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RC TIED-ARCH BRIDGES: TYPOLOGICAL ANALYSIS FOR THE DEFINITION OF RETROFIT INTERVENTIONS

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Abstract

The Italian bridge asset is characterized by aged structures, most of which made of reinforced concrete, needing retrofit interventions to improve both their seismic performance and load-bearing capacity towards the increased traffic volume. In order to provide a series of guidelines for retrofit, a research project, carried out by the ReLUIS consortium supported by the Italian Department of Civil Protection, aims to identifying typological deficiencies and vulnerability of the main type of bridges widespread on the Italian territory, defining typological interventions. This paper presents the outcomes of the ongoing research focusing on RC tied-arch bridges, frequently built in the period between the two world wars. A typological study was carried out to define the main design deficiencies and construction details, and how degradation acts on this type of bridge, besides the main structural vulnerability to both gravitational and seismic loads. Numerical and parametrical analyses were carried out on a representative prototype tied-arch bridge with RC hangers, dating back to 1930s. The structural behavior was assessed by means of numerical analysis on FEM models, allowing the evaluation of the static and seismic capacity, the definition of the most vulnerable elements, and thus, the identification of the most suitable type of retrofit interventions.

Keywords: Bridge stock, bridge degradation, condition state assessment, bridge seismic vulnerability, prioritization.

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1 INTRODUCTION

Bridges are the most critical structures in transportation networks and [1], in many developed countries, such as Italy, most of them were built more than 40 years ago [2]. According to the CNR, the National Council for Research of Italy, many of those structures are at risk nowadays for their age [3]; in addition, structural typologies, technologies, and materials used for bridges were very different from those used today [4].

An out-of-service bridge might cause significant economic losses (i.e., costs for users, owners, and operators); maintaining them in service conditions is therefore desirable [2]. Proper inspections and timely maintenance are too often unfulfilled due to limited economic budgets and a widespread approach based on emergency, which is leading to a progressive deterioration of structures [5].

In the last ten years, a series of tragic collapse of bridges occurred in Italy [6, 7], pointing out the need for a regulatory direction to the problem. Then, in 2019, novel Guidelines for existing bridges [8] were issued, defining a methodology for inspection, prioritization, and verification of existing bridges.

Research has provided scientific-based tools to manage bridge stocks [9, 10, 11, 12] and to prioritize retrofit actions [13, 14, 15, 16], while the investigation of the most suitable types of retrofit has yet to be deepen in a framework of multi-criteria typological analyses.

Hence, a national project, funded by the Italian Department of Civil Protection (DPC), has been carried out by the *ReLUIS* consortium, with the purpose of identifying typological deficiencies of the main type of bridges and thereby defining the more suitable types of retrofit interventions. The present contribution, in particular, focuses on reinforced concrete (r.c.) tied-arch bridges.

R.c. tied-arch bridges are comprised by one or more arches, a tying chord, also called bow-string girder or tie-girder, which often corresponds to the deck system (i.e., girders and slab), and a series of hangers connecting the arches to the bow-string girders. These ones, located below the arches, absorb their horizontal thrust [17], allowing, on a theoretical level, the transmission of only vertical forces to the substructures. Bridges of this type often date back to the period between the two world wars and, due to their age, their safety is jeopardized by both degradation and increasing in the traffic volume [18].

The dynamic behavior and finite element (F.E.) model calibration of this type of bridges were previously studied by Turker et al. [19] and Brisighella et al. [20], which focused their analyses on specific case studies. Similarly, an extensive study including experimental non-destructive tests was carried out on a r.c. bowstring bridge in the Sicily region (Italy) [21, 22]. The influence of the hanger arrangement was investigated by Vlad et al. [23], through numerical simulations on 3D F.E. model.

The present paper proposes a critical examination of the available literature and of retrieved original projects. In order to operate in a typological framework, the most common characteristics of r.c. tied-arch bridges in Italy are illustrated, based on data collection carried out at national scale. Moreover, numerical analyses on a FEM model of a representative case study are presented, considering both gravitational and seismic actions. The identification of typological deficiencies, confirmed by results from the analysis of the case study, allowed classes of intervention to be suggested.

