Italian Road Administration strategy to retrofit existing bridges using IABs technology

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ABSTRACT

The majority of simply supported bridges have been affected by some durability problems during their service life. For this purpose, the concept of integral abutment bridge came out which can achieve the requirement of road administrations to resolve the durability problems of broken expansion joints and damaged bearings fundamentally. In this paper, a retrofitting technology using the concept of integral abutment bridge and developed for the Italian National Road Authority (ANAS) is presented. A typical simply supported bridge "Viadotto Serrone" in Italy was chosen as case study. The corresponding finite element model was built by Sap2000 considering some critical issues. In order to find out the most critical influential factors and useful regulations which can be adopted as the guideline of this retrofitting technology, the influence of the new Italian codes on the mechanical properties of different types of bridge, including the simply supported bridge without rehabilitation and integral abutment bridges after retrofitting, were investigated using finite element model. The sensitive analysis choosing thermal load, highway load and the substructure height as the critical influential factor was carried out. Some regulations obtained can be adopted as the guideline of this retrofit technology.

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INTRODUCTION

Bridges without expansion joints are ages old, including natural stone beam bridges and stone arch bridges carved from bedrock by water and wind, stone masonry arch bridges by the Romans, reinforced concrete arch bridges constructed in the early decades of last century, rigid frame bridges constructed from the middle of last century, and so on (Burke, 2009).

In the last few years, one type of single- or multi-span bridge without expansion joints and bearings so-called as integral abutment bridge (IAB) has attracted more and more attention. The concept of IAB could be advantageously used in many situations, not only for the construction of new bridges, but also for the strengthening of existing bridges (Zordan et al., 2011a, Zordan et al., 2011b). Due to the statistics of the retrofitting method of existing bridges in 2005 (Maruri and Petro, 2005), it is found that 39% of the American States have a policy of transforming non-integral to integral abutment bridges during retrofitting phases. From 2005, the IAB consisted of fully integral abutment bridge (FIAB) and semi-integral abutment bridges (SIAB) is becoming more popular in Europe (Feldmann et al., 2010).

In this paper, the research on the retrofit technology with IAB concept was conducted. The influence of thermal load, highway live load and substructure height on the mechanical properties of different bridge types, including the existing jointed bridge and different types of FIABs after retrofit, was investigated using the finite element model built by Sap2000. The regulations can be adopted as the guideline of this retrofit technology.

This research is an international joint research composited of four groups: Italian National Road Corporation (ANAS) and Università IUAV di VENEZIA in Italy; Fuzhou University and Tongji University in China.

CASE STUDY

Project Background

The case study presented concerns a simply supported flyover 'Viadotto Serrone' located at an important highway connecting Salerno (SA) and Potenza (PZ) in the south of Italy (Figure 1 and Figure 2), which has a history of more than 40 years. This flyover is composed of two separated SSBs to satisfy the requirement of traffic in two directions (SA-PZ and PZ-SA). The geometrical information and materials of the two bridges are nearly the same, except the pier height. Therefore, one simply support bridge (SSB) (SA-PZ) is chosen as the example to analyze in this paper.

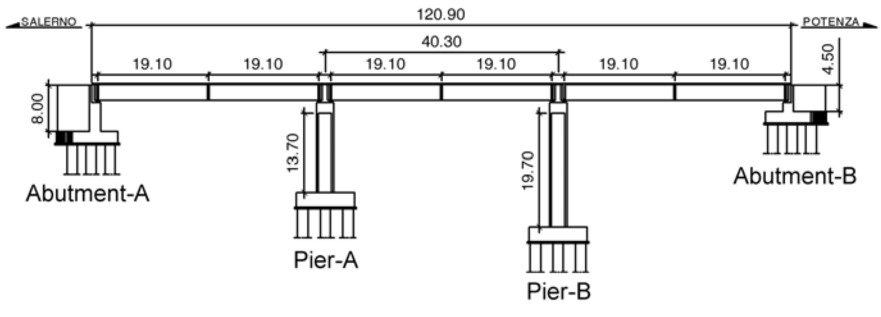
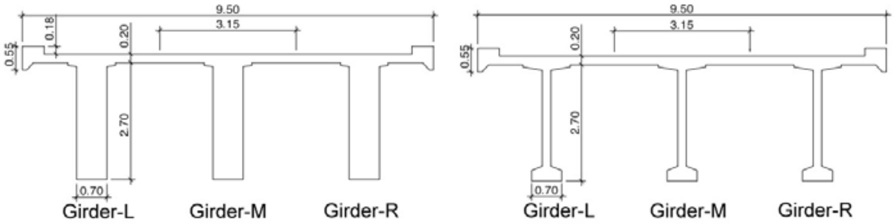


Figure 1. Elevation layout of 'Viadotto Serrone' (Unit: m)



(a) Cross section at the end of girder (b) Cross section in the middle of girder
Figure 2. Typical superstructure cross section in 'Viadotto Serrone' (Unit: m).

Finite element model

In this analysis, the most important in finite element modeling is to ensure that the finite element model can simulate the performance of bridges before and after retrofitting. It means that the appropriate finite element model used in this paper should have the main features listed in the following. The typical model scheme of the bridge after retrofitting with the details concerning the main features and the information of elements is illustrated in Figure 3.

1. The grillage method with frame element was used to simulate the superstructure of bridge. For the substructure, the frame element was also used to simulate the pier caps, pier columns and the piles beneath abutments and pier footings. The shell element was chosen to simulate the walls and footings of abutments and the pier footings.

