Diagnosis of a large steel bridge close to collapse during a fire

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Summary

The Mathilde Bridge is one of the six bridges over the Seine River in the city of Rouen and supports heavy traffic. It was built in 1976-79 and is composed of a single metal span 115 m long, consisting of an orthotropic steel deck resting on two girders. On October 29th, 2012, the Mathilde bridge was subjected to a heavy fire and was immediately closed to traffic. After recalling the events, the article describes the decisions that had to be taken in an emergency, then the extended diagnosis which was conducted in order to be able to take a rapid decision on repair or reconstruction.

The diagnosis consisted of a detailed inspection including the examination of cracks and the condition of the paint, extensive investigations carried out on samples of metal, an accurate measurement of the global deformations of the entire span, a recalculation of the stability of the burned areas, and an expertise of damaged support bearings.

Keywords: steel bridge, fire, emergency, diagnosis, assessment, investigations, recalculation, stability, repair, decision.

1. Introduction

The city of Rouen (100,000 inhabitants) is in the heart of an urban agglomeration of 450,000 inhabitants. It is organized around a bend of the Seine and its road crossings. Over the decades, the local authorities have decided to drive the transit traffic away from the center of the city without diverting the internal traffic within the agglomeration. Thus, when the Mathilde bridge was opened to traffic in 1979, the mayor of Rouen, also president of the Departmental Authority of the Seine-Maritime asked to the Government of the French State to study a new crossing in the west of Rouen. This new crossing was built 20 years later with the construction of the Flaubert lifting bridge. From a road perspective, the Rouen agglomeration is located at the intersection of flows coming from northern Europe and France and going to the West and to the Iberian peninsula, with flows between the Ile de France and western France.

The Rouen agglomeration having no ring road, the Mathilde Bridge plays a strategic role for the flow of traffic in the city. Before the fire, it supported more than 80 000 vehicles per working day, with nearly 20 % of transit traffic. Moreover, it supported a sewage pipe serving the north of the city, and an optical fiber network.

The Mathilde Bridge was built between 1976 and 1979 according to a SETRA (now CEREMA) design and has in particular two twin 115 m long steel spans; each span consists of an orthotropic deck resting on two girders which are 4 m high, 17.35 m apart and braced every 4 m. Each steel span is resting at one end on an abutment and at the other end on the extremity of a cantilever which is part of a continuous prestressed concrete box-girder bridge passing over the Lacroix Island (see figure 1).

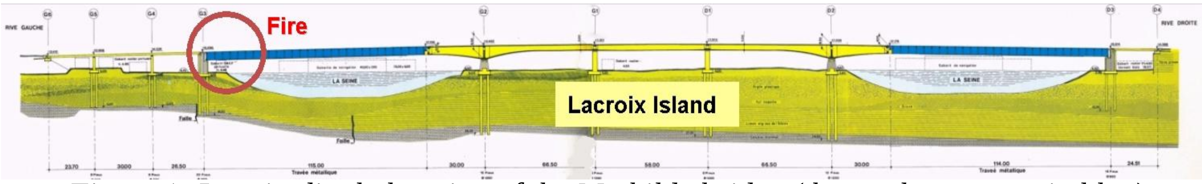

Figure 1: Longitudinal elevation of the Mathilde bridge (the steel spans are in blue)

On October 29th, 2012, a tanker truck carrying oil caught fire on the Mathilde bridge, by turning over in an access curve to the bridge. Its load spread over the whole width of the deck of the south steel span, then flowed toward the edges and ends of the bridge and set fire to fairground workers trucks that were parked under one extremity of the bridge. This latter was subjected to a heavy fire whose temperature has been estimated to reach between 650 and 800 °C.

Figure 2: View of the two fires over and under the bridge

The Firefighters responded very quickly, avoiding a full collapse of the deck, thanks to their action. Fortunately, there were no dead people and only two persons were slightly injured. The bridge was immediately closed to traffic as well as the navigation under the bridge. This decision led to the displacement of some of the boatmen on the Northern pass usually reserved for recreational activities and to the stop of the yacht club activities. These decisions were taken by the Prefect and the president of the Departmental Authority, given the uncertain condition of the bridge. The road traffic on the bridge is still closed today.

