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SEISMIC PERFORMANCE OF SCF IN ISOLATION OF STRUCTURES - ASPECTS OF EXPERIMENTAL STUDY

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ABSTRACT: This paper presents the results of an experimental study on the performance of the SCF isolation system in seismic protection of structures. A series of shake table tests was conducted on a single story frame model (with capability of stiffness change). The frame model was mounted on a sliding concave foundation (SCF) with Teflon-steel interface as its sliding surface. The effectiveness of the SCF in seismic isolation of structures subjected to base excitations with varying characteristics was evaluated from the tests. The results showed that structures fitted with SCF withstood strong earthquakes without any damage, and that the seismic forces transmitted to the structure are much lower in comparison with the conventionally founded structures.

1. Introduction

A severe earthquake can produce forces that are much more than the minimum forces given in existing seismic design codes. Current design practices allow for inelastic designs and ductility provisions for structures that can prevent major structural failure and loss of life, while reducing the cost of construction. However, the building and its contents could still be severely damaged. To prevent this, the seismic isolation concept is considered a suitable design option that can protect buildings and their contents from serious damage.

The basic concept of seismic isolation is to uncouple a structure from the ground and thus protect it and its contents from the damaging effects of earthquake motions. To achieve this objective, additional flexibility is introduced at the base of the structure. A mechanism or source of energy dissipation (damping) is also provided to control the displacements that occur at the isolation level. This concept is not new and many ideas have been proposed since the early twentieth Century for "... devices which absorb or minimize shock to buildings arising from earthquakes, vibrations caused by heavy traffic or other disturbances of the earth's surface", de Montalk (1932)

2. Overview of Seismic Isolation

In terms of behavior, seismic isolators are classified into two major groups: elastomeric and frictional isolation systems. Elastomeric isolation systems are widely accepted and have found applications in several building and bridge structures in different parts of the world. More recently, sliding systems have attracted attentions as isolation systems. A large number of theoretical and experimental studies have shown that these systems could decrease the damaging effects of earthquakes (Skinner et al, 1993, Vafai et al, 2001). To reduce permanent displacement, most of the sliding isolation systems utilize some kind of re-centering device to provide a restoring force.

In this study, SCF (Sliding Concave Foundation) isolation system (Hamidi et al, 2003a and 2003b) is investigated experimentally. The new system, similar to the famous FPS isolator (Zayas et al, 1990) utilizes friction to dissipate the earthquake energy. However, it has other features that make it an attractive base isolation system.

3. Sliding Concave Foundation (SCF) System

The main components and the basic principles of the new system (SCF) are discussed by Hamidi et al (2003a and 2003b), and shown in Figure 1. The foundation in this system consists of two parts (Figure 1(a)). The lower part (fixed foundation, or briefly, foundation) has a cylindrical concave surface at the top, which moves with the ground. The top part, sliding raft, has a cylindrical convexity which is rigidly attached to the structure and can be considered as its floor. The interface of these two parts is made of low friction materials such as Steel-Teflon or Teflon-Teflon interfaces. The component of the weight of the superstructure acting on the cylindrical surface of the foundation develops a small restoring force that beside the reduction of the permanent displacement, improves the insensitivity of the system to the frequency content of the excitations. It should be mentioned that the model shown in Figure 1(a) is two-dimensional. In practice, however, the problem is three-dimensional and there are two cylindrical sliding surfaces that are perpendicular to each other. Since the sliding on each surface is independent of the other surface, the characteristics of the SCF can be investigated using a two dimensional model. SCF can be used as a suitable isolation system for buildings and its contents including sensitive equipment and/or invaluable historical artifacts in museums.

