Comparison of Seismic Retrofit Efficiencies of Base Isolation Systems for Existing Bridges

Cho, Hyo Nam*　　Eom, Won Seok**

Abstract

In recent years, modern protective systems have been introduced to reduce the vulnerability of bridges to seismic events. These protective systems include base isolation devices of different types, damping devices and active control devices. The objective of this study is to analytically evaluate the efficiency of a seismic retrofit scheme using base isolation systems, such as lead rubber bearings and sliding isolators. In this study, a triaxial model was used, which is capable of accurately developing the behavior of sliding isolators including the influence of the changing vertical force and velocity on the friction coefficients. Seismic response analyses of the bridge before and after retrofit were carried out by using a three-dimensional nonlinear seismic analysis program, IDARC-BRIDGE. To evaluate the efficiency of a retrofit scheme using triaxial isolators, a comparative study of performances of above two base isolation systems was conducted, and the numerical results show that the triaxial isolation solution can effectively reduce the shear forces at the piers for the vertical ground motion.

1. Introduction

Base isolation is a strategy to reduce the seismic hazard for a bridge. An isolation system combines two elements: The first element is to provide a soft medium between the bridge and the ground and thus isolate the bridge from the ground; The other one is to provide energy dissipating capacity between the ground and the bridge. The two elements can be used together, and in that case the energy dissipating capacity is usually used to reduce displacements.

The installation of isolation systems does influence the structural behavior of a bridge, as in the case that a sliding isolation bearing changes from "stick" to "slip". Initially the substructure and the superstructure act as a single dynamic unit but when "slip" occurs the bridge behaves as two different dynamic entities. Therefore, the only way to capture the true behavior of the isolation system and its effect on the overall response of the bridge is to use nonlinear dynamic structural analysis.

Different kinds of mathematical models are used to represent the behavior of such isolation devices. Bilinear or trilinear models can be used to model isolation bearings like lead rubber bearings and mild steel dampers. A Coulomb model in which the transition from stick to sliding mode is controlled by stick-slip conditions has been used for modeling sliding bearings. Plasticity based yield surface models have been used to model lead rubber bearings and high damping elastomeric bearings. Constantinou et al.(1990) have used a differential equation model for biaxial interaction which was proposed by Park et al.(1986), which is an extension of the model proposed by Wen(1976) for uniaxial behavior. This model gives accurate modeling in the elastic and fully plastic zone but not in the transition zone, where the change from elastic to plastic behavior occurs. And this kind of modeling has problem in that the influence of the vertical load cannot be efficiently incorporated.

In this study, a triaxial interaction model was used to model the behavior of isolation devices including the influence of the changing vertical force. As a computational platform for evaluating the efficiency of a retrofit scheme using such devices, an analysis program IDARC(Inelastic Damage Analysis of Reinforced Concrete)-BRIDGE (Reinhorn et al., 1998) was used. IDARC-BRIDGE is a computer program for three-dimensional nonlinear seismic analysis of bridge structures before and after retrofit.

2. Seismic response analysis of bridges

In the past decades, response analysis of bridges subjected to earthquake excitations has been conducted, while the effects of the vertical ground motion are neglected in nearly all the published works. It is often argued that most structures are quite stiff vertically and they are designed with a much greater factor of safety for vertical loads than that for horizontal loads. However, it is

* KCI member, Professor, Department of Civil and Environmental Engineering, Hanyang University
** KCI member, Graduate Student, Department of Civil and Environmental Engineering, Hanyang University

possible that the vertical ground excitation plays the role of parametric excitation for the horizontal displacement of the bridge, and the presence of vertical ground motion can enhance the lateral responses of the bridge (Loh et al., 1997). Therefore, it is necessary to consider the influence of the vertical load.

Long bridges span over large distances, and therefore the ground deformations, accelerations and velocities at one support might be significantly different than at other supports in magnitude, because different soil types differently amplify the magnitude of travelling shear waves, and cause difference in excitation magnitude between different foundations. This affects the response of the bridge by changing the dynamic excitation of the bridge, in which case time history analysis can be performed to evaluate the global behavior of the bridge.

