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RETROFIT OF BRIDGES FOR AN EARTHQUAKE RESILIENT SOCIETY

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Abstract

The knowledge of earthquake load in the last 50 years has been changing according to the results of the research. In national codes and provisions of European Union, Japan, U.S., duration of most bridges is supposed to be 50 years. Thus, bridges built 30 or more years ago are designed to load that is different from today's knowledge of earthquake load. Many bridges which were built before 1970s which are still in use in either Europe or Japan or the U.S. have been designed with little or with no any consideration for seismic demand. Majority of these bridges lack the ductility and strength to resist earthquakes. Meanwhile strong earthquakes have revealed all vulnerable places and wrong detailing on almost all bridges built in seismic regions more than fifty years ago. After the 1971 San Fernando earthquake the U.S. for the first time in the world started seismic retrofit programs for bridges. Japan also started similar programs, especially after the 1995 Kobe earthquake. European Union may not be out of this global problem and must have own retrofit programs for bridges. Thousands of existing bridges all over the word built more than fifty years ago in earthquake zones are still in operation waiting to be retrofitted in order to withstand earthquake loading defined as a result of up to data of research. In this sense in this paper some solutions, recommendations and comments for retrofitting and rapid recovery of bridges after earthquake using the latest concepts for structural upgrading is presented as the main goal to contribute to the knowledge for an earthquake resilient society.

Keywords: bridges, resilience, earthquake resilient society, earthquake loading, retrofit, seismic hazard

1. Introduction

It is hopeful that the European Union in the HORIZON 2020 infrastructure call MG-7-1-2017 recognized the need for research in resilience to extreme (natural and man-made) events. Emergency functionality and rapid recovery of road networks after a strong intensity earthquake that has triggered additional hazard such as post-earthquake fires, landslides, tsunamis, bridge collapses and a series of large aftershocks is a vital requirement for the sustainability of any modern society, which, in the light of recent earthquakes in Europe and elsewhere, has not yet been properly addressed. It is the main task of our community to avoid zero functionality of bridges immediately after strong earthquake and a speedy recovery of old bridges even for extreme events. Society needs bridges in assessing the transportation needs after an extreme seismic event and during the time of recovery, and how this may lead to the identification of the most critical components and the definition of bridge performances beyond their design limit (robustness). Innovative structural concepts in designing for new and rehabilitation of existing bridges as well as introduction of structural control systems that are capable of providing the required robustness has to be a main goal of a modern society.

Due to the infrastructure increasing decay, frequently combined with the need for structural upgrading to meet more stringent requirements against seismic load, structural retrofitting is becoming more and more important and is given today considerable emphasis throughout the world. In response to this need, permanent theoretical and experimental research in seismic design of bridges as well as studies on the consequences on bridges after strong earthquakes in order to understand better retrofitting of bridges is more like a process.

The important event on this issue in the U.S. was the Annual Meeting in February 2004 in Los Angeles (theme: ten years after Northridge earthquake) organized by the U.S. Earthquake Engineering Research Institute. After the 1971 San Fernando earthquake the U.S. started several seismic retrofit programs. Retrofit programs in the 1980s included the first use of isolators on bridges and a program to retrofit

single-column bents. These programs were greatly accelerated after the 1989 Santa Cruz (Loma Prieta) and 1994 Northridge earthquakes. After the 1994 Northridge earthquake it was observed that no serious damage would have occurred if the previous retrofit program had already been implemented [1, 2, 3]. Japan also started similar programs, especially after the 1995 Kobe earthquake. Europe may not be out of this global problem and must have own retrofit programs not only for buildings but for bridges as well [4, 5, 6]. Design codes must be based on functionality criteria rather than safety.