The basic concept of SCF is shown in Figure 1(c). The motion of the structure mounted on this isolation system is similar to a compound pendulum. Therefore, both the linear inertia (mass) and the rotational inertia of the isolated structure contribute to the dynamic natural period of the system which can be expressed as (Hamidi et al, 2003a):

$$\mathrm{T} = 2\pi\sqrt{\left(\frac{\mathrm{I}_o}{\mathrm{K}_\theta}\right)} = 2\pi\sqrt{\left(\frac{\mathrm{I}_{c.g}}{\mathrm{WR}_{c.g}} + \frac{\mathrm{R}_{c.g}}{\mathrm{g}}\right)} \qquad (1)$$

where W is the total weight of the superstructure, Ic.g is rotational moment of inertia around the center of gravity of the superstructure and Rc.g is the distance of the center of gravity to the center of curvature of the foundation.

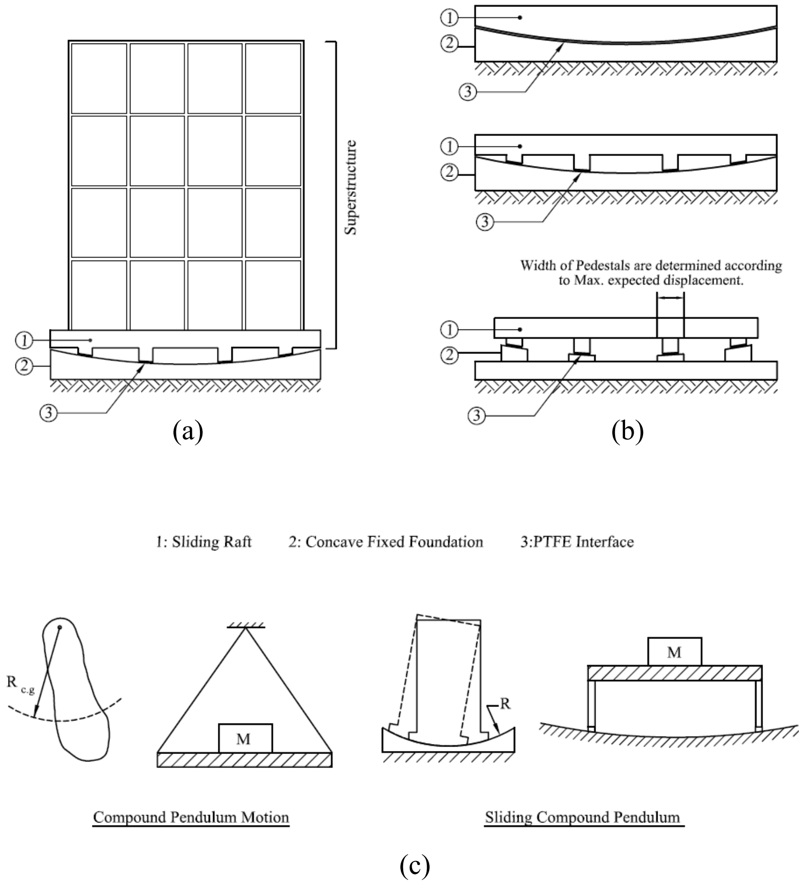
SCF shifts the fundamental period of the structural system to a very high value, which is far from the predominant frequency associated with the previously recorded earthquakes. In their earlier works, authors have theoretically studied the main characteristics of SCF (Hamidi et al, 2003a and 2003b).

4. Scope of This Study

To examine the performance of the SCF and to verify the predicted theoretical and analytical responses (Hamidi et al, 2003a and 2003b) of the new system, a comprehensive experimental study is performed. Small-scale SDOF structural models supported on SCF isolating system are tested on a shake table and are subjected to different simulated earthquake loads. The main objectives of the investigation are:

- To evaluate the effect of the SCF on the fundamental period of the structure.
- To evaluate the effect of the SCF on the base shear and drift displacements of the structure.
- To assess the sensitivity of the structural response to the frequency content of the excitation.
- To examine the effects of torsional eccentricity of the structure on the performance of SCF.
- To evaluate the after shake residual rotation/displacement.

In this short paper, only some of the results will be presented. A complete report of test results is provided by Hamidi (2006)



(a) (b)

(c)

Figure 1: Sliding Concave Foundation (SCF); (a) schematic configuration, (b) different methods of constructing a SCF bearing, (c) basic principles of SCF.

