교량에 설치된 마찰 단진자 시스템의 지진하중에 의한 거동연구

Seismic Behavior of the Friction Pendulum System in Bridge Seismic Isolation

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국문요약

본 연구는 지진격리장치의 일종인 마찰 단진자 시스템(F.P.S)의 교량에의 적용에 관한 연구이다. F.P.S에 의하여 지진 격리된 교량과 지진 격리되지 않은 교량의 지진하중 작용시의 응답을 비교하기 위하여 축소모델 교량을 이용한 진동대 실험을 수행하였다. 연구결과, 본 장치를 설치한 경우 지진하중에 대한 지지능력이 향상하는 것으로 나타났다. 또한, 활동면 곡률반경에 의해 조절이 가능한 F.P.S 베어링의 강성은 입력된 가진력의 강도와는 무관하며, 활동면의 마찰계수에 따라 속도가 변화하여 약진시에는 활동면에서의 속도가 작으므로 강진시와 비교하여 지진하중에 의하여 발생하는 마찰력도 감소하게 되었다. 한편 F.P.S 베어링의 마찰특성은 반복된 실험에서도 변화하지 않았고, 영구변형은 양적으로도 작았을 뿐만 아니라 누적되지도 않았다.

주요어 : 마찰 단진자 시스템, 교량에 대한 지진격리, 입력 가진력, 영구변형

ABSTRACT

This paper summarizes a study on the application of the friction pendulum system in bridge seismic isolation. Shaking table tests have been carried out on a model structure isolated with F.P.S and the obtained structural responses are compared to those of non-isolated. It can be concluded the F.P.S increases the earthquake resistance capacity of the isolated structure. It is also found that the stiffness of bearing, being controlled by the radius of curvature of the spherical sliding interface, is unaffected by the amplitude of the input excitation. Furthermore, the coefficient of sliding friction is velocity dependent so that in weak excitation the sliding velocity is low and, accordingly, the mobilized friction force is less than the one mobilized in strong excitation. Also, the frictional properties of the bearings remain markedly stable after extensive testing, and the permanent displacements are small and not cumulative in successive earthquakes.

Key words : *friction pendulum system, bridge seismic isolation, input excitation, permanent displacement*

1. Introduction

New and innovative concepts of structural protection have been advanced and are at various stages of development. Modern structural protective systems can be divided into three groups as seismic isolation, passive energy dissipation, and semi-active and active control. These groups can be distinguished by examining the approaches employed to manage the energy associated with transient environmental events. Among the structural protective systems, the technique of seismic isolation is now widely used in

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many parts of the world. A seismic isolation system is typically placed at the foundation of a structure. By means of its flexibility and energy absorption capability, the isolation system partially reflects and partially absorbs some of the earthquake input energy before this energy can be transmitted to the structure. The net effect is a reduction of energy dissipation demand on the structural system, resulting in an increase in its survivability.(1) Several parameters have to be considered carefully in the choice of an isolation system, in addition to its general ability of shifting the vibration period and adding damping to the structure, such as: ① deformability under frequent quasistatic load, ② yielding force and displacement, ③ ultimate and postultimate behavior, ④ capacity for self-centering after deformation, and ⑤ vertical stiffness. The concept of sliding bearings has been combined with the concept of a pendulum-type response, obtaining a conceptually interesting seismic isolation system as a friction pendulum system (F.P.S). The system is not necessarily self-centering, since the friction force could be in equilibrium with the horizontal component of the weight, but it is very easily recentered after a seismic event. The range of vertical load capacity, stiffness to lateral force, and period of vibration are of the same order of magnitude as those of lead-rubber bearings of similar size.