For seismic analysis, there are some reasons that require the modeling of the soil and bridge structures using a 3-dimensional approach. The spatial variation of propagating ground motion and base isolation systems in bridges all are influenced by three dimensional motion, and thus two dimensional models can provide only limited information, which, in many cases, may be insufficient in evaluating the overall behavior of the bridge. Therefore a 3D model of the bridge is essential in representing the true behavior of the bridge, which could be effectively analyzed by using IDARC-BRIDGE, well suited for three-dimensional nonlinear seismic analysis of bridges.

3. Modeling of lead rubber bearings

In order to represent the behavior of lead rubber bearings as shown in Fig. 1(a), the smooth bilinear model shown in Fig. 1(b) is used. This model is based on a model developed by Bouc(1971) and enhanced by Wen(1976), which represent elastic-plastic constitutive relations with smooth transition. The parameters required to define this model are: the yield force F_y, the yield displacements U_y, the parameter α, which is the ratio between $K_{initial}$ and K_{yield} (Fig. 1(b)), and the parameters β and γ, which control the shape of the unloading branch. When $\beta = \gamma$, the unloading branch of the hysteresis loop is a straight line with slope (stiffness) equal to the slope of the loading branch (initial stiffness $K_{initial} = F_y / U_y$). When β is larger than γ, the unloading stiffness is higher than $K_{initial}$ and the unloading curve is convex as shown in Fig. 1(b), when γ is larger than β, the initial unloading stiffness is smaller than $K_{initial}$ and the unloading curve is concave.

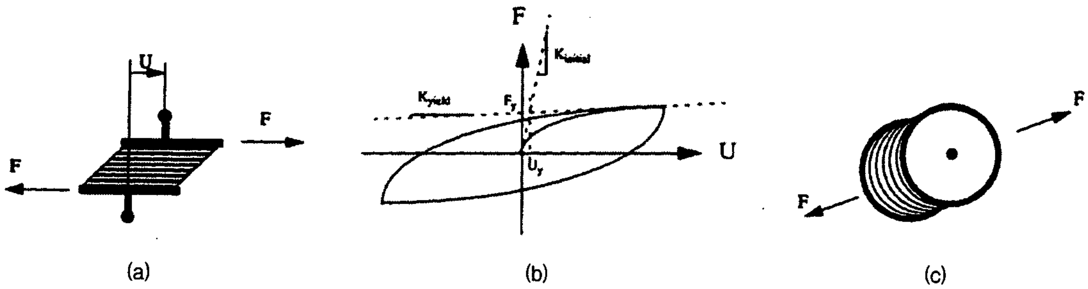


Fig. 1. Lead Rubber Bearing (elastomeric isolator)
(a) side view, (b) force-displacement relation, (c) top view of deformed isolator

The basic equation for a lead rubber bearing which is an isolator with elastic-perfectly plastic behavior is (Nagarajaiah et al., 1991):

$$F = \alpha \frac{F_y}{U_y} U + (1-\alpha) F_y Z \tag{1}$$

where F is the restoring force; α is the ratio of post yielding stiffness to the initial elastic stiffness; F_y is the yield force; U_y is the displacement at yield; U is the total displacement; and Z is a nondimensional parameter defined by the following differential equation:

$$\dot{Z} = A \frac{\dot{U}}{U_y} - |Z|^n (\gamma sgn(\dot{U}Z) + \beta) \frac{\dot{U}}{U_y} \tag{2}$$

where the value of Z is assumed to be limited $-1 \leq Z \leq 1$, $sgn()$ is the signum function; and A,

β and γ are nondimensional parameters which control the unloading slope of the hysteresis loop.

4. Modeling of triaxial isolator

Triaxial interaction model is used to model the behavior of sliding isolators subjected to triaxial loading. This model has the capability to represent triaxial behavior of a sliding isolator which includes the influence of the vertical load on the lateral force, and the dependency of the lateral forces on velocity. The friction sliding isolators have two stages, namely slip and stick. In the stick stage the isolator has elastic stiffness, $K_{initial}$. At the first sliding (slip) stage, the coefficient of friction is function of velocity (Fig. 2(c)). When the velocity exceeds the velocity limit, the coefficient of friction becomes a constant and is equal to μ_{max} (Constantinou et al., 1990). The data required for this model is as follows: P = the initial normal static force on the sliding surface without the contribution of dynamic forces; $K_{initial}$ = the sticking stiffness (no sliding); $K_{secondary}$ = the stiffness of the recentering spring during the slip mode; v_{limit} = velocity limit above which the friction coefficient is equal to μ_{max}; and μ_{min}, μ_{max}, μ_{static} = the minimum, maximum and static coefficients of friction, respectively, as described in Fig. 2(b).

