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Review

Retrofitting of Bridge Slabs for Safety Railing Refurbishment in Italy: A State-of-the-Art Review

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Abstract: The recent accident of Mestre (northern Italy), which caused 21 fatalities due to a bus falling from a bridge, strongly highlighted the safety problem related to the presence of old railings along Italian roads. Bridge railings, also known as guardrails or parapets, serve the crucial function of preventing vehicles from accidentally driving off the edge of a bridge. Performance requirements of safety railings have been recently increased due to laws and technical standards enforced in Italy and Europe. However, many bridges along important roads, such as motorways and highways, are currently equipped with outdated safety railings since they were built before these regulations came into force. Therefore, many people are daily exposed to the risk of heavy accidents due to railing failures as well as vehicles and people eventually present below such structures. This paper aims to outline the technical problems and solutions in bridge refurbishment interventions devoted to increasing traffic safety as, for example, the installation of code-conforming railings, which often require the structural retrofit of bridge elements supporting the railing. To this end, several technical solutions are described and critically compared, and, finally, an economic analysis is reported to highlight the slab retrofit influence on the total intervention cost.

Keywords: bridge; safety railings; guardrail; reinforced concrete; deck slab; retrofit; refurbishment

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1. Introduction

Road bridge railing failures can have serious consequences on the safety of both motorists and pedestrians [1]. In fact, when these railings fail or are inadequate, various safety issues can arise such as vehicle accidents. The primary purpose of bridge railings is to prevent vehicles from veering off the road and falling from the bridge. When railings fail, it increases the risk of vehicles colliding with the bridge structure, potentially causing severe accidents and injuries.

Inadequate bridge railings can lead to fatalities and injuries among occupants of vehicles involved in accidents. The absence of a reliable barrier increases the chances of vehicles plunging off the bridge or striking other vehicles.

When bridges are provided with walkways, effects on pedestrians can occur if the bridge railings on these walkways fail. This puts pedestrians at risk of falling from the bridge, which can result in severe injuries or fatalities.

In some cases, bridge railings may have design flaws that make them less effective in preventing accidents. Poorly designed railings may not provide adequate containment, allowing vehicles to easily breach them during collisions.

Even when design flaws are absent, bridge railings can deteriorate due to factors like weathering, corrosion, and vehicle impacts. Neglected maintenance and poor construction materials can exacerbate this problem. When the railings (or their connection to the bridge) degrade, their ability to withstand vehicle impacts and protect them against accidents diminishes.

In order to cover these gaps, both Italian and European authorities issued new codes pertaining to the evaluation and certification of the adequacy of new safety railings. Several codes on this topic have been issued in Italy since 1992 [2–5], and the European code EN1317 was adopted in Italy and other EU countries [6–8]. This normative framework, which is related to new road infrastructure construction, allows existing infrastructure to adopt old safety railings.

Due to this and the above-mentioned technical issues, poor-quality safety railings on older bridges may be a contributing cause to some of the major accidents observed in the last decade in Italy. For example, the recent accident of Mestre (Italy), which caused 21 fatalities and 15 injuries, is one of the most tragic road accidents that recently occurred in Italy. A bus fell from a bridge (the so-called Vempa overpass) equipped with a very old safety rail. Moreover, in the accident zone, the railing was interrupted, and most probably this facilitated the bus to overcome the parapet and fall. This tragedy strongly highlighted the need of railing retrofitting interventions along Italian roads, especially those with high traffic volume. Neglecting the causes of the vehicle skid, which are under investigation, a simple engineering analysis can easily confirm that the presence of an up-to-date barrier could have avoided or mitigated the tragedy. Another accident happened on 28 July 2013, when another bus fell from the Acqualonga bridge along the A16 motorway in southern Italy. A total of 40 people died and 8 were injured. In this case, the bus lost the brakes, and the bridge barriers failed due to the impact [9].

These two tragedies, similar to each other, caused 62 fatalities, more than the complete collapse of 250 long Morandi bridge span [10] responsible for 43 fatalities. Therefore, accidents due to the collapse of safety railings can have a human life cost similar to great natural disasters, such as earthquakes [11,12], and thus should not be considered minor issues with respect to the global safety of bridges.

Despite this fact, the importance of bridge railings is not fully recognized by the Italian technical code [13]. The recent Italian guidelines on risk classification and management of road bridges [14] are devoted to assigning the "class of attention" (a kind of risk evaluation) to all road bridges through a multilevel evaluation based on documental analysis and accurate inspections. In this code, the focus is the safety of the bridge structural members, while the railings are accounted as accessory elements with lower importance and scarce potential effects on the users' safety.

Several Italian road management bodies have started the requalification of road railings (e.g., Figure 1), even though the extension of the national road network requires huge investments that should be allocated considering precise criteria for prioritization, based on the risk generated by the traffic volume (average daily traffic, representing the exposure) and the adequacy level of installed railings, which represents the vulnerability.