2. Nonlinear area spring elements are attached perpendicularly to backwalls, stems and wingwalls to simulate the lateral soil-abutment interaction.

3. Three series of nonlinear line spring elements are attached along the full length of piles to simulate the soil-pile interaction, including two series in lateral directions and one series in vertical direction.

4. Concentrated plastic hinges are arranged at the top and bottom of piers and distributed plastic hinge zones are applied to the top part of piles.

5. The stages of retrofitting process are considered.

6. There is no approach slab in existing bridge. Therefore, the approach slab modeling in finite element model is neglected; however, the displacement transferring from bridge ends to approach slabs will be checked.

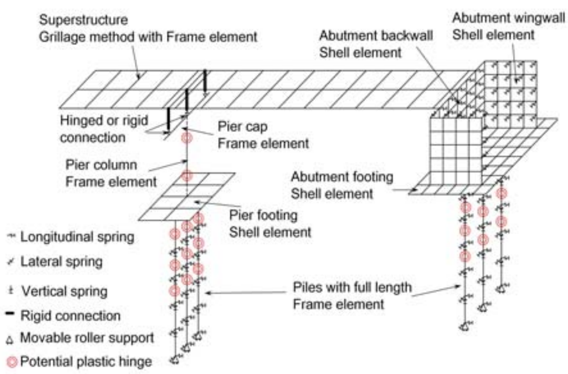


Figure 3. Typical model scheme after retrofitting.

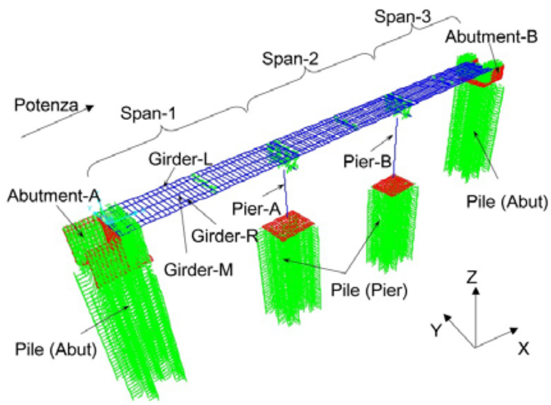


Figure 4. 3D finite element model in Sap2000.

Based on the above requirements, the 3D nonlinear structural model which can simulate the existing SSB and the different subtypes of FIABs after retrofitting can be built by the general finite element software Sap2000. In the model, the effects of different kinds of nonlinearities can be considered, including the material nonlinearity (elastic-plastic constitutive relationships and plastic hinges), the geometrical nonlinearity (P-Δ effect), the boundary condition nonlinearity (nonlinear soil-structure interactions) and the nonlinear staged construction. The 3D finite element model of the bridge after retrofitting with the number of different bridge components is illustrated in Figure 4.

In order to carry out the research on the IAB, the detailed geotechnical investigation should be performed on site to obtain the real mechanical properties of the backfill behind abutments and the soil around piles. However, in many retrofitting projects, the detailed geotechnical investigation information is limited due to several reasons. In this case, the recommended values in some codes or literatures can be chosen to calculate the soil-structure interaction for the existing bridge before and after retrofitting. Two typical kinds of soil were taken into account in this analysis, including clay and sand. Each one has three classes, which are soft, medium and stiff for clay; and loose, medium and dense for sand. The typical lateral earth pressure-abutment movement relationship curve and lateral soil-pile interaction (p-y curve) were shown respectively in Figure 5 and Figure 6.

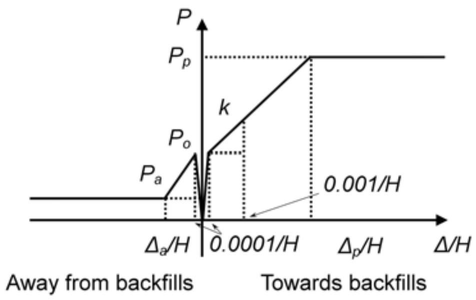


Figure 5. Typical lateral earth pressure abutment movement relationship.

