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A study on preventing the fall of skew and curved bridge decks by using rubber bearings

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Abstract. The paper deals with preventing the collapse of deck structures of skew and curved bridges during earthquakes, by the means of supporting the bridges by rubber bearings and permitting pounding between the decks and the abutments. Seismic response during pounding is characterized by various phenomena, such as the caging of bridge decks between abutments during an earthquake or decks popping out. These behaviors depend on only a small difference in seismic intensity. Regarding the global characteristics of a seismic response, smaller clearance between a deck and its abutments results in smaller impact damage of the abutments as well as lesser deformation of the rubber bearings. Similarly, smaller clearance between a deck and the side blocks results in smaller damage. The stiffnesses of the bearings and the stiffness ratio between them control the deck displacement. In short to medium length bridges, zero clearance between a deck and the abutments or the deck and the side blocks is the most effective way in preventing the deck from falling and limits the damage to the abutments or the side blocks.

Key words: prevention of deck fall; skew bridge; curved bridge; seismic response with pounding.

1. Introduction

In 1995, during the Hyogo-Ken-Nanbu Earthquake, many decks in skew and curved bridges collapsed. After the bearings were torn-off during the earthquake, these decks not only translated laterally but also rotated without restraint by the abutments. After the earthquake, the design code for road bridges in Japan (JRA 1996) was changed, requiring the addition of more stoppers and broadening the top of the abutments. The crucial means to prevent deck fall, however, is ensuring that bearings do not fail during earthquakes.

Rubber bearings have larger ductility than rocker or roller bearings. If the deformation of a rubber bearing is limited by restraining the deck displacement with the abutments, the bearing will not break and the deck will not fall. New Zealand uses the concept of “knock-off” elements (Chapman 1990) for seismically isolated bridges. At the same time, however, the abutments cannot bear damage by pounding, as the clearance between the deck and the abutment becomes too large to let emergency vehicles pass on the bridge. Therefore, the damage of the abutments and the deformation of the bearings by permitting pounding must be clear.

Research has been carried out that shows chaos phenomena even in an elasto-impact system with

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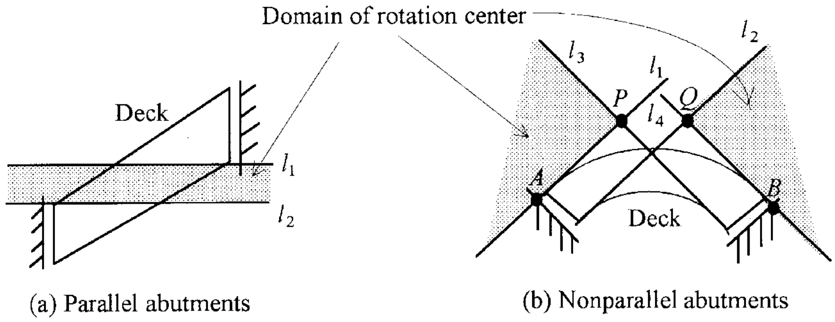


Fig. 1 Domain of center around which the decks can rotate

one degree of freedom (Oestreich 1996 and Slade 1996). Since skew or curved decks oscillate by irregular movements of the abutments and piers during an earthquake, deck corners irregularly pound on the abutments. The responses become so intricate that those calculated using only a few earthquake waves are not reliable. For example, this study shows that a deck may remain between two abutments during an earthquake or pop out of its restraints based on only a small difference in seismic intensity. Therefore, when estimating bridge safety one needs to investigate the global characteristics of the response, including pounding.

Furthermore, we propose a simple method to estimate the damage at the abutments caused by the energy absorbed during impact. An effective means to decrease the impact damage on abutments and the deformation of rubber bearings is also proposed.

2. Geometrical characteristic of skew and curved deck

When a center of rotation is in the domain shown in Fig. 1, the skew or curved deck can rotate without restraint from the abutments. The lines l_1 to l_4 cross the abutments at right angles. When a deck has a domain as in Fig. 1, even if the deck expands due to temperature changes and contacts the abutments, the deck can still move. A deck that does not have such a domain cannot rotate, and

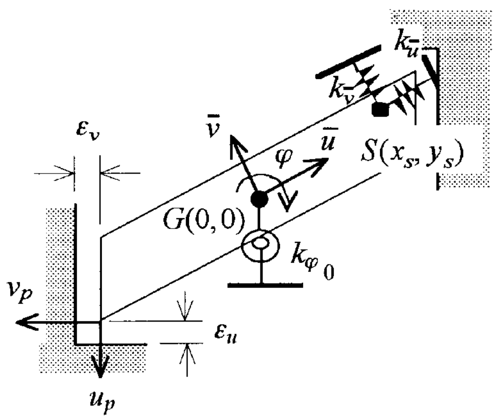


Fig. 2 Deck model and the defined coordinate

this case is not covered in this paper.

When the point P is on the right side of the point A or the point Q is on the left side of the point B, as shown in Fig. 1(b), the design code in Japan requires the top of the abutment to be widened and more stoppers to be added. The stoppers set on the top of the abutment and the piers limit the displacement of the deck. The design code assumes the deck rotates only around the deck corners. The position of P or Q, however, as shown in Section 7, is not an important factor when considering the seismic response with pounding. The seismic response is not limited to the rotation around the corners, but the rotation center of the movement takes an arbitrary position in the domain in Fig. 1.