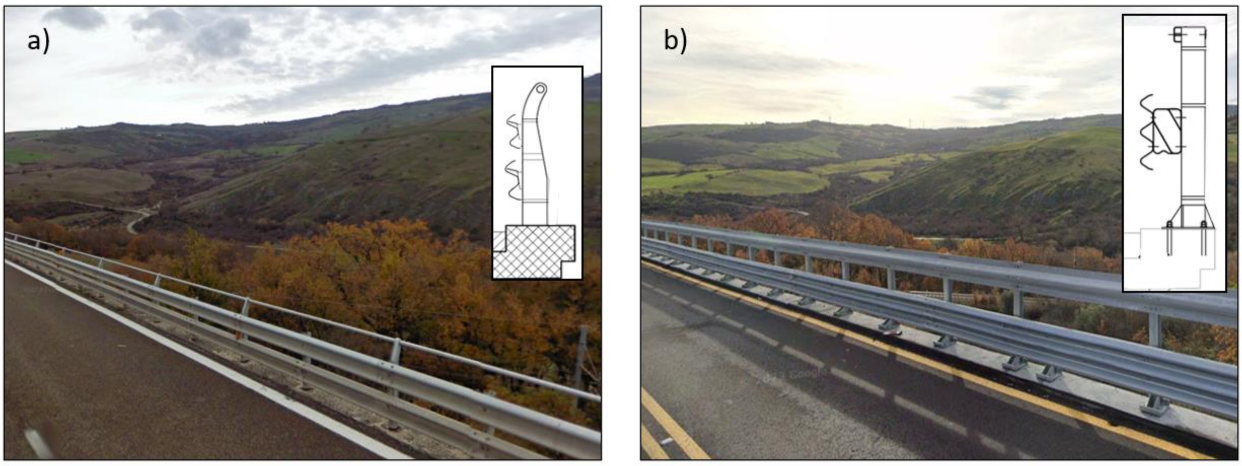

Figure 1. Photo and scheme of pre- (**a**) and post- (**b**) railing refurbishment intervention on a reinforced concrete bridge.

Such investment needs are increased by the inadequacy of supporting elements of bridge barriers. Most available research on the topic has been focused on evaluating the response of safety railings to accidental actions (crashes) [15,16], neglecting the adequacy of supporting elements like the slab.

According to [5], in case a railing is replaced, an H2, H3, or H4 class new railing must be installed depending on the type of road (motorways, extra-urban roads, and urban roads) and traffic volume (also as a percentage of commercial vehicles with mass higher than 3.5 tons). H2, H3, and H4 barriers have increasing containing capacity and are usually installed on bridge edge curbs through chemical anchors. Figure 2 compares old bridge barriers and new ones [17]. These latter (shown only as illustrative models among the wide variety of commercially available devices) are taller than the old ones and are equipped with a 3-wave profile instead of a 2-wave profile. Moreover, connecting elements placed at the top of the barrier are more robust allowing a better collaboration between consecutive posts, thus increasing the containing capacity of the device.

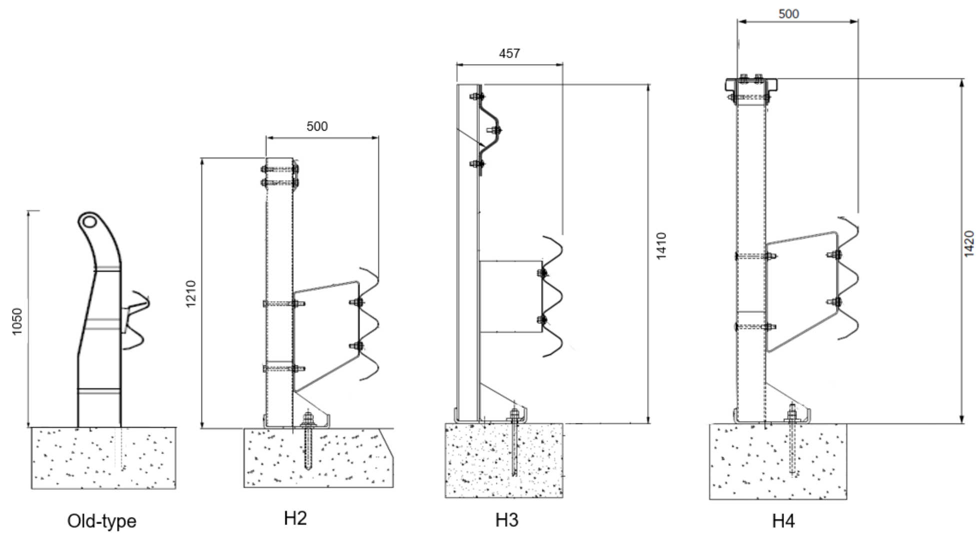

Figure 2. Typical old type and new H2, H3, and H4 bridge railings (dimensions in mm).

In most cases, the bridge slab has a structural capacity insufficient to allow the installation of an up-to-date railing. In fact, the higher the resistance of the barrier, the higher the stresses on the supporting elements. This forces to carry out strengthening interventions on the bridge slab, with a consequent increase in time and cost to carry out works. Furthermore, there can be cases in which the curb is not geometrically suitable for the new railing solution, and works are needed to adapt it. It is worth noting that the bridge edge curb is the part most sensitive to material deterioration possibly impairing the railing effectiveness. Recent studies have shown that this issue can be solved using composite materials not affected by corrosion [18]. However, the structural integrity and durability of bridge edge curbs are not the focus of this study, being devoted to bridge slab structures.

This paper is devoted to illustrating the assessment and design methods as well as the most frequently used strengthening techniques to increase the slab structural capacity making it suitable for the railings' installation in Italy. It is worth noting that possible aerodynamic issues on cable-stayed or suspended bridges due to railing installations are not treated here, and they should be addressed in a specific work. This study deals only with single- and multi-span bridges not subjected to aerodynamic problems, representing by far most Italian bridges.

2. Size of the Problem

According to the WHO (World Health Organization) report released in January 2018, about 1.35 million people are killed annually in road accidents [19,20]. At a European level, data on road safety are collected through CARE [21,22], which is a community database on road accidents (commonly referred to as "crashes") resulting in death or injury, without reporting statistics on damage-only accidents. This allows examining the data related to crashes, disaggregating them, for example, by country, type of vehicle, year, transport mode, etc. Based on CARE, Figure 3 reports the total number of killed people in 2021 across the EU per million inhabitants. As can be seen, the situation in Italy represents a sort of "average" being at the same level as France and Portugal, and significantly better than Eastern Europe countries. However, a high variability is found among European countries. Therefore, Italian authorities dealt with about 2875 killed people in 2021 due to road accidents, which was slightly decreased due to the pandemic restrictions. In fact, in 2022, the number of killed people increased to pre-pandemic levels, with the total being 3159 [23].