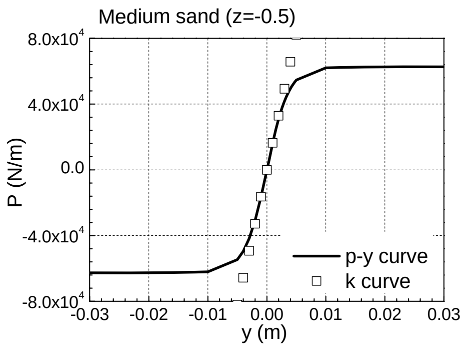
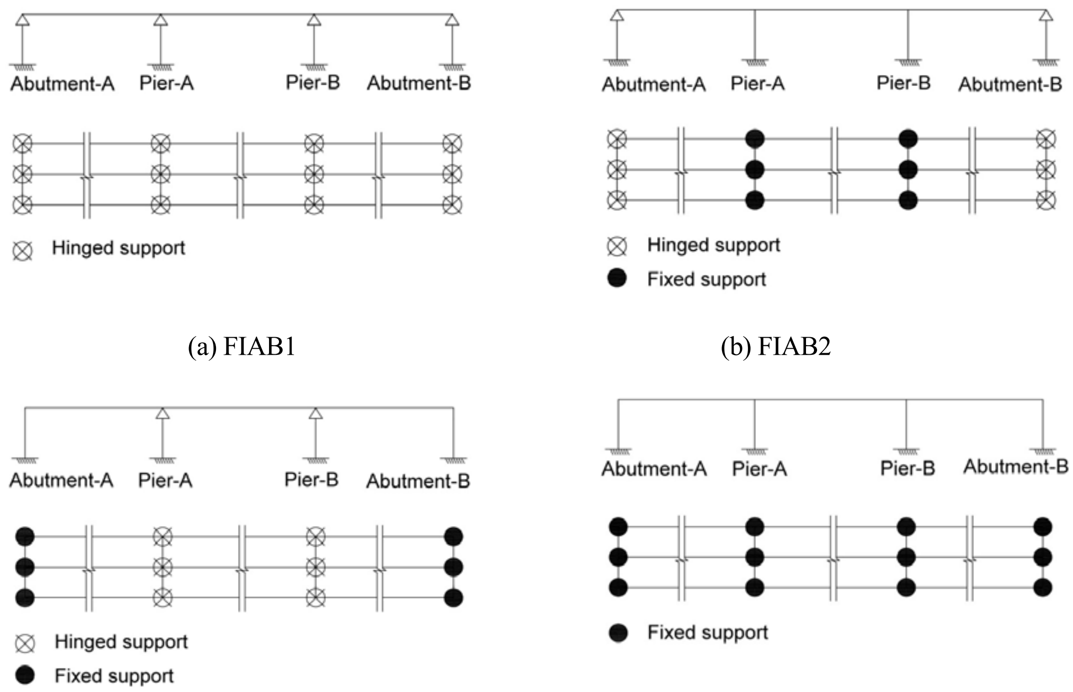


Figure 6. P-y curves of line springs for piles (Medium sand).

According to previous experience, the retrofitting process with the FIAB concept is easier than that with the SIAB concept. Moreover, the FIAB concept can resolve the potential durability problems of existing bearings. Therefore, this paper chooses the FIAB as the analytical object. According to different connection flexibility between the superstructure and the substructure, the detailed definitions of the subtypes of FIAB, including the pure hinged connection and pure rigid connection, are listed in Table I and illustrated in Figure 7 (Xue, 2013). The modeling of materials, soil-structure interaction, plastic hinge and retrofitting process can be found in Xue et al. (2012) and Xue (2013). The vertical load case, the dead load, prestressed load and superimposed dead load are all applied to bridges in the first stage, which is the SSB.

TABLE I. DETAILED DEFINITIONS OF IAB.

Superstructure-Substructure connection		Superstructure-Pier	
		Hinged	Rigid
Superstructure-Abutment	Hinged	FIAB1	FIAB2
	Rigid	FIAB3	FIAB4



(a) FIAB1 (b) FIAB2

(a) FIAB3 (b) FIAB4

Figure 7. Typical superstructure-substructure connections of three-span FIABs.

SENSITIVE ANALYSIS

Influence of thermal load

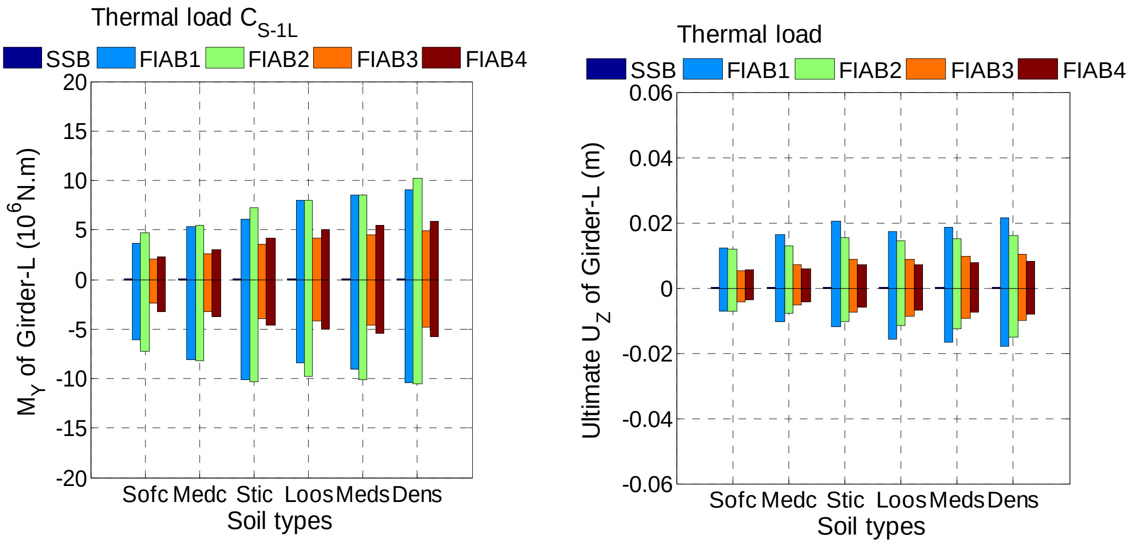
Most of the existing bridges, which need to be retrofitted in Italy, have been built more than 40 years. Therefore, the thermal load should be considered as the most important horizontal load case. In this analysis, the uniform bridge temperature components (ΔT_{exp} and ΔT_{con}) defined by formulae (1) and (2), can be applied to the finite element models to simulate the expansion and contraction cycles of bridge superstructures, respectively. According to the updated Italian code NTC 2008, ΔT_{exp} and ΔT_{con} can be set as ±15°C. Moreover, in order to expand the research scope, the ±40°C considered in some European Countries (Feldmann et al., 2010) were also taken into account as the extreme thermal load case. In USA, Europe and China, the temperature variations along the superstructure depth are considered in the codes. In this case, the temperature variations were not considered for the purpose of simplification.

$$\Delta T_{\exp} = T_{\max} - T_0 \quad (1)$$

$$T_{con} = T_0 - T_{\min} \quad (2)$$

Where, T_{max} and T_{min} are maximum and minimum uniform bridge temperature components, respectively. T_0 is initial temperature when structural element is restrained.

