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Retrofit of Ressalat jacket platform (Persian Gulf) using friction damper device

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Abstract: A friction damper device (FDD) is used for vibration control of an existing steel jacket platform under seismic excitation. First, the damping is presented for vibration mitigation of structures located in seismically active zones. A new method for quick design of friction or yielding damping devices is presented. The effectiveness of the damping system employing such FDDs in a jacket platform is evaluated numerically. The influence of key parameters of the damping system on the vibration suppression of the offshore structure is studied in detail. To examine the vibration control effectiveness of the FDD for the jacket platform, performance of the controlled structure under the seismic forces is studied using numerical simulations. A parametric study is undertaken to discover the optimized slip load and brace area of the FDD. It is shown that the FDD is effective in mitigating the dynamic responses of the offshore platform structure.

Key words: Jacket offshore platform, Seismic retrofit, Friction damper devices (FDDs)
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1 Introduction

The steel jacket structure is a kind of fixed offshore platform. It is suitable for construction in water depth from a few meters to more than 300 m. The major structural components of such an offshore platform are jacket, piles, and deck. A jacket structure that serves as bracing for the piles against lateral loads is fixed by piles driven through the inside of the legs of the jacket structure and into soil many tens of meters deep. The deck structure is fixed upon the jacket structure. Oceans in which offshore platforms are built present a set of complicated and harsh environmental conditions. Dynamic loads including wind, wave, current, and earthquakes dominate the design of offshore structures. The dynamic loads affect not only the routine operation of an offshore platform such as drilling and production activities, but also the safety and serviceability of the structure. It is indispensable for reducing the overall response of a jacket platform subjected to strong dynamic loads.

Approximately 100 template-type offshore platforms have been installed in seismically active regions of the world's oceans. Some existing platforms in seismic regions may have three types of deficiency: (1) inadequate ground motions considered in the original design; (2) structural construction which is not designed for ductile behavior; (3) reduced capacity resulting from damage, corrosion or fatigue in its life time.

Also many of these platforms are now beyond their original design life (20–25 years). From an economic aspect it is preferable to continue using an existing jacket in many cases, in comparison to a new installation.

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A relatively complete review on assessment and retrofit of jacket platforms is presented by Tabeshpour and Komachi (2011). Structural retrofit is necessary for vulnerable structures. Before retrofit, it is necessary to assess the structures. Assessment of jacket platforms has rarely been studied. For example, Golafshani *et al.* (2009) compared the FEMA-356 (2000) and API (2000) approach for assessment of jacket offshore platform structures. Komachi *et al.* (2009a) presented the performance based assessment of jacket platforms for seismic vulnerability.

Current methods for seismic upgrading of existing structures can be classified into two major groups: traditional and modern. Traditional methods aim to increase the strength and/or ductility of the structure by repairing/upgrading members. Nowadays there are some new technologies (for example, seismic isolation and energy dissipation) for seismic protection of the structures.

The passive control approach is of current concern to many researchers and there are several attempts exploring its application to offshore structures. Recently, there have been several studies for the effectiveness of active and passive control mechanisms in controlling the response of offshore platforms under wave loading.

Incorporation of energy dissipation systems in a traditional earthquake-resistant structure has been recognized as an effective strategy for seismic protection of structures (Soong and Dargush, 1997).

New vibration control technologies have been applied to offshore structures in the following cases. Vandiver and Mitome (1979) used storage tanks as tuned liquid damper (TLD) on a fixed platform to mitigate the vibration of the structure subjected to random wave forces. Kawano and Venkataramana (1992) and Kawano (1993) studied the application of an active tuned mass damper (TMD) to reduce the response of platforms due to wave loading. Abdel-Rohman (1996) analysed the dynamic response of a steel jacket platform with certain active and passive controls due to wave-induced loading. Lee (1997) used stochastic analysis and demonstrated the efficiency of mechanical dampers for an offshore platform.

Suneja and Datta (1998; 1999) investigated the efficiency of an active control system for articulated leg platforms under wave loading. Gattulli and Ghanem (1999) developed an active mass damper for suppression of vortex-induced vibrations of offshore structures. Chen *et al.* (1999) studied the response of a jacket platform installed with TLD due to earthquake loading. Ou *et al.* (1999) analysed the response reduction of jacket platforms with a viscoelastic damper with respect to ice loads. Terro *et al.* (1999) developed a multi-loop feedback-control design as applied to an offshore steel jacket platform. Both passive and active control systems for the control of offshore platforms were used by Suhardjo and Kareem (2001). Ding (2001) investigated the response reduction of jacket platforms with a viscous damper due to ice loads. Qu *et al.* (2001) presented a rational analytical method for determining the dynamic response of large truss towers equipped with friction dampers under wind-excitation and investigated the efficiency of friction dampers. Wang (2002) used magnetorheological dampers for vibration control of offshore platforms for wave-excited response.

