force-displacement hysteresis of the two specimens to the experimental measurements. A good level of agreement is observed between the LS-DYNA model and the two experiments. The results presented in this paper were obtained using the actual Modulus of Elasticity of the materials without further calibrations to match the results.



(a)



(b)

Figure 5 Numerical versus experimental hysteresis loop for a) MAE-2, b) MAE-2B

5. URM building with timber diaphragm

To demonstrate the effect of flexible timber diaphragm and its strengthening with structural plywood on response of URM buildings a hypothetical URM building is analysed using Non-Linear Time History Analysis (NLTHA) by using the Arup development version of LS-DYNA finite element software. The isometric view of the hypothetical URM building is shown in Figure 6. The more specific modelling assumptions is provided as follows:

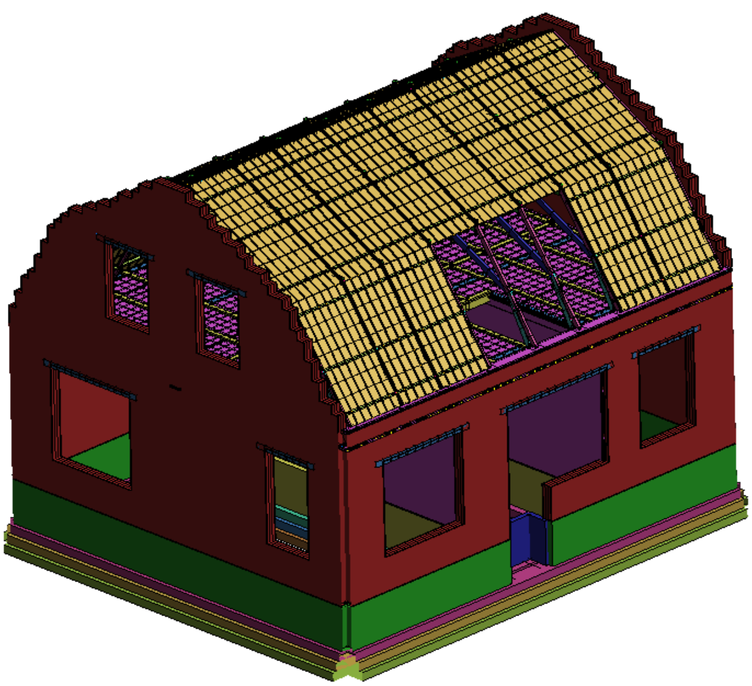


Figure 6 Isometric view of two-story URM building with flexible roof and floor

5.1. URM walls and footings

A new 2D masonry shell formulation, developed and validated against extensive experiments by Arup [11], has been used. The shell element formulation includes:

- Homogenized representation of the brick-mortar conglomerate, with 'smeared' cracking. The element size and arrangement does not have to match the actual arrangement of bricks. The stiffness of the masonry represents the smeared stiffness of brick units and mortar.
- 'Sandwich' formulation for out-of-plane behavior, with multiple layers though the thickness to permit representation of cracking though part of the thickness. Plane sections remain plane for out-of-plane effects.
- Tensile and shear failure of joints, sliding friction on joints (in-plane and out-of-plane), and compressive yielding (crushing) of masonry.
- The model recognizes the anisotropic characteristics of masonry, and considers many potential deformation and failure modes such as diagonal tensile failures.

In this study, elements with side dimensions in the range of 100 to 200 mm, and with a reasonably square aspect ratio are used.

5.2. Timber diaphragm

To demonstrate the effect of flexible diaphragm modeling in the URM building response, three different diaphragm modeling scenarios are assumed for this building: 1) Elastic diaphragm where the straight sheathing and the joist are connected to each rigidly, 2) Nonlinear roof where that the elastic straight sheathing planks are connected to the elastic joists using the nonlinear nail connections explained before, and 3) The nonlinear diaphragm in model 2 is retrofitted by 10 mm structural plywood connected to the existing straight sheathing diaphragm with nonlinear nail elements.

5.3. Connections between timber framing and masonry walls

Various types of connections were used to connect timber framing to the masonry walls depending on the construction detail and location. In general, it was assumed that the strength of anchored connections were governed by the total capacity of the applied nails with the hysteretic behavior discussed earlier. Anchored connections can be removed during the analysis if they reach their failure criteria. In addition, vertical load-dependent surface to surface friction contact with friction coefficient of 0.6 was used between any contacting surfaces within these connections.

