Diagnosis and Restoration of Four Historical Eiffel-Type Rail Viaducts

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Abstract

As part of the project management of the Auvergne rail restoration plan carried out by the Société d'études techniques et économiques (SETEC) on behalf of the French Rail Network (SNCFR, Société Nationale des Chemins de Fer Réseau), Diadès was responsible for the diagnosis evaluation of four wrought-iron nineteenth-century viaducts located on the Lavaufranche–Saint-Germain des Fossés line. Once the viaducts' archived documents had been analysed, a complete diagnostic and investigative programme was carried out, including taking dimensional measurements and samples, conducting detailed inspections, anti-corrosion diagnosis, spectrocolorimetry analysis of the gathered data and recalculation of the fatigue of the structures. These results were then used to create a procedure for the restoration and painting of two viaducts while addressing the problem of the presence of lead in the original paintwork.

The works were carried out on the Rouzat Viaduct by Lassarat, managed by Diadès.

Keywords: Eiffel, Viaducts, SETEC, SNCFR, Diadès, Auvergne Rail Lines, Restoration, wrought-iron

Introduction

As part of the Auvergne rail restoration plan agreed between the French government, the region of Auvergne and the French Rail Network (SNCFR, Société Nationale des Chemins de Fer Réseau), significant restoration works were carried out. These restoration works were carried out to the rail networks—including works to the tracks, bridges and other civil engineering structures, tunnels and earthworks. The project management for this restoration work was undertaken by SETEC. The purpose of the works was to modernise, upgrade and ensure the safety of three rail lines in Auvergne, including the Bordeaux– Lyon line, precisely between Montluçon and Gannat (lines 705 000 and 707 000), in order to eliminate and prevent delays.

The Montluçon– Gannat line, which was opened in 1868, is composed of four historical wrought-iron viaducts, two of which were built by the young Eiffel company and the other two by the Fives Lille company.

1 Description of the bridges

The Rouzat Viaduct (Figure 1) and the Neuvial Viaduct (Figure 2), built by G. Eiffel between 1867 and 1869, are in the region of Allier on the single-track line from Commentry to Gannat. These two structures have been registered on the additional inventory of historical monuments (the list of historical monuments of regional importance) since 1965.

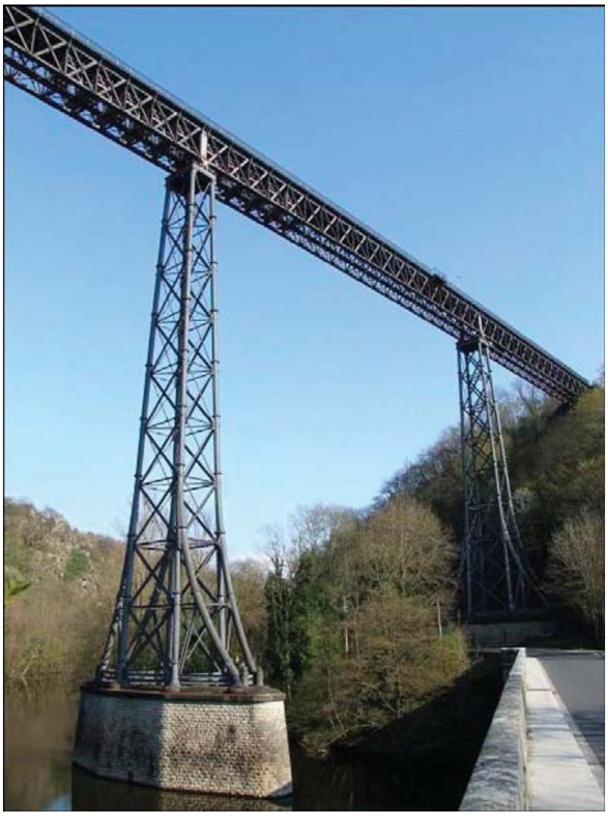

Figure 1. The Rouzat Viaduct

The Rouzat Viaduct is located in the municipality of Saint-Bonnet-de- Rochefort. It consists of three wrought- iron spans of 55.125, 57.75 and 49.125 m which are extended on the Commentry side by a stone access viaduct of approximately 13 m. The 162-m-long wrought-iron deck rests on two piers, each composed of four hollow cast-iron columns that are 500 mm in diameter.