Mahadik and Jangid (2003) studied the response of offshore jacket platforms with an active TMD under wave loading. Patil and Jangid (2005) researched the behavior of a platform with viscoelastic, viscous and friction damper for wave loads. Lee *et al.* (2006) studied the effectiveness of a tuned liquid column damper (TLCD), which dissipates energy by water flow between two water columns, for offshore structures and also, Ou *et al.* (2007) developed the application of damping isolation systems for response mitigation of offshore platform structures. Jin *et al.* (2007) studied the effect of TLD and found that the larger the ratio of water-mass to platform-mass, the higher the reduction of responses. Komachi *et al.* (2009b; 2010) presented friction damper devices (FDDs) as a control system to retrofit existing jacket offshore platforms. Golafshani and Gholizad (2009) conducted the performance of friction dampers for mitigating of wave-induced vibrations and used mathematical formulation to evaluate the response of the model. Yue *et al.* (2009) used TMD for mitigation of dynamic ice loads. Response mitigation of jacket platforms and tension leg platforms using TMD has been investigated by Tabeshpour *et al.* (2010; 2011).

Figs. 1–3 give some control systems used for control of offshore jacket platforms. Fig. 1 shows some of the energy dissipation systems such as viscoelastic, viscous and friction dampers used in jacket platforms (Patil and Jangid, 2005). In Fig. 2, the deck of the jacket is installed with a damping isolation system (Ou *et al.*, 2007). A TMD and a TLD were used for seismic control of jacket platforms (Fig. 3).

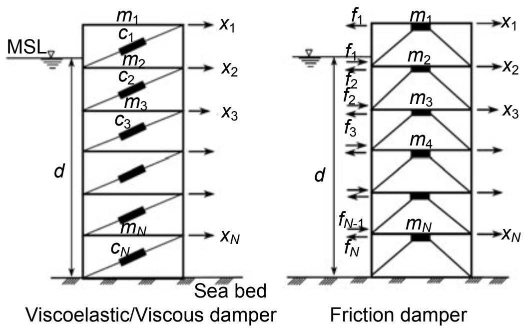

Fig. 1 Viscoelastic, viscous and friction dampers for jacket offshore platforms (Patil and Jangid, 2005)
MSL and d are the mean sea level and depth, respectively; m_i, c_i, and f_i are the mass, damping ratio of damper, and restoring force at the ith (i=1,2,…,N) level, respectively

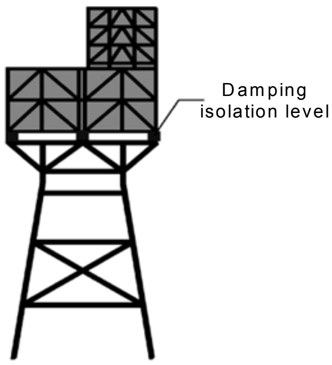

Fig. 2 Offshore jacket platform installed with damping isolation system (Ou *et al.*, 2007)

The service life of an offshore structure can be doubled if the dynamic stress amplitude reduces by 15%. Few studies have reported the effectiveness of the passive control systems using dampers in controlling the response of offshore platforms under a parametric variation studying the influence of important system parameters and comparative performance of dampers. To reduce possible damage to jacket offshore platforms in harsh marine environments, the necessity of carrying out further studies on developing efficient and practical vibration control strategies for the suppression of dynamic responses of existing offshore structures should be emphasized.

In this study, a FDD proposed by Mualla and Belev (2002) is used to mitigate the vibration of a

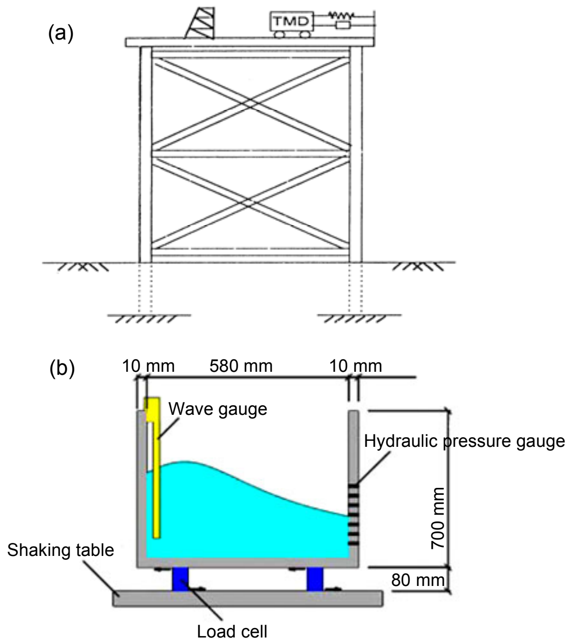

Fig. 3 Control systems for jacket platform structures
(a) Tuned mass damper; (b) Tuned liquid damper

fixed Ressalat jacket offshore platform (Persian Gulf). This study investigates the influence of the damping system parameters on vibration control of offshore platforms under the actions of earthquake excitations, and shows that FDD improves the structural behavior and performance of jacket platforms.

