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SEISMIC ISOLATION OF COMPOSITE BRIDGE WITH SKEWED DECK

M.M. Mohammadi Dehnavi[1], A. De Angelis[2], and M.R. Pecce[3]

[1]Department of Engineering - University of Sannio
e-mail: mah.moh7@gmail.com

[2]Department of Engineering - University of Sannio
e-mail: alessandra.deangelis@unisannio.it

[3]Department of Structures for Engineering and Architecture – university of Naples Federico II
e-mail: pecce@unina.it

Abstract

The seismic vulnerability of road bridges is currently a key issue in Italy due to the wide existing heritage of bridges designed according to not seismic rules or located in areas where an enhancement of hazard has been applied in the last decades. Surely the seismic upgrading by the substitution of bearings with seismic isolators is a resolute intervention that can solve further problems as the stresses due to the skewness of the decks. In fact sometimes the skewed bridge is the only alternative for viaduct that across the roadway not along the orthogonal direction, but skewness angles higher than 20° gives undesirable effects both for vertical loads and seismic actions.

In this study, a steel-concrete composite bridge with skewed decks is analyzed to design the seismic upgrading introducing seismic isolation. The positive effect of the isolators also on the bridge response under gravitational loads is discussed evidencing the benefit through the high reduction of the bearings reaction due to the skewness that means the reduction of stresses on the piers.

Keywords: Skewed Bridge, seismic upgrade, base isolation, steel- concrete composite bridge, structural analysis.

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1 INTRODUCTION

The seismic damage in bridges depends on the static scheme and material of the structure further than the design approach and hazard. In many cases in Italy the existing bridges were designed without considering seismic actions therefore an high level of damage is expected after an earthquake, therefore various upgrading interventions have been defined and studied according to the weakness of the structures. In case of bridges realized by simple supported decks the key issues of the seismic response are the piers and the bearings. The degrees of freedom of the bearings determine the masses applied on the top of the piers while the geometrical and mechanical characteristics of the piers influence a little the masses but really define the stiffness of the dynamic system and the dissipative capacity.

Further this general frame of the seismic risk of simple supported decks, damages are related to the bridge configuration, including the curve layout and skewness higher than 20°. This last aspect has been evidenced after earthquakes and studied highlighting the negative effect of a deck rotation around the vertical axis especially at the abutment, that is a rigid element so that high relative displacements are not allowed. In [1] this topic is widely discussed showing many cases of skewed bridges damaged by seismic actions. The behavioural differences are distinguished among skewed and non-skewed decks through the tendency to rotate around the vertical axis, according to the value of the skew angle, consequently to collide with the abutment if the bearing allow the horizontal displacement, or to cause high horizontal forces on fixed bearings. Also under gravitational loads the skewness gives undesirable effects as a negative moment at the ends of simple supported decks, particularly unfavorable for steel-concrete composite beams (concrete slab in tension and bottom flange of the steel beam in compression), and horizontal reactions at the bearings especially high on the abutments, which have high horizontal stiffness.

Therefore an efficient solution to improve the seismic performance is the application of a protection system by passive control substituting the bearings with seismic isolator devices[2-4].

Sometimes the requirement of relative displacement between the spans or the abutment requires complex modification of the pier head to improve the gap or the introduction of dampers coupled with the isolators to reduce the horizontal displacement when the earthquake occurs [5-7].

It is worth to notice that the use of seismic isolation allows also to reduce the effects of skewed bridge structural irregularities, both due to the seismic response but also to the vertical loads.

In this study the behavior of a steel-concrete bridge with skewness under seismic loads and also traffic loads has been analyzed by a FE model comparing the results with and without isolators.

2 CASE STUDY

The bridge consists of 3 spans of length 37.4m, 26.9m e 22.4m respectively. The deck's cross section (Figure 1) is realized by a typical composite steel section made up of three double T steel profiles, approximatively 3m spaced, with a concrete slab 0.35m thick, connected by shear studs. The steel section is equal for the two shorter spans (h=1300 mm, b_{tf}=300 mm and t_{tf}=20 mm for the top flange, b_{bf}=500 mm and t_{bf}=30 mm for the bottom flange, and t_w=10 mm for the web) and larger for the longest span (h=1300 mm, b_{tf}=350 mm and t_{tf}=25 mm for the top flange, b_{bf}=650 mm and t_{bf}=55 mm for the bottom flange, and t_w=12 mm for the web). Each span of the deck has a skewness of 60° angle,four transverse elements are present for each span, two inclined ones at the end and two intermediate ones orthogonal to the bridge axis. Each one of the two piers is realized by 3 circular independent columns, so that each steel beam is supported on one column. The section of the columns has a diameter of 1.5m and is realized by concrete reinforced with steel rebars and profiles, as reported in Figure 1. The abutments are concrete C walls. In '70 years the bridge was designed only for traffic load, without seismic action, with the bearings organization reported in Figure 1.

