SEISMIC DESIGN AND RETROFIT OF BRIDGES ON MISSOURI'S EARTHQUAKE PRIORITY ROUTES

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Abstract

The heart of the New Madrid Seismic Zone lies in the southeast corner of Missouri. This was the site of a series of very powerful earthquakes that took place during the winter of 1811-1812. The New Madrid Seismic Zone affects approximately 1,900 of the Missouri Department of Transportation's 10,000 bridges. This paper will briefly describe the seismic classification of the structures, details of a typical retrofit on a routine structure and the cost required to bring a small subset of the bridges up to the current seismic design provisions.

Introduction

New Madrid, Missouri is the location of a violent series of earthquakes that took place during the winter of 1811-1812. During this period, five major earthquakes with estimated magnitudes (Ms) greater than 7.7 and over 200 events with Ms greater than 4.3 took place. Otto Nuttli estimated that approximately 2000 total events with Ms greater than 3.0 occurred *(1)*. The New Madrid Seismic Zone (NMSZ) is located in the central United States and encompasses portions of Missouri, Illinois, Indiana, Kentucky, Tennessee, Mississippi and Arkansas.

The heart of the New Madrid Seismic Zone lies in the southeast corner of the State of Missouri. Soil conditions in this area, commonly referred to as the "Boot Heel," are primarily loose to dense sands that range from meters to a couple of kilometers thick. As one travels north along the Mississippi River the layers of sand gradually thin with competent limestone rock very near the surface in some areas. Parts of southeast Missouri underwent widespread liquefaction during the earthquakes of 1811-1812 as evidenced by numerous sand boils still visible in the area.

The potential for future large earthquakes in the NMSZ exists and potential damage to the State of Missouri's transportation infrastructure is high. Missouri began designing bridges for seismically induced forces in 1990. This paper will briefly describe: the provisions used to design bridges for seismic forces, a typical retrofit on a routine bridge and the Missouri

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Department of Transportation's (MoDOT) Earthquake Response Plan development.

Seismic Design in Missouri

Missouri currently (2003) uses the provisions of Division IA found in the 17th Edition of the AASHTO *Standard Specifications for Highway Bridges (2)*. The seismic hazard presented in the Division IA provision is based on the 1988 U.S. Geological Survey (USGS) map with a 90 percent probability of not being exceeded in 50 years. This is equivalent to a 10 percent probability of exceedance (PE) in 50 years and is approximately equivalent to a return period of 500 years. A map of Missouri showing the current acceleration coefficients is presented in Figure 1. Missouri's ten districts are also shown on the figure. The Division IA provisions divide the seismic design of structures into four seismic performance categories (SPC). Categories are labeled A, B, C and D. The seismic performance category is based on the horizontal acceleration shown on the USGS map at the bridge location and the importance classification (IC) of the structure. An importance classification is only assigned for bridges with acceleration coefficients greater than 0.29 g. Essential bridges are given the importance classification I, any other bridge is given the importance classification II. Classification of the structure is based on security/defense and social/survival requirements. Table 1, taken from the AASHTO Division IA provisions *(2)*, describes the basis for the selection of the seismic performance category.

Missouri has approximately 10,000 bridges in the state bridge inventory and approximately 13,000 additional structures under county, city or local jurisdiction. Of the 10,000 bridges in the state bridge inventory, approximately 1,900 are in seismic performance categories B, C and D. Bridges in these categories (~1,250 in B, ~520 in C and ~130 in D) require additional effort and expense to design and construct to resist the seismic hazard. The Missouri Department of Transportation (MoDOT) began designing bridges to resist seismic hazards in 1990. However, many of the structures listed above in SPC B, C and D were not designed to resist seismic induced forces. Several structures in St. Louis that were designed and constructed before 1990 have been retrofitted to resist seismic induced forces. The retrofit of a typical bridge on an earthquake priority route will be described in the next section.

Typical Seismic Retrofit of a Routine Bridge

In the past 12 years MoDOT has retrofitted a number of routine structures to resist seismic forces. Most of the structures that were retrofitted were in SPC B. Typical retrofit details on the routine structures include replacing high profile steel pin and rocker bearings with neoprene elastomeric pads, adding restrainer cables to girder expansion joints, placing steel jackets around columns and strengthening footings.

This section will describe the retrofit of a typical interstate overpass. Bridge A32073 in St. Louis County, Missouri is located on Interstate 70 and crosses the Earth City Expressway. The structure is a four span (31'-55'-55'-31', 9.45 m-16.8 m-16.8 m-9.45 m) continuous composite wide flange steel beam bridge. Total length of the structure is 175' (53.3 m) and the width is 177.5' (54.1 m). Figure 2 shows the general elevation of the structure. The retrofits to the bridge will be described beginning at the deck level and working down. Figure 3 shows the elevation of the structure and notes where seismic retrofits were applied. The contract bid cost of the retrofit was $327,673. The estimated cost to replace this structure would have been approximately $1,500,000 to $1,800,000.

