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Abstract

This paper presents a comparative study of an Optimal Sensor Placement (OSP) implementation conducted in a box girder bridge using experimental and numerical mode shapes obtained at different construction stages. It is widely recognized that monitoring the dynamic response of bridges during different construction stages provides valuable information to adjust design considerations. Therefore, there is a need for the development of OSP implementations in order to find the optimal number of sensors needed for real applications.
In the present study, an OPS method based on the maximization of the Fisher Information Matrix (FIM) is used. The use of experimentally derived and numerical based mode shapes is considered in the determination of the optimal sensor locations. Field testing results previously conducted before connecting the central segment of the main span are also included in this study. The asphalt pavement weight effect in OSP determination is also analyzed by considering field testing.

Keywords: Box girder bridge, optimal sensor placement, Fisher information matrix, modal identification, field testing.

Óptima Localización de Sensores en un Puente de Viga Cajón Utilizando Modos de Vibración Obtenidos de Análisis Numérico y Pruebas de Medición en Campo

Resumen

Este artículo presenta un estudio comparativo de óptima localización de sensores (OSP) realizado en un puente de viga cajón usando modos de vibración experimentales y numéricos obtenidos en diferentes estados de construcción del puente. Es ampliamente reconocido que el monitoreo de la respuesta dinámica de puentes durante diferentes estados de construcción provee información invaluable para ajustar las consideraciones de diseño. Por lo tanto, existe una necesidad de desarrollar estrategias para determinar la localización óptima de sensores (OSP, por sus siglas en inglés). En el presente estudio, un método OSP basado en la maximización de la matriz de información Fisher (FIM) es utilizado. El uso de modos de vibración derivados de forma experimental y numérica es considerado en la determinación las posiciones OSP. Resultados de pruebas de medición en campo ejecutadas antes de conectar la dovela central de la luz principal también se incluyen en este estudio. El peso de la carpeta asfáltica en la determinación de las posiciones OSP es también considerado en las pruebas de medición en campo.

Palabras clave: Puente de viga cajón, óptima localización de sensores, matriz de información Fisher, identificación modal, pruebas de medición en campo.

1. Introduction

In recent years, Colombia is experiencing a rapid infrastructure growth leading to the construction of a considerable number of new long and tall bridges as compared with the standards of existing infrastructure. In addition, alternative bridge construction systems have also been recently implemented in new infrastructure construction. Therefore, there exists an urgent necessity to develop alternative methodologies to guarantee correctness of design considerations using field measurements collected during the construction process. One approach is the use of the dynamic response of a bridge in order to detect large deviations between the numerical model employed in the design stage (which is commonly assumed as a reliable representation of a real bridge) and the response of the constructed bridge structure. Several experimental test campaigns haven been conducted to assess the structural integrity of existing bridges (Bagheri et al. 2018, Chen et al. 2017, Costa et al. 2016). On the other hand, new bridge projects have been open to traffic having different monitoring systems in order to monitor their static and dynamic response in a continuous manner, it is important to note that this preventive practice is not commonly used in Colombia mainly due to budget constraints. During the construction process, structural assessment practice is solely associated to guarantee material verification and accomplish code and design specifications. Dynamic monitoring systems are not commonly used in Colombia to verify design assumptions during the construction of new bridges. Such approach could provide to the owner the possibility to detect deviations from design assumptions at an early stage allowing the adoption of the necessary adjustments during the construction process. The associated sensor technology (and its cost) needed to measure the dynamic response of bridges is recently becoming more affordable as a practical tool to make diagnosis in order to determine the structural performance of existing bridge infrastructure, cost that can be included in the construction budgets prior to the construction of a bridge.