2. Loading on bridges caused by earthquake (seismic demand)

Bridge engineering uses nowadays scientifically based codes for design and construction of bridges in comparison with the provisions which were in power 50 or more years ago. The main novelty is knowledge in the field of earthquake loading on bridges. After extensive research in the last decades loading on structures caused by earthquake has been defined as seismic demand. This seismic demand is usually defined in the appropriate Euro standard [4, 5, 6] or is defined from real or artificial time-history accelerations or the earthquake response spectrum which came from time-history accelerations. In accordance to the basic condition of structural Eurocodes that the design effect of loading E_d must be lower than resistance of the structure R_d, which means seismic demand lower than seismic capacity:

$$E_d \leq R_d \;\Rightarrow\; \gamma_{dem} \cdot (Seismic\ demand) \leq \frac{1}{\gamma_{cap}} \cdot (Capacity) \tag{1}$$

where: γ_{dem} and γ_{cap} are safety coefficients, greater than 1,0.

There are linear and non-linear methods for seismic analysis of bridges (and buildings) defined in [5, 6]. For the design and construction of bridges (and buildings) in seismic areas the EU standard, as well as Japan and U.S. standards, offer two non-linear methods, namely: a non-linear pushover based static method and a non-linear dynamic method. Non-linear static procedures were developed in the world with the aim of overcoming the insufficiency and limitations of linear methods, whilst at the same time maintaining a relatively simple application. All procedures incorporate performance-based concepts paying more attention to damage control. One simple static nonlinear (pushover) method [7, 8] is introduced in EN 1998 [5].

Loading on bridges is defined through combinations of the seismic action with other actions. The design value of the effects of actions shall be determined in the seismic design combination [6]:

$$E_d = G_k \;"+"\; P_k \;"+"\; A_{Ed} \;"+"\; \psi_{2,1} \cdot Q_{k,1} \;"+"\; Q_2 \tag{2}$$

where: E_d is design value of the effects of actions; G_k is the permanent actions with their characteristic values; P_k is the characteristic value of prestressing after all losses; A_{Ed} is the design seismic action; $Q_{k,1}$ is the characteristic value of the traffic load; $\psi_{2,1}$ is the combination factor for traffic loads; Q_2 is the quasi-permanent value of actions of long duration (e.g. earth pressure, buoyancy, currents etc.).

One example of the behavior of viaduct subjected to seismic action accordance to Eurocodes is given in [9] and covers most possibilities in practice: slender piers, moderately stiff ad stiff piers, piers founded on piles, slender piers with shallow foundations, steep and moderately inclined slopes of the inundation. The analysis of seismic load on piers include both the longitudinal and transverse direction and dimensioning of the viaduct.

3. Retrofitting as the concept

Much research and testing has been done on reinforced concrete columns with steel or composite casing. The ultimate and the most important test is how well these retrofits perform during earthquake. After the 1994 Northridge earthquake [1] it was observed that no serious damage would have occurred on structures (and details) if previously the retrofit program had been implemented. The best retrofit measures are simple, easy to construct, inexpensive and dependable. Some examples of a good retrofit concept, in which simple and easy to construct retrofit measures are implemented, are made after the

Great Hanshin (Kobe, 1995) earthquake [10], Figure 1. The measures are presented in Figure 2 and Figure 3. More than 600 meters of the expressway collapsed in the Fukae section, Fig. 2(left), during the Great Hanshin (Kobe) earthquake [10]. A total length of 635 meters have now been reconstructed, with the weight of the superstructure being reduced by adopting dual 9-span continuous steel deck box girder bridges, Figure 2(right).
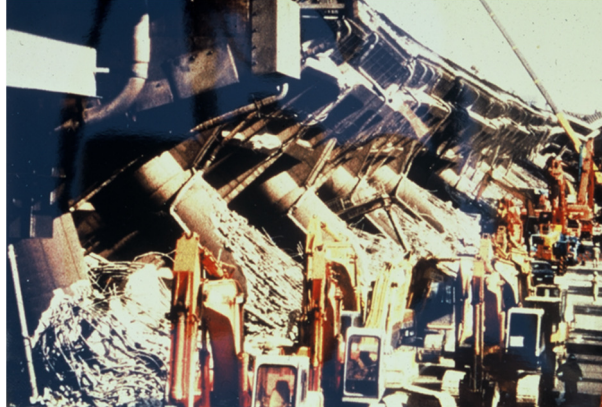

