PRACTICAL RETROFIT MEASURES TO IMPROVE THE SEISMIC PERFORMANCE OF EXISTING HIGHWAY BRIDGES

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A conclusion of the studies of the earthquakes in Alaska in 1964 and San Fernando in 1971 was that to design a bridge to entirely resist the effects of strong-motion seismic loading is both impractical and uneconomical. Interest in retrofitting existing highway bridges to minimize such damage increased dramatically after the San Fernando earthquake, which caused extensive damage to the California freeway system, including bridges under construction and those newly completed. Cost-effective retrofit measures can be practically and economically implemented and have the effect of minimizing damage resulting from strong-motion seismic loading rather than eliminating it entirely. This paper describes various types of retrofit measures and discusses a numerical seismic method of analyzing their effectiveness. A bridge in northern California, a region of high seismic activity, is described and analyzed. The bridge is mathematically modeled as a three-dimensional space frame and is subjected to a hypothetical earthquake in the form of ground surface displacement time histories based on a statistical evaluation of the seismicity of the site. The bridge is first analyzed as built to determine whether retrofitting is necessary and, if so, the failed components. The candidate retrofit measure is then incorporated into the bridge model, and the analysis is performed again. Results from both cases in the form of displacement and force-time history plots are presented and discussed, and the performance of the retrofit measure is evaluated.

•ON MARCH 25, 1964, south-central Alaska, one of the most active seismic regions in the world, suffered an earthquake of unusually large magnitude: between 8.3 and 8.6 on the Richter scale. The engineers who inspected the highway system after the earthquake concluded that to design a bridge to totally resist the effects of strong-motion seismic loading is both impractical and uneconomical (1).

The San Fernando earthquake of February 9, 1971, although of a much lower magnitude (approximately 6.6), caused considerable damage to freeway structures. A report of the damage sustained by these structures during the earthquake (2) recommended that overpasses and bridges in areas not affected by the earthquake be reëxamined to determine their seismic resistance and, if necessary, that they be modified to at least prevent collapse in the event of strong seismic loading. As a result of the San Fernando earthquake investigations, the California Department of Transportation established a $5 million retrofit program to increase the seismic resistance of 120 bridges by introducing relative longitudinal motion restrainers at points of discontinuity (i.e., hinges and bearing seats) in the superstructure (Figure 1).

Interest in retrofitting highway bridges to increase their seismic resistance has become fairly widespread since the San Fernando earthquake. Outside of California, no retrofit measures have been implemented on existing bridges. The damages sustained by bridges in both the Alaska and San Fernando earthquakes and conclusions based on postearthquake inspections indicate that, if areas of potentially low seismic resistance on a bridge could be practically and economically modified to restrict earthquake damage, the savings of money and possibly lives after just one severe earthquake would easily outweigh the cost of retrofitting. Obviously, in regions of great seismicity (a

Figure 1. California hinge restrainer type C2.