2. Friction Pendulum Seismic Isolation System

A cross section of a F.P.S is shown in Fig. 1. The bearing consists of a spherical sliding surface and an articulated slider which is faced with a high pressure capacity bearing material. The bearing is constructed of steel with the articulated slider and the spherical sliding surface made of stainless steel such as highly polished austenitic, type 316 stainless steel. All sliding interfaces, that is those of the articulated slider with the spherical surface and the supporting column, are faced with a high bearing capacity, self lubricating, PTFE-based material. The material is characterized by low friction, low wear and marked insensitivity of its frictional properties to significant temperature changes. The motion of a structure supported by these bearings is identical to that of pendulum motion with the additional beneficial effect of friction at the sliding interface. The F.P.S bearing acts like a fuse which is activated only when the earthquake forces overcome the static value of friction. When set in motion, the bearing develops a lateral force equal to the combination of the mobilized frictional force and the restoring force which develops as a result of the induced rising of the structure along the spherical surface. This restoring force is proportional to the displacement and the weight carried by the bearing and is inversely proportional to the radius of curvature of the spherical surface. Accordingly, the system has the following important properties: ① rigidity for forces up to the static value of coefficient of friction times the weight, ② lateral force which is proportional to the weight carried by the bearing. As a result of this significant property the resultant lateral force develops at the center of mass, thus eliminating eccentricities, and ③ period of vibration in the sliding mode which is independent of the mass of the structure and related only to the

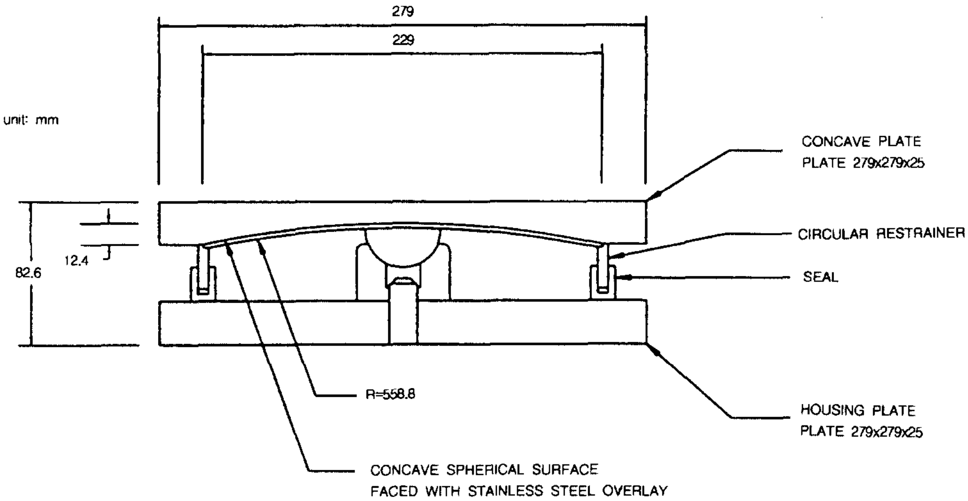


Fig. 1 F.P.S bearing

radius of curvature of the spherical surface. In addition to the above mentioned properties, the F.P.S has other properties common to sliding isolation systems, like low sensitivity to the frequency content of excitation and high degree of stability.[(2),(3),(4)]

3. Earthquake Simulation Test

3.1 Test structure

The shake table experiments were carried out with a bridge model at quarter scale. The bridge model was designed to have flexible piers and it had a clear span of 4.8 m, height of *2.53* m and total weight of *157.8* kN. The deck consisted of two *AISC W14x90* sections which were transversely connected by beams. Steel and lead blocks were used to add mass as necessary for similitude requirements bringing the model deck weight to *140 kN*. Each pier consisted of two *AISC TS* $6\times6\times5/16$ columns with a top made of channel section which was detailed to have sufficient torsional rigidity. The tube columns were connected to beams which were bolted to concrete extension of the shake table (Fig. 2).

The natural frequencies, damping ratios and mode shapes of the model structure were determined experimentally. The identification tests were carried out on the shake table using as input a *0-20 Hz* banded white noise of *0.03 g* peak acceleration. The structural parameters were identified from the absolute acceleration transfer functions of each free standing pier and of the assembled bridge model with all bearings fixed against translational movement. Fundamental period of free standing pier was equal to *0.096 sec* and that of non-isolated bridge in the longitudinal direction was equal to *0.26 sec*. These quantities compare quite closely with the design vaule of *0.1* and *0.25 sec*, respectively. Critical damping in the model was estimated to be *0.015* for the free standing piers and *0.02* for the entire model in its non-isolated condition.

