Seismic Control of Cable-Stayed Bridge Isolated by Triple Friction Pendulum System under Near-Fault Ground Excitations with Fling Steps and Forward Directivity

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Abstract: Base Isolation is widely used concept for protecting structures from seismic activity. In this study, Friction Pendulum System (FPS) and Triple Friction Pendulum System (TFPS) are used for passive control of the cable-stayed bridge. The main aim of this study is to compare seismic behaviour of bridge model isolated with FPS and TFPS using SAP2000 software. Several far-field ground excitations, near-fault ground excitations with fling steps and near-fault ground excitations with forward directivity are considered in seismic analysis of cable stayed bridge. Result of base shear and hysteresis loop are compared after analysis. It is examined that seismic behaviour of cable-stayed bridge isolated with TFPS proves to be more effective than that of cable-stayed bridge isolated with FPS.

Keywords: Base Isolation, Base Shear, Friction Pendulum System, Triple Friction Pendulum System, Hysteresis loop

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I. INTRODUCTION

Seismic protection of structures is most important as it saves structure from severe damage from earthquake. Base isolation is most broadly recognized seismic defence techniques in earthquake lying regions. It reduces the influence of earthquake forces by fundamentally detaching the structure from possibly unsafe ground excitations. The term isolation states decreased contact amongst structure and the ground. "Base Isolation" simply means placing a seismic isolation system beneath the structure. This system also provides an added means of energy dissipation, thus decreasing the transferred acceleration to the superstructure. Structure behaves more flexibly in this system which improves its response to an earthquake [1].

Seismic isolation systems are classified as sliding isolation systems and elastomeric bearings. Sliding systems are very effective to reduce high level acceleration of the superstructure under different types of earthquake loading. These sliding systems are insensitive to the frequency content of earthquake excitation. The earthquake energy is reduced and spread over a wide range of frequencies due to sliding system. In this study, FPS and TFPS are used for isolation of cable-stayed bridge.

II. PROPERTIES OF CABLE-STAYED BRIDGE

The modelling of cable-stayed bridge is done by SAP2000 software. The bridge comprises of two H-shaped concrete pylons. Height of pylon above deck is 91.46 meters. And height of pylon below deck is 30.48 meters. Total span of the bridge is 609.75 meters. The center span of the bridge is 335.36 meters and the two side spans are 137.19 meters. Steel box section is used for deck. Diameter of cables is 0.2575 meters. 24 numbers of cables are used which are anchored at equal distances to the pylon as well as to the deck. Figure 1 shows cable-stayed bridge model. Time period of non-isolated cable-stayed bridge is 2.11 seconds [2].

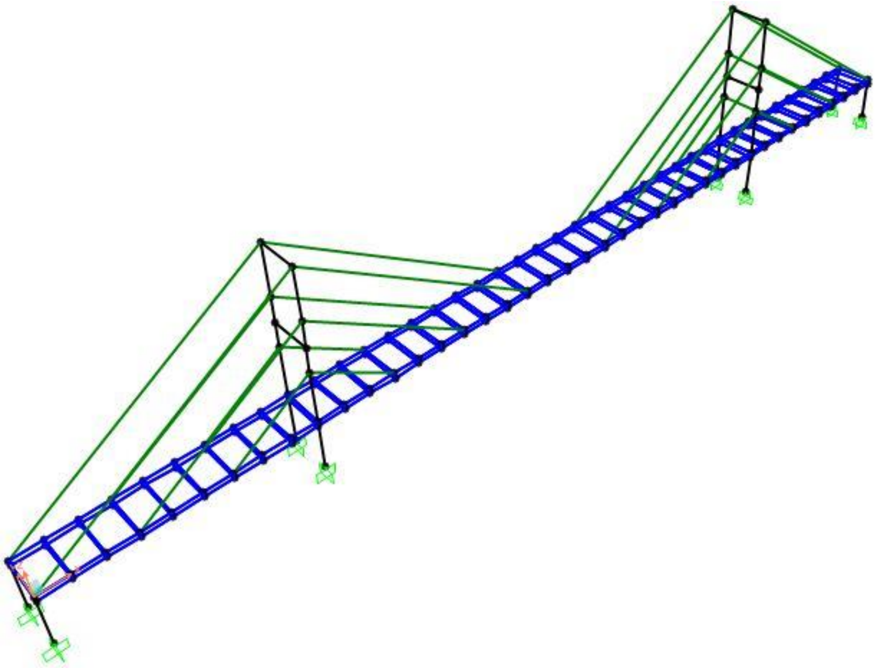

Figure 1: Model of Cable Stayed Bridge

III. DETAILS OF FRICTION PENDULUM SYSTEM (FPS)

FPS consists of a single slider moving on a concave surface. 8 numbers of isolators are used in the cable-stayed bridge model. The isolators are placed between bridge deck and piers. Figure 2 shows the response of FPS under earthquake motion. Tables 1 and 2 show linear and non-linear properties of FPS used in cable-stayed bridge model [3].

