Retrofit strategies for Maillart-arch-type bridge: the case study of Viadotto Olivieri in Salerno

Antonello De Luca[a], Laura Giovanna Guidi[a]
Dipartimento di Strutture per l'Ingegneria e l'Architettura, Università degli Studi di Napoli Federico II, Piazzale Tecchio 80, Fuorigrotta, 80125 Napoli

Keywords: Maillart-arch-type bridge, dynamic response, seismic retrofit, rubber bearing, seismic isolation, deck stiffening

ABSTRACT
This paper deals with any possible retrofit strategies for existing Maillart-arch type bridge, also known as deck stiffened arch bridge. The evaluations concern an existing case study, Viadotto Olivieri in Salerno. Based on a FEM model of the bridge at the current state, as result of a 3D scanner relief, dynamic analysis underlines bridge vulnerability to seismic force: they may worsen both arch out of plane overturning and cross walls buckling as consequence of deck sliding in transversal and longitudinal directions. Considering that bridge original design was strictly affected by vertical actions and that the overall structure is characterized by a very low live-to-dead-loads ratio (6.5%), it could be interesting to value any possible measures to guarantee bridge serviceability, also when earthquake occurs. Starting from the original configuration, having three deformable deck portions, a retrofit solution is proposed. An isolated system (IS), made of HDRs, is hypothesized, assuming to insert them by cutting the cross walls at the top. Even if the resulting benefits are clear, it cannot be neglected that, by introducing IS, the original static scheme of a Maillart-arch-type bridge will be completely modified. For this reason a complementary, option that will contemplate the strengthening and the partial modification of the original deck bridge configuration, will be compared to the previous seismic retrofit proposal.

1 MAIN FEATURES OF MAILLART-ARCH TYPE BRIDGE DESIGNED FOR VERTICAL LOADS

Maillart's way to design elegant thin concrete arch bridges dates back to 1920's: the idea came from his studies concerning the effects of live loads applied to the arch, in addiction to dead ones. According to Maillart, an arch bridge can be assimilated to an inverted cable. A cable curves downward when a weight is hung from it: the tension in the cable balances the addicted weight. An arch bridge curves upward to support roadway, and the compression in the arch balances the dead load. Once the arch form has been fixed to fit dead load, the addiction of live loads causes the arch to bend, especially in the case of asymmetric load condition. So, the arch must be strong and thick to resist to bending. Preserving also aesthetic aspect, Maillart wanted to obtain thinner arch: the innovative solution was to connect the arch to the roadway deck with transverse walls. He designed the deck to be significantly stiffer than the arch and thus able to carry most of the bending in the system. As the arch tends to bend when traffic stand over one half of the span, the cross walls make the deck to bend to the same new shape as the arch. The bending effect is shared between arch and deck: each portion carries it in proportion to its flexural stiffness. As later argued also by Billington, "a stiff deck could remove large forces from the arch, if the arch were designed to be much less stiff than the deck", (Billington, 1973), (Billington, 1983), (Billington, 1997), (Billington, 2003). Form the Schwandbach Bridge (1933) by Maillart to Infant Dom Henrique Bridge by A. Adão da Fonseca (2002), (Adão da Fonseca, 2006) (Adão da Fonseca, 2007), the deck-stiffened arch, with thin (ribbed) vault, represents an effective and no redundant structural solution. The resulting optimization in using reinforced concrete to create a slender flexible arch guarantees a high structural deformability. This makes bridge's seismic response more effective than the one we could supposed for a structure designed to resist to vertical loads only in 1960's.

2 STRUCTURAL CHARACTERIZATION OF VIADOTTO OLIVIEIR IN SALERNO

2.1 Bridge location

In 1950's the so called Cassa del Mezzogiorno, instituted by Italian Government to finance industrial initiatives in Southern Italy, put into practice a plane of measures, , including environmental renewals and construction of new highways, as Pompei-Salerno one (Grassini et al., 1962). In its picturesque scenario, overlooking the Salerno Gulf, the new highway was conceived in parallel to the existing railway. Considering the extreme local slopes, crossed by rivers, Maillart arch type bridge appeared one the most suitable one. Along this track, six out of eight bridges were designed in accordance to Maillart scheme, having a mean span length of 60.0 m and an arch rise-to-span ratio lower than 1/4. All these arch bridges, including Viadotto Olivieri, are characterized by a "Z-shaped" deck solution made of thin concrete slabs, able to minimize deck width by using two staggered carriageways. This solution avoids the discomforts due to the lamps of passing cars on opposite directions; structurally, the "Z-shape" guarantees deck cross section to carry stress due to bending moment reversal.