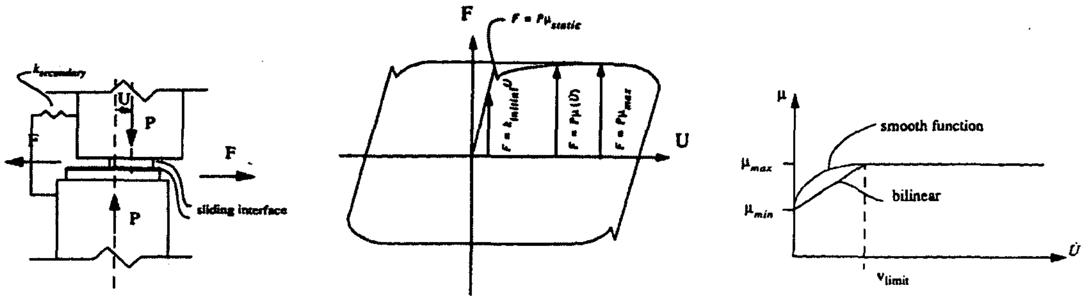


Fig. 2. Triaxial Sliding Isolator
(a) side view, (b) sliding force-displacement relation, (c) dependancy of coefficient of friction on velocity

The lateral force in the isolator, $F(t)$, is represented by an incremental formulation as a combination of three components: (i) a linear rise; (ii) a viscous component; and (iii) a "Coulomb" friction component as defined by the following rules (Reichman 1996; Mokha et al., 1993):

$$F(t) = F(t-\Delta t) + \Delta F(t) \quad (3)$$

where

$$\Delta F(t) = k_i \Delta U(t) + c_i \Delta \dot{U}(t) + \mu_i \Delta N_i(t) + s_i |F(t-\Delta t)| \Delta i(t) \quad (4)$$

where U and $\dot{U}$ are the time dependent displacement and velocity, respectively; k is the stiffness coefficient which is initially elastic stiffness and is equal to zero after sliding occurred; and c is the damping coefficient.

Note that Δ indicates the increment from time $t-\Delta t$ to time t; N is the variable normal force to the sliding surface; s_j is an indicator for biaxial effects in the sliding mode; and i is the sliding direction vector defined as

$$i(t) = \dot{U}(t) \,/\, |\, \dot{U}(t) \,| \quad (5)$$

5. Application example

5.1 Modeling of the bridge

The original bridge shown in Fig. 3 is a segmental prestressed concrete box girder bridge with seven spans, ranging between 40m and 46m in length, supported by piers of changing height of 13.4m to 22.6m. For evaluation of the seismic response using IDARC-BRIDGE, the bridge is modeled as a space frame system shown in Fig. 4. The girders of the bridge is originally supported on pot bearings. Piers are assumed to be elastic, and pier P4 is considered as fixed support. And also, the soil conditions are assumed to vary along the bridge, from very stiff soil under pier P3 and supports A1 and A2 to very soft soil under the other supports. The global structural damping is represented by using Rayleigh damping, and a 2% damping ratio which is recommended for prestressed concrete structures is used.