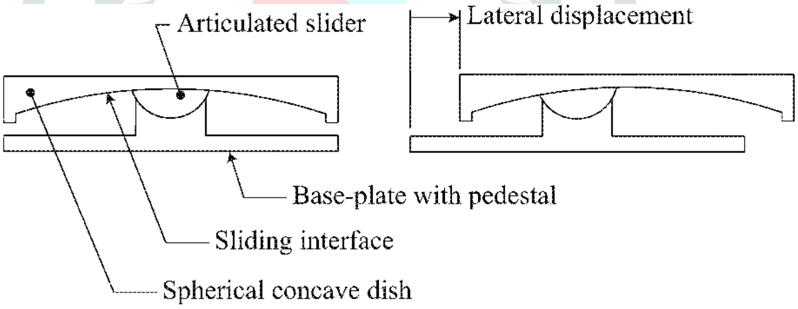

Figure 2: Cross Section of FPS and its response to earthquake motion [4]

TABLE 1: LINEAR PROPERTIES OF FPS

Parameter	Value
Effective Stiffness (kN/m)	16463.01
Effective Damping	0

TABLE 2: NON-LINEAR PROPERTIES OF FPS

Parameter	Value
Stiffness (kN/m)	282410.28
Coefficient of friction slow, μ	0.025
Coefficient of friction fast, μ	0.025
Rate parameter	1
Net Pendulum Radius (m)	0.345

IV. DETAILS OF TRIPLE FRICTION PENDULUM SYSTEM (TFPS)

TFPS includes four concave surfaces and three independent pendulum mechanisms. The three pendulums being independent activates in sequence for different earthquake intensities. For the modelling of TFPS, a specific set of spherical radii and slider height is chosen. 8 numbers of isolators are used in the cable-stayed bridge model. The isolators are placed between bridge deck and piers. Figure 4 shows response of TFPS under earthquake motion. Tables 3 and 4 show the linear and non-linear properties of TFPS [5-6].

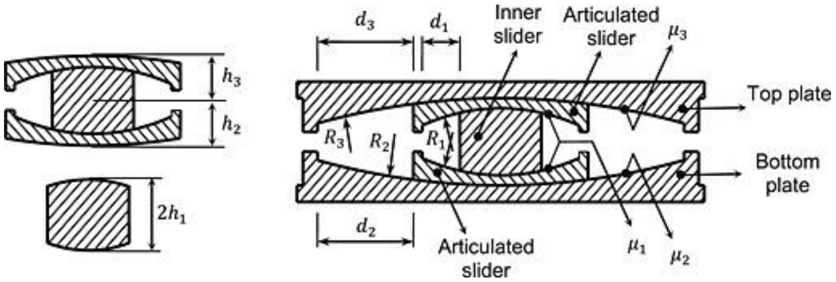

Figure 3: Cross Section of TFPS [7]

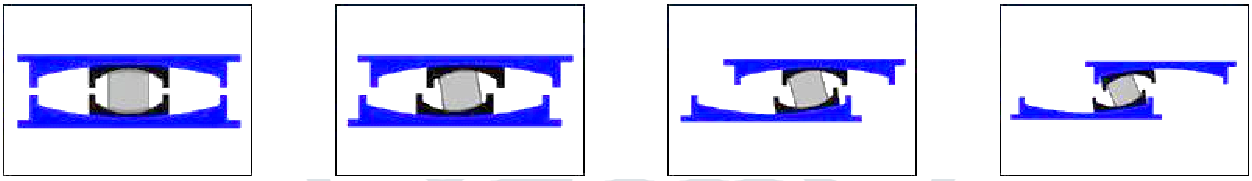

Figure 4: Response of TFPS to earthquake motion [4]

TABLE 3: LINEAR PROPERTIES OF TFPS

Parameter	**Value**
Effective stiffness in x-direction (kN/m)	1×10^{11}
Effective stiffness in y & z-directions (kN/m)	16551.107

TABLE 4: NON-LINEAR PROPERTIES OF TFPS

Parameter	**Outer Top**	**Outer Bottom**	**Inner Top**	**Inner Bottom**
Elastic stiffness (kN/m)	960194.952	395374.392	169446.168	169446.168
Coefficient of friction slow, μ	0.085	0.035	0.015	0.015
Coefficient of Friction fast, μ	0.085	0.035	0.015	0.015
Rate parameter	1	1	1	1
Radius of sliding surface (m)	0.1727	0.1727	0.028	0.028
Stop distance (m)	0.6454	0.6454	0.1046	0.1046