2 TYPOLOGICAL STUDY

R.c. arch bridges were widely built starting from the early 20th century, especially to overcome rivers where either a significant freeboard was required (e.g., for navigable canals) [24] or the clearance space between the road level and substructures was limited [21]. These bridges were frequently built in-situ by constructing a temporary centering [24].

Various sub-types of r.c. tied-arch bridges can be identified based on the following geometric and structural characteristics: i) the hanger material (i.e., r.c., prestressed r.c. or steel); ii) the hanger arrangement (i.e., vertical, radial or inclined), iii) type of crossbeams. Hence, these parameters were included in a preliminary data collection carried out at national scale which results are reported in the following section.

2.1 Dataset of r.c. tied-arch bridges in Italy

A dataset was collected, comprised of almost 90 r.c. tied-arch bridges, evenly distributed on the Italian area. The distribution of the main geometric and structural characteristics for bridges part of this stock are reported as follows.

Figure 1 reports the distribution of general characteristics of the identified bridges, i.e., the year of construction, the number of spans, and the span length. It was observed that the vast majority of the identified bridges were built in the period 1919-1946, between the two world wars; unfortunately, this datum was not available (NA) for a significant part of the stock. R.c. tied-arch bridges appeared to be mainly single-span, while span lengths were quite heterogeneous. Then, the hanger typology was observed, and Figure 2 reports the distribution of their arrangement, material, and spacing. Finally, the types of crossbeams were investigated (Figure 3). On the basis of the data collected, it was assumed that the most common type of r.c. tied-arch bridge in Italy has r.c. vertical hangers and orthogonal crossbeams.

Some examples of tied-arch bridges in Italy are reported in Figure 4.

2.2 Construction details

By consulting original project documentations retrieved for several r.c. tied arch bridges in Italy, it was possible to detect the common construction details and to deduce the design method of the time.

Concrete compressive strength ranges from high resistance (i.e., mean value of cube compressive strength R_{cm} around 40 MPa) to very low mechanical properties, found in one case [21]; these cases cannot be considered negligible due to the ancient construction age. Reinforcement bars were smooth, consistently with construction age, and small diameters (ϕ6-8 mm) were used for stirrups. Arches are segmental, with different values of the ratio between rise and span. They were designed to resist mainly to compression, based on the design criteria for masonry arches, and therefore they were relatively poorly reinforced.

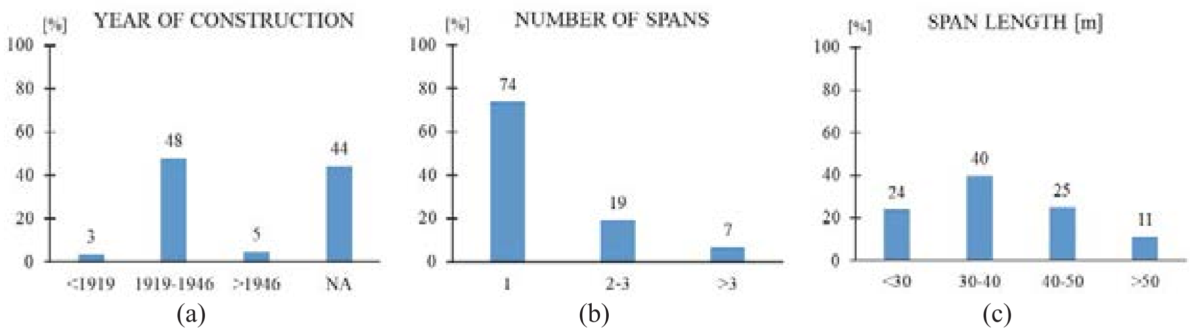
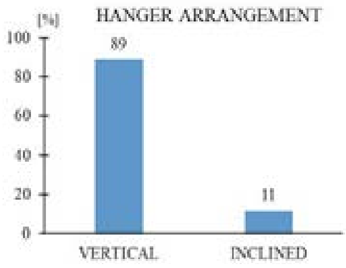
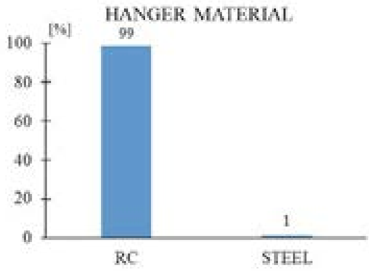


Figure 1: General characteristics of bridges in dataset: a) years of construction, b) number of spans, and c) span length.