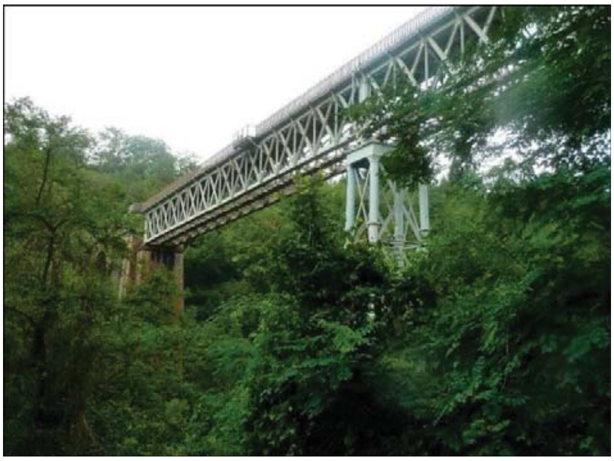

Figure 2. The Neuvial Viaduct

The piers, which are 46 and 41 m high, are linked by crosswise struts or rafters and stand on stone blocks. The pier on the Commentry side stands in the middle of the Sioule river.

The Neuvial Viaduct is in the commune of Bègues. It is composed of two wrought-iron spans of 49.2 m, extended on the Commentry side by a stone access viaduct of about 31 m and a secondary wrought-iron span of 23.5 m on the Gannat side. The 98.4- m-long wrought-iron deck stands on a pier composed of four hollow cast iron columns that are 500 mm in diameter and 41.5 m high, and which stand on a stone block.

The decks of these two bridges are 4.5 m wide between the side railings. They consist of lateral lattice girders that are 4 m in height and have a centre-to centre distance of 3.5 m. The floor beams are spaced 3 m apart and support central steel girders which were replaced in 1965. There is a fixed footbridge inside the deck which enables inspections.

The Bellon Viaduct (Figure 3) and the Bouble Viaduct (Figure 4), built by J. F. Cail and the Fives-Lille company between 1867 and 1869, are also located on the Commentry–Gannat line. The Bellon Viaduct straddles the communes of Louroux-de-Bouble and Coutansouze, and the Bouble Viaduct straddles Louroux-de-Bouble and Echassières. These two structures have been registered on the inventory of national historic monuments and sites of artistic, historical, scientific, legendary or picturesque character of the Department of Allier since 1991.

Figure 3. The Bellon Viaduct

The Bellon Viaduct consists of three spans of 40, 48 and 40 m, framed at its extremes by two stone access viaducts of 57.8 m on the Commentry side and 42 m on the Gannat side. The wrought-iron deck is 128 m long and rests on two piers, each composed of four hollow cast iron columns that are about 500 mm in diameter and stand on a stone block; the cast- and wrought-iron parts are 36 m high.