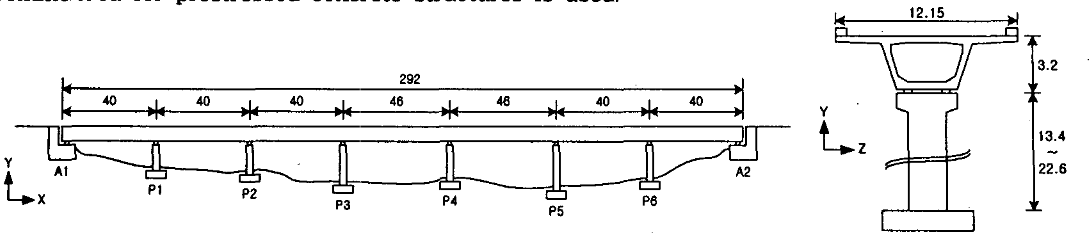


Fig. 3. Example Bridge

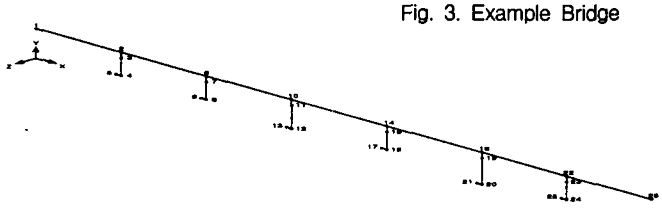


Fig. 4. Structural Model for Analysis

5.2 Retrofit of the bridge

Two retrofit schemes are considered for the bridge. The first one is a retrofit solution using lead rubber bearings, and the other is using friction devices with elastomeric restoring springs, which are modeled using triaxial isolators. According to these solutions the bridge is isolated at pier P1-P6. For the case of triaxial isolation, the friction coefficient was assumed to change, from 4% at 0 velocity to 13% at velocity of 0.1m/sec and above. The properties of the individual isolators are given in Table 1. The two retrofit schemes are compared with each other and with the original unretrofitted bridge.

Table 1. Individual Isolator Properties for Analysis

Lead rubber bearing			Triaxial isolator		
Description	Value	Notation	Description	Value	Notation
ratio of post-yield to elastic stiffness	0.15	α	initial stiffness(kN/m)	5.213e5	$K_{initial}$
loop controlling parameter	0.1	β	spring stiffness(kN/m)	4.219e7	$K_{secondary}$
loop controlling parameter	0.9	γ	velocity limit(m/sec)	0.1	v_{limit}
yield force(kN)	782	F_y	minimum coefficient of friction	0.04	μ_{min}
yield displacement(m)	0.0015	U_y	maximum coefficient of friction	0.13	μ_{max}
-	-	-	static coefficient of friction	0.15	μ_{static}

5.3 Ground excitation

Since the soil conditions under the supports vary significantly, so does the ground motion as mentioned earlier. The ground motion (Fig. 5) under the supports on the soft soil is amplified and it is much larger than the ground motion (Fig. 6) under the supports (abutments A1, A2 and pier P3) on stiff soil.

5.4 Bridge response for seismic excitation

When both horizontal and vertical ground motions are applied to this bridge, the significant influence obtained by using base isolation for the bridge can be observed.

In X (longitudinal) direction, there is no significant reduction in shear forces in piers P1 and P5 due to isolation solution. The isolated bridge, however, experiences much smaller shear forces, in both retrofit cases, as compared with that of the original bridge in pier P4 which is considered as fixed support (Fig. 8).

The effect of triaxial isolation on the bridge response when subjected to both horizontal and vertical excitations is very significant in Z (transverse) direction. The relative displacements between top and bottom of the piers are effectively reduced at the expense of the relative deformations of triaxial isolators, as shown in Fig. 7, and this results in significantly smaller shear forces as compared to the case of retrofit scheme using lead rubber bearings, because the influence of the vertical motion is efficiently reduced due to the frictional force. The differences between the shear forces of the two retrofitted bridges are shown in Fig. 8.