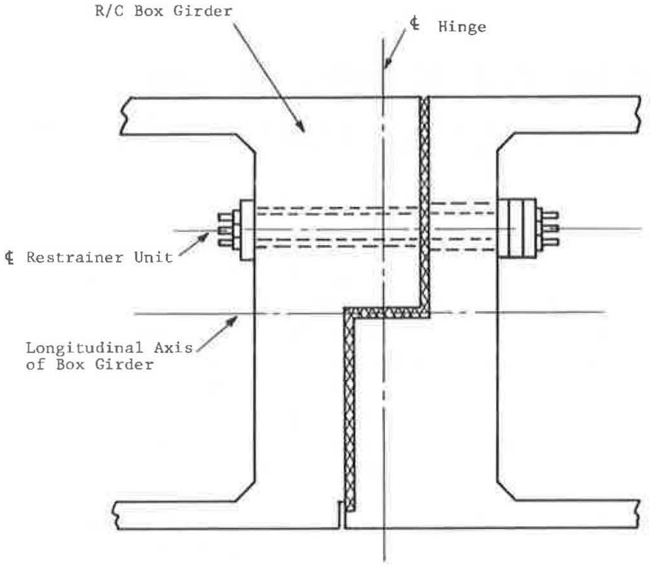
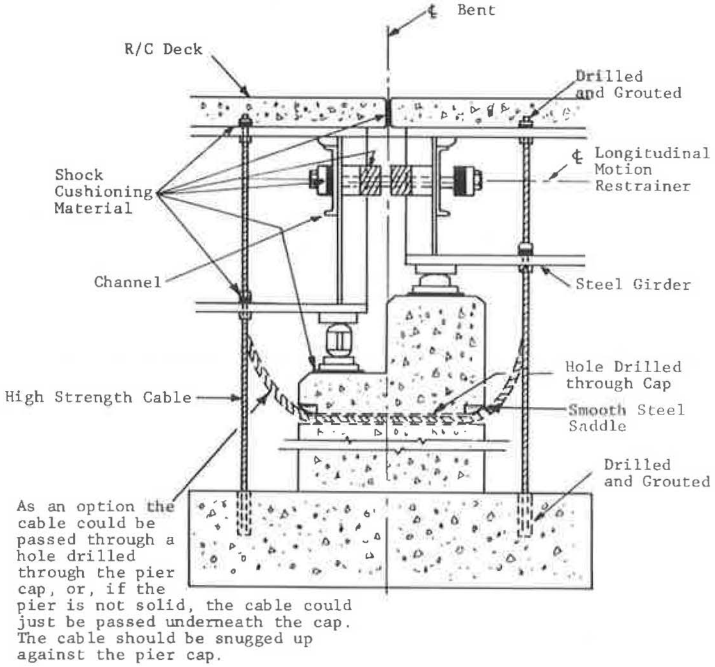


Figure 2. Relative longitudinal motion restrainer and high-strength cable for preventing uplift of superstructure.



function of the frequency of occurrence and the magnitude of earthquakes) the possible benefits are great.

Before any bridge is retrofitted, decisions must be made on whether the bridge actually needs retrofitting and, if it does, what types of retrofit measures to use. For a retrofit measure to be cost effective, it must be both practical and economically feasible to use, and its purpose is to minimize damage rather than to eliminate it entirely. One method for determining whether a bridge needs retrofitting is a numerical seismic analysis of the candidate bridge subjected to a hypothetical earthquake based on the seismicity of the bridge locality (unless the bridge can be analyzed by thoroughly inspecting the bridge details). If the analysis indicates that some type of critical failure (extensive enough so that the bridge could not remain in even emergency use) will occur, the retrofit measure should be based on the mode and extent of failure. Strengthening a component that is susceptible to a particular mode of seismic damage may actually lead to a different mode of failure or possibly to failure of another component. For example, a bridge may experience large relative longitudinal displacements between spans or at the abutments. Reducing these displacements by some type of longitudinal motion restrainer can increase the seismic loading of an intermediate support, which may fail and, in turn, lead to failure of the superstructure. The retrofit measure selected should be incorporated into the numerical bridge model, and the model should again be subjected to seismic loading to check its effectiveness in minimizing damage.

RETROFIT MEASURES

A retrofit measure is any means of increasing the seismic resistance of an existing bridge. There are many ways to do this; the problem is to find those that are cost effective. The following retrofit measures are being investigated (3):

