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ECONOMICAL DESIGN OF EARTHQUAKE-RESISTANT BRIDGES

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ABSTRACT

With the occurrence of every major earthquake, there has been in the past, almost a world-wide tendency to increase the capacity demand of the structure to counteract such events. It is only in the last decade that new strategies have been successfully developed to handle this problem economically. The current international practice has shifted towards a performance-based engineering design, wherein the accent is on serviceability and safety under different levels of magnitude of earthquakes. Also there is an increasing realization that apart from techniques for improving ductility, the structural engineer's tool-box should include energy-dissipating and energy-sharing devices and those that can control the response of the system. There have also been further advances on appropriate methods and devices of preventing 'dislodgement' or 'unseating' of the superstructure in the event of severe ground shaking. How these ideas can be used in economical earthquake resistant design of bridges is the subject of this paper.

PLASTIC HINGING AND DURABILITY

There is a marked difference in seismic design aspects of bridges and buildings. The reduced degree of indeterminacy of bridge structures leads to reduced potential of dissipating energy and load re-distribution. In bridges, the superstructures (piers and abutments) are the main structural elements which provide resistance to seismic action. For energy dissipation, ductile behaviour is necessary during flexure of these structural elements under lateral seismic loads. This essentially means that the formation of plastic hinges or flexural yielding is allowed to occur in these elements during severe shaking to bring down the lateral design forces to acceptable levels. Since yielding would lead to damage, plastic hinging are localized by design at points accessible for inspection and repair, i.e., parts of the substructure that lie from foundation upwards (see Figure 1). No plastic hinges are, of course, allowed to occur in the foundations or in the bridge deck.

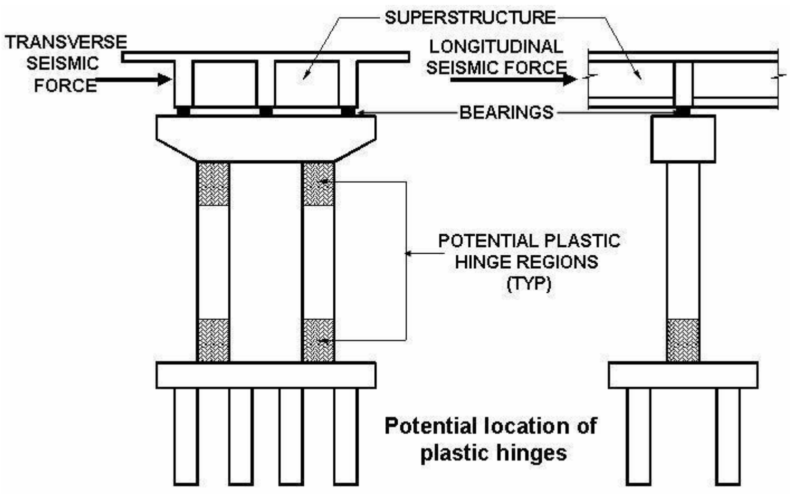


Fig. 1 Well-designed structures dissipate seismic energy by inelastic deformations in localized zones of selected members

Ductile behaviour is ensured by confinement of the concrete compression zone lying in the plastic hinge region of the sub-structures. Closely spaced horizontal hoops, restraining the main vertical reinforcement bars of the substructure, are effectively used for this purpose.

The main functions of the hoops and ties in the substructure can be summarized as follows:

- Confining of concrete core so as to enhance concrete strengths and to sustain higher compressive strains,
- Restrain longitudinal reinforcement against buckling,
- Provide shear resistance during flexure.

Earthquake engineering is indeed the 'art of designing bridges with controlled damage'. Due to the potential spalling off of the concrete cover (see Figure 2), special detailing rules for plastic hinge regions are available in codes of practice (AASHTO, 1999; BIS, 1993; CEN, 2005).