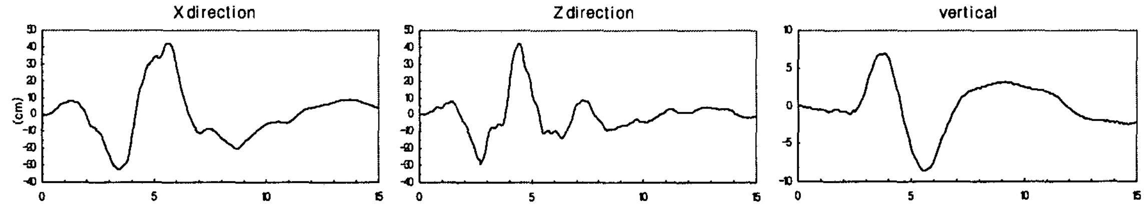


Fig. 5. Ground Displacement on Soft Soil

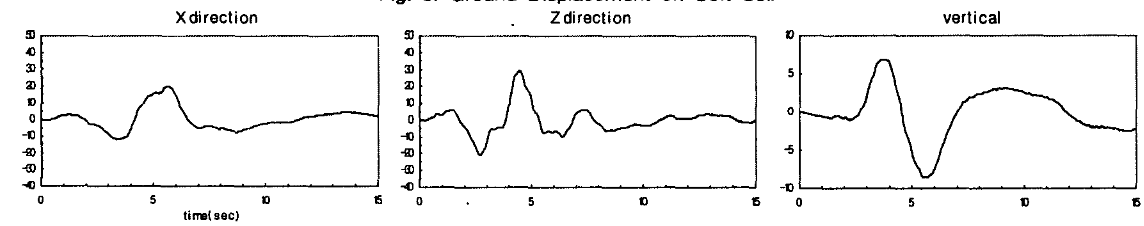


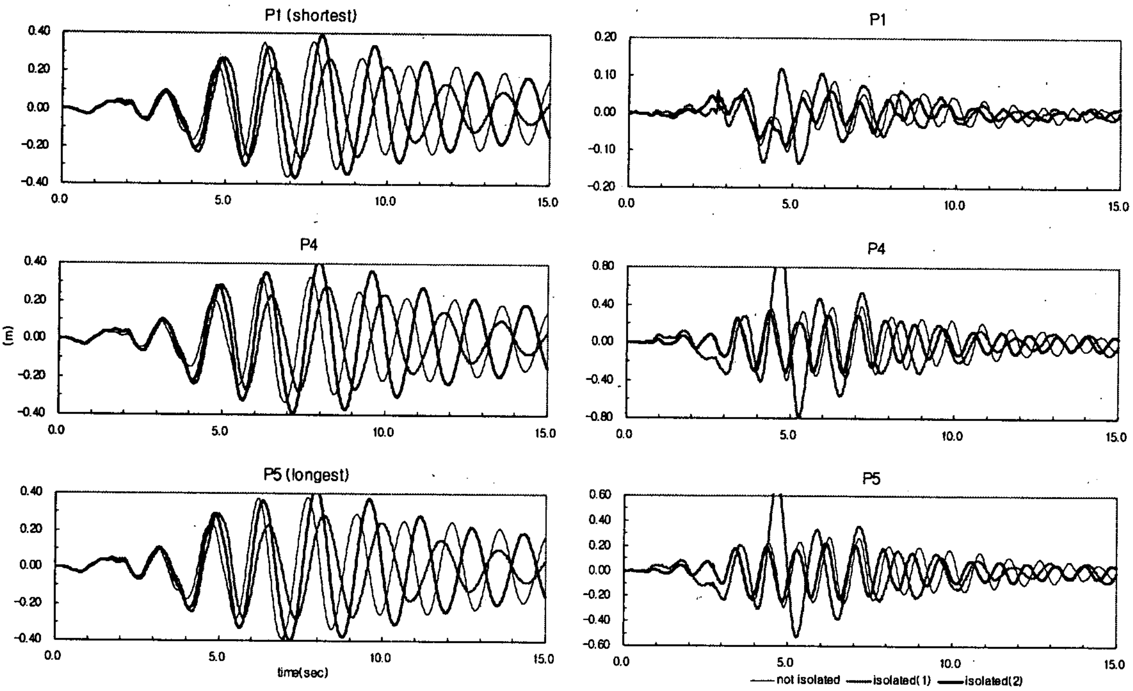
Fig. 6. Ground Displacement on Stiff Soil

6. Conclusions

A seismic retrofit scheme using base isolation systems was presented to reduce the seismic hazard for bridge structures. In this study, two types of isolation systems such as lead rubber bearings and sliding isolators were used. The behavior of sliding isolators was modeled by triaxial interaction model, which includes the influence of the changing vertical force and the dependency of the friction coefficient on velocity. Seismic response analyses of the bridge before and after retrofit were effectively carried out by using IDARC-BRIDGE. A comparative study was performed to evaluate the efficiency of a retrofit scheme using triaxial isolators, and the numerical results show that the triaxial isolation solution can efficiently reduce the responses of the bridge such as base shear forces for the vertical ground excitation. Accordingly, the triaxial isolation model can be used for a more realistic modeling of sliding base isolation system, and also for the selection of optimal retrofit strategies for existing bridges.