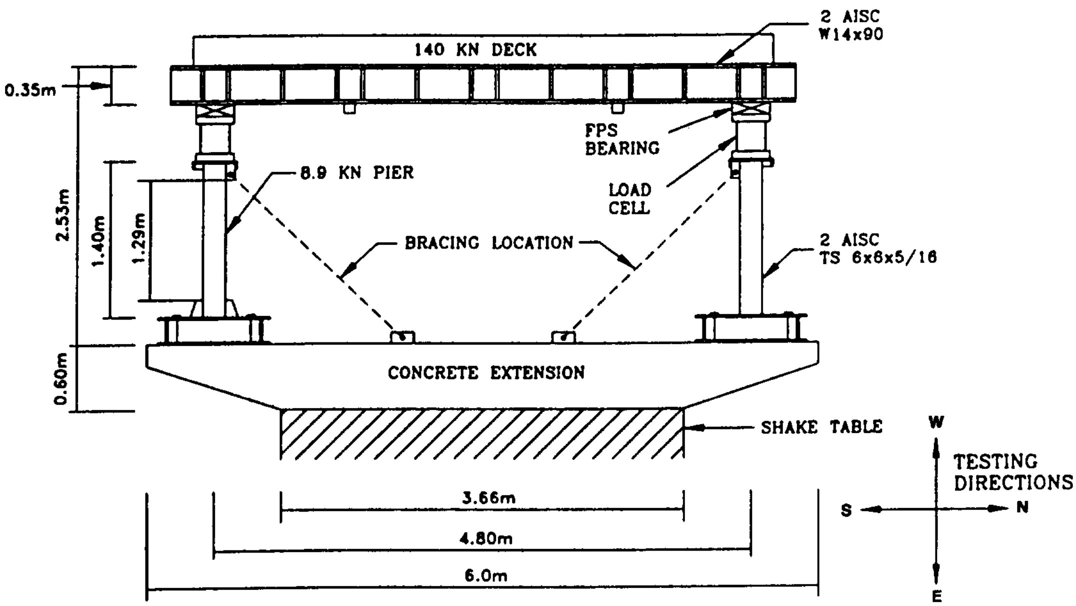


Fig. 2 Test set-up of bridge model

3.2 Isolation system

The isolation system consisted of four F.P.S bearings which were located on top of load cells. The bearings were installed with the spherical surface facing down. The radius of curvature of the spherical sliding surface was *R=558.8* mm so that the period of vibration of the isolation system was *1.5 sec.*

$$T = 2\pi\left(\frac{R}{g}\right)^{1/2} \tag{1}$$

The displacement capacity of the bearing was *89 mm* in all directions. Four different materials were used at the sliding interface. All four were self-lubricating PTFE-based composites. The frictional properties of these four materials in contact with polished stainless steel were determined in identification tests prior to and following the seismic testing. The shake table was driven in displacement controlled mode with specified frequency and amplitude of harmonic motion. The coefficient of friction was extracted from recorded loops of force versus bearing displacement during seismic testing. The coefficient of friction follows the relation proposed by Ref. 5.

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

where f_{max} is the coefficient of friction at high velocity of sliding, f_{min} is the coefficient of friction at essentially zero velocity of sliding and a is a parameter controlling the variation of the coefficient with velocity of sliding. The experimental results agree well with the predictions of the calibrated model of Eq. (2).

3.3 Test program

Testing of the bridge model was performed in five different configurations.

