

RESPONSE OF A SUBSTANDARD TWO-COLUMN BRIDGE BENT SUBJECTED TO NEAR-FAULT GROUND MOTION

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ABSTRACT

Near-fault ground motions can cause extensive damage to substandard reinforced concrete bridge structures. It is essential to understand how these structures will behave during and after a strong near-fault ground motion. A two-column bent with diamond shaped columns was constructed at the University of Nevada, Reno and will be used for shake table testing. In order to understand how the specimen will behave during shake table testing the specimen was analyzed using a non-linear dynamic analysis program. The analysis consisted of subjecting a computer model of the specimen to ten recorded near-fault ground motions. The data was then analyzed by examining the residual drift and the displacement versus time that the specimen experienced for each of the ground motions. The acceleration history recorded by the Rinaldi receiving station during the 1994 Northridge earthquake was selected for the future shake table testing of the specimen. In addition, a shake table testing protocol was developed based on a scaled version of the Rinaldi acceleration history.

KEY WORDS: near-fault ground motion, substandard design, specimen response

1 INTRODUCTION

1.1 Background

Prior to 1971, bridges were inadequately designed to resist the forces of earthquakes. Some bridges were designed to only support gravity loads. Design was completed in this manner because, at the time, there was not enough information to design for seismic forces. It is essential to understand how these structures will behave during a large earthquake. It is evident

strike of the fault (Somerville 2002). This large pulse motion consists of a large spike in the velocity component of a ground motion. The spike in velocity should be around 152 cm/sec (60 in/sec) in order to be classified as a near-fault ground motion. However, this is only an estimate and ground motions with lower peak velocities can be classified as near-fault ground motions as well. Figure 1.2 shows an example of a near-fault velocity spike. A diagram of the large directivity pulse of motion, which propagates from the fault at a direction perpendicular to the strike of the fault, can be seen in Fig. 1.3. Another factor for classifying ground motions as 'near-fault' is the distance to the epicenter of the earthquake. The epicenter should be within 15 km (10 miles) of a structure of interest.

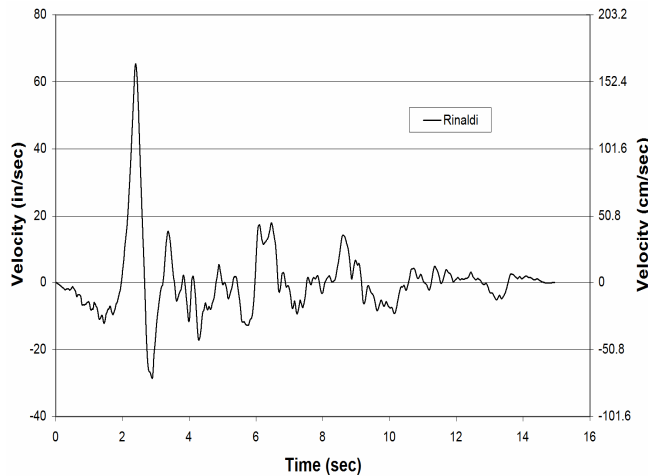


Figure 1.2 Velocity spike

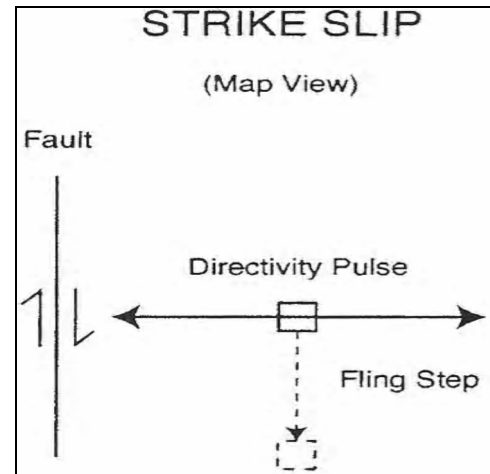


Figure 1.3 Directivity pulse (Somerville)

The effects of near-fault ground motions on structures that have been adequately designed and detailed, non-substandard, have been studied at UNR (Phan et al. 2007, Choi et al. 2005). Six columns were tested to failure under near-fault ground motion. It was concluded that all of the columns experienced a large amount of residual displacement. The residual displacement is due to the large one directional pulse loading that is typical of near-fault ground motions. This type of loading caused the columns to deflect past the elastic range and not return to the original position. After examining the effects of near-fault ground motions on non-substandard structures, it was determined that the effects of near-fault ground motions on substandard structures need to be studied. This is due to the fact that there are numerous structures which are of the substandard design.

1.2 Objective and Scope

The objective of this analysis was to select a ground motion and a testing protocol for the future near-fault testing of the substandard two-column diamond shaped bridge bent that was previously constructed at UNR, here after referred to as (S2DB). This was completed by comparing the specimen responses for 10 different near-fault ground motions. The goal was to

determine how the structure would behave in terms of residual displacement, displacement vs. time and displacement history.

2 ANALYSIS PROCEDURE

2.1 Ground Motion Selection

In order to analyze S2DB, sample ground motions needed to be obtained. It was desirable to have recorded ground motions from past earthquakes, versus synthetic ground motions, because this is the most accurate and real data. Thus, ground motions were downloaded from the Pacific Earthquake Engineering Research Center (PEER) Strong Motion Database. This web site has numerous records from past earthquakes. The records were recorded by ground motion monitoring stations in the vicinity of the earthquakes. The data from the PEER Strong Motion Database consists of a record of the ground acceleration, the ground velocity and the ground displacement for each earthquake. A list of the ground motions used for this analysis can be found in Table 2.1. When selecting a ground motion to be analyzed, the first step was to examine the maximum velocity associated with that particular ground motion. As was explained in section 1.1, near-fault ground motion consists of a large spike in the velocity component of a ground motion. If a particular ground motion contained the spike in velocity, the ground motion was a candidate for further analysis. While the velocity component of the ground motion dictates which ground motion to select, it was the acceleration component that was used for the analysis. The acceleration history was then downloaded and input to a nonlinear dynamic computer analysis program.