3. Equation of motion of rigid deck

Assuming a rigid deck, and putting the stiffnesses of rubber bearings and piers together, the equation of the motion of the deck is,

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & J \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}} \\ \ddot{\bar{v}} \\ \ddot{\varphi} \end{bmatrix} + \begin{bmatrix} c & 0 & 0 \\ 0 & c & 0 \\ 0 & 0 & r^2 c \end{bmatrix} \begin{bmatrix} \dot{\bar{u}} \\ \dot{\bar{v}} \\ \dot{\varphi} \end{bmatrix} + \begin{bmatrix} k_{\bar{u}} & 0 & -k_{\bar{u}} y_s \\ 0 & k_{\bar{v}} & k_{\bar{v}} x_s \\ -k_{\bar{u}} y_s & k_{\bar{v}} x_s & k_{\varphi} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \bar{v} \\ \varphi \end{bmatrix} = \begin{bmatrix} -M\ddot{\phi}_{\bar{u}} \\ -M\ddot{\phi}_{\bar{v}} \\ 0 \end{bmatrix} \tag{1}$$

where M is the mass of the deck, J is the moment inertia of the deck, c is the damping coeffieient, γ is the radius-of-gyration of the deck, (x_s, y_s) is the position of the center of stiffness, $\ddot{\phi}_{\bar{u}}$ and $\ddot{\phi}_{\bar{v}}$ are the two components of acceleration of the given earthquake, $\bar{u}, \bar{v}$ and φ are the displacement at the center of gravity, and $k_{\bar{u}}, k_{\bar{v}}$ and k_{φ} are the condensed stiffness of the rubber bearings and the piers.

When a brige has a single span or the stiffness of piers is constant in direction around, the two stiffnesses against translation are the same. We discuss this case in the response with pounding. The stifnesses in Eq. (1) become,

$$k_{\bar{u}} = k_{\bar{v}} = \sum_j k_j \equiv k \tag{2}$$

$$k_{\varphi} = l_k^2 k \tag{3}$$

where k_j is the stiffness of the bearing on the abutment or the stiffness composed by the bearings and a pier, and l_k is,

$$l_k^2 = \frac{\sum_j l_j^2 k_j}{k} \tag{4}$$

where l_j is the distance from the center of gravity to the position of the spring k_j. The radius-of-gyration r is obtained from the moment of inertia, while l_k is obtained from the moment of the spring constants. Hence we call l_k the radius-of-stiffness, similar to the radius-of-gyration.

When the two stiffnesses against translation are the same, if the center of stiffness does not coincide with the center of gravity, one of the three modes is the translation mode, and the other two modes are the rotation modes. The natural circular frequency of the translation mode is n_0=

$\sqrt{k/M}$, and the natural rotation modes are,

$$n_{1,2} = \frac{n_0}{\sqrt{2}}\sqrt{1 + \left(\frac{l_k}{r}\right)^2 \mp \sqrt{\left\{1 - \left(\frac{l_k}{r}\right)^2\right\}^2 + 4\left(\frac{l_s}{r}\right)^2}} \tag{5}$$

where l_s is the distance between the center of gravity and the center of stiffness.

The displacement of the translation mode is along the line which passes through the center of gravity and the center of stiffness. The centers of the rotation modes are on the line. The distances between the center of the rotation modes and the center of gravity are,

$$l_{1,2} = \frac{2l_s}{1 - \left(\frac{l_k}{r}\right)^2 \pm \sqrt{\left\{1 - \left(\frac{l_k}{r}\right)^2\right\}^2 + 4\left(\frac{l_s}{r}\right)^2}} \tag{6}$$

From Eqs. (5) and (6), the characteristics of free vibration of the deck are determined by the natural frequency of the translation mode, the radius-of-gyration, the distance from the center of gravity to the center of stiffness and the ratio of the radius-of-stiffness to the radius-of-gyration.

When the center of stiffness coincides with the center of gravity, the translation mode does not have a specific direction, and the center of the rotation mode, which is only a single point, is the same as the center of gravity. The natural frequency of the rotation mode in this case is certainly larger than the lower natural frequency of the rotation modes when the center of stiffness and the center of gravity are in different places.

If the centers of the rotation modes do not lie in the domain in Fig. 1, and if the abutments always restrict the translation mode, the amplitude of the response is expected to be reduced during an earthquake. Section 6.3, however, shows the expectation is not valid.

4. Impact model

When the deck rotates in a seismic response, the corners of the deck collide with the abutments or with the side blocks as stoppers. Assuming a linear relation between the velocities at the corners before and after collision, the components of the velocity after collision are,

$$\dot{u}_p^+ = e_f\,\dot{u}_p^-, \qquad \dot{v}_p^+ = e_r\dot{v}_p^- \tag{7a, b}$$

$$\dot{u}_p^+ = e_r\,\dot{u}_p^-, \qquad \dot{v}_p^+ = e_f\,\dot{v}_p^- \tag{8a, b}$$

where the rate of change of the component along the impact surface is e_f, and the rate of change of the component normal to the impact surface is e_r. Eq. (7a, b) shows the collision between the corners of the deck and the abutments, and Eq. (8a, b) shows the collision between the corners and the side block. The components of the velocity defined above are shown in Fig. 2.

The components of the impulsive force acting on the deck at collision are,

$$\begin{Bmatrix} S_u \\ S_v \end{Bmatrix} = \frac{M}{r^2 + l_p^2}\begin{bmatrix} (e_f - 1)(r^2 + x_p^2) & (e_r - 1)x_p y_p \\ (e_f - 1)x_p y_p & (e_r - 1)(r^2 + y_p^2) \end{bmatrix}\begin{Bmatrix} \dot{u}_p^- \\ \dot{v}_p^- \end{Bmatrix} \tag{9}$$

where the position of the corner is (x_p, y_p) in a coordinate system where the center of gravity is the origin, and the length from the center of gravity to the corner is l_p. Eq. (9) shows the case of the corner and an abutment colliding. In the case of the corner and a side block impact, e_f and e_r swap with each other.

Using Eq. (9), the changes of the velocity at the center of gravity at collision are,

$$\Delta\dot{u} = \dot{u}^{-}-\dot{u}^{+}=-\frac{S_u}{M},\quad \Delta\dot{v} = \dot{v}^{-}-\dot{v}^{+}=-\frac{S_u}{M},\quad \Delta\dot{\varphi} = \dot{\varphi}^{-}-\dot{\varphi}^{+} = \frac{x_p}{r^2}\Delta\dot{v}-\frac{y_p}{r^2}\Delta\dot{u} \qquad \text{(10a, b, c)}$$

where the component u is parallel to the abutment with which the corner collides, and v is normal to the abutment.

When computing the seismic response with pounding, the displacement of a corner is evaluated in terms of whether or not it collides with the abutment or the side block. Eq. (10) gives the velocity at the center of gravity after the collision, and the displacement and the acceleration are the same as before the collision.