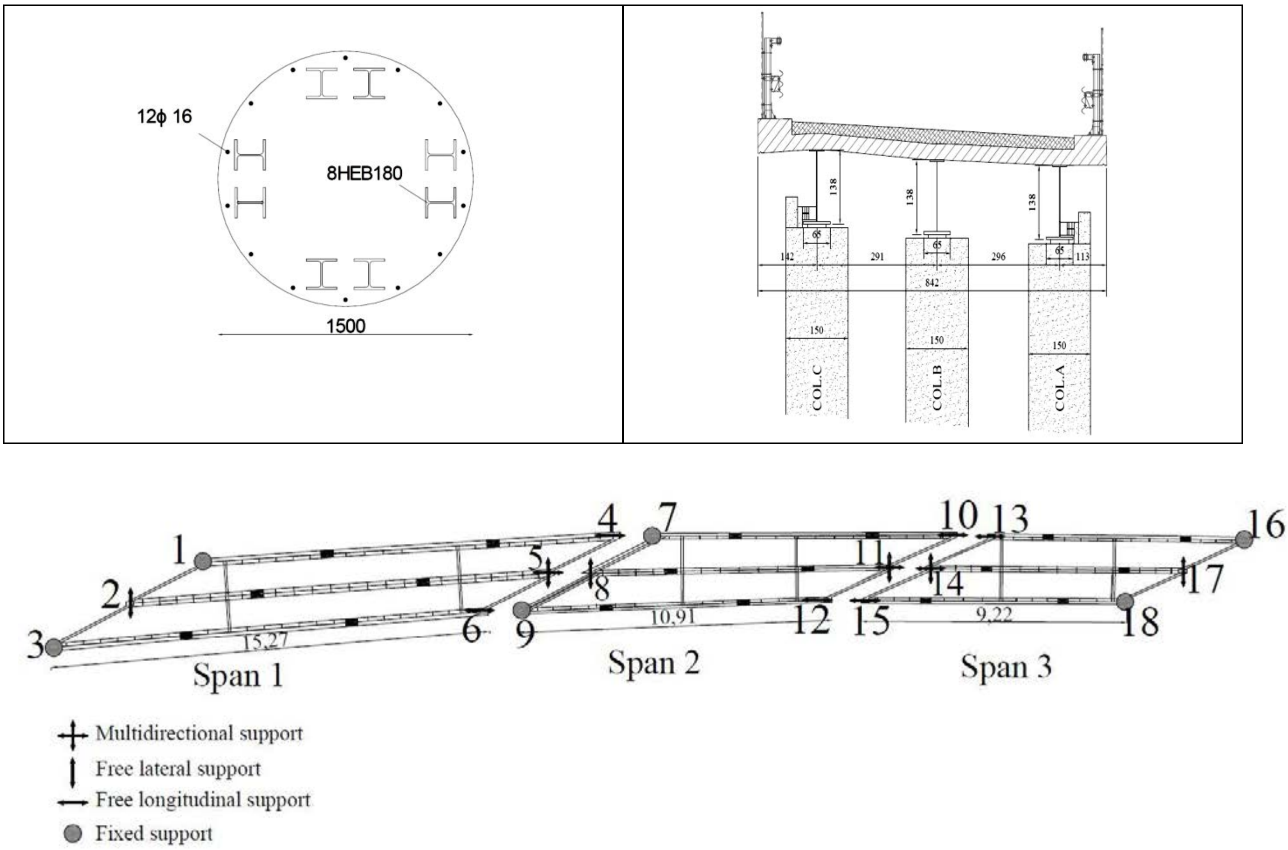

Figure 1- Pier section, cross section of the longer span, plan of the deck.

The software SAP2000 [8] was used to create the 3D linear model. Various modeling approaches have been proposed in the literature [9,10] also to analyze the constructions phases of composite bridges, but in the present study only the assessment of the existing configuration has to be considered. Therefore the deck is modeled by shell elements for the slab and frames for the beams and columns, while the abutments are not modeled but only the end restraints are introduced at the deck ends because the stiffness of the abutment is very high and its effect is negligible. The columns are considered cracked in the model when the existing bearings are implemented and un-cracked when the isolators are used; the cracked stiffness is assumed as 50% of the un-cracked one. The bearings are introduced in the model as links with free or restrained degree of freedom while the isolators are characterized by a horizontal elastic behavior in all directions.