TABLE 5: PROPERTIES OF FPS AND TFPS HAVING SAME EFFECTIVE TIME PERIOD AND DESIGN DISPLACEMENT

Isolator	T_{eff} (s)	D (m)	R_{eff1}	R_{eff2}	R_{eff3}	R_{eff4}	μ_1	μ_2	μ_3	μ_1
FPS	1.17	1.5	0.345	-	-	-	0.025	-	-	-
TFPS	1.17	1.5	0.1727	0.028	0.028	0.1727	0.035	0.015	0.015	0.085

V. DETAILS OF EARTHQUAKE GROUND EXCITATIONS (TIME HISTORY)

TABLE 6: DETAILS OF FAR-FIELD GROUND EXCITATIONS

Sr. No.	Earthquake	Magnitude (Mw)	Station	PGA (g)
1	Chamoli, 1999	6.4	Chamoli	0.359
2	Superstition Hill, 1987	6.7	El Centro Imp. Co.	0.512
3	Imperial Valley, 1940	6.95	El Centro	0.313
4	Northridge, 1994	6.7	Canoga Park -Topanga Canyon	0.477

TABLE 7: DETAILS OF NEAR-FAULT GROUND EXCITATIONS WITH FORWARD DIRECTIVITY

Sr. No.	Earthquake	Magnitude (Mw)	Station	PGA (g)
1	Imperial Valley, 1979	6.4	El Centro Array #5	0.370
2	Imperial Valley, 1979	6.4	El Centro Array #7	0.460
3	Northridge, 1994	6.7	Newhall	0.720
4	Landers, 1992	7.3	Lucerne Valley	0.710

TABLE 8: DETAILS OF NEAR-FAULT GROUND EXCITATIONS WITH FLING STEPS

Sr. No.	Earthquake	Magnitude (Mw)	Station	PGA (g)
1	Chi-Chi, 1999	7.6	TCU074_EW	0.590
2	Chi-Chi, 1999	7.6	TCU084_NS	0.420
3	Chi-Chi, 1999	7.6	TCU129_NS	0.610
4	Kocaeli, 1999	7.4	YPT_NS	0.230