Assuming a linear law of velocity change at collision, a clearance, ε, can be used to normalize the response with pounding so that the following parameters are used:

$$\frac{u}{\varepsilon},\quad \frac{v}{\varepsilon},\quad \frac{\varphi}{\varepsilon},\quad \frac{\ddot{\phi}_{\bar{u}}}{\varepsilon},\quad \frac{\ddot{\phi}_{\bar{v}}}{\varepsilon}$$

The clearance, ε, can be chosen from any among several clearances between collision partners. However, the ratios of those clearances are constant in the normalization. If one of the ratios is changed, the normalization is not valid.

The maximum response is not proportional to an increase in seismic intensity because of pounding. However, if a clearance between a deck and the abutments is doubled when an earthquake wave amplitude is doubled, the response is also doubled. This is because the time and the direction at each collision are identical. The normalization shows that the ratio of the clearance makes the relation between the seismic intensity and the response of the deck similar.

5. Evaluation of absorbed energy at collision

When a collision of a deck corner ruptures a parapet in an abutment, the abutment can not give restitution to the deck. Therefore, the rupture of the abutment means e_r=0 in Eq. (7b). In this condition, from the difference of the kinetic energies of the deck before and after the collision, the abutment and its soil backfill have to absorb the following energy:

$$\Delta E = \frac{1}{2}M(2\dot{\phi}_u + \Delta\dot{u})\Delta\dot{u} + \frac{1}{2}M(2\dot{\phi}_v + \Delta\dot{v})\Delta\dot{v} + \frac{1}{2}J\varphi^2 \qquad (11)$$

From the direction of the impulsive force, the energy engaging in moving the deck along the bridge line after the rupture is given by Eq. (12a). If the side block ruptures, the energy used in moving the deck after the rupture is given by Eq. (12b).

$$\Delta E_v = \frac{1}{2}M\left(2\dot{\phi}_v + \frac{r^2+x_p^2}{r^2}\Delta\dot{v}\right)\Delta\dot{v} \qquad \text{(12a)}$$

$$\Delta E_u = \frac{1}{2}M\left(2\dot{\phi}_u + \frac{r^2 + y_p^2}{r^2}\Delta\dot{u}\right)\Delta\dot{u} \tag{12b}$$

Strictly, the energies should include the strain energy in the rubber bearing and the piers accompanying the movement of deck after the rupture. However, we may consider neglecting these energies because in the following evaluation the smaller energies give results on the safe side. If the relation between the horizontal force and the deformation of an abutment or a side block is known, the energies of Eq. (12a, b) enable us to anticipate the deformation.

To evaluate the energies, it is simplest to compare the energy absorbed by an abutment of a straight bridge with the energy of Eq. (12a, b). The clearance of the straight bridge is zero. Therefore, the abutment of the straight bridge has to be able to absorb the maximum kinetic energy of the deck during an earthquake. Since a deck with zero clearance almost exactly oscillates with the ground motion, the maximum kinetic energy is expressed by the mass of the deck and the maximum velocity of the earthquake motion. If the energy of Eq. (12a, b) is less than the maximum kinetic energy of the straight bridge,

$$\Delta E_{v,\,\max} \le \frac{1}{2}M\dot{\phi}_{v,\,\max}{}^2, \qquad \Delta E_{u,\,\max} \le \frac{1}{2}M\dot{\phi}_{u,\,\max}{}^2 \tag{13a, b}$$

Substituting Eq. (12a, b) in Eq. (13a, b),

$$\Delta\dot{v}_{\max} \le \frac{\sqrt{2 + (x_p/r)^2} - 1}{1 + (x_p/r)^2}\dot{\phi}_{v,\,\max} = \mu_v\dot{\phi}_{v,\,\max} \tag{14a}$$

$$\Delta\dot{u}_{\max} \le \frac{\sqrt{2 + (y_p/r)^2} - 1}{1 + (y_p/r)^2}\dot{\phi}_{u,\,\max} = \mu_u\dot{\phi}_{u,\,\max} \tag{14b}$$

In Eq. (14a, b), the nondimensional coefficients μ_u and μ_v are determined by only the deck shape of a skew bridge or a curved bridge. We can call the coefficients the effective coefficients at collision. Smaller coefficients require larger energy to be absorbed by the abutments or the side blocks at collision.

Dividing the velocity change at collision by the maximum velocity of the earthquake, we can compare its nondimensional velocity with the effective coefficients. On the other hand, dividing the velocity change at collision by the effective coefficients gives the equivalent effect for an abutment in a straight bridge with zero clearance. Namely, the velocity can be regarded as the velocity of the earthquake wave shaking the straight bridge, hence it is termed the the equivalent velocity.

In a skew bridge, when a corner with an acute angle collides with an abutment or a side block, the abutment or the side block has to absorb larger energy than a corner with an obtuse angle. In a curved bridge, when a corner on the outside arc collides with an abutment or a side block, the abutment or the side block has to absorb larger energy than a corner on the inside arc.

Limiting the collision to these corners, and assuming the mass is homogeneously distributed in the deck, we derive the effective coefficients in Eq. (14), shown in Figs. 3 and 4. In the figures, the axis θ is the acute angle in a skew bridge or the center angle of the arc in a curved bridge. The parameter b' is the ratio between the width at the deck edge and the deck length in a skew bridge or the ratio between the deck width and the average radius of the inside and outside arcs in a curved bridge. The effective coefficients are from 0.3 to 0.414 for almost all shapes of decks, as shown in Figs. 3 and 4.