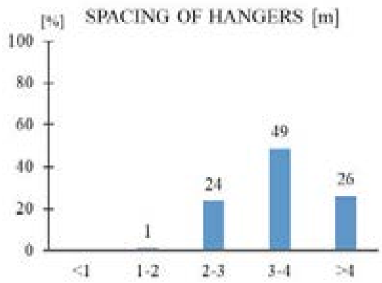
Hanger spacing varies in the range 2 - 4 meters, depending on the span of the bridge, and therefore on the generated stresses. The hanger joints, both to the arch and to the tie-girder, were designed as hinges, with insufficient reinforcement details to transfer flexural actions.



(a)



(b)



(c)

Figure 2: Hanger characteristics for bridges in dataset a) arrangement, b) material, and c) spacing.

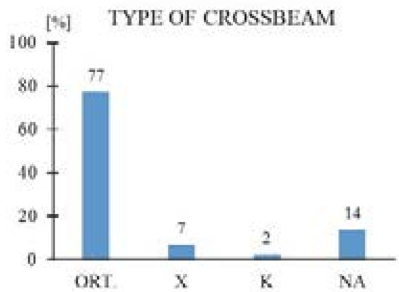


Figure 3: Distribution of type of crossbeams for bridges in dataset.

(a)

(b)

(c)

(d)

Figure 4: Bridges characterized by a) vertical r.c. hangers [25], b) vertical r.c. hangers and orthogonal crossbeams, c) vertical r.c. hangers and orthogonal crossbeams (multi-span) [25], and d) inclined r.c. hangers and orthogonal crossbeams (multi-span) [25].

2.3 Degradation and structural deficiencies

The macro-class of bridges here investigated resulted to be subjected to degradation effects and structural deficiencies, both affected the structural safety. The present section describes the main typical issues that can be found in r.c. tied-arch bridges.

The effects of degradation are caused by environmental actions (i.e., physical, chemical, and biological), and aggravated by many factors, such as incorrect construction details, low quality of materials, and lack or insufficient maintenance. The main and most common effect of degradation on r.c. bridges is the spalling of concrete, with consequent corrosion of the exposed reinforcement bars. Besides the susceptibility to degradation of all the elements of a r.c. tied-arch bridge, the observation of this phenomenon [26] suggests that hangers and deck structure are the most affected elements (Figure 5). To preserve both deck system and substructures, an effective system to drain rainwater is needed. In the case of steel hangers, the degradation of the material can cause the relaxation of hangers, with consequent redistribution of stresses, and the damage of anchors, which might lead to the detachment of the relative hangers.

(a) (b)

Figure 5: Spalling of concrete and corrosion of exposed rebars on: a) r.c. hanger and b) deck [25].

Not only is structural safety threatened by degradation, it might be also reduced by structural deficiencies influencing the response to both static and seismic loads.

Considering gravitational loads, substructures can be statically inadequate, as a result of original design deficiency and/or an increase in traffic loads (e.g., an increase in the arch thrust, no longer absorbed by the tie-girder, transferred to the abutments). The low quality of materials, poorly reinforced sections, and inadequate supports are the main static design deficiencies for the superstructure. As commonly found in existing bridges, the supporting system, connecting the substructure to the superstructure, is often inadequate to current traffic loads.