High profile steel bearings at each of the intermediate bents were replaced with neoprene elastomeric pads. Intermediate bent number 3 was the fixed pin of the bridge in the original configuration. Intermediate bents number 2 and 4 both had rocker bearings, as did the end bents number 1 and 5. Figure 4 shows the front and side view of the replacement elastomeric bearing pad detail. During earthquake shaking the high profile steel rocker bearings had the potential to become unstable and tip over. The rocker bearings at end bents number 1 and 5 were left in place but bearing blocks were added to restrain lateral motion of the end of the girder and catch the beam if the rocker bearing was on the verge of tipping over. See Figure 5.

All columns of the intermediate bents received a 5/16-inch (8 mm) thick steel jacket on the top and bottom of the column. The steel jackets were intended to restrain the plastic hinge joint locations on the columns. The length of the steel jacket on the top and bottom of all interior columns was 3 feet (0.91 m) and 4.25 feet (1.30 m) on the top and bottom of the exterior columns of each intermediate bent. See Figure 6. The inside diameter of the steel jacket was 1.5 inches (38 mm) greater than the diameter of the existing column. This void was filled with grout after the steel jacket was installed on the column.

The existing footings did not have any reinforcing steel in the top of the footing. This makes the footings susceptible to cracking on the top surface as the bridge rocks back and forth during an earthquake. To prevent this cracking, an additional 12" (305 mm) of concrete and two layers of reinforcing steel were added to the top of each footing. The additional concrete and reinforcing was attached to the existing concrete with a series of "L" shaped bars that were resin anchored to the existing footing. Figure 7 shows the typical detail for adding reinforcing steel to the top of the footing and the resin anchor detail.

MoDOT Earthquake Response Plan

In 1999, the Missouri Department of Transportation in collaboration with the State

Emergency Management Agency created an Earthquake Response Plan as a manual for operations after a major earthquake in the New Madrid Seismic Zone. The plan serves as a guide of action to ensure and restore the operational capabilities of the transportation system in the areas affected by an earthquake in the NMSZ. A Bridge Engineering Unit plan was also created as a part of the larger Department response plan. Earthquake Priority Routes were selected as part of the development of the plan. The primary purpose of the priority routes is to have roads identified for personnel, equipment and materials to travel from the MoDOT Headquarters located in Jefferson City to the District 10 Headquarters in Sikeston and the District 6 Headquarters in St. Louis after a large earthquake event. The majority (~1,850) of the bridges in SPC B, C and D are located in Districts 6 and 10.

Two main criteria were used to select the priority routes: avoid major river crossings (if possible) and follow the ridges of the topography. These two criteria were selected to limit the number of structures on the priority routes. Both the route to District 6 and District 10 had to cross the Osage River (a large river crossing) outside of Jefferson City. However, both of the structures on Route 50/63 over the Osage River are newly constructed (one is currently under construction) and designed to resist seismic forces. The structures are also located in SPC A so it is anticipated that the structures will suffer little, if any, damage. Once the routes were selected, the Bridge Engineering Unit and the Maintenance Unit visited each bridge site to take photographs and notes. Information on availability of detours and seismically sensitive details such as girder hinges, short columns and beam seat width were noted. This field information was summarized into a report for each priority route.

The first priority routes from Jefferson City (GHQ) to District 6 (D6) and Jefferson City (GHQ) to District 10 (D10) were further studied to determine the cost to retrofit or replace the deficient bridges on the routes. Additional lower priority routes were also selected for travel between GHQ and D6 and GHQ and D10. However, on these lower priority routes costs and deficiencies were not estimated. A map of the first and second priority routes from GHQ to D6 and GHQ to D10 is shown in Figure 8.

On the route from Jefferson City to St. Louis, GHQ to D6, there are a total of 35 bridges, 29 in SPC A and 6 in SPC B. An estimate was calculated to retrofit and replace all the deficient bridges on the first priority route. Nine of the structures on the route were recently constructed to current seismic design standards. For the remaining 26 structures it was estimated to cost $5,000,000 to retrofit and $29,000,000 to replace the structures. Further screening removed an additional 10 bridges that were deemed to have an "easy" detour. This would include using exit ramps to bypass a damaged or collapsed overpass or using pipes and rock to cross small streams. The estimates to retrofit or replace the remaining 16 bridges were $3,000,000 and $20,000,000 respectively.