2.2 Bridge layout

Olivieri Bridge has an overall length of 136.80 m. It consists of three portions, Figure 1: a central Maillart arch bridge, standing form pier 2 to pier 12, spanning 76.00 m with a rise (r) of 19.30m (r/L= 1/4); an access ramp at Salerno side, standing from pier 13 to SA-abutment, a 6-spans-concrete-beam bridge, 45.60 m long; an access ramp at Napoli side, from NA-abutment to pier 1, a 2-spans-concrete-beam bridge, 15.20m long.

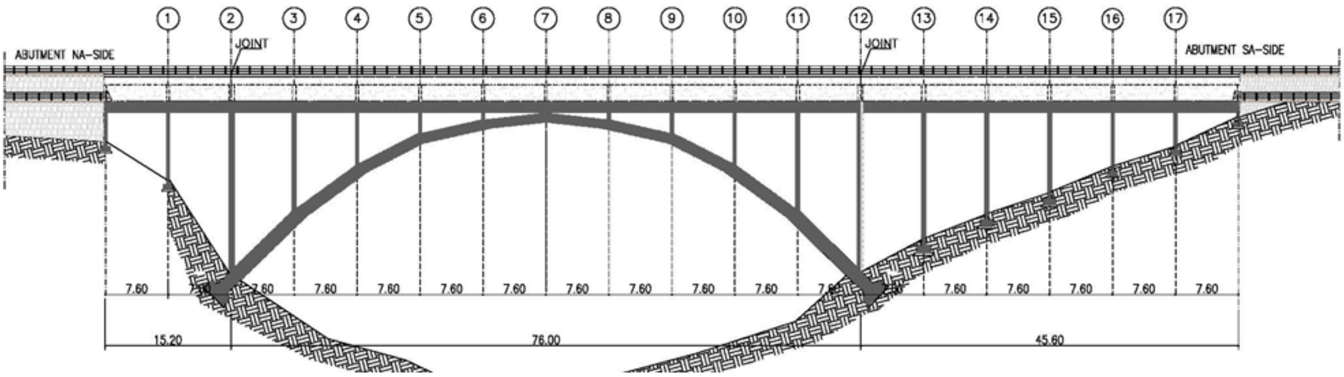
Each portion is connected to the adjacent one by a 6 cm wide joint.

The concrete parabolic vault, Figure 2, made of a 20cm-thick slab, is stiffened by using five arched ribs with variable cross sections. The thin arch is linked to the upper rigid deck by a series of slender cross walls. They are made of a thin concrete slab (12 cm thick), stiffened by 5 columns, whose cross section size grows from the middle portion to the edge of the cross wall.

In relation to their low shear stiffness, cross walls can be assimilated to pendulums, Figure 3. As argued in the companion paper, bridge load estimation points out a live-to-dead loads ration nearly 1:6.

Figure 2. Olivieri Bridge layout and detail of ribbed vault

Figure 1. Olivieri Bridge longitudinal layout (below)



In particular, dead load aliquot corresponds to 75% of the overall applied loads, superimposed-dead loads reach 11%, while live loads percentage is about 14%, Table 1. Concerning dead loads, arch contribution is approximatively 20%, deck aliquot corresponds to 56% while cross walls cover 24%.

Figure 3. Olivieri Bridge: joint section (above); cross walls detail at the joint section and attach to foundation (below)

Table 1. Olivieri Bridge Loads (overall length L=137,10m; deck loaded width w= 15.83m)

Type	P[t]	$[FL^{-2}]$ (t/m^2)	$[FL^{-1}]$ (t/m)	% Tot
Dead	4814.94	2.22	35.14	75.27%
Super.dead	682.97	0.32	5.07	10.87%
Live	911.74	0.41	6.49	13.86%
Tot	6409.65	2.95	46.68	-

Considering bridge configuration, its load distribution and the great deformability of the slender arch and the upper cross walls, the worst loads condition is related to any horizontal forces, acting both in longitudinal direction and out of plane. FEM modelling (by using Sap2000) has been used to define dynamic characterization of Viadotto Olivieri.

Looking at geometrical and technical complexity of this bridge, a cloud of points, coming from 3d-scanner relief, has been adopted as guide to modelling the structure. Bridge has been discretized using frame and shell elements: arches and beams, making the "skeleton" of this structure, have been modelled as frame elements, corresponding to their barycentre axis; wall and slab have been defined as shell elements.