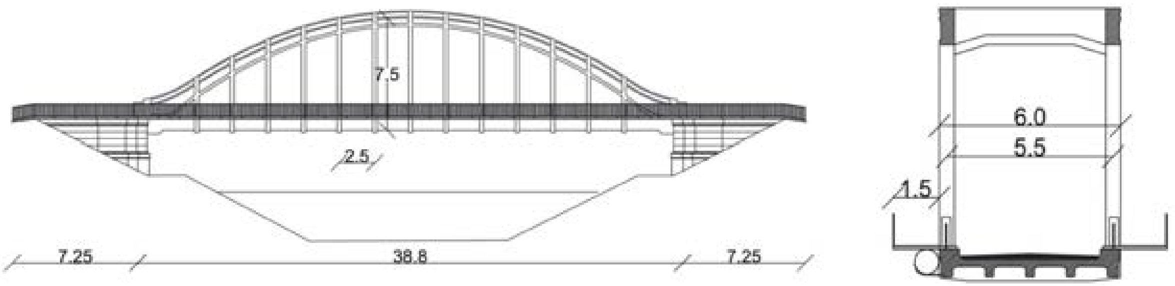
Most of r.c. tied-arch bridges in Italy were built long before the emanation of seismic codes, they were therefore not designed for seismic actions, making these structures intrinsically vulnerable to earthquakes. The most significant inadequacy is found for supports and substructures, due to both high levels of stress born by devices and the risk of support loss that can occurred in simply supported bridges. Poorly reinforced piers are vulnerable to horizontal stresses, towards either flexural or shear mechanisms. Focusing on the arches, the phenomenon of out-of-plane instability due to seismic actions is not negligible, mainly in case of missing or insufficient bracing system.

3 CASE STUDY

The case study presented and analyzed hereinafter is an existing r.c. tied-arch bridge, dating back to 1931 and located in the Veneto region, in north-east Italy. The case study was selected based on representativeness criteria, as it has a series of widespread characteristics, previously illustrated in the national dataset presentation. In detail, it is a single-span bridge, with a span length of almost 40 meters; it has r.c. vertical hangers (spacing 2.5 meters) and three orthogonal r.c. crossbeams (Figure 6 and 7). The deck consists of longitudinal and transverse beams, and a slab. The r.c. abutments founded on piles.

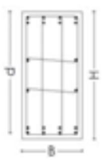
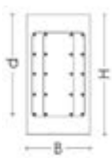
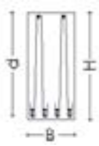
Furthermore, prior to implement analyses, original project documentation was retrieved, including representation of the construction details, which are reported in Table 1. No data was available on concrete, which were then assumed according to a similar bridge built in the region [27]. Two different set of data were available deriving from experimental tests carried out on two r.c. tied-arch bridges in the Veneto region. The one providing lower material strength was chosen based on both conservative criteria and geographic similarity of sites, leading to assume a concrete resistance class C20/25.

Figure 6: Case study – r.c. tied-arch bridge.



(a) (b)

Figure 7: a) Longitudinal and b) transverse view of case study.

Element	Section		Reinf.	Element	Section		Reinf.
		B=0.50 H=1.05	4+4Φ20 2Φ14 2Φ14 4+4Φ20			B=0.45 H=0.85	4Φ30 4Φ30 4Φ30 4Φ30 4Φ30
		B=0.20 H=0.50	2Φ16 4Φ20 4Φ16			B=0.30 H=0.40	2Φ22 4Φ28 4Φ28

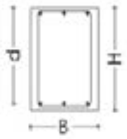
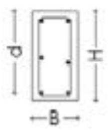
		B=0.40 H=0.60	$3\Phi18$ $3\Phi18$			B=0.25 H=0.50	$2\Phi22$ $2\Phi22$ $2\Phi22$

Table 1: Section and reinforcements of bridge elements.

In 1994, a restoration intervention was carried out, by rebuilding the deck slab and restoring all the concrete elements, which showed diffused spalling. During this intervention two metal footways were added on the outer sides. Prior to the restoration intervention, experimental tests were performed on the smooth reinforcement bars, which showed a yield strength greater than 450 MPa, and an ultimate strength greater than 600 MPa.

Traffic loads have been limited to 7.5 tons, as a result of the static verification performed in 1994; the limitation persists nowadays, thus it was considered in the definition of loads for the analysis.

3.1 FE model

A 3D F.E. models was implemented using the software Midas Civil [28], according to the current configuration, with the external metal footways (Figure 9). All of the bridge members were modelled through *beam* elements.

Figure 9: F.E. model based on current configuration.

Specific attention was paid to the study on the joints between hangers and the tie-girder or the arch, respectively. To study the behavior of these connections, a parametric analysis was carried out, modelling the hangers through either *beam* or *truss* elements.

