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SEISMIC RESPONSE OF BASE-ISOLATED STRUCTURES USING DCFP BEARINGS WITH TRI-LINEAR AND BI-LINEAR BEHAVIORS

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Abstract

Double concave friction pendulum (DCFP) system is the new developed kind of friction pendulum systems that consists of two sliding surfaces. In the current paper, the seismic response of three dimensional base-isolated structures using DCFP systems considering tri-linear and bi-linear behaviors have investigated. After deriving the coupled differential equation of motion, a computer program has been developed in order to obtain the time history response of base-isolated structures under earthquake excitations. Advantages and disadvantages of tri-linear behavior over bi-linear one are scrutinized by studying the effect of main parameters such as isolation period, amplitude of the ground motion, and friction coefficient of the surfaces on the peak responses under seven earthquakes. It is demonstrated that tri-linear DCFP bearings, in comparison with bi-linear bearings, can decrease the base shear up to about 48 percent. However, tri-linear DCFP bearings cause bigger displacements of sliding surfaces than bi-linear ones that reach to 57%.

Keywords: Double concave friction pendulum (DCFP), tri-linear, bi-linear, isolation period, radius of curvature, friction coefficient.

1. Introduction

Base isolation systems are new devices that are used to protect structures against seismic hazard. Seismic isolation is the separation of structures from the injurious motion of the ground by providing flexibility and energy dissipation capability through the insertion of so-called isolators between the foundation and the superstructure. The first base isolated structure was built in the United States of America in 1985 (Zayas *et al*. 1987). Isolators are classified in two major groups: elastomeric and

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frictional isolators. Frictional isolators use velocity dependent friction between composite materials which are usually composed of Polytetrafluoroethylene (PTFE) and a stainless steel plate as its energy dissipation system (Soong and Constantinou 1992).

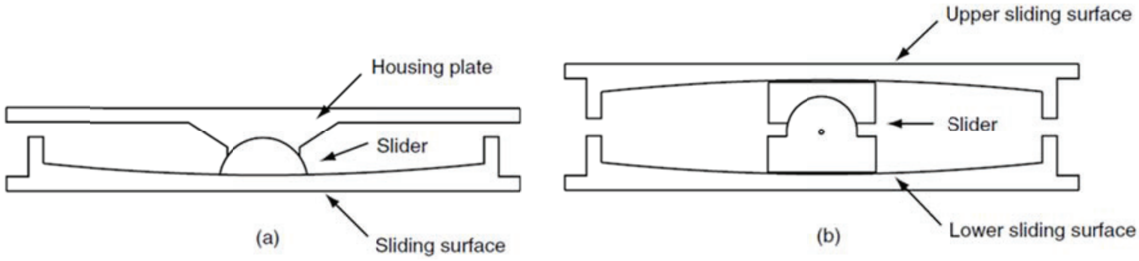

Figure 1. Cross section of: (a) FPS; and (b) DCFP systems

The friction pendulum system (FPS) is a sliding type seismic isolation system which uses its surface curvature to make the restoring force from the pendulum action of the weight of the structure on the FPS (Figure 1(a)). Double concave friction pendulum (DCFP) system is a newly developed device which is similar to FPS system with two sliding surfaces. The behavior of an FPS can be made more effective by introducing a second sliding surface as shown in Figure 1(b). DCFP system has been used in a few buildings in Japan (Hyakuda *et al.* 2001) and a bridge in Canada (Constantinou 2004). Kim and Yun (2007) studied the advantages of tri-linear DCFP over the bi-linear DCFP for isolating of the bridges from strong motions. They concluded that tri-linear DCFP causes reduction effect on the base shear of the pier in the range of 15% -40% over bi-linear DCFP. Their investigation was performed only for bridges and there is not any special study on the structures isolated with bi-linear and tri-linear DCFP bearings. The previous investigations were almost for isolated structures with DCFP under one or two horizontal components of earthquakes. Therefore the present investigation is performed to study the effect of three components of ground motions on the isolated structure using DCFP bearings with bi-linear and tri-linear behaviors and attempt is to made comparison between the behavior of isolated structures with bi-linear and tri-linear DCFPs.

