Effects of Pier-superstructure Connection Conditions on a RC Bridge Response

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Abstract

This paper shows the effects of pier-superstructure connection conditions, on a reinforced concrete bridge. At this aim, a variant based on an existing reinforced concrete bridge structure on the Skopje - Veles motorway (bridging Vardar River near Veles) has been chosen. The superstructure, composed of four “I” shape precast prestressed main girders with 2m of height, connected by transverse-girders and an in-situ reinforced concrete deck, is supported by the abutments and 10 central solid cross-section piers, with 11 equal spans of about 33m and a total length of 363m. For analysis purposes, a simplified 3D (three dimensional) linear model is formulated. The loading and mass distribution conditions are simplified, and also the interaction soil-structure is neglected, considering central piers as absolutely fixed at the base. Two different pier-superstructure connection conditions are discussed: hinged and fixed. Using an appropriate FEM software, static and dynamic/ time history analysis were performed. By comparing the analysis results regarding the nodal displacements, base shear, bending moment and shear forces in the superstructure’s beams and piers, it can be noticed that the pier-superstructure connection conditions affect the structural response of the bridge, mainly in the longitudinal direction. However, in order to have more general conclusion, it is necessary to evaluate the bridge response under other seismic conditions with different frequency content.

Keywords

RC bridge, piers, superstructure, bridge response, pier-superstructure connection, time history

Introduction

Bridges, due to their function, are very important and in most of the cases, quite complex structures. Their design as a consequence is a major task, influenced by a number of different factors: site position and conditions, geometry/ architectural requirements, materials, type of structural system, connections conditions between structural elements, bearings characteristics, possible dissipating systems, seismic and other loading conditions, construction methodology, etc., that can affect differently, qualitatively and/or quantitatively different design situations. In this paper the focus is toward the effects of pier-superstructure connection conditions on reinforced concrete bridges. Two different pier-superstructure connection conditions are discussed: hinged and fixed. With a moment resisting connection, the potential for additional redundancy of energy dissipation exists, since plastic hinges can form at top and bottom of the columns, at least under longitudinal response. Lateral resistance will thus be increased for a given column size, and as a consequence, the column dimensions may be in theory reduced. The fixed-top connection detail also allows the designer to consider the option of pinned connections between the column base and foundations when multi-column piers are utilized. A major disadvantage of the monolithic connection detail is that seismic moments developed at the top of the pier are transmitted to the superstructure. Anchorage of the column flexural reinforcement in the cap beam, and joint shear stresses may cause design problems, and special reinforcement details, such as confinement reinforcement, and hooked longitudinal bars may be necessary. Bearing supported superstructures, i.e. hinged pier-superstructure, have the advantage of avoiding the problems associated with the moment transfer, joint-shear and anchorage issues. Seismic displacements in the hinged case will generally be larger than those in the case of monolithic connection and the sensitivity to seismic intensity exceeding the design level will also be increased. Only some of these briefly mentioned aspects, mostly related to the overall bridge response and behavior, will be verified in the following numerical application.
Case study

The reinforced concrete bridge chosen to be analyzed, is based on the existing one, part of the Skopje - Veles motorway (bridging Vardar River near Veles), with 11 equal spans of about 33.0m and a total length of 363.0m. In here, is given a simple description of the bridge, not mentioning every single detail but trying to simplify the content in function of the interest of this study. The superstructure, is composed by four “I” shape precast and prestressed main girders with 2.0m of height, connected by four transverse-girders (two at the ends and two in between) and an in-situ reinforced concrete deck, constant thickness 0.18m. It is supported by the abutments and 10 central solid cross-section piers with dimensions (4.0mx1.0m) and variable height due to the site topography. Piers are supported by stepped foundations.

![Figure 1: Longitudinal section of the bridge - schematic representation](image1.png)

<table>
<thead>
<tr>
<th>Pier ID</th>
<th>P-1</th>
<th>P-2</th>
<th>P-3</th>
<th>P-4</th>
<th>P-5</th>
<th>P-6</th>
<th>P-7</th>
<th>P-8</th>
<th>P-9</th>
<th>P-10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (m)</td>
<td>13.50</td>
<td>21.60</td>
<td>26.40</td>
<td>29.00</td>
<td>35.00</td>
<td>35.00</td>
<td>27.30</td>
<td>24.00</td>
<td>19.00</td>
<td>17.50</td>
</tr>
</tbody>
</table>

![Figure 2: Bridge superstructure cross section geometrical characteristics](image2.png)