The assumption of beam elements to model the behavior of hangers undergo the condition that the flexural stresses at the joints does not overcome the resistant bending moment. This condition resulted to be not verified. Moreover, reinforcements of the hangers consist in steel bars hooked at the ends, with insufficient degree of connection to transfer flexural stresses. Thus, it can be stated that hangers mainly have an axial behavior, which is better modelled through *truss* elements.

A comparison was also made of the stresses deriving from the two above-mentioned models, in order to verify that modelling with truss was conservative.

In general, the model with *truss* elements showed increased stresses for both the arch and the tie-girder, and a relative increase in vertical displacements. An exception is given by bending moments acting on both the arch and the tie-girders for self-weight, which were reduced in the model with *truss* elements.

Nevertheless, using *truss* elements to model hangers resulted to be more suitable for this type of bridges, and thus, safety verifications were carried out on this model configuration. Results of the comparison between modelling strategies are shown in Table 2.

		Arch			**Tie-girder**		
		M [kNm]	**N [kN]**	**Dz [mm]**	**M [kNm]**	**N [kN]**	**Dz [mm]**
Self-weight	*Beam*	125	-1593	6,8	53	1263	6,9
	Truss	109	-1603	6,9	45	1277	7,1
	Δ [%]	-13%	+1%	+2%	-15%	+1%	+3%
Permanent and accidental loads	*Beam*	1229	-4541	24,5	650	3619	27,1
	Truss	1387	-4579	27,9	734	3677	30,6
	Δ [%]	+12%	+1%	+14%	+13%	+2%	+13%

Table 2: Stress comparison between modelling strategies for hangers: using *truss* or *beam* elements.

3.2 Static and seismic assessment

Due to the lack of in situ investigations on materials, the level of knowledge for the structure was defined as limited (KL1) and thus a confidence factor CF=1.35 was assumed [29]. Safety verifications towards both static and seismic load combinations were performed according to Italian regulations, included the novel guidelines for existing bridges [8].

Four traffic load combinations were considered for static verifications, the first was defined according to Italian code [30, 31] and thus referred to as "NTC18" hereinafter. Three load combinations were assumed according to Italian Guidelines for existing bridges [8] to evaluate the level of safety ensured by the structure: operativity, transitability 1, and transitability 2. In fact, each of these combinations corresponds to traffic load layouts with decreasing return periods, thus providing an effective tool for the evaluation of measures to be adopted. The load combination transitability 2 was defined considering a traffic limitation that allows the transit of vehicles up to 7.5 tons.

The values of stresses resulted from the analyses are reported in Table 3. A general relief of the elements can be observed, due to the decrease in traffic loads with respect to NTC18 configuration.

Results of ULS strenght verifications are reported in Figure 10, which represents the minimum demand/capacity ratio (D_d/C_d) for each element. The tie-girders and the longitudinal beams results to be the most critical elements, which satisfy the verifications only for the less demanding load combination (i.e., transitability 2). The deck deficiencies stem from the poor distribution capacity of the slab, besides the increased in traffic loads with respect to the period of construction.

Figure 11 compares outcomes from the analyses in terms of axial load and bending moment with the limit domain of tie-girders.

Safety verification towards seismic action were carried out with reference to three decreasing return period T_R (i.e., 75 years, 30 years, and 5 years); the first one refered to a design working life of 50 years increased of a factor 1.5 for relevan structures, according to Italian Code [30], while lower return period were assumed according to Italian Guidelines for existing bridges [8].

The elastic response spectrum was conventionally referred to L'Aquila, Italy, a site with moderate-high seismicity.

A linear dynamic analysis was carried out. The obtained first three modes of vibration are shown in Figure 12: the first one results to be transverse, which corresponds to the out-of-plane direction of the arches; the second mode is vertical; and the third one have a predominantly torsional component.