3 DYNAMIC RESPONSE OF VIADOTTO OLIVIERI

With a view to FEM analysis, bridge at the current state can be assimilated to a three deformable deck model with fixed joints at the base: for each cross walls, the stiffening columns are directly connected to foundation plinths, while the concrete membrane is cut at the ground level. To characterize bridge seismic vulnerability, outputs form linear static analysis have been compared to modal analysis ones. In the first case, the effect of seismic action has been valued applying horizontal forces (in longitudinal and transversal direction), assumed as 10% of the overall permanent loads. Rotational equilibrium is computed, in order to define the weakest parts. On the other hand, modal deformed shapes and the corresponding mass participation ratio lead to identify the most vulnerable portions.

3.1 Linear elastic analysis: the effect of horizontal forces

As argued in the companion paper, when horizontal forces act in both directions, arch portion records the worst effects. In the case of longitudinal forces (x-direction), Figure 4, the stiffer side portions show little sliding effects, while the thin arch, as the most vulnerable portion, bends as the upper rigid deck in a way that buckling effects occur to the intermediate cross walls. Total shear force is carried by the abutments for 38%, while the arch carries about 60% of the overall.

Out of plane horizontal forces (y-direction), Figure 5, cause central arch uplift, while side spans preserve their original configuration.

In this last case, about 60% of the overall shear force is carried by the arch, while the abutments are the lowest excited section, Table 2 and Table 3.

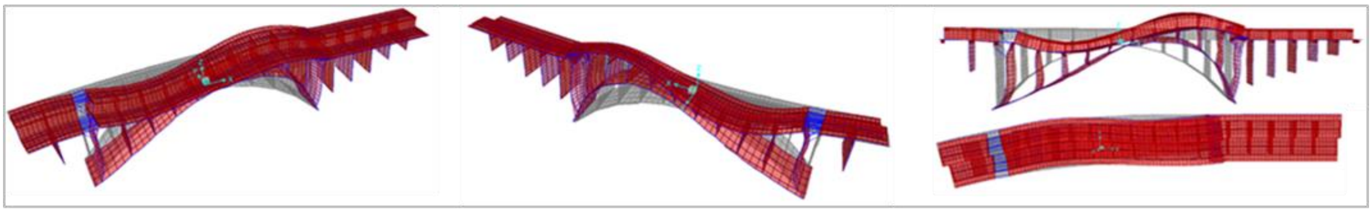


Figure 4. (above) FEM modelling deformed shapes for longitudinal horizontal forces (FOX = 10% WTOT).

Table 2. Rotational equilibrium for out of plane horizontal forces: 3-deformable decks model with fixed joints (part 1)

Portion	Ty (t)	Mxx (tm)	Mxx (Ty) (t m)	M (ΔN) (t m)	M tot (t m)
NA-abut.	10.91	19.52	187.4	-80.9	125.9
Pier 1	53.13	7.20	668.5	635.1	1310.
Arch	303.2	123.1	470.0	7337	7930
P. 13 -17	147.9	118.1	1688	1408	3215
SA-abut.	8.717	8.73	175.9	-81.4	103.1
∑	523.85	276.6	3190	9218	1268

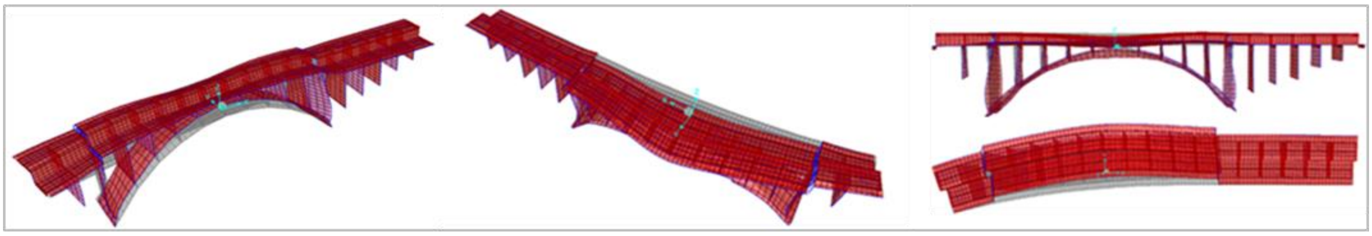
Table 3. Rotational equilibrium for out of plane horizontal forces: 3-deformable decks model with fixed joints (part 2)

Portion	Ty %	Mxx %	Mxx (Ty) %	M (ΔN) %	M Tot %
NA- abut.	2.09	7.1	5.9	-0.88	0.99
Pier 1	10.18	2.6	21.0	6.89	10.33
Arch	58.1	44.5	14.7	79.5	62.51
P. 13 -17	28.35	42.7	52.9	15.2	25.35
SA-abut.	1.67	3.2	5.5	-0.88	0.81

More than 60% of the global moment is borne by the arch; the remaining 30% is distributed among the intermediate cross walls, while final piers are almost unloaded.