2 Friction damper devices (FDDs)

Passive control systems have been successfully used for reducing the dynamic response of structures subjected to lateral loads such as wind and seismic forces. Friction dampers have often been employed as a device for this purpose presenting high energy-dissipation potential with relatively low cost. Recently, a novel FDD was presented by Mualla and Belev (2002) and Mualla and Nielsen (2002). The efficiency of the special devices proposed by Mualla and Belev (2002) was investigated by Tabeshpour and Ebrahimian (2010) for seismic retrofit of building structures.

The main parts of the damper are the central (vertical) plate, two side (horizontal) plates, two circular friction pads placed in between the steel plates and bracing members as shown in Fig. 4 (Mualla and Nielsen, 2002). When the girder tends to displace the bracing system horizontally, the forces of friction developed at the interface of the steel plates and friction pads will resist the horizontal motion.

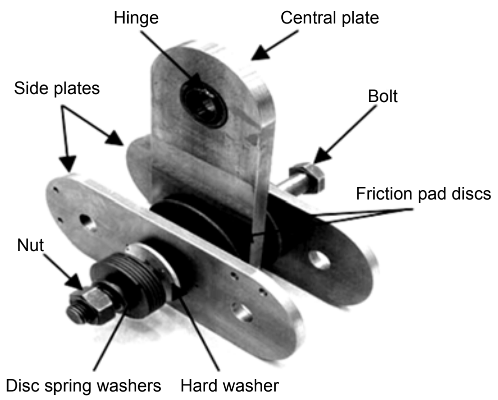

Fig. 4 Components of FDD (Mualla and Nielsen, 2002)

As shown in Fig. 4, the device is very simple in its components and can be arranged within different bracing configurations to obtain a complete damping system. The damper device can be used in the jacket platforms in several configurations as shown in Fig. 5.

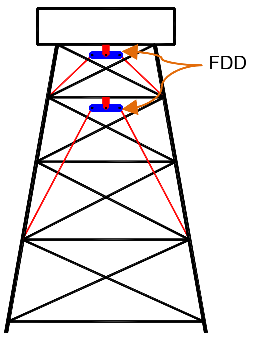

Fig. 5 Jacket platform retrofitted with FDD

The friction damper is velocity-independent and linearly dependent on the displacement amplitude. Fig. 6 shows the hysteretic behavior of FDD for various forcing frequencies that are obtained from experimental results (Mualla and Nielsen, 2002). For a given force (P) and displacement (Δ) in a damper, the energy dissipation of a friction damper is greater than those of other damping devices (Fig. 7). They are not active during low velocity wind and service loads. They do not cause leakage or damage. Therefore, they do not need regular inspection, maintenance, repair or replacement before and after the earthquake. The two phases of damper deformation are the sticking and sliding phases. The frictional moment M_f limits the moment in the frictional hinge. This type of friction damper is defined by a slip load, F_h, an elastic stiffness, K_{bd}, and a ductility ratio, $\mu_d=D_u/D_{yd}$, where D_u and D_{yd} are the ultimate and yield displacements of the FDD, respectively. Energy dissipation per cycle in the frictional hinge can be written approximately as

$$E_D = 4K_{bd}D_{yd}(D_u - D_{yd}). \tag{1}$$

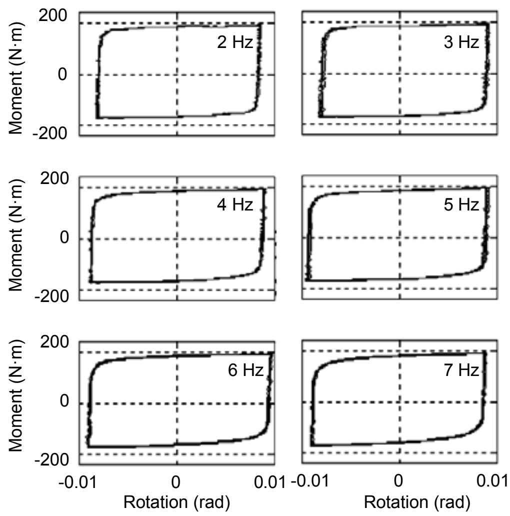

Fig. 6 Effect of forcing frequency on hysteretic loop (Mualla and Belev, 2002)