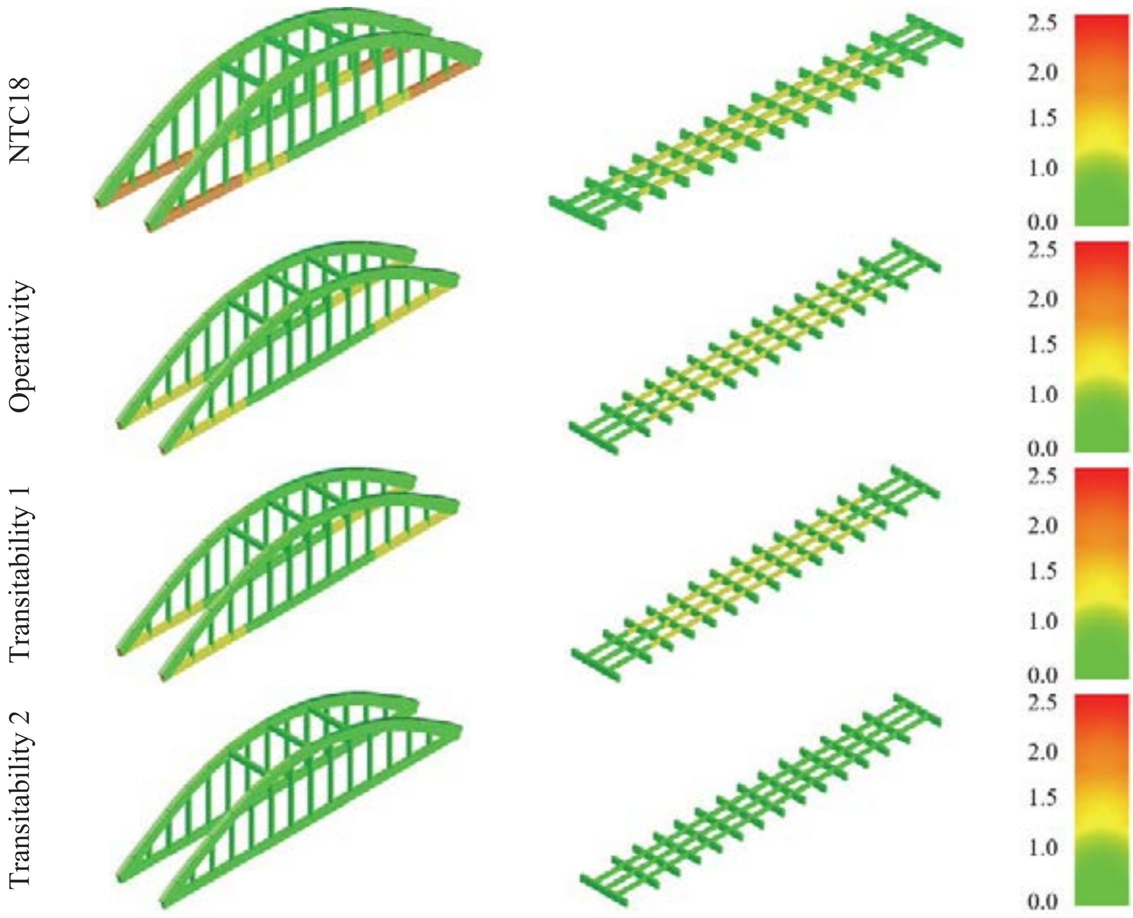


Figure 10: Safety verifications for static load combinations in terms of demand/capacity ratio.

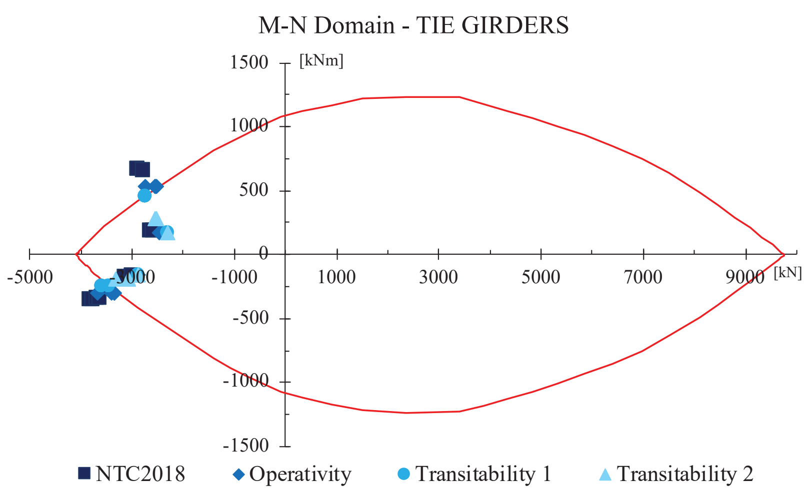


Figure 11: M-N limit domain of tie-girders with plotted outcomes of static analyses.

