# DESIGN OF SEISMIC CABLE HINGE RESTRAINERS FOR BRIDGES

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**ABSTRACT:** The collapse of bridges due to unseating at intermediate (in-span) hinges during recent earthquakes emphasizes the need to provide an adequate number of restrainers to limit the relative displacement between frames in a bridge with inadequate hinge seat width. Current restrainer design procedures do not account for the factors affecting the earthquake response of multiple-frame bridges. A parameter study indicates that maximum hinge displacement is a function of the frame period ratio, frame ductility, and the characteristics of the ground motion. A new design procedure for hinge restrainers, based on a linearized model, is developed. The procedure accounts for the dynamic characteristics out-of-phase motion of adjacent bridge frames. Inelastic behavior of frames is accounted for by using the substitute structure method. Parameter studies and case studies using over 26 different ground motion records show that the new procedure limits and the relative hinge displacement to a designer-specified value for a wide range of bridges.

## INTRODUCTION

Long bridges are often constructed as multiple frames in the longitudinal direction. The frames are usually separated by intermediate hinges in the superstructure. During an earthquake, adjacent frames can vibrate out-of-phase, producing a relative displacement at the hinge, as illustrated in Fig. 1. If the displacement between the frames exceeds the support provided by the hinge seat, the supported span will collapse. The 1971 San Fernando earthquake showed that bridges are vulnerable to hinge unseating (Jennings 1971). To address the problem in California, the Department of Transportation (Caltrans) initiated a retrofit program that included linking frames with cable restrainers at the intermediate hinges. In subsequent earthquakes, hinge restrainers generally prevented bridge spans from unseating. However, the 1989 Loma Prieta earthquake caused several cases of hinge restrainer failures (Saiidi et al. 1993). During the 1994 Northridge earthquake several bridges that had been retrofitted with cable restrainers collapsed due to unseating (Moehle 1995), notably the Gavin Canyon bridge. In the 1995 Kobe earthquake, over 60% of the bridges in the Kobe area were damaged (Comartin et al. 1995), and a major problem was excessive movement at the hinges due to bearing and restrainer failure.

A widely used design procedure for hinge restrainers in the equivalent static procedure (*Bridge* 1990). The procedure uses response spectrum analyses of the frames on each side of the hinge assuming they respond to the earthquake independently. Restrainers are provided until the stiffest frame has a displacement less than the allowable hinge seat width, assuming the restrainers are rigidly anchored at the far end. The restrainers are typically proportioned to remain elastic at the allowable hinge displacement to avoid progressive yielding and residual deformation. Trochalakis et al. (1997) proposed a modification to the equivalent static procedure. Using the independent frame displacements without restrainers, the maximum hinge displacement is estimated from the following expression for the maximum hinge opening:

$$D_{eq} = \frac{D_{avg}}{2}\frac{T_L}{T_S} \leq 2D_{avg} \quad (1)$$

where $D_{avg}$ = average independent frame displacement; and $T_L$ and $T_S$ = longer and shorter periods of the uncoupled frames, respectively. Eq. (1) is based on regression analysis of a large number of cases, and it is an improvement over the equivalent static procedure (*Bridge* 1990). The Trochalakis et al. (1997) procedure is based on analysis of bridges with ductile frames, but the level of inelastic deformation is not explicitly included.

The American Association of State Highway and Transportation Officials (AASHTO) specification requires a positive horizontal linkage between adjacent frames of the superstructure (*Standard* 1992). The required linkage force is equal to the design acceleration coefficient multiplied by the weight of the lighter of the two adjoining spans. Similarly, the Japanese specifications require a horizontal restrainer force between frames equal to twice the vertical reaction at the hinge multiplied by the design acceleration coefficient (Takahashi 1990). Neither the AASHTO nor the Japanese procedures consider the relative displacement between frames or the vibration period of the frames, which are the controlling factors in determining the maximum hinge opening (DesRoches and Fenves 1997b).

Several studies have investigated the performance, design,

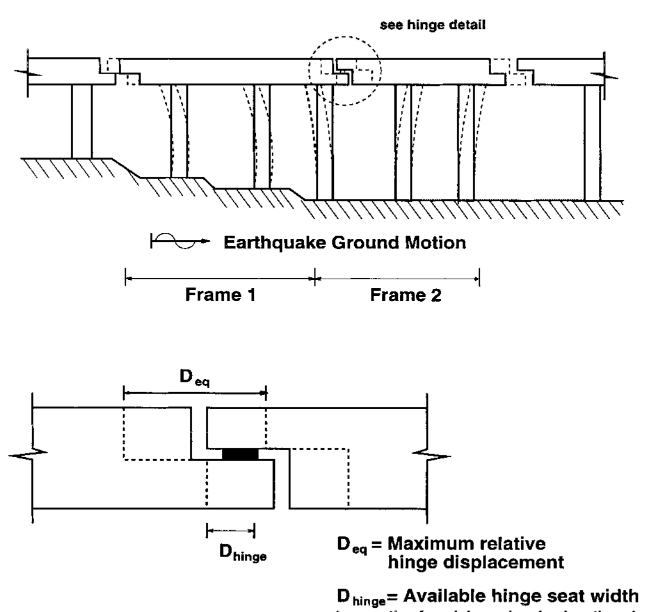


**FIG. 1. Multiple-Frame Bridge with Intermediate Hinges**

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and analysis of multiple-frame bridges with restrainers. Saiidi et al. (1993) studied the performance of four bridges with cable strainers during the 1989 Loma Prieta earthquake. The study concluded that the effectiveness of restrainers depends on many factors including the amplitude and frequency of the ground motion, foundation flexibility, and flexibility of the substructure. Because the study indicated a sensitivity of the hinge displacement to vibration properties and ground motion characteristics, it was concluded that nonlinear time history analysis is necessary to determine the number of restrainers to limit hinge displacement. Another study showed that nonlinear time history analysis can accurately capture the response of intermediate hinges and the effects of restrainers (DesRoches and Fenves 1997b). A parameter study on the effect of hinge restrainers on the earthquake response of multiple-frame bridges (Saiidi et al. 1996) suggested a range of restrainer slack that should be considered in the design because the maximum hinge displacement may be sensitive to the slack.

Using a two-degree-of-freedom (2-DOF) model to represent the longitudinal earthquake response of two frames, Yang et al. (1994) showed that the equivalent static procedure (*Bridge* 1990) underestimates the hinge displacement for frames with large stiffness ratios. However, for frames with stiffness ratios approaching unity, the procedure is very conservative because it does not represent the in-phase motion of the frames. The study showed that the effectiveness of restrainers in limiting hinge displacement depends on the frame stiffness ratio. At low frame stiffness ratios, the restrainers have a significant influence on the hinge displacement, particularly when the restrainer stiffness is equal to or greater than the stiffness of the more flexible frame. The study also found that decreasing the yield strength of frames resulted in smaller hinge displacements. Trochalakis et al. (1997) performed a parameter study similar to Yang (1994). The study found that the abutment stiffness, restrainer gap, Coulomb friction of the bearing, and frame weight had a small effect on the hinge displacement. To quantify hinge displacements, Kawashima and Sato (1996) developed a relative displacement response spectrum using a 2-DOF model. The relative displacement was found to depend on earthquake magnitude, epicentral distance, and site classification.

With this background, the goal of this paper is to examine the factors affecting the response of intermediate hinges in multiple-frame bridges subjected to longitudinal earthquake ground motion. A new design procedure for hinge restrainers is developed to account for the characteristics of the bridge and ground motion. Parameter studies and case studies are performed to validate the new design procedure. Finally, the new restrainer design procedure is compared with current procedures to evaluate its effectiveness in limiting the hinge displacement to a specified value.