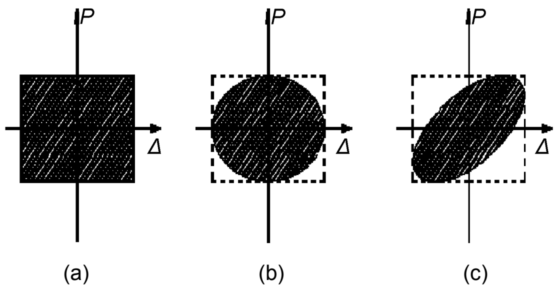

Fig. 7 Comparison of hysteresis loops of different dampers

(a) Friction damper; (b) Viscous damper; (c) Viscoelastic damper

Structure and FDD act in parallel and can be described as a dual system. For a system with a single degree of freedom and assuming that basic system remains elastic, the equivalent viscous damping ratio is obtained by

$$\beta_{eff} = \frac{E_D}{4\pi E_S} = \frac{2}{\pi}\frac{FR(SR - FR)}{(SR + FR^2)}, \quad \frac{FR}{SR} < 1, \tag{2}$$

where FR=F_{hf}/F_s is the ratio of damper yield force to the total structure force exhibited by the structure, SR=K_{bd}/K_s is the ratio of damper stiffness to the total structure stiffness, and E_s is the maximum strain energy.

This formulation is well suited for making a first order estimate of the required damper properties for the design. The relation for β can be used to generate a family of curves as a function of FR and SR as shown in Fig. 8 (Tabeshpour and Ebrahimian, 2010).

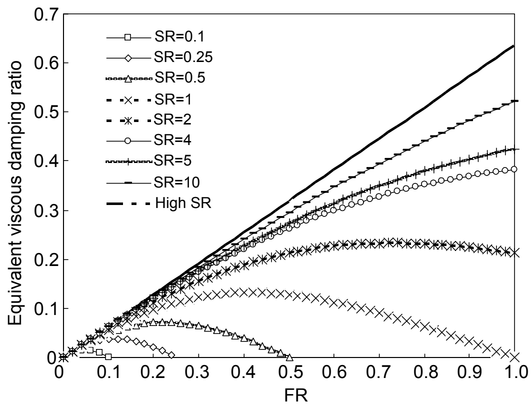

Fig. 8 Equivalent viscous damping ratio for dual system (Tabeshpour and Ebrahimian, 2010)

3 Description of the jacket platform

Ressalat field is located in Iranian waters of the Persian Gulf, about 80 km to the south of Lavan island, in water depth of 67 m. The existing Ressalat offshore consists of a drilling platform, a production platform, a service platform and a flare tripod in the field. The field was originally developed and started production in 1968. There was some damage during the Iran/Iraq war and some other extended damage later due to adverse climate conditions. The service platform consists of a four-legged battered jacket and topside located in 67.40 m water depth which is connected to the production platform by means of one existing bridge. The service life of the platform is 25 years. A perspective plot of the model and details of the structure are shown in Figs. 9 and 10, respectively. This study describes the retrofit of the existing four-legged service platform of the Ressalat (R1) Oil Field, during earthquake shaking. A parametric study for the jacket offshore platform with installation of the damping system is presented.