2. Mathematical modelling of DCFP

Governing equations of the concave friction pendulum (FPS) are very similar to DCFPs ones. So first of all, the governing equations of FPS bearing will be explained and then DCFPs equations will be examined. The force displacement relationships of FPS bearings undergoing bi-directional excitations can be described by (Park *et al*. 1986; Constantinou *et al*. 1990):

$$F_x = \frac{N}{R} u_x + \mu N Z_x \tag{1}$$

$$F_y = \frac{N}{R} u_y + \mu N Z_y \tag{2}$$

Where F_x and F_y are the resisting forces , u_x and u_y are bearing displacements, N is the normal load on the bearing, R is the radius of curvature of sliding surfaces, μ is the coefficient of friction that depends on relative velocity of bearings. In these relations Z_x and Z_y can be approximately expressed by solving the following differential matrix as : (Park *et al*. 1986; Constantinou *et al*. 1990):

$$\begin{Bmatrix} \dot{Z}_x Y \\ \dot{Z}_y Y \end{Bmatrix} = \begin{Bmatrix} A\dot{u}_x \\ A\dot{u}_y \end{Bmatrix} - \begin{bmatrix} Z_x^{\,2}(\gamma\,\mathrm{sgn}(\dot{u}_x Z_x)+\beta) & Z_x Z_y(\gamma\,\mathrm{sgn}(\dot{u}_y Z_y)+\beta) \\ Z_x Z_y(\gamma\,\mathrm{sgn}(\dot{u}_x Z_x)+\beta) & Z_y^{\,2}(\gamma\,\mathrm{sgn}(\dot{u}_y Z_y)+\beta) \end{bmatrix} \begin{Bmatrix} \dot{u}_x \\ \dot{u}_y \end{Bmatrix} \tag{3}$$

A, β and γ are dimensionless variables that control the shape of the hysteretic loop. Sliding friction coefficients of FPS are modeled as the velocity dependent coefficients of friction as the following equation (Mokha *et al.* 1988; Constantinou 2004):

$$\mu = f_{\max} - (f_{\max} - f_{\min})\exp(-a|\dot{u}|) \tag{4}$$

Where $f_{\max}$ is the maximum sliding friction coefficient at high sliding velocity; $f_{\min}$ is the minimum sliding friction coefficient at essentially zero sliding velocity; $\dot{u}$ is the total sliding velocity and a is a parameter controlling the variation of sliding velocity coefficient.

The previous equations are valid for the friction pendulum system (FPS). DCFPs equations are similar to FPS equations, but the behavior of DCFP can be modeled using two FP link elements acting in series and therefore by defining two separate single concave FP elements and then connecting them in series with a small point mass (m_1) representing the articulated slider, the overall behavior of DCFP is obtained.

3. Modeling of base-isolated structures

An appropriate model needed for modeling of structures mounted on DCFP bearings. In this study, the model of isolated building consists of a linear elastic superstructure and a nonlinear base isolator. Figure 2 shows the assumed structural system which is an idealized three dimensional single story building model subjected to three components of earthquake and mounted on a DCFP bearing.

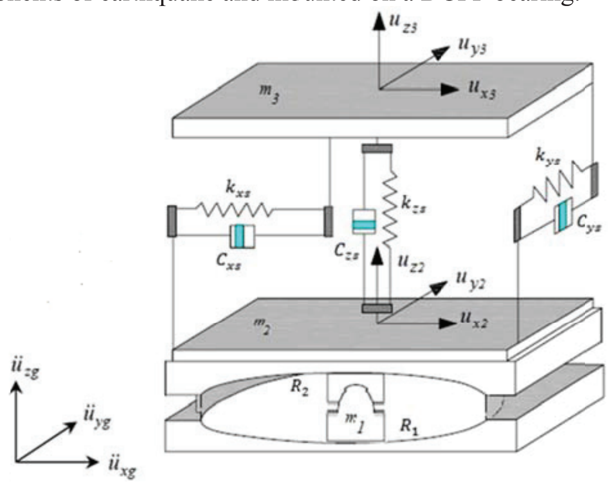

Figure 2: Idealized there-dimensional single-story structure mounted on DCFP system