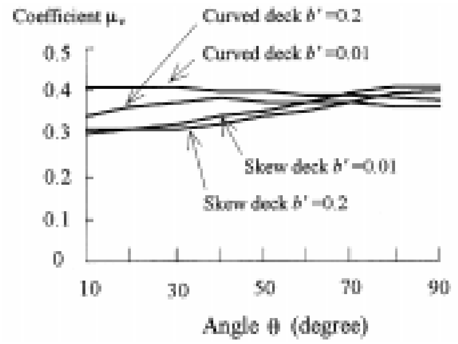


Fig. 3 Effective coefficient on abutment

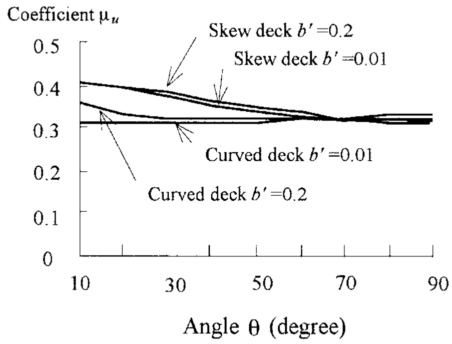


Fig. 4 Effective coefficient on side block

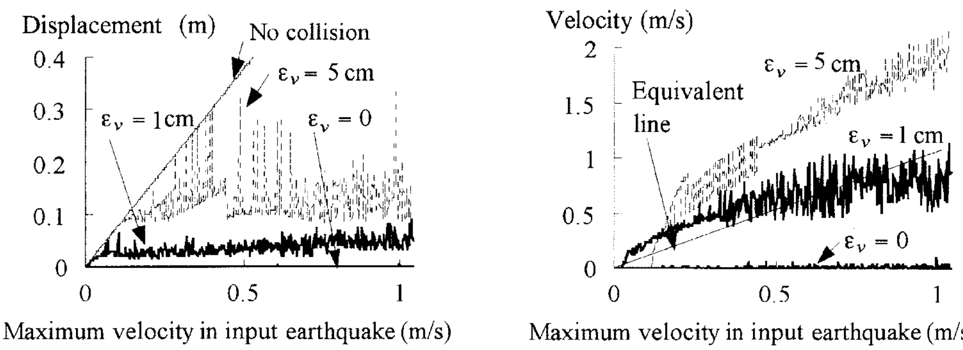
6. Effects of several factors on the response with collisions

In the computation of the seismic response with pounding, the earthquake waves used are the E-W component and the N-S component in the records from the Kobe Marine Meteorological Observatory in the 1995 Hyogo-Ken-Nanbu earthquake. The E-W component has a maximum of 619 gal. The N-S component has a maximum of 820 gal. The two components were used to simultaneously shake the decks.

Responses with pounding are chaotic phenomena. Therefore, a response computed by only using the above accelero records is not reliable to exactly evaluate factors influencing the response. A small difference in the wave shapes produces a quite different response. Therefore, using the accelero waves for the computation changing the intensity, we can evaluate the factors from the global characteristics in the change. The earthquake intensity is changed by linearly scaling the accelero records by the ratio between a given maximum acceleration and the real maximum of 820 gal. Scaling the earthquake intensity guarantees the same scaling of velocity, because the time axis is not scaled.

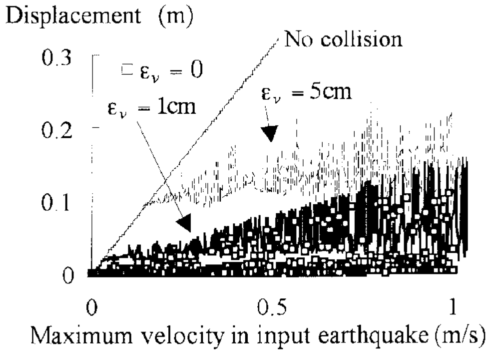
The response is computed using Newmark's β method. The time interval used is 0.0005 second, and the damping constant is 0.02, which is a general value for rubber bearings.

The skew deck is 100 m in length and 10 m in width at the deck edge. The acute angle is 60

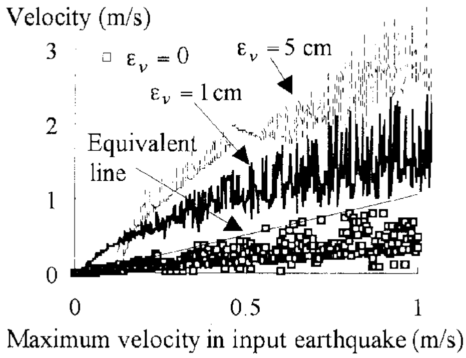


(a) Maximum displacement at the corners
(b) Maximum equivalent velocity

Fig. 5 Effects of clearance on the responses of a skew deck



(a) Maximum displacement at the corners



(b) Maximum equivalent velocity

Fig. 6 Effects of clearance on the responses of a curved deck

degrees. The curved deck is 100 m in length and 10 m in width. The center angle of the arc is 30 degrees. Decks of 100 m in length generally have about a 5cm clearance for temperature expansion. The bridges, except when used in Section 6.5, do not have side blocks, as shown in Fig. 2, so the deck pounds only with the abutments.

The E-W component shakes the skew deck in the direction parallel to the face of the abutments, and the curved deck in the direction parallel to the symmetric axis. The N-S component shakes the decks in the perpendicular directions. Using the two components of the earthquake wave, the changing of the angle of the incident wave did not influence the global characteristic of the response with pounding.

6.1 Clearance

Fig. 5 shows the effects of the clearance on the maximum displacement at the corners and the maximum equivalent velocity of the skew deck. Fig. 6 shows these same components for the curved deck. The horizontal axes in these figures are the maximum velocity in each earthquake wave.

The results present typical phenomena of the seismic response with pounding. The maximum displacement at the corners fluctuates sharply under small differences in the earthquake intensity. The fluctuation appears in all values of clearance except the skew deck with zero clearance. The lower parts in the fluctuation mean that the deck remains between the abutments during the earthquake. The peaks in the fluctuations mean that the deck pops out of the restraint by the abutments. The seismic responses with pounding computed by only several earthquakes may not always show such peaks of displacement; consequently the results are insufficient to evaluate the safety of the bridge. The evaluation needs many different responses such as those obtained by slightly modifying the earthquake intensity to provide a range of velocities.

The maximum equivalent velocity also fluctuates sharply with small differences in seismic intensity. When the equivalent velocity is over the equivalence line, the abutments of both bridges have to absorb more energy than the abutment in a straight bridge with zero clearance.

Figs. 5 and 6 are computed without being normalized by the clearance value. The graphs show the response for a clearance of 5 cm is similar to the response for a clearance of 1 cm, and the former response is 5 times the latter for both axes. In the case of zero clearance, however, the displacement of the deck does not completely reach zero because the skew and curved decks can move even with zero clearance, as shown in Fig. 1. Therefore, the response is not similar for all values of clearance.