Table 2.1 Ground motion data

Record ID	Earthquake	Station	Data Source	Record/Component	HP (Hz)	LP (Hz)	PGA (g)	PGV (cm/s)	PGD (cm)
P0934	Northridge 1994/01/17 12:31	24514 Sylmar - Olive View Med FF	CDMG	NORTHR/SYL090	0.12	23	0.604	78.2	16.05
P0934	Northridge 1994/01/17 12:31	24514 Sylmar - Olive View Med FF	CDMG	NORTHR/SYL360	0.12	23	0.843	129.6	32.68
P1005	Northridge 1994/01/17 12:31	77 Rinaldi Receiving Sta	DWP	NORTHR/RRS228	null	null	0.838	166.1	28.78
P1443	Chi-Chi, Taiwan 1999/09/20	TCU068	CWB	CHICHI/TCU068-W	0.03	50	0.566	176.6	324.11
P1540	Duzce, Turkey 1999/11/12	Duzce	ERD	DUZCE/DZC270	0.08	50	0.535	83.5	51.59
P0178	Imperial Valley 1979/10/15 23:16	942 El Centro Array #6	CDMG	IMPVALL/H-E06230	0.1	40	0.439	109.8	65.89
P1057	Kobe 1995/01/16 20:46	0 Takatori	CUE	KOBE/TAK000	null	null	0.611	127.1	35.77
P0082	San Fernando 1971/02/09 14:00	279 Pacoima Dam	CDMG	SFERN/PCD164	0.1	35	1.226	112.5	35.5
P0720	Superstition Hills(B) 1987/11/24 13:16	5051 Parachute Test Site	USGS	SUPERST/B-PTS225	0.06	20	0.455	112	52.8
P0144	Tabas, Iran 1978/09/16	9101 Tabas		TABAS/TAB-TR	0.05	null	0.852	121.4	94.58

2.2 RCShake

Once a ground motion was selected for analysis, there were several parameters which needed to be addressed. These parameters were related to the mass of the specimen. A nonlinear dynamic computer analysis program was developed at UNR. The program models how a specimen is predicted to behave when subjected to an earthquake on the shake tables at the UNR Center for Civil Earthquake Engineering Research (CCEER). The program is titled RCShake and its application in pre-shake table testing is crucial. The program has numerous input parameters: the mass rig system weights; specimen weights; specimen dimensions; and specimen dampening. Figure 2.1 displays the mass rig set-up, and Table 2.2 lists the mass rig system weights. The measured components in Table 2.2 can be seen in mass rig diagram in Fig. 2.1. The mass rig is used as a safety device. When testing specimens on the shake tables, it is very important that not only is the safety of persons in the lab ensured, but the safety of the lab equipment as well. The mass rig supports the specimen and prevents the total collapse of the specimen. This is a complicated interaction process between the mass rig and the specimen, and all of the interaction needs to be taken into account. By inputting the above mentioned parameters, RCShake calculates the effective lateral weight, the mass rig P-Delta weight, and the specimen P-Delta weight. These values are then used in the next step of the analysis.

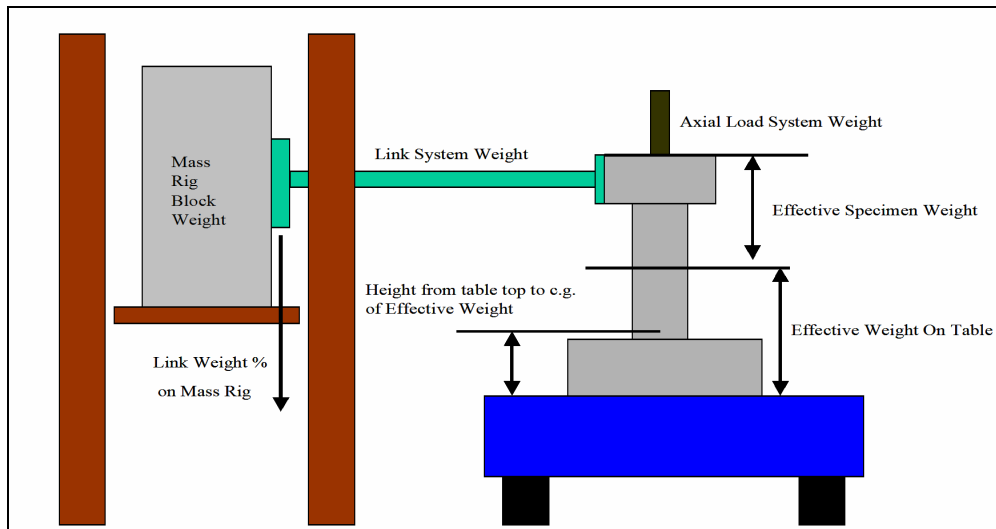


Figure 2.1 Mass rig system

Table 2.2 Mass rig system weights

Link System Weights:			
Component	Dimensions	Number Used	Total Weight
Swivel Link	450 lb	2	900 lb
Short Adaptor	60 lb	1	60 lb
Load Cell + Adaptor	120 lb	1	120 lb
Bent Link	130 lb	1	130 lb
Conection Plate	1000 lb	1	1000 lb
			2.21 kips

Axial Load System Weight			
Component	Dimensions	Number Used	Total Weight
Axial Ram	10 lb	10	100 lb
Load Transfer Beam	2470 lb	1	2470 lb
			2.57 kips

Mass Rig Block Weight			
Component	Dimensions	Number Used	Total Weight
Reaction Block	20000 lb	2	40000 lb
			40.00 kips

2.3 DARCO

DARCO is an extension of the RCShake computer analysis program. RCShake has numerous hysteresis functions that can be selected for modeling. However, because near-fault ground motion is still a relatively new concept, RCShake does not calculate the specimen hysteresis loop for this type of ground motion. DARCO is used to bridge the gap. It calculates the residual displacement, displacement vs. time and creates a hysteresis graph. DARCO is a Matlab based program. The program works through the design of an m-file, which is processed by Matlab. All of the results are calculated and displayed in Matlab.