The route from Jefferson City to Sikeston, GHQ to D10, is significantly longer than the route from GHQ to D6. There are a total of 93 bridges on this first priority route. Nine structures on this route were also recently constructed to current seismic design standards and therefore require no additional upgrades. The initial estimate to retrofit and replace the remaining 84 structures was $13,000,000 and $64,000,000 respectively. As before the list of structures was reduced by eliminating bridges with "easy" detours or adjacent seismically designed twin structures. A total of 38 bridges remained which did not have a readily available bypass. Estimates to retrofit and replace the remaining 38 structures was $8,000,000 and $35,000,000 respectively.

In summary, there are a total of 128 bridges on the two seismic priority routes that will enable personnel, equipment and materials to travel from the MoDOT General Headquarters to the District offices in the two Districts that will be most affected by a major earthquake. It was estimated (in year 2001 dollars) to cost $18,000,000 to retrofit all the seismically substandard structures on the two routes and $93,000,000 to replace all substandard bridges. These estimates only include bridge related costs and do not include costs of roadway modifications or right-of-way acquisition. One will note that it is substantially less expensive to retrofit the seismically substandard bridges than it is to replace the structures. However, retrofitting many of the structures will only remove the seismic deficiencies while still leaving an inadequate roadway width or load carrying capacity by today's standards. Even with the higher cost of replacement, it was deemed prudent to recommend replacement of many of the structures to address the other deficiencies.

Current funds for replacement of structures are limited and many other priorities exist. Discussions on how to fund the needs to replace deficient structures on the earthquake priority routes took place. It was suggested that a modification in the current funding prioritization method be made to place a higher emphasis for bridges on the earthquake priority routes. However, since the earthquake priority routes only include 67 bridges of the approximately 1,900 bridges in the SPC B, C and D it was thought that the structures would probably not move up much in the funding priority list when all other factors are taken into account.

Bridge Retrofit and Replacement Cost Estimates

Retrofit and replacement cost estimates were based on square feet of existing bridge deck, structure type, and seismic performance category. Deck area of the existing structure was increased by 15 percent when calculating the replacement cost to account for substandard roadway widths and hydraulic conditions. Dollar amounts per square foot of deck area were estimated for five different structure types and the four different seismic performance categories (SPC). The structure types were: plate girders, prestressed concrete beams, deck girders (reinforced concrete tee-beams), slabs and trusses. The estimated costs per square foot of deck area to retrofit and replace are presented in Table 2.

The cost estimates presented in Table 2 are based on actual retrofit costs on structures that were let for bid in the previous years. As mentioned above, the costs were estimated for five types of bridge structures and the four seismic performance categories. Costs were adjusted to account for inflation and reflect year 2001 dollars.

For bridges in SPC B the primary retrofit method for plate girders and prestressed I-girders consisted of applying a steel jacket on single column bents and placing steel restrainer rods across expansion gaps. On steel plate girders, high profile steel bearings were also replaced with elastomeric bearings. On prestressed I-girders the bearings were modified to include dowels to anchor the bearings to the beam cap. Slab and deck girder bridges were also retrofitted with dowel bars to restrain motion at selected supports. Truss structures required modifications to the bearings and anchorage to piers.

Bridges located in SPC C required more extensive retrofit than SPC B. Plate girder retrofit costs were calculated based on a 6-inch concrete jacket on all columns, and lead-rubber isolation bearings. Prestressed I-girders, slab structures and deck girders also required a 6-inch concrete jacket on all columns in addition to the retrofits necessary for SPC B. Since a limited number of retrofits were completed and none of the retrofits were in SPC D the costs estimates for SPC D were obtained by increasing the cost of retrofit for SPC C by 25 percent.

Since adequate funds are not available to upgrade all structures located in zones that may experience seismic hazard, MoDOT is currently creating a policy to further prioritize which structures will be seismically upgraded. Factors influencing which structures are seismically upgraded include: average daily traffic (ADT), is an adjacent twin structure designed with seismic resistance, is the structure on a priority route and can the structure be easily bypassed. For routine structures, seismic upgrade will generally only be considered when the structure is scheduled for rehabilitation due to poor condition of the bridge.

