Numerical study of the dynamic characteristics of a hybrid steel-concrete bridge

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Abstract. Due to the continuous development of the transportation sector and the industrial areas, the roads network has become complex nowadays. The administrators of these networks are thus responsible for maintaining it in proper conditions, using the limited budget available, insufficient for the many structures and problems identified across the network. Therefore, effective systems have been created and developed to prioritize the required works, and the benefits of their implementation have been ascertained from the early stages of the degradation development. One of these systems is the modern methodology for assessing the structural state of bridges, called Structural Health Monitoring (SHM), responsible for discovering and monitoring the degradation occurrence and development. In this paper, the authors present the numerical modelling and the dynamic analysis of a bridge with mixed steel-concrete structure. The bridge is located in Romania, ensuring the continuity of DN 28 road near Scheia. The bridge superstructure, 220.70 m in length, was fully modelled using the SAP2000 program, highlighting the specific behaviour of a continuous girder. The frequencies and deformations for the first four vibration modes were determined. The data will be used in a forthcoming experimental study and compared to those recorded in-situ, in order to determine the structural degradation.

1. Introduction

Bridges have been designed and erected since ancient times to ensure the crossing of various obstacles, with the aim of establishing the economic relations between different areas [1]. Nowadays, in many countries, most of the transport infrastructure is already built, the main challenge being to maintain it in operational conditions, using the limited budget funds available.

The road infrastructure is continuously degrading and, in some particular cases, various defects may occur even during the construction phase. In order to ensure that the traffic is conducted in proper safety and operational conditions, various methodologies for the structural assessment have been developed over time. Among these methodologies, visual inspection is the most used, with many significant disadvantages however. In recent years, modern sustainability tracking methodologies have been developed, generically called Structural Health Monitoring (SHM) [2, 3].
The SHM systems involve analyzing the behaviour of a bridge over a period of time (which may vary between a few hours and a few years) based on the data recorded directly from the site. These analysis parameters are selected by the personnel responsible for designing such a system, by considering only the dynamic parameters that define the behaviour of the monitored construction [4-6].

To detect the degradation occurrence or spread, the information captured from the structure is compared to a set of reference data. The latter may describe the behaviour of the structure without degradations, being recorded at the time of opening the traffic, in the case of new structures, or after the completion of an extensive rehabilitation process. When there is a need to implement a SHM system but no reference datasets are available, researchers recommend modelling the structure as appropriate as possible, using any suitable design program based on the Finite Element Method. In this way, the dynamic characteristics of the structure that do not present any degradation are determined.

The main purpose of this paper is to describe and discuss the results of a numerical analysis performed on the Scheia Bridge, located on the national road DN 28 at km 6+957, near Scheia, Romania. The chosen structure and how the modeling was performed are also briefly presented.

2. Description of the Scheia Bridge superstructure
Scheia Bridge is located in the eastern part of Romania, ensuring the continuity of traffic on the national road DN 28, near Scheia, at km 6+957. The structure has a particular importance to the administrator due to the specific nature of the national road that it serves. DN 28 is part of the European route E 583, being one of the most used traffic routes connecting Iași to the rest of the country.

Due to the specificity of the road served, the structure ensures the traffic of the vehicles on two lanes, one for each direction, resulting in a 7.44 m wide road section. Being located outside the locality, the bridge is equipped with two small sidewalks, 0.85 m each, with functional role only. Therefore, the total width of the bridge is 9.52 m (figure 1), measured between the inner faces of the safety parapets.

![Figure 1. View of the carriageway of the Scheia Bridge.](image)

Crossing the Siret River, the bridge has a 236.90 m long superstructure (figure 2), built in a slight curve to the left. Infrastructures consist of 2 ledges and 3 piers, resulting in a continuous girder structure with four openings. These openings have different lengths, as follows: 50.35 m + 60.00 m + 60.00 m + 50.35 m.
In the cross-section (figure 3), the superstructure consists of 2 plate girders with a constant height of 2400 mm and 4 longitudinal beams of 1200 mm. The distribution of loads between the girders and the longitudinal beams is made by means of the 1000 mm high struts placed every 5.00 m along the bridge. At the top of the metal structure there is a reinforced concrete slab with the role of supporting the traffic. The connection between the girders and the concrete plate is achieved only through gravity and the frictional forces between the elements.

3. Numerical modelling of the steel-concrete composite structure of the Scheia Bridge, using the SAP2000 program

The first stage of the study aims to numerically determine the dynamic characteristics encountered within the entire steel-concrete mixed structure of the Scheia Bridge. A complete modelling along the entire length is required due to the girder scheme (a continuous beam with 4 spans) exhibiting a special operating behaviour.