The input parameters for DACRO consisted of the following; the basic mass of the specimen, the column height, the damping, the earthquake time step, the convergence rate, the basic stiffness of the model, the basic properties of the model and the O-Hyst parameter. As mentioned in section 2.2 of this report, the basic mass of the specimen was found from RCShake. The column height was 1.5-m (5-ft) (Sureshkumar et al. 2004). The damping factor was input as 2.0%, chosen because of the low amount of reinforcing steel in S2BD. The earthquake time step was provided as part of the data from the PEER Strong Motion Data Base. However, the time step was scaled to account for the scaling of the specimen. A time scale factor of 0.478 was calculated in Sureshkumar et al. (2004) and used to scale all of the time steps for the sample ground motions. The convergence rate was input as 0.001. This value was chosen in order to have a significant number of iterations for the DARCO analysis to compute, which ensures a greater degree of accuracy. The basic stiffness of the model was based on the measured force vs. displacement from Sureshkumar's test. In Fig. 2.2, B2DA is the recorded force versus displacement data from Sureshkumar's test. The idealized elastic stiffness was represented by k_1 and the idealized plastic stiffness was represented by k_2 . Figure 2.2 shows the idealized force-displacement envelope. This was completed by creating an energy balance, which balances the area above and below the elastic and plastic envelopes with the area of the measured force-displacement curve. The basic properties of the model consisted of the yield force (F_y) and the yield displacement

(D_y). These values are found at the intersection of the k_1 and k_2 idealized slopes (Fig.2.2). These values are critical because they will be a reference point for where the specimen should yield during shake table testing.

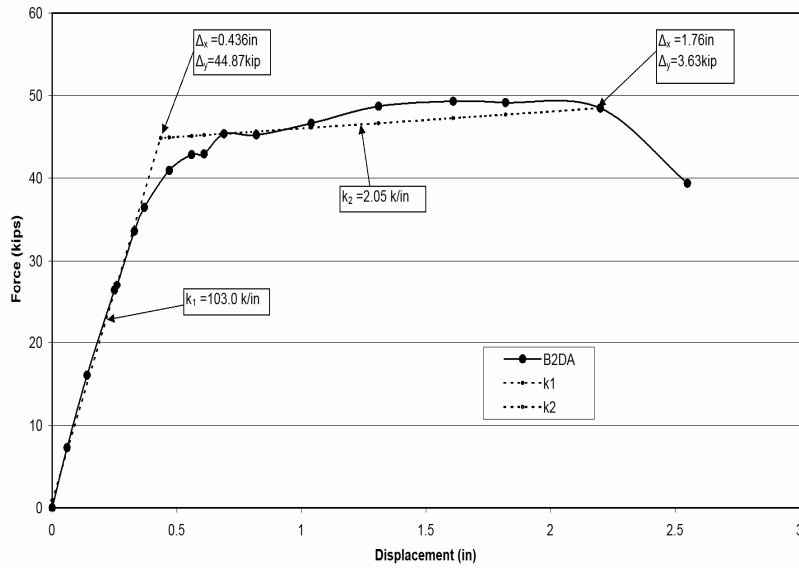


Figure 2.2 Measured & idealized force-displacement envelope

Another variable that was input into DARCO was the type of hysteresis loop. The type of hysteresis loop will dictate how the specimen deflects and returns to the original position when forces are applied. For near-fault ground motions, a typical hysteresis is modified into a hysteresis loop with an offset (Fig. 2.3). In DARCO this variable is named an O-Hyst and has a value of $F_y/3$.

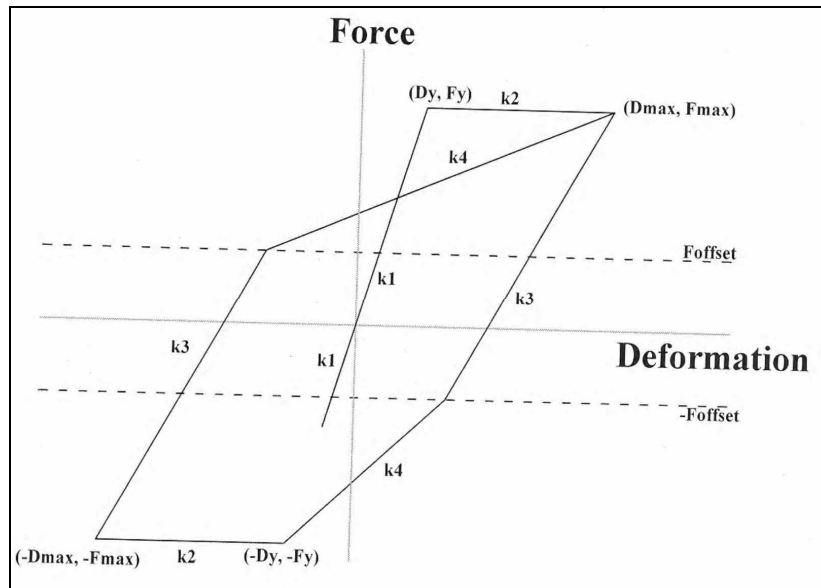


Figure 2.3 O-Hyst model

Another variable that was input to DARCO was the unloading factor (Beta). This factor comes from Equation 1.

