Earthquake Remediation by Use of Rocking Columns – Finite Element Method Simulations

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***Abstract*—Rocking columns have been used in ancient civilization in the form of large stone columns supporting massive stones above them in seismically active regions such as Greece and Rome; however, their behavior under earthquakes is not well investigated using modern computer simulation technologies. Rocking columns generate a form of seismic isolation of earthquake forces and unlike conventional seismic isolators, rocking columns do not have a constant period of rocking. The natural frequency and stiffness of a rocking column changes based on the amount of horizontal displacement. Therefore, the system over rocking columns has ever changing natural (fundamental) frequency and does not get into a resonance state with the dominant earthquake frequencies. This paper includes a detailed investigation of rocking columns by using nonlinear and large deformation analysis techniques, which were compared and validated against rocking columns in the lab. The verification process enabled simulation of full-size rocking columns of modern buildings.**

***Keywords*—rocking column, finite element model, earthquake remediation**

I. Introduction

Earthquakes have caused collapse of buildings, major damage to cities, and have caused disasters. Therefore, the study of earthquakes and their remedial measures, primarily for buildings where people live and work, is of utmost importance and this paper explores the same area of research. Rocking of a rigid rectangular (or circular) column may be defined as the to-and-fro motion of the column in which column rotates about one edge or point having no contact of the other edges with the ground or vice versa. The study of rocking columns is inspired from earthquake response of ancient rocking columns used in Greek Civilization as well as Pagoda structures constructed mostly in Japan, where the first floor or all stories are flexible and behave like isolators. Rocking columns have been used in ancient civilization in the form of large stone columns supporting massive stones above them in seismically active regions such as Greece and Rome; however, their behavior under earthquakes is not well investigated using modern computer simulation technologies.

Earthquake remediation by use of rocking columns has been investigated by many researchers in the past [1]. The dynamic behavior of rigid-block structure resting on a rigid foundation and subjected to ground excitation has been a matter of investigation for many years. The idea to isolate a structure using the concept of rocking columns has been replicated in the laboratories by [2,3]. Researchers have explained the vibration of massive radioactive shielding concrete blocks, heavy laboratory equipment, and masonry facades cracked at the bottom with the help of rocking column concept [4-7].

Perhaps, Housner [8] was the first who explored survival of tall and slender structures during Chilean earthquake 1960 and pioneered the theory of rocking blocks. Ishiyama [9] explained the overturning criteria and argued that rocking column might undergo slide, twist and jump during rocking.

The rocking exhibits varying frequency during its vibration and it is dependent upon the amplitude of vibration. This varying frequency phenomenon associated with the rocking of columns causes a changing resonance frequency during vibration, which is not the case with elastic single degree of freedom structures. This ever-changing resonance frequency does not allow the structure to fall into resonance [5, 10, 11]

II. Research Methodology

The Finite Element (FE) model of rocking column is vulnerable to change in response due to small perturbations in ground excitation, rocking column size, equivalent damping and slenderness of rocking column [12]

Therefore, the experimental validation of the proposed FEM is inevitable. The first step is to develop an FEM using a well-known structural analysis and design framework, i.e., SAP2000v21. The next step is to validate proposed FEM with the help of laboratory experiments. The experimental validation comprises of rocking of a prototype excited under manual vibrations at the base. The prototype is a wooden podium structure which is made up of four rocking wooden columns and a stiff roofing board resting at top of these four columns.

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III. THEORY AND FINITE ELEMENT MODEL OF ROCKING COLUMN

An example of a solitary rectangular column is presented below to comprehend the theory of rocking column. Fig. 1 shows a single rectangular column supporting the weight (**W**) of the super structure. The lateral force due to earthquake is $\mathbf{F}_{EQ}$, the width of the rocking column is b, and the height of the rocking column is h. The column observes rocking if the moment due to the lateral ground force $\mathbf{F}_{EQ}$ exceeds the restoring moment due the weight of superstructure **W** (ignoring the self-weight of the column as compared with the weight **W** of the superstructure and vertical component of ground excitation). Hence, the rocking initiates if the acceleration due to ground motion (a_{EQ}) is greater than the 'b/h' ratio multiplied by the gravitational acceleration 'g'. The inequality $a_{EQ} > g \cdot b/h$ states the necessary condition to trigger rocking of column. This behavior is superior to some low stiffness base isolation systems where the isolator may be triggered due to strong wind or small earthquakes.