VI. HYSTERESIS BEHAVIOUR OF FPS AND TFPS

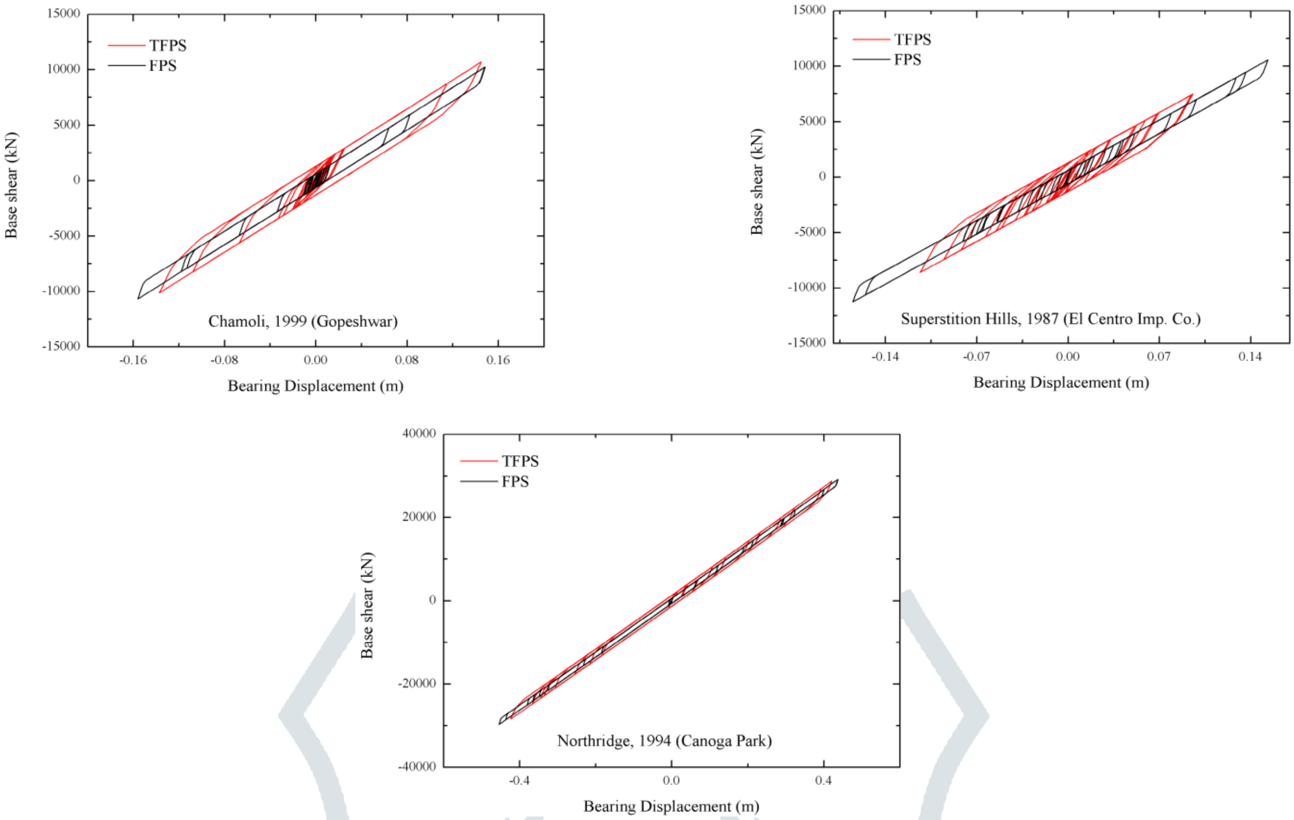

Figure 5: Comparison of hysteresis loop of cable-stayed bridge isolated with FPS and TFPS under far-field ground excitations

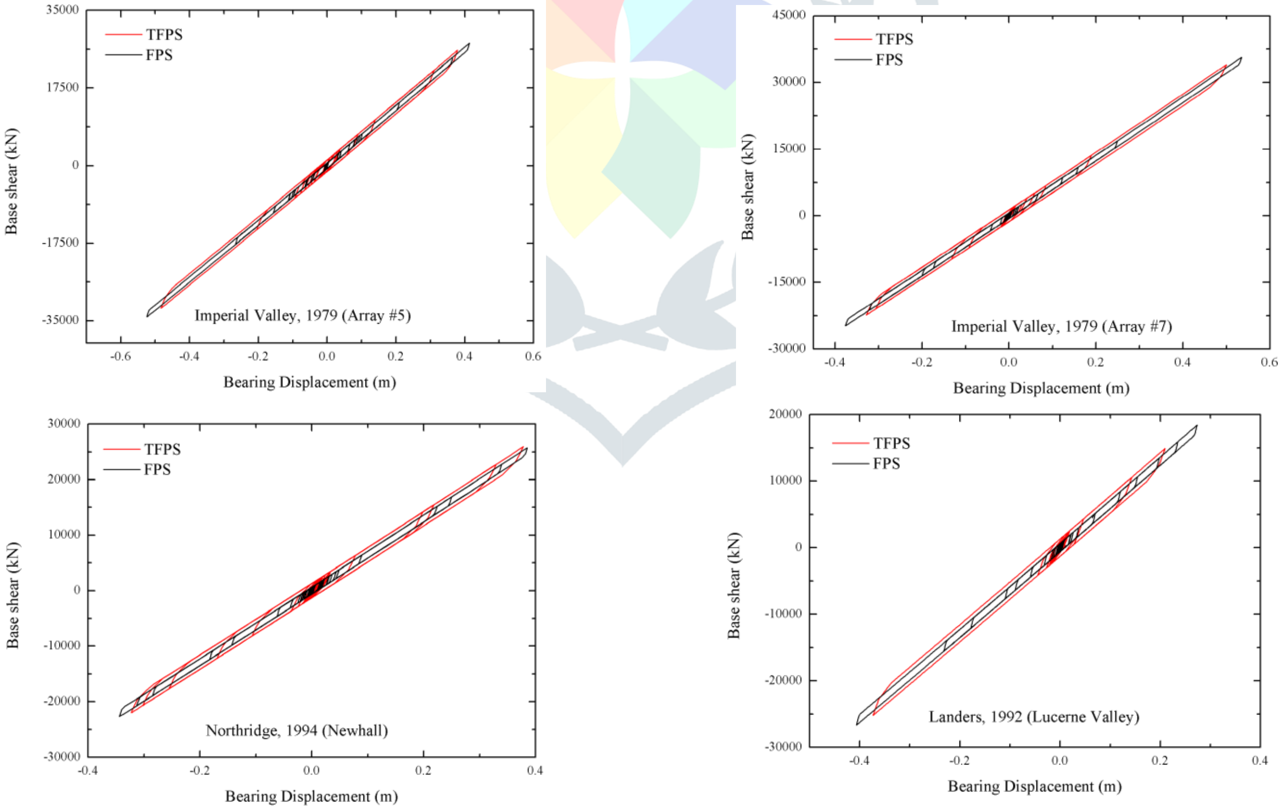

Figure 6: Comparison of hysteresis loop of cable-stayed bridge isolated with FPS and TFPS under near-fault ground excitations with forward directivity

