The influence of track characteristics on the stresses introduced in operation in the frame of the electric locomotive class 43, EC 3400 kW

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Abstract. In order to carry out maintenance in accordance with the state of the system, the locomotives in operation should be equipped with a system to monitor the main parameters and characteristics of safe operation and minimum risk. This work presents the method of determining the strains and influencing the configuration of the track on specific strains in the case of operation of the electric locomotive class 43, 3400 kW (4620 hp). Two tensometric rosettes with three strain gauges each, from which signals were taken when the electric locomotive operated in operation on a set route, with a trainset. The area in which the transducers were installed was determined by a previous analysis of the locomotive beat. The signals taken from the tensometric transducers were processed by obtaining the main stresses from the assembly points of the brands. The results obtained, i.e. the main stresses were correlated with the geometric configuration of the rail.

1. Introduction, objective, purpose

The locomotives used on the railway, as a result of the operation in conditions of dynamic stress, are subjected to maintenance processes at certain time intervals. In addition to the operating requirements taken into account in the construction of locomotives, there are also demands in service caused by several factors: road imperfections, extreme weather conditions, the appearance on the road of various abrasive materials or changing the coefficient of friction and so on [1,2]. Given that some of these influences are less predictable, the establishment of scheduled maintenance may not be sufficient for the safe operation of locomotives [3,4]. One way to detect possible malfunctions is to check the condition of the locomotive during operation [5]. For this purpose, a monitoring system for the service status of the locomotive must be designed. This system must contain: sensors or elements from which data on the variation of certain characteristics and parameters must be acquired during operation, a system for the acquisition and processing of received data, a system for transforming data into alarms, when a parameter exceeds a prescribed value, models of proper operation of the locomotive [6].

The research in this paper aims to assess the additional stresses introduced during operation, due to the dynamics of stresses from several factors: dynamic traction stress, stresses due to infrastructure irregularities, imperfect wheel-rail contacts, movement in curves, slopes, ramps, etc. The experiments were performed on the EC type locomotive with a bogie built by Rade Končar Zagreb. It has a standard gauge of 1435 mm and is powered by catenary at alternating current with a stress of 25 kV and a frequency of 50 Hz. The electric locomotive class 43, of 3400 kW (4620 HP), has the formula of Bo'Bo
'axles, figure 1, maximum speed 120 km / h, the year of manufacture being 1973-1984. During the repairs, it was found that several cracks appeared on the mentioned bogie. A finite element analysis performed on the bogie did not show stresses that exceed the flow limit of the material and, under these conditions, to create plastic strains followed by the propagation of cracks. Figure 1 shows one view of the locomotive bogie. It is found that the drive motors of the axles, as well as the corresponding reducers observed are located on the diagonal of the bogie frame. The necessary repairs were made, the locomotive being put into operation. Under these conditions, the problem that arises is whether cracks will appear and what is the cause of their appearance. The experimental incursion carried out in this work has as main purpose the evaluation of the safety and lifespan of the two-axle bogie with which the class 43 electric locomotive is equipped. From several factors: the dynamic stress produced by the traction, the stresses produced as a result of the infrastructure irregularities, imperfect wheel-rail contacts, movement in curves, slopes, ramps, etc.

Figure 1. Electric locomotive bogie class 43 and location of electrotensometric transducers.

2. Location and verification of tensometric strain gauge
Two tensometric rosettes, of the type shown in figure 2, were placed on the locomotive bogie, figure 1. The mounting place of the two tensometric rosettes was chosen as follows:

- A finite element analysis was made from where the place where the maximum stresses were recorded;
- In the vicinity of the areas with maximum stresses, a flat area was chosen to present subsequent accessibility in order to carry out any repairs;
- The resistance structure of the bogie is almost symmetrical, however the static load coming from the location of the traction motors and reducers is asymmetric;
- Even in these conditions, two symmetrical areas were chosen in relation to the longitudinal axis of the bogie in order to highlight the dynamism of the asymmetrical load and its action on the bogie structure.