Figure 1. Concrete column failure caused by ductile detailing problems of the Fukae section Kobe Route expressway after January 17, 1995, the Great Hanshin (Kobe) Earthquake.
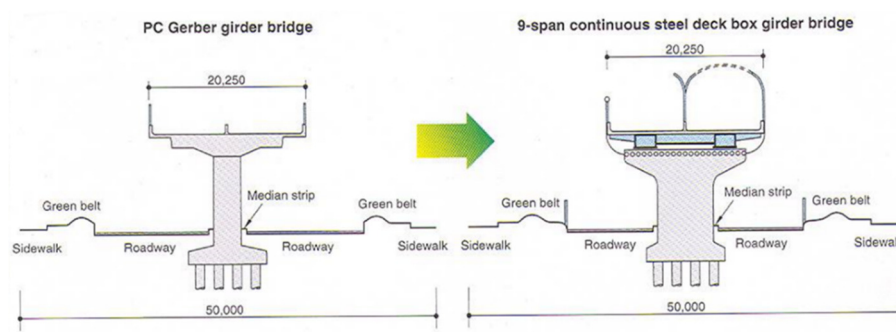

Figure 2. Retrofit of the Fukae section on Kobe Route expressway after January 17, 1995, The Great Hanshin (Kobe) Earthquake.

Loads on the existing foundations have been cut down by introducing base isolators that can absorb seismic forces. The columns are now composed of reinforced concrete and their transverse width has been almost doubled to 6 meters to increase earthquake resistance, Figure 2, Figure 3.

Figure 3. The Fukae section Kobe Route expressway after retrofit implementing measured presented in Fig. 6b (Copyright: M. Čaušević)

Figure 4 presents the continuous 686 meters Benton section. Instead of previous 2 or 3-span continuous non-composite plate bridge, the steel piers and girders of the 19-span continuous new bridge have been

designed to form a rigid frame. Base isolators have been placed at the bottom of the piers, the world first use of such system for road bridges.
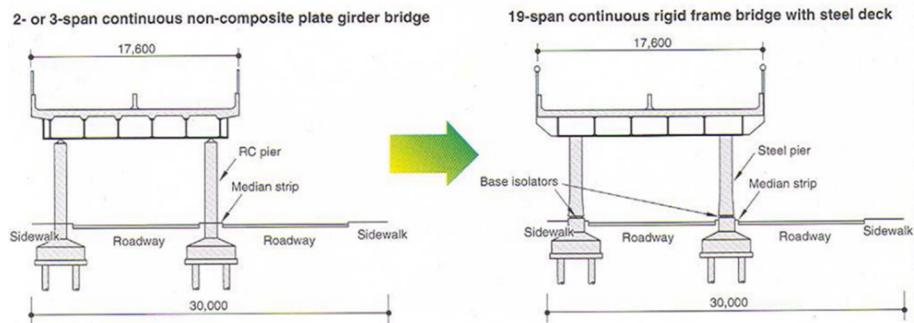

Figure 4. Retrofit of the Benton section on Kobe Route expressway after January 17, 1995, The Great Hanshin Earthquake.

4. Some retrofitting of abutments, columns, connections and bearings of bridges

4.1 Abutments

Very little research has been made on abutment retrofits. To avoid the situation like in Figure 5 anchoring an abutment to the surrounding soil to increase its stiffness and damping effects could be implemented. Figure 6a presents a waffle approach slab that is used to increase bridge stiffness in the longitudinal direction. The slab indentations increase friction and the piles provide additional stiffness. A similar strategy is to construct waffles along the back wall to provide additional resistance for the abutment in the transverse direction.

In the background of bridge in Figure 5 a residential complex is visible with structure partly composed of eccentrically braced frames which represent excellent system of construction for implementation in earthquake prone zones [11]. This building behaved excellently in Kobe 1995 earthquake.