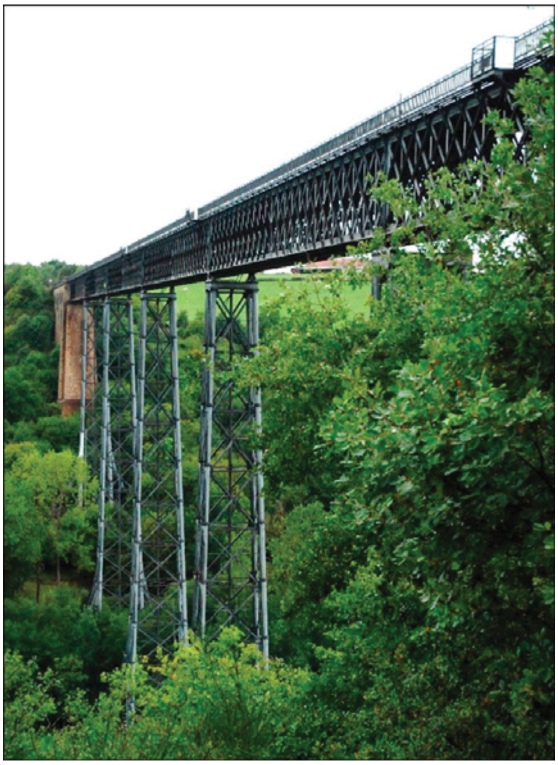

Figure 4. The Bouble Viaduct

The Bouble Viaduct is composed of six spans of 50 m surrounded by two stone access viaducts that are 71.3 m in length on the Commentry side and 23.7 m in length on the Gannat side. The 395-m-long wrought-iron deck rests on five piers, each composed of four hollow cast-iron columns that are 500 mm—with crosswise struts—and stand on a stone block; the cast- and wrought-iron parts are between 40 and 55 m high, meaning that the structure stands around 70 m above Bouble Valley (Figure 5).

The decks of these two structures are 4.5 m in width between the side railings. They are composed of multiple fourth-order lateral lattice girders and are 4.54 m high with a centre-to-centre distance of 3.5 m. The floor beams are spaced 2 m apart and support central steel girders which were replaced in 1965. There is a fixed footbridge inside the deck which enables inspections, and which was also replaced in 1965.

Figure 5. Visits by means of rope access works

2 Diagnosis

The purpose of the preliminary diagnostic phase was to analyse the general state of these structures by checking that they were in a good state of repair in order to meet the load and frequency conditions of the railway line. In each case, the final reinforcement measures required to ensure the viaduct's service and the temporary reinforcement measures required in order to implement any programme of restoration works were defined. In order to ensure a thorough understanding of the structures based mainly on the information in the project files, specific investigations were carried out which incorporated the following activities:

- Brief visits were carried out with rope access works (Figure 5) and completed at night using hydraulic cradles (Figure 6) designed to provide up-to-date information on all the defects which may affect the structures (elements coming apart, splitting, possible cracking, etc.).

Figure 6. Inspection using hydraulic cradles

- Brief visits were carried out with rope access works (Figure 5) and completed at night using hydraulic cradles (Figure 6) designed to provide up-to-date information on all the defects which may affect the structures (elements coming apart, splitting, possible cracking, etc.).
- Magnetoscopic inspections of a few compositions were carried out in order to search for signs of damage in sensitive areas that are imperceptible to the naked eye and to measure the general structural state of the connections.
- An anti-corrosion diagnosis was carried out to reveal in particular the presence of lead oxide in the existing anti-corrosion system and then decide the best way in which to refurbish the anti-corrosion system. A visual examination was used to define the general state of the anti-corrosion protection. This was completed by evaluating the chemical nature of the paint, examining the layers, testing the quality of the adherence to the steel parts with cut-cross tests and traction tests and using porosimetry to test the water tightness of the paint. This examination brought to light significant defects in the paint (lack of adherence, blistering, lack of paint, etc.) which resulted in the need for additional works.
- At the request of the architects of French buildings (ABF), spectrocolorimetry was used to examine the tints of the paint that was originally used.
- Samples were taken, and chemical and mechanical analyses were carried out in order to ensure the accuracy and reliability of the information regarding the materials in - situ. From these samples, the features of the wrought iron (flexible limit, tensile strength, Young's modulus) were determined and incorporated into the calculations.
- Whole models of structures were modelled using the Pythagore® software, developed by SETEC TPI.
- Finally, loading tests were carried out at night, coupled with measurements to help ensure the accuracy of the FEMl model. From the displacements and the distortions measured in the wrought iron and the rotations of some sections, the models were upgraded (limit conditions, global units of distortion) as having a consistent representation of the properties of the structure.