The following specifications are made regarding the installation of the electrotensometric transducers and of the signals to be acquired:

- After mounting the electrotensometric transducers, soldering the conductors and checking the connections, and after other interventions and repairs performed on the entire structure, the cabin was mounted on the bogie, the reducers, motors, etc.;
- When moving the locomotive with wagons in traction, the signal of all the channels from the Vishay bridge on which the acquisition was made, were balanced and brought to zero;
- Consequently, the acquired signals come exclusively from the additional dynamic stresses to which the bogie frame was subjected.
As shown, two active electrotensometric transducers and two passive electrotensometric transducers, type CEA-06-250UR-350, stacked rosette, figure 2, were mounted on the bogie frame, each having three tensometric strain gauges with 350Ω electrical resistance [7].

Figure 2. Transducers (rectangular rosettes) type CEA-06-250UR-350, with three offset strain gauges, having axes offset by 45° [7], (a); notations used for transducers (b) [8].

For resistive but also thermal balancing, as shown, two other transducers with three tensometric strain gauges were mounted, each on a separate, unsolicited plate. The connections were made in the Wheatstone bridge, the connections being made in the half-bridge. Thus, a Wheatstone bridge was formed of an active strain gauge, subject to the request, a passive strain gauge, glued on an unsolicited plate and balancing resistances that are found in the Vishay P3 bridge.

The transducers were applied in two symmetrical sections in relation to the longitudinal axis of the bogie frame: the section located 230mm from the front. Each set of two tensometric strain gauges (one active and one passive) was connected to a channel of a Vishay P3 tensometric bridge. Since there are 2 transducers with three strain gauges each, 6 acquisition channels were required, this being the reason why two tensometric bridges were used, each with four channels. The type of binding was in the half-bridge, the balancing of the strain gauges being done automatically in the P3 bridge. As mentioned, the balancing of the Whitestone bridges formed with each pair of tensile strain gauges was performed with the help of Vishay P3 type tensometric bridges, their balancing being done by means of specialized software for this purpose.

3. Data acquisition and correlation

For the acquisition of specific strains, the locomotive was connected to passenger wagons, following the Iaşi-Paşcani route, with 8 stations. The tensometric bridges formed by the six strain gauges (three on the left transducer and three on the right transducer) were balanced to zero. In this way, the specific strains acquired were caused only by the dynamism of the stress.

Considering that two tensometric transducers were glued on the bogie frame, as shown above, each of these transducers having three tensometric strain gauges, during the Iaşi-Paşcani route 6 specific strains were acquired. Two Vishay bridges were used for data acquisition, hereinafter referred to as bridge 1 and bridge 2. Three of the channels of each Vishay bridge were connected to the three brands of electrotensometric transducers, the fourth channel of the two Vishay bridges was used to capture the signal from the springs, which will be discussed in one of the following paragraphs.

The following are the specific strains acquired from 6 tensometric strain gauges, for the entire route, from Iasi to Paşcani. For technical reasons, on bridge 1, the data was acquired only after the Leţcani station. Moreover, also on bridge 1, in some stations the acquisition was interrupted in order to record the data. Instead, on bridge 2, data was acquired on the entire Iaşi-Paşcani route.

In order to correlate in time, the two acquisitions, from bridge 1 and from bridge 2, we used the overlapping of the column representing the time, at both Vishay bridges fixing the time before the acquisition. First, the data file showing, among other things, the variation of speed over time was taken from the on-board computer of the locomotive. As previously mentioned, for technical reasons related
to the second locomotive (the towed one) the maximum speed had to be maintained around 70 km / h. The diagram in figure 3 shows the speed variation on the Iaşi-Paşcani route, with zero speed in the stations. In figure 3 the stations were superimposed on the diagram to establish a correspondence between the travel speed and the sizes of the specific strains, respectively of the stresses.

![Figure 3. Signals taken from the locomotive's on-board computer.](image)

4. Calculation relations and experimental data processing

Based on the acquired data, a series of specific quantities were determined, the significance and calculation relationships of which are presented below.