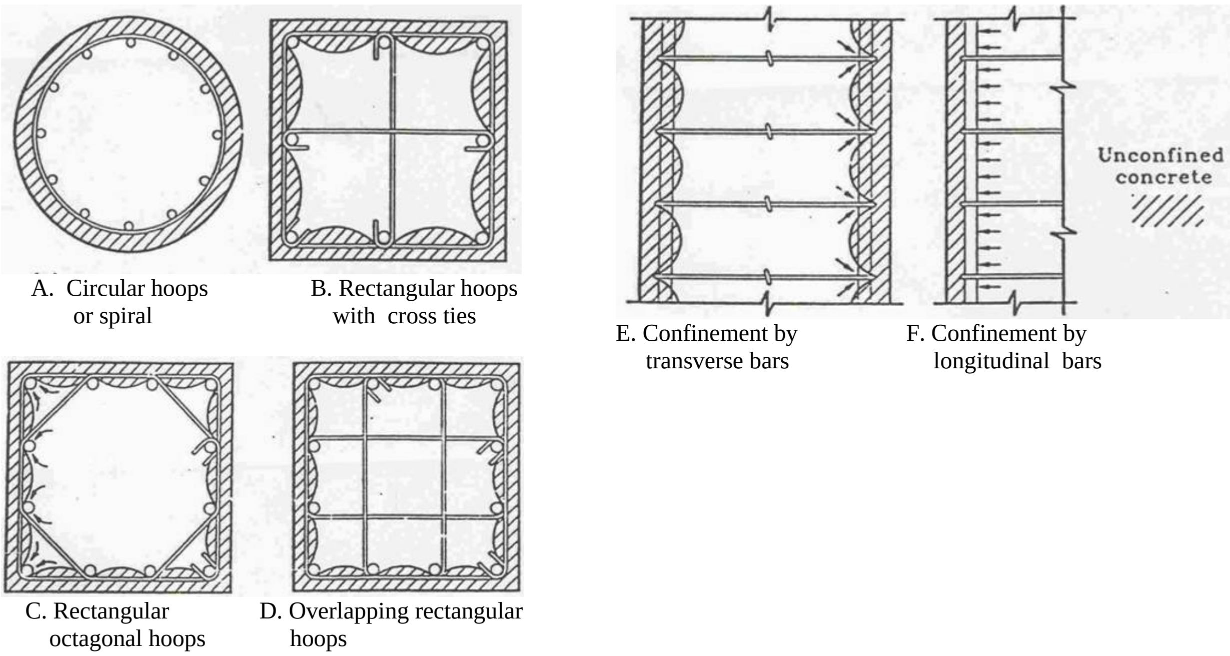


Fig. 2 Confinement of column sections by transverse and longitudinal reinforcement (after Priestley et al. (1996))

SUPERSTRUCTURE DISLODGEMENT PREVENTION AND INTEGRAL BRIDGES

Bearings, in general, are comparatively fragile and brittle elements (see Figure 3). Usual bearings of various types (metallic, elastomeric, pot, etc.) can be designed to have the capacity of sustaining lateral forces of about 25-30% of their vertical load carrying capacity (IRC, 1999). For larger lateral forces, as in the cases of Zones IV and V (IRC, 2000; BIS, 2002), it is more suitable and economical to provide resistance to these forces separately by some other structural element.

Superstructures, by themselves, usually have adequate strength to resist seismic forces, though this requires to be checked in the course of design work in accordance with IRC (2000). Application of vertical seismic forces for prestressed concrete structures in combination with other relevant loads is also mandatory. In many earthquakes it was noticed that the superstructure was dislodged and had fallen onto the ground or was damaged due to loss of support caused by large displacements of elastomeric bearings (see Figure 4), or due to out-of-phase displacement of piers. To counteract such failures the following counter measures are suggested:

- Provide "reaction blocks" or other types of seismic restrainers for preventing dislodgement of superstructure at pier/abutment cap level,
- Provide adequate support lengths for superstructure on pier/abutment cap,

- Design and construct "integral" bridges whereby the substructure and superstructure can be made monolithic.

Fig. 3 Surajbari Old Bridge: Metallic bearings destroyed during earthquake

Fig. 4 Girder shifted in the longitudinal direction with loss of seating during shaking

Counter-measures for (i) and (ii) have been discussed in detail in a previous paper (Tandon, 2001), and examples indicative of these features have also been included in IRC (2000). In some recent projects of continuous prestressed concrete bridges, "reaction blocks" were provided for longitudinal seismic forces as shown in Figures 5 and 6. The provision of elastomeric pads on a vertical face (see Figure 7) not only ensures even distribution of the longitudinal force to the reaction block but also acts as a "buffer", thereby introducing more damping into the system. Figure 8 shows the use of prestressing bars to prevent dislodgement of the superstructure. Minimum dimensions for support lengths have been indicated in IRC (2000), as reproduced in Figure 9, which are similar to those in AASHTO (1999).