## BASIS FOR HINGE RESTRAINER DESIGN PROCEDURE

The response of a multiple-frame bridge is nonlinear because of opening and closing of the hinges, tension-only restrainers, and friction induced by large displacements at the hinge seat. During an earthquake the condition of an intermediate hinge alternates between the closed and open positions. In the closed position, adjacent frames vibrate together, whereas in the open position the frames vibrate independently if the restrainers have not engaged. The new design procedure is based on a simplified model representing each frame as a single DOF system linked by a linear spring, as illustrated in Fig. 2. The tension-only stiffness of the restrainers is linearized using the restrainer stiffness $K_r$. The effect of impact at the hinge is not presented in the linearized design model because in the majority of cases the hinge opening is primarily affected by the restrainers in tension.

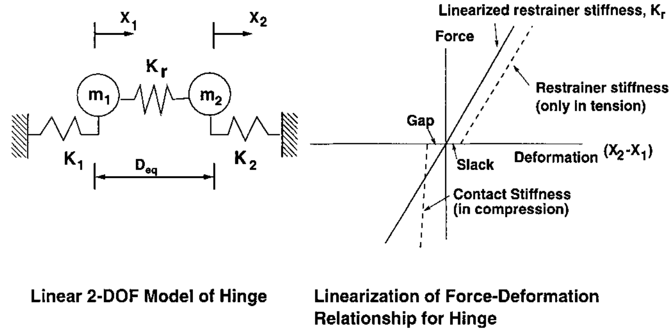


**FIG. 2. Linear Model for Longitudinal Earthquake Response of Adjacent Bridge Frames**

The linearized restrainer design procedure is based on the behavior of two frames. However, all of the frames of a bridge may have an effect on the hinge response because of different combinations of open and closed hinges. To account for this interaction, frame combinations on either side of the hinge should be considered. For example, in a four-frame bridge with three intermediate hinges, the design of restrainers for the middle hinge should consider combinations of frames 1 and 2 and frames 3 and 4. The combination, which leads to the maximum number of restrainers, is used to proportion restrainers for the middle hinge. A previous study showed that these bounding models adequately account for the effects of interacting frames (DesRoches and Fenves 1997a). To simplify the model for the design procedure further, abutments are not included because abutments for a long, multiple-frame bridge have little effect on the relative hinge displacements (Trochalakis et al. 1997). If the fame adjacent to the abutment is stiffer than other frames, the hinge response is not significantly affected by the abutments.

Using the linearized model, the restrainer design procedure has two parts: (1) Estimate the maximum displacement between the frames $D_{eq}$; and (2) select the restrainer stiffness $K_r$ required to limit the hinge displacement of the specified target $D_r$. The maximum relative displacement is obtained from the modal analysis of the 2-DOF linearized system. The restrainer stiffness is calculated from a sensitivity analysis of the linearized model. The procedure iterates until the restrainer stiffness and hinge displacement are consistent.

## Modal Analysis

The linearized equations of motion for the linear 2-DOF system shown in Fig. 2 are as follows:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = -\mathbf{M}\mathbf{1}\ddot{u}_g(t) \quad (2)$$

where **M**, **C**, and **K** = mass, damping, and linearized stiffness matrices for the two frames, respectively. The hinge displacement $D_{eq} = x_2 - x_1$ is obtained from a response spectrum analysis and the complete quadratic combination (CQC) rule (Der Kiureghian 1980). Studies of pounding of adjacent buildings show that the CQC rule provides a good estimate of the relative displacement between buildings (Kasai et al. 1996; Penzien 1997). The CQC rule is expressed as follows:

$$D_{eq} = \sqrt{D_1^2 + D_2^2 + 2\rho_{12}D_1D_2} \quad (3)$$

where $D_1$ and $D_2$ = hinge displacements in modes 1 and 2, respectively. The cross-correlation coefficients $\rho_{12}$ for the modal responses are (Der Kiureghian 1980)

$$\rho_{12} = \frac{8\sqrt{\xi_1\xi_2}(\xi_1 + \beta\xi_2)\beta^{3/2}}{(1 - \beta^2)^2 + 4\xi_1\xi_2\beta(1 + \beta^2) + 4(\xi_1^2 + \xi_2^2)\beta^2} \quad (4)$$

where $\xi_1$ and $\xi_2$ = modal damping ratios; and $\beta$ = ratio of modal frequencies $\omega_1/\omega_2$ or periods $T_2/T_1$. The hinge displacement $D_i$ in mode $i$ is

$$D_i = P_i S_{a_i}(T_i, \xi_i) \tag{5}$$

where $S_{a_i}(T_i, \xi_i)$ = pseudoacceleration response ordinate for period $T_i = 2\pi/\omega_i$ and damping ratio $\xi_i$. The participation factor for the hinge displacement is

$$P_i = \frac{\mathbf{\Phi}_i^T \mathbf{M1}}{\mathbf{\Phi}_i^T \mathbf{K} \mathbf{\Phi}_i} (\mathbf{a}^T \mathbf{\Phi}_i) \tag{6}$$

where $\mathbf{\Phi}_i$ = mode shape; and $\mathbf{a}^T = [-1 \;\; 1]$. The vibration frequencies and mode shapes are the solutions of the eigenvalue problem

$$\mathbf{K\Phi}_i = \Omega_i^2 \mathbf{M\Phi}_i \tag{7}$$

## Required Restrainer Stiffness

With the estimate of the hinge displacement $D_{eq}$ from (3), the strainer stiffness needed to limit the hinge displacement to $D_r$ is determined from a sensitivity analysis. For the linearized model subjected to the effective modal earthquake load $\mathbf{P}_i$, the displacements in mode $i$ are given by $\mathbf{Kx}_i = \mathbf{P}_i$. Taking the partial derivative with respect to the restrainer stiffness $K_r$ gives

$$\frac{\partial \mathbf{K}}{\partial K_r} \mathbf{x}_i + \mathbf{K} \frac{\partial \mathbf{x}_i}{\partial K_r} = 0 \tag{8}$$

where it is assumed that the change in effective earthquake load in mode $i$, with respect to the change in the restrainer stiffness, is zero. In reality the effective earthquake load does depend on $K_r$, but the change in earthquake load is accommodated by iterations in the design procedure. Expanding (8) for the 2-DOF model results in

$$\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix}_i + \begin{bmatrix} K_1 + K_r & -K_r \\ -K_r & K_2 + K_r \end{bmatrix} \begin{Bmatrix} \dfrac{\partial x_1}{\partial K_r} \\ \dfrac{\partial x_2}{\partial K_r} \end{Bmatrix}_i = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{9}$$

where $x_{1_i}$ and $x_{2_i}$ = peak displacements of frames 1 and 2 in mode $i$, respectively. Defining the modal hinge displacement as $D_i = x_{2_i} - x_{1_i}$ and solving for $\partial D_i/\partial K_r$ gives the sensitivity of the hinge displacement to the restrainer stiffness for mode $i$

$$\frac{\partial D_i}{\partial K_r} = -\frac{1}{K_m + K_r} D_i \tag{10}$$

The flexibility coefficient $1/K_m = 1/K_1 + 1/K_2$ is the sum of the flexibilities of the two frames, and it is equal to the hinge displacement due to self-equilibrating unit loads at the hinge. The hinge displacement in (10) is for a single mode $i$, but it can be shown that the CQC combination of the sensitivity of the individual modes leads to the same result as performing the sensitivity analysis on the combined hinge displacement $D_{eq}$. In the following presentation, therefore, $D_{eq}$ is the combined hinge displacement.