One of the most important aspects to be considered in the determination of the budget associated to construction of new bridges, is the number of sensors to be used in the dynamic monitoring system. The use of large number of sensors will not always lead to improvement in modal identification results. Therefore, the area of Optimal Sensor Placement (OSP) have received special attention during recent years. The main objective has been to develop OSP methodologies to determine the number and locations of the minimum number of sensors required to guarantee reliable modal identification results. Other OSP approaches have been developed in order to detect and locate structural damage, such approaches are usually based on the use of modal strain energy and require the use of mass normalized mode shapes. Kammer (1996) developed the Effective Independence (EFI) method which have been employed by several researchers. Meo and Zumpano (2005) using an updated Finite Element (FE) model of the Nottingham suspension bridge compared the performance of 6 OSP methods including the EFI method. The Mean Square Error (MSE) was used to assess the deviation between the FE updated model mode shapes and the mode shapes obtained by a cubic spline interpolation using the measured displacement at instrumented sensor locations. The superior performance of the EFI based techniques was highlighted by Meo and Zumpano (2005). Another study conducted by Chang et al. (2014) presented an OSP method called Modified Variance (MV) method which is based on Principal Component Analysis (PCA). Identified mode shapes obtained from ambient vibration data of the Golden Gate bridge were used to study the performance of 3 EFI based methods and the proposed MV method using the Modal Assurance Criterion (MAC). Considering a number of sensors lower than 10, the results presented by Chang et al. (2014) showed similar modal identification performance of the aforementioned methods. Prabhu and Atamturktur (2013) proposed a modified EFI Method by introducing a Distance-Based Criterion (DBC) in order to prevent clustered sensor locations. Based on a parametric study conducted using the FE model of the Gothic Revival Cathedral, the authors determined a list of regions suitable for sensor placement and concluded that use of previously determined sensor locations reduces the necessary resources and facilitates full-scale field testing.

More recently, Vicenzi and Simonini (2017) studied the influence of model errors in OSP using an updated FE model of the Corregio footbridge located in Italy. The authors emphasized the fact that maximization of the FI matrix determinant leads to similar results when minimization of the information entropy is used instead. By conducting a parametric study, the authors found that variation of the elastic modulus significantly modifies mode shapes and their order. Therefore, they recommended the use of mode shapes with the highest participation masses when sensor placement is conducted. Liu et al. (2018) conducted a thorough review considering modal identification performance of existing OSP methods. Based on numerical models concluded that the EFI approach provides the greatest amount of information based on the determinant of the FIM. Finally, Kim et al. (2018) target model uncertainty and proposed an analytical EFI based method to overcome this limitation. Using numerical simulation, the authors demonstrated that an increase of model uncertainty affects sensor selection. Based on the aforementioned facts, it is clear that there still exists the need for the development of OSP approaches using field testing in order to overcome the inherent difficulties associated to model uncertainty and limited modal information. In addition, variation of structural properties during the construction of a bridge adds more uncertainties to the development of dynamic based systems especially designed to guarantee design assumptions. This study presents the results of OSP implementation in a box girder bridge using mode shapes obtained from field testing at different construction stages. The main difference between the two construction stages is related to the loading effect of the weight of formwork travellers employed during the construction of the bridge when the two sections of the bridge are not connected leading to a model responding as a cantilever beam. Once the central connection is achieved, the loading effect associated to the asphalt pavement is also considered in the determination of the mode shapes used in the OSP implementation.

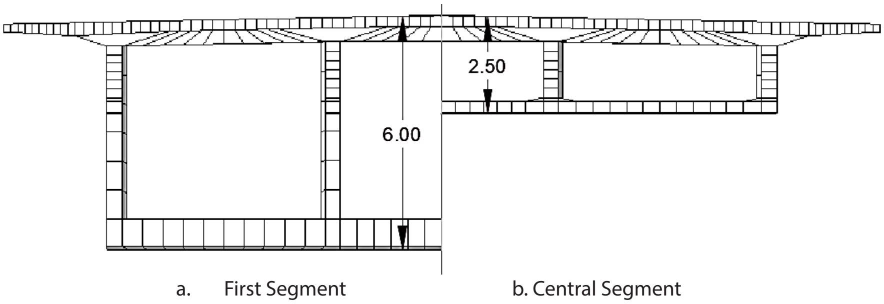
2. Bridge Structure

2.1 Bridge modeling considerations

The box girder bridge selected in the present study is located in Bucaramanga and corresponds to the main component of the newly constructed La Union viaduct. The construction of the bridge was intended to ease traffic congestion in an existing viaduct called Garcia Cadena. **Figure 1** shows the bridge and **Figure 2** shows the cross section of the bridge that consists on a 22.5 wide tricellular concrete box girder of varying height (2.5 m to 6 m). The main span is 110 m long with two side spans of 52.45 m and 55.5 m long, respectively. During the construction process the bridge can be firstly treated as two double cantilever structures defined as north and south sections based on its geographical orientation, and therefore leading to a completely different dynamic response of the sections when compared with the bridge having the central segment constructed. The north section having 100 m long is composed of 13 pairs of segments and the south section having 108.5 m is composed of 14 pairs of segments as shown in **Figure 3**.