Coming to option (iii), integral bridges need wide exposure because bearings and expansion joints are elements that are of serious concern in earthquake-prone areas. As already mentioned, they also happen to be the weak points in bridge structures from the point of view of strength, durability and maintenance. Their elimination in many types of bridges has now become a distinct possibility. Whereas the employment of advanced design techniques is essential, the construction could possibly become simpler and safer. It is of interest to note that in U.K. all bridges up to 60 m in length have to be of the integral type unless such conception is especially unsuitable in a particular case (HA, 1996). HA (1996) quite unnecessarily limits the definition of integral bridges to those where the abutment is made monolithic with the deck, keeping in view that piers are equally important, if not more so, in enhancing the overall performance of the structure during earthquakes. IRC (2000) also recommends the usage of integral bridges for improved performance.

Fig. 5 Example of longitudinal seismic restrainer for continuous bridges

Fig. 6 Britannia Chowk Flyover: Elevation of restrained pier

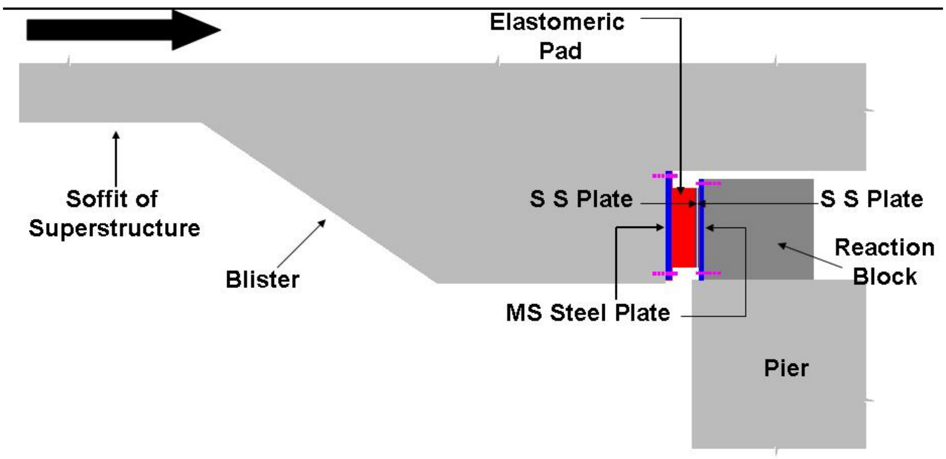
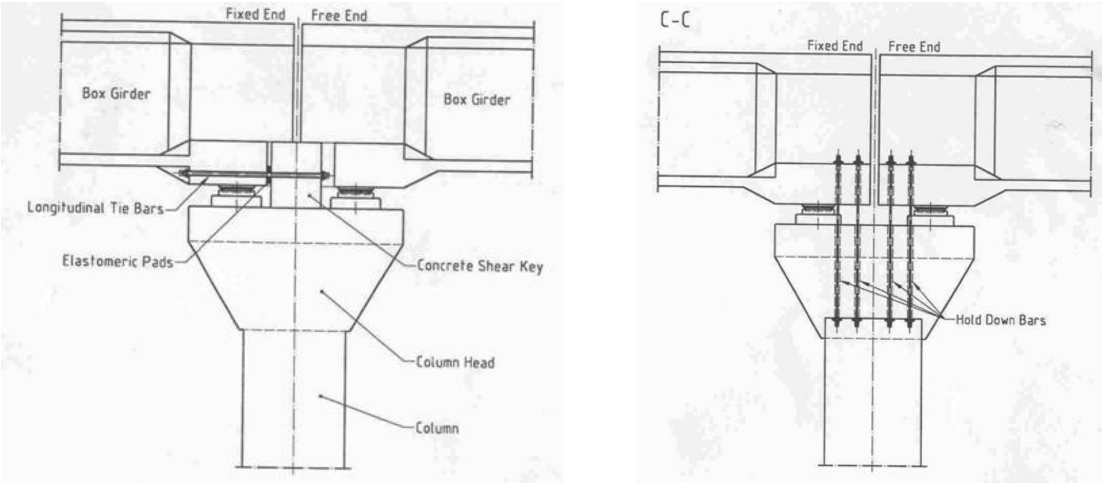