A Taylor series expansion about the hinge displacement in iteration $j$, $D_{eq_j}$ gives the hinge displacement $D_{eq_{j+1}}$, due to a change in the restrainer stiffness from $K_{r_j}$ to $K_{r_{j+1}}$

$$D_{eq_{j+1}} = D_{eq_j} + \left. \frac{\partial D_{eq}}{\partial K_r} \right|_{D_{eq_j}} (K_{r_{j+1}} - K_{r_j}) \tag{11}$$

Eq. (11) can be used to iterate on the restrainer stiffness $K_r$ required to limit the hinge displacement to $D_r$. Setting $D_{eq_{j+1}}$ at each step to $D_r$, substituting (10) into (11), and solving for $K_{r_{j+1}}$ gives the next estimate for the restrainer stiffness

$$K_{r_{j+1}} = K_{r_j} + (K_m + K_{r_j}) \frac{(D_{eq_j} - D_r)}{D_{eq_j}} \tag{12}$$

as a function of the current restrainer stiffness $K_{r_j}$, hinge opening $D_{eq_j}$, and the target $D_r$. Eq. (12) gives an iterative procedure that converges to a $K_r$ for $D_{eq} = D_r$.

There are important similarities between the new procedure and the equivalent static procedure (*Bridge* 1990). In the latter procedure the restrainer stiffness is determined by the stiffest frame

$$K_r D_r = \max(K_1, K_2)(D_{eq_0} - D_r) \tag{13}$$

The right-hand side of (13) is the force required to move the stiffest frame from the unrestrained displacement $D_{eq_0}$ to the target displacement $D_r$. The restrainer stiffness $K_r$ is based on developing an equal force over a restrainer extension of $D_r$. Considering the new procedure, evaluation of (12) for the first iteration ($j = 0$) gives

$$K_r D_{eq_0} = K_m(D_{eq_0} - D_r) \tag{14}$$

The right-hand side of (14) is the self-equilibrating restrainer force required to displace the two frames an amount $D_{eq_0} - D_r$. Because $K_m \leq \max(K_1, K_2)$, the restrainer force is always less than that given by (13). The restrainer stiffness $K_r$ in (14) is based on the restrainer force acting through the displacement $D_{eq_0}$ of the hinge, as a consequence of the sensitivity analysis. Subsequent iterations give increasing $K_r$ until $D_{eq} \leq D_r$. The convergence rate of the procedure depends on the properties of the bridge and the shape of the response spectrum.

## Linearization for Ductile Frames

Ductile bridge frames are expected to undergo inelastic deformation during a major earthquake. The nonlinearity of the frames is accounted for in the restrainer design procedure by using equivalent stiffnesses and damping ratios based on the maximum displacement of the frames (Gulkan and Sozen 1974). The effective stiffness and effective damping are selected such that the displacement of the inelastic frame is equal to that of the substitute structure model. The two parameters for the substitute structure method are the effective stiffness $K_{eff}$ and effective damping $\xi_{eff}$. For idealized elastic-perfectly plastic hysteresis, the effective stiffness decreases linearly with increasing displacement ductility $\mu$ of the frame. Various relationships of effective damping versus ductility factor have been developed. The relationship based on the Takeda stiffness degrading model is used in the restrainer design procedure (MacRae et al. 1994)

$$K_{eff} = \frac{1}{\mu} K \tag{15}$$

$$\xi_{eff} = \xi + \frac{1 - \dfrac{0.95}{\sqrt{\mu}} - 0.05\sqrt{\mu}}{\pi} \tag{16}$$

# NEW RESTRAINER DESIGN PROCEDURE

An iterative design procedure is based on the theory presented in the previous section. The objective is to provide sufficient restrainers to limit the displacement of the intermediate hinge between two frames to the available hinge seat $D_{\text{hinge}}$. The mass, stiffness, design ductility of the frames, and the restrainer properties are required for the procedure. The restrainer slack $D_s$ is estimated from the initial slack and a range of ambient temperatures. The earthquake characteristics are represented by a pseudoacceleration response spectrum $S_a(T, \xi)$. Given this information, the design procedure for intermediate hinge restrainers process in the following six steps.

## Step 1: Maximum Hinge Displacement

The designer selects a maximum allowable hinge displacement $D_r$ based on the available hinge seat and the minimum bearing length and initial gap. The target yield displacement of the restrainers is the difference between the maximum allowable hinge displacement and the restrainer slack according to $D_y = D_r - D_s$, where $D_y$ is the restrainer elongation at yield and $D_s$ is the restrainer slack. To achieve the yield displacement, the length of the restrainer cable is $L = D_y E/F_y$.

## Step 2: Initial Hinge Displacement

The initial hinge displacement is obtained from (3)

$$D_{eq_0} = \sqrt{D_{1_0}^2 + D_{2_0}^2 - 2\rho_{12} D_{1_0} D_{2_0}}$$

where $D_{1_0}$ and $D_{2_0}$ = individual frame displacements. Given the effective period and damping of the frames, the displacements are obtained from the acceleration response spectrum.

If $D_{eq_0} \le D_r$, restrainers are not needed to limit hinge displacement, but a minimum number of restrainers should be provided. If $D_{eq_0} > D_r$, restrainers must be provided according to the iterations in the subsequent steps.

## Step 3: Initial Restrainer Stiffness

The restrainer stiffness is estimated from (1) for the first iteration ($j = 0$)

$$K_{r_1} = \frac{K_{m_{eff}}(D_{eq_0} - D_r)}{D_{eq_0}}$$

where the effective stiffness is given by the effective stiffness of the individual frames

$$K_{m_{eff}} = \frac{K_{eff_1} K_{eff_2}}{(K_{eff_1} + K_{eff_2})} \qquad (17)$$

## Step 4: Hinge Displacement

The hinge displacement is determined from a 2-DOF modal analysis of the frames with the current restrainer stiffness. The hinge displacement is given by (3)

$$D_{eq_j} = \sqrt{D_1^2 + D_2^2 + 2\rho_{12} D_1 D_2}$$

where $D_1$ and $D_2$ = hinge displacements in the two modes. If $D_{eq_j} \le D_r$, go to Step 6 and calculate the required number of restrainers based on the last value of $K_r$. Otherwise continue with Step 5.

## Step 5: Restrainer Stiffness

The modified restrainer stiffness is given by (12)

$$K_{r_{j+1}} = K_{r_j} + (K_{m_{eff}} + K_{r_j}) \frac{(D_{eq_j} - D_r)}{D_{eq_j}} \qquad (18)$$

Increment $j$ and go to Step 4.

## Step 6: Number of Restrainers

As with the equivalent static procedure (*Bridge* 1990), the number of restrainers is based on the linearized stiffness $K_r$ over the hinge displacement $D_r = D_y + D_s$. Consequently, the desired restrainer force is $K_r D_r$, and the number of restrainers is given by

$$N_r = \frac{K_r D_r}{F_y A_r} \qquad (19)$$

## Minimum Restrainer Stiffness

For cases in which the procedure indicates few or no restrainers, a minimum restrainer stiffness should be provided because of the many assumptions and uncertainties in the frame properties and ground motion. A recommended minimum restrainer stiffness of $K_r = 0.50K_{m_{eff}}$ is based on an extensive parameter study (DesRoches and Fenves 1997b).