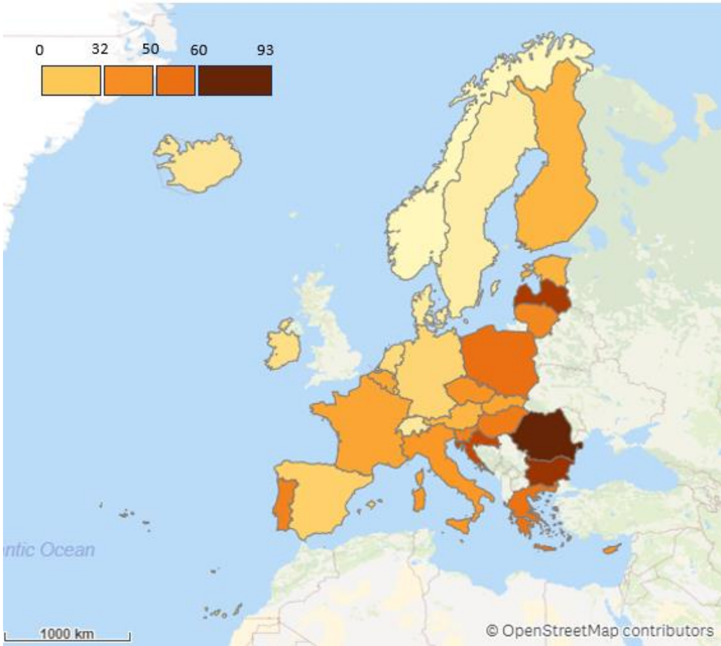

Figure 3. Killed people in road accidents per million inhabitants across EU (including EFTA member states).

To face this problem, the Italian Ministry of Infrastructure and Transportation issued a national plan to strongly reduce the road victims with the objective of halving killed people by 2030 [24]. This plan is consistent with the UN Resolution by the General Assembly 74/299 of 2020 [25] and the EU directive of 2021 [26].

The Italian plan is ambitious and based on the following main steps:

- legislative actions;
- measures to strengthen control and repression;
- interventions to improve the safety of road infrastructures;
- communication and awareness campaigns.

Among the actions on infrastructures, it highlighted the willingness to "Raise awareness among owners or road managers on effects of deficiency maintenance of the infrastructure, on the importance of scheduled maintenance and of the installation of so-called barriers save-motorcyclists". There is no specific reference to the need for a general refurbishment of road railings, even though the main road management bodies are realizing works to modernize safety devices along the nationwide road network. However, the plan estimated the fund allocation needed to deploy its actions, corresponding to EUR 1.4 billion. This amount does not consider the work to be carried out that is much higher.

In fact, Italy has about 167,000 km of roads made of (in decreasing order of importance) motorways; highways (state roads); and regional, provincial, and municipal infrastructures. According to [14], the total number of bridges is estimated around 120,000. Referring to the bridge database reported in [27], the average length of highway bridges is about 220 m. Therefore, a preliminary estimate of the total bridge length in Italy is approaching 26,400 km. To estimate the fund allocation needed to provide these bridges with up-to-date railings, several design documents and price lists issued by road management bodies were examined to find out some indication of an average unit cost [28]. Therefore, after the review of slab-strengthening techniques reported in Section 3, Section 4 shows a rough estimate of intervention costs. However, the number (or the length) of already refurbished bridges is unknown, and, therefore, an evaluation of the national investment to solve this problem cannot be carried out.

3. Slab Assessment and Retrofitting Approaches

3.1. Structural Assessment

When the guardrails on a bridge are replaced with newer and more resistant ones, the forces transferred in case of an accident, especially due to trucks, can be significantly higher. For this reason, the structural assessment of the elements supporting the barriers is mandatory.

When installing a new railing (Figure 4a), checking the needed geometric requirements is necessary. In particular, the dimensions of the edge curb should fit the barrier base plate dimensions. If this check gives a positive result, the effect of the barrier failure in case of a crash must be evaluated. In this case, it can be assumed that the railing posts are subjected to plastic deformation as happens in crash tests performed to approve a safety device. Therefore, the plastic bending moment of the post must be evaluated as a consequence of the truck crash (Figure 4c). Given that they are made of ordinary steel, simple structural engineering methods may be adopted. Based on the post actions, sections 1, 2, and 3 in Figure 5a must be checked. Sections 1 and 2 are subjected to shear, bending moment and axial load, while Section 3 is subjected to shear and overturning moment.