① The bearings were locked by side plates to represent a non-isolated bridge. In this configuration the structure was identified in tests with banded white noise table motion. Furthermore, a selected number of seismic tests was conducted.
② Braces were installed to stiffen the piers and the deck was connected by stiff rods to a nearby reaction wall. In this configuration, the shake table was driven displacement-controlled mode with specified frequency and amplitude of harmonic motion. This motion was nearly the motion experienced by the F.P.S bearings. Loops of bearing horizontal force versus bearing displacement were recorded and used to extract the frictional properties of the F.P.S bearings.
③ Both piers were stiffened by braces so that they represented stiff abutments. In this configuration the model resembled a single span isolated bridge.
④ The south location pier was stiffened by braces so that it represented a stiff abutment. In this configuration the model resembled a two-span bridge with two stiff abutments and a centrally located flexible pier.
⑤ A configuration with two flexible piers which resembled portion of a multiple span bridge between expansion joints.

Earthquake simulation tests were performed on the model bridge with only horizontal input and with combined horizontal and vertical input. The earthquake signals consisted of historic earthquakes and artificial motions. Each record was compressed in time by factor of two to satisfy the similitude requirements.

4. Earthquake Simulator Test Results

4.1 Behavior of isolation system

Tests were conducted with four different sliding interfaces at low and very high bearing pressures. The four interfaces exhibited simliar fricitonal behavior so that, effectively, testing was conducted at two levels of friction: ① at low level of friction with $f_{max}=0.058$, and ② at medium level of friction with $f_{max}=0.10$ to 0.12. The isolation system with low friction ($f_{max}=0.058$) and isolation period of *1.5 sec* (3.0 sec in prototype scale) is appropriate for application in areas of moderate seismicity. Accordingly, tests were primarily conducted with moderate excitation. For such excitations it would be expected that bearings displacments be small and, thus, the developed restoring forces would be insufficient to re-center the isolated bridge. The test results are summarized in Table 1 where they are compared to the results of the non-isolated bridge. The latter results were either directly obtained in tests or extrapolated from test results of the non-isolated bridge by assuming linear behavior. Evidently, the isolated bridge performs significantly better than the non-isolated bridge. Deck accelerations and accordingly forces in the substructure are lower by factors of the order of *4* to *6*, while bearing dispalcement are of the same order or less than the deck to ground displacement of the non-isolated bridge. Furthermore, the permanent displacement in the F.P.S bearings is very small and does not accumulate with repeated testing.

Table 1 Comparison of response of isolated (case of low friction) and non-isolated bridge

EXCITATION	ISOLATED (f_{max} = 0.058)			NON-ISOLATED	
	DECK ACCEL. (g)	PEAK BEARING DISPL.(mm)	PERM. BEARING DISPL.(mm)	DECK ACCEL. (g)	DISPL. OF DECK W.R.T TABLE(mm)
EL CENTRO S00E 50%	0.082	5.6	1.7	0.500	9.8*
EL CENTRO S00E 100%	0.097	16.0	0.9	INELASTIC BEHAVIOR*	
TAFT N21E 100%	0.081	3.5	0.5	0.333	6.6*
TAFT N21E 200%	0.094	15.3	0.5	INELASTIC BEHAVIOR*	
TAFT N21E 300%	0.137	37.0	0.5	INELASTIC BEHAVIOR*	
MIYAGIKENOKI E-W 130%	0.087	5.0	0.5	0.509	11.4
HACHINOHE N-S 100%	0.096	14.2	3.7	0.360	8.0

* EXTRAPOLATED FROM LOWER AMPLITUDE TESTS AND ASSUMING LINEAR BEHAVIOR WHEN (PIER SHEAR FORCE)/(AXIAL LOAD) IS LESS THAN OR EQUAL TO 0.5 .

The isolation system with medium level friction (f_{max}=0.104, 0.120) is appropriate for application in areas of strong seismicity. Nevertheless, the system was found to be effective at all levels of input excitation. This is vividly illustrated in Fig. 3 where the pier shear force of the isolated and non-isolated bridge models is plotted against the peak table acceleration for all conducted tests. In contrast to the behavior of the non-isolated bridge, the isolated one exhibits a response which is nearly unaffected by the level of input excitation. The pier shear force between *0.1W* and nearly *0.25W* (W=axial load carried by pier), while the table acceleration varies between *0.1g* and nearly *1.0g*. This demonstrates the significant benefits offered by seismic isolation. The stiffness, being controlled by the radius of curvature of the spherical sliding interface, is unaffected by the amplitude of motion. Furthermore, the coefficient of sliding friction is velocity dependent so that in weak excitation the sliding velocity is low