5. Low Friction Interface Material

The value of friction coefficient plays a predominant role in the response of any friction based isolation system, including SCF. So far, different materials have been employed in sliding isolation systems, among them Teflon proved to be the best choice. Teflon sheets (along with different fillers) can be manufactured to fulfill the required design criteria and can be used as a good option in the SCF isolation system.

In this study, the model of Constantinou et al, (1990) is employed to consider the variations of μ with velocity and normal pressure. According to this model, the dynamic coefficient of friction is given by:

$$\mu = f_{\max} - (f_{\max} - f_{\min})\exp(-a|\dot{U}|) \tag{2}$$

where $f_{\max}$ (dynamic coefficient of friction at high sliding velocity) and $f_{\min}$ (dynamic coefficient of friction at zero velocity) define the range of variations of μ with sliding speed ($\dot{U}$) and a is a constant that depends on the pressure and the condition of the interface. The values of a, $f_{\max}$ and $f_{\min}$ should be determined experimentally.

A test set up was designed to measure the required parameters in Equation 2 (Hamidi 2006). Based on the experimental results, the following formula is suggested for the sliding coefficient of friction of the sliding surface of the SCF bearing:

$$\mu = 0.125 - .045\exp(-0.22|\dot{U}|) \tag{3}$$

The values of a, $f_{\max}$ and $f_{\min}$ are obtained by curve fitting Equation 3 to the experimental data and are found to be 0.22 (sec/cm), 0.125 and 0.08, respectively. Figure 2 shows a plot of Equation 3 along with the related experimental data.

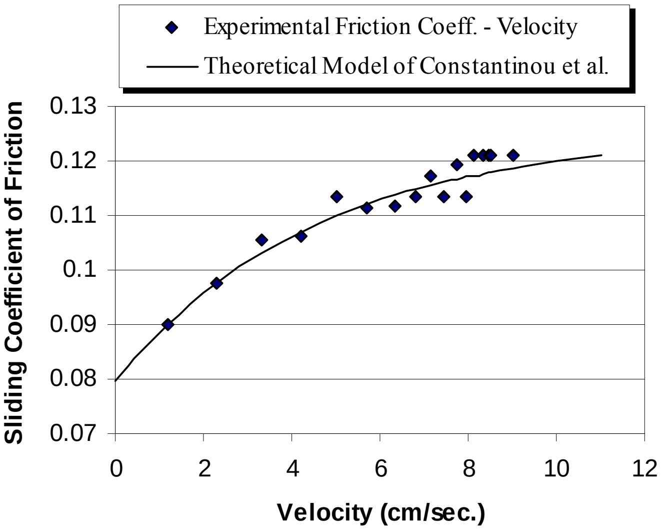


Figure 2: Experimental measurements of friction coefficient of the sliding interface and the proposed formula (Equation 3) according to the model of Constantinou et al (1990).

6. Test Model

To verify the performance of SCF in isolating structures, three one-story shear building models (structures I to III) that have different natural periods are to be tested on shake table. The models will simulate full-scale structures with periods ranging from 0.4 sec to 2.0 sec. (buildings of approximately 4 to 20 stories in height). This permits investigations of the effectiveness of the SCF system for relatively short to tall buildings. Changing the mass and/or lateral stiffness can generate different structural periods for the model structure.

The general configurations and details of the test structure are given in Figure 3 and their general properties are summarized in Tables 1. Basically, as shown in Figure 3, the test structure consists of a rather rigid floor carried by four vertical, both ends pinned columns which do not contribute in lateral stiffness of the test model. A central steel strip (with clamped ends) provides total lateral stiffness. By changing the cross sectional dimensions of this central strip, structures with different flexibility can be produced (the length of the strip is fixed as shown in Figure 3). For this study three strips I (142mmx19.0mm), II (90mmx15.8mm) and III (140mmx9.5mm) are used which generate model structures I, II and III respectively. Effective story mass (including part of columns and central strip masses) and the lateral stiffness of the test structures are given in Table 1.

