Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1065

THREE-DIMENSIONAL NONLINEAR DYNAMIC ANALYSIS OF MULTI-BASE SEISMICALLY ISOLATED STRUCTURES WITH UPLIFT POTENTIAL

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ABSTRACT

The complexity of modern seismically isolated structures requires tools for fast, accurate and reliable analysis and the ability to capture potential discontinuous phenomena such as isolator uplift and their effects on the superstructures and the isolation hardware. In this paper an analytical model is developed and a computational algorithm is formulated to analyze complex seismically-isolated superstructures even when undergoing highly-nonlinear phenomena such as uplift. The computational model developed has the capability of modeling various types of isolation devices with strong nonlinearities, analyzing multiple superstructures on multiple bases, and capturing the effects of lateral loads on bearing axial forces, including bearing uplift. The model developed herein has been utilized to form the software platform 3D-BASIS-ME-MB, which provides to the practicing engineering community a versatile tool for analysis and design of complex structures with modern isolation systems. For purposes of verification, two numerical examples have been analyzed using 3D-BASIS-ME-MB and key results are compared to experimental results, or results obtained from other structural/finite element programs. In both examples, the analyzed structure is excited under conditions of bearing uplift, thus yielding a case of much interest in verifying the capabilities of the developed analysis tool.

Introduction

Despite its increasing influence on aseismic design, the efficacy of seismic isolation in structures subjected to strong ground excitation, is potentially compromised by situations that induce undesirable uplift (or tension) in the isolation bearings. Development of tensile forces or uplift in isolation bearings may produce, under certain conditions, detrimental effects in the form of local instability or rupture of elastomeric bearings, and damage to sliding bearings due to large compressive forces on reengagement following uplift, which may include impact effects. Loss of contact and impact on return can further yield higher-mode response and large axial forces in columns.

In fact, a variety of conditions may contribute to the development of either tensile forces (in bolted rubber bearings) or uplift (in sliding bearings and doweled rubber bearings). Typical examples include slender structures with large height-to-width aspect ratios, certain types of bridges with large ratios of height of the centroidal axis to the distance between the bearings, and

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buildings incorporating bearings below braced columns or stiff walls.

In this study, the seismic response of base-isolated structures under conditions of bearing uplift is investigated. The analysis tool employed for this purpose is the newly-developed program 3D-BASIS-ME-MB. Used by the engineering and academic communities, the 3D-BASIS class of computer programs is widely accepted for the nonlinear dynamic analysis of three-dimensional seismically isolated structures. The program contributed to the verification and development of new standards for the design of seismically isolated structures and contributed to the advancement of seismic isolation.

Built on the core philosophy of its predecessors, program 3D-BASIS-ME-MB represents an enhanced version of program 3D-BASIS-ME (Tsopelas et al. 1994), which is a further extension of the original program 3D-BASIS (Nagarajaiah et al. 1989).

The new program 3D-BASIS-ME-MB offers the following additional features:

1. Analyzes multiple superstructures (up to five separate superstructures) on multiple bases (up to five bases) as illustrated in Figures 1 and 2.
2. The isolation system has the following new elements:

   • The new XY-FP bearing capable of sustaining tension is represented (Roussis and Constantinou 2005, 2006a, 2006b). The orientation of the bearing may be in an arbitrary direction with respect to the global reference frame.

   • The existing viscous damper element is modified to have a more general constitutive relation and to have capability for placement in an arbitrary direction with respect to the global reference frame.
3. Overturning moment effects are captured in a more complex and accurate way. The axial load on each isolator is calculated at each time step through a procedure that relates the instantaneous floor inertia forces to the axial load on the bearings. This relation can be derived exactly from a static analysis model of the complete structural system (say in a program SAP2000 or ETABS), including cases in which uplift occurs. When bearing uplift occurs, the program returns zero axial bearing force for the bearings which uplift and redistributes axial forces to the other bearings so that equilibrium in the vertical direction is satisfied.

The enhanced 3D-BASIS-ME-MB program is primarily useful in (a) performing analyses for schematic designs where speed in modeling of the isolated structure and speed in performing multiple dynamic analyses is desired, and (b) verifying the validity of modeling assumptions and the accuracy of solutions of more complex analysis programs, such as SAP2000 and ETABS.