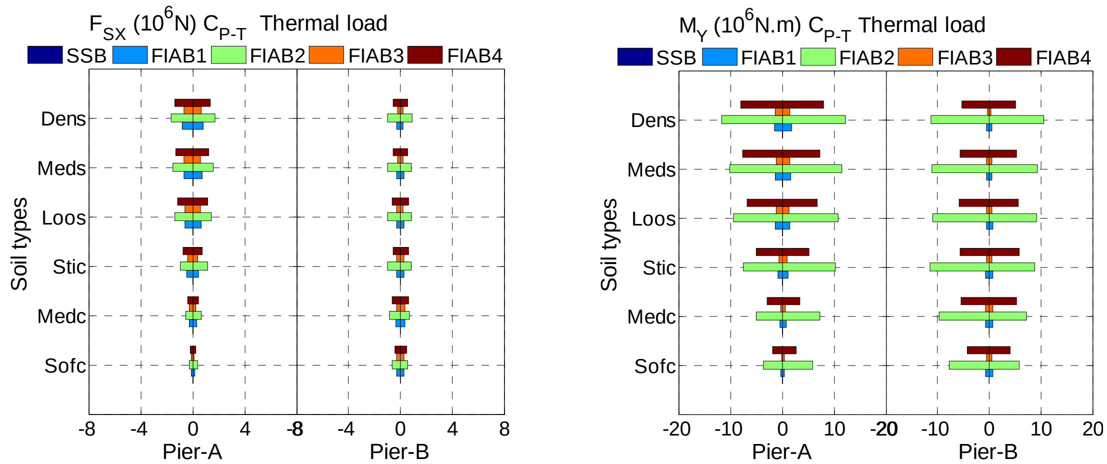
The bending moment in transverse direction (M_Y) at the corresponding critical sections of Girder-L in different bridge types under thermal load (±40°C) are illustrated in Figure 8(a). For the displacement in vertical direction (U_Z) of Girder-L, the locations of the ultimate values in different bridge types are different. Therefore, the maximum vertical deflection and invert arch of girder in different bridge types due to positive and negative thermal loads are compared in Figure 8(b). The results indicate that the ultimate M_Y and U_Z of girders in FIAB1 and FIAB2 are significantly larger than those in FIAB3 and FIAB4.



(a) M_Y at C_{S-1L} of Girder-L (b) Ultimate U_Z of Girder-L

Figure 8. Influence of different bridge types on girder under thermal load.

The shear force (F_{SX}) and M_Y at the critical sections of piers in different bridge types subjected to thermal load (±40°C) are compared in Figure 9. It could be found that the F_{SX} and M_Y of piers in four subtypes of FIABs are different. The ultimate F_{SX} and M_Y at the top of piers in FIAB2 and FIAB4 are larger than those in FIAB1 and FIAB3. Moreover, for the M_Y at bottom of piers, the differences among different retrofitting approaches is not quite large.

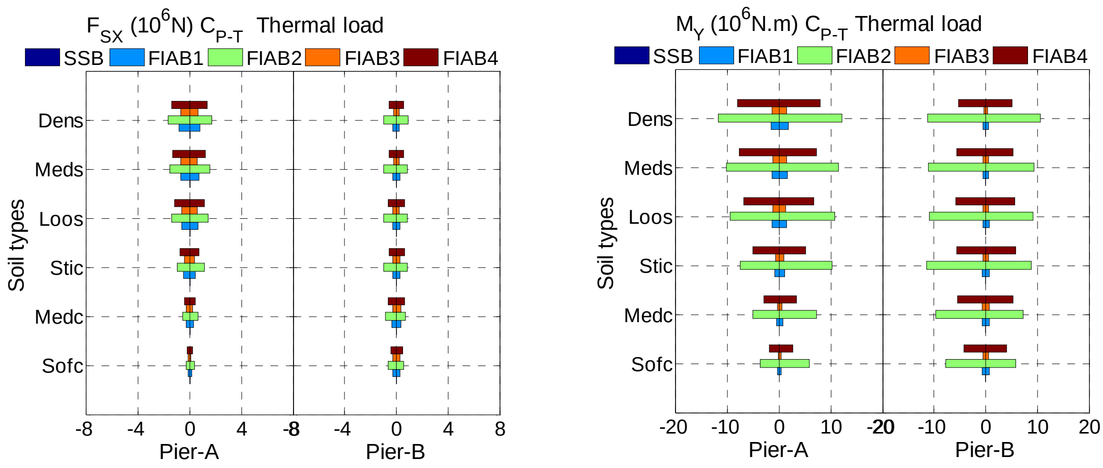


(a) F_{SX} at C_{P-T} of piers (b) M_Y at C_{P-T} of piers

Figure 9. Influence of different bridge types on pier under thermal load

The F_{SX} and M_Y at the critical sections of abutment stems in different subtypes of FIABs subjected to thermal load (±40°C) are illustrated in Figure 10. The comparisons indicate that the

F_{SX} at top of abutment stem ($C_{A\text{-}T}$) in FIAB3 and FIAB4 are slightly smaller than those in FIAB1 and FIAB2. On the contrary, the M_Y at bottom of abutment stem ($C_{A\text{-}B}$) in FIAB3 and FIAB4 are slightly larger than those in FIAB1 and FIAB2.