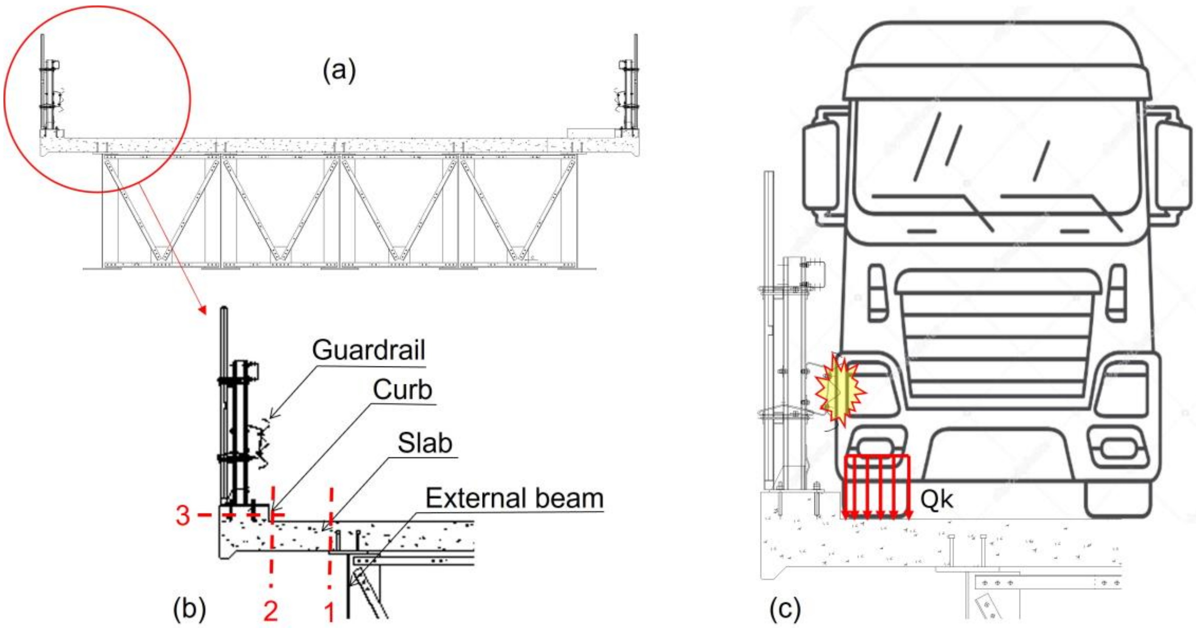

Figure 4. (**a**) Bridge deck section with reinforced concrete slab, (**b**) guardrail supporting elements and critical sections, and (**c**) truck impact position.

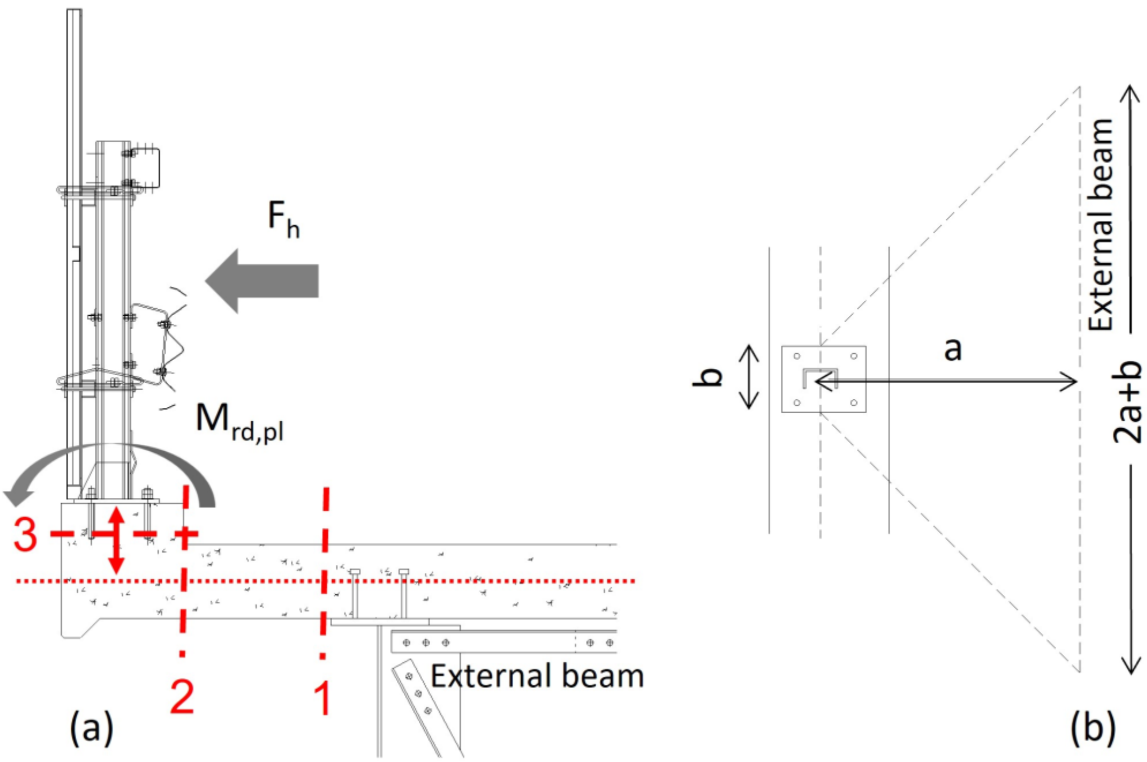

Figure 5. (**a**) Crash actions on the railing and (**b**) plan view of the effective slab sections.

Once the post plastic moment $M_{rd,pl}$ is calculated, the horizontal crash force F_h should be derived taking into account a height of 1.00 m from the road pavement, as reported by the Italian and European codes [29–31]. It is worth noting that F_h represents the tensile axial load acting on slab sections 1 and 2 (Figure 5a). Section 1 has a width equal to $2a + b$, where b is the barrier plate width, and a is the slab cantilever length (Figure 5b). This assumption is based on the commonly adopted 45° stress diffusion, even though more refined methods can be used (e.g., finite-element analyses). Once the crash loads are computed, they must be increased by a factor of 1.5 according to the Italian code and combined with other live and dead loads. Among the live loads, the weight of the truck wheel applied near the curb (Qk in Figure 4c) must be considered (200 kN according to the Italian code [29]). The load combination must be applied to a simple structural scheme represented by the bridge slab cantilever extending from the external beam.

Safety checks in sections 1, 2, and 3 must be performed based on an accurate knowledge of the existing bridge. Information on geometry, material properties, and structural details must be gathered through inspections and in situ and laboratory tests.

Figure 6 shows investigations for the design of a safety railing refurbishment of an RC bridge. Note that the parapet in Figure 6a,b is made of provisional elements installed only for the safety of workers, while the type of guardrail to be installed is similar to that shown in Figure 2 (H2, H3, or H4). In particular, the investigations of Figure 6 are devoted to detecting the type and number of rebars placed in correspondence with the external beam axis, which is the most stressed section of the slab. This must be performed by removing road pavement and concrete cover until reaching the reinforcement. Moreover, further investigation is necessary on the edge curb (Figure 6a). The number of these investigations should be set based on the availability of bridge design documents as well as its total extension. It is worth noting that most bridges built in the period 1950–1970 have no design documents, and, in those cases, the in situ investigations should be more accurate since the structural knowledge must be obtained starting from scratch.