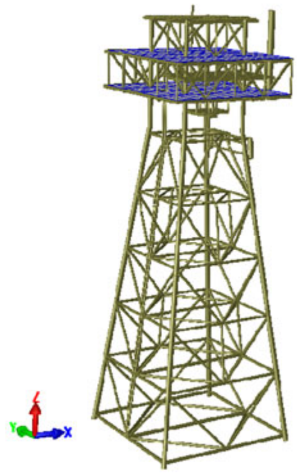

Fig. 9 Perspective plot of Ressalat service platform

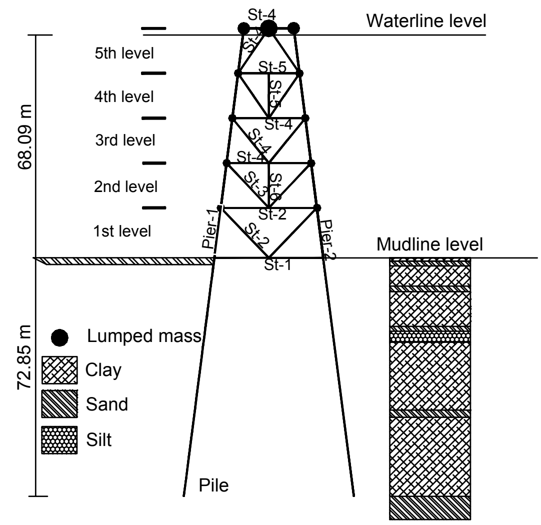

Fig. 10 Soil profile and other specifications

4 Structural modeling

Analytical models were created using the open source finite element platform, OpenSees (2005). A 2D model of a single frame is developed for the structure. A force-based nonlinear beam-column element (using a layered fiber section) is used to model all the components of the frame (Fig. 11). Steel material is modeled using a bilinear stress-strain curve with 3% post-yield hardening. Initial imperfections in the struts are taken into account with the value of 0.001L, where L is the length of the member. This idea is useful for modeling of post-buckling and post-yielding behavior of the strut and portal members, respectively.

The mathematical model of the pile-soil system consists of the following sets of elements (Fig. 12): (1) Pile elements, modeled by a number of nonlinear beam-column elements. (2) Far-field soil model representing the free-field motion of the soil column, vertically and horizontally that is unaffected by the pile motions. The soil is modeled using elastic quad elements. The nodes that are at the same depth are constrained. (3) Near-field elements that connect the piles to the soil vertically and horizontally. The strength and stiffness of these elements depend on the state of the far-field soil and the relative motion of the pile and far-field soil. The interface between the pile and surrounding soil is modeled using *p-y*, *t-z*, *q-z* nonlinear spring elements. Hysteretic and radiation damping are considered using these elements. The group effects are not considered. The input motion is applied to the fixed nodes at the bottom of the soil column. The seismic record at bedrock is found from the input motion at the surface. Hydrodynamic effects are considered in terms of hydrodynamic damping from drag forces and added masses.

According to API, in computing the dynamic characteristics of braced pile-supported steel structures, uniform modal damping ratios of five percent of critical should be used for an elastic analysis. The analysis was performed assuming rigid joints.

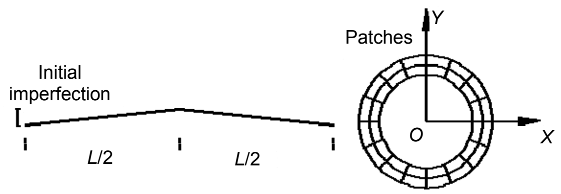

Fig. 11 Modeling of strut and portal members

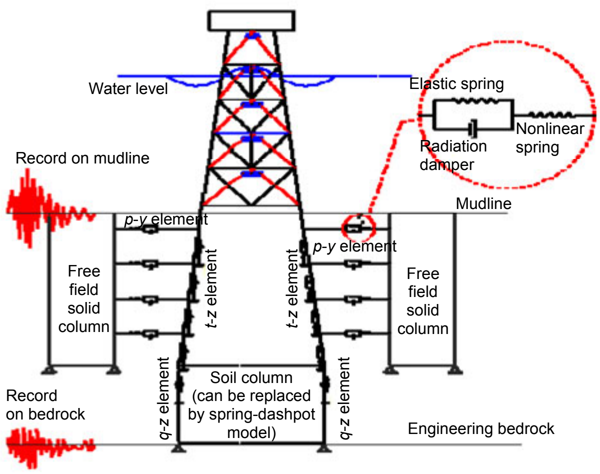

Fig. 12 Modeling of pile-soil-structure interaction

The zero-length element of the program was used for modeling of friction hinge. This model was verified with results from Mualla and Belev (2002). The Portal model of Filiatrault and Cherry (1989) was used in this case. Fig. 13 shows roof displacement vs. pretension force of damper bars for two cases. Variation of hinge rotation with ground motion is shown in Fig. 14. These figures show that results are well-matched for the Mualla and Belev (2002) and OpenSees models.