Fig. 7 Longitudinal seismic restrainer (vertical elastomeric pad introduces damping to longitudinal forces)



Longitudinal Tie Bars **Holding-Down Bars**

Fig. 8 Prevention of dislodgement

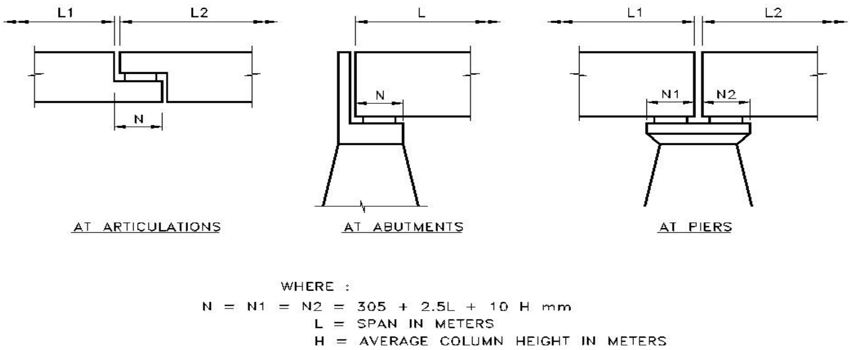


Fig. 9 Minimum dimensions for support lengths (after IRC (2000) and AASHTO (1999))

Integral bridges can be made earthquake-resistant more conveniently than bridges with bearings. Apart form obviating the necessity of providing seismic restrainers and/or wide support lengths for the superstructure, the number of potential locations of plastic hinges can be increased, and ductility of a high order introduced into the system. A good example of an integral bridge is shown in Figure 10 wherein the potential seismic performance was greatly enhanced and the associated problems of a deck with significant skew (70^0) were overcome. Another recent example of a flyover designed on the integral bridge principle is shown in Figure 11.

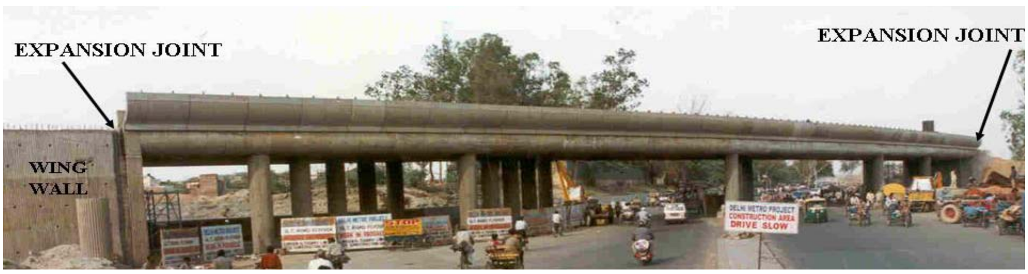


Fig. 10 Flyover using 'Integral Bridge' concept for Delhi Metro (the curved flyover has 70º skew and has no bearings or expansion joints on piers/abutments; length: 115 m)

Fig. 11 Kalkaiji Flyover: Integral construction, high durability, low maintenance, increased safety during earthquakes

BASE ISOLATION, ENERGY DISSIPATION AND ELASTOMERIC BEARINGS

The use of special devices that reduce the seismic forces can be effectively utilized in the structure. By decoupling the structure from seismic ground motions it is possible to reduce the earthquake-induced forces in it. This can be done in two ways:

- Increase natural period of the structure by base isolation,
- Increase damping of the system by energy-dissipating devices.

The central issues are to limit the seismic energy entering into the structure from the ground in the first place and then to dissipate as much of it as possible by damping devices.