$$\text{Beta} = -0.0075 \cdot \text{AR} - 0.2755 \cdot \text{LSR} + 0.6571 \cdot \text{TSR} + 0.153 \quad (\text{Eq. 1})$$

where:

AR = aspect ratio

LSR = longitudinal steel ratio

TSR = transverse steel ratio

The aspect ratio for the specimen was determined by dividing the specimen height by the width of one of the columns. The longitudinal/transverse steel ratios were determined from Sureshkumar et al. (2004). The beta factor calculation can be found in Table 2.3.

Table 2.3 Beta factor

Beta = -0.0075*AR - 0.2755*LSR + 0.6571*TSR + 0.153	
Aspect Ratio (AR)	2.875
Specimen Height	57.5 in
Specimen Width	20.0 in
Longitudinal Steel Ratio (LSR)	2.60%
Transverse Steel Ratio (TSR)	0.105%
TSR Short Direction	0.11%
TSR Long Direction	0.10%
Beta = 0.1250	

When conducting the analysis a control factor was used. There are several directional components of a ground motion that are recorded during an earthquake. The Sylmar ground motion record that was used when testing Sureshkumar's bent was the 90 component of the ground motion. There were two components of the Sylmar ground motion record used in this analysis, the 90 and 360 components. The 90 component is a far-field ground motion and the 360 is a near-fault ground motion. The far-field component of the ground motion was used in this analysis in order to ensure that the computer analysis was outputting results similar to those during Sureshkumar's shake table test. This was accomplished, and it can be assumed that the input parameters entered into the computer analysis software are correct. Table 2.4 shows a comparison of the residual displacement for Sureshkumar's test and for this computer analysis. In addition, the hysteresis loop generated during Sureshkumar's test and this computer analysis can be found in Figure 2.4 and 2.5 respectively.

Table 2.4 Sureshkumar’s test vs. computer analysis residual displacement

	Sureshkumar (2004)	Brown (2007)
Residual Displacement	0.07 in	0.056 in

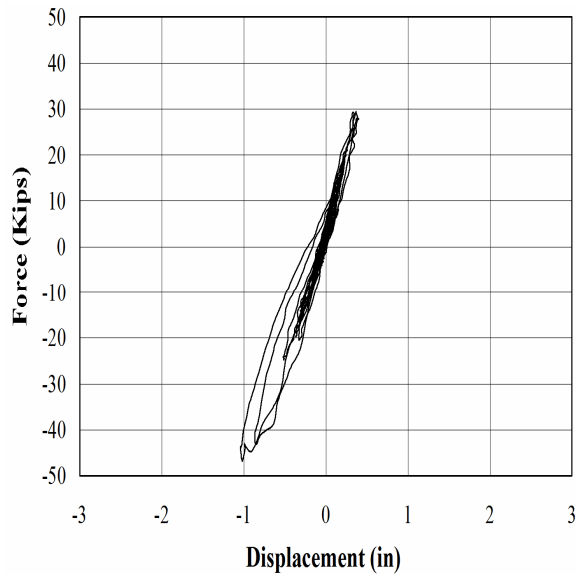


Figure 2.4 Sureshkumar’s hysteresis loop

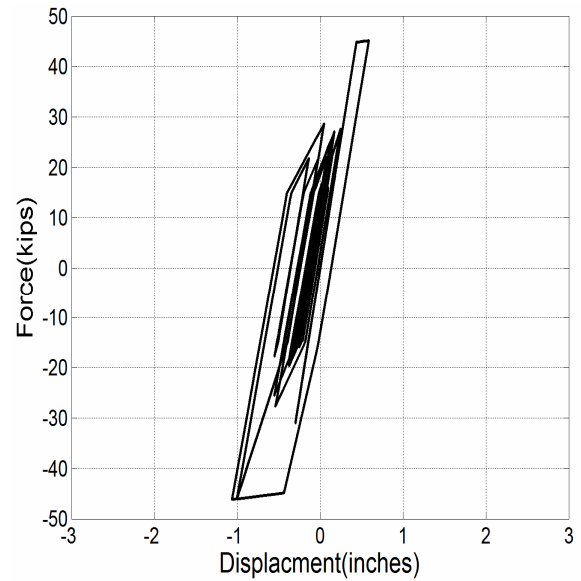


Figure 2.5 Computer analysis hysteresis loop

3 RESULTS

Upon completing the specimen response analysis, the results were compiled for review. The residual displacement and the ductility demand for each ground motion can be found in Table 3.1, and the maximum/minimum and other statistical values of residual displacement and ductility demand can be found in Table 3.2. The results show that S2DB can expect to see a maximum residual displacement of 0.657 inches when tested under the Rinaldi ground motion and a minimum of 0.022 inches when tested under the Kobe ground motion. The results show positive and negative residual displacement because of the direction that the columns end at after the test. The ductility results show that a maximum ductility demand of 6.26 must be achieved by the specimen if tested under the Rinaldi ground motion and a minimum ductility demand of 1.19 by the specimen if tested under the ChiChi ground motion. The hysteresis plots and displacement versus time plots generated by DARCO can be found in Figures 3.1-3.9 and Figures 3.10-3.18 respectively. The results show a wide variety of data for the tested ground motions.