Summary

The Missouri Department of Transportation currently has about 1,900 (out of a total of approximately 10,000) structures that are located in seismically active zones. Many of the structures were built before 1990 when MoDOT began designing structures to resist seismic forces. Therefore, a large percentage of the structures are vulnerable to the seismic hazard that is inherent to their location in the New Madrid Seismic Zone. Several structures have been retrofitted to resist seismic forces. Typical details used on one structure are presented in this paper. MoDOT developed an Earthquake Response Plan that includes the identification of Seismic Priority Routes to enable manpower, equipment and materials to travel from the MoDOT General Headquarters to District Offices that will be most affected by an earthquake in Missouri. Lists of bridges on the priority routes were studied for seismic deficiencies and a cost was estimated to retrofit or replace the deficient structures. Inadequate funds are available to bring all deficient structures up to current seismic design standards so MoDOT is currently devising a method to prioritize which structures will be upgraded with the very limited funds available.

References

1. United States Geological Survey. "Large Earthquakes in the United States: New Madrid 1811-1812." http://neic.usgs.gov/neis/eqlists/USA/1811-1812.html. Accessed September 10, 2003.

2. AASHTO. *Standard Specifications for Highway Bridges*, 17th ed., 2002. American Association of State Highway and Transportation Officials, Washington, D.C.

Table 1 Seismic Performance Category (SPC)

Acceleration Coefficient	Importance Classification (IC)	
A (% of g)	I	II
A ≤ 0.09	A	A
0.09 < A ≤ 0.19	B	B
0.19 < A ≤ 0.29	C	C
0.29 < A	D	C

Taken from AASHTO (2002) Division IA – Seismic Design *(2)*

Table 2 Retrofit and Replacement Costs Per Square Foot of Deck Area (based on year 2001 dollars)

Cost for retrofit ($/ft^2)	SPC			
	A	B	C	D
Plate Girder	$12.70	$25.39	$25.96	$32.45
Prestressed Concrete Girder	$9.87	$19.74	$23.49	$29.36
Slab Structure	$1.89	$1.89	$21.86	$27.32
Deck Girder	$10.56	$21.11	$37.10	$46.35
Truss Structure	$9.45	$18.89	$78.43	$98.04

Cost for replacement ($/ft^2)	SPC			
	A	B	C	D
Plate Girder	$76.00	$80.00	$95.00	$112.00
Prestressed Concrete Girder	$57.00	$60.00	$72.00	$84.00
Slab Structure	$80.75	$85.00	$102.00	$119.00
Deck Girder	$76.00	$80.00	$95.00	$112.00
Truss Structure	$166.25	$175.00	$210.00	$245.00