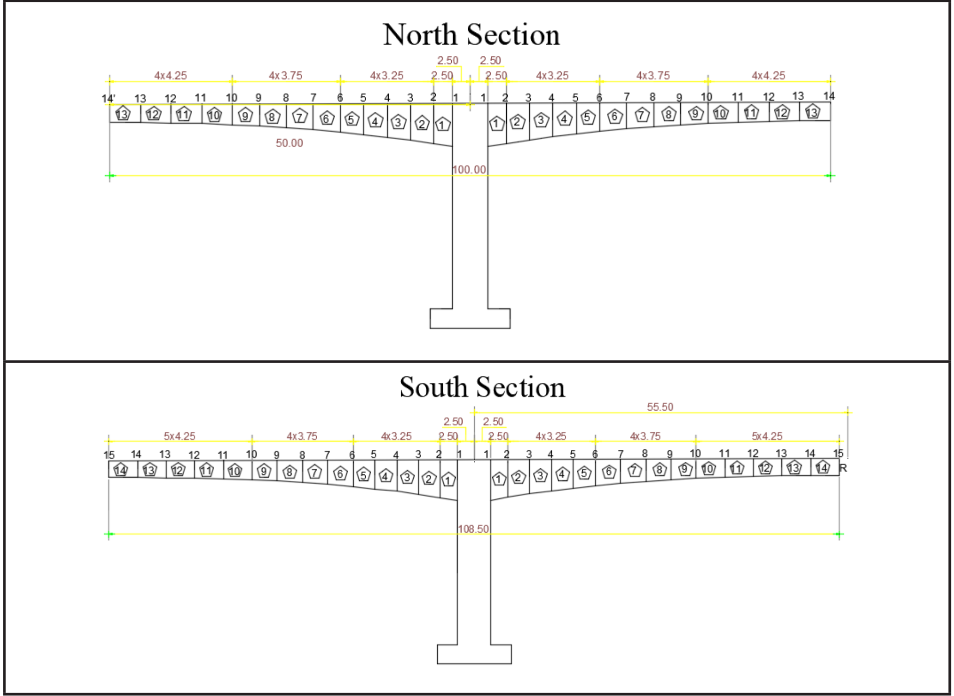
Figure 1. La Unión Viaduct (Left Side). **Source:** Authors.

Figure 2 La Unión Viaduct Cross Section. **Source: Authors.**



a. First Segment b. Central Segment

Figure 3. Construction Stage 1 (North and South Sections). **Source:** Authors.



Hernandez et al. (2018) previously developed an updated FE model of the bridge selected in this study using field measurements. The developed FE model represents the dynamic response of the bridge prior to traffic opening and therefore is only suitable for continuous monitoring applications. In addition, Hernandez et al. (2018) developed two FE models before the central segment of the bridge was constructed in order to update their corresponding FE models using field measurements, large deviations were found when the model updating process was conducted and therefore the FE models could not accurately represent the dynamic response of the bridge. A parametric study was conducted in order to study the effect of the weight of the formwork travellers and the construction loads acting on the bridge when field testing was conducted in order to consider more realistic load construction values. The loading effect of the formwork traveller and the construction materials placed on the superstructure of a bridge inevitably modify the mass of the bridge structure leading to the necessity to conduct OSP analysis when a new segment is constructed. This fact shows the importance of weight determination during the construction process, however such kind of approach will not be completely suitable for real applications due to physical limitations related to determination of the real weight of the various components needed during the construction process of a segmental bridge. Even though accurate load construction prediction is not possible due to inherent load variation during any construction process, it is desirable to conduct construction load verification in order to check allowable limits of such loads with those considered in the design of the bridge. Determination of formwork traveller weights and load construction will greatly improve the quality of the numerical obtained mode shapes for OSP implementations. Other important aspect to be considered is the possibility to interrupt the construction process of the bridge during field testing in order to improve the quality of the modal identification results. Finally, deviations of the compressive strength of concrete from the design specified values will also affect identified mode shapes. The above mentioned facts imply current limitations in numerical based OPS implementations when target monitoring of bridges at different construction stages.