Figure 5. Sliding displacement of a bearing device of bridge superstructure and inclination (damage) of reinforced concrete pier wall, Ashya Seaside Village in Kobe, the 1995 Kobe earthquake;
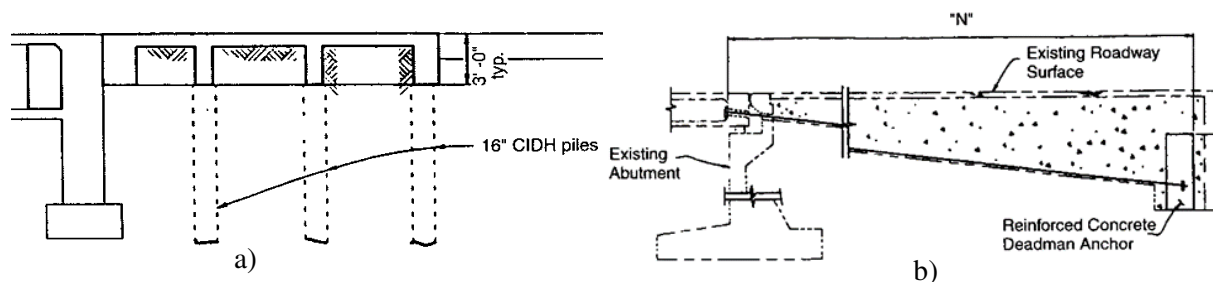

Figure 6. a) Retrofit with waffle approach slab on piles
b) Retrofit to prevent excessive longitudinal movement of the superstructure

For seat-type abutments, a retrofit to restrain the longitudinal movement of the superstructure and prevent unseating during an earthquake may be constructed with longitudinal anchors into the embankment. Figure 6b presents longitudinal anchorage systems with a buried "deadman" installed to prevent excessive movement of the superstructure.

Figure 7a shows a retrofit to limit both transverse and longitudinal movement of the superstructure at a seat-type abutment with bearings. Additional reinforced concrete is cast around the existing abutment to provide transverse restraint. Timber blocks between the superstructure and the back wall lessen the potential dynamic impact and immediately engage the soil during an earthquake.
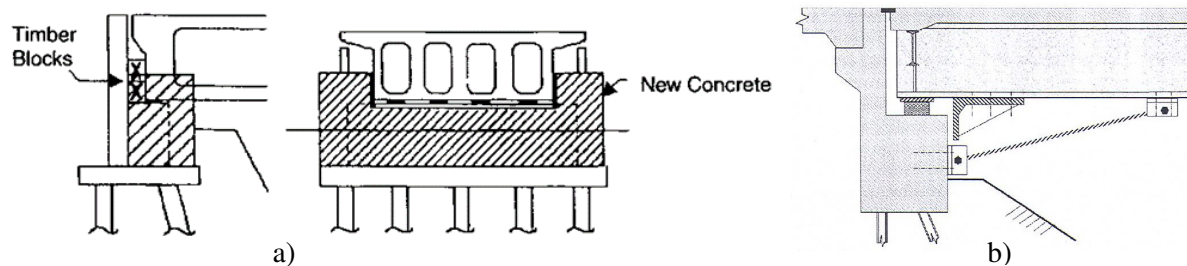

Figure 7. a) Retrofit to prevent excessive transverse and longitudinal movements of the superstructure
b) Longitudinal cable restrainer, bumper, and tie

The longitudinal movement of a superstructure can be limited by installing cable restrainers between the superstructure and the abutments or piers, Figure 7b. The cable should be designed and installed with proper slack to allow thermal movement while preventing excessive longitudinal movement during an earthquake.

Some solutions, recommendations and comments for retrofitting the abutment, bent and column of concrete bridges was presented in more details in [12, 13, 14 and 15].