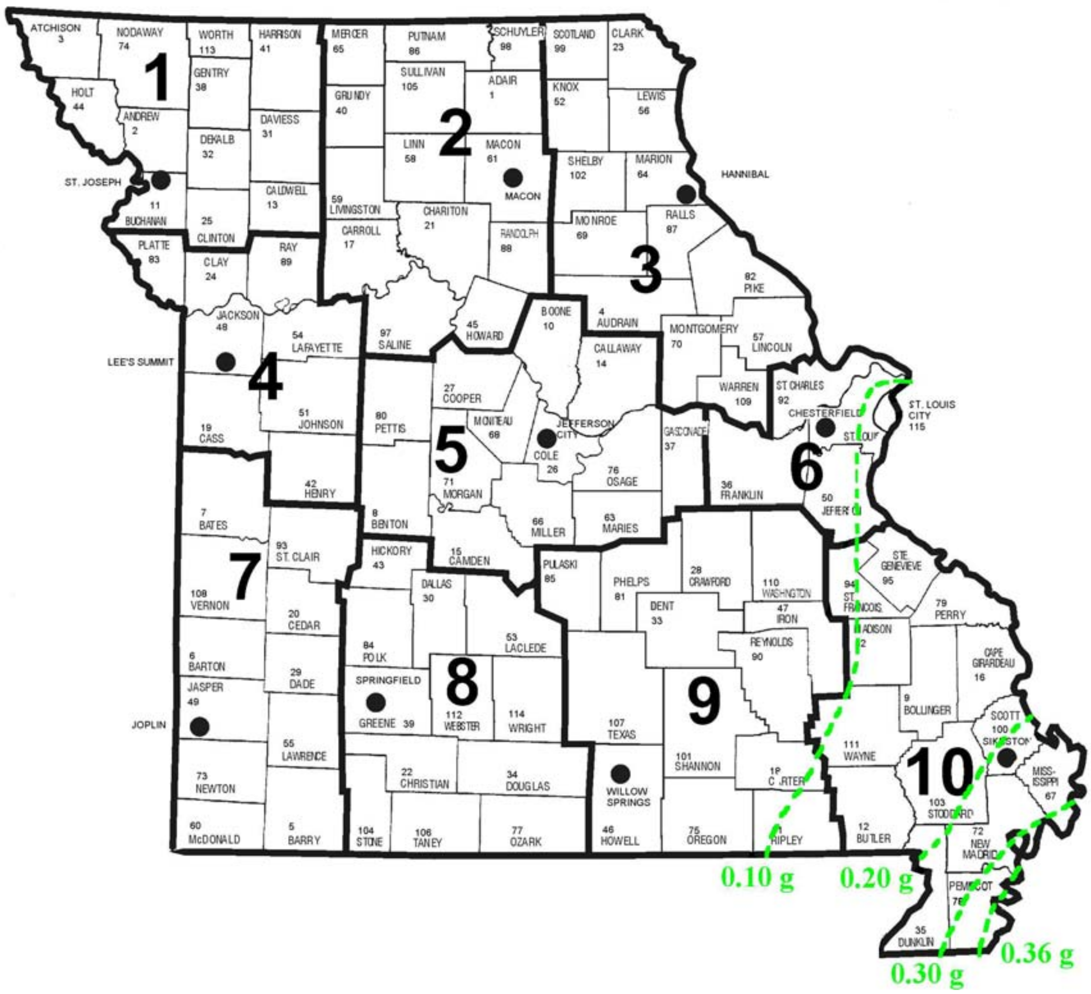

Figure 1 Current AASHTO Division IA seismic acceleration coefficients with a 10% probability of exceedance in 50 years

Figure 2 Elevation of Bridge A32073

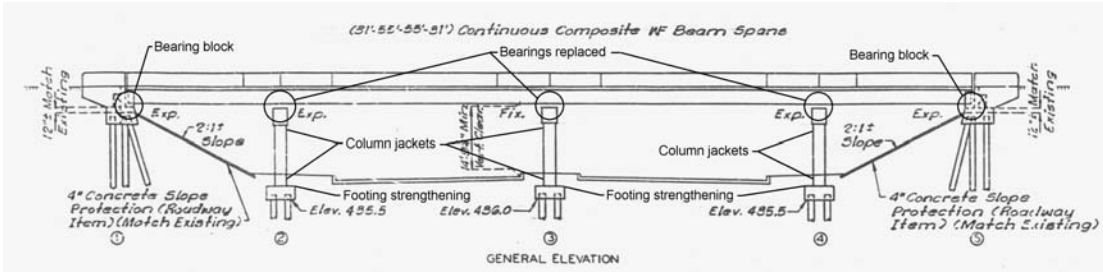

Figure 3 Elevation of Bridge A32073 detailing locations of seismic retrofits

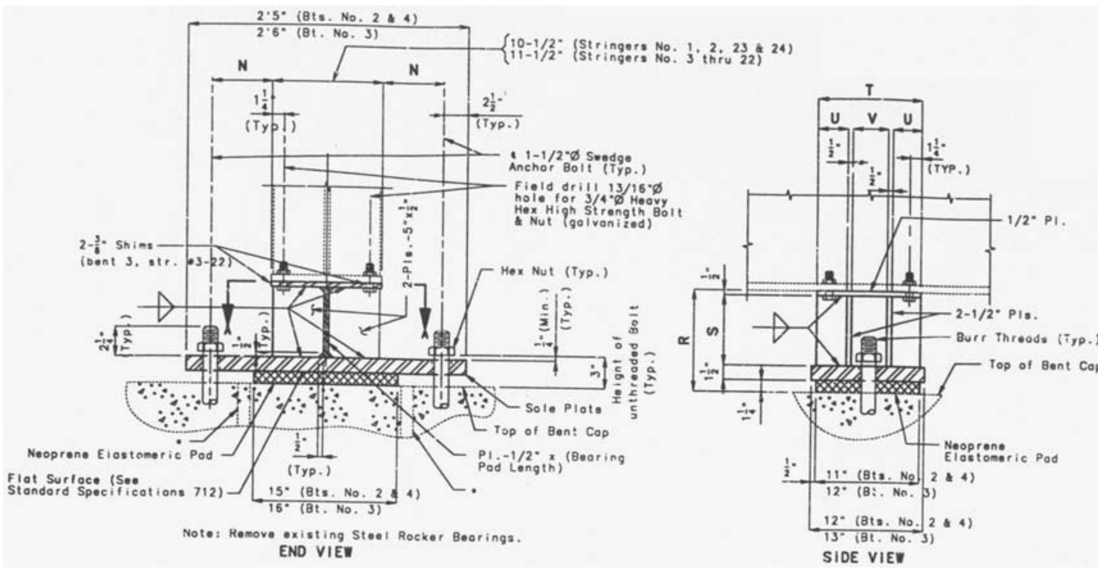

Figure 4 Typical detail of neoprene elastomeric pad used as a replacement for steel bearings at intermediate supports