The rate of increase of the maximum displacement with increase in the earthquake intensity is smaller than the linear increase of the displacement assuming no collisions. The rate of increase of the maximum equivalent velocity also gradually decreases with increased earthquake intensity. From the results, smaller clearances give smaller responses. Therefore, a zero clearance is most effective in regard to a seismic response with pounding, provided that the equivalent velocity does not represent continuous contact of the deck with the abutment but only the effect at collision. For a design on the safe side, consideration must be given to whether the abutment's ability to absorb the kinetic energy of the deck at the maximum velocity of the input wave.

From Figs. 5(b) and 6(b), the design of a bridge having a large clearance due to the use of seismic isolation, needs attention to ensure that the deck does not pound with the abutment. Greater clearance results in a steeper rate of increase in the equivalent velocity at the critical intensity of an earthquake at which collision occurs. Therefore, a large clearance results in heavy damage caused by collision.

In the computaion of these figures, the increment of the maximum velocity is 0.26 cm/s. The rate of the velocity change at collision is zero both parallel and normal to the abutment. From Eqs. (5) and (6), the following values can determine the characteristics of free vibration of the decks. The translation mode of each deck has a natural frequency of 1 Hz. The center of stiffness in the skew deck is positioned at half of the radius-of-gyration from the center of gravity on the bridge axis. The center of stiffness in the curved deck is also positioned at half of the radius-of-gyration from the center of gravity on the symmetric axis. The radius-of-stiffness is 1.5 times the radius-of-gyration in each deck.

6.2 Rate of velocity change at collision

In real collision phenomena, the rate of velocity change at collision is uncertain. Fig. 7 shows several cases of the rate of change in a curved deck. In the computation, the clearance is 1 cm, and the other factors are the same as in Fig. 6.

The rupture of abutments means e_r=0 in Eq. (7b). On the other hand, the coefficient of restitution between steel and steel is 5/9, and the coefficient between steel and concrete is smaller than the

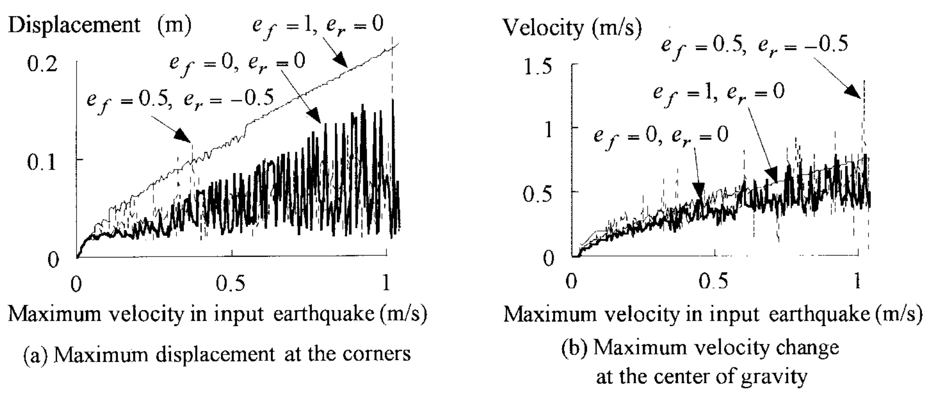


Fig. 7 Effects of change rate of velocity at collision on the responses of a curved deck

value between steel and steel. Therefore, e_r=–0.5 as a near value and e_r=0 are compared in Fig. 7. In order to discuss the effect of friction, e_f=1 and 0 as extreme values are also compared: e_f=1 means zero friction. Since the equivalent velocity is limited to the case of e_r=0 and e_f=0, the vertical axis in Fig. 7(b) uses the maximum velocity change at the center of gravity at collision.

The maximum displacement at the corners in the response with zero friction is larger than the response with friction. However, the maximum velocity change with zero friction is included among the fluctuations of the response with friction. When the coefficient of restitution is not zero, the peaks in the maximum displacement are occasionally higher than the maximums in the response with zero resititution. The maximum velocity change with zero restitution is also the same. If the bridge design permits pounding during an earthquake, the bridge may need to cushion the pounding in order to reduce local damage to the deck as well as to the abutment. This case can be considered by taking the rate of velocity change as nearly zero. Therefore, in real bridges, the extent of the difference shown in Fig. 7 is reduced, so that the response of e_r=0 and e_f=0 can be used for the evaluation.

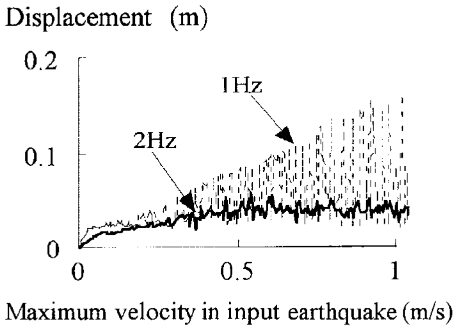
6.3 Stiffness of bearings and piers

Fig. 8 shows the effect of the bearing and pier stiffnesses on the response with pounding. In Fig. 8, 1 and 2 Hz mean the natural frequencies of the translation modes of the curved deck. The nautral frequency represents the stiffnesses of the bearings and the piers. The clearance is 1 cm and the other factors are the same as in Fig. 6.

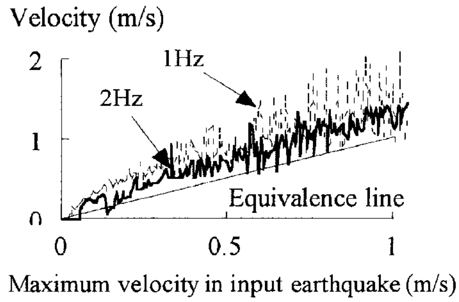
Increasing the stiffness reduces the fluctuation of the maximum displacement. Though the equivalent velocity is also reduced, the extent is small. Since the equivalent velocity represents the energy absorbed at the deck ends and the abutments, the results show that the stiffnesses of the bearings and the piers cannot sufficiently reduce the energy.