This study considers OSP configurations obtained before and after the central segment is constructed. Therefore, numerical obtained mode shapes are used at three construction stages, before construction of the central segment (north and south sections), and with and without considering the asphalt pavement weight. The first construction stage consists of two structural systems acting as a double cantilever beam leading to more complex response of the bridge when considering the weight of the formwork travellers. Although segmental bridge construction is commonly used in box girder type bridges, it is also important to note that this construction system is also used to construct cable-stayed bridges. Therefore, the study of the dynamic influence of the weight of the formwork travellers in the determination of dynamic properties at different construction stages is an important research issue. In practical applications, the loading effect of the asphalt pavement adds more mass to the structural system leading to a final OSP configuration obtained from a bridge responding under service loads. This construction stage represents the closets OSP configuration that resembles the OSP configuration when the bridge is open to traffic.

A more straightforward approach will be the use of modal information collected from OSP locations obtained from numerical models using construction load values verified on construction site, and then conduct field testing avoiding construction load variation. It can be achieved if field testing is adequately coordinated with the construction process and conducted without interrupting the construction of the bridge, also when large variation of construction loads is not expected. Experimentally derive mode shapes are then obtained to adjust OPS locations and then conduct field testing. It is impractical the calibration of a new FE model when a new superstructure segment or group of superstructure segments are constructed, and therefore information collected using the proposed procedure can be used to assess quality construction by collecting modal identification results from the best possible OSP configuration experimentally optimized at each construction stage. Field testing must be previously defined in accordance with the number of construction stages of the bridge to be verified. The proposed OSP approach will inevitably impact construction budget, but it can provide high quality information needed to update FE models if results of the measured compressive strength of concrete are included at different construction stages. Current model updating procedures usually assume a constant value of Young's Modulus without considering that segmental bridges have inevitably variation of the Young's modulus for the different segments in which such bridges are constructed.

2.2 OSP implementation

The OSP method selected in this study is based on the maximization of the FIM. The EFI method is then selected based on the adequate performance of the method as previously mentioned. The EFI method determines OSP locations using the concept of linear independence of the mode shapes. The FIM is then obtained from the transpose of the mode shape matrix multiplied by the mode shape matrix and is defined symmetric and positive definite. The dimension of the mode shape matrix corresponds to the number of mode shapes considered in the OSP implementation. An eigenvector analysis is then performed in order to obtain its corresponding eigenvalues and eigenvectors defined as y , respectively. The contribution of a sensor candidate location to each mode shape is obtained from the squaring the product of . By dividing each of the element of by and summing up all the terms related to a sensor location, the contribution of that sensor location to the mode shapes considered in the analysis is determined (Riveros et al. 2013). The main idea behind the EFI method is to select OSP locations based on large contribution to the target mode shapes. It is clear that accurate determination of mode shapes greatly affects OSP locations.

Considering that EFI results mainly depend on the ability of the monitoring system to correctly identify the selected mode shapes. The main budget constraint is related to the number of sensors employed in field testing, as the number of sensors is reduced modal identification quality is compromised. To optimally determine the number of sensors is important to identify the type of ambient excitation sources that will excite the bridge at different construction stages. On the other hand, the use of forced vibration may be prohibitive in order to avoid damage in newly constructed segments. Ambient excitation sources are therefore more favorable in order to conduct field testing when a bridge is under construction. Hernandez et al. (2018) assembled two FE models for the north and south sections of the bridge in MIDAS engineering software (2016) using the geometry, material properties, and load considerations (including a 1067.57 kN formwork traveller) provided by the bridge contractor (Consorcio Vial Puerta de Sol). Three (3) high sensitivity accelerometers Obsidian Kinemetrics® (2016) were used to conduct field testing, ten (10) sensor locations are then defined by considering two (2) symmetrically distributed locations of five (5) sensors on each side of the superstructure. **Tables 1** and **2** show the mode shapes obtained from FE analysis and field testing. X, Y and Z are associated to mode shapes acting in the longitudinal direction, transverse direction and vertical direction, respectively (Hernandez et al. 2018).