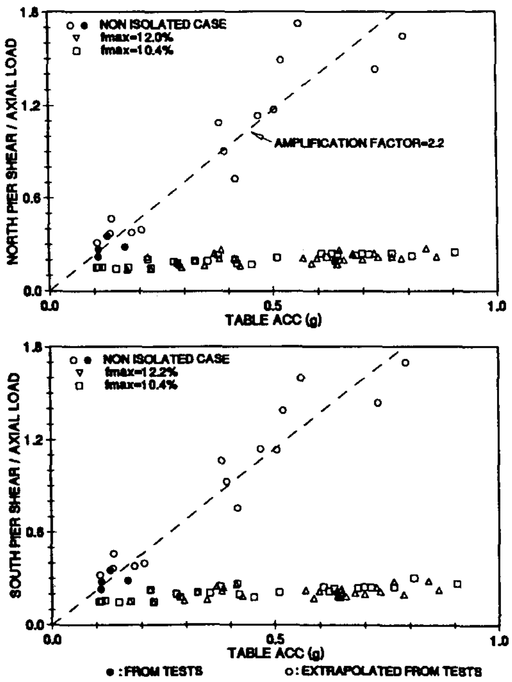


Fig. 3 Comparison of response of medium friciton isolated bridge to response of non-isolated bridge

and, accordingly, the mobilized friction force is less than the one mobilized in strong excitation(Fig. 4). Fig. 5 provides evidence for the performance of the medium friction isolation system at low level excitation. The figure compares the response of the isolated bridge at low pressure with $f_{max}=0.104$ to that of the non-isolated bridge. The effectiveness of the isolation system in weak motion is clearly evident in the recorded loops of pier shear force versus pier drift. Shear force and drift in the piers of the isolated bridge are approximately half of those in the non-isolated bridge.

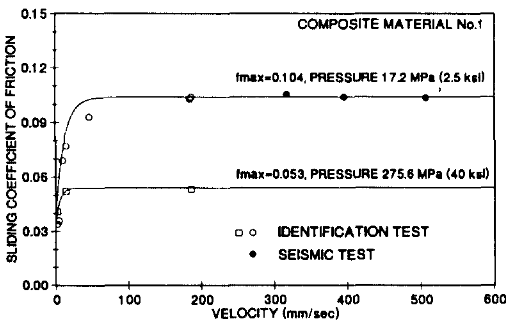
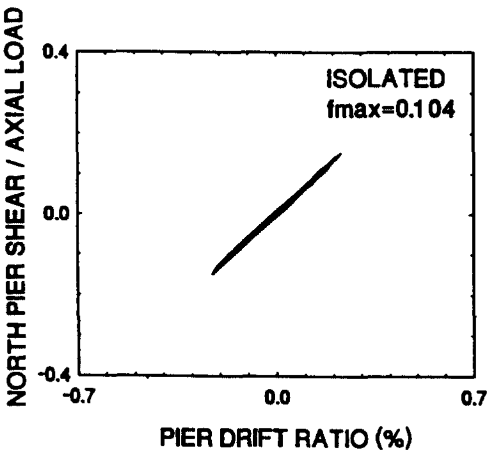


Fig. 4 Coefficient of sliding friction as function of bearing pressure and sliding velocity



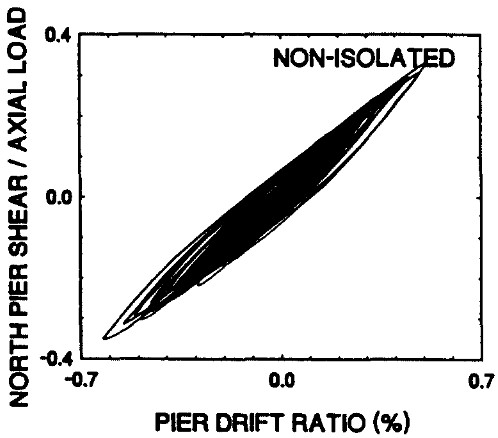


Fig. 5 Comparison of response of isolated bridge to response of non-isolated bridge