All of the test structures were mounted on the same SCF foundation. The sliding surface consists of Teflon (Graphite PTFE)-Steel interface (the friction coefficient of which is given by Equation (3)). The radius of the SCF is selected to be 2.5m. Using 1/2, 1/4 or 1/5 time scale for the earthquake inputs, this foundation simulates full-scale foundations with the radii of 10m, 40m and 62.5m respectively. The fixed part of the foundation has a mass of 115 kg and the mass of sliding raft is 180 kg. Considering that the mass of the floor is about 110 kg (for all three structures), the model has a total mass of about 405 kg or a weight of about 4000N.

TABLE 1. Structure Properties (Values in the parenthesis are analytical)

Structure	Storey Height (m)	Effective Storey Mass (kg)	Storey Stiffness (N/m)	Period of the Structures (sec.)	Damping Ratios of the Structures
I	1.0	111.8	196338	0.19 (0.15)	0.040
II	1.0	106.6	72013	0.25 (0.24)	0.055
III	1.0	106.1	24197	0.39 (0.42)	0.095

Free vibration tests were performed on the model structures and the displacements of the story were recorded. The period of the models were determined directly from the time history of the displacement and the damping ratios were calculated from the same graphs using the amplitude decay concept. The fundamental periods and damping ratios of the model structures (I to III), under fixed base conditions, were determined analytically and experimentally which are listed in Table 1. It can be seen from Table 1 that except for structure I, the analytical and experimental results are in good agreement. The difference in case of structure I can be attributed to the relative flexibility of the grips at the ends of the central steel strip. Since, for structure I the stiffness is very high compared to the other two structures, this flexibility affects the total stiffness and thus the period. In the rest of our analytical calculations the experimental periods would be used.

Other structural model variations include different torsional eccentricities for structure I (Figure 3(d)). The location of the central steel strip is changed to obtain torsional eccentricities of 0%, 7%, 14%, 29% and 36% which correspond to structures I, Ia, Ib, Ic and Id respectively. Eccentricity is expressed as a percent of the width of the model.

7. Test Model Setup

The models were tested on the shaking table at the Boundary Layer Wind Tunnel Laboratory (BLWTL) of the University of Western Ontario (Western). The shake table is capable of simulating different ground motions in one or two horizontal directions.

Electronic instrumentation was used to record the horizontal accelerations, and total and relative displacements at different locations of the model. The instrument locations are shown schematically in Figure 3a.

A number of simulated earthquake loadings were performed on the test structures. These included the simulated time histories of the 1940 El Centro, 1971 Pacoima Dam, 1985 Mexico City, 1966 Park field, and three different records of the 1994 Northridge earthquake (Tarzana, Sylmar and Newhall records). These records have significantly different frequency contents. The input motions can be scaled to obtain ground motions ranging from low to extremely severe excitations. These earthquakes were also compressed by the appropriate time scale factor to achieve the desired prototype building simulations.

Because of the inherent limitations of the available shake table, the output accelerations of the table were different from that of the original records. The mass of the model structure and the frequency content of the input motion influenced the output of the shake table, varying it from the real (input) record. In fact, the peak acceleration of the table output was reduced remarkably compared to the input motion. This means the measured accelerations and forces were smaller than that of the real earthquake. Furthermore, the simulated records have higher energy in the range of longer periods of the spectrum as compared to the original records. This leads to high lateral displacements for long period structures when subjected to the table generated motions.