Structural system configuration

Program 3D-BASIS-ME-MB offers the capability to analyze multiple superstructures (up to five separate superstructures) on multiple bases (up to five bases), hence the extension MB over its predecessor program 3D-BASIS-ME (Tsopelas et al. 1994). Fig. 1 illustrates what the program can analyze: a number of superstructures (here shown as three superstructures) supported by a number of bases (here shown as three bases). The bases are interconnected with linear elastic and viscous elements (representing structural elements such as columns, braces, walls, etc.). The bases are also connecting to the ground through elements that represent seismic isolation hardware. Each base is considered rigid in its own plane and described by its mass, the moment of inertia about the center of mass, and the location of the center of mass.

The motion of each base is calculated with respect to the position of the ground, which is described with respect to a fixed reference frame. The motion of each base is described by two displacements in the horizontal direction and a rotation about the vertical axis at the center of mass, all with respect to the instantaneous position of the ground. The ground motion consists of translational three-dimensional components along the global axes. Each superstructure consists of floors that are rigid, with motion described with respect to the superstructure reference frame that parallels the fixed reference frame, and is attached to the center of mass of the first (top) base. The superstructure reference frame serves as the global reference system with respect to which all coordinates are measured.

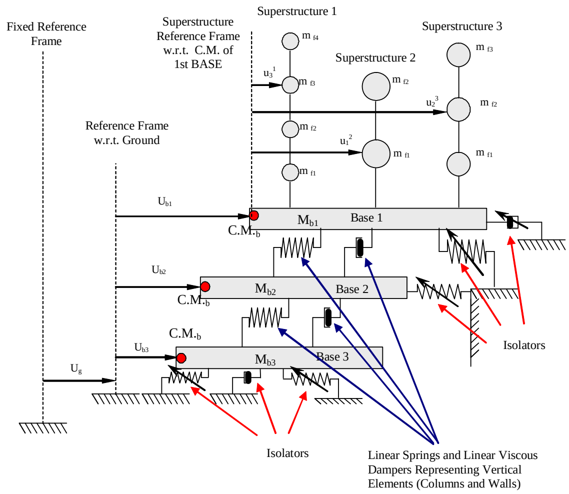


Figure 1. Degrees of freedom and reference frames in 3D-BASIS-ME-MB.

Isolation System Configuration

The isolation system is modeled with spatial distribution and explicit nonlinear force-displacement relation for each isolator. The isolators are considered rigid in the vertical direction and to have negligible resistance to torsion. Program 3D-BASIS-ME-MB has the following elements for modeling the behavior of isolators:

(i) Linear elastic element.

(ii) Linear and nonlinear viscous elements for fluid viscous dampers or other devices displaying viscous behavior.

(iii) Hysteretic element for elastomeric bearings and steel dampers.

(iv) Stiffening (biaxial) hysteretic element for elastomeric bearings.

(v) Hysteretic element for flat sliding bearings.

(vi) Hysteretic element for spherical sliding (Friction Pendulum) bearings.

(vii) Hysteretic element for the uplift-restraining FP (XY-FP) bearings.

Isolator elements can be placed below each base of the structure (see Figures 1 and 2). The description and mathematical model of each element can be found in Tsopelas et al. (2005).Both justified and ragged right margins are acceptable. However, as some word processors justify right margins with awkward character and word spacing, authors should exercise their judgment and select the option that provides the best presentation for their papers.

Seismic Response of Base-Isolated Structures Under Conditions of Bearing Uplift

Two examples of seismically isolated structures under conditions of bearing uplift are analyzed in 3D-BASIS-ME-MB. In both cases the analyzed structure is seismically isolated with Friction Pendulum bearings and is excited under conditions of bearing uplift. This represents the most extreme condition that bearings are subjected to and is a case of much interest in verifying the capabilities of analysis software. Extensive results of analysis are presented in Tsopelas et al. (2009, 2005) and Roussis et al. (2009).

The first example is a seven-story model structure that was tested on the shake table at the University at Buffalo (Al-Hussaini et al. 1994). This example is of much interest since it was studied in verification examples of program SAP2000 (Scheller and Constantinou 1999, and Computers and Structures 2003). Results of analysis by program 3D-BASIS-ME-MB and by program ABAQUS (ABAQUS 2004) are compared to experimental results.

The second example is a two-tower multi-story structure with a split seismic-isolation-system level. The isolation system again consists of Friction Pendulum bearings and the structure is excited under conditions of bearing uplift. Results of analysis by program 3D-BASIS-ME-MB are compared to results produced by program ABAQUS.

Seven-Story Isolated Model

Fig. 2 illustrates the seven-story model of this verification study. It was tested by Al-Hussaini et al. (1994). Additional information on this model may be found in Scheller and Constantinou (1999) and in Computers and Structures (2003).