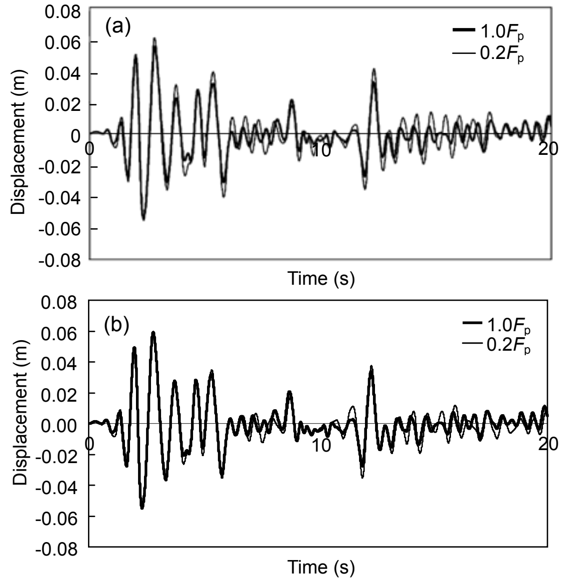

Fig. 13 Effect of pretension force (F_p) of damper bars on displacement response

(a) Mualla and Belev (2002); (b) OpenSees model

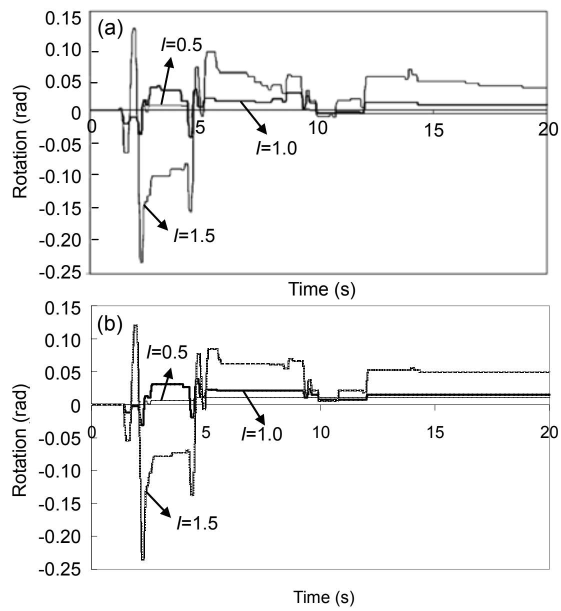

Fig. 14 Effect of ground motions on damper performance

(a) Mualla and Belev (2002); (b) OpenSees model. *I* is the scale factor imposed to the ground motion

Fig. 23 shows normalized deck displacement vs. normalized strength of damper for ELC-NS record (PGA=3.4 m/s^2). Two values are assumed for damper stiffness. K_{bd} is for the cases where the stiffness ratio of the damper is one. This figure shows that for low and medium values of damper strength, structural performance is relatively good. It can be seen that in the case of a large value of damper strength, lower stiffness of damper leads to better performance of the system.

Fig. 24 provides normalized deck displacement vs. normalized strength of damper for ICC000 record (PGA=8.25 m/s^2). This figure shows that the higher the nonlinear behavior of the structure, the more the reduction of deck displacement. It is shown that the more section area of the bars leads to more reduction of response.

Fig. 25 shows normalized deck displacement vs. yield moment of damper for CHY101W record (PGA =7.6 m/s^2). This figure shows that for higher nonlinear

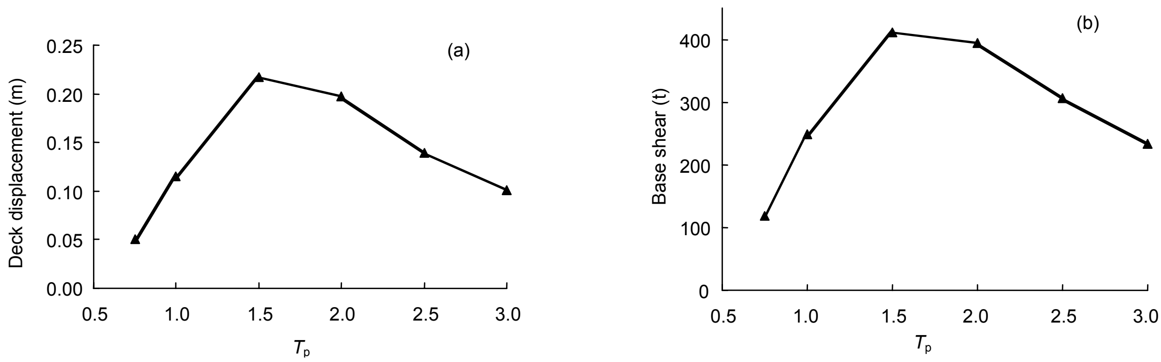

Fig. 20 Responses of jacket vs. period of equivalent pulse of near-fault earthquake (PGA=1 m/s^2)
(a) Deck displacement; (b) Base shear