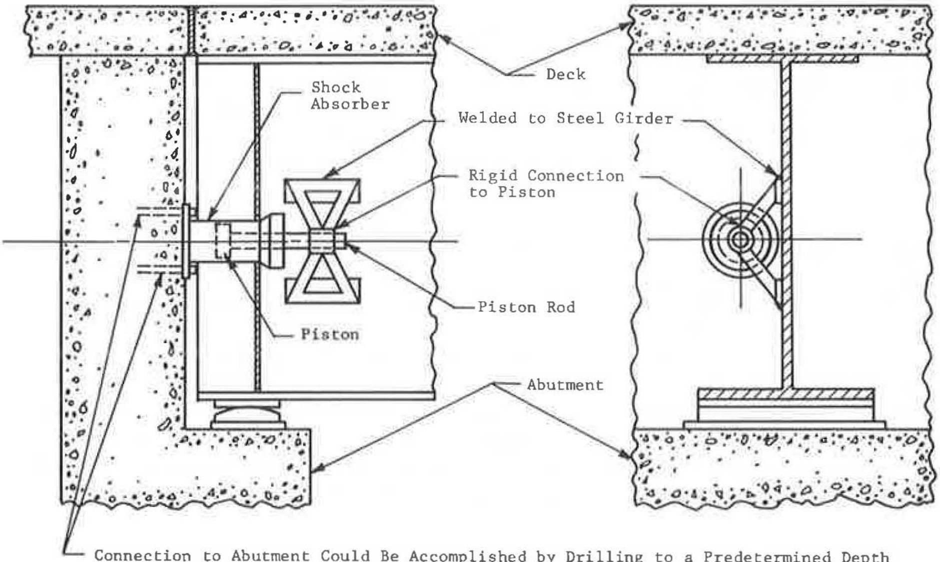
1. Restricting longitudinal, vertical, and lateral relative displacements of the superstructure at expansion joints, bearing seats, and so on by means of cables, tie bars, shear keys, extra anchor bolts, and metal stoppers (Figure 2);
2. Restricting rigid body motion of the superstructure by connecting it (e.g., with high-strength steel cables as in Figure 2) to a supporting or an adjacent foundation or pier cap, by enlarging bearing areas, or by placing stoppers at edges of bearing areas;
3. Reducing induced vibrations by installing energy absorbing devices such as elastomeric bearing pads at bearing seats or adapting the new Japanese shock absorber type of damper that allows slow movement, such as displacement due to creep, shrinkage, and temperature change, with negligible resistance but that develops a large resistance in the case of a rapid displacement, i.e., high velocity, such as that caused by an earthquake (4) (Figure 3); and
4. Strengthening supporting structures.

As a specific example of item 4, the strength of an existing column can be increased by adding longitudinal and spiral reinforcement to the exterior of the column and then bonding the added reinforcement with a new layer of high-strength concrete by using pressure grouting procedures or gunite. The additional longitudinal reinforcement can also be extended into the cap and the footing, and thus the flexural strength of the column-to-cap and column-to-footing connections is increased (Figure 4).

These are not the only methods of cost-effective retrofitting. Numerical seismic analysis, based on the finite element method, allows us to approximate the differential equations of motion for a structure by a system of linear algebraic equations. The degree of accuracy attainable is limited by factors such as the time and money available; hence, the determining test of the cost effectiveness of some retrofit measures may be their performance during actual seismic loading.

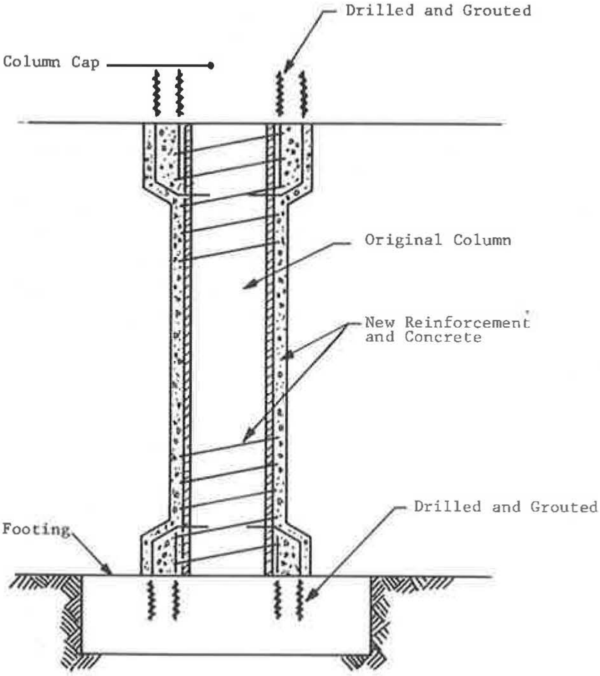
Using the shaking table to test retrofit devices will probably be proposed in the near future. Such testing will require that the bridge, or a portion thereof, be modeled along with the retrofit device. Again, time and money are the factors to be considered. The time involved in the mathematical modeling of a bridge is considerably less than that