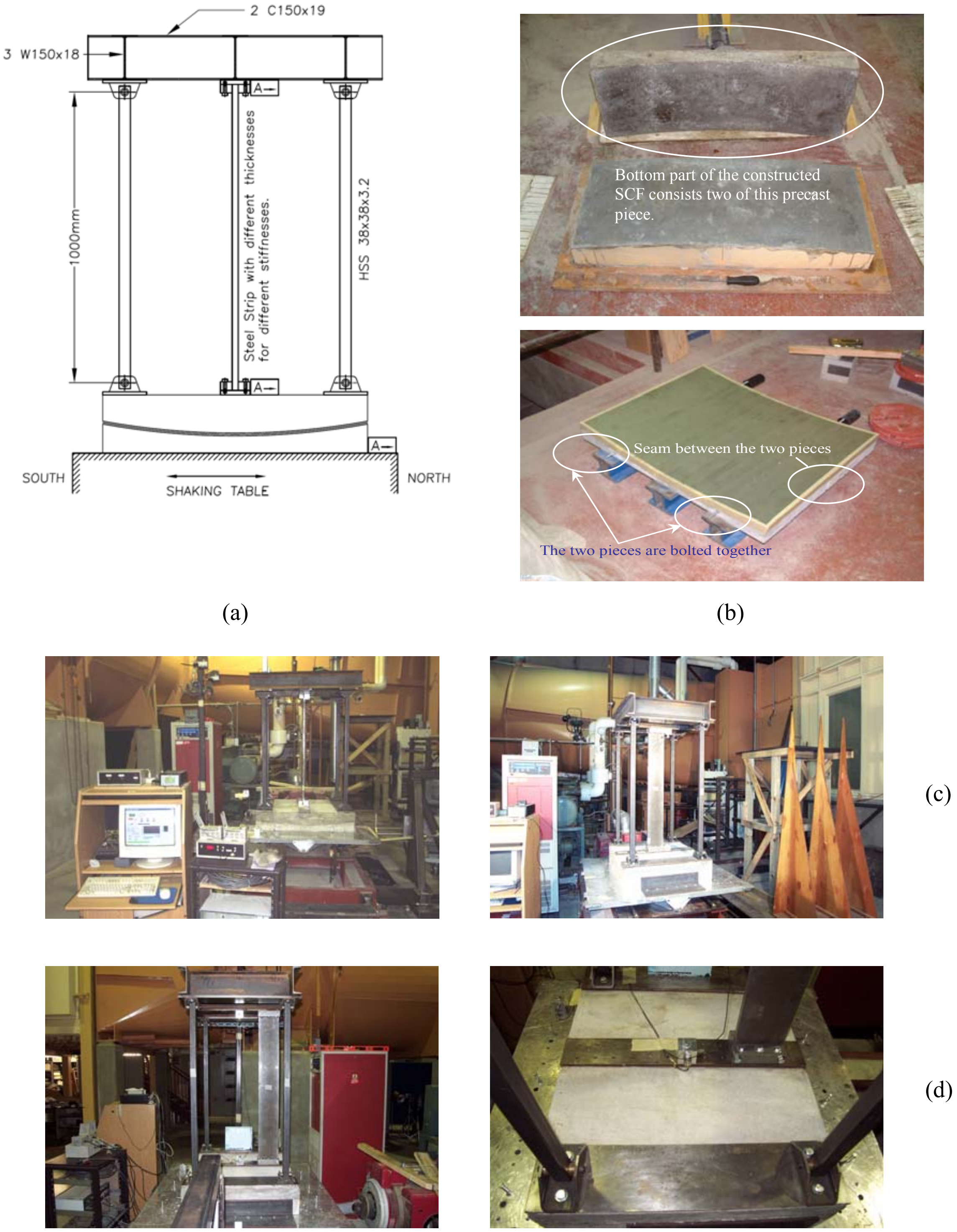


Figure 3: Test model for isolation of buildings with SCF; (a) General configuration; (b) SCF in construction process; (c) Completed Model; (d) Eccentric configuration.

8. Analytical Verification

A computer program has been developed to analyze the response of SCF isolated structures (Hamidi et al, 2003a and 2003b). The coefficient of friction measured as part of this study (Equation 3) was used to characterize the sliding surface in the model. The dynamic properties of the model structures used in the analysis were verified through comparing the natural period of the structure calculated using the developed algorithm with that determined from free vibration tests (Table 1). The program was then used to analyze the response of different model structures subjected to the table generated motions and the results were compared with the measured values. These analyses verified the experimental results and the good agreement validated the program developed. After verifying the program, it can be used for the design of SCF isolation systems and predict the responses of the isolated structure.