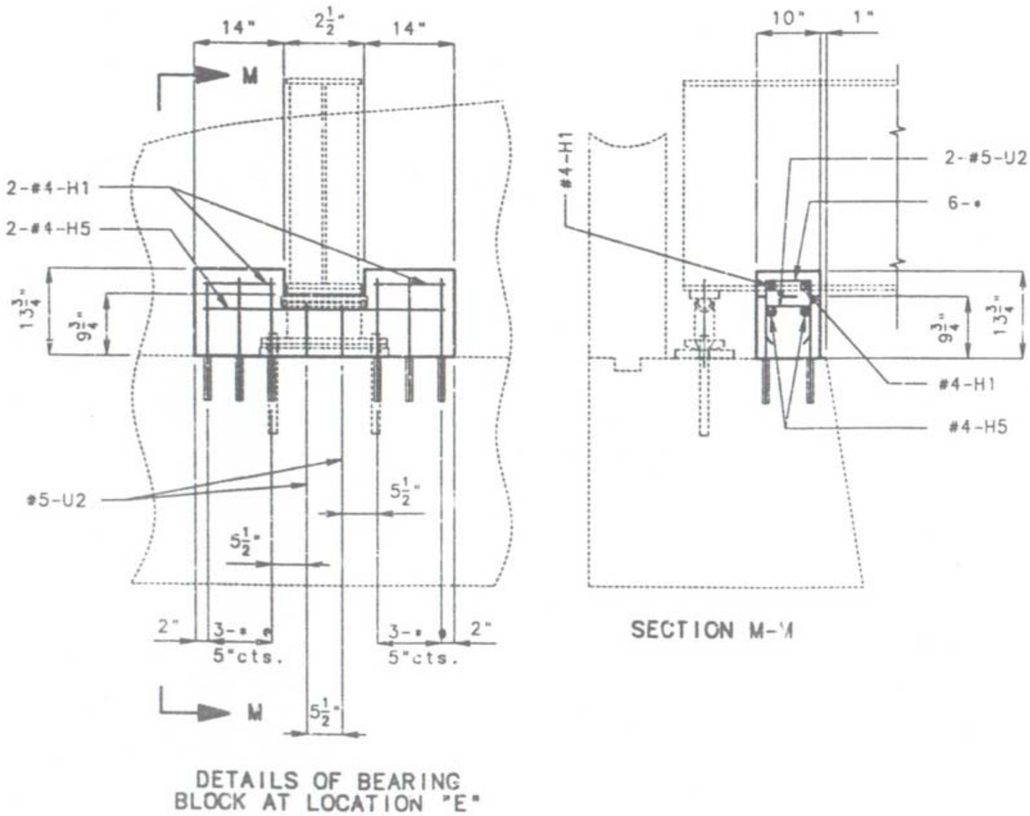

Figure 5   Typical detail of bearing block used at end bents

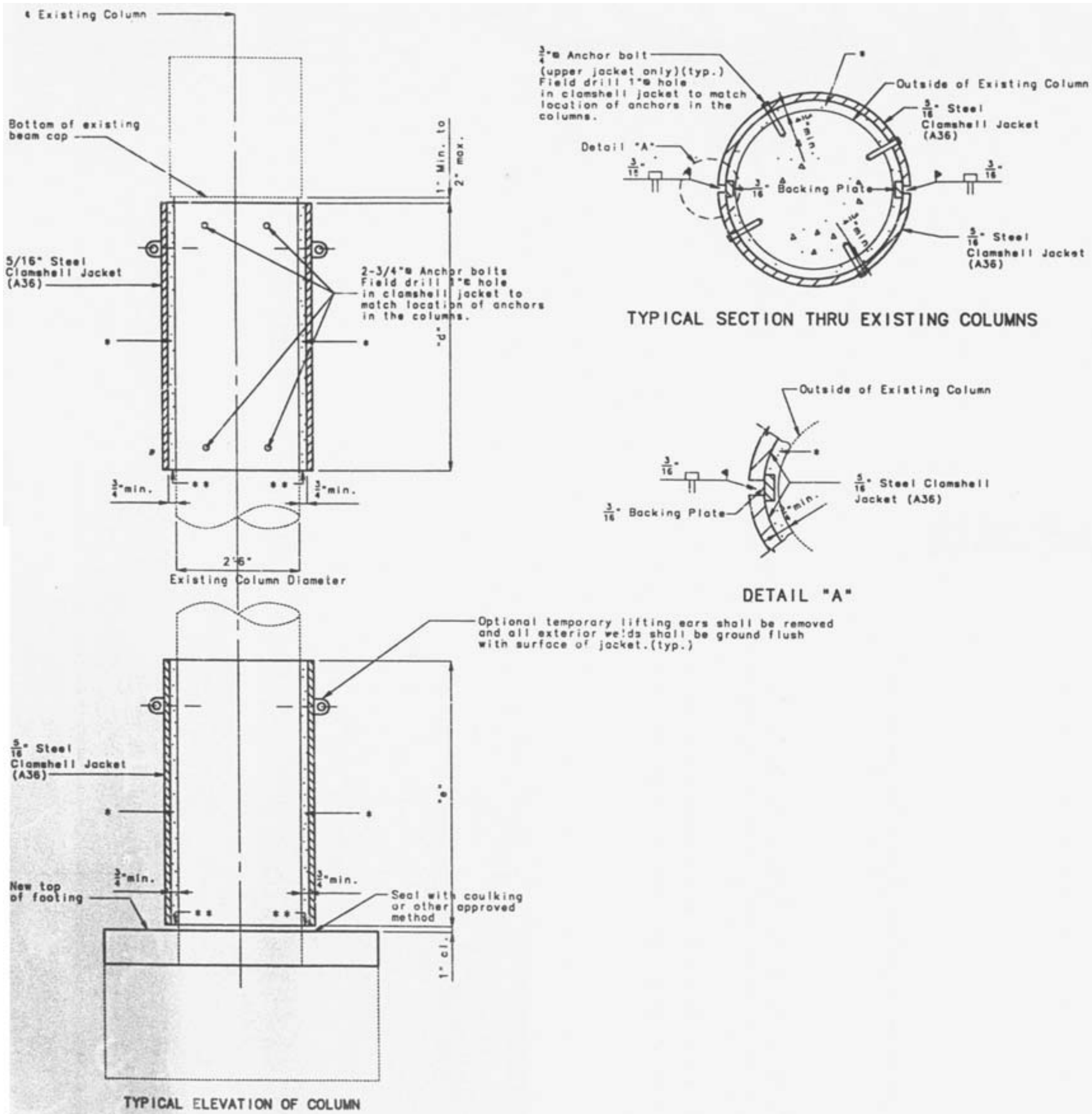

Figure 6 Steel jacket used at top and bottom of all columns on the intermediate bents