4.2 Concrete columns

A column retrofit may remedy one or more deficiencies such as a short lap splice, inadequate shear and/or flexural capacity, or insufficient confinement. Figure 8a(left) presents an example where deficiencies and lack of appropriate detailing for concrete columns in seismic areas caused column failure. Practical and effective retrofit measure to provide confinement and prevent a lap splice failure of the main column reinforcement in general is presented in Figure 8a(right). The level of confinement may be adjusted by tie spacing and post-tensioning force in the ties.
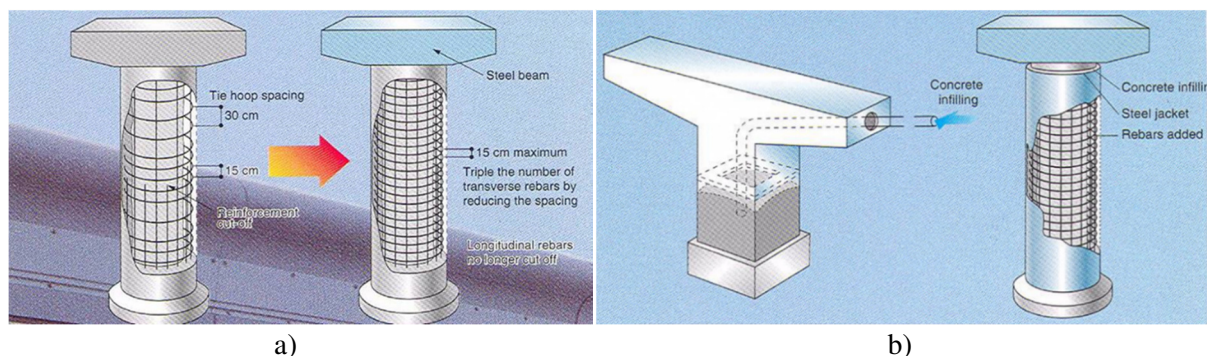

Figure 8. a) Post-tensioned ties to improve confinement in reconstruction of reinforced concrete piers
b) Strengthening steel piers by infilling with concrete (left); Concrete column with metal shell added (right)

It is observed after the past strong earthquakes [10] that hollow steel piers were seriously damaged. Strengthening of the hollow steel pier is recommended by infilling with concrete, Figure 8b(left). A more popular retrofit measure for concrete columns is to provide a metal shell around the column. The space between the shell and the column may be grouted, Figure 8b(right).

4.3 Connections in steel bridges

Additionally, the retrofitting of connections and bearings of steel bridges will be here presented. Below it will be presented some of the most common cases of damage to steel bridges in the earthquake and relatively simple measures to be taken to make the damaged bridges rapid recovery for their basic function in the shortest possible time.

In a non-composite deck, the concrete slab is not connected to the girders, and it can form a sliding surface during a strong earthquake, particularly when steel girders are used. The relative movement dissipates seismic energy [2]. When a connection is not in compression and deemed necessary to transfer inertial forces, anchor bolts should be attached on each side of the flange to stich the girder to the slab, Figure 9a.

Steel diaphragms are vulnerable to transverse seismic forces near the supports. Where the transverse diaphragm over a support does not extend to the full depth of the girder, the girder web will be subjected to out-of-plane bending during an earthquake. Figure 9b shows a knee-brace strengthening detail that may be used to prevent out-of-plane bending of web plates [13].

a)   b)
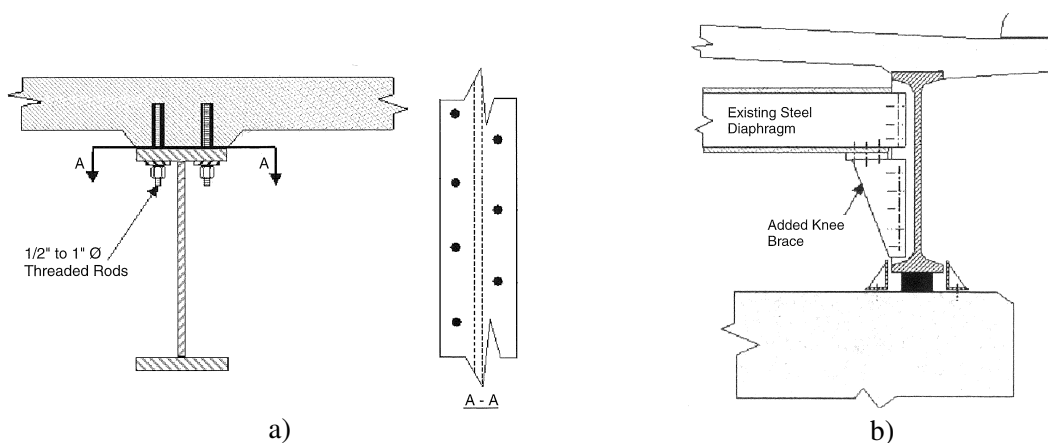
Figure 9. a) Beam-slab connection
b) Steel I-girder retrofit over the support