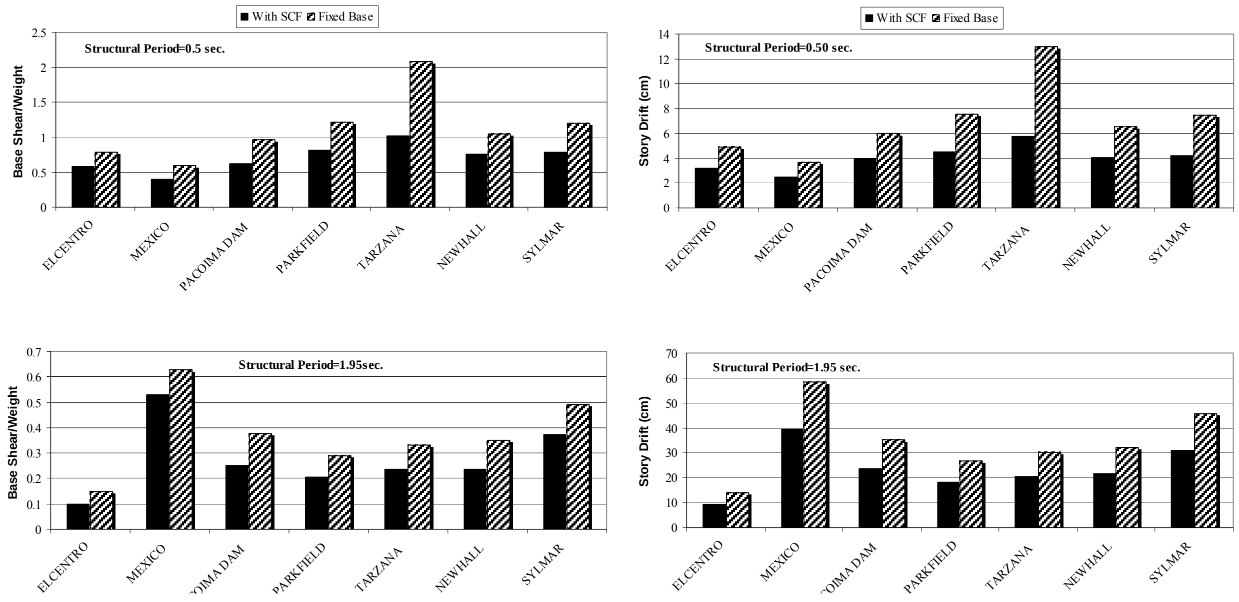
9. Test Results

A complete report of test results is provided by Hamidi (2006). In this section, the accelerations of the model structures are reported in g's. The lateral shear forces, F, are normalized by the total weight, W, of the upper structure, i.e. F/W (the weight of the raft is not included in W). The accelerations and normalized forces are the same for the prototype and model structures and need not to be scaled. For simplicity and clarity, the experimental results are reported in the prototype scale. The prototype scale values are denoted E.F.S. (Equivalent Full Scale) in the following sections. These E.F.S. data are directly applicable to full scale structures.

9.1. Base shear and story drift

The test structures I to III represent full scale buildings with natural periods ranging from 0.38 to 1.95 sec. The results therefore represent the performance of the SCF system in isolating different buildings within a reasonable range of structural periods.

The maximum base shear forces and story drifts for some of the experiments are shown in Figure 4. The results are shown for two low and high structural periods. The measured values of the maximum base shear for the isolated structures are compared to the calculated values of maximum base shear of the structures with fixed base conditions.



(a) (b)

Figure 4: E.F.S. base shear and story drifts of model structures subjected to simulated excitations for different time scales.

Figure 4(a) shows that the SCF reduced the resulting base shear for all earthquake records considered. However, the amount of reduction depends on the strength of the earthquake. The effectiveness of the SCF in reducing the base shear is more pronounced for stronger earthquakes, as can be deduced by comparing the transmitted base shear in the case of Tarzana record with that of Mexico City record for a structure with a period of 0.5 sec.