The isolation system of this model structure consisted of eight Friction Pendulum bearings with radius of curvature equal to 9.75 in. and coefficient of friction in high-velocity motion equal to 0.06. The total weight on the eight bearings was 47.5 kip. In one test in configuration MFUIS with El Centro motion, component S00E, scaled to peak acceleration of 0.58g, the model experienced uplift. This case is modeled in programs 3D-BASIS-ME-MB and ABAQUS and compared to experimental results. Details on the modeling of structures isolated with Friction Pendulum bearings in program ABAQUS may be found in Tsopelas et al. (2005) and Clarke et al. (2005).

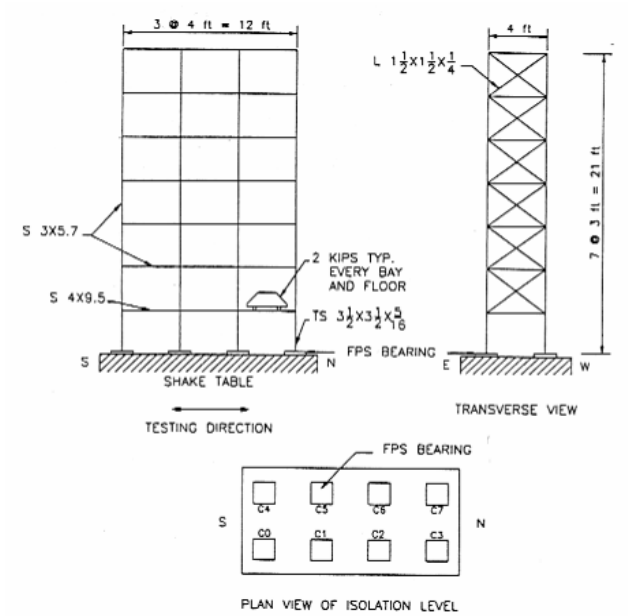
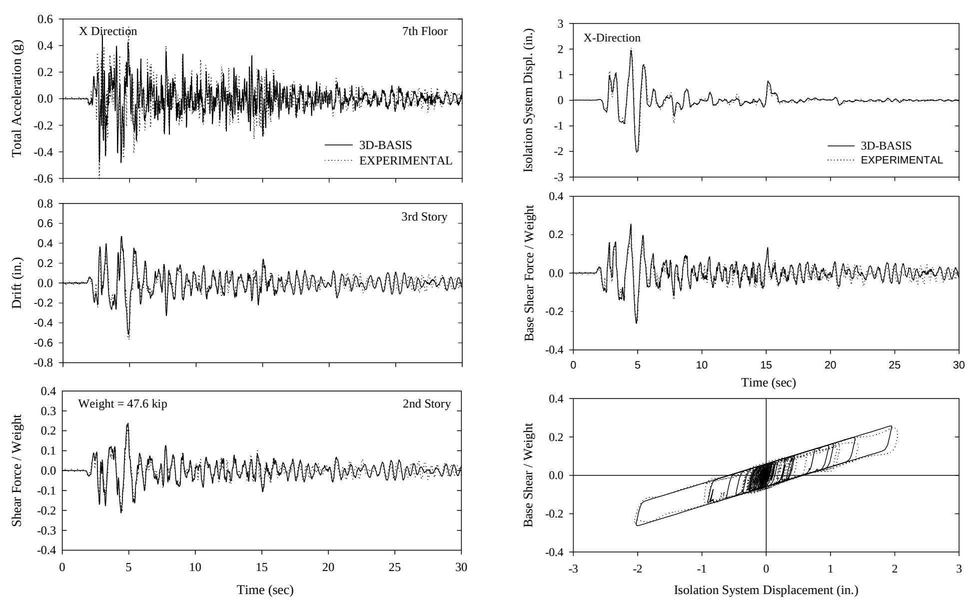