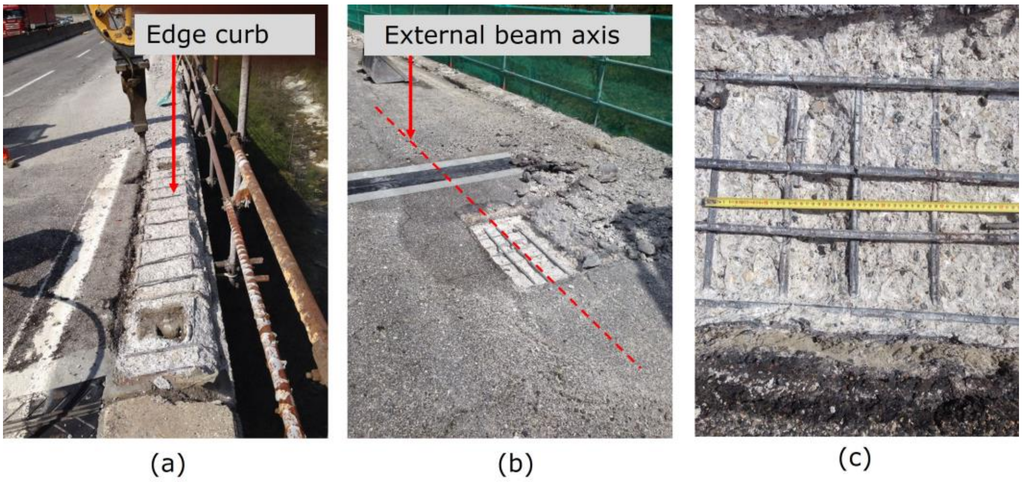

Figure 6. Example of in situ investigations for (**a**) edge curb detailing, (**b**) slab reinforcement across the external beam, and (**c**) detailed survey of reinforcement reported in (**b**).

In the occasion of these investigations, material sampling is also to be performed to determine strength values to be used in safety checks. According to the Italian building code [29,30] and the code for bridge assessment [13], structural investigations can be consistent with three increasing knowledge levels, KL1, KL2, and KL3. Based on the chosen KL, the number of samples to be extracted from the structure is determined. In the case of bridge assessment, the maximum knowledge level should be selected, also based on the indication reported in [13].

Indications on the number of samples and investigations are reported in [29], even though it is mainly related to building structures rather than bridges. Therefore, according to Table 1, in the case of KL3, the building floor area can be converted into a bridge deck area.

Table 1. Minimum number of samples and investigations to be extracted according to KL3.

	Concrete Cores	Rebars
300 m^2 of building floor	2	2
300 m^2 of bridge deck	2	2

Furthermore, it is required to check the reinforcement detailing on 15% of structural elements (e.g., columns and beams). This indication can be applied to bridges converting 15% of structural elements into 15% of the deck surface. Thus, the removal of road pavement and concrete cover to check slab reinforcement details should be made on 15% of the slab's cantilever part.

3.2. Slab Retrofit Approaches

Reinforced concrete slabs in bridges are considered secondary elements, and most of the research on retrofitting solution is related to primary elements like girders and piers, e.g., [32,33]. In this case, the focus is the slab strengthening, which can be performed through several techniques based on increasing the amount of reinforcement on the top part of the slab section across the cantilever part [34]. Both the truck wheel load and the crash impact force generate a negative moment that may require additional reinforcement where tensile stresses are present (i.e., at the extrados). Four approaches can be used:

1. Additional steel rebars in correspondence with barrier posts
2. Additional steel rebars along the whole slab length
3. Near surface mounted (NSM) ordinary steel plates connected through chemical anchors
4. NSM bars, laminates, or textile composites

Techniques 1 and 2 differ only in terms of extension of the slab-strengthening intervention and, for this reason, will be described in the same section.

It is worth noting that when performing safety checks under flexure in the presence of new additional reinforcement, the existing concrete properties must be used. In fact, although a new concrete cover made of high-strength cementitious grout is realized on the slab extrados, the intrados (resisting compression stresses) is made of existing concrete. Therefore, a reliable evaluation of its properties through core drilling and laboratory testing is of paramount importance. In the same way, the existing reinforcement should be considered in the safety checks. In order to corroborate the information gathered through investigations, existing sources of information can be used regarding the analyses of databases including historical concrete and steel testing results, which can help in recognizing the concrete and steel grades used at the time of construction [35,36].

3.2.1. Additional Steel Rebars

As can be seen from Figure 7 (showing the section and plan views of the intervention details), the additional reinforcement in terms of rebars is placed across the external beam to provide the necessary development length, obtaining a total width of intervention equal to W. New rebars are installed only in correspondence with the new barrier post axis to limit the invasiveness of works. This requires a precise cut in the slab concrete cover and the hydrodemolition commonly of about 5 cm or until finding the existing rebars. New rebars are anchored in the curb through an inclined branch. Once the main rebars are installed, vertical anchors are realized through vertical holes and epoxy resin. The concrete cuttings are finally filled with high-strength fiber-reinforced grout and a waterproofing layer. Thus, the road pavement is restored to complete the intervention.