The story drifts are shown in Figure 4(b). Story drifts are due to the flexural deformations of the structural members only and, therefore, are an important measure of the anticipated earthquake damage to the structure. In Figure 4(b), the story drifts are shown for the structures with and without SCF isolation. It is obvious from Figure 4(b) that the SCF reduced the story drifts for all test structures and all simulated ground motions. In most cases, the reduction ranged between 25% and 30%, but for strong motions that can induce higher drifts, the reduction amounted to 50%.

9.2. Sliding displacement

The sliding displacement of the raft and the total displacement at the top of the test structure are shown in Figure 5. The total displacement at the top of the building is the sum of story drift and the sliding displacement of the raft, which reflects the total displacement of the top relative to the ground. The total displacement is important because it dictates the size of gap between adjacent structures required to prevent pounding during an earthquake. The story displacements are also shown in Figure 5 for comparison purposes. The figure shows that the raft and the top displacement of isolated structures were higher than that of the fixed structure (without SCF) for short (short period) structures. For taller structures, however, the top displacement of the fixed structure exceeded the raft displacement and was almost equal to the total displacement at the top of the isolated structure.

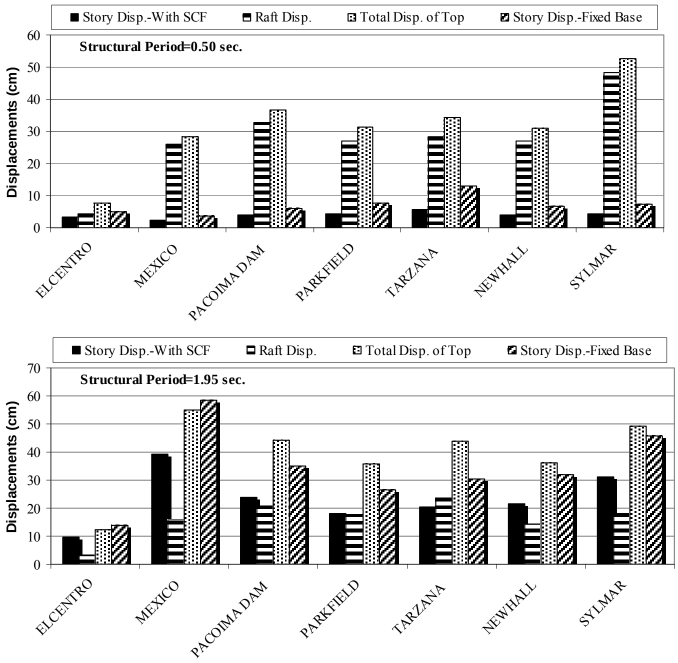


Figure 5: E.F.S. Raft Displacement of different model structures (I, II, and III) using different time scales.

9.3. Analytical versus experimental results

The developed numerical program (Hamidi et al, 2003a and 2003b) has been employed to calculate the response of the test structures for conditions identical to those which resulted in the experimental responses. The calculated responses are then compared with the measured values (for a complete report of these comparisons refer to Hamidi (2006). Figure 6 show the analytical and experimental responses for the simulated Tarzana excitation.