## Example of New Restrainer Design Procedure

The new procedure is applied to two frames of a typical bridge with a hinge seat width of 200 mm. The frames are supported by multiple column bents with longitudinal stiffnesses of 357 and 89.3 kN/mm for frames 1 and 2, respectively, based on cracked section properties. The 1.5-m square columns vary in height from 10 to 15 m. The number of columns in frames 1 and 2 are 9 and 6, respectively. Both frames weigh 22.3 MN, and a 5% viscous damping ratio is assumed. The frames are designed for a displacement ductility $\mu$ of 4. The bridge is sited on firm soil, and the flexibility of the footings is assumed to be small. The bridge is subjected to the 1940 El Centro S00E record, scaled to a peak ground acceleration of $0.70g$.

### *Step 1: Maximum Hinge Displacement*

With a hinge seat width of 200 mm, assume 80 mm is minimum required for bearing; therefore, an allowable hinge displacement of $D_r = 200 - 80 = 120$ mm is determined. The nominal restrainer slack is 12.7 mm. The yield displacement for the restrainer is

$$D_y = 120 - 12.7 = 107 \text{ mm}$$

### *Step 2: Initial Hinge Displacement*

$$K_{eff_1} = 357/4 = 89.3 \text{ kN/mm}$$

$$K_{eff_2} = 89.3/4 = 22.4 \text{ kN/mm}$$

$$T_{eff_1} = 2\pi\sqrt{22.3/(9.81)/22.4} = 2.0 \text{ s}$$

$$T_{eff_2} = 2\pi\sqrt{22.3/(9.81)/89.3} = 1.0 \text{ s}$$

$$\xi_{eff} = 0.05 + (1 - 0.95/\sqrt{4} - 0.05\sqrt{4})/\pi = 0.19$$

$$\rho_{12} = \frac{8(0.19)^2(1 + 0.5)2^{3/2}}{(1 - 0.5^2)^2 + 4(0.19)^2(0.5)(1 + 0.5)^2} = 0.21$$

$$D_{1_0} = \left(\frac{2.0}{2\pi}\right)^2 S_a(2.0, 0.19) = 247 \text{ mm}$$

$$D_{2_0} = \left(\frac{1.0}{2\pi}\right)^2 S_a(1.0, 0.19) = 121 \text{ mm}$$

$$D_{eq_0} = \sqrt{(247)^2 + (121)^2 - (0.21)(247)(121)} = 251 \text{ mm}$$

Because 251 mm > 120 mm, restrainers are required.

### *Step 3: Initial Restrainer Stiffness*

$$K_{m_{eff}} = (89.3)(22.4)/(89.3 + 22.4) = 17.9 \text{ kN/mm}$$

$$K_{r_1} = (17.9)(251 - 120)/251 = 9.36 \text{ kN/mm}$$

### *Step 4: Hinge Displacement*

Solve eigenvalue problem for the vibration modes

$$\begin{bmatrix} 98.7 & -9.36 \\ -9.36 & 31.9 \end{bmatrix} \mathbf{\Phi}_i = \omega_{eff_i}^2 \begin{bmatrix} 2.27 & 0 \\ 0 & 2.27 \end{bmatrix} \mathbf{\Phi}_i$$

$$\omega_{eff_1} = \sqrt{13.4}\ 1/\text{s}; \quad \omega_{eff_2} = \sqrt{44.2}\ 1/\text{s}$$

$$T_{eff_1} = 2\pi/\sqrt{13.4} = 1.71\ \text{s}; \quad T_{eff_2} = 2\pi/\sqrt{44.2} = 0.95\ \text{s}$$

$$\mathbf{\Phi}_1 = \begin{Bmatrix} 0.13 \\ 1.00 \end{Bmatrix}; \quad \mathbf{\Phi}_2 = \begin{Bmatrix} 1.00 \\ -0.13 \end{Bmatrix}$$

Calculate participation factors

$$P_1 = \frac{\{0.13 \quad 1.00\} \begin{bmatrix} 2.27 & 0 \\ 0 & 2.27 \end{bmatrix} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}}{\{0.13 \quad 1.00\} \begin{bmatrix} 98.7 & -9.36 \\ -9.36 & 31.9 \end{bmatrix} \begin{Bmatrix} 0.13 \\ 1.00 \end{Bmatrix}} \cdot \left( \{-1 \quad 1\} \begin{Bmatrix} 0.13 \\ 1.00 \end{Bmatrix} \right) = 0.072\ \text{s}^2$$

similarly, $P_2 = -0.022\ \text{s}^2$.

Calculate hinge displacement by using the response spectrum for the scaled El Centro earthquake

$$S_{a_1} = 2{,}400\ \text{mm/s}^2; \quad S_{a_2} = 5{,}180\ \text{mm/s}^2$$

$$D_1 = (0.072)(2{,}440) = 176\ \text{mm}$$

$$D_2 = (-0.022)(5{,}180) = -114\ \text{mm}$$

$$\beta = 0.95/1.71 = 0.56$$

$$\rho_{12} = \frac{8(0.19)^2(1 + 0.56)0.56^{3/2}}{(1 - 0.56)^2 + 4(0.19)^2(0.56)(1 + 0.56)^2} = 0.27$$

$$D_{eq} = \sqrt{(176)^2 + (-114)^2 + 2(0.27)(176)(-114)} = 182\ \text{mm}$$

Because $D_{eq} > D_r$, proceed to Step 5.

*Step 5: Restrainer Stiffness*

$$K_{r_1} = 9.36 + (17.9 + 9.36)(182 - 120)/182 = 18.7\ \text{kN/mm}$$

Repeat Steps 4 and 5 until $D_{eq} < D_r$. Table 1 summarizes the important values for the iterations. After four iterations, $K_r$ = 27.0 kN/mm, $D_{eq}$ = 120 mm.

*Step 6: Number of Restrainers*

$$N_r = (27.0 \cdot 120)/(1.21 \cdot 143) = 19$$

where standard cables have a yield stress $F_y$ = 1.21 kN/mm$^2$ and cross-sectional area $A_r$ = 143 mm$^2$.

The design procedure gives 19 restrainer cables. From Step 1, the restrainer yield displacement is 107 mm, giving a cable length of 6.10 m. The restrainer units typically have 5 cables; therefore, four sets (20 restrainer cables) would be used. For this example, the minimum restrainer stiffness, based on $K_r = 0.50K_{m_{eff}}$, is approximately 9 kN/mm (6 restrainer cables). If a 100-mm bearing length is considered, $D_r$ = 100 mm, and the required stiffness to limit the hinge displacement to 87.3 mm would be $K_r$ = 35.4 kN/mm, or $N_r$ = 21 restrainers.

## EVALUATION OF RESTRAINER DESIGN PROCEDURE

In this section, the new restrainer design procedure is evaluated for a wide range of parameters representing typical bridge frames. The important factors affecting the hinge response in multiple-frame bridges are the frame period ratio $T_1/T_2$, target displacement ductility $\mu$ for the frame, and the frequency content of the ground motion, represented by the ratio of the frame 2 period $T_2$ to the characteristic period of the ground motion $T_g$. The frame strength for the displacement ductility is determined from a constant ductility response spectrum for each independent frame. Using the new procedure, the restrainer stiffness required to limit hinge displacement to $D_r$, chosen to be a fraction of the initial hinge displacement $D_{eq_0}$ is computed. The nondimensional parameter $D_r/D_{eq_0}$ partially accounts for the effect of the amplitude of ground motion. For a fixed $D_r$, an increasing amplitude of ground motion requires more restrainers as the ratio $D_r/D_{eq_0}$ decreases.

To evaluate the effectiveness of the procedure, the restrainer stiffness given by the new procedure is used in a nonlinear time history analysis of the two frames to determine the maximum hinge displacement. The accuracy of the new procedure is presented in terms of a normalized hinge displacement, which is the ratio of the maximum hinge displacement from the nonlinear analysis to the target displacement. A normalized displacement less than unity indicates that the design procedure provides sufficient restrainers to limit displacement, whereas a normalized displacement greater than unity indicates that the design procedure underestimates the restrainer stiffness.