4. Tri-linear and Bi-linear DCFP bearings

When sliding surfaces with equal friction coefficient are used ($\mu_2 = \mu_1$), there is simultaneous sliding on both surfaces over the entire range of motion, regardless of the radii of curvature. The hysteretic behavior is so called bi-linear like that of the traditional FPS (Constantaniou 2004). During this regime, the isolation period (T_i) can be described by Eqn 5 (Kim and Yun 2007). Figure 3 illustrates hysteretic loops of bi-linear DCFP and tri-linear DCFP.

$$T_{comb} = 2\pi\sqrt{\frac{R_1 + R_2}{g}} = \sqrt{T_1^2 + T_2^2} \tag{5}$$

$$T_1 = 2\pi\sqrt{\frac{R_1}{g}} \quad , T_2 = 2\pi\sqrt{\frac{R_2}{g}} \tag{6}$$

T_1 and T_2 are restoring periods of the lower and upper sliding surfaces in the same order.

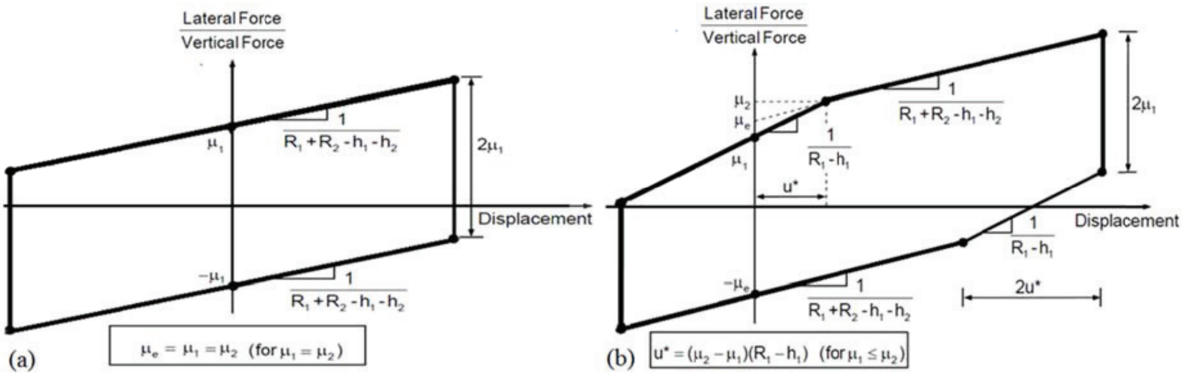

Figure 3: The hysteretic curve of: (a) bi-linear DCFP (b) tri-linear DCFP

When friction coefficient is different on the upper and lower concave sliding surfaces ($\mu_2 \neq \mu_1$), motion initiates on the surface of least friction coefficient and continues on this surface for a distance u^*. During this sliding regime, the isolation period equals to T_1 for $\mu_1 < \mu_2$ and equals to T_2 for $\mu_1 > \mu_2$. After the displacement exceeds u^*, there is sufficient horizontal force to initiate sliding on the surface of higher friction and motion continues with simultaneous sliding on both sliding surfaces. During this regime, the isolation period is equal to T_{comb}. For tri-linear DCFPs, an equivalent friction coefficient and u^* are assumed by following equations (Constantaniou 2004):

$$\mu_{eq} = \frac{\mu_1(R_1 - h_1) + \mu_2(R_2 - h_2)}{R_1 + R_2 - h_1 - h_2} \tag{7}$$

$$u^* = (\mu_2 - \mu_1)(R_1 - h_1) \tag{8}$$

Based on above equations, a computer program was written using MATLAB to investigate the effect of three components of earthquakes on the response of isolated structures resting on DCFP system with bi-linear and tri-linear behaviors.

5. Verification

The accuracy of developed program was verified by comparing the result obtained from the program with the results derived from two papers performed by Khoshnoudian and Rabiei (2010) and Almazan *et al*. (1998). Their structural model was a 3D single story building, similar to the Figure 2.

Almazan *et al*. (1998) investigated the response of FP base-isolated structures using various FPSs. Their structural model was a 3D single story building, similar to Figure 2, with a FP bearing and throughout the study, the friction coefficient of the sliding was kept constant and equal to 0.07. To model of the FP bearing using the developed program, the radius of the upper and lower concaves are assumed to be the same and equal to the half of radius curvature of FP bearing (Constantinou 2004). Based on the mentioned investigation, the following parameters are used for modeling the FP base-isolated structure: $f_{\min} = f_{\max} = 0.07, m_2 / m_3 = 0.2, T_s = 0.5Sec$.