In the 1994 Northridge earthquake as well as in the 1995 Kobe earthquake it was observed serious damage in connecting steel girders at a transverse joint over a pear [14 ,15, 16]. The retrofit should be designed to support a girder in case the span falls off its support, Figure 10. To accommodate thermal movement at the expansion support, slotted holes may be provided in the connecting plates.
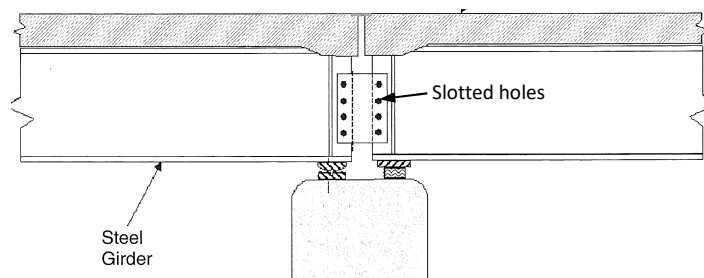

Figure 10. Web plate retrofit

The design effective area of cross-section of the connected web plate when subjected to uniform compression $A_{d.eff}$ as well as the design net area of cross-section subjected to tension $A_{d.net}$ can be denoted as A_d and may be determined from the equation (3):

$$E_d \leq R_d = \frac{2n \cdot A_d \cdot f_y}{\gamma_{M0}} \; ; \qquad A_d \geq \frac{E_d \cdot \gamma_{M0}}{2n \cdot f_y} \tag{3}$$

where: E_d is the design value of the seismic force in the longitudinal direction of the bridge; R_d is the

plastic resistance of web plate cross section; n is the number of steel girders in cross section of the bridge; $2n$ is the number of web plates; f_y is yield strength, γ_{M0} is partial factor for resistance.

4.4 Bearings in steel bridges

During past earthquakes, excessive transverse movement of bridge superstructure caused loss of support on a number of bridges. To transfer lateral seismic forces and prevent excessive displacements, transverse restrainers should be used at the bearings [14, 15, and 16]. Figure 11a presents steel angles as restrainers used with an elastomeric bearing that has sliding surface (a) and with a regular elastomeric bearing (b). For designers of new bridges and retrofit of bridges the reference [16] is highly recommended.
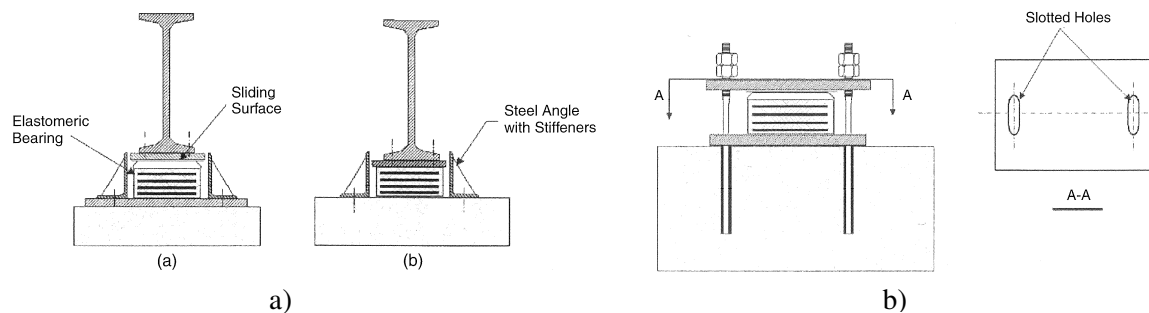