Shear-induced moment, as Mxx(Ty), is carried by the cross walls for a percentage higher than 50%. On the contrary, the worst bending contribution for the arch is due to axial force-induced moment, defined as M(ΔN): the corresponding aliquot, nearly 80%, justifies the arch uplifts, resulting from FEM analysis.

Figure 5. (below) FEM modelling deformed shapes for out of plane horizontal forces (FOY = 10% WTOT)



3.2 *Modal analysis: bridge dynamic response*

As underlined in the companion paper, modal analysis output for Olivieri Bridge model point out that the worst effects are due to translational local modes, both in longitudinal and in transversal directions; except in rare cases, rotational contribution are negligible.

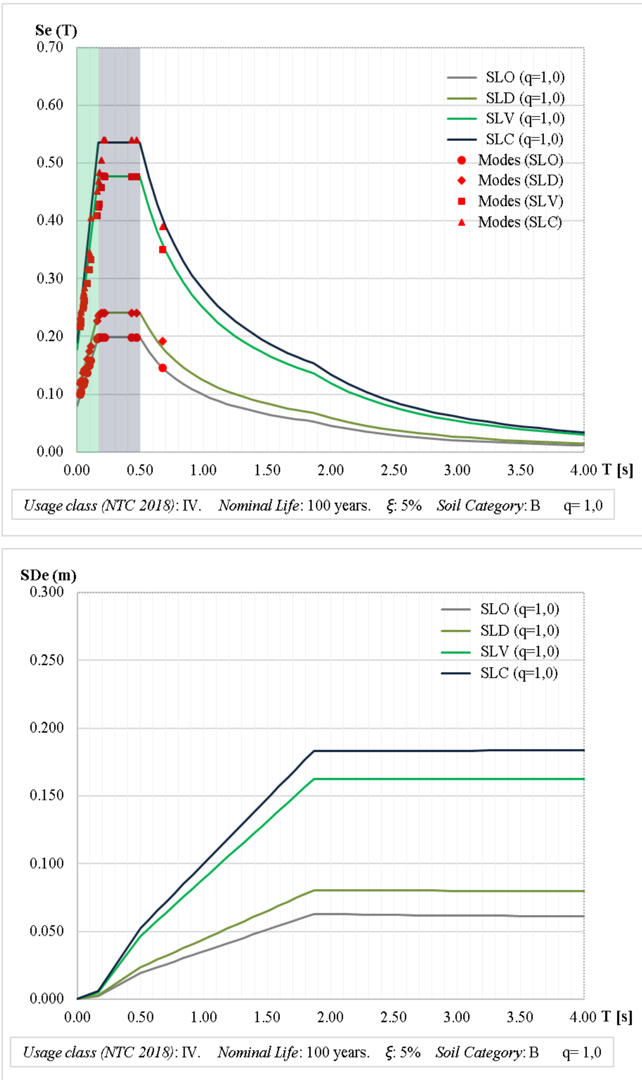


Figure 6. Olivieri Bridge design response spectra, in terms of acceleration (above) and displacements (below).