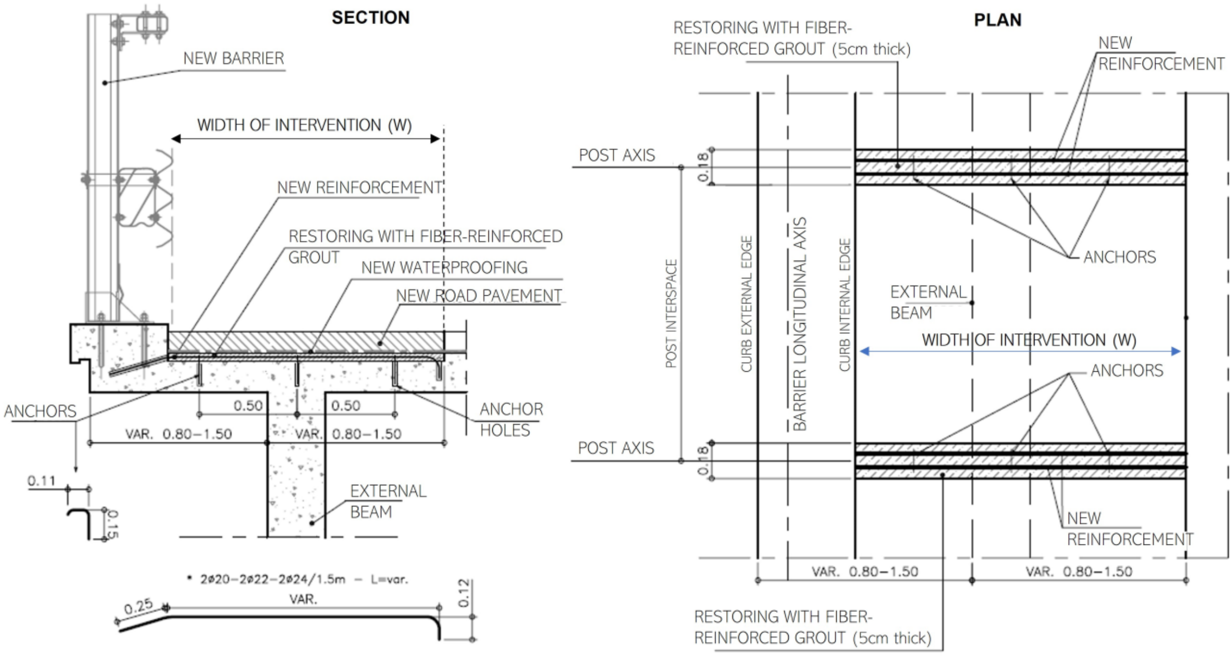

Figure 7. Slab strengthening through additional rebars.

Referring to technique no. 2, the only difference can be found in the fact that additional rebars are distributed throughout the slab length and not only close to the post axis. Therefore, lower-diameter rebars are used, and more cover demolition is necessary. This approach allows neglecting the final position of posts since the slab is uniformly upgraded. However, it is more expensive and impacting on the slab.

3.2.2. NSM Steel Plates

Technique no. 3 is based on the use of steel plates provided with holes that can be coupled with chemical anchors made of threaded rods (Figure 8). This is necessary to make the plates collaborate with the existing concrete. In fact, due to ordinary steel's smoothness, the steel–concrete bond is not effective. Concrete cover cutting has a lower depth (usually 2 instead of 5 cm related to techniques 1 and 2). It requires the complete curb demolition in order to allow the plates to properly extend.

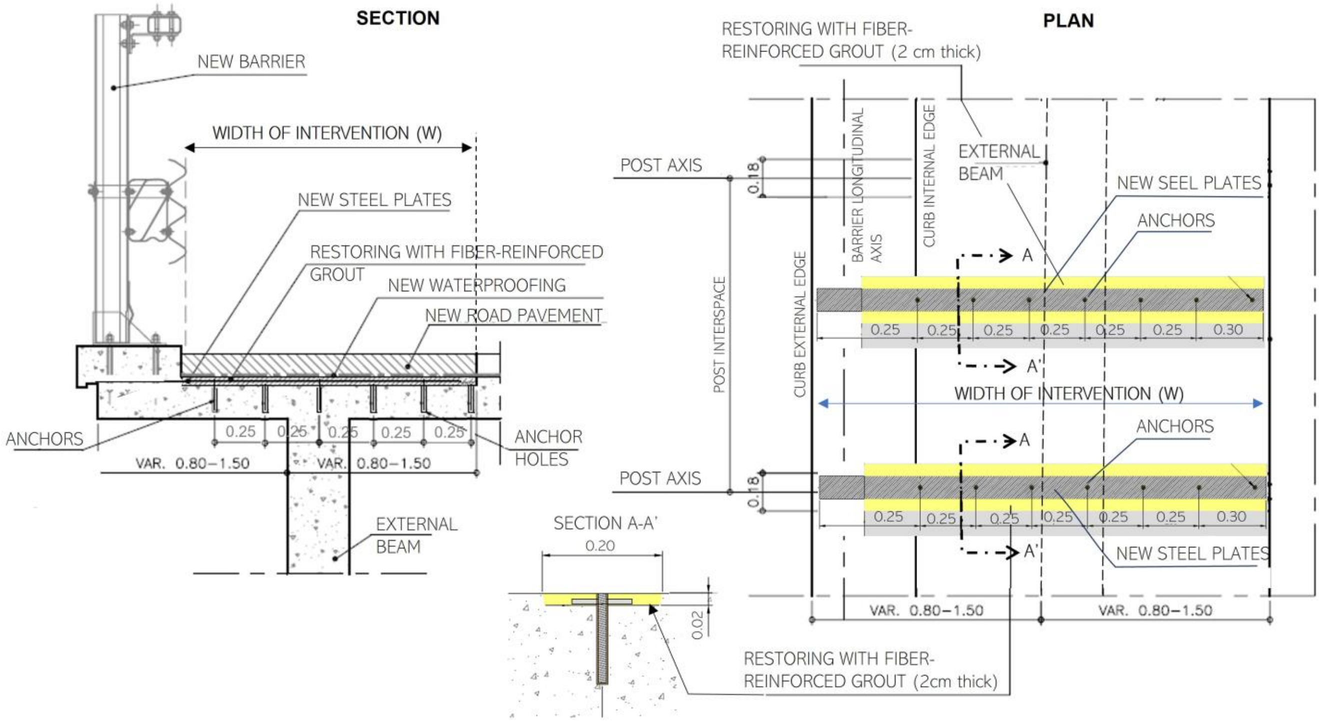

Figure 8. Slab strengthening through NSM steel plates.