Using the facilities provided by the numerical analysis program, the Scheia Bridge was modelled taking into account the type of materials in the building structure and all particularities of the component elements (figure 4). However, the modelling did not take into account the degradations encountered since its purpose was to study the behaviour of the structure without any degradation. During the modelling, two types of construction materials were defined: S235 steel used for all structural steel elements and C30/37 concrete class for the bearing plate. In order to further increase the accuracy of the resulting data, all elements of the structure were modelled as Shell elements.
Figure 4. The structure of the Scheia Bridge, modelled in the SAP2000 program.

To simulate the actual behaviour of the structure, the gravitational and frictional forces developed at the interface between the steel girders and the concrete slab were assimilated with a vertical movement blocking. This blocking was done in a minimum number of points so as not to influence the effects of the lack of cooperation, a serious defect of the studied structure.

The next stage in the modelling is defining the structure supports, taking into consideration the actual conditions in the site. The displacements were blocked in all the directions along pier P2 (figure 2) to ensure the conditions of a joint. In the rest of the cases, the restrictions of simple supports were simulated and only the movements in longitudinal direction were restricted.

To prepare the model for analysis, the structure was meshed as shown in figure 5, taking into account all its particularities. Thus, the data provided by this modelling is considered to be sufficiently accurate to be used in the next steps of the experimental study.

Figure 5. Discretization of the model structure.

Following the run of the program, the first four vibration modes of the mixed steel-concrete structure and the characteristic frequencies of each mode were determined. Only the gravitational load was considered for this analysis.

4. Modal analysis of the composite steel-concrete structure of the Scheia Bridge
The frequencies and the periods corresponding to each mode, along with the circular frequency were determined from the vibration modes analysed. The values of these characteristics were centralized and presented in table 1.
Table 1. Values of the dynamic characteristics of the composite steel-concrete structure according to the vibration mode.

| Vibration mode | Frequencies | Period   | CircFreq     |
|----------------|-------------|----------|--------------|
| 1              | 1.3080 Hz   | 0.7645 sec | 8.2186 rad/sec |
| 2              | 1.7336 Hz   | 0.5768 sec | 10.8923 rad/sec |
| 3              | 2.2127 Hz   | 0.4519 sec | 13.9027 rad/sec |
| 4              | 2.5083 Hz   | 0.3987 sec | 15.7602 rad/sec |

The deformations of the structure corresponding to the vibration modes of table 1 are shown in figures 6, 8, 10 and 14. Figures 7, 9, 11, 12, 13 and 15 provide details of the maximum displacement values for each deformed shape and their place of occurrence, values that will be centralized in the final part of this chapter in table 2.

By analysing figures 6, 7 and 8, vibration mod no. 1, corresponding to a frequency of 1.3080 Hz, exhibits displacements in both the concrete slab and the metal girder. In this case, both elements work simultaneously. Three inflection points corresponding to the cross sections of the supports were found. The openings in which the largest deformed are recorded are the opening O2 and the opening O3, both located in the central part of the structure. However, their displacement values have opposite signs.

Figure 6. First vibration mode of the concrete-steel structure of the Scheia Bridge.

Figure 7. The maximum vertical movement values recorded in the O2 opening.
By recording a period of 0.5768 sec at a frequency of 1.7336 Hz, in the vibration mode no. 2, the structure undergoes the deformation exemplified in figure 8. As shown, one of the most important features of this mode is the change in movement directions. It follows that O1 and O4 are deformed in the same direction, while O2 and O3 openings suffer opposite sign shifts. The values of these displacements are approximately equal for openings with the same meaning of the deformations. Thus, 38.3 mm (O1) and 38.4 mm (O4) displacements are recorded at the centre of the openings O1 and O4 (figures 9(a) and 9(d)), the difference being below 2%. In the case of openings O2 and O3, this characteristic is more pronounced, the displacement values being equal (figures 9(b) and 9(c)).

**Figure 8.** Second vibration mode of the concrete-steel structure of the Scheia Bridge.

**Figure 9.** Maximum vertical displacement values recorded for vibration mode no 2 for all (4) openings.

The vibration mode no. 3 corresponds to a frequency of 2.2127 Hz and a period of 0.4519 sec.; the deformation is shown in figure 10. The deformation shape records positive values of the vertical displacements for the openings O1 and O2. At the same time, the openings O3 and O4 show opposite displacements, thus emphasizing the importance of the abutment point next to the pier P2, a section in which the fixed supports are arranged. An interesting feature of the deformation of this vibration mode...
is represented by the position in which the maximum displacement is recorded. Thus, this value occurs at a third of the opening O1, as shown in figure 11, representing a vertical displacement of 48.1 mm.