Fig. 9 shows the effect variations in the position of the center of stiffness caused by changes in the relative stiffnesses between the rubber bearings including the piers. The changes in the stiffness ratio do not also decrease the equivalent velocity but influence the displacement of the deck. Therefore, only the maximum displacement is shown.

In Fig. 9(a), in one case the center of stiffness is at the center of gravity in the curved deck, in the other the center of stiffness is positioned at a distance of 1.2 times the radius-of-gyration away from

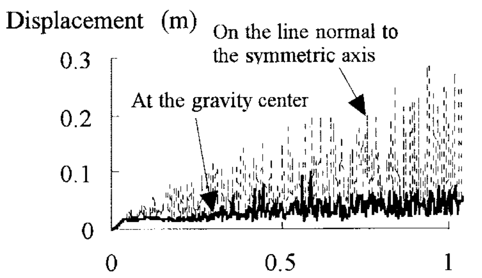


(a) Maximum displacement at the corners

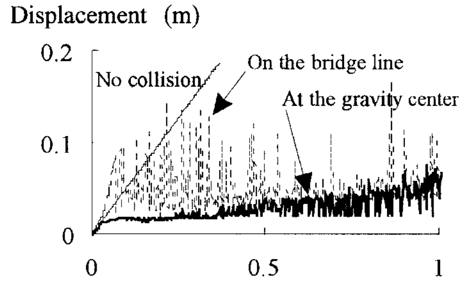


(b) Maximum equivalent velocity

Fig. 8 Effects of stiffness of rubber bearings and piers on the responses of a curved deck



(a) Maximum displacement of a curved deck



(b) Maximum displacement of a skew deck

Fig. 9 Effect variations in the position of a center of stiffness on the responses

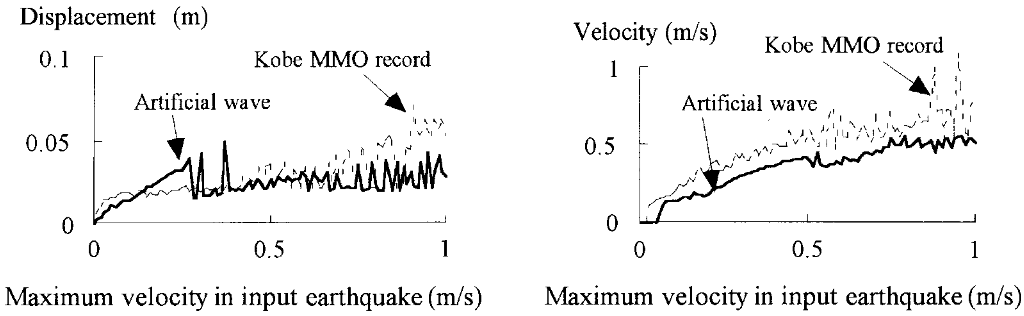
the center of gravity on the line normal to the symmetric axis. In the latter case, the translation mode oscillates in the normal direction and the rotation modes have rotation centers outside the domain shown in Fig. 1(b). Therefore, if the modes contribute to the response with pounding, the modes are expected not to grow during an earthquake because of constant restriction by the abutments. Fig. 9(a), however, shows that even if the abutments restrict the modes, the displacement of the deck in the case where the center of stiffness is away from the center of gravity, is larger than when the center of stiffness is at the center of gravity. This is because the further the center of stiffness is away from the center of gravity, the smaller is the natural frequency of the lowest mode of rotation. In other words, the stiffness against rotation of the deck becomes small. Adding the condition that the rotation centers of the modes exist in the domain in Fig. 1, for example Fig. 9(b), the displacement of the deck is sometimes larger than for the case with no collisions. In Fig. 9(b), in one case the center of stiffness is at the center of gravity of the skew deck, in the other the center of stiffness is positioned at a distance of the radius-of-gyration away from the center of gravity on the bridge axis. In the latter case, both rotation modes have rotation centers inside the domain in Fig. 1(a).

In a building with seismic isolation, in order to reduce the displacement caused by an earthquake, the center of stiffness has to be very near the center of gravity. The design concept is to prevent collision between the building and partition walls. In a bridge permitting pounding the center of stiffness should also be near the center of gravity.

6.4 Earthquake wave

Peaks of the displacement of the decks are phenomena of popping out and the modes do not contribute to the seismic response with pounding. Furthermore, frequent pounding during an earthquake makes the deck response have a very short period. These qualitative characteristics imply that the frequency characteristics of an earthquake wave do not seriously influence the seismic response.

Fig. 10 shows the seismic responses of the skew deck when acted on by different earthquake waves. The response of the Kobe MMO records is slightly larger than the response of the artificial wave as a whole. The Kobe MMO records comprise the N-S component and E-W component of the Kobe Marine Meteorological Observatory records as used before. The artificial wave comprises the two waves prescribed by the Ministry of Construction (1992) which are used for the design of bridges with seismic isolation in Japan. There is a remarkable difference between the maximum accelerations as well as the frequency characteristics of the two waves. When each wave comprising



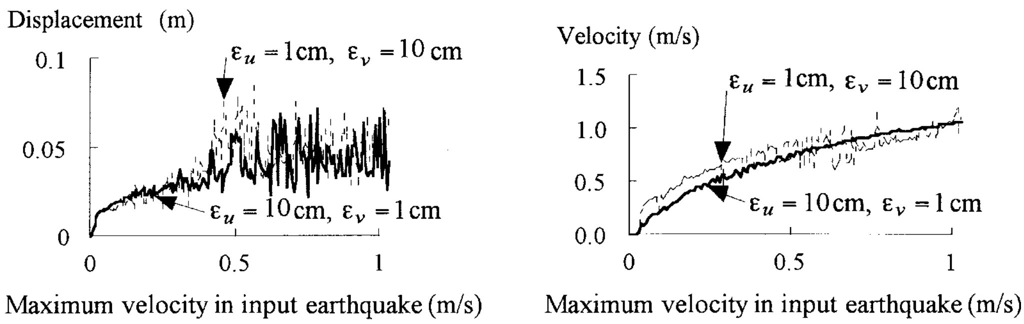
(a) Maximum displacement at the corners (b) Maximum equivalent velocity