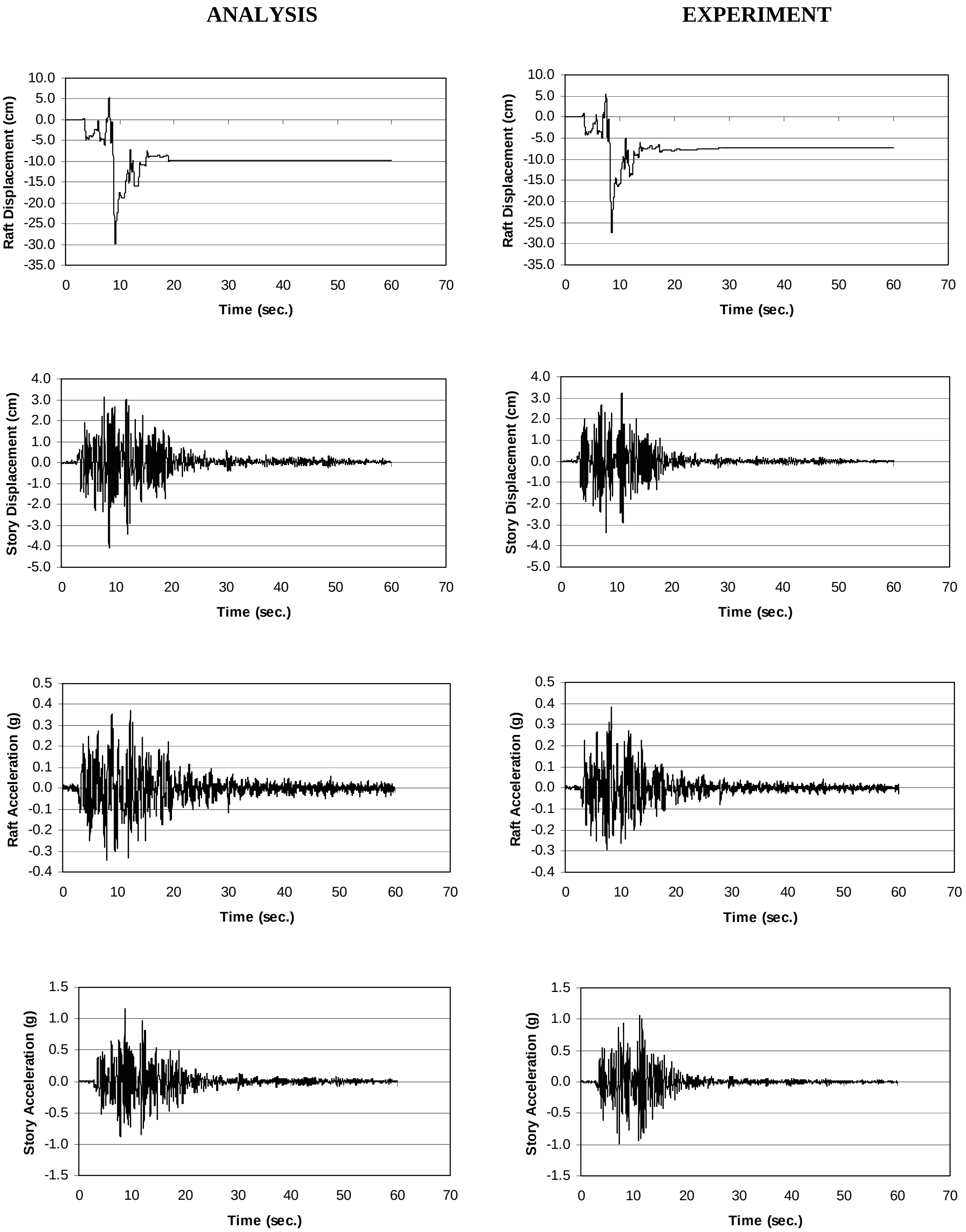


Figure 6: Comparison between analysis and experimental E.F.S. results: Simulated Tarzana record, Model structure I, Time scale = ½

As can be seen from these figures, the analytical and experimental results agree well. It is noted that the analytical method not only can predict the peak response values but also is capable of reproducing almost every detail of the observed response. This excellent agreement verifies the experimental program and also validates the developed analysis incorporated in the computer program.

10. Conclusion

Shake table tests have been conducted to evaluate the seismic performance of the sliding concave foundation (SCF) in isolating structures with different fundamental periods. An analytical model has been developed to calculate the dynamic response of the system under different experimental conditions. Based on the experimental and analytical results, the following conclusions may be drawn:

SCF effectively reduces the lateral drift of the story (which represents the demands on the structure and can be considered as a measure of potential damage to the structure when subjected to strong ground motions).

The SCF effectively isolated the upper structure by shifting the period of the structure; and significantly reduced the seismic loads (base shear) transmitted to the supported structure in comparison with the fixed base structure.

The SCF effectively dissipated the earthquake energy and reduced the structural frame drifts and displacements, and consequently, reduced the damage potential significantly for structures with natural periods ranging from 0.4 to 2.0 sec.

The analytical results agreed well with the experimental results, verifying the ability of the analytical method model to predict the responses of SCF isolated structures.

11. Acknowledgments

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