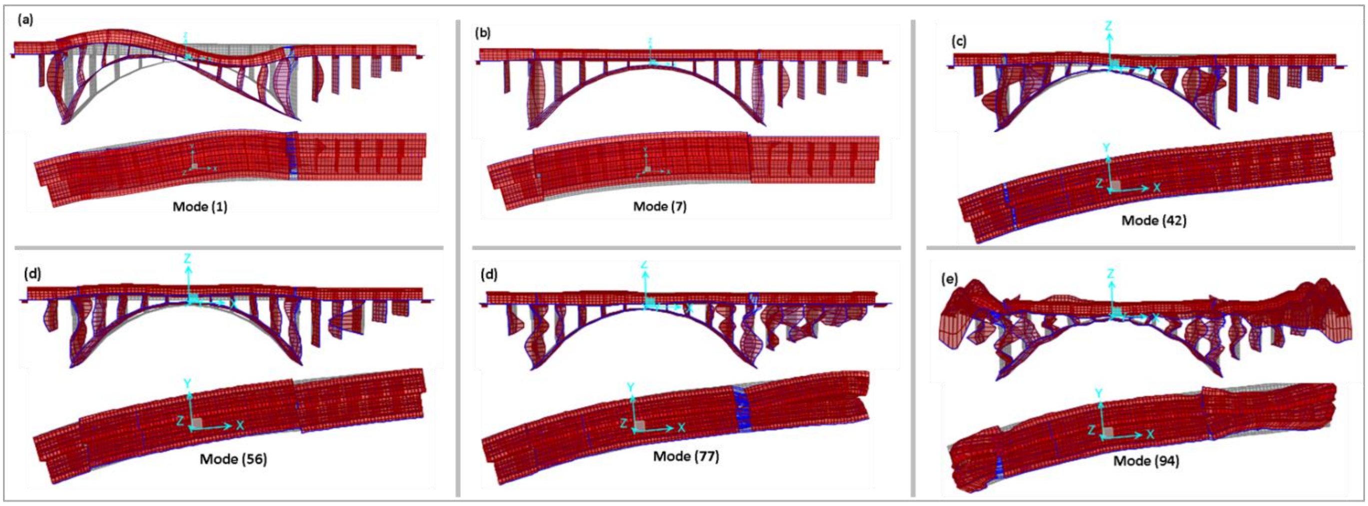


Figure 7. (above) Modal deformed shapes mainly involving translational displacements. (a) Mode : T= 0.674 s, UX = 31.3%, RY = 9.01%; (b) Mode 7: T= 0.472 s, UY = 49.73%, RX = 8.33%, RZ = 5.50%; (c) Mode 42: T= 0.215 s, UX= 11.70%; (d) Mode 56: T= 0.172 s, UZ= 41.37%; (e) Mode 77: T= 0.099 s, UX = 12.71%; (f) Mode 94: T= 0.0383 s, UZ = 7.2%.

Periods associates to the main modes are lower than 1.0 s, as presumable for a rigid structure. Main modes fall within the first two spectrum sections, above all in the first on, Figure 6. The corresponding spectral displacements don’t exceed 0.05 m. Comparing modal shapes, Figure 7 and Figure 8, it is visible that only few macro-elements are involved in each mode: as expected, this kind of bridge has a dynamic behaviour greatly different from that of ordinary structures. Despite this bridge is a complex multi degree of freedom system, 100 modes are sufficient to involve about 100% of participating mass.

4 POSSIBLE RETROFIT SOLUTIONS

FEM analysis outputs highlight a certain vulnerability of this Maillart-arch-type bridge to seismic actions. At the current state, with three deformable portions, horizontal forces could cause arch uplift, when they act out of plane.

Figure 8. (below) Modal deformed shapes mainly involving rotations. (a) Mode 53: T= 0.175 s, UY = 7.73%, RZ = 9.045; (b) Mode 58: UY = 5.84%, RX = 9.08%; (c) Mode 86: T= 0.063 s, RX = 9.56%

These forces can also lead to possible buckling effects at the cross walls as consequence of deck sliding in longitudinal and transversal directions.

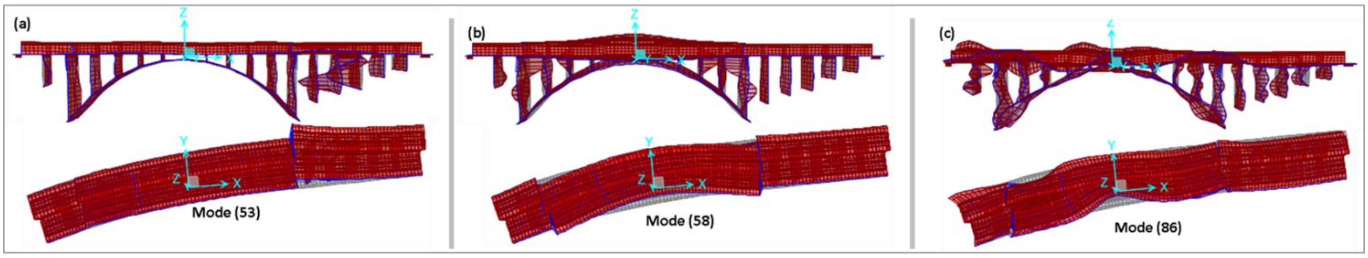
Considering that bridge design was strictly affected by vertical loads, having a low live-to dead loads ratio (1:6.5), the evaluation of possible measures to improve seismic behaviour of this structure are proposed.

Even though modal analysis results suggest that at the current state Viadotto Olivieri is a rigid enough structure, as demonstrated by main vibration periods lower than 1.0 s, its seismic response is favoured by bridge layout. Its flexible thin cross walls, connecting as pendulums the lower ribbed vault with the upper rigid deck, give to a Maillart-arch-type bridge a great capacity to accommodate large displacements when horizontal forces act.