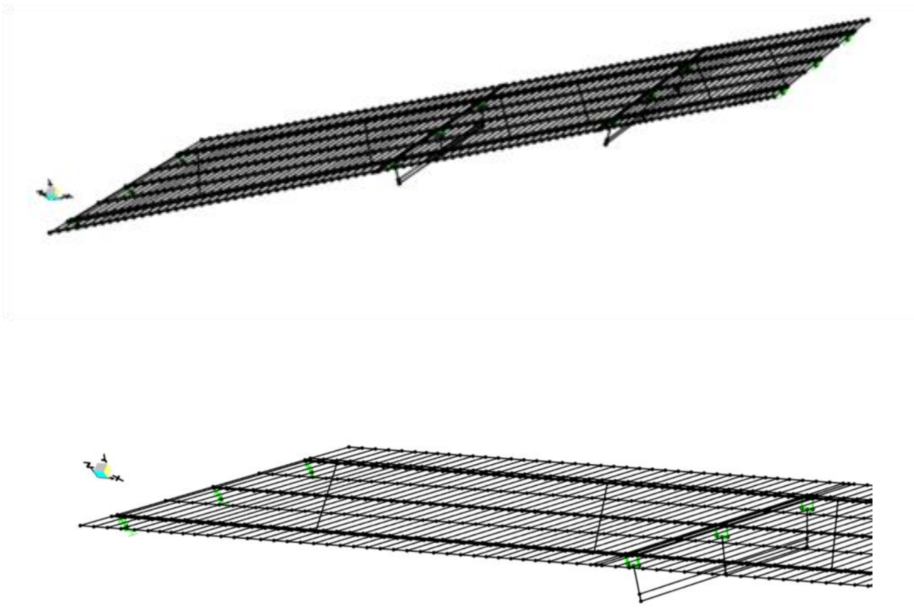

Figure2- 3D finite element model of the entire bridge and detail of the longer span

Experimental campaigns on the existing structure were carried out to define the material properties. A characteristic concrete cylinder strength in compression of f_c=30 MPa for the slab and 27 MPa for the piers, and a yield strength for the construction steel of 354 MPa were estimated. In this paper only the comparison between the stresses in the bearings, that are significant of the shear on the piers, and deck is reported considering a linear elastic behavior of the structure and developing a linear modal analysis with response spectrum for the seismic action. Therefore the capacity of the structure is not considered and only the elastic moduli are used in the model, that are E_c=33260 MPa for concrete, evaluated by the formulation of Eurocode 2[11] using the mean experimental strength of concrete, and E_s=210000 MPa for steel, according literature values.

3 BASE ISOLATION UPGRADING

3.1 Base isolation design

In girder bridges, the isolation devices can rather easily incorporated by replacing the conventional bridge bearings by isolation devices installed on the top of piers and abutments. The modelling of a seismic isolated bridge is simple as a conventional bridge, as all the structural members can be assumed to behave elastically, but a correct design of the isolators is necessary [12,13]. A variety of seismic-isolation devices including elastomeric bearing with and without lead core, frictional/sliding systems, and roller bearings have been used and developed in the last years, in the case study presented herein high damping rubber bearings (HDRB) were introduced. The design of base isolation is based on regulations of NTC Italian code [14] and the Eurocodes.

For the purpose of sizing the isolators, it is assumed that the deck is rigid in its own plane, with the effective stiffness at each substructure being equal to the sum of the piers/abutments stiffness and the insulator, but the piers/abutments contribution to stiffness can be ignored without significantly affecting accuracy because is much greater than the isolator one. Thus the structure can be assumed as a linear system with one degree of freedom (simple oscillator) characterized by a period T:

$$T = 2\pi\sqrt{\frac{m}{K}}$$

where, m and K are the mass of the deck and stiffness of the structure respectively but really the stiffness can be considered due to the isolators.

This bridge is located in a seismic zone characterized by a PGA of 0.2532g at the SLV and 0.297g at the SLC considering soil Type B, topography T1 and a return 949 years (Class IV due to the importance of the highway).

