SEISMIC RETROFITTING OF EXISTING ROAD BRIDGES – CURRENT STATE OF PRACTICE

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Abstract

Seismic assessment and subsequent retrofitting of existing road bridges is a growing challenge for structural engineers in earthquake-prone areas. Following the two catastrophic earthquakes which occurred in the last two years in Croatia, the awareness (both from the engineers and public) for older existing road bridges is heightened. As they were designed according to old codes, and due to their age, deterioration, and increased traffic volume over the last decades, these bridges are in need of assessment (and retrofitting when required). The first part of the paper provides a theoretical overview of bridge behavior during seismic events and the identification of critical structural elements, based on the bridge type and size. In the second part, the review on the most commonly used techniques for seismic retrofitting of these bridges is given, with practical examples were available. The techniques are divided based on the corresponding structural elements and bridge types, with a focus on reinforced and prestressed concrete bridges as the most common bridge types in Croatia and the surrounding region.

Keywords: existing bridges, seismic retrofitting, earthquake, seismic assessment

1 Introduction

Existing road bridges and viaducts, as integral parts of the transportation infrastructure networks in the United States and Western Europe, are primarily built in the post-World War II era. As such, the majority of those bridges already reached their designed service life and are in need of assessment and evaluation for their continued and safe use. Due to their complexity and the fact that the traffic volume and weight have increased rapidly in the last four decades, these bridges are deemed as critical parts of the infrastructure networks [1]. Public awareness for the safety of existing bridges was recently heightened as a result of two bridge collapses in 2018. The first and more famous one was the Morandi Bridge which collapsed during the extreme storm in August, and the second one was the pedestrian overpass in Miami that collapsed during the construction. Both of these collapses resulted in extensive property damage and multiple causalities, and the aftermath led to extensive reports of the “crumbling post-ware infrastructure” in industrial countries [2]. Similar examples of complete bridge failures are very rare, but due to the severe consequences, they always attract widespread attention and are often the basis for the revision of design and maintenance codes and guidelines. Based on the analysis of the available database in [1], extreme events are the main reasons for 21 % of the major bridge collapses in the last 70 years. These include natural events such as floods, landslides, earthquakes, and human-made events such as terrorism and explosions.

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The earthquakes represent only 3 % of these cases (Figure 1), the bridges in seismic active areas are very sensitive to their effects, especially displacements and vibrations due to peak ground accelerations (PGA). During the last half-decade the bridge design codes in earthquake-prone countries, such as the western part of the USA and Japan, were often modified and improved in the aftermath of significant earthquakes. The most notable examples are San Fernando (1971) and Loma Prieta (1989) earthquakes, after the former the California bridge retrofit program was initiated and after the latter, it was mandatory for all west-coast bridges [3]. In Japan, the Great Hanshin earthquake (1995) resulted in the total collapse of 18 spans of the elevated Kobe expressway and is considered one of the most significant events in the history of earthquake structural engineering [4] due to its effects on design codes not only in Japan but also worldwide.

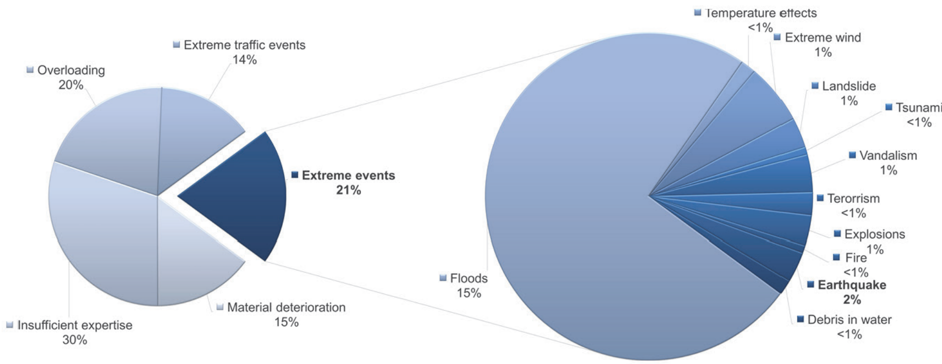


Figure 1 Extreme events as the main reasons for bridge collapse [1]

In Croatia, the safety of existing bridges came under the public eye after two major earthquakes which hit both the capital of Zagreb and Sisak-Moslavina County (SMC) in 2020. In March 2020, a strong earthquake hit Zagreb and its surroundings, followed by numerous aftershocks. The epicenter was located about 7 km from the city center, the magnitude was ML=5.5 and the intensity VII according to EMS -98 scale. The second earthquake occurred on December 29th, with an epicenter of about 3 km from the town of Petrinja in Sisak-Moslavina County. The magnitude of the earthquake was ML=6.2 and with an intensity between VIII and IX according to the EMS-98 scale. Both earthquakes resulted in massive property damage and, unfortunately, fatalities [5]. In the aftermath of the SMC earthquake, the authors were in charge of the rapid inspection and assessment of the multiple bridges in Glina county [6].