ARCH								
	N_{max}		**M_{ymax}**		**M_{ymin}**		**V_{max}**	
	[kN]	[%]	[kNm]	[%]	[kNm]	[%]	[kN]	[%]
NTC18	-3664		1250		263		273	
Operativity	-3293	10%	1021	18%	225	15%	225	17%
Transitability 1	-3402	7%	895	28%	258	2%	200	27%
Transitability 2	-3190	13%	608	51%	177	33%	140	49%
TIE-GIRDER								
	N_{max}		**M_{ymax}**		**M_{ymin}**		**V_{max}**	
	[kN]	[%]	[kNm]	[%]	[kNm]	[%]	[kN]	[%]
NTC18	3821		657		-360		497	
Operativity	3402	11%	527	20%	-305	15%	417	16%
Transitability 1	3468	9%	455	31%	-250	31%	329	34%
Transitability 2	3231	15%	275	58%	-192	47%	244	51%
HANGER								
	N_{max}							
	[kN]	[%]						
NTC18	531							
Operativity	454	15%						
Transitability 1	415	22%						
Transitability 2	330	38%						

Table 3: Comparison of stresses acting on bridge for the analyzed traffic load combinations.

1st mode 2nd mode 3rd mode

Figure 12: First three modes of vibration of analyzed bridge.

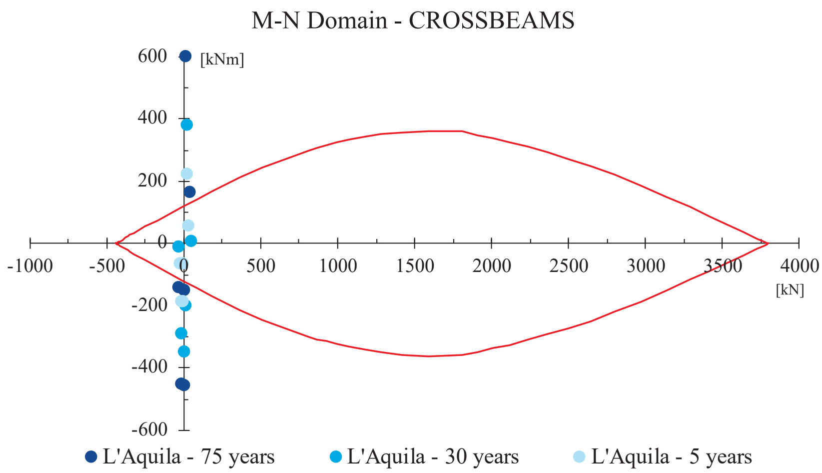


Figure 13: M-N limit domain of crossbeams with plotted outcomes of seismic analyses.