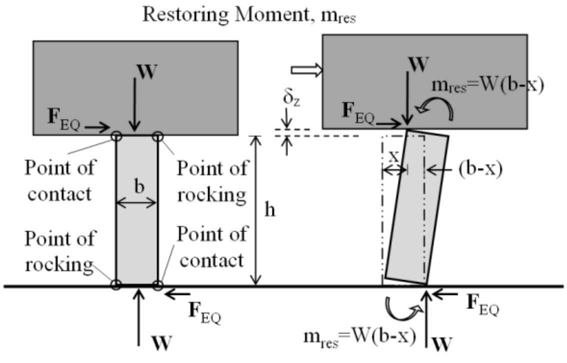

Figure 1. Diagram showing the forces required to trigger the rocking of column, and the restoring moment m_{res}.

The restoring moment, $m_{res} = W \cdot (b\text{-}x)$, is present during rocking only, and it tries to bring the column back to its original position. The geometry of the rocking column is drawn in Fig. 2 to derive the lateral force vs. lateral displacement relationship. In Fig. 2, F(x) is the force required to produce a lateral displacement 'x,' and 'W' is the load from super structure. Rectangle aecd is the original position of column before rocking and rectangle a'ec'd' is the position of column after rocking.

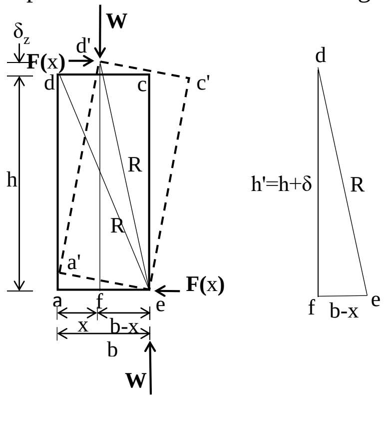

Figure 2. Free body diagram and geometry of rocking column.

The width of column is b and the height is h. After the start of rocking motion, as the top edge of the column displaces at 'x' amount of distance, the super structure experiences a vertical uplift being equal to δ_z. It is essential to derive lateral displacement vs. lateral force relationship to compute the stiffness of the column during rocking motion. The stiffness of the rocking column is maximum at lateral displacement x = 0, and it decreases to zero at lateral displacement x = b. At x > b, system becomes unstable due to overturning; therefore, a stopper mechanism is required to restrain the rocking column before 'x' reaches 'b' (x≤b). Otherwise, the rocking column will overturn and the structural system will become unstable. Eq. (1) is derived from right angle triangle shown in Fig. 2 as follows:

$$(b-x)^2 + (h+\delta_z)^2 = R^2 \qquad (1)$$

The vertical uplift δ_z may be expressed as a function of lateral displacement x and geometrical properties of the column, b, h, and R, as shown in Eq. (2).

$$\delta_z = \sqrt{R^2 - (b-x)^2} - h \qquad (2)$$

$\delta_z = 0$ @ x = 0; and $\delta_z = (R - h)$ @ x = b

Conservation of energy approach may be used to find the lateral force F(x) as a function of lateral displacement. The work done to uplift the weight 'W' by a distance 'δ_z' is equal to the energy stored in the system ($E = W.\delta_z$). The lateral force may be obtained after taking the first derivative of the energy 'E' with respect to the 'x'. Eq. (3) and Eq. (4) show the expression for the lateral force, and Eq. (5) shows the final form of the expression.

$$F(x) = \frac{dE}{dx} \qquad (3)$$

$$F(x) = \frac{d\left[\left(\sqrt{R^2-(b-x)^2}-h\right)W\right]}{dx} \qquad (4)$$

$$F(x) = W \times \frac{b-x}{\sqrt{R^2-(b-x)^2}} \qquad (5)$$

The normalized lateral displacement vs. normalized lateral force curve is shown in Fig. 3. The behavior of F(x) vs. x is nonlinear for high ratios of b/h but it becomes reasonably linear for b/h ratios less than 0.2. In most of the practical cases, b/h ratios of the rocking columns are usually less than 0.2; therefore, it is appropriate to simplify the above expression in Eq. (5) into a linear expression. For b/h < 0.2, let us assume that $h \approx \sqrt{R^2-(b-x)^2} = h'$, the Eq. (5) can be re-written in form of Eq. (6) as below:

$$F(x) \cong W \times \frac{b-x}{h} \qquad (6)$$

The Eq. (6) applies to b/h ratios lesser than 0.2 as shown in Fig. 4.