4.2 System adequacy

The performance of isolation bearings is assessed by testing as adequate if certain conditions are satisfied. The AASHTO, 1991[6] requires that in over three cycles of testing at five different amplitudes of displacement (*0.25, 0.50, 0.75, 1.00* and *1.25* times the total design displacement) the effective stiffness of the specimen differs by not more than *10 %* from the average effective stiffness. Furthermore, the AASHTO requires that in tests with at least 10 cycles of motion at the total design displacement, there is no greater than *20 %* change in either the effective stiffness or the effective damping between the first and any subsequent cycles. In F.P.S bearings the stiffness is entirely controlled by the radius of curvature of the spherical sliding surface. Thus, the stiffness can not change with repeated testing. However, the coefficient of friction may change and this will affect both the effective stiffness and the effective damping. Evidence for the exceptional stability of the frictional properties of the sliding interface in the tested F.P.S bearings is provided in Fig. 6. The figure shows recorded force-displacement loops of bearings in identification tests using the model. Five cycles of harmonic motion with *75 mm* amplitude and *0.4 Hz* frequency were imposed. The peak velocity of sliding exceeded *188 mm/sec.* One test was conducted prior to the seismic testing and the other identical test was conducted following seismic tests. It may be observed that the loops prior and following the seismic tests are identical. The friction coefficient remained unchanged after at least 30 cycles at approximately the displacement capacity of the bearings and over 100 cycles at lower displacement.

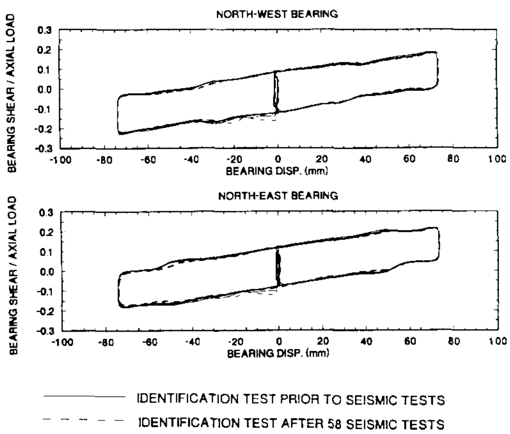


Fig. 6 Recorded F.P.S bearing force-displacement loops for five cycles of harmonic motion of amplitude=*75 mm*, frequency=*0.4 Hz* and pressure=*17.2 MPa*

4.3 Permanent displacements

Permanent displacements may develop in all hysteretic isolation systems. The AASHTO (AASHTO 1991) and UBC (ICBO 1991)[7] specifications attempt to account for this possibility by either specifying minimum stiffness requirements or by penalizing systems which lack sufficient stiffness. Particularly, the AASHTO specifications require that the restoring force of an isolation system at the design displacement, di, be at least *0.025W* (W=total seismic dead load) greater than the restoring force at displacement equal to $d_i/2$. Systems which do not meet this criterion need to be configured to accommodate displacements equal to at least $3d_i$. The assumption in AASHTO is that systems which do not meet the aforementioned criteria will have large permanent displacements of (the order of d_i) which will accumulate in successive earthquakes. Indeed, this may be the case in systems which completely lack restoring force. The tested isolation system had a force-displacement relation expressed by Eq. (2). The force developed at displacement d_i is, thus, given by

$$F_i = f_{max}\ W + \{(d_i W)/R\} \tag{3}$$

The requirement of AASHTO on the lateral restoring force is equivalent to

$$(d_i/R) > 0.05 \tag{4}$$

For the tested F.P.S bearings, $R=558.8\ mm$, so that Eq. (4) is equivalent to $d_i > 27.9\ mm$. Therefore according to AASHTO, it would be expected that in the tests with peak bearing displacement exceeding this limit, the permanent displacements are small and not cumulative. Indeed this has been the case. An inspection of the test results reveals that the permanent displacements were small and not cumulative. However, the same behavior was also observed in tests with weak excitation when the bearing displacements were less than the limit of *27.9 mm*. In nine of the ten conducted tests, the bearing displacements were less than this limit. Yet, the permanent displacements were small and not cumulative.