Using the relationships presented below, the values of these quantities, presented in the following tables, were determined, specific to each point where a tensometric transducer was mounted, respectively: maximum normal main stresses, \( \sigma_{\text{max}} \), maximum main strains direction angle, \( \theta \), and shear maximum stresses, \( \tau_{\text{max}} \).

The calculation relationships for these quantities are presented below [7]. The placement of the strain gauges in the tensometric transducers was with strain gauge A parallel to the longitudinal direction of the bogie frame, figure 2b.

- maximum normal main stress, \( \sigma_{\text{max}} \):

\[
\sigma_{\text{max}} = \frac{E}{2(1-\nu^2)} \left[ (1 + \nu)(\varepsilon_a + \varepsilon_c) + (1 - \nu)\sqrt{2[(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2]} \right]
\]

(1)

- the angle of direction of the maximum principal strain, \( \theta \):

\[
\theta = \frac{1}{2} \arctg \left[ \frac{2(\varepsilon_b - \varepsilon_a - \varepsilon_c)}{\varepsilon_a - \varepsilon_c} \right] \text{[rad]}
\]

(2)

- maximum shear stress, \( \tau_{\text{max}} \):

\[
\tau_{\text{max}} = \frac{E}{2(1+\nu)} \left[ \sqrt{2[(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2]} \right]
\]

(3)

Figure 4a shows the main normal stresses in relation to the measuring directions of the tensometric strain gauges, for certain values of the specific strains measured in the directions a, b and c. When the main stresses are both positive and with certain values, the angle \( \theta \) is placed between 0 and 90°. On the area element considered in figure 5a, when on its sides we have the main normal stresses \( \sigma_1 \) and \( \sigma_2 \), on the same sides the shear stresses are equal to zero.

Figure 4b shows the main normal stresses in relation to the measuring directions of the tensometric strain gauges, when the minimum main stress is negative. In this case, for a certain combination of values of the main stresses, the angle \( \theta \) is placed between after the value of 90°. On the area element considered in figure 4b, when on its sides we have the main normal stresses \( \sigma_1 \) and \( \sigma_2 \), on the same sides the shear stresses are equal to zero.
Figure 4c shows the average normal stresses in relation to the measuring directions of the tensometric strain gauges, when the shear stress is maximum:

\[
\tau_{\text{max}} = \frac{\sigma_1 - \sigma_2}{2}
\]

\[
\sigma_{\text{med}} = \frac{\sigma_1 + \sigma_2}{2}
\]

The direction angle of the average normal stress is \(\theta + 45^0\).

With the help of all the acquired data and the calculation relations previously presented in the following figures, the following were represented:

- Figure 5: variation of the maximum main normal stresses in the two points where the two electrotensometric transducers were mounted;
- Figure 6 the variation of the maximum shear stresses in the two points where the two electrotensometric transducers were mounted;
- Figure 7: variation of the angle of the direction of the maximum main normal stress in relation to the direction of the strain gauge A, figure 2b.

As previously mentioned, we specify that the data acquisitions on bridge 2 were made from the beginning to the end of the trip, respectively, from Iaşi station to Paşcani station. From bridge 1, due to technical problems, the data acquisition started after Leţcani station, as seen previously, the signals from the two Vishay P3 bridges, which represent the acquisitions in the two areas where the electrotensometric transducers were located, were very well correlated, so that the overlapping signals, which can be seen in the previous figures, is correct. Under these conditions, the conclusions drawn taking into account the same size of the two measuring areas, taking into account the time parameter, take into account the correct conditions of overlapping signals.