A simple finite element model is proposed which can be easily modelled in the already available software like

SAP2000. Fig. 5 shows the fundamental diagram of the free rocking column model.

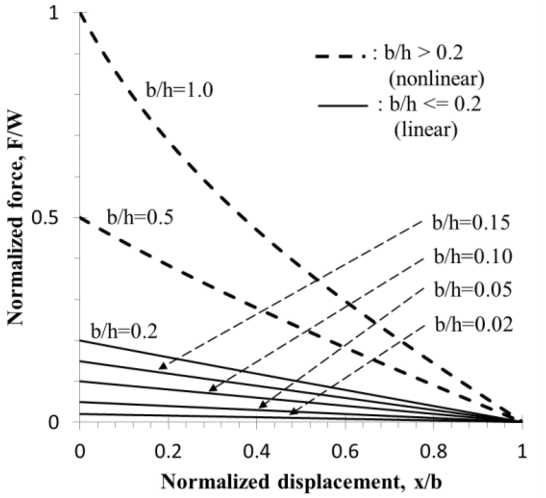

Figure 3. Normalized displacement vs. normalized force for different b/h ratios.

In this model, the column is made up of a rigid material such as concrete or steel. The bottom edges of the rectangular column (about which the column is assumed to rock alternatively) are attached with the ground using nonlinear springs. The nonlinear spring is defined to be very stiff under compression and very flexible under tension. In this way, the spring allows the corner to uplift but does not allow the corner to sink. The rigid shear link in Fig. 5 is in the form of a prismatic truss element and provided to restrain the sliding and slip of rocking column. The axial deformation of the shear link is negligible due to the large stiffness assigned to it. In actual scenario, both ends of the column experience rocking motion; therefore, it is necessary to replicate the same rocking model at the top of the column as well. Fig. 6 shows a column supporting a slab at top of it and experiencing rocking at both ends.

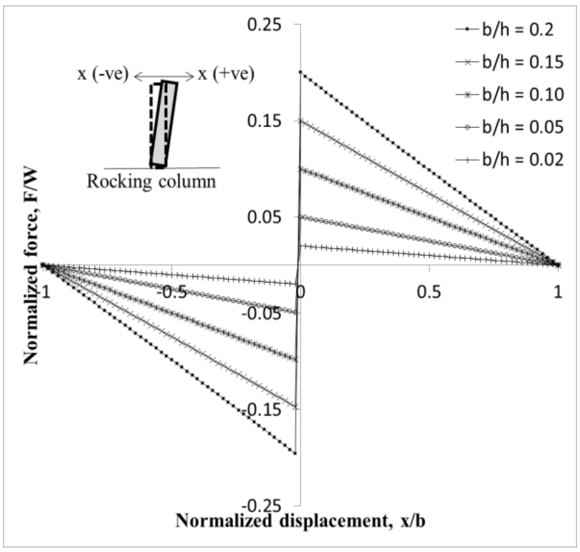

Figure 4. Linear approximation of F(x) vs. x relationship.

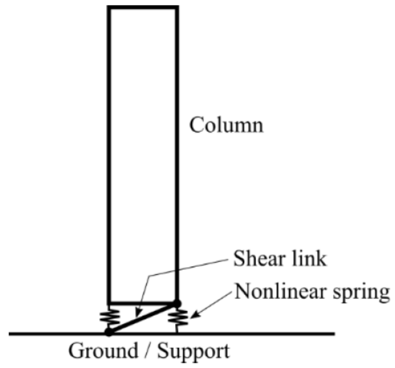

Figure 5. Numerical model of free-standing rocking column.

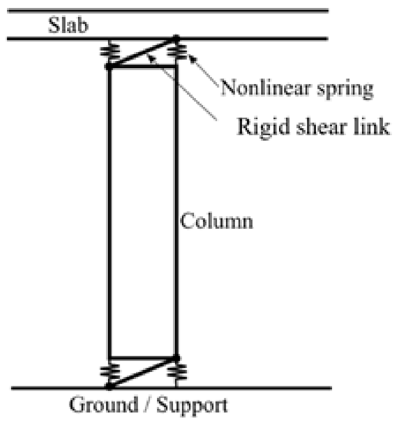

Figure 6. Numerical model of a rocking column supporting a slab on its top.