4.4 Effect of impact on the displacement restrainer

In some tests with very strong excitation, such as the Pacoima Dam S16E component, or long period excitation, such as the Mexico City(amplified to *20 %*) excitation, the bearing displacement demand exceeded the bearing displacement capacity. The displacement restrainer of the F.P.S bearings was engaged and prevented further displacement at the expense of higher accelerations in the superstructure and higher forces in the substructure. Fig. 7 provides evidence to the effects of engaging the restrainer in the tests with Pacoima Dam S16E input. In this case the impact at the engagement of the restrainer is on an essentially rigid pier and the result is an almost *50 %* increase in deck acceleration. Evidently, it is a prudent design practice to design the F.P.S bearings with sufficient displacement capacity to prevent engagement of the restrainer. Nevertheless, the engagement of the displacement restrainer does not result in response values which exceed the values of the non-isolated bridge. An example is provided in Fig. 8 which compares the response of the isolated bridge to the response of the non-isolated bridge model.

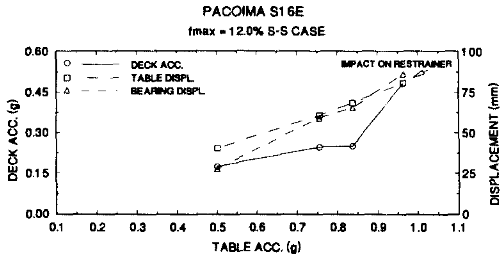


Fig. 7 Response of isolated bridge model under increasing earthquake intencity (S-S: case of stiff piers)

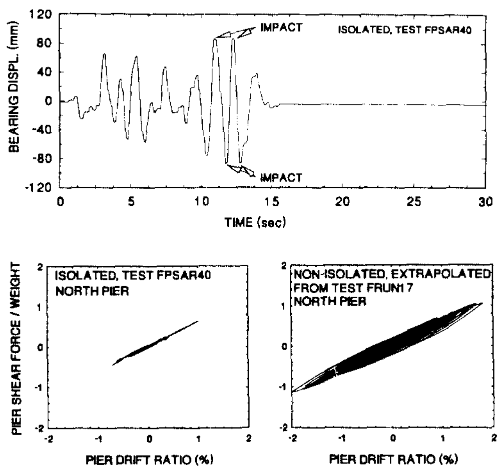


Fig. 8 Comparison of response of isolated bridge with engagement of displacement restrainer to response of non-isolated bridge

5. Conclusions

Shake table tests have been performed to evaluate the behavior of the Friction Pendulum System installed in a bridge model structure. The conditions of testing allowed the study of a number of effects, such as the pier flexibility, realistic energy dissipation in the piers, permanent displacement and low amplitude excitation. The results show that:

(1) The isolated bridge model performed better than the non-isolated bridge in weak seismic excitations. In these motions with peak ground acceleration of only about 0.1g, the piers of the isolated bridge had less than half shear force and drift than the piers of the non-isolated bridge.

(2) The medium friction isolation system was designed for good performance in strong seismic excitation. Indeed, the test results demonstrated substantially reductions of deck acceleration and pier shear force and drift in comparison to the response of a non-isolated comparable bridge.

(3) The frictional properties of the bearings remained markedly stable after extensive testing. Recorded loops of shear force versus displacement of the F.P.S bearings prior and following seismic tests were identical.

(4) Permanent displacements were found to be very small and not cumulative in successive earthquakes. This was true even in weak excitation in which the bearing displacements were not sufficiently large to mobilize strong restoring force.

(5) The engagement of the displacement restrainer of the F.P.S bearings resulted in considerable increase in the substructure forces and displacements. Nevertheless, these forces and displacements were much less than those in the non-isolated bridge.

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