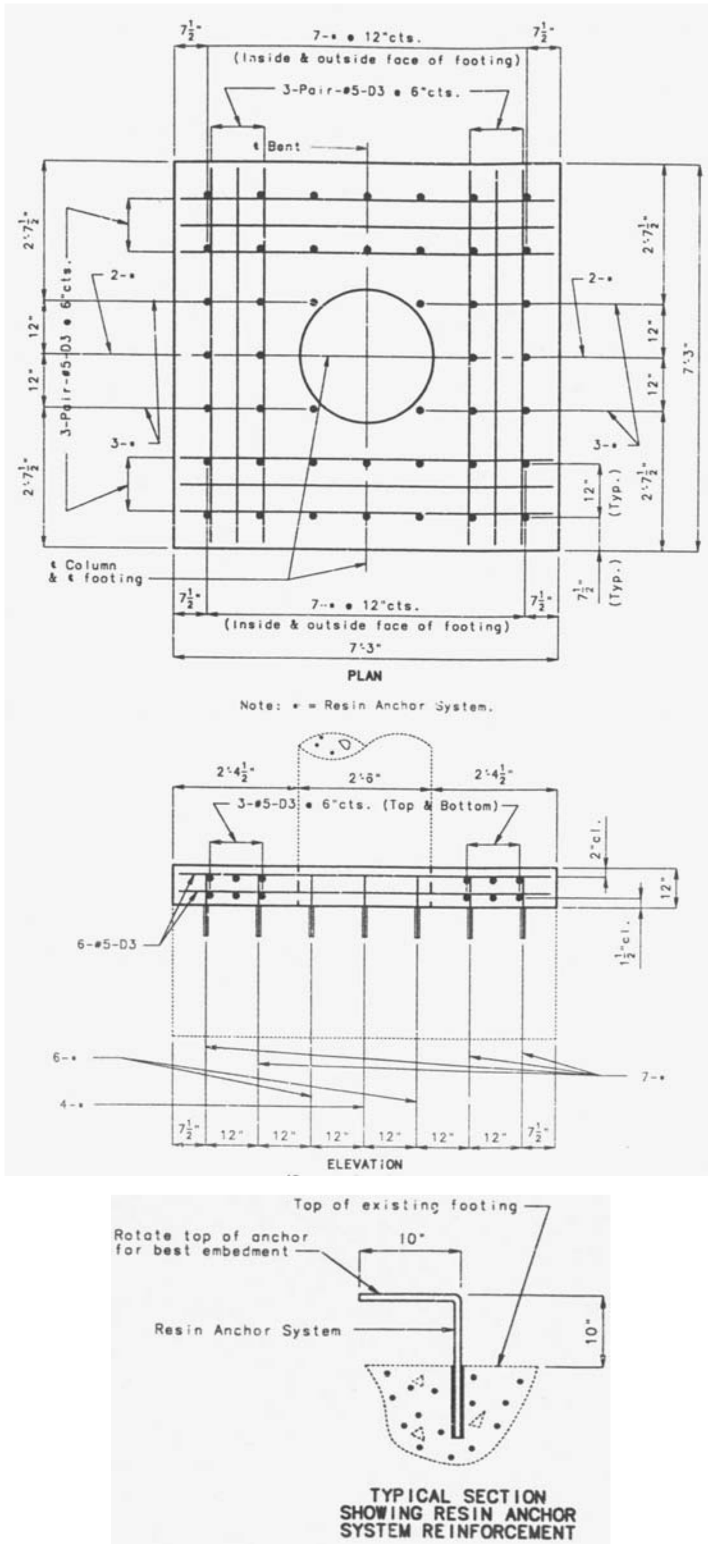

Figure 7 Typical footing retrofit to add reinforcing steel to top of footing