Table 3.1 Residual displacement & ductility data

	Sylmar-090	Sylmar-360	Rinaldi	ChiChi	Duzce	Imperial Valley	Kobe	San Fernando	Superstition Hills	Tabas
Residual Displacement (in)	-0.0556	-0.2112	0.6570	0.2454	-0.0305	-0.0348	-0.0223	0.1658	0.1233	-0.0507
Ductility	2.4393	2.9669	6.2546	2.5082	1.3825	1.1898	3.3413	1.8196	1.5304	2.9734

Table 3.2 Max. & min. values for residual displacement and ductility

Residual Displacement		Ductility	
Maximum	Rinaldi 0.657 (in)	Maximum	Rinaldi 6.255
Minimum	Kobe 0.022 (in)	Minimum	Imperial Valley 1.190
Average	0.16 (in)	Average	2.641
Standard Deviation	0.192 (in)	Standard Deviation	1.469

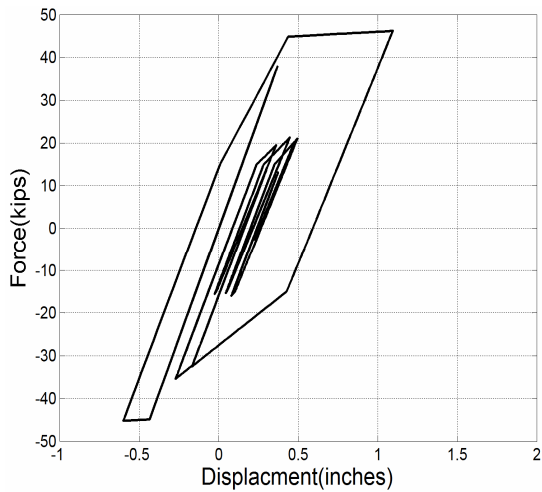


Figure 3.1 ChiChi hysteresis

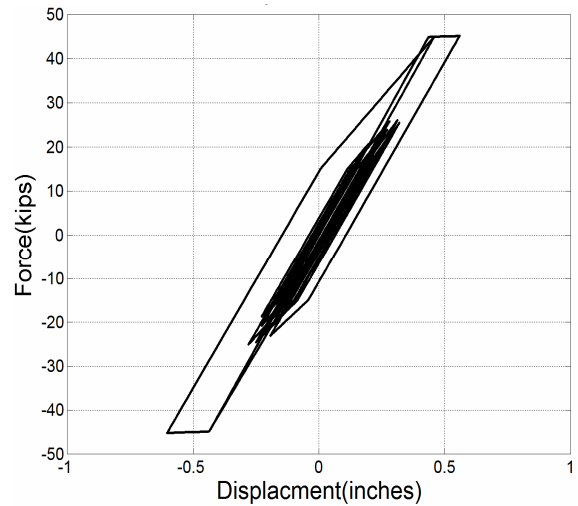


Figure 3.2 Duzce hysteresis

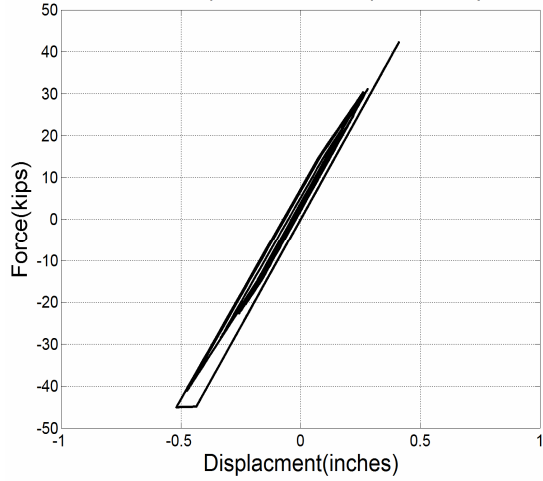


Figure 3.3 Imperial Valley hysteresis

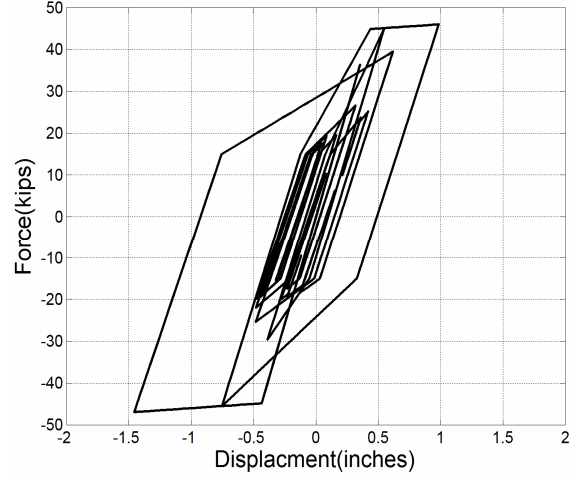


Figure 3.4 Kobe hysteresis

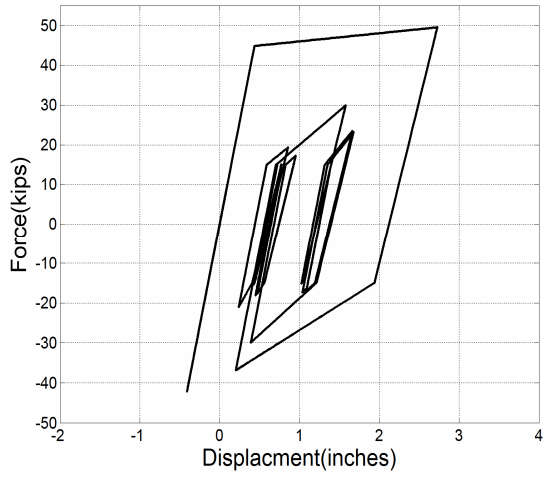


Figure 3.5 Rinaldi hysteresis

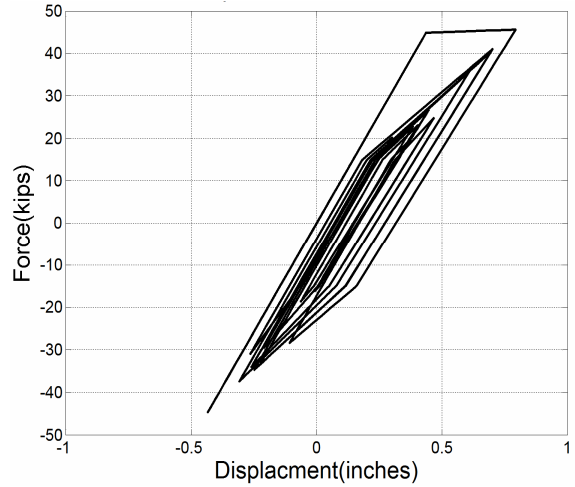


Figure 3.6 San Fernando hysteresis

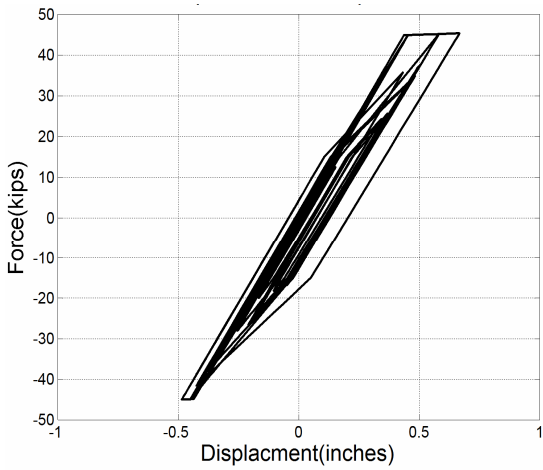


Figure 3.7 Superstition Hills hysteresis

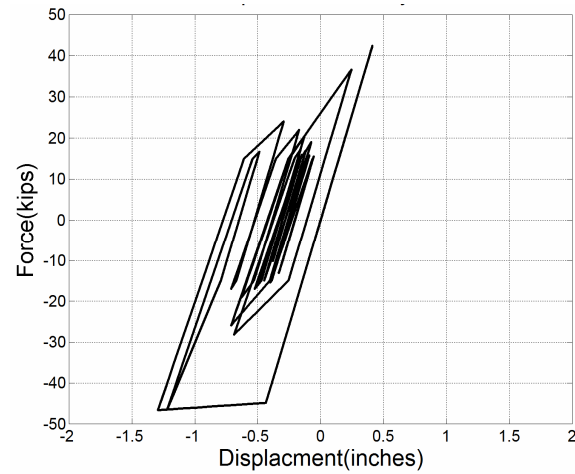


Figure 3.8 Sylmar (360) hysteresis

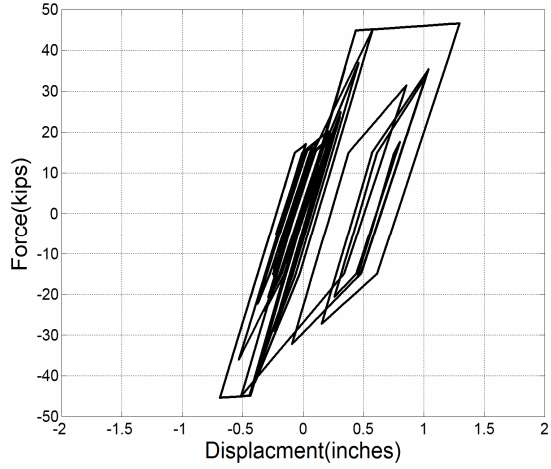


Figure 3.9 Tabas hysteresis

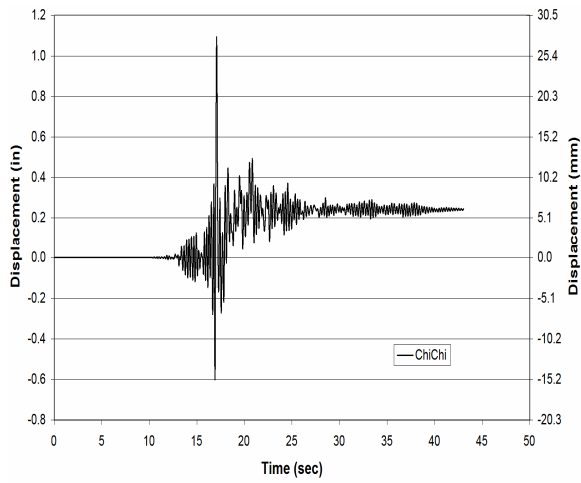


Figure 3.10 ChiChi Displacement vs. Time

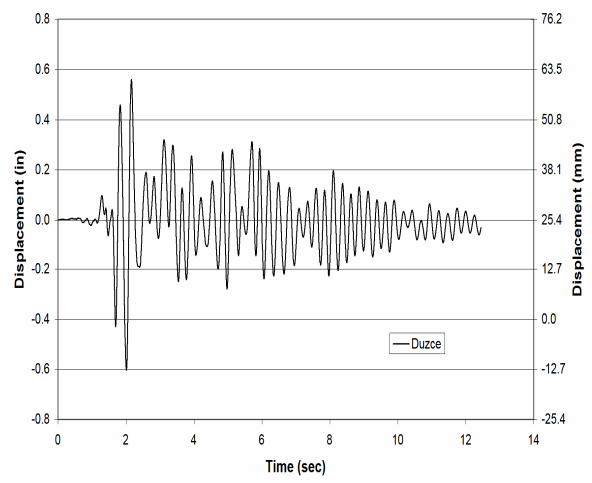


Figure 3.11 Duzce Displacement vs. Time

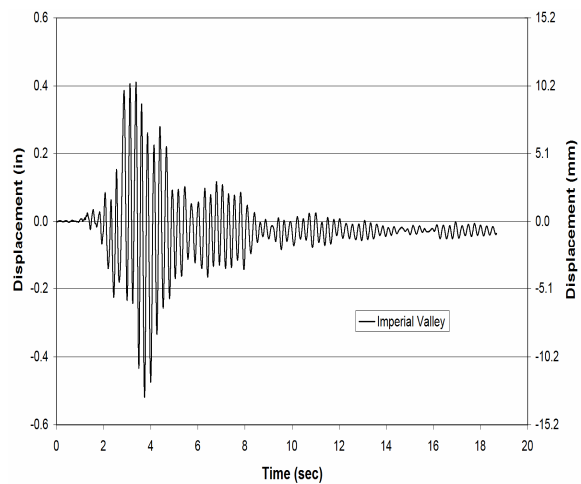


Figure 3.12 Imperial Valley Disp. vs. Time

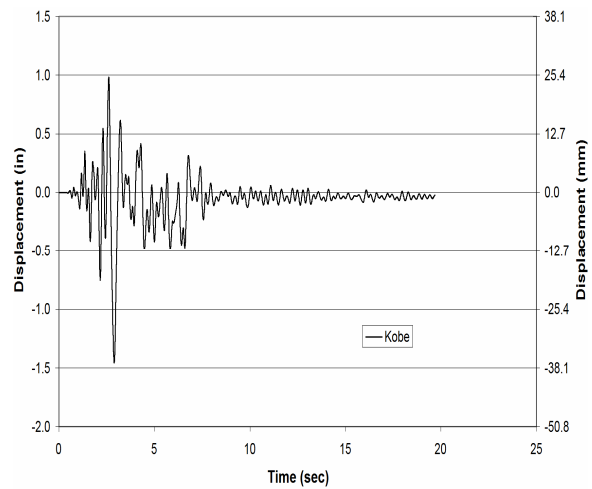