Using a design approach trough a spectral analysis, a target period corresponding to a seismic demand lower than the capacity of the structure can be fixed and the stiffness of the isolators can be calculated. The intervention was dimensioned considering the shifting of the fundamental period of vibration of the existing bridge (T=0.35 for the main transversal mode and T=0.20-0.25s for the main longitudinal mode) assimilated to a SDOF system, towards the point where the seismic demand equals the capacity of the systems, that resulted T_{si}=2s. At this condition the elastic spectral acceleration S_e results:

for Life Safety (LS) T= 2 s $\rightarrow S_e = 0.168g$

for Near Collapse (NC) T=2s $\rightarrow S_e = 0.226g$

Introducing equal isolator devices instead of each bearing (six isolators for each span) a required horizontal stiffness of the isolator results of 0.67 kN/m for the longer span, but it was assumed for all the spans to sick of simplicity of the installation.
Considering real products available on the market, high damping rubber bearing (HDRB) with horizontal stiffness 0.75 kN/m were chosen that are characterized by an equivalent dynamic shear modulus at G_{din} between 0.4 and 1.4 MPa and an equivalent viscous damping coefficient ξ equal to 10% or 15% according to shear-strain level indicated in the manufacturer technical data sheet.

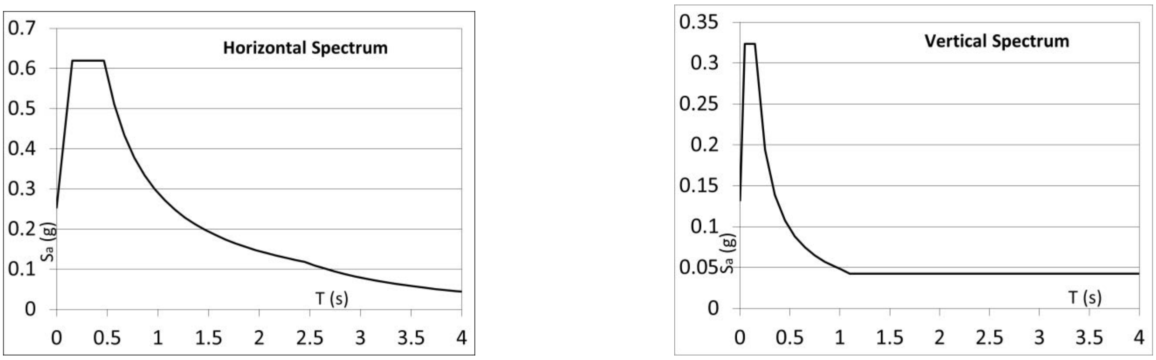

Figure3- The horizontal and Vertical Spectrum according to NTC 2018 [14]

3.2 Results and discussion

The analysis of the case study was carried out considering two different load conditions because the main aim is to compare the effect of base isolations both on traffic load and seismic action in case of skewed bridges. The traffic loads and seismic action have been calculated and applied based on Italian code but is coincident with Eurocodes provisions. The results are presented comparing the reactions of the bearings of the longer span before and after the introduction of isolators in terms of vertical force (Fz) and horizontal forces (Vy in the transversal direction and Vx in the longitudinal direction). Firstly the maximum vertical reaction F_z of all the isolators (2674kN) is compared with the maximum forces allowed by the chosen device under traffic load, F_{ZD}=5740kN, and the same for the seismic action (F_{zmax}=1338kN<V=1410kN).

In Table 1 the effect of the isolators on the skewed bridge is analysed in the case of traffic loads comparing the horizontal forces on the bearings before and after the introduction of the isolators at the Ultimate Limit State (ULS). In the two last columns the ratio of the stresses in the two conditions is reported highlighting a reduction between 14% (for a low stressed bearing in transversal direction y) and 99% (for the bearings that had very high horizontal shear in longitudinal direction). Clearly the reduction of the horizontal reactions in the bearings becomes the reduction of the shear and bending moment in the piers that were very high also due to the traffic load in the case of this large skewness angle. In Figure 4 the bending moment along the deck due to permanent and traffic loads at ULS is also reported evidencing also the benefit of reduction of the negative moment at the ends of the deck. Finally in Table 2 the horizontal forces in the bearing before and after the use of isolators (BI) are reported for the seismic condition, the reduction ranges between 45% and 97%.

The role of the bearings and the efficiency of the isolators both for traffic and seismic action are evident.