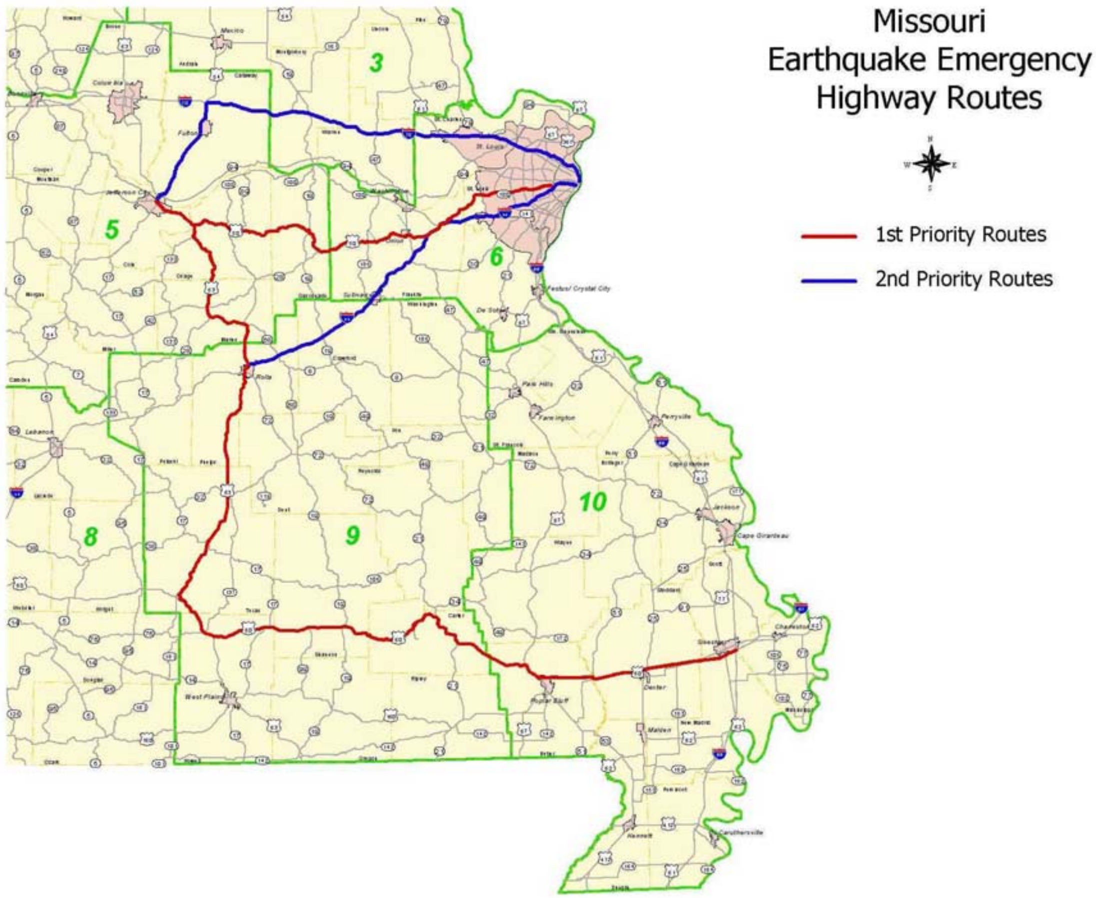

Figure 8 Earthquake priority routes from Jefferson City to St. Louis and Sikeston