Figure 11. a) Transverse restrainer angles
b) Restrainer anchor bolts

Figure 11b presents an anchor bolts restrainer for an elastomeric bearing that has a sliding surface. The sliding surface and the bearing both accommodate longitudinal thermal movement over a rigid support. The slotted holes in the top plate allow longitudinal movement of the superstructure but resist transverse movement to the flexural deformation of the bolts. Transverse restraints should be designed to remain elastic and resist the lateral forces corresponding to plastic hinges of the columns.

A type of bearing commonly used on existing bridges is high-profile rocking or fixed bearing that is vulnerable to toppling during earthquakes. This toppling may be prevented by welding wedge-shaped steel plates to bearing [16] as shown in Figure 12a. The increase in the longitudinal resisting force F_h developed by the wedge plates can be estimated from the equation (4):

$$F_h = G \tan \alpha \tag{4}$$

where G is dead load reaction of the bearing; α is slope angle of the added wedge plate.
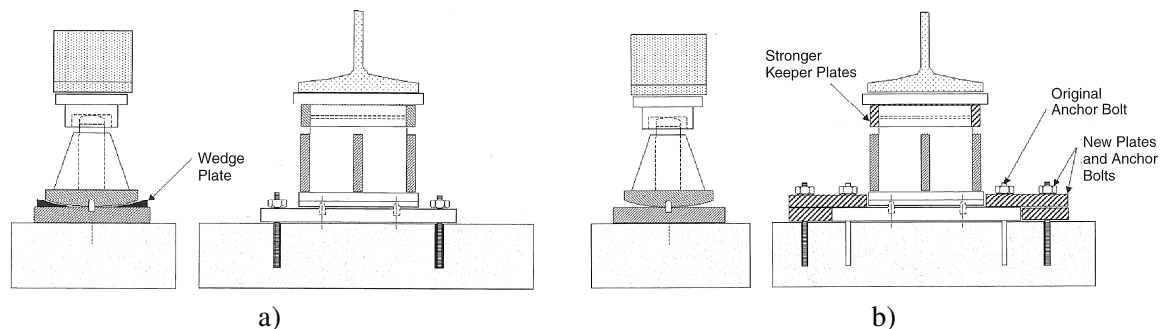

Figure 12. a) Tack-welded retrofit
b) Transverse restrainer and connection retrofit

Another deficiency is the bolted or welded connections between the bearing and the substructure or superstructure. Replacing the bolts with larger, stronger, or additional anchor bolts may be considered to strengthen a bolted connection. A welded connection can also be strengthened by adding bolts or additional welds. Figure 12b presents additional keeper plates at the top of the bearing and base plate extensions and additional plates and anchor bolts at the bottom to restrain the transverse movement [17].

5. Conclusions

To provide adequate resilience, functionality requirements for bridges three states of network operation must be defined: (1) during an extreme intensity earthquake (2) immediately after, especially with respect to search, rescue and evacuation and (3) to ensure recovery of complete functionality within an acceptable time. The knowledge about earthquake loading on bridges which were built 50 or more years ago was very low in comparison with the nowadays knowledge. As the consequence many of old bridges are vulnerable and must be retrofitted for the next event. Finding some new methods for recovery of bridges are here presented which should be implemented on existing bridges identifying their remaining structural capacity before the next extreme event occurs. It is the main task of our community to avoid zero functionality for old bridges and a speedy recovery of old bridges even for extreme events. Still, we have tools to predict the seismic response of individual bridge but we lack methods to predict response of the entire regional highway system to a disaster, and methods to design a process of highway system recovery after disaster. This is the great task for the community in the future.

6. Acknowledgement

7. References

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