TABLE 1. IDENTIFIED MODE SHAPES. **SOURCE:** AUTHORS.

North Section

Numerical (Hz)	Experimental (Hz)
Z 1.46	1.66
Y 1.799	1.851
X 1.1837	1.982

South Section

Numerical (Hz)	Experimental (Hz)
Z 1.239	1.461
Y 1.728	1.733
X 1.812	1.724

TABLE 2. IDENTIFIED MODE SHAPES. **SOURCE:** AUTHORS.

No Asphalt Pavement

Numerical (Hz)	Experimental (Hz)
Z 1.32	1.58
Y 1.82	1.84
X 1.41	1.67

With Asphalt Pavement

Numerical (Hz)	Experimental (Hz)
Z 1.27	1.54
Y 1.76	1.81
X 1.37	1.74

OSP analysis is then conducted using the above mentioned numerical and experimental obtained mode shapes. The SHM Tools developed by the LANL/UCSD Engineering Institute is used to conduct OSP analysis (LANL/UCSD Engineering Institute, 2010). Figures 4 to 7 show the OSP configurations obtained when 4 OSP locations are selected for north and south sections, respectively. Large deviations are found when numerical mode shapes are used in contrast with the use experimental mode shapes. It is noticeable that OSP configurations obtained from field testing tend to concentrate OSP locations at the ends of the cantilevers. As previously mentioned, formwork traveller weight was assumed from data provided from the bridge contractor, but load verification on construction site is desirable. Another important aspect to be considered in order to improve modal identification results is the use of Young's modulus derived from compressive strength of concrete tests.

Figure 4. FE based OSP North Section. **Source:** Authors.

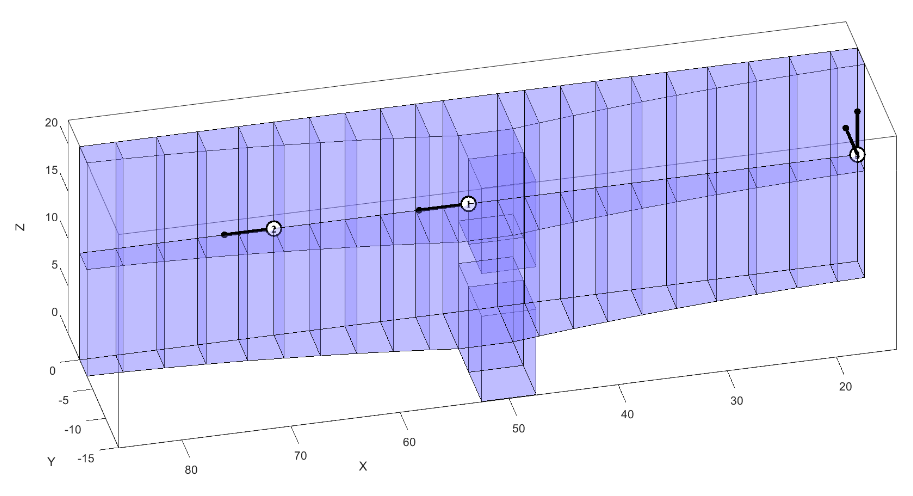


Figure 5. Field Testing based OSP North Section. **Source:** Authors.