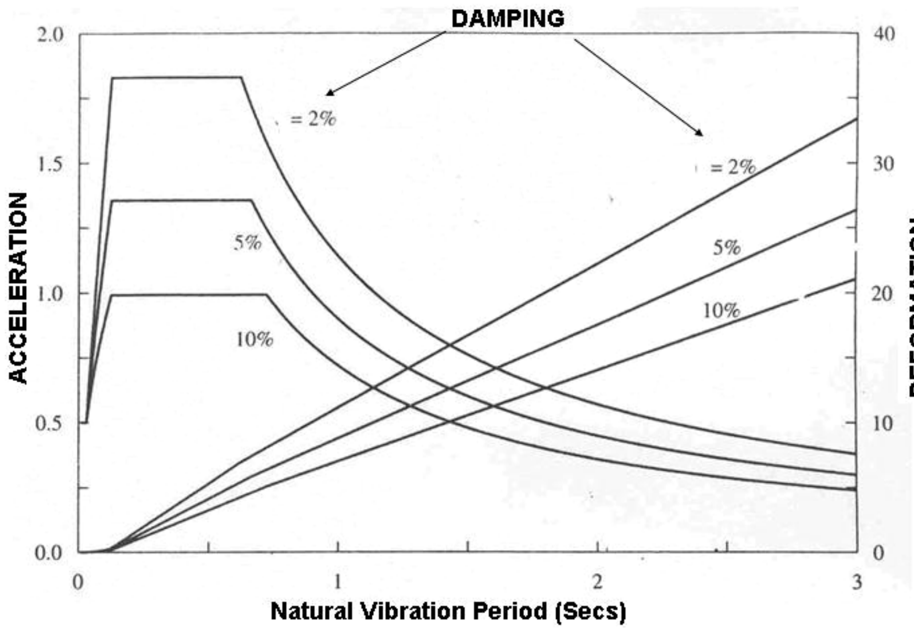


Fig. 12 Elastic response spectrum

By incorporating a layer of discontinuity (such as a properly designed elastomeric bearing) which has a low lateral stiffness as compared to the structural elements above and below it, the natural period of the structure with a "fixed-base" can be elongated substantially. Increasing the natural period of the structure invariably results in increased deformations (see Figure 12). Such deformations need to be controlled so that the resulting stiffness of the structure is appropriate to its serviceability requirements. Some devices incorporate features of both base isolation as well as energy dissipation. Examples of such devices include high damping rubber bearings (HDR) and lead rubber dampings (LRB) as shown in Figure 13. It is highlighted that usual elastomeric bearings designed in accordance with IRC (1999) may not be suitable in this regard. Only standard devices having detailed experimental data of their performance should be used (BIS, 2002). Eurocode 8 (CEN, 2005) distinguishes between “special” and “normal” elastomeric bearings. Only the former type can be used for base isolation/energy dissipation, subject to prototype tests prescribed in an appendix to the same code.

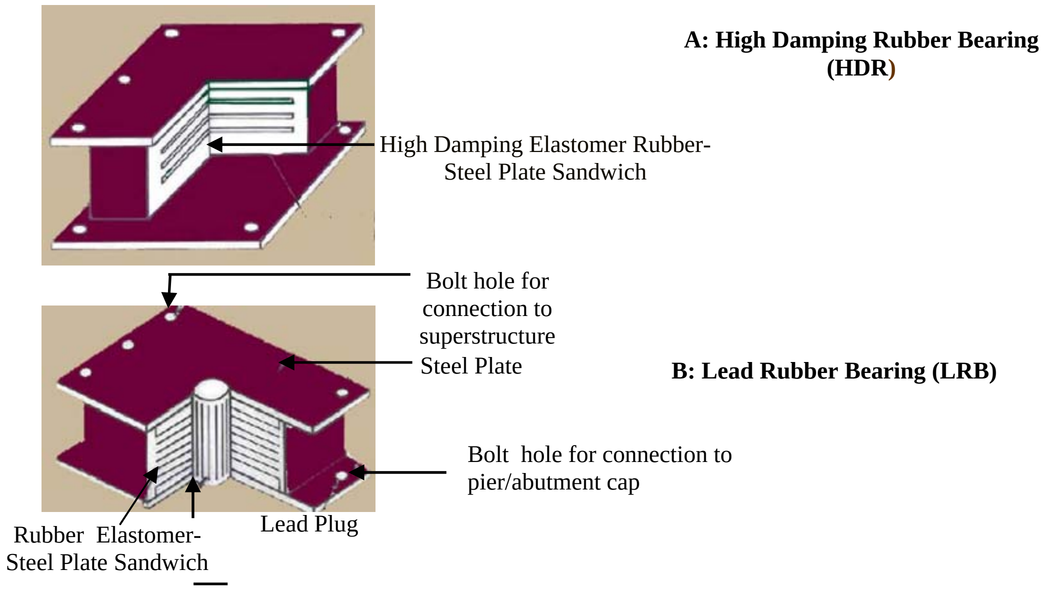


Fig. 13 Base isolation and energy dissipation (two in one)