Channels created to install the plates are made through hydrodemolition and are following filled with fiber-reinforced cementitious grout. It is worth noting that anchors, in this case, must be installed before the plates, and, therefore, a greater precision is requested during the works. Moreover, ordinary steel used for the plates is provided with a lower yielding stress, forcing to use a larger reinforcement area compared with strengthening options 1 and 2, which adopt deformed bars.

3.2.3. NSM Composites

A typical application of NSM composites is depicted in Figure 9. As can be seen, no anchors are needed due to the epoxy resin connection. A small cut (obtained by milling) in the slab transverse direction is sufficient to install the carbon (or other material) fiber bars after a bed of epoxy resin is created. To strengthen the interface between the curb and slab, in this case, the curb should be demolished and subsequently reconstructed. It is worth noting that concrete members reinforced with composites usually fail by delamination (i.e., concrete failure at the interface with composites) resulting in fragile structural behavior. However, works for this type of intervention are less invasive on the existing slab structure. On the other hand, they are more expensive due to the use of composite bars and a significant amount of epoxy resin, also needing more skilled workmanship.

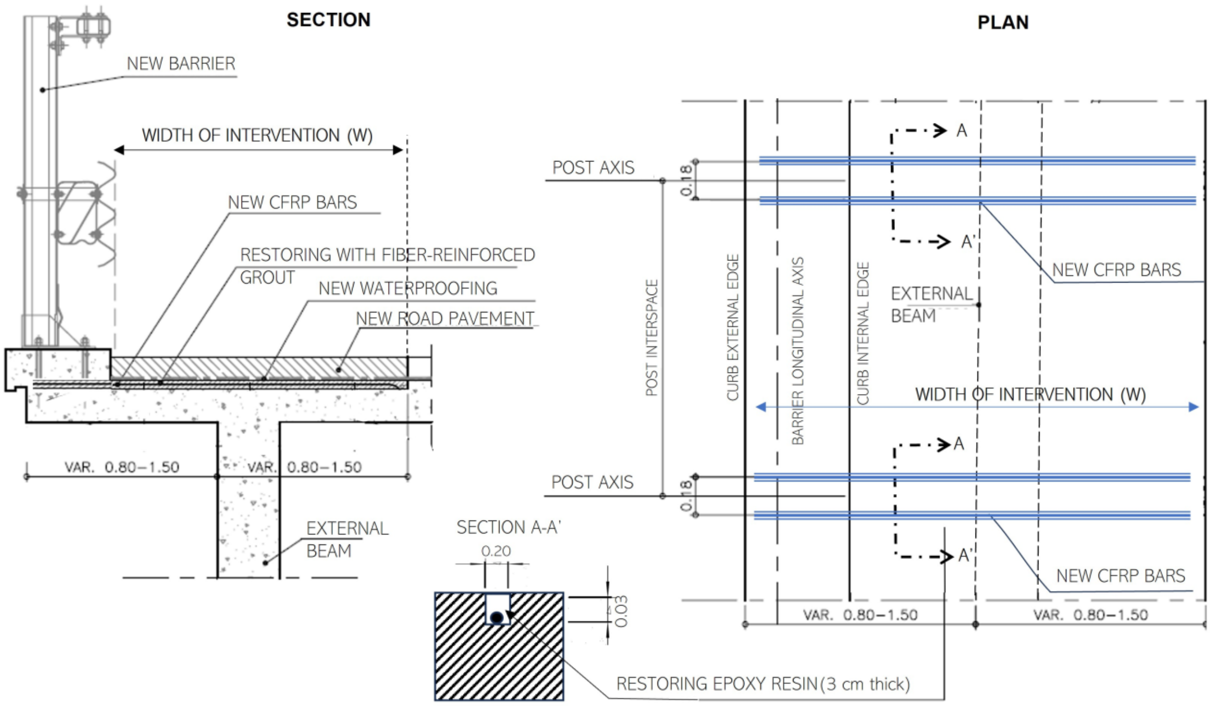

Figure 9. Slab strengthening through NSM composite bars.

4. Discussion

The presented slab-strengthening techniques have been derived from real structural design documents and guide manuals issued by road management bodies [34]. Therefore, they are used in practical applications mainly along motorways and highways in Italy. A critical comparison can be useful to determine their applicability as well as the pros and cons, as reported in Table 2, also referring to durability requirements [37], impact on the existing structure, and costs.

As can be seen, techniques no. 1 and no. 2 are the cheapest since they are based on consolidated techniques of RC elements' jacketing. On the other hand, they are exposed to possible corrosion (like technique no. 3), although the presence of a waterproofing layer on the slab extrados significantly reduces this risk. However, corrosion risk is absent in technique no. 4 due to the absence of metallic materials. Currently, the most used technique is no. 1 due to its versatility. In fact, as the anchors are installed after the additional rebars, small imprecisions in their positioning are admitted and do not compromise the effectiveness of interventions.

Based on the work price lists of the major Italian road management agency (ANAS) [28], the cost of intervention no. 1 per unit bridge length has been computed as a function of the intervention width (W in Figure 6). W depends on both the slab cantilever dimension and the rebar diameter and grade, which determine the development length to be adopted beyond the external beam.

As can be seen from Figure 10, the intervention cost is proportional to the intervention width. Based on inspected design documents of real bridges, the most frequent W value is 2 m corresponding to an intervention cost of EUR 843/m including the cost of new railings and all the works needed for the slab retrofit. These data are strongly susceptible to increase in the near future given the current inflation rates across the EU. Therefore, it should be treated as a temporary estimate.