However, additional measures are needed to prevent excessive deformation or arch overturning effects. To this aim, benefits from a hypothetical isolated solution are compared to a stiffening proposal that foresees the jointing of the three adjacent deck portions. Seismic isolated proposal with rubber bearing devices

4.1 *Seismic isolated proposal with rubber bearing devices:*

To improve seismic response of this Maillart-arch-type bridge, a proposal of seismic retrofit is considered. An isolated system (IS) made of High



D Rubber Bearing, also known as HDR, is hypothesized, assuming to insert them by cutting the cross walls at the top, before creating appropriate pier caps. However, in this way the original static scheme of Maillart-arch bridge will be completely modified. A solution of this kind cannot be effectively put into practice, but it can be assumed as a term of comparison to check seism attitude of Olivieri Bridge at the current state.

This hypothetical solution includes a pre-dimnsioning of the isolation system (IS): a design period T_{iso}= 2.50s is assumed, corresponding to a maximum displacement of 250mm, Figure 9.

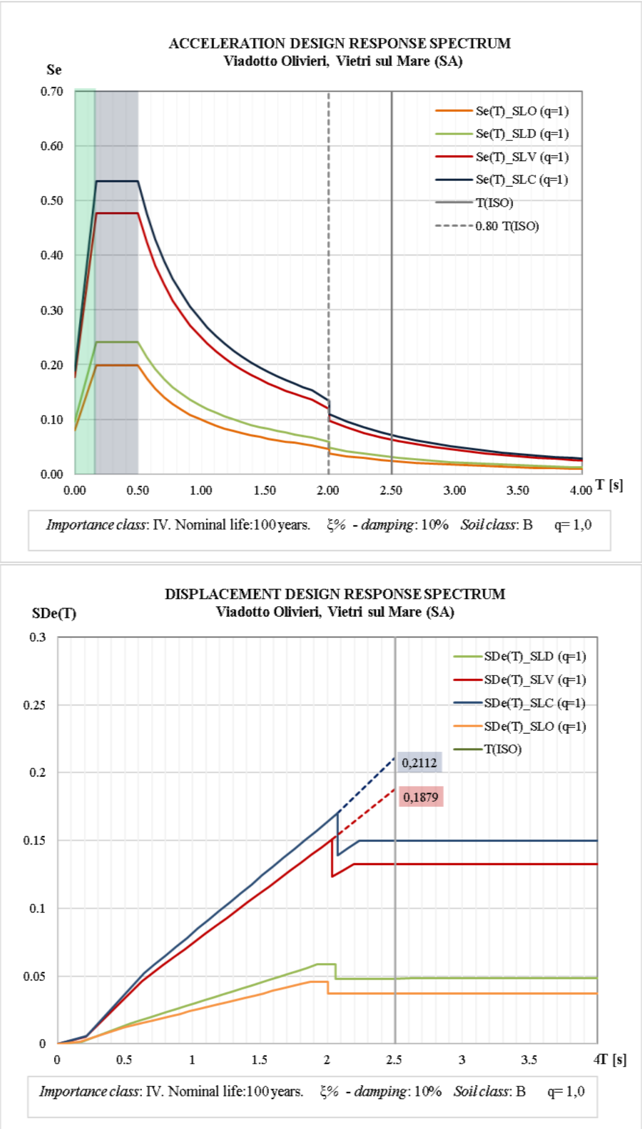


Figure 9. Design response spectra for Isolated solution, in terms of acceleration (above) and displacements (below).

The effective sesimic weight, W, used to define the overall seismic r force at the base of the strucutre, is given by bridge permanent loads (only referred to the upper deck) plus a percentage of live ones. According to italian Building Code (NTC 2018) for a busy bridge 20% of the overall live load can be considered in defining seimic weight, W, Table 4.

Table 4. Seismic weight (W) of Olivieri Bridge

Load Type	Fk (t)	γ	γFk(t)
Dead (arch)	2667	1.00	2667
Superimposed dead	683	1.00	683
Live	912	0.20	182
Total	4262	-	3532

. It is assumed that the three deck portions are ridgly connected in a single deck and that each of 17 intermediate corss wall is cut at the top, as close as possible to the upper deck: high damping rubber bearigns would be inserted at the top of the columns that rib the cross walls, after creating appropriate pier caps. Each isolator will carry about 37 t.