IV. Research Methodology

The experimental setup consists of the rocking of a single-story podium prototype. It is a simple structure in which four columns at its corners support roofing board. The dimensions of the roofing board is 48.1 x 60.2 cm2. The rocking columns are made up of wood having a rectangular cross-section of 5.0 cm x 5.0 cm. The connections between the roofing boards and the columns are made so that the columns may exhibit the rocking behavior. Particular hinges are made in the laboratory of the Civil Engineering Department, METU, to allow the rocking of the structure. The detailed drawing of the experimental setup used for the second phase of experiments is shown in Fig. 7.

V. Results and Discussion

A manual ground shaking is applied at the base board of the prototype. The accelerations at the base and the roof are observed with the help of the accelerometers for each manual ground shaking. Figs. 8-12 show the manual ground excitations induced to the prototype and the accelerations observed at the roof level. Instead of whole base acceleration history, a segment of the base acceleration is selected for the finite element analyses in Sap2000. For example, in trigger 02 (Fig. 8), instead of whole acceleration history of 40 sec, a segment of time history from 8 sec to 29 sec is selected for the validation of SAP2000 finite element model. Similarly, time history segments from 7 to 14 sec, 13 to 20.5 sec, 17 to 31 sec, and 5 to 29 sec are selected for trigger 03 (Fig. 9), trigger 04 (Fig. 10), trigger 05 (Fig. 11), and trigger 06 (Fig. 12) respectively.

The Fast Fourier Transform (FFT) analyses are executed on the selected segments of acceleration time histories. The results of the FFT are shown in Fig. 13. The segments selected for the input ground acceleration of SAP2000 are analyzed to get an idea about the frequency range of the input ground acceleration.

For the experiments, trigger 04, trigger 05, and trigger 06, metallic pieces are glued at the rocking surfaces to achieve improved rocking behavior. All the experimental results are generated using the proposed rocking model in SAP2000 software. The SAP2000 results are well matched with the experimental results, as shown from Fig. 13.

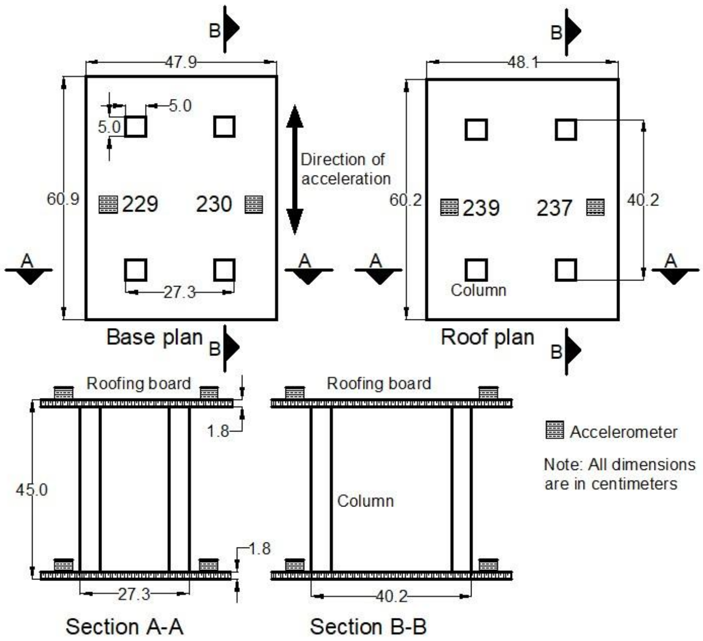

Figure 7. Experimental setup for the experiments of rocking podium structure.