Figure 3.13 Kobe Displacement vs. Time

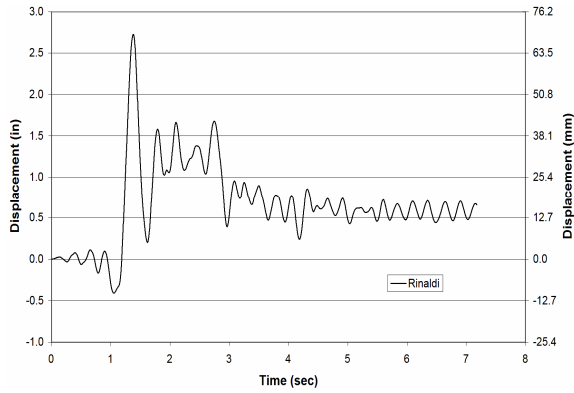


Figure 3.14 Rinaldi Displacement. vs. Time

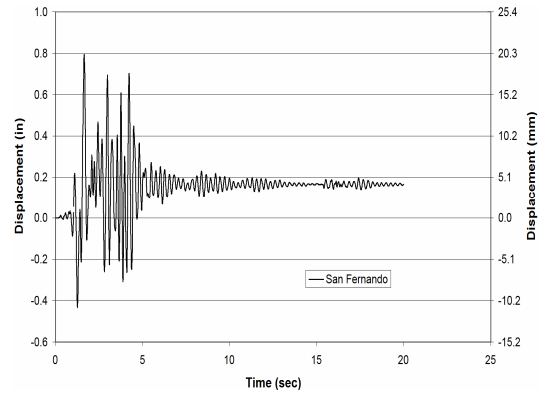


Figure 3.15 San Fernando Disp. vs. Time

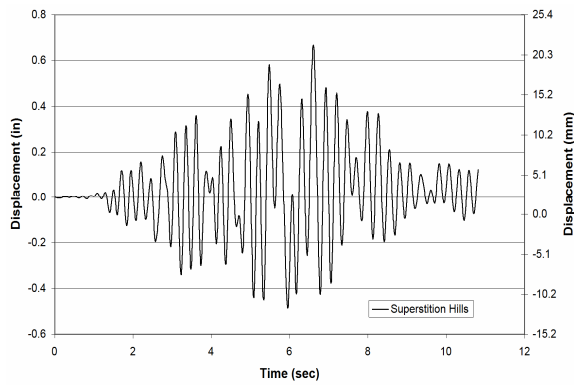


Figure 3.16 Superstition Hills Disp. vs. Time

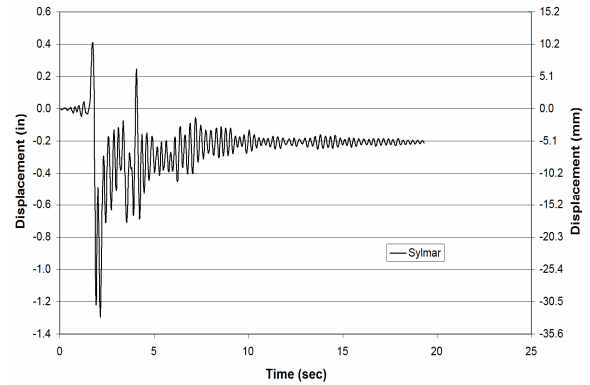


Figure 3.17 Sylmar (360) Disp. vs. Time

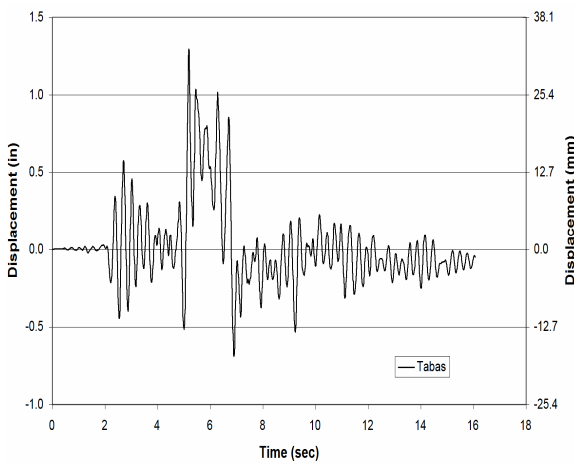


Figure 3.18 Tabas Displacement. vs. Time

When selecting the ground motion to be used for future shake table testing, the residual displacement and the hysteresis graph were the first points of reference. Residual displacement is one of the characteristics seen in structures after a near-fault earthquake. In order to model a near-fault earthquake, the specimen must experience a significant amount of residual displacement. The hysteresis graph gives an insight as to how the specimen should deflect during shake table testing. If a ground motion has a hysteresis with very little displacement or an abrupt transition from yielding to failure, it is not desirable to use. Upon analyzing the data, it was seen that the Rinaldi ground motion caused S2DB to experience the largest residual displacement. In addition, by examining the hysteresis graphs, the Rinaldi ground motion caused S2DB to hit the yield point of the specimen and then continue to displace in the plastic region of the specimen before causing the specimen to fail. These factors led to the selection of the Rinaldi ground motion for the future shake table testing of S2DB.

4 TESTING PROTOCOL