Figure 3. Possible adaptation of Japanese shock absorber type of damper.



Connection to Abutment Could Be Accomplished by Drilling to a Predetermined Depth and Grouting in Anchor Bolts, Or, If Possible, Drilling All the Way through the Back Wall and Connecting to a Steel Plate.

Figure 4. Strengthening of column.



required to make a realistic scale model of the whole bridge or even of just selected portions of interest. Constructing a physical model of only a portion of a bridge eliminates the ability to see how different parts of the bridge interact with each other, which is important in determining the cost effectiveness of a retrofit measure. After the mathematical model of the bridge is completed, relatively little time is required to incorporate various retrofit measures into the model. Aside from the difficulty of modeling a bridge for shaking table testing, there is also the problem of applying realistic seismic loading. The problem is not difficult numerically, but with a shaking table it requires inducing three independent directions of translational motion, which, to the authors' knowledge, cannot be achieved by any existing shaking tables.

A shaking table test could be used to check the results of a numerical analysis. If a mathematically modeled bridge were subjected to the type of motion reproducible by a shaking table, the response should be the same from both tests. Hence, shaking table testing could have an important role in the development of seismic analysis computer programs.

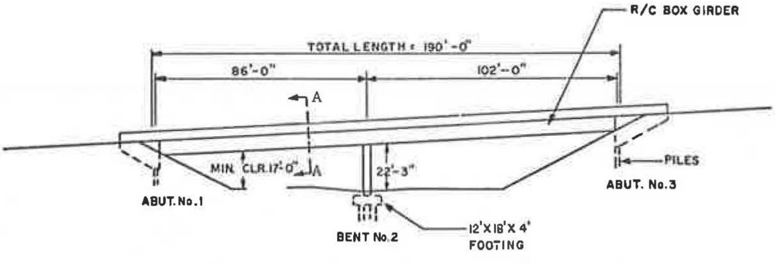
APPLICATION OF TECHNIQUE

The bridge chosen for the analysis, one of seven currently being studied (3), is the Bahia Overcrossing, bridge number 23-161, near Benecia, California (Figure 5). It is a two-span continuously reinforced concrete box girder, built-in at the abutments, with a single-column reinforced concrete bent [3 by 8-ft (0.9 by 2.4-m) cross section] as the intermediate support. The stub abutments are founded on a single row of piles with enough flexibility to allow for normal longitudinal movement. The intermediate support is founded on pile footing. The soil of the bridge site consists primarily of loose to dense dark brown silt with some fine to coarse sand and gravel.

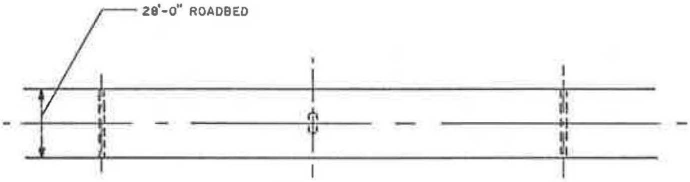
The hypothetical earthquake used in the bridge analysis was generated by a procedure (3) that, based on a statistical evaluation of the seismicity of the bridge site, results in simulated ground surface displacement time histories (Figure 6). Figures 7 through 9 show selected displacement, force, and moment time histories resulting from the seismic analysis of the unretrofitted bridge. When these results were compared with previously calculated ultimate moments, shear, and axial forces, the internal bending moment near the top of the column about the lateral axis of the structure approached and exceeded the ultimate value (the largest magnitude attained was 120 percent of the ultimate) repeatedly for approximately 16 sec corresponding to the period of strongest vertical and horizontal motion. The axial force in the superstructure repeatedly approached the calculated ultimate during this same time interval, but this is not deemed to be a serious threat to the structural integrity of the bridge.