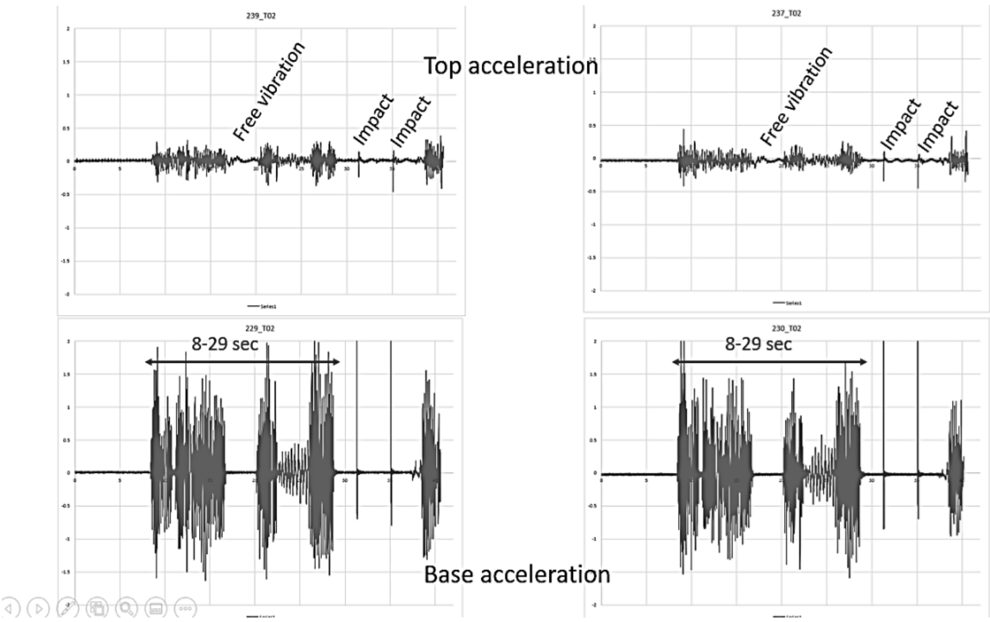

Figure 8. Base and roof accelerations of the rocking podium structure; Trigger 02.

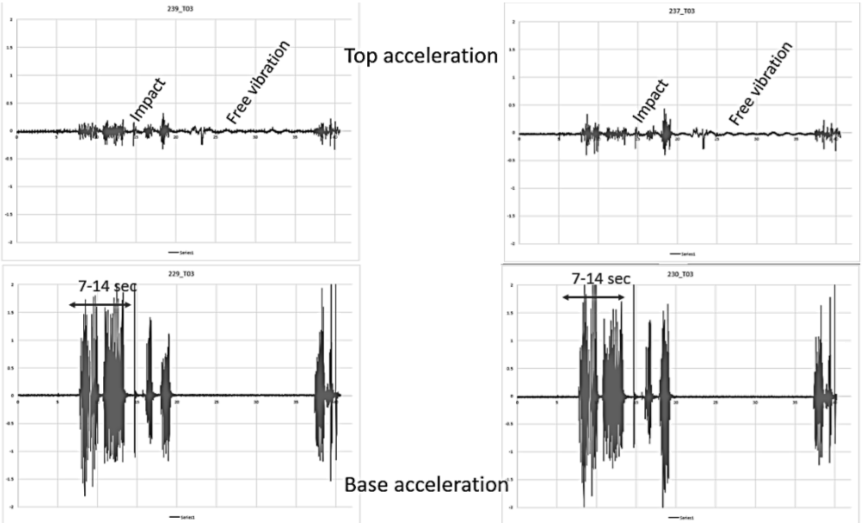

Figure 9. Base and roof acceleration of rocking podium structure with additional mass; Trigger 03.

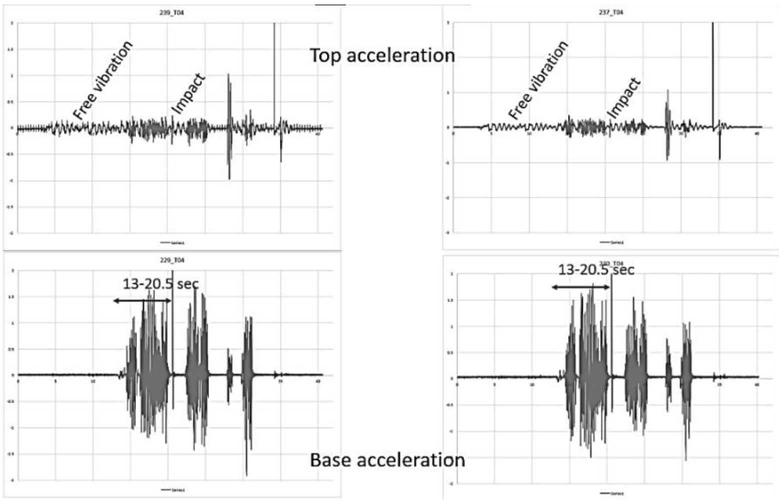

Figure 10. Base and roof acceleration of rocking podium structure with metallic rocking surface; Trigger 04.