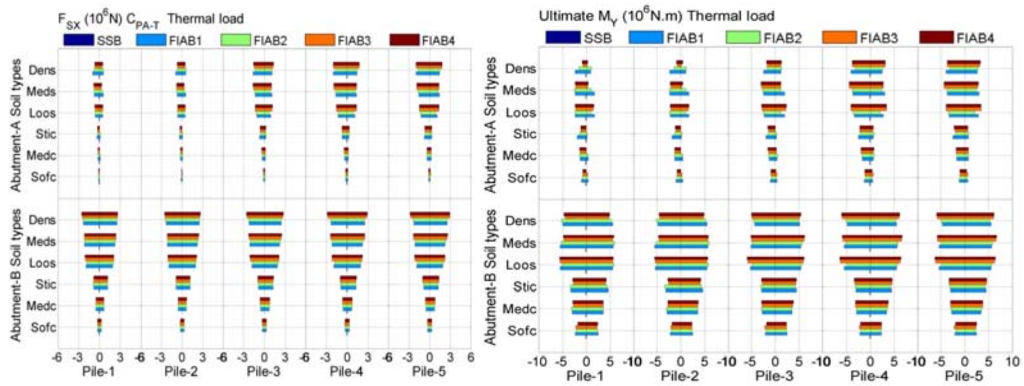


(a) F_{SX} at $C_{A\text{-}T}$ of Abutment stems (b) M_Y at $C_{A\text{-}B}$ of Abutment stems

Figure 10. Influence of different bridge types on abutment stem under thermal load.

By comparing the performance of piles under thermal load, it could be found that the performance of piles beneath abutments subjected to thermal load is significantly larger than those of piles beneath piers in FIABs. In 'Viadotto Serrone', the cross sections and the material properties of all piles are the same. Therefore, only the performance of piles beneath abutments under thermal load will be taken into account in the following analysis.

The internal forces at the critical sections of piles in different subtypes of FIABs subjected to thermal load (±40°C) are compared in Figure 11, which indicates that the differences among the performance of piles beneath abutments in four subtypes of FIABs subjected to the thermal load are quite small.

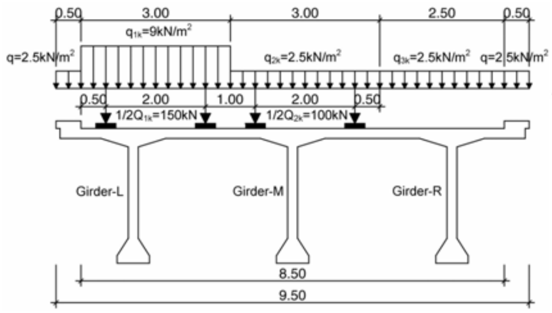


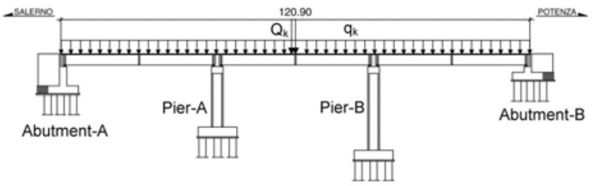
(a) F_{SX} at CPA-T of piles (b) Ultimate M_Y of piles

Figure 11. Influence of different bridge types on pile under thermal loads.

Influence of highway live load

According to the comparisons between original code DM 1990 and updated code NTC2008, it could be found that the influence under static loads combination in NTC 2008 is slightly smaller than that in DM 1990 and the gap less than 10%; however, the influence under highway live load and response spectrum in NTC 2008 is larger than that in the original codes, which are 20~30% and 70~80%, respectively. Consequently, the NTC 2008 could be chosen as the design code in this paper. According to NTC 2008, two load lines could be arranged with the width of 3×2=6m. The width of remaining area is 2.5m. The crowd load could be applied to both footpaths with each 0.5m wide. Similar to the DM 1990, the typical asymmetrical arrangement of traffic load lines and crowd load lines in the transverse direction is illustrated in Figure 12(a), which can be also used to consider the most unfavorable loading state for Girder-L. In the longitudinal direction, the concentrate loads can move along the whole superstructure length and the distributed loads (q_{ik}) could be applied to the whole superstructure length. The arrangement of traffic loads in longitudinal direction is shown in Figure 12(b).





(a) Transverse direction (b) Longitudinal direction

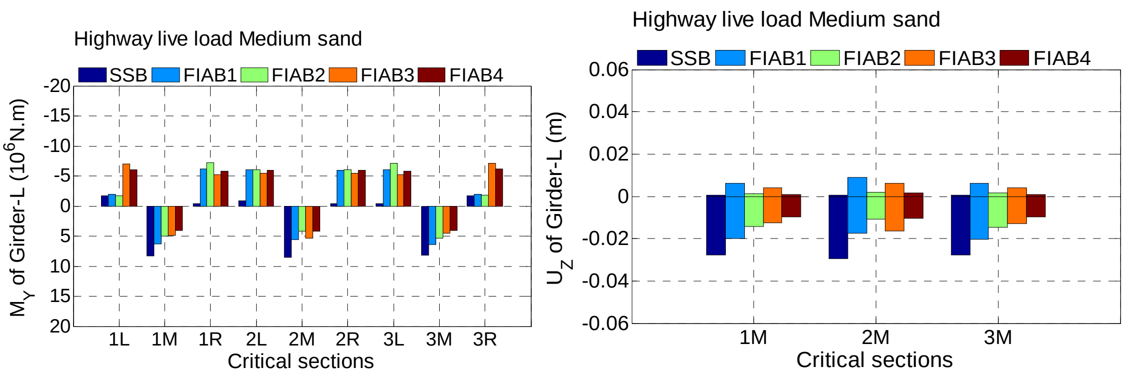
Figure 12. Arrangement of highway live load in NTC 2008.