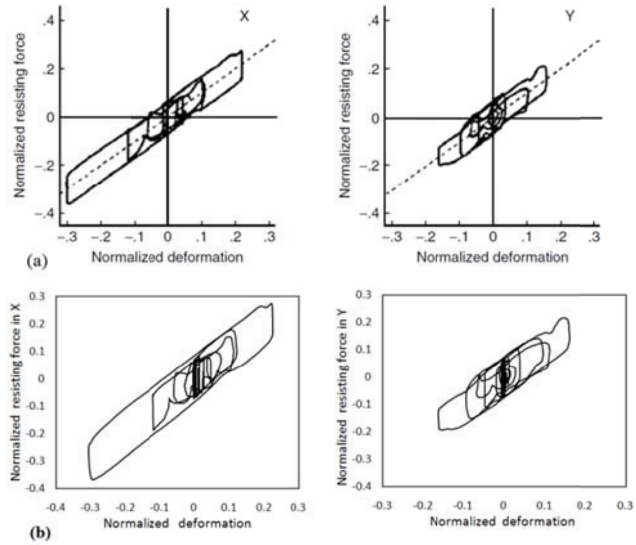

Figure 4: Comparison of hysteretic curves obtained from: (a) Almazan *et al*. (1998) (b) Developed computer program in x and y directions under Northridge earthquake

In these figures, the bearing displacements are normalized by bearing radii of curvature. The obtained results demonstrated the validity of the program.

6. Numerical study

The response of three dimensional single story building resting on the tri-linear or bi-linear DCFP bearing subjected to three components of earthquakes has been studied. The responses of isolated structures are the base shear of superstructure and the relative bearing displacement. The damping ratio of the superstructure is assumed to be 2% of critical damping. The time step was chosen 0.001 Sec. For the current study, seven earthquake records with different sources, mechanisms, intensities and duration are considered and applied to the isolated structure. These earthquake records are Cape Mendocino (1992), Turkey Duzce (1999), Turkey Erzincan (1992), Kobe (1995), Northridge (1994), N.Palm Springs (1986) and Northridge (1994).

In this study, the friction coefficient of sliding surfaces, isolation period (T_i) and intensity of ground motion are considered as the variable parameters and attempt is made to examine the effect of DCFP bearings hysteretic behavior, bi-linear and tri-linear DCFPs on the earthquake response of isolated structure resting on DCFP bearings.

6.1 Bi-linear and Tri-linear DCFPs

In this section, various DCFPs are assumed and for having tri-linear and bi-linear DCFPs, f_{max} of two sliding surfaces are supposed to be variable. f_{max1} decreases from 0.1 to 0.03 and inverse f_{max2} increases from 0.1 to 0.17. During this variation, equivalent friction coefficients are kept constant and equal 0.1 at high sliding velocity and 0.03 for zero sliding velocity ($f_{max\,eq} = 0.1, f_{min\,eq} = 0.03$). In addition, the radii of sliding surfaces are assumed to be the same. Some analyzes are performed for different values of isolation period, differences of friction coefficients of sliding surfaces and also magnitude of ground motions.

6.1.1. Isolation period

In this section attempt is made to examine the effects of changes in the isolation period on the isolated structure responses resting on bi-linear or tri-linear DCFPs. In next figures the horizontal axe presents the difference of f_{max2} and f_{max1} ($f_{max2} - f_{max1}$) which is increased from zero to 0.14. When $f_{max2} - f_{max1} = 0$, DCFP has bi-linear behavior and for another value of $f_{max2} - f_{max1}$, DCFP has tri-linear behavior. The vertical axe shows the values of the responses which is normalized to the responses when $f_{max2} - f_{max1} = 0$. Responses are obtained from average of the seven records. In addition, responses for each record are the maximum value of response during time history analysis. The period of structure (T_s) is kept constant and is equal to 0.5 Sec and the isolation period (T_i) varies from 2 to 5 sec.
The maximum bearing displacement in x and y directions during increasing in differences of friction coefficients of sliding surfaces are illustrated in Figure 5. As the figure depicts, when the difference of friction coefficient of sliding surfaces increases, the bearing displacement increases. Because when the value of difference of friction coefficient increases, the amount of u^* grows up and therefore the bearing displacement increases. The growing percentage of the bearing displacement with various amount of the isolation period is different. This figure clearly indicates the fact that in the upper periods of base isolation, the increasing percentage of bearing displacement grows up. The reason of this fact are related to increasing in the isolation period and also increasing of differences of the friction coefficient of upper and lower sliding surfaces.