Fig. 10 Effect of earthquake wave on the responses of a skew deck

the two components has the maximum velocity of 1 m/s, the acceleration of the Kobe MMO records has a maximum of 802 gal, and the acceleration of the artificial waves has a maximum of 319 gal. Therefore, the main frequency range in the former is higher than in the latter. The responses, however, are not so different as the maximum accelerations of the two waves. Therefore, the velocity of the input wave has a greater influence on the seismic response than the acceleration, and the frequency characteristics of an input wave are not so important. When undertaking an analysis, simply an irregular wave in plane is sufficient and comprehensive enough to determine the seismic response with pounding. Therefore, though the results shown so far use only the Kobe MMO records, the results using the maximum velocity to represent the seismic intensity can also represent responses by other earthquake waves. Furthermore, since changing the wave angle incident to the deck means changing the wave shape on condition that the wave has two components with similar intensities, the effect of the incident wave angle is small and the global characteristics of the response are not significantly different. However, using a wave only with one component, the incident wave angle influences the response because of the limitations on the diversity of the impact directions and the velocities at collisions.

6.5 Collisions between side block and deck

Fig. 11 compares collisions between the side blocks and the skew deck with those between the



(a) Maximum displacement at the corners (b) Maximum equivalent velocity

Fig. 11 Difference between collision partners of a skew deck abutments and the skew deck. The clearance between the deck and its collision partner is 1 cm in each case, i.e., ε_u=1 represents the case where collision will occur with the side blocks and ε_v=1 represents collision with the abutments. As shown in Figs. 3 and 4, the effective coefficient of collision with the side blocks is not very different from that with the abutments. Besides, even if the collision partner changes to the side blocks, the global characteristics of the response barely changes, as shown in Fig. 11.

7. Discussion on preventing deck fall

This Section evaluates the effect of deck shape on the response with pounding, ensuring clearance for temperature elongation.

Figs. 12 and 13 show the response of decks having various shapes, but without side blocks. The decks are 100 m in length and 10 m in width. The 5 cm clearance is nearly equal to the general clearance to allow deck elongation caused by temperature variations. In order to keep the displacement of the decks small, the stiffness of rubber bearings should be large and the natural frequency of the translation mode is increased to 2 Hz for each deck. The center of stiffness of each deck is the same as the center of gravity. In Fig. 12, the angle θ is the acute angle of the skew decks. In

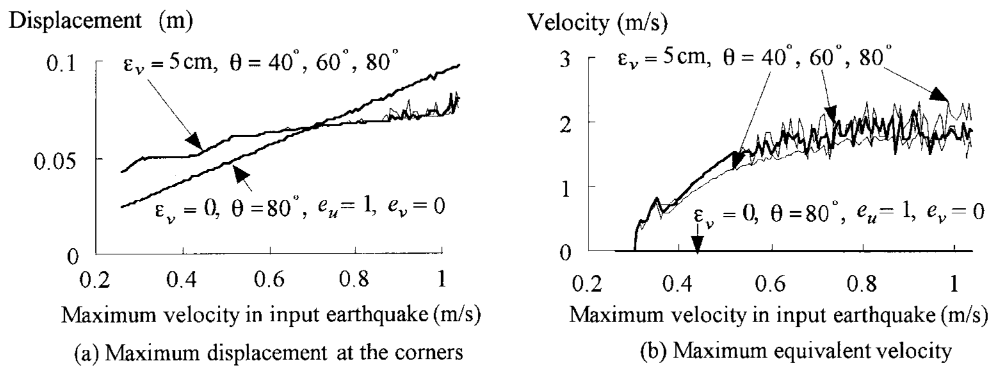


Fig. 12 Effect of skew deck shapes on the responses

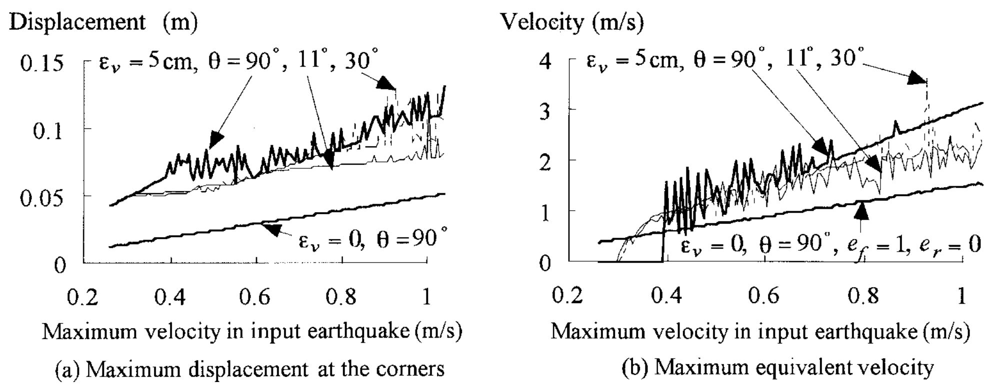


Fig. 13 Effect of curved deck shapes on the responses

Fig. 13, the angle θ is the center angle of an arc in the curved decks. In the deck with the center angle of 11°, point P is on the left side of point A in Fig. 1(b). Therefore, the design code in Japan does not require the addition of stoppers and broadening the tops of the abutments. Comparing the displacement of the decks, however, the displacement does not clearly become small. If the shape has such a domain as in Fig. 1(b), the displacement of deck does not depend on the deck shape.

In Fig. 12 and 13, the displacement at the corners is less than 15 cm even when subjected to an earthquake having a maximum velocity of 1 m/s. Therefore, the extent of this deformation can be allowed for the design of the rubber bearings. The equivalent velocity in the curved decks, however, is more than three times the maximum velocity in the input wave. This shows that the abutment has to absorb more than ten times the energy absorbed by the abutment in a straight bridge with zero clearance. Therefore, when permitting pounding, a deck and an abutment with a clearance of 5 cm need enough strength in order to prevent heavy damages.