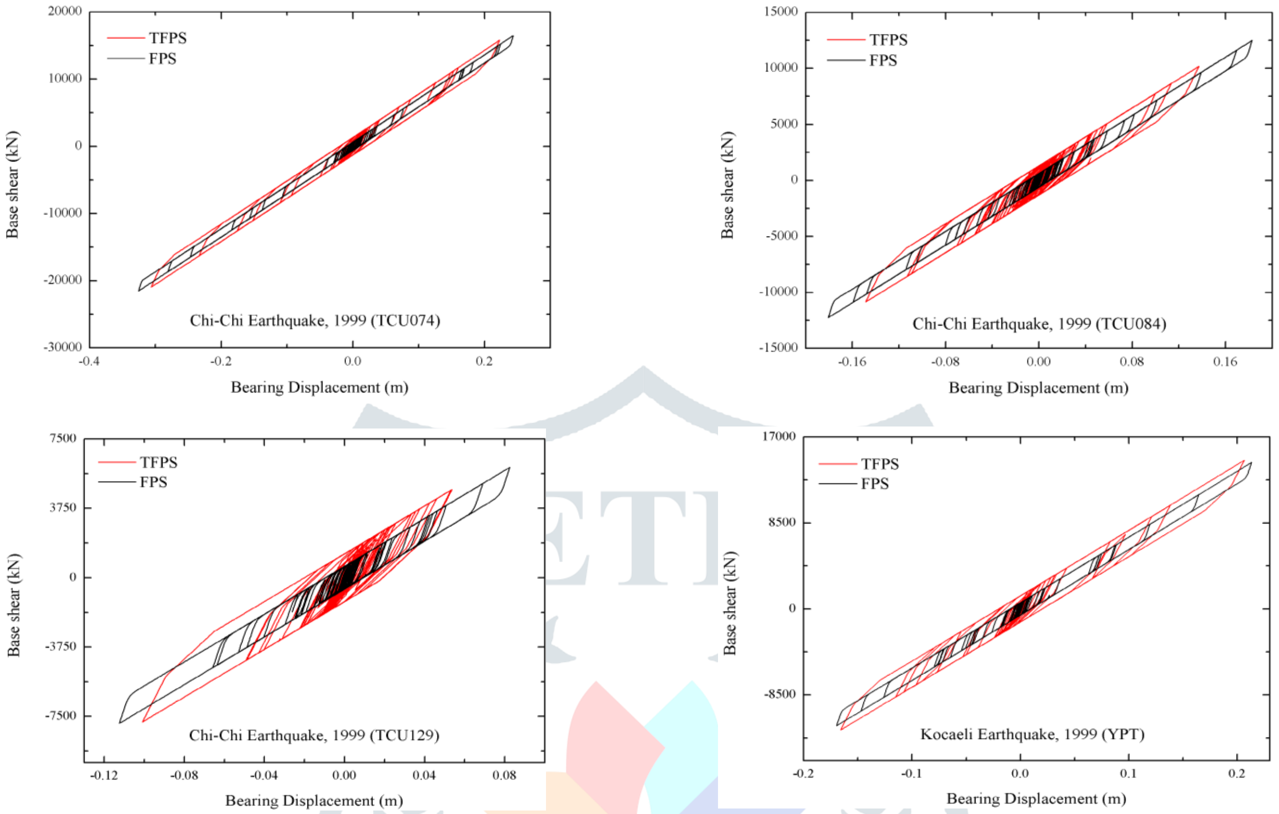

Figure 7: Comparison of hysteresis loop of cable-stayed bridge isolated with FPS and TFPS under near-fault ground excitations with fling steps