**Figure 10.** Vibration mode no 3 of the steel-concrete structure of the Scheia Bridge.

![Vibration mode no 3 of the steel-concrete structure of the Scheia Bridge](image)

**Figure 11.** Maximum vertical displacement values recorded for vibration mode no 3 for O1 opening.

Analysing the case of the opening O2, it was found that the recorded movements had the same sign as those encountered in the case of opening O1. The main difference is the magnitude of these displacements, which are about half of the O1 displacements. Thus, a positive displacement of 22.8 mm is recorded in the centre of the opening O2, (figure 12).

**Figure 12.** Maximum vertical displacement values recorded for vibration mode no 3 for O2 opening.

![Maximum vertical displacement values recorded for vibration mode no 3 for O2 opening](image)

The displacements of the openings O3 and O4 have opposite signs, although they are not equal. The deflection recorded at the centre of the O3 opening is 14.3 mm (figure 13) at the concrete slab, the value of which is significantly increased at the bottom of the girder, reaching 22.1 mm (figure 14). The
O4 opening have same displacement values as those recorded for O1, but of opposite signs. Thus, a negative vertical displacement of 48.2 mm on the concrete slab is recorded at the centre of the opened aperture (figure 15).

![Diagram](image1.png)

**Figure 13.** Maximum vertical displacement values recorded for vibration mode no 3 for O3 opening at the concrete slab.

![Diagram](image2.png)

**Figure 14.** Maximum vertical displacement values recorded for vibration mode no 3 for O3 at the girder level.

![Diagram](image3.png)

**Figure 15.** Maximum vertical displacement values recorded for vibration mode no 3 for O4 opening at the concrete slab.

The 4th and last vibration mode studied (figure 16) corresponds to a frequency of 2.5083 Hz and a period of 0.3987 sec. The distorted motion is relatively equal to the previous cases. A feature of this case is that in all four openings there are simultaneous movements in the same direction.
Figure 16. Vibration mode no 4 of the steel-concrete structure of the Scheia Bridge.

Movement values are relatively equal in all openings. The maximum displacements are recorded in the centre sections with the following values: 37.8 mm for opening O1 (figure 17(a)), 39.3 mm for opening O2 (figure 17(b)), 39.4 mm for opening O3 (figure 17(c)) and 37.7 mm for opening O4 (figure 17(d)). The plan displacements symmetry can be seen next to the abutment section corresponding to pier P2.

(a) The maximum displacement value in vertical direction in opening O1.

(b) The maximum displacement value in vertical direction in opening O2.
The maximum displacement value in vertical direction in opening O3.

(d) The maximum displacement value in vertical direction in opening O4.

Figure 17. Maximum vertical displacement values recorded for vibration mode no 4 for all 4 openings.

Table 2 summarizes the minimum and maximum displacement values recorded in the four analysed vibration modes, centralised by the FEM program used. It can be seen that most values (7 out of 8 offered) appear in the vertical direction.

| Vibration mode | Minimum displacement | Maximum displacement |
|----------------|----------------------|----------------------|
| 1              | -43.456 (on the Z axis) | +43.456 (on the Z axis) |
| 2              | -34.995 (on the Z axis) | +38.776 (on the Z axis) |
| 3              | -49.390 (on the Z axis) | +49.390 (on the Z axis) |
| 4              | -39.798 (on the Z axis) | +5.330 (on the X axis) |

5. Conclusions
This paper presents the modal analysis of the Scheia Bridge. The bridge has a mixed steel-concrete structure, ensuring the traffic from the national road DN 28 at km 6+957 under normal operation conditions. The numerical study described represents the first stage of implementing a modern SHM-type system especially developed for this structure.

Analyzing the resulting data, the research team will decide the type of SHM system components, along with the way the information is transmitted. At the same time, the locations of the respective units are determined in order to reduce the costs of implementing the new technology as much as possible. The accelerometers will be arranged in the cross sections where the largest displacements are expected to occur and will be positioned at the stemming level.
The next stage of the experimental study consists in a short team monitoring of the structure. The frequencies recorded, and the deformation patterns of the structure will be processed and compared to the modelling analysis results in order to determine the degradations that could endanger the safety of the traffic and the structure in general.

The paper is part of a complex research program, developed within the “Gheorghe Asachi” Technical University, Faculty of Civil Engineering and Building Services in Iasi, Romania. This program focuses on developing a modern methodology for tracking bridges over time, using modern, automated tools that minimize the involvement of the human factor.

6. References

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