For the M_Y of girders under highway live load (Figure 13 (a)), the retrofit with the FIAB concept could reduce the positive M_Y at the mid-span points of each span. However, these retrofitting approaches increase the unfavorable negative M_Y at the both girder ends of each span. Considering the critical sections near abutments ($C_{S\text{-}1L}$ and $C_{S\text{-}3R}$), the M_Y of girders in FIAB3 and FIAB4 after retrofitting are larger than those in FIAB1 and FIAB2. Moreover, considering the critical sections near piers ($C_{S\text{-}1R}$, $C_{S\text{-}2L}$, $C_{S\text{-}2R}$ and $C_{S\text{-}3L}$), all the retrofitting methods increase the M_Y of girders subjected to highway live load a lot. The U_Z at the mid-span points of each span in SSB under highway live load could be reduced through retrofitting, as illustrated in Figure 13 (b).

The M_Y at the top and bottom points of two piers in different bridge types under highway live load are compared in Figure 14. It could be observed that the M_Y at the top of piers in FIAB2 and FIAB4 are larger than those in FIAB1 and FIAB3.

The M_Y at the top points of abutment stems ($C_{A\text{-}T}$) in different bridge types under highway live load are compared in Figure 15. It could be observed that the M_Y at the top points of abutment stems in FIAB3 and FIAB4 under highway live load are larger than those in FIAB1 and FIAB2.

Under highway live load, the M_Y of piles in all bridge types are quite small and the result is not presented here.



(a) M_Y of Girder-L (b) U_Z of Girder-L

Figure 13. Influence of different bridge types on girder under highway live load

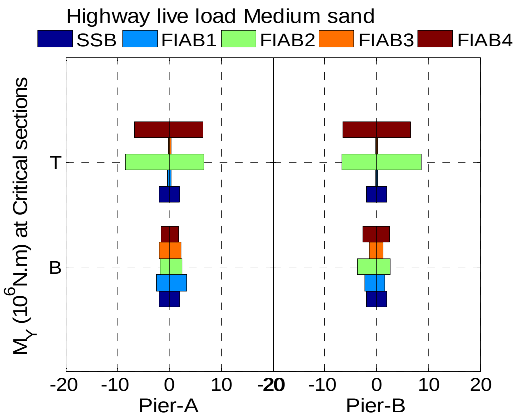


Figure 14. Influence on pier

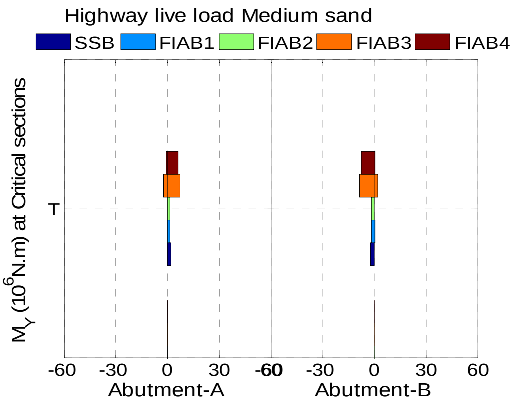


Figure 15. Influence on abutment

Influence of substructure height

In this section, the heights of piers and abutments (including the backwall and stem) are chosen as the parameters. Based on two pier heights in real case (13.7m and 19.7m), another two assumed values (7.7m and 25.7m) were chosen. These four heights could form an arithmetic sequence and cover the range of pier heights in normal cases. For the abutment heights, two values in real case (4.5m and 8m) were taken into account, which could cover the range of abutment heights in normal cases. Based on these assumptions, fifteen cases, including fourteen idealized cases and one real case, as listed in Table II, could be used to investigate the influence of substructure heights.

TABLE II. RESEARCH CASES

	Column	1	2	3	4	5
Row	Case	H_{PA}= H_{PB} =7.7	H_{PA}= H_{PB} =13.7	H_{PA}= H_{PB} =19.7	H_{PA}= H_{PB} =25.7	H_{PA}=13.7 H_{PB}=19.7
1	H_{AA}=H_{AB}=4.5	a4.5p7.7	a4.5p13.7	a4.5p19.7	a4.5p25.7	a4.5pReal
2	H_{AA}=H_{AB}=8	a8p7.7	a8p13.7	a8p19.7	a8p25.7	a8pReal
3	H_{AA}=8 H_{AB}=4.5	aRealp7.7	aRealp13.7	aRealp19.7	aRealp25.7	Real case
H_{PA} means the height of Pier-A; H_{PB} means the height of Pier-B; H_{AA} means the height of Abutment-A; H_{AB} means the height of Abutment-B; Real means that the heights of piers and abutments are the same as those in 'Viadotto Serrone'						