The model for the nonlinear analysis consists of two single DOF systems, each representing the longitudinal response of a bridge fame. As illustrated in Fig. 3 the frames are modeled by the Q-hyst stiffness degrading hysteretic relationship (Saiidi and Sozen 1979). The restrainers are modeled as bilinear springs in tension, as shown in Fig. 3(b). Friction is represented by an elastoplastic spring whose yield force of 445 kN represents the frictional force developed across the hinge. Because the friction force is typically small compared with the force in frames and restrainers, the approximate model for friction is adequate for assessing the efficacy of the restrainer design procedure (Yang et al. 1994; DesRoches and Fenves 1997b).

The equations of motion are solved numerically using Newmark's constant acceleration method (Clough and Penzien 1993). The contact condition is checked at the end of each time step. If contact occurs, the velocities are modified based on conservation of momentum and restriction of impacting masses with a coefficient of restitution $e$ = 0.80.

### Evaluation of Restrainer Design for One Ground Motion

The restrainer design procedure is first evaluated for the 1940 El Centro earthquake, scaled to a peak ground acceler-

**TABLE 1. Results of Iterations for Restrainer Design Procedure Applied to Two-Frame Bridge**

| Iteration (1) | Restrainer stiffness $K_r$ (kN/mm) (2) | Modal Periods | | Participation Factors | | Modal Hinge Displacements | | Combined hinge displacements $D_{eq}$ (mm) (9) |
|---|---|---|---|---|---|---|---|---|
| | | $T_{eff_1}$ (s) (3) | $T_{eff_2}$ (s) (4) | $P_1$ (s$^2$) (5) | $P_2$ (s$^2$) (6) | $D_1$ (mm) (7) | $D_2$ (mm) (8) | |
| 0 | 0 | 2.0 | 1.0 | 0.100[a] | −0.025[a] | 247 | 121 | 251 |
| 1 | 9.36 | 1.71 | 0.95 | 0.072 | −0.022 | 176 | −114 | 182 |
| 2 | 18.7 | 1.57 | 0.88 | 0.055 | −0.018 | 136 | −99.6 | 145 |
| 3 | 25.2 | 1.51 | 0.85 | 0.047 | −0.015 | 117 | −86.9 | 124 |
| 4 | 27.0 | 1.50 | 0.85 | 0.045 | −0.014 | 112 | −82.0 | 120 |

[a]Participation factors not needed in iteration 0.

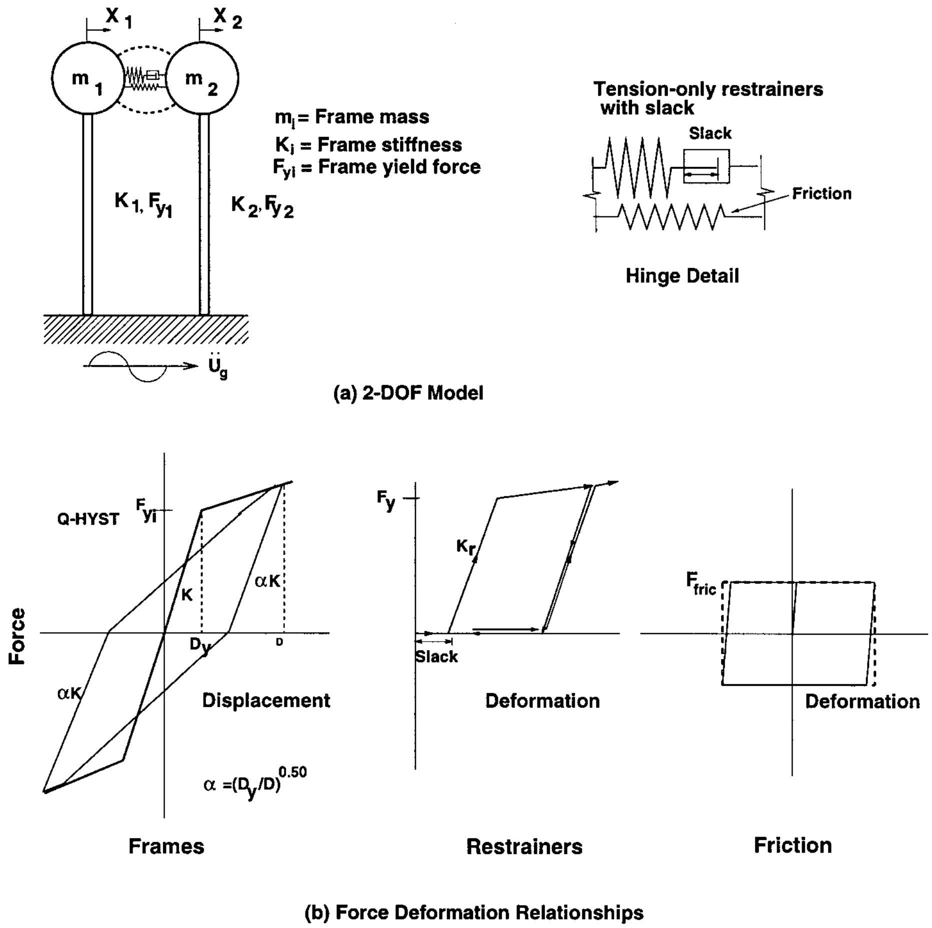


FIG. 3. Nonlinear Model for Longitudinal Earthquake Response of Adjacent Bridge Frames

ation of 0.70$g$ and applied in both longitudinal directions to account for polarity in the nonlinear response. The period of one frame is 1 s, equal to the characteristic period $T_g$ of the ground motion. The specified hinge displacement is set to $D_r/D_{eq_0}$ = 0.50, for which $D_r$ is 120–140 mm for the periods considered. The required restrainer stiffness for the range of the period ratio and displacement ductility is shown in Fig. 4. The restrainer stiffness varies from 175 kN/mm for out-of-phase elastic frames ($T_1/T_2$ = 0.30) to <8.75 kN/mm for ductile frames with $T_1/T_2 > 0.70$. An increase in the displacement ductility $\mu$ from 1 to 4 reduces the required restrainer stiffness by approximately 75% for the entire range of frame period ratios. As the displacement ductility increases, the restrainer stiffness reduces because (1) the effective stiffness of the frames decreases; and (2) a decrease of out-of-phase response from increased hysteretic energy dissipation.

The normalized displacement ranges from a value of zero to 1.05, as illustrated in Fig. 4. For highly out-of-phase elastic frames ($T_1/T_2 < 0.50$) the procedure is slightly unconservative. Pounding of out-of-phase frames increases the elastic response ($\mu$ = 1), which is not accounted for in the linearized model. For period ratios between 0.70 and 1.0, the procedure gives hinge displacements less than the target. For frames that are nearly in-phase, pounding disrupts the buildup of response and decreases the hinge displacement. In addition, friction has more effect with closely spaced frame periods because the force required to limit hinge displacement is relatively small.

### Evaluation for Several Ground Motion Records

The effectiveness of the design procedure is next evaluated for 26 earthquake ground motions. The ground motions listed in Table 2 represent a wide range of characteristic periods, peak ground accelerations, peak ground velocities, epicentral distances, and durations. Fig. 5 shows the normalized displacement for $D_r/D_{eq_0}$ = 0.50, and $T_2/T_g$ = 1.0. The procedure is effective in providing a restrainer stiffness to limit hinge displacement. The largest mean and standard deviation are 1.05 and 0.35, respectively, for the case with $\mu$ = 6, and $T_1/T_2$ = 0.60. As the target displacement ductility increases, the variability between different cases increases. The design procedure is slightly unconservative for a few cases with low period ratios and is conservative for frame period ratios approaching unity. The mean +1 standard deviation of the normalized hinge displacement may be as large as 1.4; hence, it is important to have the target displacement $D_r$ slightly less than the available hinge seat width $D_{\text{hinge}}$. Overall, Fig. 5 shows that the new procedure works well for a range of ground motions and frame properties.