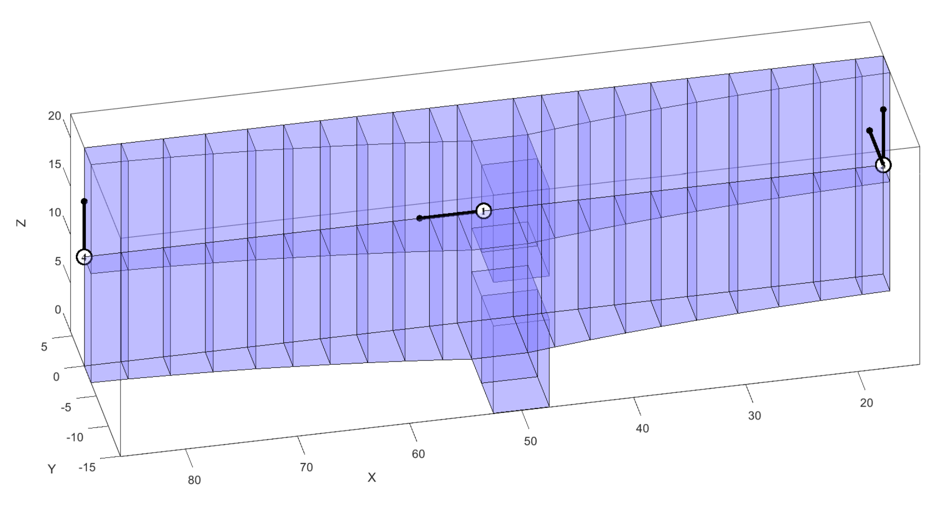


Figure 6. FE based OSP South Section. **Source:** Authors.

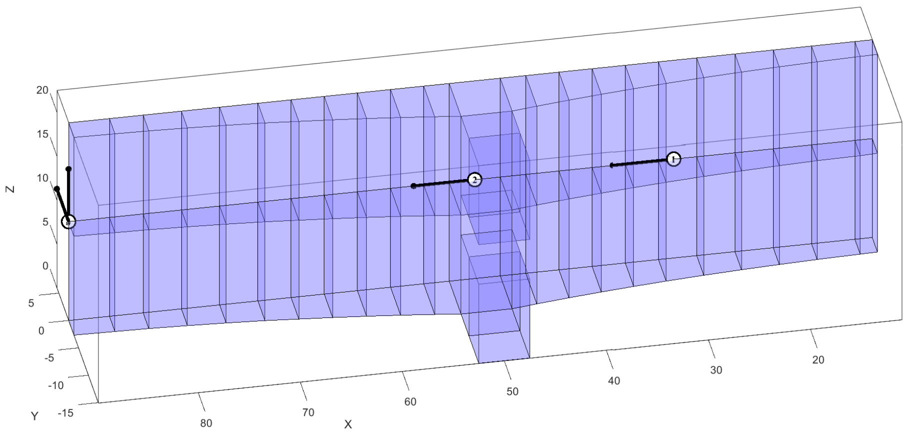
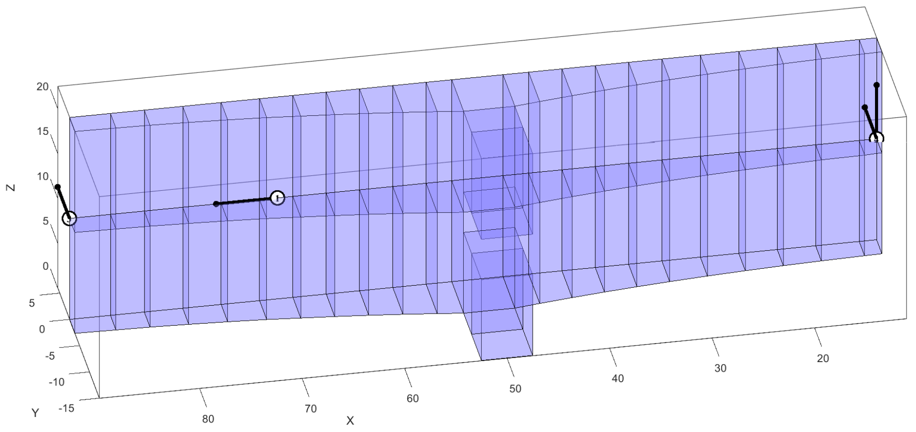


Figure 7. Field Testing based OSP South Section. **Source:** Authors.



After construction of the central segment of the bridge is achieved and the north and south sections of the bridge are connected, and prior to the placement of the asphalt pavement, Hernandez et al. (2018) assembled another FE model and additional FE model is assembled to consider the effect of the weight of the asphalt pavement. It is widely recognized that thickness of the asphalt pavement greatly affects the structural mass of the system. Therefore, it is intended to capture the dynamic response variation that will suffer the bridge when for example asphalt pavement replacement is conducted. In Colombia, it is commonly assumed as a design load one additional asphalt pavement layer. **Figures 8** to **11** show the OSP configurations obtained when 8 OSP locations are selected with and without considering the weight of asphalt pavement, respectively.