Link	F_z (kN)	$F_z(BI)/F_z$	V_x (kN)	V_y (kN)	$V_x(BI)/V_x$	$V_y(BI)/V_y$
1	1282	0.89	-624	354	0.08	0.17
	3109	0.86	-6232	-1179	0.01	0.07
2	484	1.51	927	0	0.06	-
	2011	0.91	753	0	0.09	-
3	24	16.18	5644	604	0.01	0.12
	898	1.13	734	-889	0.09	0.07
4	501	1.16	0	386	-	0.17
	1304	1.15	0	82	-	0.86
5	584	1.40	0	0	-	-
	1727	1.10	0	0	-	-
6	1283	0.76	0	765	-	0.10
	2597	0.82	0	182	-	0.33

Table 1- The bearing reaction in span 1 under traffic loads with and without base isolation

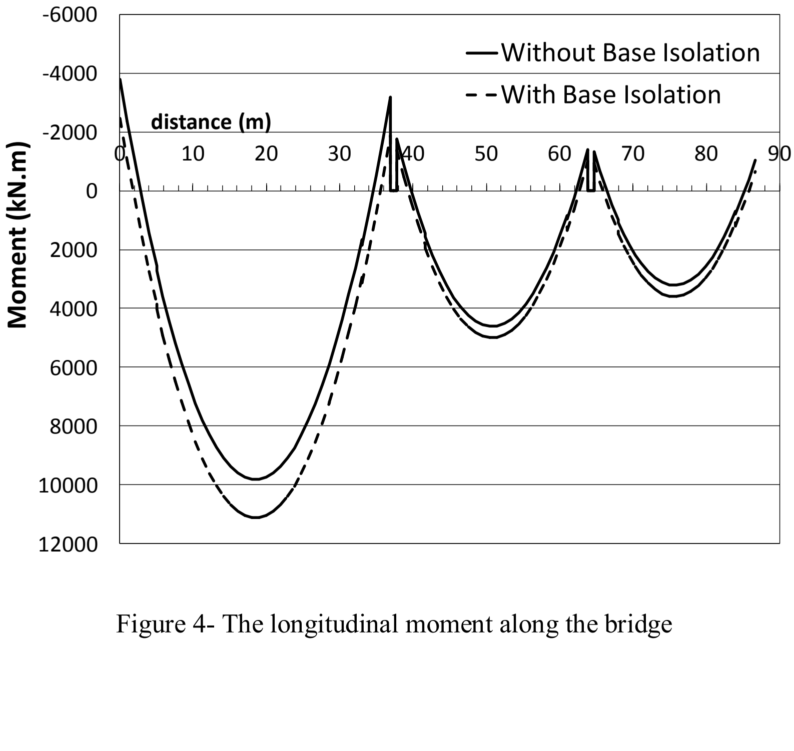

Figure 4- The longitudinal moment along the bridge

Link	F_z (kN)	$F_z(BI)/F_z$	V_x (kN)	V_y (kN)	$V_x(BI)/V_x$	$V_y(BI)/V_y$
1	665	1.52	893	491	0.12	0.21
	2029	0.66	4603	887	0.03	0.13
2	-548	1.05	952	444	0.11	-
	861	0.79	459	857	0.25	-
3	53	8.86	3828	198	0.03	0.55
	731	0.84	257	296	0.45	0.34
4	188	2.92	0	373	-	0.31
	869	0.83	0	356	-	0.34
5	490	1.33	0	676	-	-
	647	1.23	0	407	-	-
6	860	1.03	0	827	-	0.15
	1721	0.68	0	206	-	0.53

Table 2- The bearing reactions in span 1 under seismic loads with and without base isolation

4 CONCLUSIONS

The case study proposed in this paper is a steel concrete composite bridge with a 60° skewed deck that can evidence the benefit of seismic isolation also to avoid the unfavourable stresses under traffic loads due to fixed bearings. Comparing the bearing reactions before and after the substitution of bearings with isolators the following observations can be summarized:

- Base isolation can successfully reduce the stresses under traffic loads in skewed bridges, especially in terms of shear on piers and abutment. The high stresses on piers but especially on rigid abutments can reduce long-term durability and enhance maintenance costs, therefore the introduction of elastic bearings or isolators can give a convenient contribution to an upgrade intervention on the existing bridge. When the base isolation is designed in skewed bridges also the benefit on the effect of skewness has to be considered in the design.
- The skewed bridges present higher seismic vulnerability respect not skewed bridges according to the skewness angle. The isolation system can greatly lower the spectral acceleration due to seismic actions in general enhancing the bridge performance, but also annulling the negative effect of skewness.

Overall, the use of base isolation can be an effective strategy for improving the performance of skewed bridges under both traffic and seismic loads. Therefore the design convenience of the intervention has to take into account also the benefit in terms of performance under traffic loads both in ULS but also at serviceability conditions.

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