2 Seismic assessment of existing bridges - overview

Bridges as structural systems are sensitive to the seismic effects, mainly to the transverse forces and displacements caused by ground movement. The seismic behavior of bridges, in general, depends on the fragility of the substructure (piers and abutments) and bearings, which are often described as critical parts of the bridge in the event of an earthquake. The superstructure, on the other hand, can, in general, be modeled using linear elastic analysis as its stiffness does not have a significant effect on the bridge behavior. Current seismic design codes for new bridges, EN 1998-2 [7] therefore require high ductility of the reinforced concrete piers and abutments to allow the transfer of large transverse forces and displacements. The ductility is achieved with the confinement of reinforcement, and the potential plastic hinges regions are defined for the extreme seismic events.

The buckling of the longitudinal reinforcement in compression zones is not allowed, and the displacements of the superstructure are limited with bearings, dumpers, or seismic blocks. Unfortunately, many existing bridges both in Croatia and worldwide were built according to old design codes in which the seismic actions were taken into account with insufficient PGA or they were not modeled at all. Examples of the bridge behavior during the seismic events prove that the age of the bridge can be used as an indicator of its seismic fragility and performance. For example, during the Great Hanshin earthquake, 18 spans of the Route 3 Hanshin expressway, built in 1965, collapsed due to the shear failure of the RC piers. On the other hand, Route 5 which is parallel to Route 3 but was built in the 1990s, lost only a single span [4] due to ground deformations.

At the moment there are still no European codes for the assessment of existing bridges, and in most cases, engineers worldwide apply the same analysis procedures which are used for new bridges. They are based on the development of a numerical model of the selected bridge using the available documentation, on-site measurements, and seismic parameters of the location (PGAs, soil type). There are several methods of analysis that are used for the determination of both seismic demand and the capacity of the existing bridges, divided into linear and non-linear methods. Besides their complexity, the selection of the method depends mostly on the bridge type, material, structural characteristics, etc. Linear methods are more simple and convenient to use, but to the disadvantage that they do not take into account redistribution of forces in the event of plastic joint(s) development. On the other hand, non-linear analyses are based on the rotational capacity of structural elements (M-φ curves) and are taking into account corresponding new failure modes and dissipations of the seismic force through deformations. The most common nonlinear analysis used in the assessment procedures for existing bridges is the static nonlinear analysis (pushover method) since the dynamic ones (cyclic loading - time history analysis) are time-consuming and require data sets from realistic earthquakes. The principle of the analysis is to apply a longitudinal and/or transverse force on the bridge structure and to define a curve that represents the load to displacement ratio. The analysis is based on the assumption that the superstructure remains in the linear elastic region of the stress-strain diagram and only transmits the shear force to the piers and abutments [5]. For the preliminary analysis of a large number of bridges and bridge stocks with similar characteristics, the fragility curves provide a convenient method. These curves in general represent the ability of the bridge to withstand seismic events as a ratio between the demand (D) and capacity (C) of the system. In most cases, the demand is presented as PGA, while the capacity is given as the probability of failure of a certain bridge element or the whole system [8]. An example of fragility curves for the four most common bridge types in the USA is given in [9], while the curves for bridges in North Italy can be found in [10]. The fragility curves for assessing the bridge seismic performance based on its age are used both in California and Japan. A more comprehensive overview of the seismic analysis methods for existing bridges can be found in [5].

3 Seismic retrofitting of existing road bridges

3.1 Overview

The general principle in the selection of seismic retrofitting strategy for any type of structure is that should be made with the aim of minimizing the costs while providing the structure with adequate seismic resilience. Furthermore, as bridges are integral parts of transportation networks, the retrofitting should have minimal disruption on the traffic flow, both on and under the bridge. The most commonly used retrofitting methods are presented in Table 1, based on the extensive literature review given in [5]. The ones listed in Table 1 are related to the substructure and bearings, as critical elements of the bridge during the seismic event.

Table 1 Selected seismic retrofitting methods – existing bridges [5]

Method	Bridge element
RC jacketing	Bridge RC piers/Cap beams
Steel jacketing	Bridge RC piers
CFRP jacketing	
FRCM jacketing	
ECC, AFRP, etc. jacketing	
Seismic isolation	Bearings/Cap beams/Superstructure
Restrainers	
Bumper blocks	
Dampers	
Seat extenders	Abutments/Cap beams
Wing walls stabilization	Abutment

3.2 Jacketing

Various types of jacketing are the most commonly used method for seismic retrofitting of existing RC bridge piers and abutments. The principle of the technique is simple, based on the physical increase of the cross-section (concrete jacketing) or by sheeting the cross-section with steel plates or using one of the high-performance materials (FRP, etc.). The purpose of the method is to increase both ductility and shear capacity of the existing RC pier, either by adding a new layer of confined reinforcement and concrete or using prefabricated (steel or FRP) sheeting plates [5]. Traditionally, RC jacketing is the most commonly used one, followed by steel and in the last decades, many research projects were focused on the developments of jacketing with high-performance materials [11]. Each method has certain advantages and disadvantages, and different effects on the retrofitted element. The main characteristics are summarized in Table 2. An example of the RC and steel jacketing is presented in Fig. 2.