On the other hand, as expressed in Section 2, if a deck has such a domain as in Fig. 1, the deck can move without restriction by the abutments, even with zero clearance. However, the friction between the deck and the abutment must be small. The responses of the skew deck and the curved deck with zero clearance and zero friction are also shown in Figs. 12 and 13. Though the displacement of this skew deck can become larger than the response for a clearance of 5 cm, the value is less than 10 cm and the equivalent velocity is nearly zero. In a curved deck with zero clearance, the maximum equivalent velocity becomes slightly larger than the maximum velocity of the input wave. The maximum equivalent velocity is, however, as a whole, smaller than the maximum for a deck with a clearance of 5 cm. If the abutment can absorb, with slight damage, the kinetic energy of the deck at a maximum equivalent velocity of 1.2 m/s, the design with zero clearance is a useful measure to prevent deck fall.

When a skew deck or a curved deck with zero clearance elongates due to temperature increases, the abutments have to sustain the restoring force following the deformation of rubber bearings. We should examine the force for the design. When the center of stiffness agrees with the center of gravity, the abutments have to receive the restoring forces, as shown in Fig. 14.

The force in the skew bridge and the force in the curved bridge are respectively,

$$N = \frac{k_{\varphi}\varepsilon\sin\theta}{l(\cos\theta - b')\sqrt{1 + 2b'\cos\theta + b'^2}} \tag{15}$$

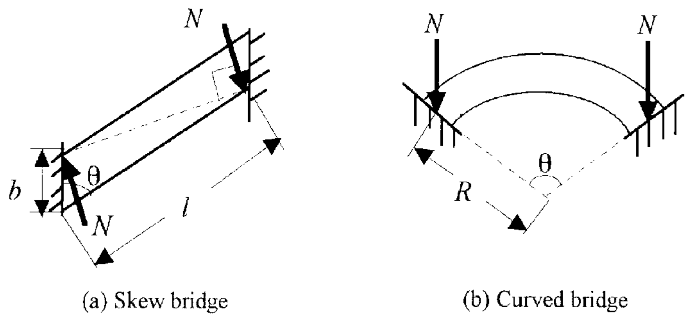


Fig. 14 Forces caused by temparature elongation

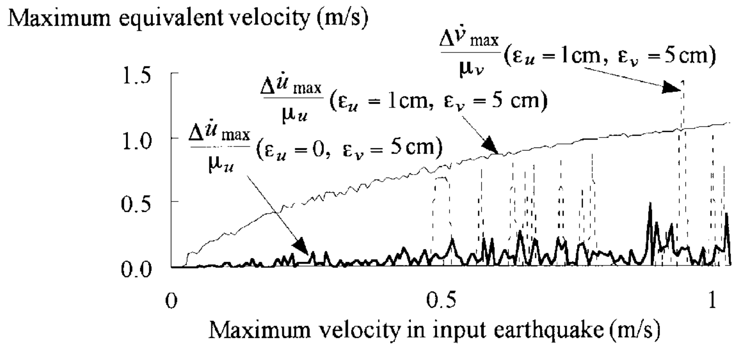


Fig. 15 Effect of clearance between a deck and side blocks

$$N = \frac{1}{2}k\varepsilon R\cos\frac{\theta}{2} \tag{16}$$

where the strain due to temperature effects is ε, the spring constant of rotation around the center of gravity is k_φ, the spring constant of translation is k, and $b' = b/l$.

As an example, take the case of a skew deck with zero clearance having a length of 100 m, a mass of 800 tons, an acute angle of 60^o, a natural rotation mode of 2 Hz frequency, b' = 0.1, and a strain of 720 μ, where the force becomes 1.69 MN. The normal component to the abutment is 0.71 MN. Similarly, take a curved deck with a length of 100 m, a mass of 800 tons, a center angle of 60^o, a natural translation mode of 2 Hz frequency and a strain of 720 μ, where the force becomes 3.76 MN. The normal component to the abutment is 1.88 MN.

When an abutment cannot sustain the forces in Eqs. (15) or (16), side blocks are a useful measure to prevent deck fall. If it is easy to provide side blocks having sufficient strength, the side block is preferable. Fig. 15 shows the effect of the clearance between the skew deck and the side block on the equivalent velocity at collision. The skew deck has a clearance of either 1 cm or zero clearance. The clearance between the deck and the abutment remains at 5 cm for temperature elongation. The deck with the clearance of 1 cm collides with both the side blocks and the abutments. The deck with zero clearance pounds only with the side blocks. It is proper that zero clearance between the deck and the side blocks reduces the equivalent velocity. A designer has to pay attention to ensure that the side block with zero clearance, however, can absorb the kinetic energy of the deck at the maximum velocity of the input wave as well as for the case of an abutment with zero clearance.

8. Conclusions

The paper deals with preventing the fall of skew and curved bridge decks by using rubber bearings and permitting pounding between the decks and the abutments or between the decks and the side blocks. To evaluate damage of the abutments during collisions, equivalent velocity is used, which equates the effect of the collision with the damage to an abutment in a straight bridge having zero clearance. The straight deck has the same mass as the skew or curved bridge.

The seismic response with pounding fluctuates considerably with small variations in seismic intensity. The effect of differences in the coefficients of friction or restitution at collision is varied. The frequency characteristics and the acceleration of the input wave are not important in the response, the dominant factor being the velocity.

The most effective measure to reduce deformations of the rubber bearings and the damage caused by collision is to have zero clearance between the deck and the abutments or between the deck and the side blocks. The stiffness of rubber bearings should be large and the center of stiffness should coincide with the center of gravity, provided that the effect is to reduce only the deformation of rubber bearings. When the clearance between the decks and the abutments is zero, the abutments have to sustain the force caused by temperature elongation. This force, however, results from the restoring force of the rubber bearings as the deck moves and not directly from deck elongation. A side block with zero clearance is also useful and there is no need to take care of the deck extension by temperature in the measure. The deck pounds only with the side block, so that the clearance between the deck and the abutment does not relate to pounding.

Though zero clearance decreases the damage by pounding, the side block needs to be able to absorb the same energy as the abutment in a straight bridge on the safe side. If a bridge is long, the side blocks at the abutments cannot resist the inertia of the deck or cannot absorb the energy. The bridge may need more stoppers or side blocks on the piers. Though stoppers or side blocks on the piers were not considered, it is supposed that zero clearance here would also reduce the response.

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