Figure 8. FE based OSP no Asphalt Pavement. **Source:** Authors.

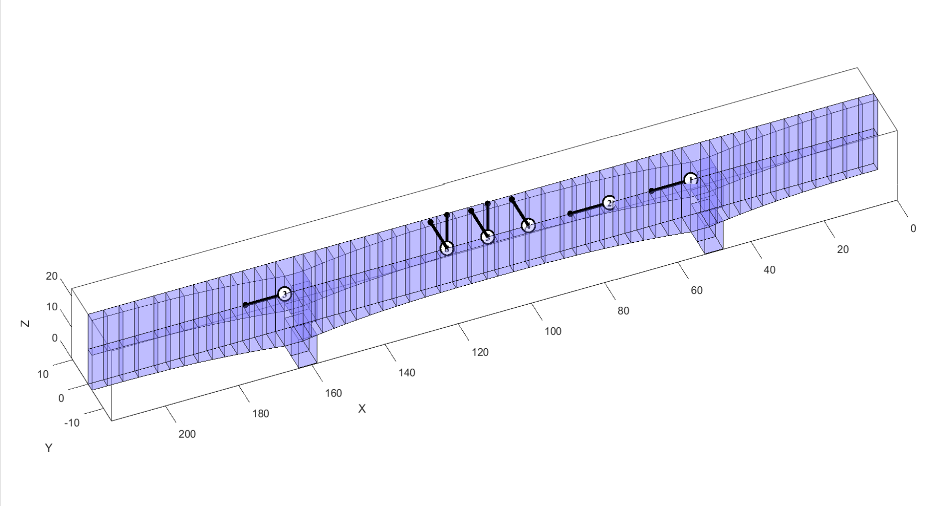


Figure 9. Field Testing based OSP no Asphalt Pavement. **Source:** Authors.

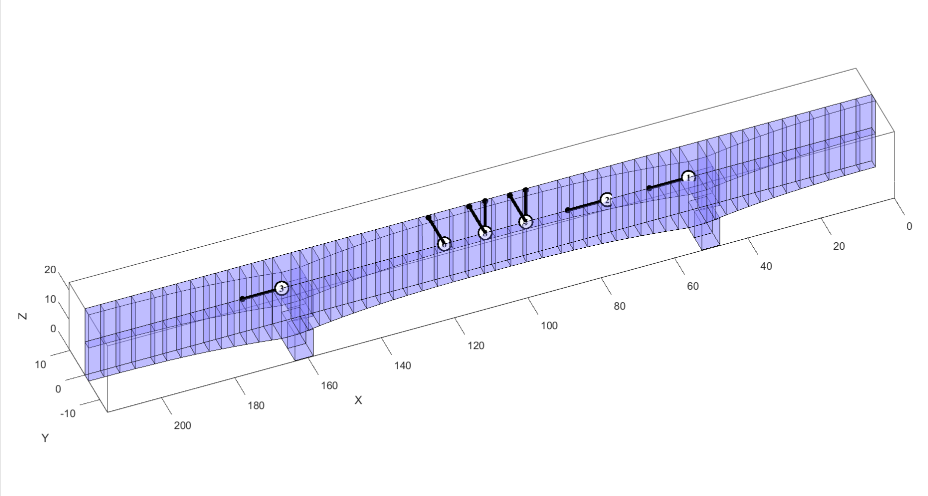


Figure 10. FE based OSP with Asphalt Pavement. **Source:** Authors.