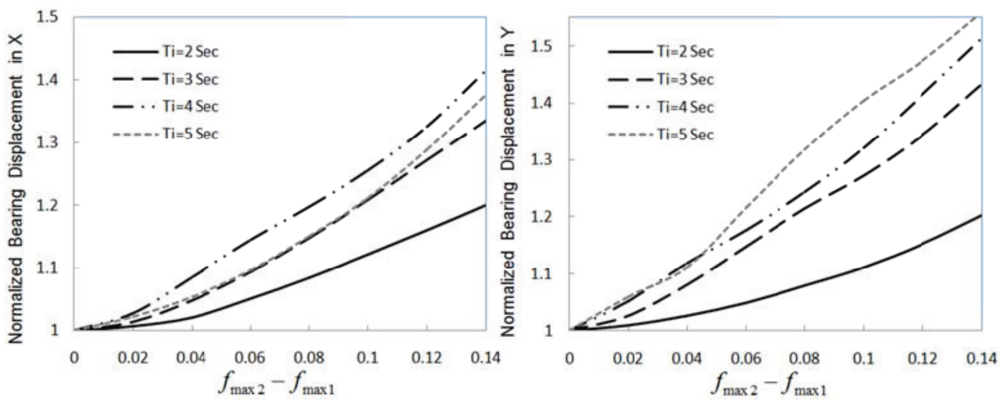

Figure 5: The maximum bearing displacement in x and y directions

Figure 6 shows the influence of increase in the differences of friction coefficient of sliding surfaces on the base shear with variation of the isolation period. As the figure illustrates, when difference of friction coefficient of sliding surfaces increases, the base shear decreases. According to the figure the effect of differences in bearing coefficient of friction in the lower isolation period is insignificant ($T_i = 2,3\,\text{sec}$). Because in the lower isolation period , the structure period is close to the isolation period and thus the base isolator works far from its real behavior. Contrary to the previous result, in the upper period of isolation, the effect of differences of friction coefficient on the base shear is remarkable. It can be concluded that the base shear in isolated structure with tri-linear DCFP is less than bi-linear DCFP one in the same conditions.

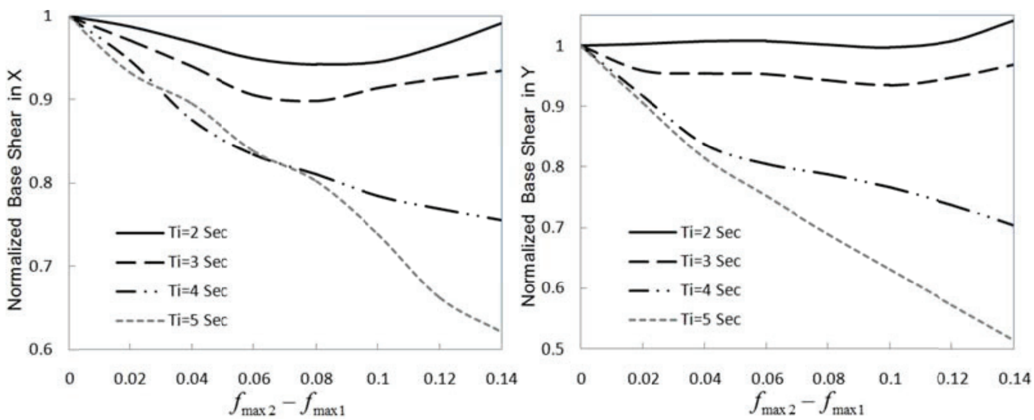

Figure 6: The maximum base shear in x and y directions

6.1.2. Amplitude of the ground motion

In this section, the selected records are scaled to three values (0.5, 0.7 and 0.9) g and the effect of the amplitude of ground motions on the response of isolated structure resting on bi-linear or tri-linear DCFP system is investigated. The isolation period and the superstructure period are assumed constant and equal to 4 and 0.5 Sec respectively. Figure 7 depicts the influence of amplitude of ground motions on the bearing displacement. The figure shows as the difference of friction coefficient of sliding surfaces increases, the bearing displacement grows up and this increasing is less significant for stronger earthquake records.