It should be noted that the computed ultimate bending moment was based on the assumption that the column was under pure bending. This results in a lower ultimate than one based on combined axial and bending loading, which is actually the case. To determine the effectiveness of the retrofit measure, however, we will assume that the column failed in flexure. The area most vulnerable to damage is the top portion of the column. An immediate retrofit measure is to strengthen the column by using the method shown in Figure 4. Figure 10 shows the time history plot of the internal bending moment near the top of the retrofitted column. The largest magnitude attained is 88 percent of the computed ultimate bending moment for the retrofitted column. Adding longitudinal reinforcing bars and concrete to the exterior of the column leads to an increase in the maximum bending moment of the column during the hypothetical seismic loading. The ratio of the moment for the retrofitted case to the unretrofitted is 1.19. At the same time, the retrofit leads to a 61 percent increase in the computed ultimate bending moment; the ratio of the retrofitted case to the unretrofitted was 1.61. There was essentially no increase in the internal forces for the unretrofitted portions of the structure, i.e., the superstructure.

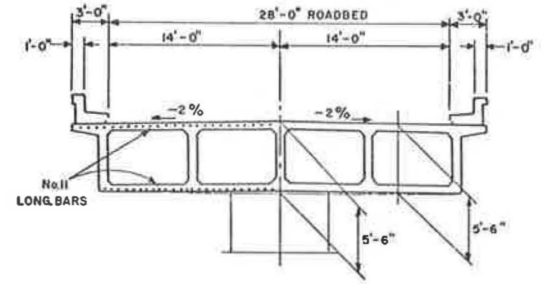
Figure 5. Bahia Overcrossing, 5 miles (8 km) northwest of Benecia, California.



Elevation

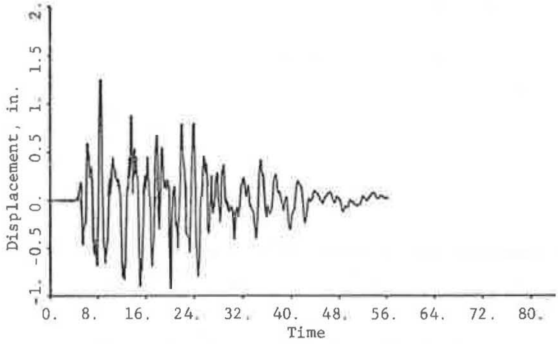


Plan

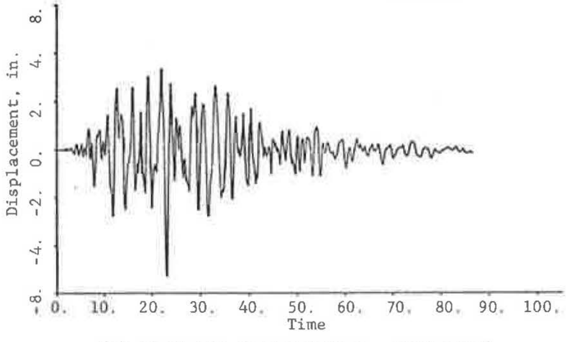


A-A: Typical Section

Figure 6. Seismic characteristics of bridge site.



(a) Simulated Ground Motion - Vertical



(b) Simulated Ground Motion - Horizontal

Engineering Seismicity: 5.295
Richter Magnitude: 8.10
Maximum Horizontal Ground Displacement (inches): 5.25
Maximum Vertical Ground Displacement (inches): 1.25

Figure 7. Vertical displacement at middle of span 1 over time.