VII. COMPARATIVE STUDY

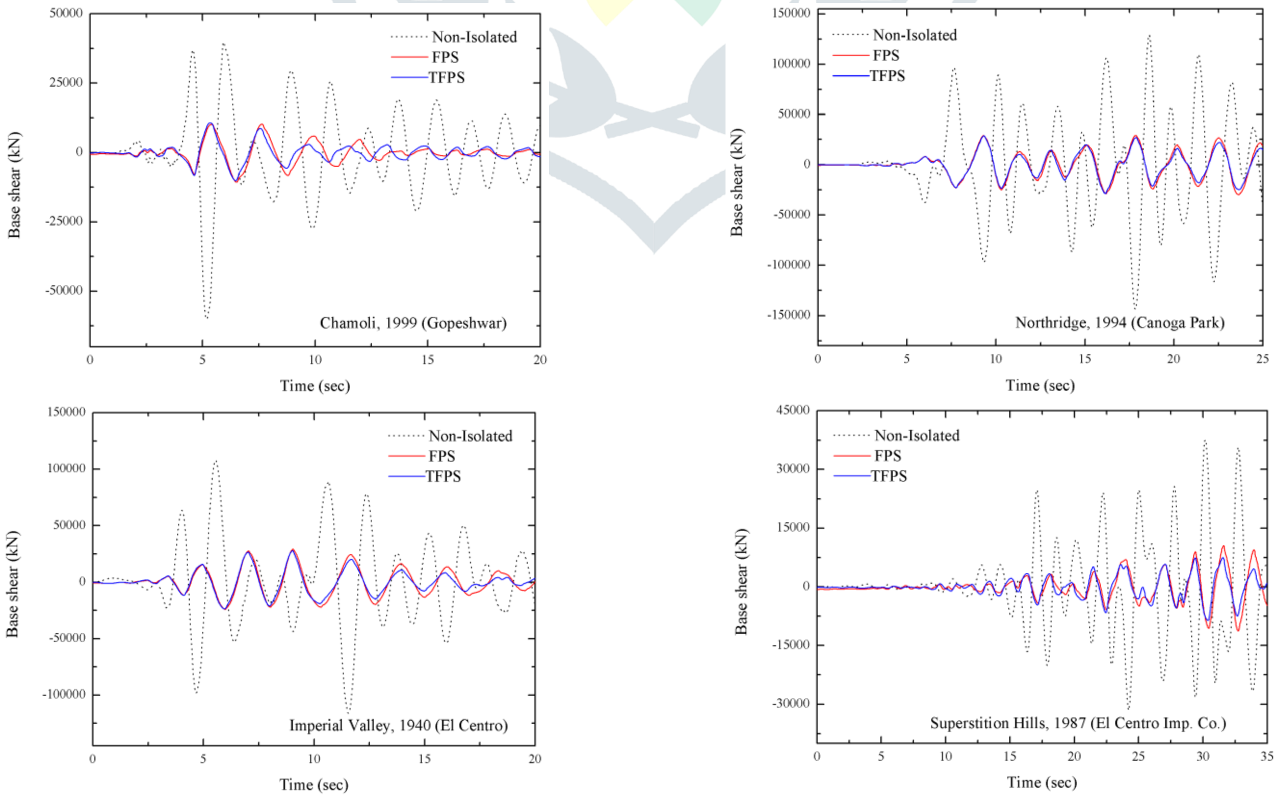

Figure 8: Comparison of base shear of non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS and TFPS under far-field ground excitations