Table 2 Main characteristics of different jacketing methods [5]

Method	Effect on the structural element			Cost
	Strength	Ductility	Stiffness	
RC jacketing	Increase	Increase	Increase	Very high
Steel jacketing	Significant increase	Significant increase	Increase	High
FRP jacketing	Increase	Significant increase	No effect	Moderate

As most commonly used, RC jacketing has an obvious disadvantage of cost and time inefficiency due to required formwork, especially on tall piers. Furthermore, as it increases the ductility, mass, and stiffness of the pier, it affects the behavior and base shear force of the whole bridge. Finally, it is not convenient to use when the space under the bridge is restricted due to vehicle passages and there is no room for increasing the cross-section. On the other hand, steel jacketing increases the cross-section for only a few centimeters but is not practical on rectangular cross-sections. It is most effective on circular piers as the steel jacket is prefabricated in two parts which are positioned and welded around the pier (Fig. 2).

The gap between the two materials is additionally grouted to ensure the effective connection of the new composite section. Similar to the RC, steel jackets also increase the stiffness and therefore affect the behavior of the bridge. There are examples of combined steel and RC jacketing, where the steel is also used as formwork. Slender RC piers of the Pag bridge (Fig. 3) are retrofitted using the combined technique [12]. Steel and RC jacketing were used for retrofitting more than 100 piers on the Hanshin expressway after the 1995 earthquake [4]. Jacketing with FRP materials has several advantages, speed and simplicity of installation, high strength-to-weight ratio, and the minimal increase in the cross-section, the material is environmentally friendly. On the other hand, the efficiency of these materials is lower, due to premature bonding, their utilization is only 30 to 35 % [11].

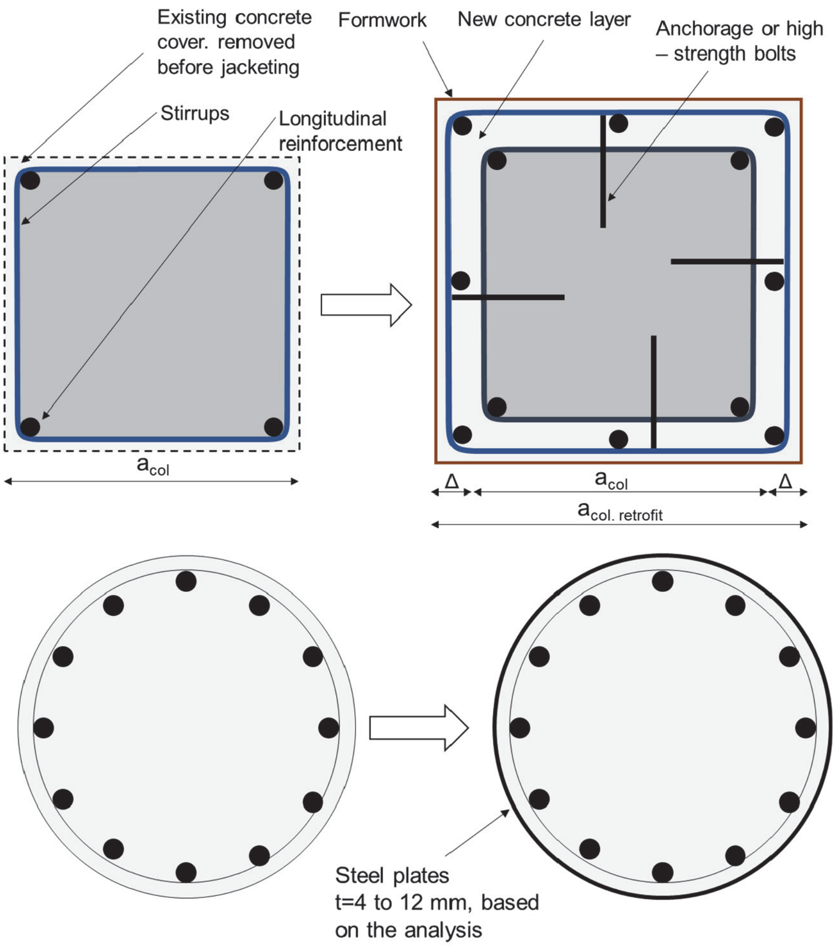


Figure 2 Example of RC (top) and steel (bottom) jacketing [1]