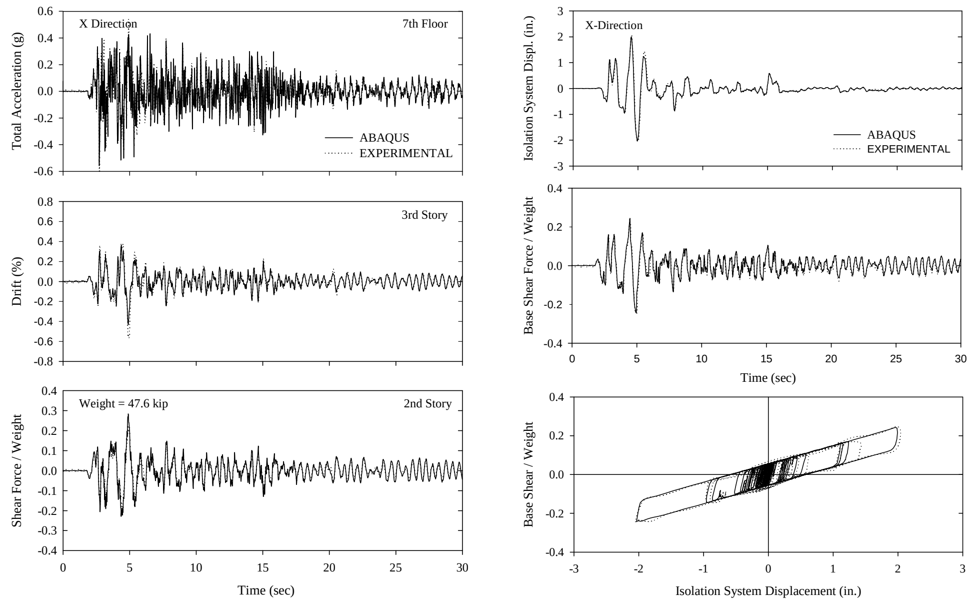
Figure 2. Schematic of seven-story model tested on shake table (Al Hussaini et al, 1994)

Results of program 3D-BASIS-ME-MB plotted against experimental results are presented in Fig. 3, and results of program ABAQUS plotted against experimental results are presented in Fig. 4. It may be observed in the results of Figs. 3 and 4 that programs 3D-BASIS-ME-MB and ABAQUS predict very well the experimental response.



(a) (b)

Figure 3. Comparison of experimental and 3D-BASIS-ME-MB results: (a) superstructure and (b) isolation system response in El Centro S00E 200%.



(a) (b)

Figure 4. Comparison of experimental and ABAQUS results: (a) superstructure and (b) isolation system response in El Centro S00E 200%.

Two-Tower, Split-Level Isolated Structure

The second example concerns a two-tower multi-story structure with a split seismic-isolation-system level. The model geometry is illustrated in the schematic of Fig. 5. The isolation system consists of Friction Pendulum bearings with radius of curvature equal to 169 in. and coefficient of friction in high-velocity motion equal to 0.07. Further details on the modeling of the structure and the input file used in program 3D-BASIS-ME-MB can be found in Tsopelas et al. (2005).

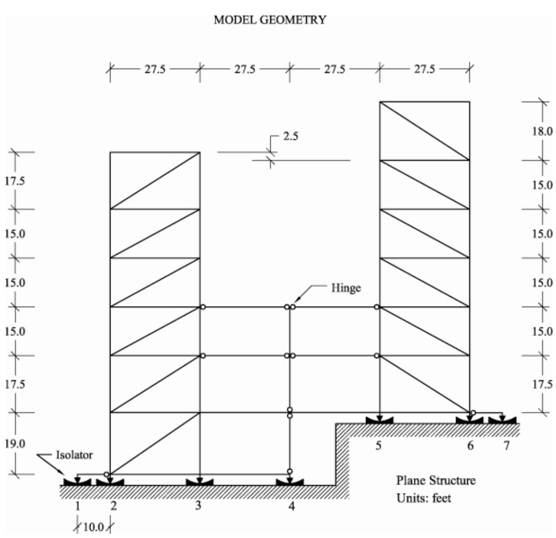


Figure 5. Schematic of two-tower split-level isolated structure

In comparing the results obtained by programs ABAQUS and 3D-BASIS-ME-MB, it is important to note that the analyzed structure experiences considerable bearing uplift. As an example, Fig. 6 presents the uplift displacement history calculated in ABAQUS for isolator No. 2 (similar behavior was calculated for bearing 3 and to a lesser extent for bearings 5 and 6, those directly below the two towers). The maximum uplift displacement is about 0.45 in. and the duration of each uplift episode is about 0.5 second. That is, the analyzed structure is in a state of rocking mode, which can be accurately captured only in an analysis in which geometric nonlinearities are accounted for. Nevertheless, the results obtained by program 3D-BASIS-ME-MB, which does not have geometric nonlinearity capabilities, favorably compare to those obtained by program ABAQUS. Figs. 7 through 11 present a comparison of results obtained with programs 3D-BASIS-ME-MB and ABAQUS.