Fixing an isolation period T_{iso} = 2.50s, the overall horizontal stiffness of IS system can be defined in accordance to formula (1); each device should have an horizontal stiffness no lower than $K_{iso,i}$ in accordance to formula (2):

$$K_{iso}=(4W\pi^2)/(T_{iso}^2) = 2287 \text{ kN/m} \quad (1)$$

$$K_{iso,i}= K_{iso}/n = 248 \text{ kN/m} \quad (2)$$

In this particular case, the choice of device diameter is greatly influenced by cross walls' geometry: these columns have a concrete cross section varying from a maximum (45 cm x 30 cm) to a minimum of (30 cm x 30 cm). A diameter not exciding 300mm can be adopted. In particular, this simulation provides for the use of HDRB ϕ 300, having soft compound with a dynamic shear modulus G = 0.40 MPa and an equivalent viscous damping coefficient equal to 10%. The parameters that better synthetize device geometry are the primary (S_1) and secondary (S_2)shape factors, defined as follows:

$$S_1= \phi/4t_i \quad (3)$$

$$S_2= \phi/t_e \quad (4)$$

Design guidelines (Presidenza del Consiglio Superiore dei Lavori Pubblici, 1998) (NTC 2018) and literature (Naeim, Kelly, 1999) (Montuori et al, 2016) suggest, for S_1, the range 10 - 30, and, for S_2, the range 3 – 5. Recent design in Japan adopts larger values for S_1 and S_2, the first reaching 50, and the second using values greater than 5.

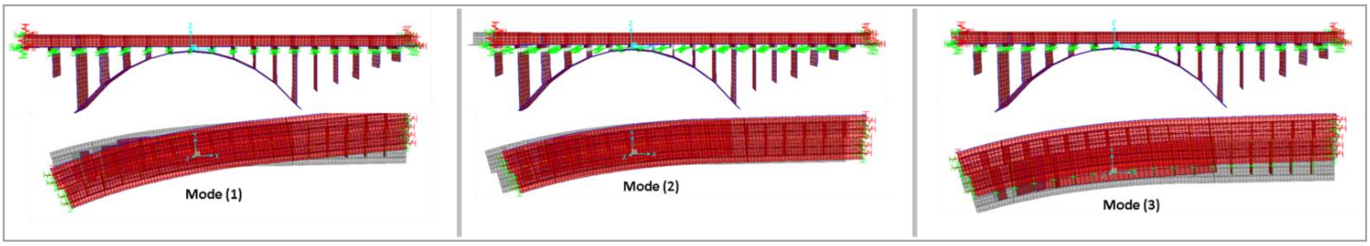


Figure 10. Main modal deformed shapes fro IS solution. Mode 1: T= 1.507 s, RZ= 69.65%; Mode 2: T=1.432 s, UX= 61.62%; Mode 3: T= 1.428 s, UY=61.59%

In this case it is assumed S_1= 10 and S_2 = 2.50, corresponding to a total rubber thickness (t_e)of 120mm and a single rubber layer thickness (ti) of 7.5mm. The main characteristics of rubber devices are synthetized in the Table 5.

Table 2. IS solution: Main Characteristic of rubber bearing devices

ϕ	G MPa	S_1	S_2	te mm	t_i mm	N_{crit} t	σ_{crit} MPa
300	0.40	10	3	120	7.50	71	10

The resulting critical loads, defined in accordance to the following formula (5), is higher than the maximum design vertical load applied to each isolator.

$$N_{crit}= G*A_r*S_1*S_2 = 70.70t \qquad (5)$$

Compared to structure at the current state, modal analysis outputs for this isolated single deck model, Table 6 and Table 7, reveal an increase of the vibration periods and a more regular dynamic response: earliest three modes includes about 70% of mass participation mass ratio, involving deck torsional displacements, as well as sliding motions in longitudinal and transversal directions. The introduction of IS system guarantee the bridge to have a more "regular" seismic response, with a fundamental period (related to first mode) of 1.50sec and a participating mass ratio RZ of about 70%, corresponding to torsional effect in deck plane. On the contrary, the successive modes are characterized mainly by translations, either in longitudinal or in transversal direction, as visible from Figure 10.

No combined effects occurred. On the other side, IS solution increase bridge deformability: this makes the thin cross walls more vulnerable to buckling effects, while any possible arch uplift seem to be reduced in comparison to the current state. The seismic isolated hypothesis guarantees to reduce the percentage of global shear force carried by the arch, passing from a mean value of 60% for the current structure to 30%.