By analyze the results illustrated in Figure 16, it could be found that the influence of different pier heights on the performance of Pier-A in FIABs under thermal load is significant. Considering the cases that have equal pier heights (‘a4.5p7.7’, ‘a4.5p13.7’, ‘a4.5p19.7’ and ‘a4.5p25.7’), with the pier heights increase, the F_{SX} of piers decrease; however, the displacement in longitudinal direction (U_X) of piers increase. The M_Y of piers could be divided into two conditions corresponding to different types of superstructure-pier connections. For FIAB1 and FIAB3 that have hinged superstructure-pier connections, the M_Y of piers decrease with the pier heights increase. For FIAB2 and FIAB4 that have rigid superstructure-pier connections, with the pier heights increase, the M_Y at the bottom of piers decrease, while, the M_Y at the top of piers increase. By comparison, it could be found that the influence of different pier heights on the performance of abutment stems under thermal load is negligible.

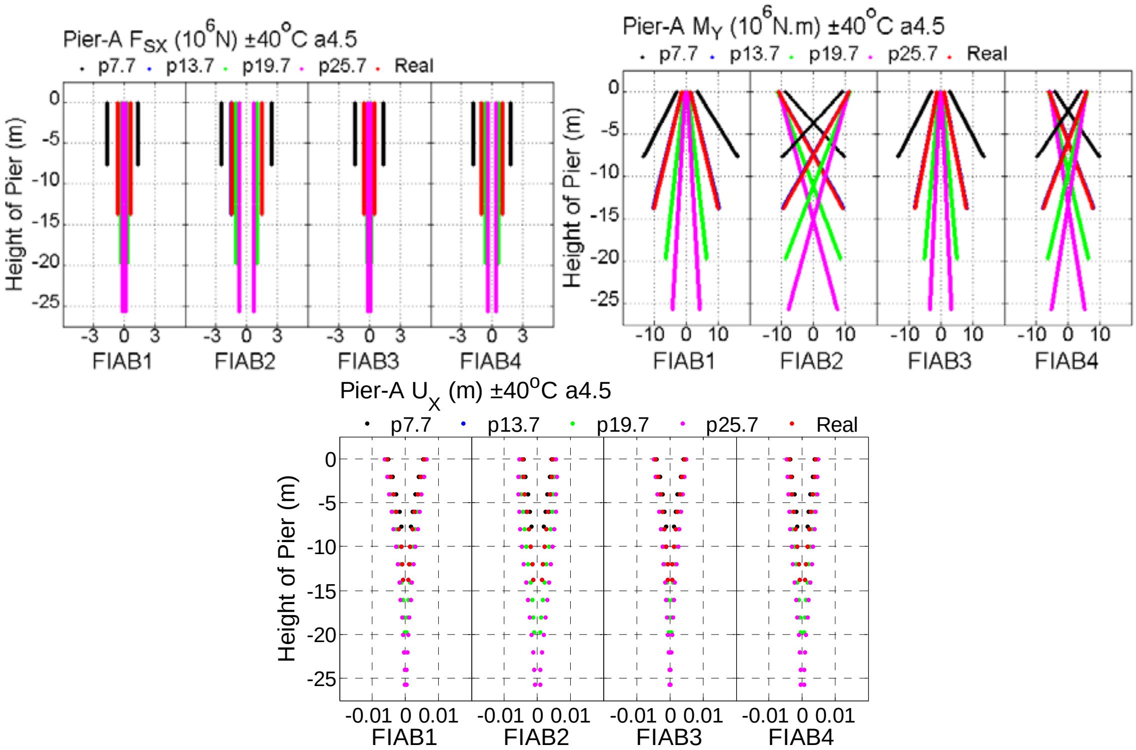


Figure 16. Influence of different pier heights on the performance of pier under thermal load.

The influence of different abutment heights on the performance of Abutment-A stem in FIABs under thermal load is illustrated in Figure 17. By comparing ‘a4.5p7.7’ and ‘a8p7.7’, it could be found that the effect of different abutment heights on the performance of abutment stems is significant. With the abutment heights increase, the F_{SX} of abutment stems decrease; however, the U_X and M_Y of abutment stems increase.

The influence of different abutment heights on the performance of Pile-5 beneath Abutment-A in FIABs under thermal load is illustrated in Figure 18. By comparing ‘a4.5p7.7’ and ‘a8p7.7’, it could be found that under thermal load, the effect of different abutment heights on the performance of piles beneath abutments is significant. The F_{SX}, M_Y and U_X of piles beneath abutments would decrease with the abutment heights increase.