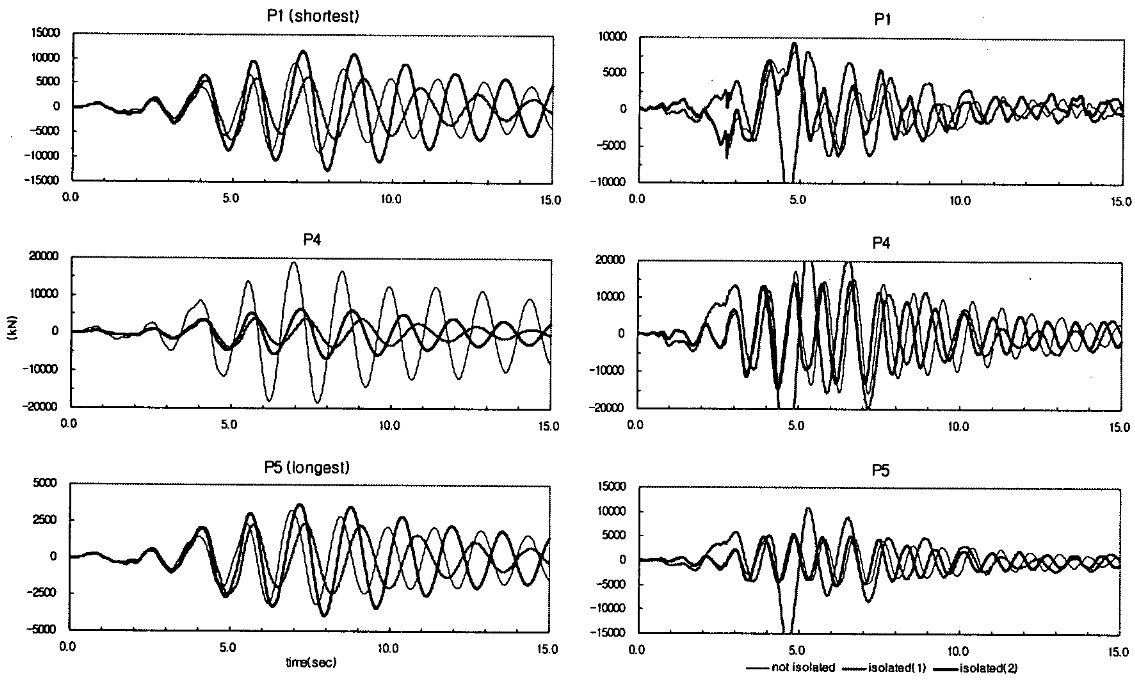
References

1. Constantinou, M.C., Mokha, A. and Reinhorn, A.M. (1990) Teflon bearings in base isolation II: modeling, *Journal of Structural Engineering*, ASCE, Vol. 116, No. 2, pp. 455-474.
2. Loh, C.H. and Ma, M.J. (1997) Reliability assessment of structure subjected to horizontal-vertical random earthquake excitations, *Structural Safety*, Vol. 19, No. 1, pp. 153-168.
3. Mokha, A., Constantinou, M.C. and Reinhorn, A.M. (1993) Verification of friction model of Teflon bearings under triaxial load, *Journal of Structural Engineering*, ASCE, Vol. 119, No. 1, pp. 240-260.
4. Nagarajaiah, S., Reinhorn, A.M. and Constantinou, M.C. (1991) Nonlinear dynamic analysis of 3D-base-isolated structures, *Journal of Structural Engineering*, ASCE, Vol. 117, No. 7, pp. 2035-2054.
5. Park, Y.J., Wen, Y.K. and Ang, A.H.S. (1986) Random vibration of hysteretic systems under bidirectional ground motions, *Earthquake Engineering & Structural Dynamics*, 14(4), pp. 543-557.
6. Reichman, Y. (1996) *Evaluation of bridge structures subjected to severe earthquakes*, Ph.D. dissertation, State University of New York, Buffalo, New York, USA.
7. Reinhorn, A.M., Simeonov, V., Mylonakis, G. and Reichman, Y. (1998) *IDARC Bridge: a computational platform for seismic damage assessment of bridge structures*, Report No. MCEER-98-0011, Multidisciplinary Center for Earthquake Engineering Research, State University of New York, Buffalo, New York.
8. Wen, Y.K. (1976) Method for random vibration of hysteretic systems, *Journal of the Engineering Mechanics Division*, ASCE, Vol. 102, No. EM2, pp. 249-263.



X (longitudinal) direction Z (transverse) direction

Fig. 7. Relative Deformations Between Ground and Deck at Piers



X (longitudinal) direction Z (transverse) direction

Fig. 8. Comparison of Shear Forces for Piers P1, P4 and P5