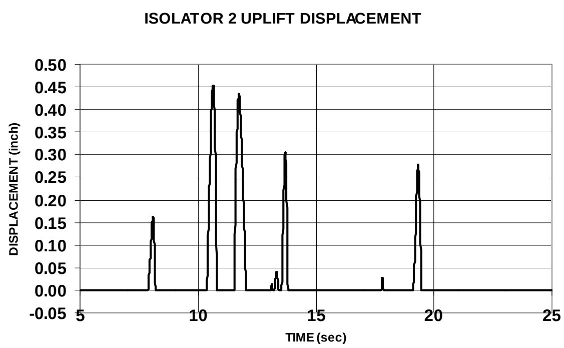


Figure 6. Uplift displacement history of isolator 2 as predicted in ABAQUS.

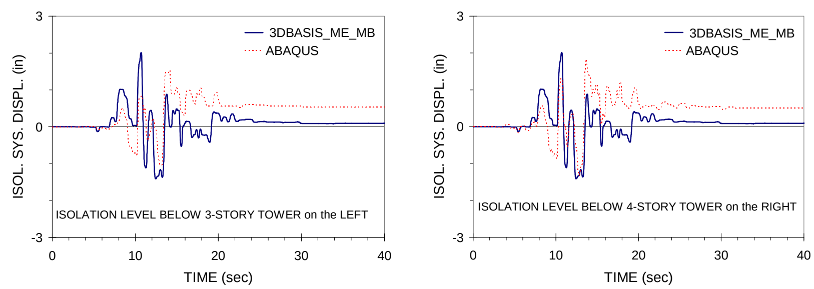


Figure 7. Isolation system displacement histories.