5.4. Damping ratio

In all numerical simulations, constant 2% of critical damping is considered over a frequency range 1-30 Hz. Additionally; stiffness proportional damping with damping coefficient 0.05 is specified only for masonry materials to reduce high frequency numerical noise and to assist numerical stability. At the frequencies associated with primary structural behaviors this specification provides negligible damping and therefore does not affect results of engineering significance.

6. Results and discussion

The damage parameter in the masonry walls are plotted for the models with elastic roof and the nonlinear roof in Figure 7. It can be seen that the damage in the model with elastic roof is less than the model with nonlinear model due to the fact that elastic modeling of the roof without considering the nail connection flexibility and strength results in stiffer roof diaphragm.

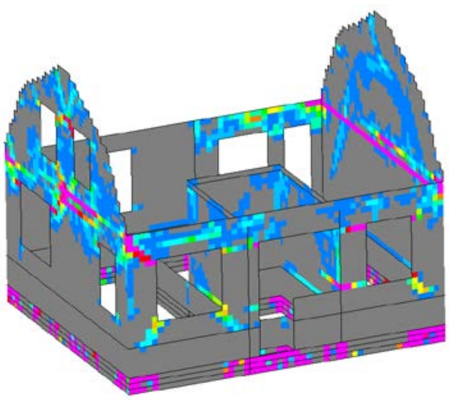


Figure 7 Damage index in masonry walls (a) Elastic model, (b) Nonlinear model

As explained before, in the third model the roof and floor diaphragms are retrofitted by adding plywood nailed to the existing plank system. The roof relative displacement for all three models is plotted in the Figure 8. It can be seen that the roof relative displacement is significantly decreased by nailing plywood to the existing diaphragm system. The maximum roof displacement in the elastic model is around 4 cm whereas the maximum roof displacement in the nonlinear existing model is around 7.9 cm and after retrofitted by plywood is in the range of 5 cm.

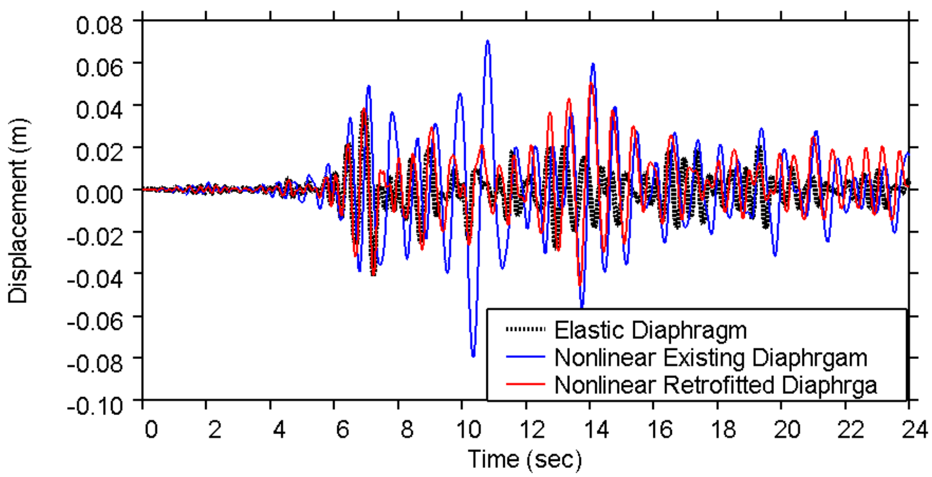


Figure 8 Roof relative displacement.

7. Summary and Conclusions

Numerical modeling of flexible timber diaphragms in URM buildings are explained and validated against available experimental data. It has been shown that the proposed modeling method which consists of elastic elements representing timber members connected with nonlinear shear elements representing nails can simulate the stiffness and strength of flexible timber diaphragm accurately. The effect of diaphragm stiffness and strength modeling on the seismic assessment of URM buildings has been shown using nonlinear time history analysis of a two-story URM building with various diaphragm modeling assumptions. It has been shown that equivalent elastic modeling technique can result in wrongfully strong and stiff diaphragm model and smaller relative roof displacement in the URM building.

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