## COMPARISON OF RESTRAINER DESIGN PROCEDURES

This section compares the equivalent static (*Bridge* 1990), AASHTO (*Standard* 1992), and Trochalakis et al. (1997) procedures with the new design procedure. Bridge frames subjected to strong ground motion are designed to yield and deform inelastically. However, to illustrate the effect of yielding frames on restrainers, the equivalent static design procedure is applied to elastic frames ($\mu$ = 1) and yielding frames ($\mu$ = 4). The Trochalakis procedure is not shown for the elastic frame comparison because it is based on ductile frames only. The procedures are compared for frames with a period ratio $T_1/T_2$ ranging from 0.30 to 0.98, with $T_2$ = 1 s and $D_r$ = 120 mm. The earthquake ground motion is the 1940 El Centro earth-

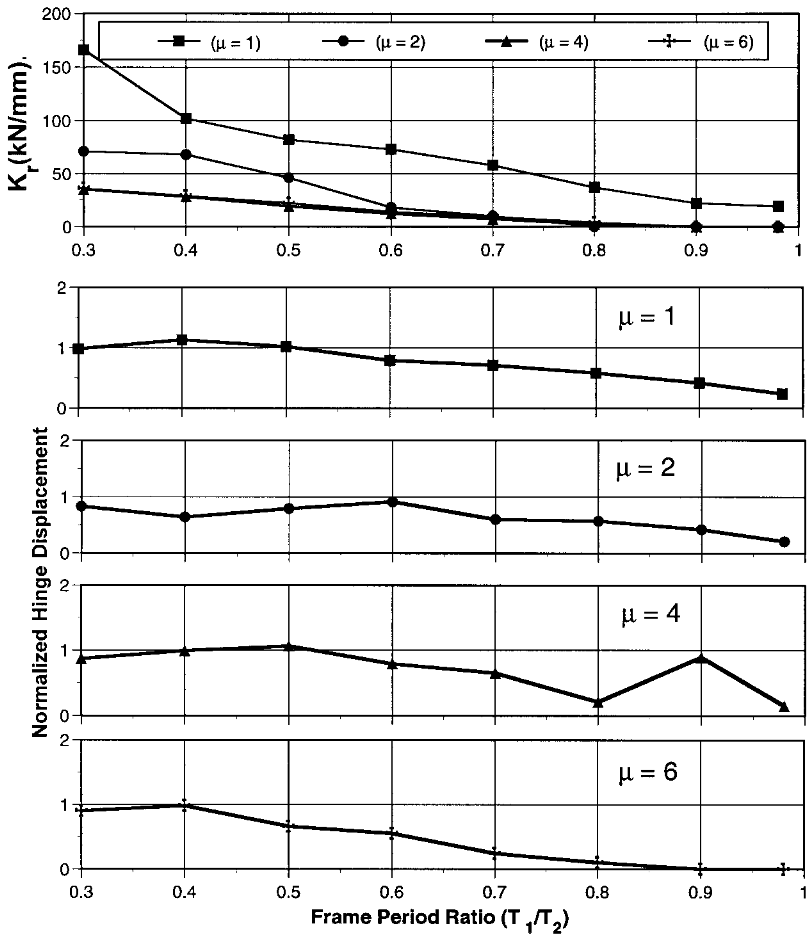


**FIG. 4. Restrainer Stiffness and Normalized Hinge Displacement from Design Procedure for Two-Frame Bridge Subjected to 1940 El Centro Earthquake (S00E Component), Scaled to 0.70*g*, $D_r/D_{eq_0}$ = 0.50, $T_2/T_g$ = 1.0**

**TABLE 2. Free-Field Ground Motions in Major Principal Axis Listed in Decreasing Characteristic Period $T_g$**

| Earthquake record (1) | Location (2) | Mag $M_s$ (3) | EPD[a] (km) (4) | PGA[b] (g) (5) | $T_g$ (s) (6) |
|---|---|---|---|---|---|
| 1992 Cape Mend. | Fortuna | 6.9 | 28 | 0.12 | 2.30 |
| 1992 Landers | Amboy | 7.5 | 74 | 0.15 | 2.29 |
| 1989 Loma Prieta | Saratoga | 7.1 | 28 | 0.47 | 1.79 |
| 1987 Whittier | Alhambra | 6.1 | 7 | 0.25 | 1.84 |
| 1992 Landers | Baker Fire | 7.5 | 122 | 0.11 | 1.70 |
| 1994 Northridge | Sylmar | 6.7 | 15 | 0.90 | 1.60 |
| 1995 Kobe | Osaka | 6.9 | 17 | 0.08 | 1.17 |
| 1995 Kobe | Fukushima | 6.9 | 17 | 0.04 | 1.15 |
| 1971 San Fernando | Pacoima Dam | 7.4 | 8 | 1.36 | 1.13 |
| 1940 Imperial Valley | El Centro | 6.9 | 12 | 0.35 | 1.00 |
| 1994 Northridge | Arleta | 6.8 | 10 | 0.32 | 0.97 |
| 1995 Kobe | Kobe | 6.9 | 5 | 0.85 | 0.87 |
| 1994 Northridge | Pico | 6.8 | 31 | 0.19 | 0.83 |
| 1994 Northridge | Pacific Dam (KC) | 6.8 | 18 | 0.52 | 0.83 |
| 1984 Morgan Hill | Coyote Dam | 6.2 | 24 | 1.12 | 0.79 |
| 1992 Cape Mend. | Petrolia | 6.9 | 5 | 0.70 | 0.70 |
| 1979 El Centro | Bonds Corner | 6.6 | 28 | 0.78 | 0.62 |
| 1989 Loma Prieta | Corralitos | 7.1 | 8 | 0.65 | 0.43 |
| 1980 Mammoth Lk. | HS Gym | 6.5 | 11 | 0.34 | 0.43 |
| 1994 Northridge | LA Obrego Park | 6.7 | 39 | 0.45 | 0.39 |
| 1994 Northridge | Downey County | 6.7 | 47 | 0.25 | 0.38 |
| 1994 Northridge | Tarzana | 6.7 | 5 | 0.65 | 0.33 |
| 1994 Northridge | Inglewood | 6.7 | 42 | 0.26 | 0.30 |
| 1994 Northridge | Pacific Dam (DS) | 6.7 | 17 | 0.50 | 0.27 |
| 1994 Northridge | Mt. Wilson | 6.7 | 45 | 0.26 | 0.24 |
| 1994 Northridge | Lake Hughes | 6.7 | 44 | 0.27 | 0.21 |

[a]Epicentral distance.
[b]Peak ground acceleration.

quake S00E component, scaled to a peak ground acceleration of 0.70g.

Fig. 6(a) shows the restrainer stiffness required to limit hinge displacement assuming the frames remain elastic for the new procedure along with the results from the equivalent static (*Bridge* 1990) procedure. Also shown in the figure is the restrainer stiffness determined from nonlinear time history analysis. The latter shows that restrainer stiffnesses required to limit hinge displacement to 120 mm varies from 271 kN/mm for highly out-of-phase frames to no restrainers for frames with period ratios >0.80. The new procedure underestimates the restrainer stiffness for frame period ratios <0.50 and overestimates the stiffness for frame period ratios >0.50. The equivalent static procedure significantly underestimates the required restrainer stiffness for highly out-of-phase frames, and is conservative for in-phase frames. By using the smallest frame displacement as the hinge displacement, the equivalent static procedure significantly underestimates the hinge displacement. As the frame period ratio approaches unity, the procedure does not account for the reduction in hinge displacement due to the predominate in-phase motion of the frames.