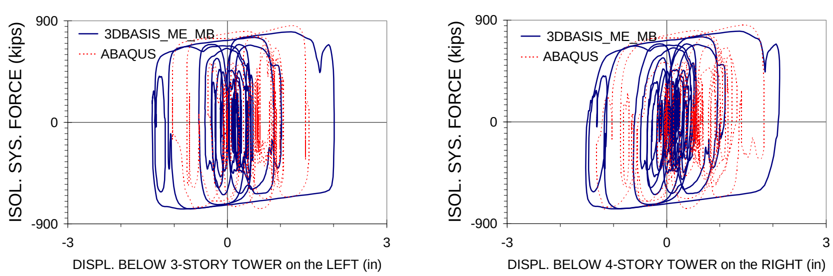


Figure 8. Isolation system force-displacement loops

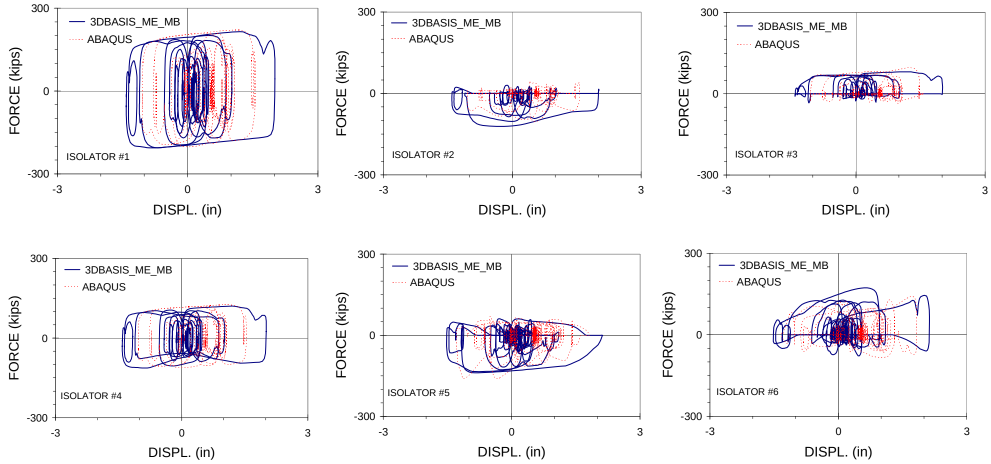


Figure 9. Isolator force-displacement loops

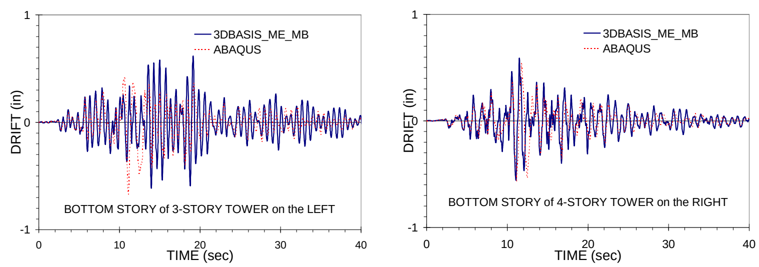


Figure 10. Story drift histories

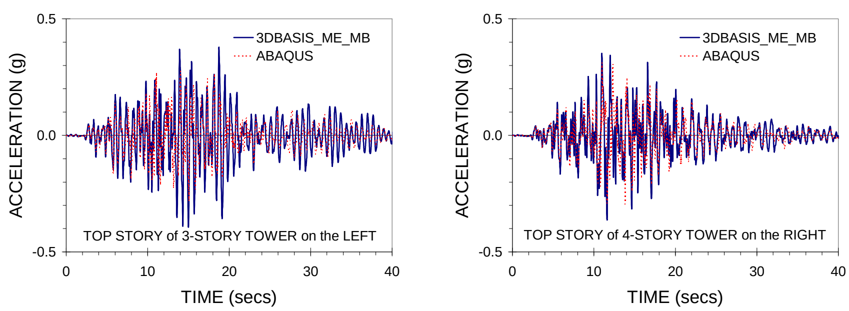


Figure 11. Acceleration histories

The following observations may be made from the comparison of results:

1. The bearing displacement histories appear different in the predictions of the two programs. The differences are attributed to the tendency of program ABAQUS to predict larger permanent displacement. A likely explanation for this behavior are small differences in modeling the velocity dependency of the coefficient of friction in the two programs, and differences in modeling frictional behavior (viscoplasticity-based model in 3D-BASIS-ME-MB and direct friction model in ABAQUS). While these differences in modeling are typically insignificant in high-velocity motions, they are important in low-velocity motions as those in this example.

2. Force-displacement loops of individual bearings and of the isolation system at the two levels compare well in the predictions of the two programs. Particularly interesting are the loops for isolators No. 2 and 3, which indicate that the two bearings experience much more uplift than any of the other bearings. Nevertheless, the predictions of program 3D-BASIS-ME-MB favorably compares to those of the much more sophisticated program ABAQUS.

3. The drift history predicted by 3D-BASIS-ME-MB for the bottom story of the 4-story tower on the right compare very well with those of ABAQUS. However, the comparison is not as good for the drift history predicted for the bottom story of the 3-story tower on the left. This is the result of the significant uplift experienced by isolators No. 2 and 3 and the resulting rocking of the left tower. The results on drift presented for ABAQUS include the rigid-body rocking effect, whereas those of 3D-BASIS-ME-MB do not. The rigid-body contribution to drift (difference in displacement between top and bottom of story) is as much as 0.45x15/27.5=0.25 in., where 0.45 in. is the maximum uplift displacement, 15 ft is the story height, and 27.5 ft is the span between the uplifting bearings.

4. The predictions of the two programs for the top-floor accelerations of the two towers compare well, although program 3D-BASIS-ME-MB predicts larger acceleration than program ABAQUS. This appears as a paradox given that program 3D-BASIS-ME-MB does not account for the additional acceleration due to the rigid-body rocking motion effect when uplift occurs. However, program ABAQUS with its geometric nonlinearity capabilities captures the effects of rocking on reducing the inertia effects due to lengthening of the period of oscillations, resulting in a canceling of the effects.

Summary

In this study, the seismic response of base-isolated structures under conditions of bearing uplift is investigated. The analysis tool employed for this purpose is the newly-developed program 3D-BASIS-ME-MB, which represents a versatile tool for the analysis of complex seismically-isolated structures.

The paper presents two examples of base-isolated structures analyzed in 3D-BASIS-ME-MB. The first example is a seven-story model structure that was tested on the earthquake simulator of the University at Buffalo and was also used as a verification example for program SAP2000. The second example is a two-tower, multi-story structure with a split-level seismic isolation system. In both examples the analyzed structure is excited under conditions of bearing uplift, thus yielding a case of much interest in verifying the capabilities of analysis software. In the first example, analysis results obtained from program 3D-BASIS-ME-MB and program ABAQUS are compared with experimental results, whereas in the second example, results of analysis produced by program 3D-BASIS-ME-MB are compared with results obtained from program ABAQUS. The satisfactory comparisons of results in both examples demonstrate the capabilities of analysis software tools in capturing accurately the dynamic response of base-isolated structures even under the extreme conditions of bearing uplift.

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