ENERGY SHARING

Sometimes it is advantageous that the seismic energy entering from the ground into the structure does not get localized. Special devices exist which can avoid significant energy accumulation and ensure its distribution to various structural elements. Here, the idea is not to reduce the total seismic energy entering into the structure but to judiciously distribute it amongst all the designated resisting elements. Such devices go by the name of Shock Transmission Units (STUs). Their action is shown in Figure 14, the behaviour being similar to a car seat-belt. As Structure A and Structure B move slowly relative to each other, the fluid is able to migrate through narrow orifices from one side of the piston to the other. For rapid movements (e.g., earthquakes) the transfer of fluid is not possible thereby locking the piston to its cylinder. In such circumstances the device acts as a rigid link between Structure A and Structure B. In bridge structures the inertial force from the superstructure can be transmitted to designated sub-structures. Application of STUs to a 1.0 km long bridge with expansion joints only at the abutments and central pier is shown in Figure 15, wherein the seismic forces are transmitted to three piers in each of the two halves of the structure.

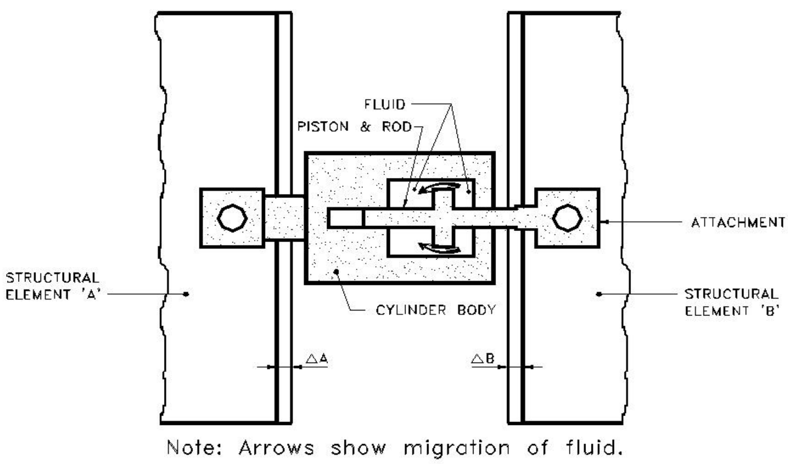


Fig. 14 Shock Transmission Unit – The principle

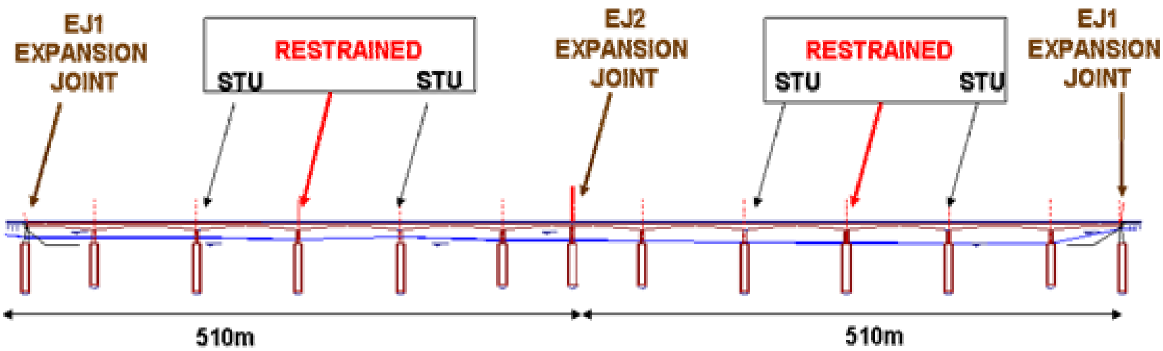


Fig. 15 NHAI's Ganga Bridge at Allahabad showing application of STUs

CONCLUSION

There is scope after both 'passive' control by prescribed detailing procedures as well as 'active' control by specific devices for earthquake-resistant bridges. The judicious use of these ideas can lead to economical and safe bridge structures.

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