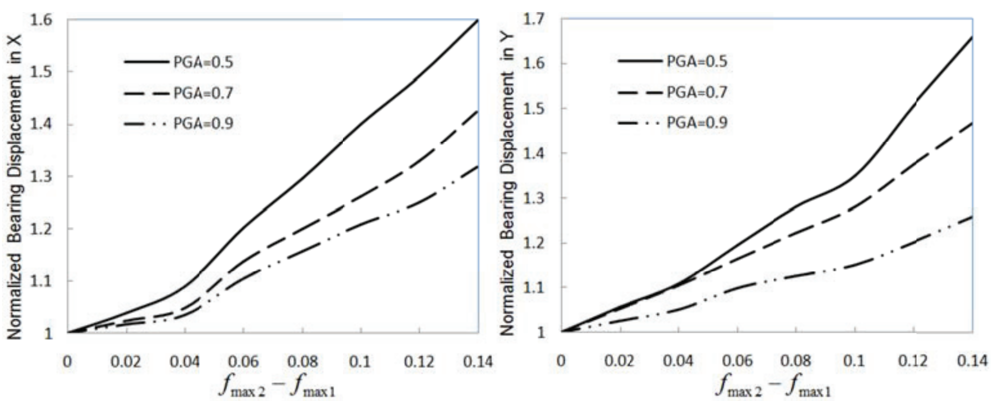

Figure 7: The maximum bearing displacement in x and y directions

Figure 8 presents the effect of differences in the bearing coefficient of friction on the base shear in various amplitudes of ground motion. According to this figure, increase of difference in the bearing coefficient of friction causes the decrease in base shear. The maximum of decreasing percentage depends on the amplitude of ground motions.

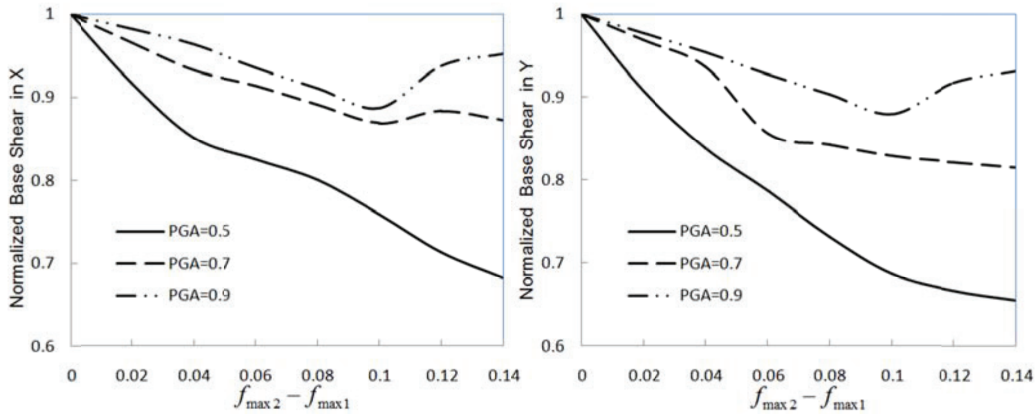

Figure 8: The maximum base shear in x and y directions

7. Conclusions

The results of this study are summarized as follows:

1. A change in DCFP bearing behavior from bi-linear to tri-linear generally results in an increase in the bearing displacements, but a decrease in the base shear.
2. The base shear forces of isolated structures resting on tri-linear DCFP system are found to be consistently smaller than bi-linear DCFP one, particularly for low amplitude of ground motion and significant values of the base isolation period. The maximum decrease of the response recorded in this study is 48% related to the base shear.
3. The bearing displacements of the tri-linear DCFPs are larger than those of the bi-linear ones especially for the weak earthquakes and upper values of the base isolation period. The additional deformations reach to 57% in upper values of the isolation period and under weak earthquake excitations.

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