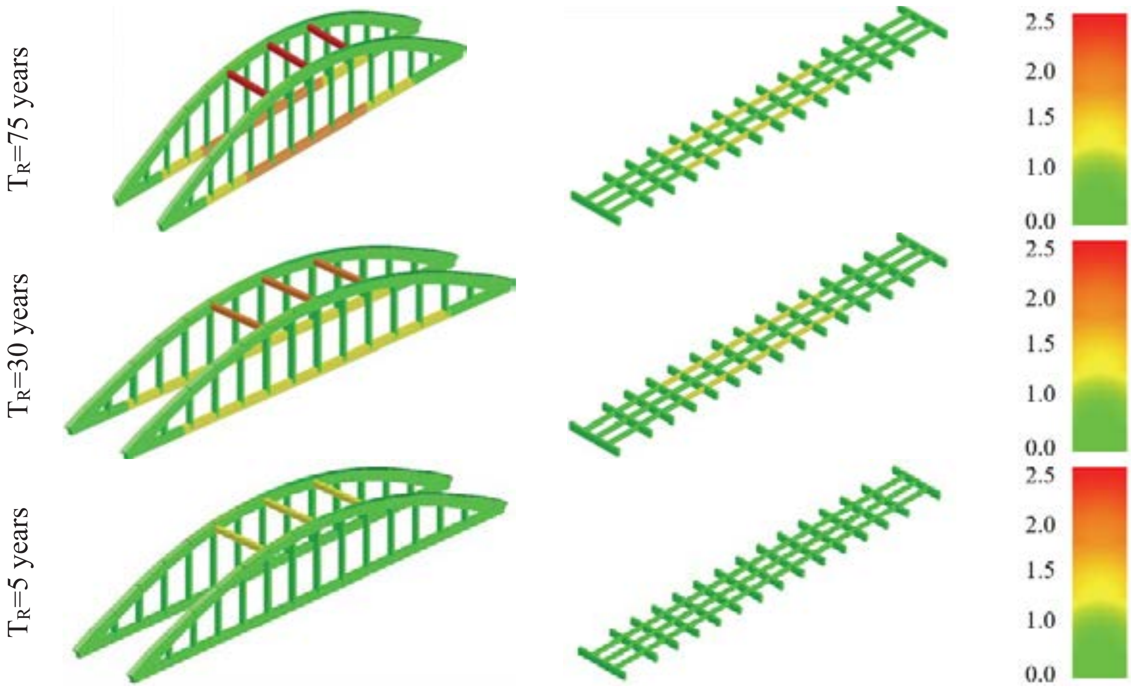


Figure 14: Safety verifications for seismic load combinations in terms of demand/capacity ratio.

According to the results of seismic verifications, the most stressed elements are the crossbeams, which have the function of preventing the out-of-plane instability of the arches. Crossbeams appear to have a significant seismic vulnerability, showing inadequate safety indeces also for low seismic actions (Figure 13). In addition, tie-girders shows a deficiency for seismic actions as well. Figure 14 reports the results of seismic verifications in terms of minimum demand/capacity ratio for each structural member.

Results suggest the most suitable classes of intervention to be applied to r.c. tied-arch bridges. Being aware of specific features of each unique existing structures is fundamental to design the proper retrofit intervention; however, useful direction can stem from typological studies. In the present study the following typological classes of intervention were identified:

- post-stressing the tie-girders, in order to improve the capacity of absorbing the arch trust;
- replacing supports with a novel isolation system, able to reduce actions on both substructures and superstructures.

In addition, since the r.c. deck slab is commonly inadequate in existing r.c. bridges [26], a strengthening intervention on this element shall be considered.

4 CONCLUSIONS

- A typological study of RC tied-arch bridges in Italy was carried out in order to identify structural characteristics and main deficiencies. Various sub-types of r.c. tied-arch bridges have been identified based on the hanger material and arrangement, and the arch bracing system. On the basis of data collected at national scale, it was assumed that the most common type of r.c. tied-arch bridge has r.c. vertical hangers and orthogonal crossbeams.
- Increasing traffic loads, poorly reinforced sections and degradation (mainly acting on hangers and deck structure) are the main causes of reduced structural safety. In addition, due to their age of construction, most r.c. tied-arch bridges in Italy were not designed for seismic actions, making them intrinsically vulnerable to earthquakes.

- Based on representativeness criteria, a case study was selected and analyzed through numerical modeling. It is a single-span bridge built in 1931; it has r.c. vertical hangers and orthogonal r.c. crossbeams. The tie-girders and the longitudinal beams results to be the most critical elements towards static combinations, while crossbeams have a significant seismic vulnerability, showing inadequate safety indeces also for low seismic actions.
- Future developments will focus on improving the knowledge of the case study and on identifying the most suitable type of retrofit interventions. The former will be pursued through a dynamic identification and experimental tests on materials. The presented study suggests that the most suitable types of intervention are the following: i) the application of a post-stress system to the tie-girders, in order to improve the capacity of absorbing the arch trust, and ii) the replacement of supports with a novel isolation system.

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