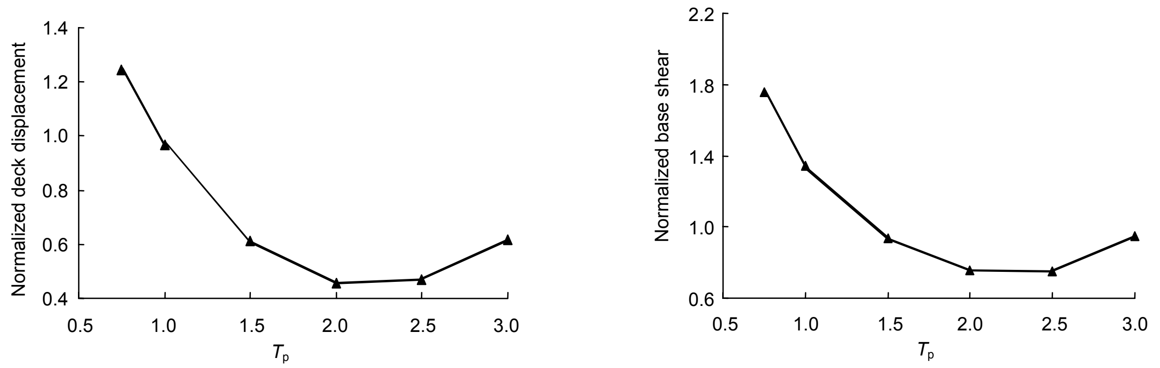

Fig. 21 Normalized responses of jacket vs. period of equivalent pulse of near-fault earthquake (PGA=6 m/s^2)
(a) Deck displacement; (b) Base shear

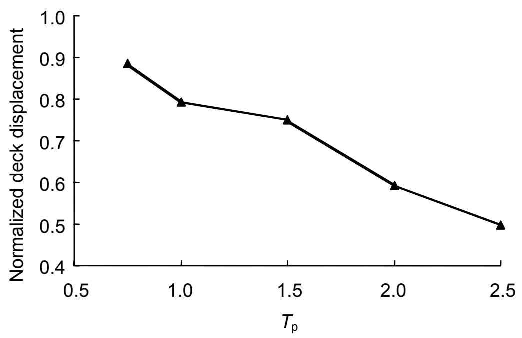

Fig. 22 Normalized deck displacement of jacket vs. period of equivalent pulse of near-fault earthquake (PGA=6 m/s^2)

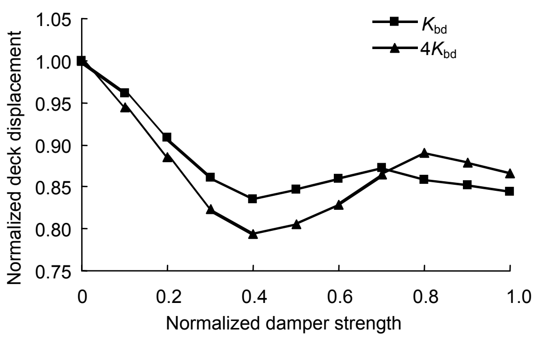

Fig. 23 Normalized deck displacement of jacket vs. normalized strength of damper for ELC-NS record (PGA=3.4 m/s^2)

behavior of the structure, the performance of damper increases. The efficiency of the friction damper is high and leads to about 55% to 65% reduction in displacement. It can be seen that for various ultimate strengths of damper, deck displacement reduces uniformly.

Normalized deck displacement of jacket for various normalized damper strengths of damper is shown in Fig. 26. It is observed, however, that deck displacement is decreased with increasing damper strength but displacement reduction is relatively insensitive to damper strength variation. Reduction of deck displacement is between 17% and 20% for normalized strength in the range of 0.1 to 1.0.

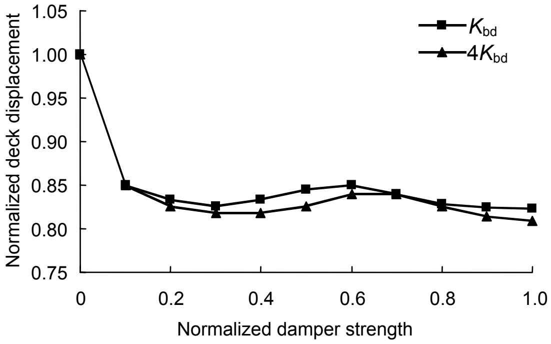

Fig. 24 Normalized deck displacement of jacket vs. normalized strength of damper for ICC000 record (PGA =8.25 m/s^2)

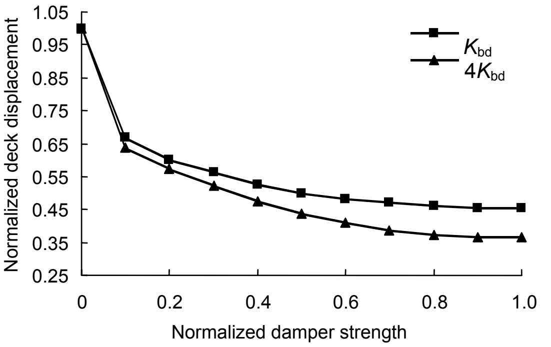

Fig. 25 Normalized deck displacement of jacket vs. normalized strength of damper for CHY101W record (PGA =7.6 m/s^2)