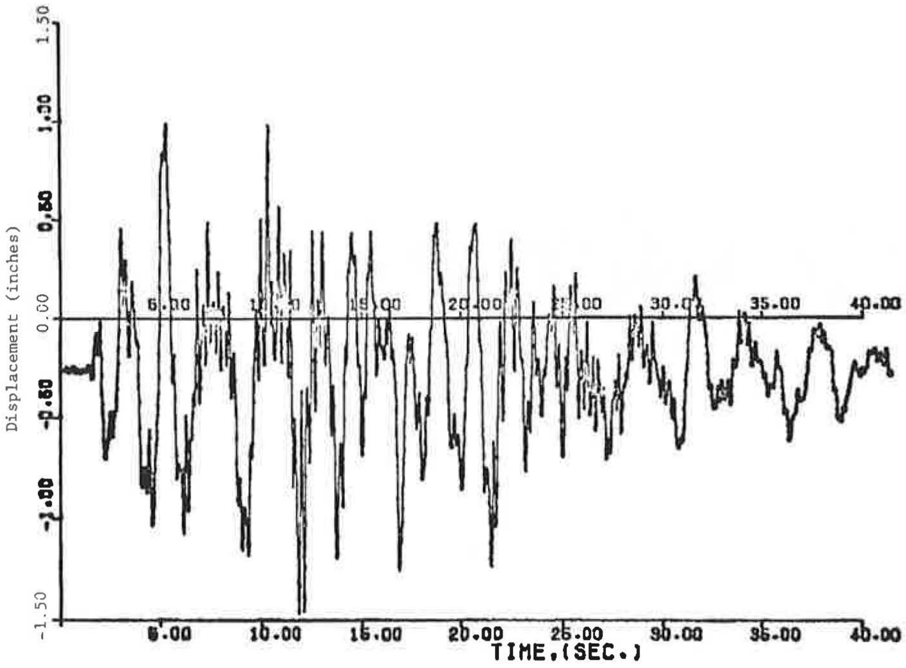


Figure 8. Axial force in superstructure over time.

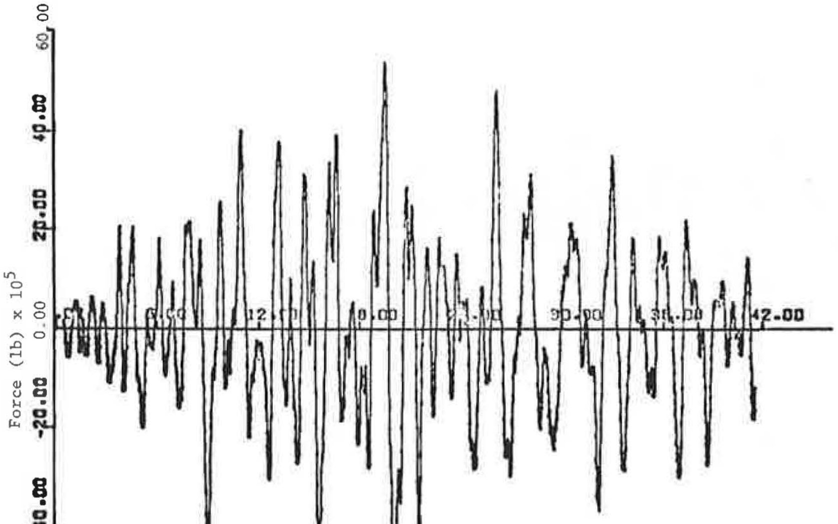


Figure 9. Bending moment at top of column over time.