Once it was decided to use the Rinaldi ground motion, a testing protocol was developed for S2DB. The development of a testing protocol is essential when analyzing a ground motion for shake table testing. The testing protocol is a series of scaled versions of the ground motion. The protocol is developed by determining how the specimen should fail. This was accomplished by examining the force versus displacement graph for (B2DA), which was plotted during Sureshkumar's test (Fig. 2.2). The graph is a reference for what displacements will cause the specimen to change from an elastic state to a plastic state and then cause failure. The goal was to make a testing protocol that will make S2DB go through an elastic deformation, a plastic deformation and finally reach a displacement value which will cause failure. In order to accomplish this, the acceleration component of the Rinaldi ground motion was scaled. The scale factor was chosen as 0.25 (Table 4.1). Next, the displacement history of the specimen was calculated by using DARCO. The program completed the analysis and output the deflection history for S2DB. This process was then repeated for each scaled version of the Rinaldi ground motion. The deflection histories for each scaled version were then compiled into one graph comprising the deflection history for the testing protocol (Fig. 4.1). From Fig. 4.1, it can be seen that test number one should produce a displacement in the elastic region of the specimen, test number two and three should produce a displacement in the plastic region of the specimen, and test number four should produce a displacement that will make the specimen fail. By developing this testing protocol there will be numerous points of data to analyze when S2DB is tested on the shake tables at UNR.