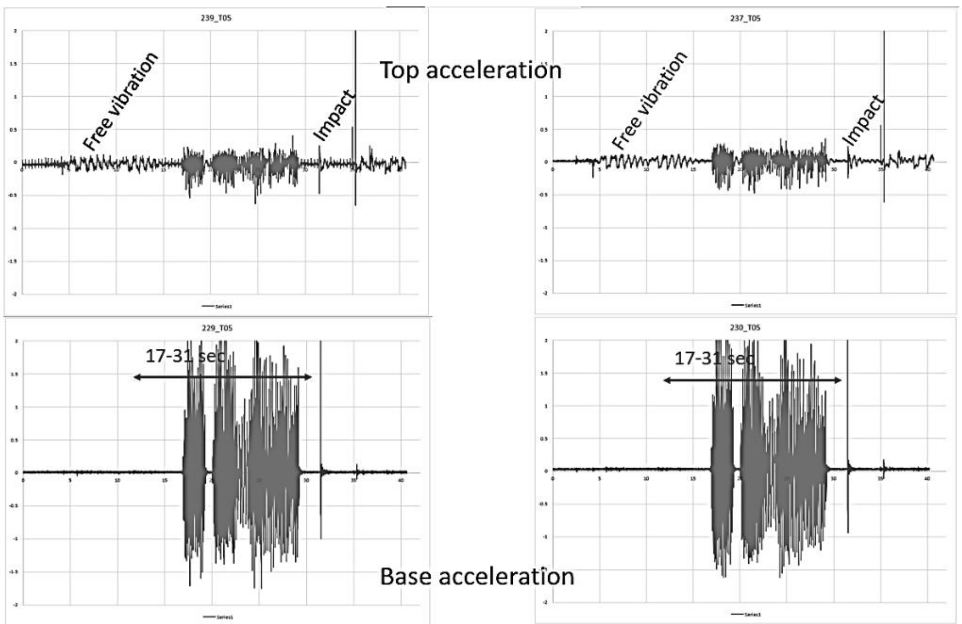

Figure 11. Base and roof acceleration of rocking podium structure with metallic rocking surfaces and additional mass at the top; Trigger 05.

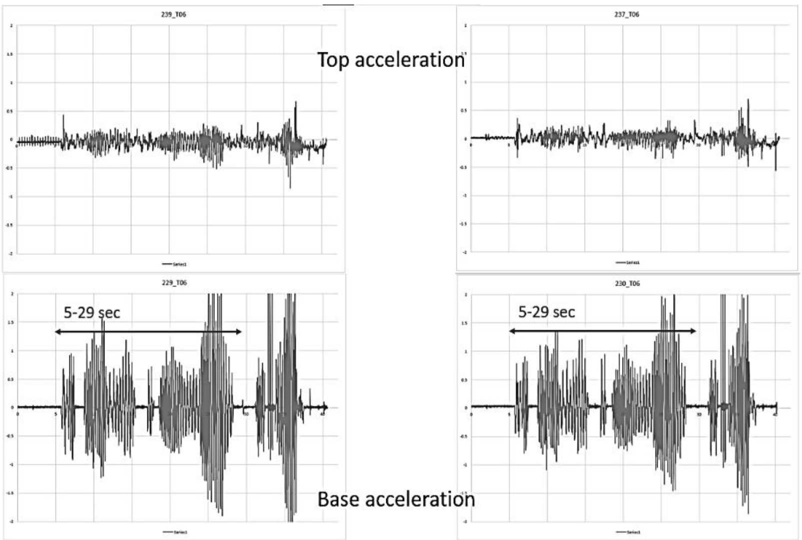

Figure 12. Base and roof acceleration of rocking podium structure with metallic rocking surfaces and additional mass at the top; Trigger 06.