3 Structural Analysis

Because of the presence of lead in the original paint it was necessary to use watertight containment to avoid polluting the environment in any way during repainting. This containment was achieved by protecting against the wind, and it needed special structural examination to approve the method. Indeed, the side effects on the watertight containment caused by the wind were more important than those caused by the wind on the grid surfaces. The project plan consisted of using mobile scaffoldingof between 20 to 21 m high, depending on the structure, together with the complete containment of a pier and the use of a recycled abrasive technique.

The global FEM model of each bridge was created by SETEC TPI and Diadès using the Pythagore® software to check the structure of the bridges for cases of unusual loads. These prototypes were constructed using the results of the investigations, in particular the detailed dimensional measurements and the results of the samples taken to test the characteristics of the wrought iron. Even though the results of the tensile tests were heterogeneous, the yield and breakage limits of the samples were higher than those in the literature [1]. In order to ensure the accuracy and reliability of the results of the calculations that predicted the performance of these bridges, the models were based on the instrumentation and load tests carried out during the diagnosis phase (Figure 7).

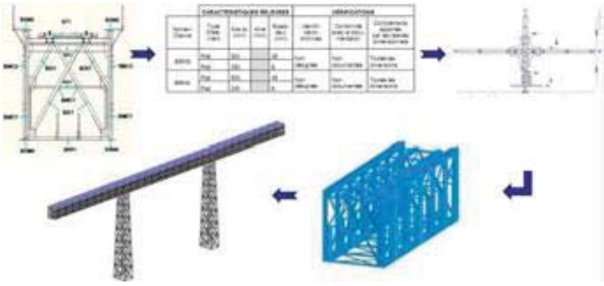

Figure 7. Structural analysis

4 Fatigue Calculations and Crack Detection

Given the age of these four wrought iron viaducts, fatigue calculations were carried out in order to detect the presence of any hotspots and thus the accumulation of damage to the structures that these might indicate. On the basis of estimates produced on the volume of traffic since 1869 [2] and the counts available for the period from 2000 to 2007, a histogram of the loads was drawn up, which distinguished between freight and passenger trains. For each fragile section of structure, the accumulation of damage was calculated after having established stress histograms using the rain flow method in Pythagore®. The results revealed the accumulation of theoretical damage that was sometimes superior to 1, along with potential damage in some specific sections. However, the traffic was estimated in an unfavourable way, particularly for the early decades, considering the maximum number of trains matching with the potential traffic that the line can handle.

In order to remove all doubt about the presence of cracks due to fatigue, additional investigations of the hotspots initially identified by the calculations were carried out using magnetoscopy (for simple structures) and radiography (for structures showing more than two flats). The radiography tests were carried out using a source of iridium 192 and D4 and D5 double films. These investigations did not reveal significant structural defects induced by fatigue and provided reassurance to the client in terms of its decision to invest in the repainting of the bridges.

5 Preparation of the Restoration Works to the Rouzat Viaduct

The Rouzat Viaduct was in fact the only one of the four bridges to undergo restoration works and repainting in the second half of 2013, as the anti-corrosion system of the three other viaducts was in a better shape the works have been postponed. Lassarat was responsible for these works with an alternative proposal which involved using two 18-m mobile scaffolding units on the deck in conjunction with the complete containment of the two piers (Figure 8).

Figure 8. Scaffolding on the Rouzat Viaduct

During a mandatory period of track closure, a study was carried out in close collaboration with the project manager, Lassarat and its design offices IOA and SEMI in order to ensure the technical feasibility of this procedure. The purpose of the study was to check that the reinforcements could be implemented without drilling the existing structure. The study highlighted the need to carry out provisional reinforcements to the bottom brace of the deck (excessive compression and risk of buckling) with pliers and areas of splitting to the shafts of the piers to the right of the rafters (excessive traction in the cast iron). The wrought- and cast-iron piers were in part prestressed by 80 t anchored into the stone,20 t per shaft. Finally, a specific method of wind control was drawn up to provide for the partial emergency removal of the mobile scaffolding in the event that the wind speed exceeded the safety limit. Considering the limited size of the site and the significant heights, these operations required significant resources of material handling to be implemented. Therefore, a 120-t crane was used to convey reinforcement collars for the piers; this required the closure of the RD 37 route, which the viaduct crosses.