Table 6. Modal analysis outputs for IS solution – main mode with translational effects

Mode	T [sec]	UX %	UY%	UZ%
2	1.4324	61.72	0.161	2.5E-08
3	1.4281	0.177	61.595	2.5E-06
63	0.0565	0.0052	0.0040	10.398
66	0.0525	0.178	0.0003	14.282
67	0.0520	0.24	0.0078	16.243
77	0.0399	0.078	4.429	0.489
90	0.0208	5.932	0.037	0.023

Table 7. Modal analysis outputs for IS solution – main mode with rotational effects

Mode	T [sec]	RX %	RY%	RZ%
1	1.5075	0.073	0.0057	69.347
3	1.4281	16.724	0.0028	1.469
63	0.0565	5.096	0.0004	0.0007
75	0.0412	6.331	0.031	0.33
77	0.0399	6.932	0.116	4.843

There is, however, a downside: outputs from modal response spectrum analysis in X-X direction show that only 20-25% of FX(tot) and FY(tot) are burden arch, while 20-30% is carried by the external abutments: this means that cross walls are overloaded (+40%), in comparison to the current state. Similar evaluation can be done considering outputs from modal response spectrum analysis in Y-Y direction. In this last case, 40% of Fx(tot) is carried by arch and 20% by abutments, while the remaining 40% burden cross walls; on the contrary, only 20% of global Fy is carried by arch, i.e. that, apart from the abutments(20%) , again cross walls are overloaded (+50%), in comparison to the current state.

4.2 The alternative solution of a single stiffer deck

An alternative and less invasive solution lead to make the three portions forming a single deck. In this case, sliding and overturning effects on the arch will be greatly reduced. Considering the effects of out of plane forces, shear force distribution is completely inverted in comparison to that occurring at the current state. In this case, abutments become the most loaded portions, carrying about 60% of the whole shear force.

Arch contribution reaches 10% and intermediate cross walls not exceed 7% each one. This cheapest and less invasive proposal would make the central arch portion the less loaded one, while terminal abutments will carry about 80% of the over base , also guaranteeing a reduction of ΔN of about 35%; in this case uplift effect is almost negligible, except for abutments. The choice of jointing deck three portions gives the possibility to reduce base reactions of about 20% in X-X direction, and of about 25% in Y-Y, compared to current state outputs. As argued in the companion paper, the continuous deck increases static redundancy of the original solution, making the whole structure more rigid. This justifies the fact that periods associated to the main modes are lower than 1.0s. Despite of the rigid continuous deck, also this case only few macro elements are involved in each mode.

5 CONCLUSIVE REMARKS

Viadotto Olivieri is a typical example of Maillart-arch-type bridge, designed in 1960's. At the current state this bridge is characterized by a rigid deck, divided in three portions. Upper deck is connected to the lower slender arch, whose shape is funicular of permanent loads, by thin cross walls. So, as the arch tends to bend when loaded by traffic over one half of the span, the cross walls make the deck bend to the same new shape as the arch. The bending effect is shared between arch and deck in proportion to their stiffness. A certain deformability is due to bridge layout: this configuration makes the slender arch mainly affected by overturning effects when out of plane horizontal forces act, while thin cross walls are susceptible to buckling effects as consequence of deck sliding in longitudinal direction. Modal analysis confirms that local translations (in both directions) involve modes with higher participation mass ration, while among rotations only RZ contribution is significant. The corresponding period, not exceeding 1.0 s, fall within the first two spectrum sections mainly, underlining the need to improve bridge seismic response. A hypothetical isolated solution has been valued to retrofit bridge at the current state. The introduction of rubber device requires a cut at the top of each cross walls, changing bridge original scheme. It results a more "regular" dynamic behaviour, i.e. main modes that do not involve translational effects combined to rotational ones. If the IS solution reduces overturning problems for central arch portion, on the other end, this proposal further emphasizes deck sliding, worsening buckling effects on cross walls. An alternative solution take advantage from the deformability of the lower portion (arch and cross walls) to counteract seismic action. It is proposed to joint three deck portions in such a way the central arch results the less loaded part: compared to the current state this alternative proposal leads to reduce arch moment of 40%, axial force variation of 70% and shear force of 50%. With the minimum effort, in this case arch uplift effects will be negligible, except for abutments.

ACKNOWLEDGEMENTS

This study was funded by ReLUIS – Research Project 2018 "Rete di Laboratori Universitari Ingegneria Sismica", in the context of the activities for task "Base isolation and Dissipative Systems", at the Department of Structure for Engineering and Architecture of Federico II University in Naples. Bridge layout data by courtesy of SAM (Società Autostrade Meridionali), represented by Dr. Giulio Barrel, as Managing Director of Società Autostrade Meridionali.

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