Formulation of linear 3D bridge model

Linear 3D bridge model (nonlinear procedures are not part of this study) can be formulated correctly by interpreting the number/geometry of its structural elements, or trying to make any possible simplification to them related, while not changing their basic characteristics: materials, strength, stiffness and ductility. The first alternative is as pointed, “correct”, but it takes quite some time to be formulated, even with a structural software like the one used in here (SAP 2000), and it would be very complex indeed, in fact more than it should for our goal. The second alternative is more appropriate. The superstructure can be simplified and considered as a simple linear element, with discreet cross section dimensions with equivalent resistance and stiffness characteristics with the real cross section (Fig. 2). Connection conditions abutments/piers-superstructure can also be easily applied and the time needed to complete the analysis would be reduced. This type of model is widely recommended whenever needed to analyze the behavior/response of bridges and especially of its piers under seismic loading (not only), giving acceptable results for further engineering judgments and/or analysis.
The design loads/actions usually considered in bridge analysis are different in type/nature and intensity. For this application, due to simplicity reason, only the Dead Loads and the Seismic Action are considered, meaning that the results, in case of other probable analysis or design procedure of the bridge, must be reinterpreted quantitatively (and not only) under real/more exact loading conditions, as per codes requirements. The Dead Loads are mainly related to the structure materials and geometry. Except the self-weight of the structure, calculated automatically be the software (SAP2000), a uniformly distributed Dead Load per unit area is considered and applied too, with a 4kN/m² intensity. So, the linear frame element representing the superstructure in the model, is loaded, except its own weight, with a uniformly distributed load for unit length of: 4kN/m² x 10.6m = 42.4kN/m (10.6m is the width of the superstructure). The mass of the structure due to its self-weight can be also automatically calculated by the software, but the mass related to the additional load is expressed as a nodal mass, assuming a discretization of the beam/superstructure in four sub elements per span with length equal to 8.25m. The nodal mass is given numerically: \( m_i = \frac{8.25 \times 42.4}{9.81} = 35.66 \text{ kNs}^2/\text{m} \)

In order to have better results on the bridge behaviour, a time history analysis will be performed. Seismic action, considering only its horizontal components (the vertical component does not affect the expected results) will be based on the records of the famous earthquake of 1940, El Centro, California, U.S.
In conclusion, as pointed out in the Introduction paragraph, two different cases are analyzed: 1) considering piers-superstructure connections (all of them) as (ideally) fixed, 2) considering piers-superstructure connections as hinged, (hereafter are referred as the “Case 1” and “Case 2”).

Analysis results

The results presented in graphical or tabular manner, are interpreted in a skeptical form, assuming as true what was listed in the first paragraph of this paper (literature based facts). The vibration modes of the bridge are as expected: the first is according to the longitudinal axis of the structure, and the others perpendicular with it. It can be easily noticed, by comparing the values of natural periods, the stiffening effect of the fixed connections.

<table>
<thead>
<tr>
<th>Case</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed</td>
<td>1.41</td>
<td>1.07</td>
<td>0.73</td>
<td>0.55</td>
<td>0.42</td>
</tr>
<tr>
<td>Hinged</td>
<td>2.64</td>
<td>1.08</td>
<td>0.74</td>
<td>0.56</td>
<td>0.47</td>
</tr>
</tbody>
</table>

This effect influences mainly/ strongly the longitudinal response of the bridge (see first mode shape and its corresponding period), and not the transverse one (see other mode shapes and their periods). In order to have good conclusions, many aspects of the bridge behavior/response have been considered and presented below (these aspects must be interpreted according to the global coordinative system attached, Fig. 5), other than its vibrations characteristics. At this aim, the most representative sections and elements were chosen to be discussed, on logical engineering bases and in function of the type/nature of the studied structure aspect/characteristic. So, the superstructure’s accelerations, its velocities and displacements in plan are given related to the mid-span section. For bending moments and shear forces, end and middle positioned beams or piers (respectively shortest and longest) were selected. Nodes and elements labels are shown in Fig. 6.
In conclusion for Case 1:

- the acceleration/displacement response in Y direction is higher than in X direction; this means the base shear has also higher values in this direction.
- bending moments and shear forces time histories are higher in the end beam compared with the middle beam of the structure.
- bending moments and shear forces time histories for the end short pier and middle long pier are noticeably bigger in Y direction then in X direction; meanwhile, the end short pier has higher bending moments and shear forces response compared with middle long pier (as it should logically happen).
In conclusion for Case 2:

- the acceleration/displacement response in Y direction is higher than in X direction; this means that the base shear has also higher values in this direction.
- bending moments and shear forces time histories are quite the same for the end beam and middle beam of the structure (not as in the Case 1).
- bending moments and shear forces time histories for the end short pier and middle long pier are noticeably bigger in Y direction than in X direction; meanwhile, the end short pier has higher bending moments and shear forces response compared with middle long pier (as it should logically happen).
related to the longitudinal direction excitation
In conclusion of the comparative analysis:

- the bridge structure with the fixed piers-superstructure connections, Case 1 is stiffer than the one with hinged connections, Case 2 (Tab. 2).
- the response of structure related to the displacements in X direction, in Case 1 is lower than in Case 2 - even though the acceleration response is quite the same - stiffening effect.
- the response of structure related to the displacements in Y direction, is quite the same for both of the cases, independent form the connection type applied.
- the base shear response for both directions, X and Y is quite the same for both of the cases.

The bending moments response of the beams/superstructure in Case 1 is higher than in Case 2, due to the fact that seismic moments developed at the top of the piers are transmitted to the superstructure.

The X-direction bending moment and shear force response in the two discussed piers, is lower in Case 1 than in Case 2, while in the Y-direction the response for these aspects for these piers is “similar”.

In the end, it can be noticed that the pier-superstructure connection conditions affect the structural response of the bridge, mainly in the longitudinal direction. However, in order to have more general and acceptable conclusions, it is necessary to evaluate the bridge response under other seismic conditions with different frequency content, and to perform even other types of analysis in function of other subject related discussions.

References