Work to erect the scaffolding around the piers commenced on 15 April 2013, and access to the deck was strictly forbidden during this phase of the works, except at those times when the viaduct had been closed to trains. Once the whole bridge was placed under the responsibility of Lassarat on 24 June 2013, a 200-t crane was used to place the mobile scaffolding on the deck.

6 Implementation of the Works

As the Sioule is regulated by an upstream dam, it was possible to set up the site installations along the river without fear of flooding. Two offices, a canteen, showers and changing rooms suitable for 20 workers were built close to the road below the bridge. A power generator, a dry compressed air generator and a suction device for vacuuming sand particles were also set up nearby.

The whole area around the pier along the road was used to house the lift, necessary to transport the teams and equipment 52 m above the road and to make transporting the crew up to the viaduct more efficient - as well as a three-compartment airlock to mitigate the risk of lead contamination from the sanding and filtering workshops. The sanding machines were held in a container, above which stood an abrasive tank container (Figure 9). This equipment, which was developed by Lassarat, gravity fed the sanding machines with minimal handling and reduced outage times. The proximity to the road made it easier to supply the abrasive, which was delivered by silo trucks. An area was also set up to collect polluted sand particles in a watertight container which were automatically bagged. This system was also used where the risk of asbestos was present. Finally, the regenerative air plant with a total filtering ability of 60 000 m3/h provided recycled air in the containments of between 6 and 8 volumes per h, depending on the sections.

Figure 9. Sanding machines and abrasive tank containers

To protect the workers against road risks, a footbridge was built for both workers and power networks to cross the RD 37 motorway. Due to the presence of lead, the sanding operations had to be carried out in a confined environment [3], which was created using heat-sealed tarpaulin with a thickness of 230 µm at the sides and 600 µm on the floor of the mobile scaffolding unit on the deck. Air openings were carefully positioned to provide the recycling of air within the confined area, which had a lower pressure because of the dedicated suction plant. In cramped spaces where there was a risk that workers may inadvertently perforate the containment, protection was provided with plywood boards or by reinforcing the tarpaulin. All workers had medical assessments and blood tests prior to starting the work and then on a monthly basis in order to reduce the risk of getting lead contamination in their blood.

During the design phase, a preliminary consultation process was set up with the Pensions and Occupational Health Fund and the Professional Organisation for Prevention in Construction and Public Works (OPPBTP AQ27), which promote health and safety and the prevention of injury in the workplace. In order to manage the wind risks, wind gauges were placed at different locations around the structure. The procedures for the emergency removal of the containment and the monitoring of weather forecasts were strictly followed in the event of violent winds.

The weather forecasts allowed these events to be anticipated and meant that the works could be organised to prevent risk of damage from the environment if containment had to be breached.

During the compliance tests, a particular problem was discovered regarding the stripping of the cast-iron piers: there were patches of carbon deposits on the cast iron. In order to achieve even anti-corrosion protection across the entire surface of the piers, it was decided that all traces of carbon deposits should be removed, and that stripping be carried out to a Sa2 ½ grade.

The structure is old and made up mainly of wrought-iron angles that have been connected using rivets, which produces many rough patches and air gaps. Therefore, stripping these surfaces takes a lot of time and significant experience of sanding is needed in order to understand how to attain medium G-type roughness without wrapping the iron by repeatedly blasting it with the abrasive. A total of 27 t of abrasives was used each week during the peak production periods, which was achieved by two teams of six sandblasters working in two shifts. The sandblasters wore full-face helmets, including drapes that covered their shoulders and a glass visor to protect them against the abrasive particles bouncing off the substrate.