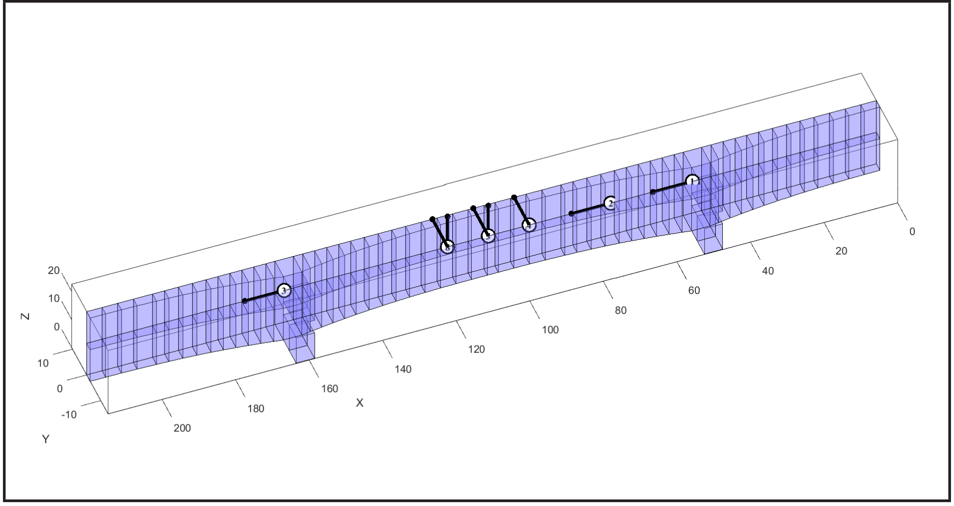
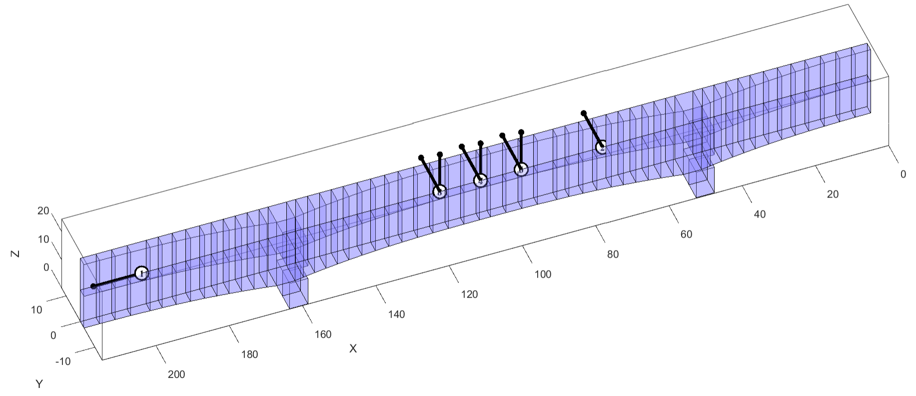


Figure 11. Field Testing based OSP with Asphalt Pavement. **Source:** Authors.



OSP configurations tend to locate sensors at the center of the main span. The results show that for practical applications is advisable to use mode shapes derived from FE analysis in order to conduct OSP analysis. The objective of an updated model will be to find the same OSP locations when data from field testing is used. There exists an uncertainty related to Young's modulus. Although model updating is conducted by adjusting the design value of f'c=28 MPa to f'c= 35 MPa for the double-column pylons and the design value of f'c=35 MPa to f'c=49 MPa for the segmental beams achieving good correlation between the updated FE model and measurements from field testing (Hernandez et al. 2018). It is important to emphasized that segmental construction will inevitably lead to Young's modulus variation when a new segment is constructed and therefore the assumption of a constant Young's modulus to conduct model updating is inaccurate. As previously mentioned, including compressive strength of concrete tests will partially eliminate the effect of this parameter in the determination of the rigidity of a bridge.

3. Conclusions

This paper presents OSP implementations conducted in a segmental bridge in the context of field verification of design assumptions. The results show that the mass of the formwork travellers and construction loads greatly affect the resulting OSP configurations and therefore it is necessary to determine such loads on construction site in order to obtain similar OSP configurations between FE analysis and field testing. The effect of the weight of asphalt pavement in OSP analysis does not significantly affect the resulting OSP configurations for the type of bridge considered in this study. In Colombia construction of bridges are based on code standards that must be applied in design specifications and drawings without any additional field verification. Although code standards are founded on international experience achieved during several years, current facts have shown that it is necessary to adopt a more robust approach by field verification of the response of the bridge during different construction stages. Final verification of the response of the bridge may not include local variation of parameters such as Young's modulus and mass variation. The proposed approach is based on field testing using OSP configurations obtained from numerical and experimental data. Therefore, deviations from design assumptions can be detected at an early stage in order to adopt prompt actions to adjust design assumptions or apply more rigorous construction material and load control. This approach will produce bridge structures having the high potential to be easily and effectively instrumented, even in cases where monitoring systems were not considered in the design stage.

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