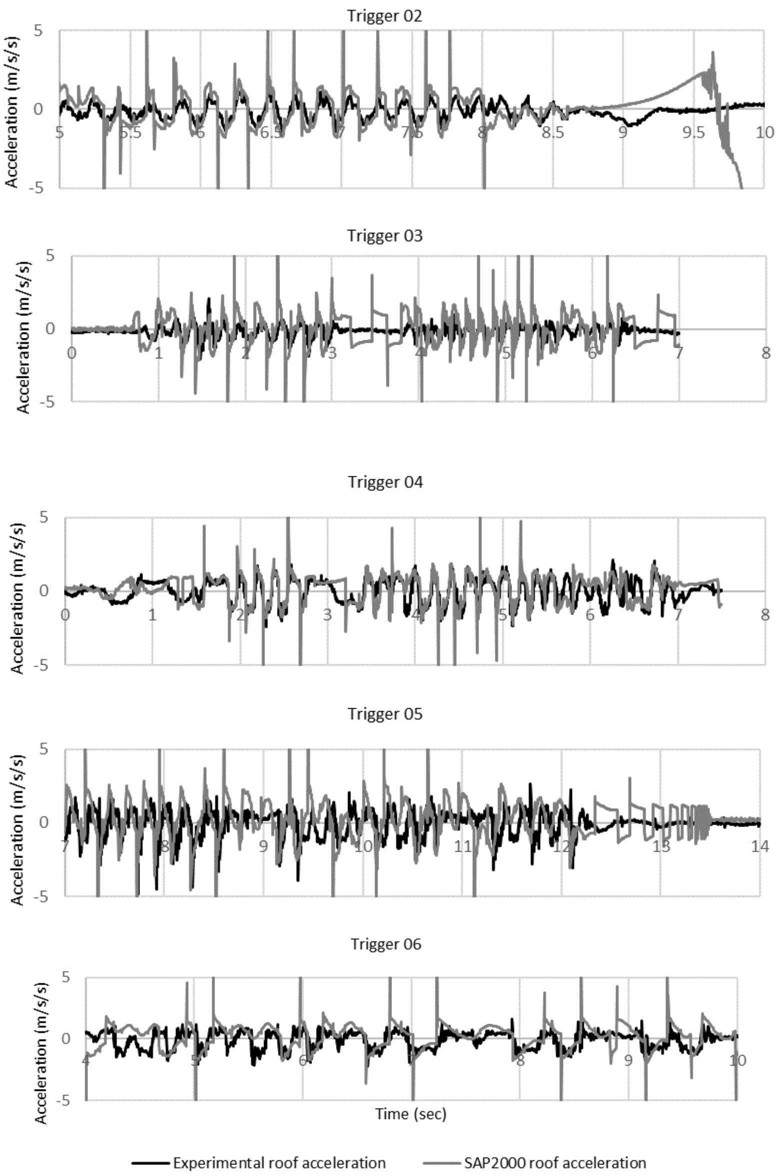

Figure 13. Comparison of roof accelerations; experimental vs. SAP2000 results; trigger 06.

VI. Conclusions

The experiments of small-scale single-story podium structure with rocking columns are performed and the respective finite element models are developed in a finite element software (SAP2000). The comparison of the numerical model defined in the SAP2000 and the experimental observation is concluded as follows:

- The numerical model defined in SAP2000 software is sensitive to the change in the integration time step, α-value (Hilber-Hughes-Taylor Alpha method), and damping ratio.
- The observed acceleration spikes at the impacts, in the SAP2000 results, are false as these spikes are not present in the experimental results. These false acceleration spikes appeared in the SAP2000 results may be ignored since they were not observed in the experiments.
- The comparison of acceleration at the top floor and the base of the rocking single story podium prototype shows the absolute earthquake remediation of structures by use of rocking column.
- Rocking columns have a large potential for earthquake damage remediation, which is not fully comprehended by the international community until today.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N. Javed and A. Turer manufactured the small-scale prototype for testing and performed the laboratory experiments together in the laboratory of Civil Engineering, Middle East Technical University, Ankara, Turkey. N. Javed wrote the preliminary draft of the paper and A. Turer updated it in terms of value addition, proof reading, corrections and completion. All authors had approved the final version.

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Prof. Dr. Ahmet Turer graduated from METU - Civil Engineering Department in 1993 and worked as structural engineer for two years after which he pursued his graduate studies at University of Cincinnati between 1995 – 1997 for MS and 1997-2000 for PhD. He has been a fulltime faculty member at METU – Department of Civil Engineering, Ankara, Turkey since 2000. His research interests are Structural Health Monitoring and applications, historic structures, structural evaluation and strengthening, forensic structural damage investigation & root cause determination, bridges, strengthening masonry structures against earthquakes, timber structures, steel structures, storage tanks, solar – hydroelectric – wind energy plants, marine structures, pipe structural damage, and Finite Element Modeling.