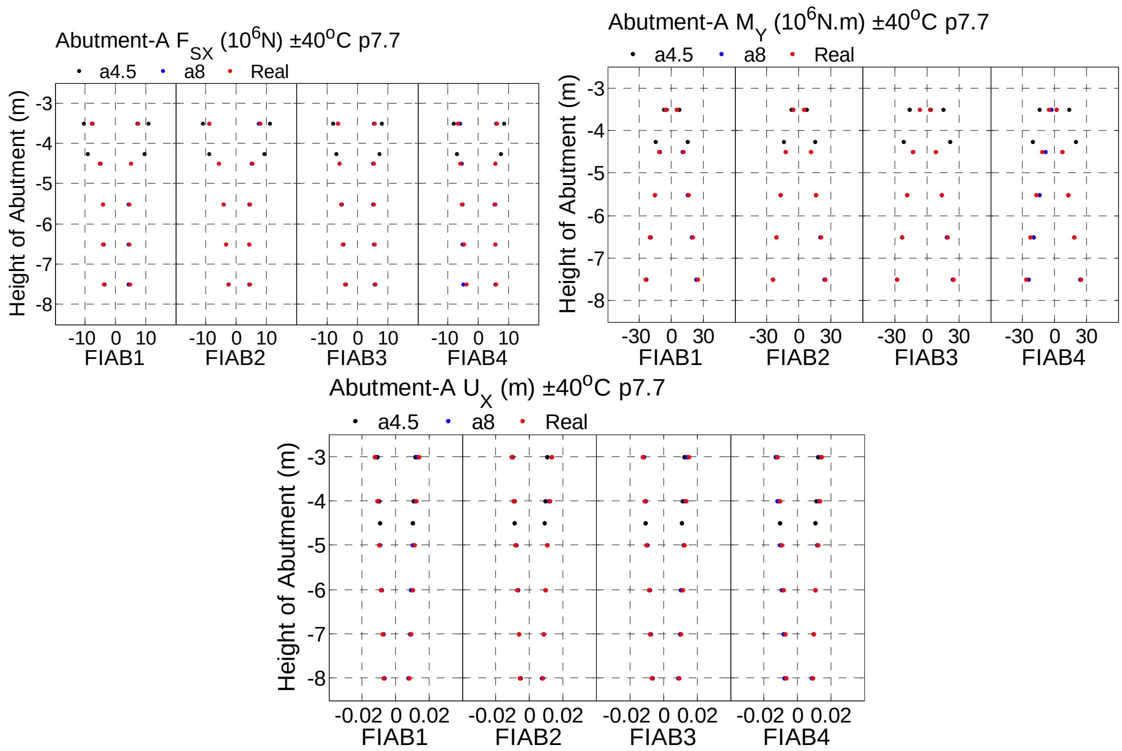


Figure 17. Influence of different abutment heights on the performance of Abutment-A stem under thermal load.

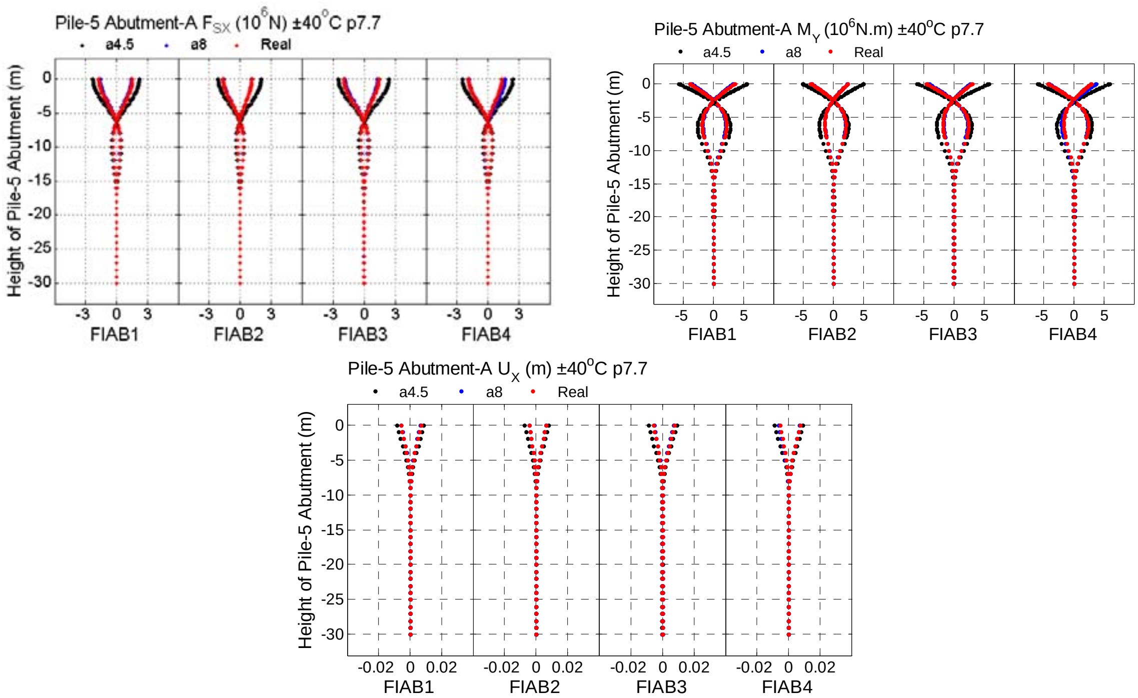


Figure 18. Influence of different abutment heights on the performance of Pile-5 beneath Abutment-A under thermal load.

CONCLUSIONS

In this paper, assuming the soil type as medium sand, the influence of different substructure heights on the performance of different types of FIABs under thermal load is analyzed. Some regulations are listed as following.

(1) Due to the advantages in terms of life-cycle costs, durability, enhanced structural response and ease of maintenance, the IAB's concept can be fruit-fully applied in the retrofitting process of existing simply supported bridge.

(2) From the knowledge and experience of the author and from the case study, it is proved that the introduction of updated code causes an increase in the forces acting on the bridge superstructure and foundations in both static and seismic points of view.

(3) In order to choose the recommended subtype of FIAB for retrofitting, the difficulties of the retrofit on different bridge components in real case should be considered.

(4) The influence of different abutment heights on the performance of girders, abutment stems and piles beneath abutments is noticeable or remarkable; however, different pier heights can only affect the performance of piers.

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