The glass visor was regularly changed as it was polished by the abrasive.

Each operator received fresh air through a full-face mask placed under the helmet, connected to a compressor equipped with suitable filters. The change of air, set to a minimum of 6 volumes per h, provided proper visibility within the sandblasting enclosure.

The cleaning phase was carried out in several stages. Firstly, as much residue as possible was vacuumed up. After this, all the surfaces were swept and air-blown and the area was vacuumed again. A final blast with dry air, to prevent the corrosion of the bare steel, was required prior to starting the painting works.

The painting phase was carried out from the top downwards to avoid depositing particles—often found in the scaffold elements—onto the freshly treated surfaces, and the application of each coat of paint followed a specific protocol. The weather conditions were an important factor, as the tolerance of the selected paint requires the relative humidity to be less than 85%, the ambient temperature to be 3 to 35°C and the temperature of the substrate to be at least 3°C higher than the dewpoint. If these conditions were not naturally occurring, then they were created artificially using air heaters or heating systems in the enclosed areas.

Pre-painting touches were applied to the angles and rivets by brush prior to the application of the three coats of paint using airless sprayers from the C4AMV system in order to attain the required minimum thickness of paint across the entire structure.

The whole process lasted eight months from start to finish, for which the railway line was closed for six months and the deck was managed by Lassarat for four and a half months. The restoration of the line was completed to schedule and commercial traffic resumed on 16 December 2013 on the fully restored viaduct (Figure 10).

Figure 10. The fully restored Rouzat Viaduct

Conclusions

Although the Rouzat viaduct is still in operation and in good condition after 145 years inuse, showing the great durability of the structures built by Gustave Eiffel and the quality of the maintenance provided by the SNCF on these bridges,it was decided to carry out restoration work on the viaduct. Through this study comprising a thorough diagnosis, a structural assessment and monitoring of repair works; it is the question of the follow-up of these old structures that has been asked.

The particularities of the materials encountered (wrought iron and cast iron) and the specific lattice geometry of these structures call on notions and knowledge that are no longer found in present texts. Therefore, such studies require taking a step back from modern regulatory approaches to fully understand the behaviour of these structures and to define repair solutions adapted to their age.

This starts with inspections to assess the condition of many of the connections, which include the checking of the element dimensions, and even the reconstitution of past plans. A thorough diagnosis validates the input assumptions needed to fully understand the actual behaviour of the structure. Calculations are carried outto study its current and future behaviour. These studies must also consider the current condition of the structure, like losses of metal thickness or degradation of connections. Finally, it may be necessary to evaluate the risk of fatigue deterioration given the large number of loading cycles that the structure is subjected to, and if necessary, to carry out further targeted investigations for a specific study of fatigue cracks. These studies of fatigue remain complex because of the difficulties to estimate the loads, as much as in terms of mass as in terms of the numbers.

In all cases, it is therefore necessary to remain pragmatic in seeking to ensure the structure is safe. The approach is taken not to necessarily make the structure strictly conform to the regulations, particularly with respect to fatigue criteria that are not suitable for these old structures.

Finally, this work on old structures must also take into account the possible presence of dangerous materials like lead or asbestos which have a strong impact on the restoration processes implemented, as they have the potential to significantly impact both the environment and the costs of the repair works.

7 References

[1] IN1263 Notice technique VB95c: Règles concernant la vérification des ponts métalliques sous rails. Société Nationale des Chemins de Fer Français, Paris, 1963.

[2] Circulaire du 29 août 1891 relative à la revision de la circulaire de 1877: Nouvelles règles relatives aux épreuves des ponts métalliques.

[3] Code du travail – article L4412-1 – Dispositions particulières aux agents chimiques dangereux cancérigènes, mutagènes et toxiques pour la reproduction.