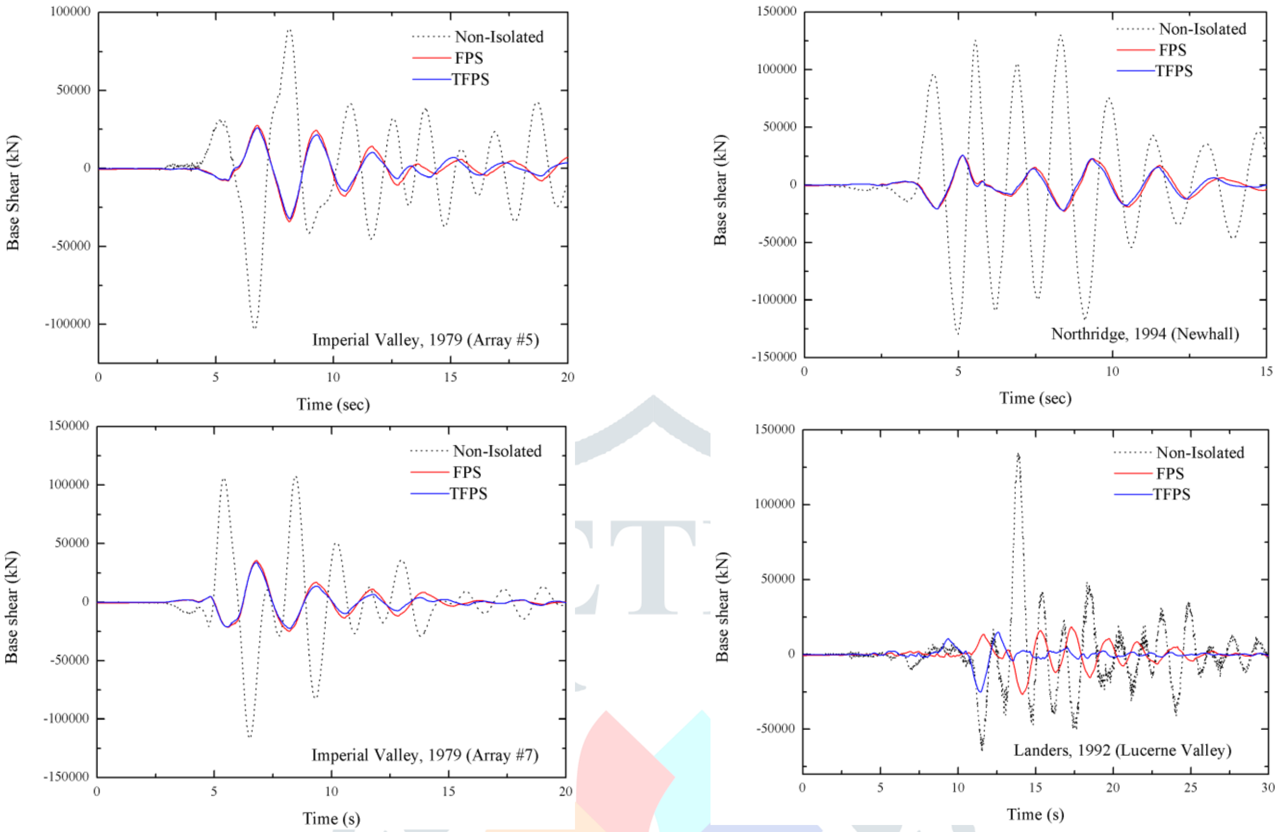

Figure 9: Comparison of base shear of non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS and TFPS under near-fault ground excitations with forward directivity

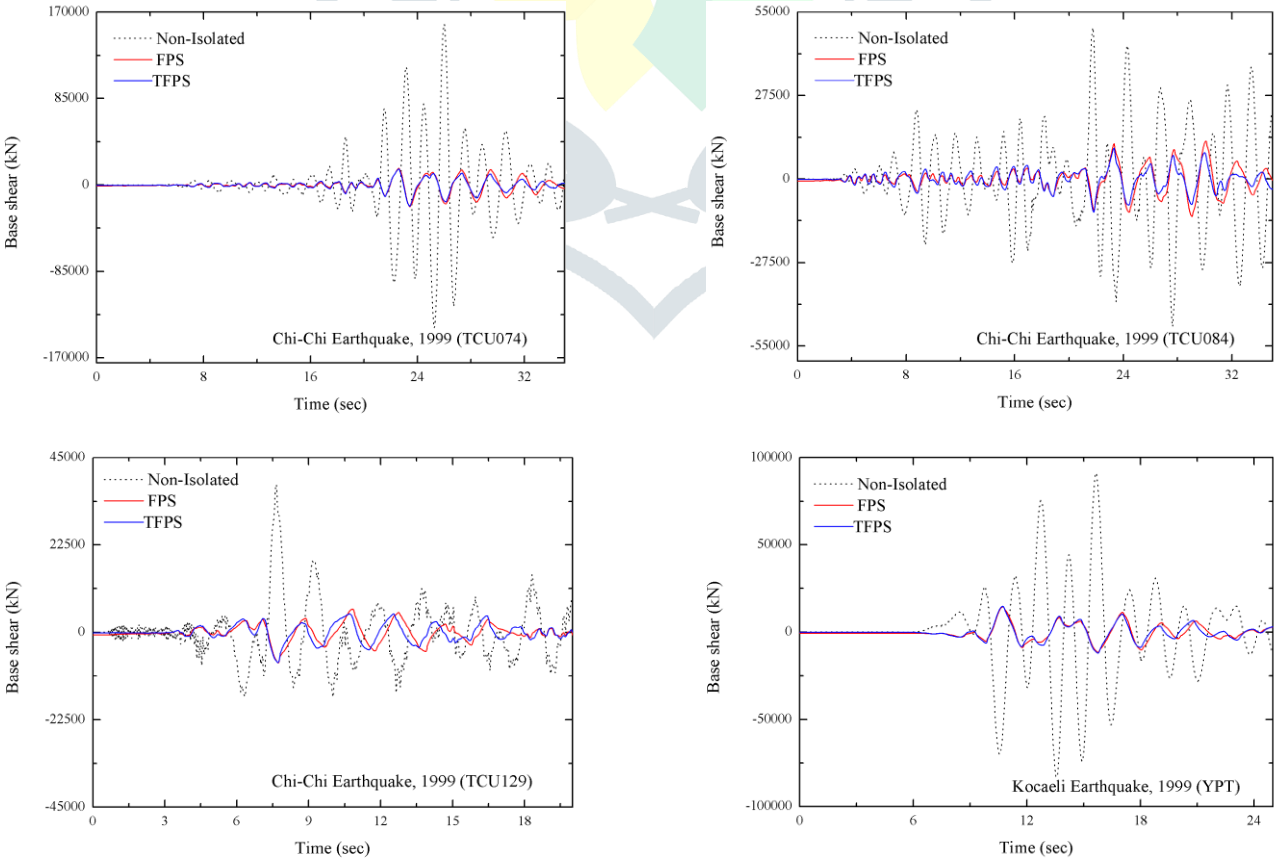

Figure 10: Comparison of base shear of non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS and TFPS under near-fault ground excitations with fling steps