Table 4.1 Testing protocol

Test Number	Amplitude Multiplier	Peak Acceleration (g)
1	0.25	0.210
2	0.50	0.419
3	0.75	0.629
4	1.0	0.838

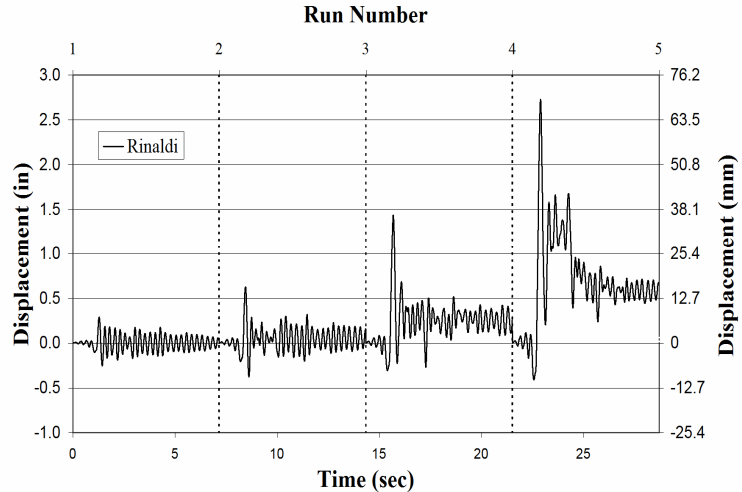


Figure 4.1 Displacement history for Rinaldi

5 CONCLUSIONS

The effects of near-fault ground motions are not well understood. It is essential to study the potentially devastating effects that this type of ground motion can cause. A special topic of concern is in the response of substandard structures. Typically, these types of structures do not have the seismic structural capacity to resist the large forces that are exerted during an earthquake.

The two-column bent with diamond shaped columns, which is located at the University of Nevada, Reno, will be used for shake table testing. The specimen exhibits the substandard design typical of structures built prior to 1971. A shake table response analysis was completed for 10 recorded ground motions. Based on the study, it was determined that the ground motion recorded at the Rinaldi station during the 1994 Northridge earthquake is appropriate for future shake table testing. A testing protocol was developed by scaling the acceleration history of the ground motion. This testing protocol will test the specimen in the elastic range, the plastic range and then to failure.

The future work will consist of examining the condition of the specimen and then testing the specimen on the shake tables at the University of Nevada, Reno.

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