For ductile frames with a target displacement ductility μ of 4, the required restrainer stiffness obtained from nonlinear time history analysis reduces significantly compared with the elastic frames case, as shown in Fig. 6(b). The restrainer stiffness ranges from 50 kN/mm for $T_1/T_2$ = 0.30 to zero for frames with period ratios >0.80. The new procedure gives restrainers that compare favorably with the results from nonlinear time history analysis, and it represents the reduction in the restrainer stiffness due to frame ductility. The equivalent static procedure gives the same restrainer stiffness regardless of the frame duc-

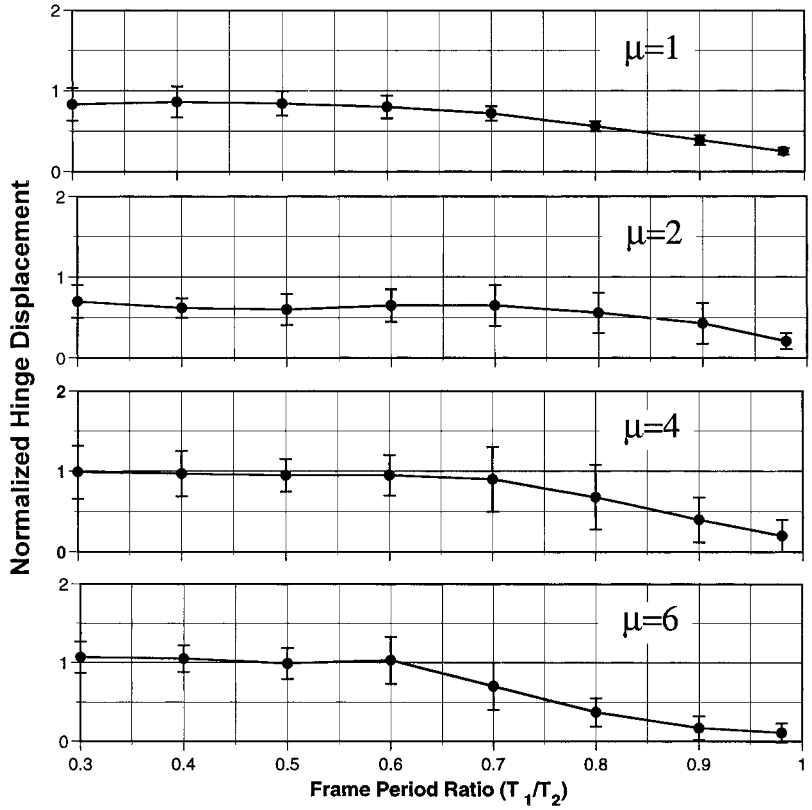


**FIG. 5. Mean and Mean ± 1 Standard Deviation of Normalized Hinge Displacement for Restrainers from Design Procedure for Ground Motions Listed in Table 3, $D_r/D_{eq_0}$ = 0.50, $T_2/T_g$ = 1.0**

tility, amplifying the trends noted in Fig. 6(a) for elastic frames. The AASHTO procedure with 6.10-m-length cable restrainers is quite conservative for the entire range of period ratios, giving restrainer stiffnesses that are nearly three times greater than that required to limit the hinge displacement, as determined by a nonlinear analysis. It is interesting to note that if shorter restrainers were used, the AASHTO procedure would provide a larger restrainer stiffness. The Trochalakis et al. (1997) procedure correctly represents the trend in restrainer stiffness, as does the new procedure, compared with the results from the time history analysis. The Trochalakis et al. procedure generally gives 50–75% more restrainers than the new procedure for the cases considered.

## APPLICATION TO CURVED MULTIPLE-FRAME BRIDGE

As a final example, the new procedure is compared with the AASHTO (*Standard* 1992) and equivalent static (*Bridge* 1990) procedures for a bridge with six frames. The bridge is 774 m long with 16 spans supported by single column bents and diaphragm abutments as shown in Fig. 7. Strong motion data from extensive instrumentation of the bridge in the 1992 Landers and Big Bear earthquakes were used to study the dynamic response and the performance of the intermediate hinge restrainers (DesRoches and Fenves 1997a). For this example the columns are modeled with elastic frame members, and nonlinear compression-only and tension-only elements are used at the intermediate hinges to represent pounding and restrainers. The stiffness of the abutments is included in the model.

The new restrainer design procedure is applied to the bridge subjected to the Landers earthquake, scaled to 0.30*g*. The procedure is applied by rotating the input ground motion into two components at each of the five hinges in the bridge. The ground motion component longitudinal to the hinge is used to design the restrainers. The interaction of frames is accounted for by considering possible hinge conditions (completely open or completely closed) two frames away from the hinge being considered. For example the restrainer design at hinge 7 considers four cases: (1) frame 2 and frame 3 alone; (2) frames 1 and 2 locked and frame 3 alone; (c) frames 3 and 4 locked and frame 2 alone; and (d) frames 1 and 2 locked and frames 3 and 4 locked. The target hinge displacement is 120 mm, and the assumed restrainer slack is 12.7 mm.

As summarized in Table 3 the results of the equivalent static, AASHTO, and new procedure vary greatly. The equivalent static procedure indicates that no restrainers are required. A nonlinear time history analysis of the bridge without restrainers shows that the displacement at hinges H3 and H7 exceed the target displacement by as much as 75 mm. The time history analysis using the restrainer stiffness from the AASHTO procedure shows that the displacements at hinges H3 and H9 are greater than the target displacement, and the displacements at H11 and H13 are significantly less than the target.

The restrainers determined by the new procedure are shown in Table 3. Hinge H3 requires 64 restrainer cables, more than twice the number from the AASHTO procedure. Hinge H7 requires 31 restrainers, which is slightly greater than the number from the AASHTO procedure. Hinge H11 requires a small number of restrainers (8), and hinges H9 and H13 do not require restrainers. When the stiffness of these restrainers is included in a time history analysis of the bridge, the hinge displacements do not exceed the target of 120 mm, as shown in the last column of Table 3. The new procedure provides a large number of restrainers in hinges where the frames are highly out-of-phase (H3 and H7), and few or no restrainers where the frames are more in-phase (H9, H11, and H13). Although the new design procedure is applied without consideration of the abutments, the time history analyses show that the assumption is valid for this case. The end frames in this bridge are very