From figure 5, respectively, the variation of the maximum main normal stresses in the two points where the two electrotensometric transducers were mounted, the following conclusions can be deduced:

- Bridge 2 measured the specific strains for the electrotensometric transducer placed to the right of the bogie resistance structure. It is found that from the Iaşi station, the additional stresses introduced as a result of the dynamics of the requests were kept at low values, below 20 MPa. However, a stress peak of about 60 MPa was also recorded on this route. This sudden variation of the stresses is attributed to a deterioration of the running track, figure 5. The normal variation of the additional stresses is the one that can be visualized up to approximately 830 sec. since leaving Iaşi station. Variations of up to 20 MPa are attributed to the asymmetry of the tensile forces that are transmitted to the resistance structure by its vibrations.
Also between Lețcani and Podu Iloaie stations, there are stress peaks which, most probably, are due to geometric deviations, imperfections, road damage. A continuous increase and decrease of the main stresses can take place due to cornering or acceleration. Tension peaks are due to damage or geometric deviations from the running track. Higher or lower stress peaks are also recorded between the other stations. Between the Podu Iloaie and Budai stations, the stresses are low, and, apart from the departure from Podu Iloaie, they are due to the dynamism produced by the vibrations introduced by the traction motors. Unlike this route, the one between Budai and Sârca contains relatively high stress peaks (540 MPa) due to deviations and road degradations.

5. Conclusions on the variation of the main normal stresses

- In the measurement area with bridge 1 (electrotensometric transducer on the left) between Podu Iloaie and Ruginoasa stations it is found that the maximum main normal stresses do not vary significantly in this area of the bogie resistance frame. Instead, after the Ruginoasa station there are larger variations, of about 25 MPa, although not as large as in the area on the right (70 MPa). We remind you that the transducers were mounted symmetrically with respect to the longitudinal axis of the bogie, see figure 1.
- The small values of the stresses measured in the left area of the frame where the acquisition is made with bridge 1 are common and come from the occurrence of specific strains produced by the vibrations transmitted by the operation of the power motors.
- However, after the Ruginoasa station, there are variations of the stresses that overlap, temporarily, with similar variations of the stresses determined with bridge 2. As a result, we can see from here that these variations are due to the ramp route of the gasket [9], the need for power higher and, consequently, more accentuated vibrations transmitted in both measuring areas of the structure.
- On the other hand, there is an asymmetry in the positioning of traction motors and gearboxes that we will talk about later in this paper.

In figure 6 on observe that the maximum shear stresses measured with bridge 2 are much higher than those measured with bridge 1.

The pitch of the variations of the maximum shear stresses measured with bridge 2 and bridge 1 is similar to that given by the variation of the maximum main stresses. There is some difference between Ruginoasa and Pașcani stations when the maximum shear stresses measured with bridge 1 always remain positive as opposed to the maximum normal stress values which vary towards negative values.
Figure 6. Variation of the maximum shear stresses in the two mounting points of the electrotensometric transducers

Figure 7 shows the variation of the angle of the direction of the maximum main normal stress in relation to the direction of the strain gauge A, in the acquisition area with the bridge 2. For the measuring area of bridge 2 there are certain variations of the direction of the maximum main normal stress, between 0 and 175 degrees.

Figure 7. Variation of the angle of the direction of the maximum main stress in relation to the direction of the strain gauge A, figure 2b

It is found that most of the angles are in the area of 150 degrees in relation to the direction of the strain gauge A, respectively at 30 degrees in relation to the direction of the longitudinal axis of the bogie. Zero variations of the theta angle occur when the expression $(2\varepsilon_b-\varepsilon_a-\varepsilon_c) \rightarrow 0$. No explanation has been found that the angle of the direction of the maximum main stress varies sharply to zero, possibly due to shocks or vibrations. At points where $\theta \rightarrow 0$ there are no significant increases in any of the main stresses, maxima or minima. Regarding the variation of the angle $\theta$ of the direction of the maximum normal stress determined on the basis of the acquisitions with the bridge 2, it is found that there are relatively few points where $\theta \rightarrow 0$, most points being kept in the area of the angle of 150°.

Figure 8 shows the variations of the main maximum normal stresses in relation to the height configuration of the Iași-Pașcani route. It is found that there are portions of the route which, through the ramps present on the route, influence the stresses on the respective portion. It is obvious that this is not enough, stress peaks and even high stresses over longer distances are possible due to cornering or road imperfections [9].
Figure 8. Variation of the maximum main stresses in relation to the configuration on height and in plan of the Iaşi-Paşcani route

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