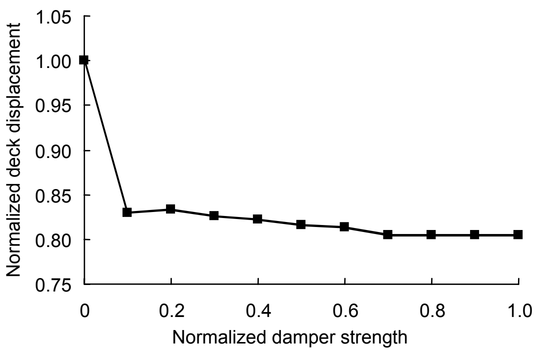

Fig. 26 Normalized deck displacement of jacket vs. normalized strength of damper for Sylmar record

10 Responses vs. PGA of the input motion

Fig. 27 shows normalized responses of the jacket for various PGAs of CHY101W record. This figure shows that efficiency of damper for displacement reduction increases as PGA increases. A great reduction in deck displacement is observed at PGA= 0.7 m/s^2 in which the strength of jacket is degraded instantly. A similar state also occurs at PGA=0.95 m/s^2. It can be seen, as expected, that the performance of the jacket where dampers are installed in all levels is better than that of three levels by up to 10%. For large PGA, deck displacement decreases by up to one third for a jacket retrofitted with five dampers and 0.45 for a jacket retrofitted with three dampers.

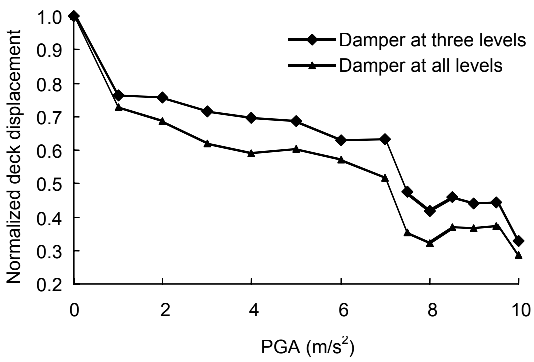

Fig. 27 Normalized deck displacement of jacket vs. PGA of CHY101W record

Fig. 28 shows normalized deck displacement (jacket retrofitted in all levels, SR=1.0) for Sylmar near-fault record. This figure shows that by increasing PGA the efficiency of damper for displacement reduction increases. It is seen that FDD is very efficient at large values of PGAs.

11 Conclusions

FDD is used for seismic retrofit of jacket platform structures. The device is velocity independent

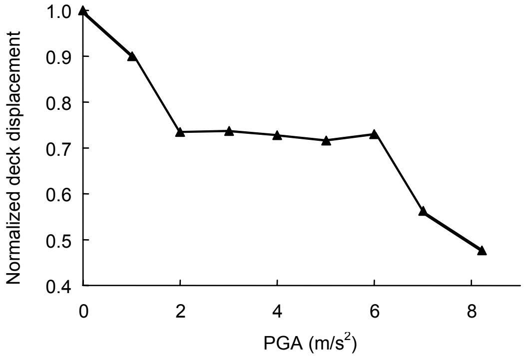

Fig. 28 Normalized deck displacement of jacket vs. PGA of Sylmar record

within a certain range and linearly dependent on the displacement amplitude.

This system was used on a steel jacket platform located in Iranian waters of the Persian Gulf. Results show that responses of jacket reduce dramatically. A numerical study was performed using pushover and nonlinear dynamic analysis.

Pushover analysis results show that the use of FDD system reduce target displacement of the structure and also show that a sudden decrease of jacket strength does not occur when this system is installed on the structure. Due to the low redundancy of jacket platform structures, the strength of these structures can decrease suddenly and the use of FDD systems can be extremely useful.

Parametric study for far-fault and near-fault earthquake records was made and the efficiency of the friction damper was assessed. This study was undertaken for various values of friction damper specifications and also for various PGAs of earthquake records. Analysis results show that for wide range of record acceleration, friction damper greatly reduces deck displacement. It is observed that for large record accelerations structure behavior becomes highly nonlinear and the performance of the friction damper for response reduction increases (for example up to 65% deck displacement reductions). It is also observed that base shear reduces in many situations but increases in some states even the increase is low.

The numerical studies reported clearly that this control system presents a practical alternative for retrofit of existing structures. The device is economic and easily installed and protects structures from structural and non-structural damages in moderate and severe earthquakes.

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