VIII. ANALYSIS RESULTS

TABLE 9: COMPARISON OF BASE SHEAR OF NON-ISOLATED CABLE-STAYED BRIDGE AND CABLE-STAYED BRIDGE ISOLATED WITH FPS AND TFPS

BASE SHEAR (kN)			
Far-field ground excitations	**Non-isolated**	**FPS**	**TFPS**
Chamoli, 1999	60004	10669	10695
Superstition hill, 1987	37603	11247	8601
Imperial Valley, 1940	116172	29230	27795
Northridge, 1994	143540	29690	28756
Near-fault ground excitations with Forward directivity	**Non-isolated**	**FPS**	**TFPS**
Imperial Valley, 1979 (Array #5)	103104	34140	32155
Imperial Valley, 1979 (Array #7)	116759	35648	33989
Northridge, 1994 (Newhall)	130071	25759	25938
Landers, 1992 (Lucerne Valley)	134697	26666	25207
Near-fault ground excitations with Fling steps	**Non-isolated**	**FPS**	**TFPS**
Chi-Chi, 1999 (TCU074_EW)	158179	21520	20937
Chi-Chi, 1999 (TCU084_NS)	49860	12495	10855
Chi-Chi, 1999 (TCU129_NS)	38097	7871	7792
Kocaeli, 1999 (YPT_NS)	91237	14484	14701

TABLE 10: COMPARISION OF BEARING DISPLACEMENT OF CABLE-STAYED BRIDGE ISOLATED WITH FPS AND TFPS

BEARING DISPLACEMENT (m)		
Far-field ground excitations	**FPS**	**TFPS**
Chamoli, 1999 (Gopeshwar)	0.156	0.145
Superstition hill, 1987 (El Centro Imp. Co.)	0.165	0.114
Imperial Valley, 1940 (El Centro)	0.438	0.406
Northridge, 1994 (Canoga Park - Topanga Canyon)	0.454	0.424
Near-fault ground excitations with Forward directivity	**FPS**	**TFPS**
Imperial Valley, 1979 (Array #5)	0.524	0.483
Imperial Valley, 1979 (Array #7)	0.535	0.500
Northridge, 1994 (Newhall station)	0.385	0.378
Landers, 1992 (Lucerne valley station)	0.406	0.373
Near-fault ground excitations with Fling steps	**FPS**	**TFPS**
Chi-Chi, 1999 (TCU074_EW)	0.325	0.306
Chi-Chi, 1999 (TCU084_NS)	0.183	0.149
Chi-Chi, 1999 (TCU129_NS)	0.113	0.0053
Kocaeli, 1999 (YPT_NS)	0.213	0.206

IX. CONCLUSIONS

From the comparison between non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS and TFPS following observations can be made on the basis of the obtained results.

1. It is observed that seismic behaviour of cable-stayed bridge when exposed to far-field ground excitations significantly varies with seismic isolator. It is examined that seismic behaviour of cable-stayed bridge isolated with TFPS proves more efficient than that of cable-stayed bridge isolated with FPS. Base Shear in the cable-stayed bridge considerably decreases in TFPS as compared to non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS. It is also seen that displacement of the cable-stayed bridge in TFPS is almost equal to the displacement of cable-stayed bridge in FPS.
2. Cable-stayed bridge isolated with TFPS when exposed to near-fault ground excitations with forward directivity has noteworthy decrement in base shear and displacement when compared to the non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS. On the other hand, displacement in cable-stayed bridge remains almost equal when the cable-stayed bridge is isolated with FPS and TFPS.
3. When cable-stayed bridge is isolated with FPS and exposed to near-fault ground excitations with fling steps, reduction in base shear is observed in TFPS as compared to non-isolated cable-stayed bridge and cable-stayed bridge isolated with FPS. On the other hand, cable-stayed bridge isolated with TFPS shows almost equal displacement variation when compared to the cable-stayed bridge isolated with FPS.
4. It is examined that result of base shear and bearing displacement is much lesser in cable-stayed bridge isolated with FPS and TFPS under near fault ground excitations with fling steps than that of cable-stayed bridge isolated with FPS and TFPS under near-fault ground excitations with forward directivity.
5. Thus, it can be concluded that TFPS proves more effective then FPS in isolation of cable-stayed bridge as significant reduction of base shear is observed in TFPS.

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