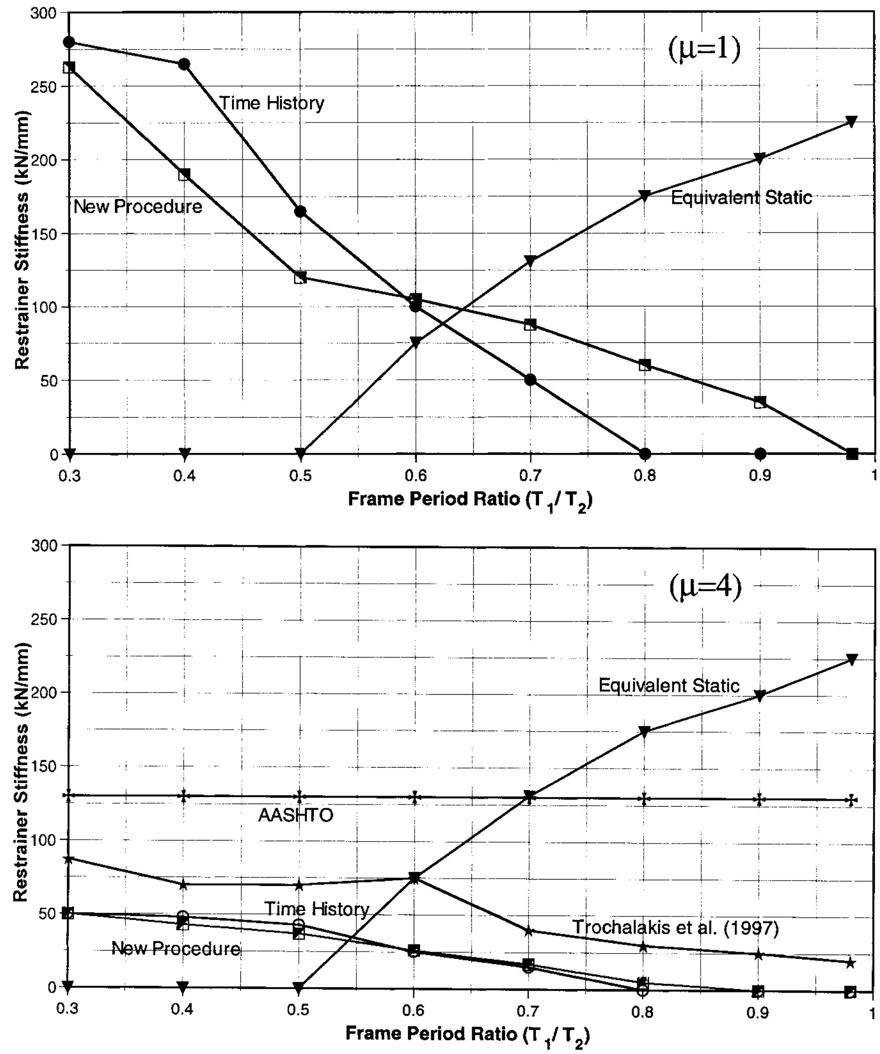


**FIG. 6. Comparison of Required Restrainer Stiffness Determined by Restrainer Design Procedures for Two-Frame Bridge Subjected to 1940 El Centro Earthquake (S00E Component), Scaled to 0.70*g*, $D_r$ = 120 mm: (a) μ = 1; (b) μ = 4**

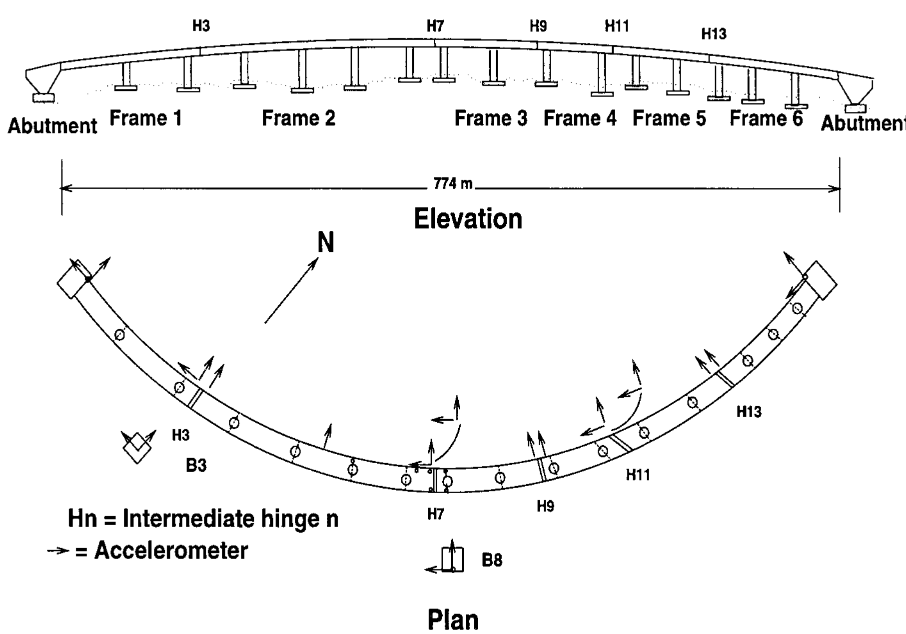


**FIG. 7. General Plan and Strong Motion Instrumentation of Curved Multiple-Frame Bridge (DesRoches and Fenves 1997a)**

**TABLE 3. Comparison of Restrainer Design Procedures for Curved Bridge Subjected to Landers Earthquake, Scaled to Peak Ground Acceleration = 0.30*g*, $D_r$ = 120 mm**

| Hinge (1) | Caltrans Procedure $K_r$ ($N_r$) (kN/mm) (2) | Caltrans Procedure $D_{eq}$ (mm) (3) | AASHTO Procedure $K_r$ ($N_r$) (kN/mm) (4) | AASHTO Procedure $D_{eq}$ (mm) (5) | New Procedure $K_r$ ($N_r$) (kN/mm) (6) | New Procedure $D_{eq}$ (mm) (7) |
|---|---|---|---|---|---|---|
| H3 | 0 (0) | **185** | 40.2 (28) | **162** | 93.3 (64) | 116 |
| H7 | 0 (0) | **195** | 36.6 (25) | 121 | 45.5 (31) | 99.0 |
| H9 | 0 (0) | 15.3 | 31.6 (22) | **134** | 0 (0) | 102 |
| H11 | 0 (0) | 54.9 | 31.6 (22) | 45.7 | 12.3 (8) | 39.6 |
| H13 | 0 (0) | 79.3 | 39.9 (7) | 45.7 | 0 (0) | 64.0 |

Note: Boldface values represent displacements that have exceeded target hinge displacement.

stiff; therefore, the displacement at hinges H3 and H13 are controlled by frame 2 and frame 5, respectively.

## CONCLUSIONS

A new design procedure for restrainers at intermediate hinges of bridges has been developed to limit hinge displacement to a specified level during an earthquake. The procedure is based on a linearized model, which allows the use of modal analysis. Ductility of the frames is represented by the substitute structure method. Although the results from the parameter study show that the procedure is effective for a wide range of parameters, the procedure has a few limitations. For cases with highly out-of-phase frames, the effects of pounding control the hinge opening. In general, the procedure should be limited to frames with period ratios $T_1/T_2$ > 0.30. The procedure does not account for the effect of abutments in the response of the hinge. Therefore, it should only be used for hinges located at least one frame from the end frame. However, if the end frames are very stiff compared with the interior frames, the procedure may be valid for the intermediate hinges closest to the abutments. The effect of interacting frames is accounted for by considering combinations of hinge conditions up to two frames away from the hinge under construction. Finally, the procedure has not been validated for bridges with large skew angles (>30%) or bridges subjected to nonuniform support motion.

The following conclusions are a result of the study:

- The maximum hinge displacement is a function of the frame period ratio, frame target displacement ductility, and characteristics of the ground motion.
- Pounding of highly out-of-phase frames can increase the hinge displacement compared with linear analysis. However, for frames that are nearly in-phase, pounding tends to reduce the response, because pounding disrupts the buildup of resonant response.
- Frames with higher ductility levels exhibit in-phase motion, thereby reducing the hinge displacements. As a result, ductile frames require fewer restrainers to limit their displacements compared with elastic frames.
- Current specifications for restrainers do not account for the factors controlling the response of hinges in multiple-frame bridges. The equivalent static procedure for hinge restrainers is unconservative for out-of-phase frames and conservative for frames that are in-phase.

Future extensions of the design procedure include the effects of transverse earthquake response, skew supports, and the effects of abutments.

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