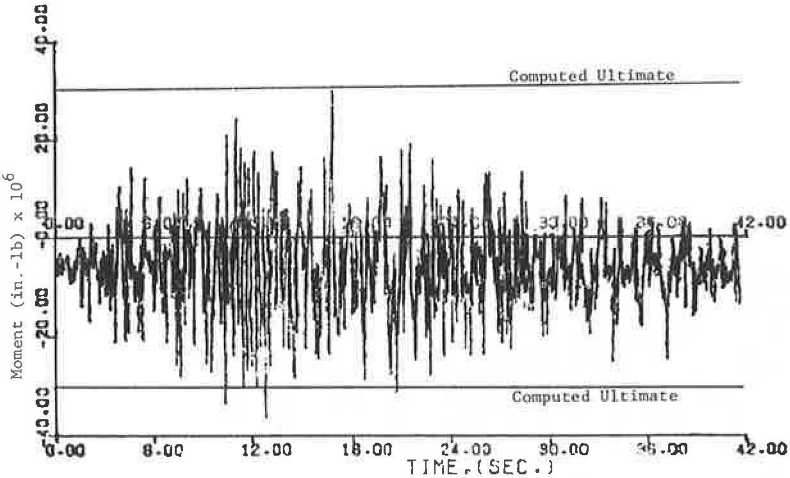
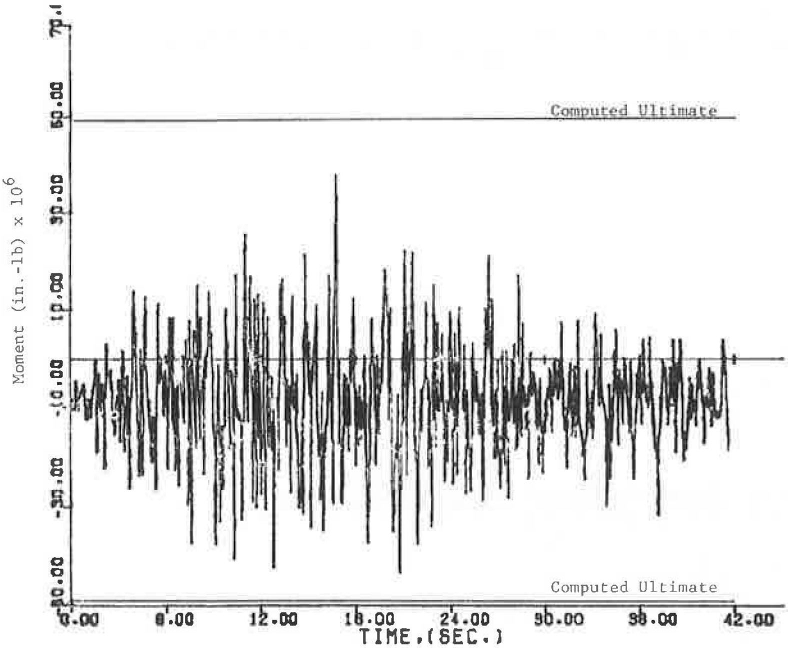


Figure 10. Bending moment at top of retrofitted column over time.



SUMMARY AND CONCLUSIONS

Designing a bridge to totally resist damage caused by strong-motion seismic loading is both impractical and uneconomical. If areas of potentially low seismic resistance on an existing bridge could be practically and economically modified (retrofitted) to restrict earthquake damage, the saving of money (and possibly lives) after just one severe earthquake would easily outweigh the cost of retrofitting.

When a mathematically modeled bridge was subjected to a hypothetical earthquake, an area of possible failure was the top portion of the column, where the bending moment (about the lateral axis of the structure) attained a value 20 percent greater than the computed ultimate. After the model was altered to simulate the strengthening of the column by using the method shown in Figure 4, the bending moment of the retrofitted column reached a peak value of 88 percent of the computed ultimate for the retrofitted column. This, combined with the observation that the structural integrity of the superstructure was not affected by the retrofit, leads to the conclusion that, for this bridge, strengthening the column by adding longitudinal reinforcing bars and concrete to the exterior of the existing column is an effective retrofit measure. Also, because interference with traffic would be minimal and the cost would be fairly low, we can say that this is a cost-effective retrofit measure for this bridge.

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