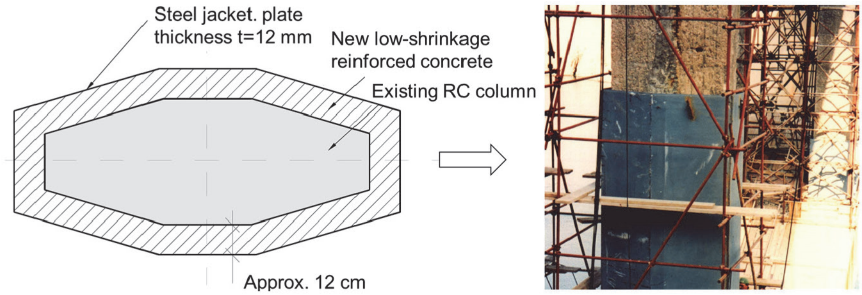


Figure 3 Example of combined RC and steel jacketing – Pag bridge [12]

3.3 Base isolation/damping of existing bridges

Seismic isolation is often described as the most effective seismic protection measure, not only for bridges but for other structures as well. The general principle of this method is to detach (or decouple) the ground motion and the vibration of the structure. By doing so, the lateral forces which are induced in the structure are reduced, as they are proportional to the structural stiffness. The concept itself is several centuries old and is described in detail in [13]. When used as a retrofitting technique for existing bridges, superstructure and substructure are "decoupled" by installing the seismic isolator bearings (SIBs). Older bridges, designed according to the codes which did not take into account seismic activity, were often supported on non-reinforced elastomeric bearings. These were primarily used for the transfer of vertical load, and the insignificant horizontal loads due to temperature effects. In cases of significant earthquakes, the piers of these bridges are subjected to lateral forces which exceed their capacity and the risk of failure is high. In California, seismic isolation was applied widely after the Loma Prieta earthquake. In general, there are two versions of SIBs, the elastomeric ones (reinforced rubber) and sliding ones (based on friction principle – pot bearings), both presented in Fig 4. The former is used primarily on simply supported bridges, while the latter is nowadays a standard for continuous girder bridges [5].

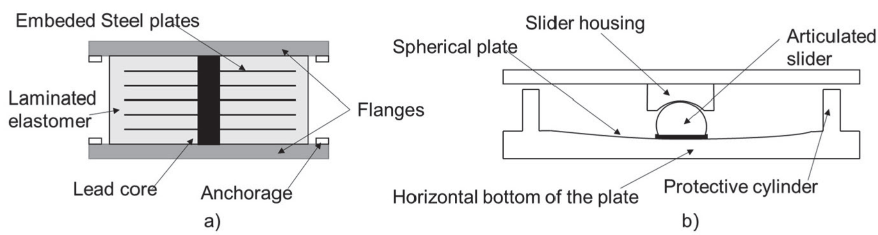
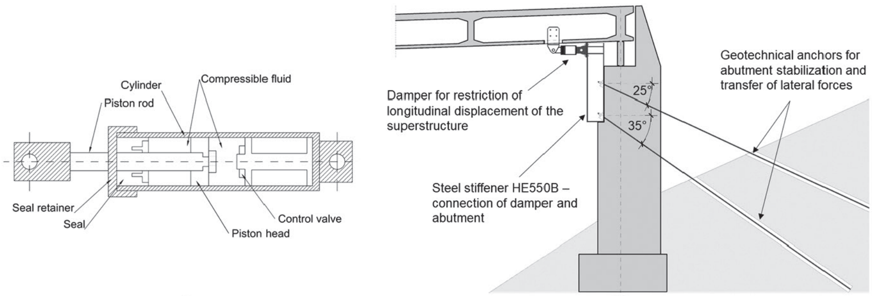


Figure 4 a) Elastomeric bearings; b) Pot bearings [5]

The disadvantage of the seismic bearings is a result of the decreased stiffness of the structure, causing higher natural periods and correspondent displacement. This issue is accounted for by using energy dissipators, either built-in or external ones, called viscous dampers. An example of theoretical retrofitting measures for the bridge in Croatia is presented in Fig. 5, along with the schematic of the damper [5, 14].



a) b)

Figure 5 a) Viscous damper schematic [14]; b) Retroffiting proposal [5]

4 Conclusion

The retrofitting methods for existing road bridges in earthquake-prone areas are summarized in Table 1, based on the corresponding structural element. The most vulnerable parts of the common bridge types are piers and bearings, as they are sensitive to lateral loads caused by seismic events. The selection of the method is based on the site-specific characteristics, but RC and steel jacketing, along with seismic isolation are still the most successful seismic risk mitigation measures. The future remarks and research must be based on modern, environmentally friendly high-performance materials, which are nowadays still not in wide practical use due to their nonefficient bonding.

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