Table 2. Comparison of slab-strengthening intervention techniques.

#	Description	Advantages	Limitation	Cost
1	Steel rebars on posts	• No curb demolition • Flexible position of anchors	• Possible corrosion effects in the long-term • Need to fix posts' positions before the intervention	Low
2	Distributed steel rebars	• No curb demolition • Flexible position of anchors and rebars	• Possible corrosion effects in the long-term • Hydrodemolition impact on the existing structure	Medium-low
3	NSM steel plates	• Lower impact of hydrodemolition on the existing structure	• Fixed position of vertical rods • Using lower-yielding strength ordinary steel • Curb demolition	Medium
4	NSM composites	• Lowest impact of hydrodemolition on the existing structure • No corrosion • No anchors	• Curb demolition • Possible delamination and fragile structural behavior	High

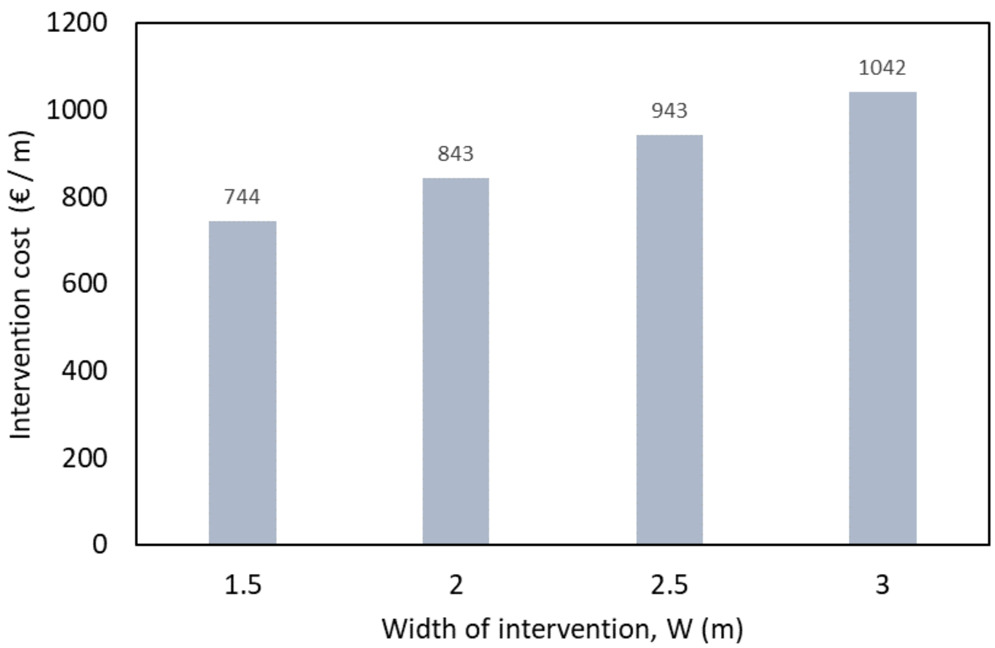

Figure 10. Unit length cost of strengthening solution no. 1.

Looking at Figure 11, the cost of the slab retrofit varies between 50 and 60% of the total intervention cost, being in most cases higher than the new railing cost. This means that low-impact and cheap slab retrofit solutions can greatly reduce the overall cost of interventions of the wide national bridge asset.

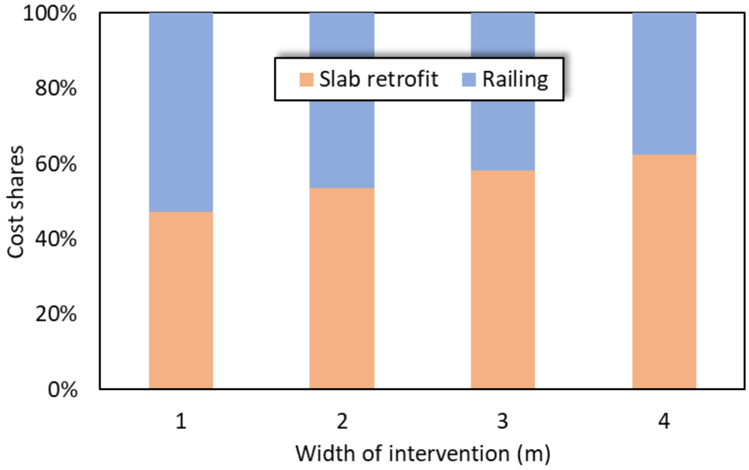

Figure 11. Relative cost of new barrier and slab retrofit for solution no. 1.

5. Conclusions

Although Italy is facing the refurbishment of bridge railings along its road network, some severe accidents still happen, causing huge human life losses. The replacement of old-type railings with new high-performance railing systems, able to avoid vehicles falling from bridges, often requires the reinforced concrete slabs' structural retrofit, which has not been properly investigated in the current literature. This paper wants to provide an overview of the issues related to the presence of weak retaining systems placed along edge bridge curbs, designed according to outdated codes, and working on high-traffic roads. After a description of the problem size at the Italian and European levels and an illustrative comparison of old type and new bridge railings, the general description of the assessment and retrofitting procedures available for the bridge slab retrofitting is reported along with a critical comparison. The more feasible is technique no. 1, where new steel reinforcement is installed on the slab extrados only in correspondence with posts. This technique is based on a concrete jacketing approach widely used in reinforced concrete building strengthening interventions. This technical option does not require curb demolition, resulting in the less expensive of the analyzed approaches. Among the other techniques, the installation of composite materials provides more durable interventions even though more expensive. In summary, the assessment and retrofit procedures here described may be useful to practitioners, to road management agencies for road maintenance activities, and to researchers investigating new solutions able to reduce cost while improving safety.

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