2. The management of the crisis

On October 30th, a specialized consultant was commissioned to make a first diagnosis, a crisis cell was activated by the Prefect, involving all road managers: City, Agglomeration, Department, State, motorway concessionaires, and the gendarmerie and police services. The prefect asked also for the help of the State national services to provide technical assistance to the Department services. A technical committee was formed with experts and met in early November to provide further diagnosis and to propose investigations.

Meanwhile, a new traffic plan was implemented and adjusted each day to take into account the daily specificities. The city of Rouen opened a website in order to know at anytime the status of the traffic in Rouen (http://trafic.rouen.fr/trafic). The Departmental Authority opened also an information website (http://www.inforoute76.fr/) and the Agglomeration reinforced the buses network. The Departmental Authority reinforced the movement of ferries in the west of the city with 3 river crossings. The Agglomeration and Orange Company worked in emergency to restore the sewage system and the optical fiber network by temporary deviations via the Corneille bridge located nearby.

Some private companies and public services adapted the work schedules of their employees by allowing them to start early and leave before the evening rush. Some companies offered two work sites, one on the right bank of the Seine river and the other on the left bank.

Communication activities were undertaken by the city and the Departmental Authority to encourage the use of public transport and carpooling. Carpool areas were urgently arranged on the periphery. The Police was mobilized to manage traffic around eight major strategic crossroads. Some works were undertaken to modify the geography of some intersections and delete conflicting movements.

2.1 Description of the main disorders of the frame

Before describing the main disorders, it should be noticed that firefighters were able to intervene quickly with water, which helped limit the temperature in the steel frame before it reaches the critical temperature of 723 ° C. If this action, that probably prevented the bridge from collapse, has not been carried out very quickly, the effect of metallurgical quenching on a steel having exceeded the critical temperature would have caused a steel embrittlement.

The deck remained distorted like an accordion over a length of about 40 meters from the south abutment (Fig. 3). The transverse beams supporting the deck were alternately raised and lowered due to the combined effect of heat which lowers the modulus of elasticity, and predominantly of the compression that occurred during the fire in the deck due to the restrained expansion of the deck. The web of the downstream girder was distorted dramatically during the fire (Fig. 4): a tensioned diagonal has formed over a length of 8 meters from the abutment with a wave folding the first intermediate vertical stiffener located at 4 meters from the abutment.

Figure 3: Waves of the deck

Figure 4: Deformations of the webs of the two first panels of the downstream girder

2.2 First decisions of the Departmental Authority in association with the Technical Committee

A Technical Committee (TC) chaired by Mrs Evelyne Humbert was formed to coordinate the interventions of experts from CEREMA, IFSTTAR and DRIEA. Its objective was:
- To advise the Department of Seine- Maritime, owner of the bridge,
- to specify the conditions for reopening the river navigation in the South channel,
- to assess the condition of the structure and its supports,
- to evaluate scenarios of repair or replacement,
- to give an opinion on the conditions for carrying out the repair work.

Although the bridge did not collapse under its own weight, the TC recommended that no prop be installed. Such a prop profoundly alters the distribution of forces in the structure and represents a serious obstacle for the navigation in the South channel. Therefore, the navigation on the Seine river was restored at the end of December 2012.

A heating of the end of the downstream girder over a length of 10 meters from the abutment was set up in December to avoid any brittle failure of the welds during the cold weather in winter. This precautionary measure was taken because the weld beads located in the deformed areas could be subjected to a steel embrittlement, without knowing the investigations results. Moreover, damaged cornice elements were removed to prevent them from falling.

3. Specific investigations regarding the effects of the heat on the deck

The investigations carried out on the Mathilde bridge were derived from the emergency procedures established by CEREMA to evaluate the condition of a bridge after a fire accident.

3.1 Observation of colors and laser topographic survey

The observation of the residual deformations and colors taken by the corrosion protection containing lead minium indicate that the temperature has reached at least 600 ° C on significant areas (Fig. 5). It could be noticed the white lead oxides of the primer over the entire height of the web and a complete disappearance of the primer in the center of this area.

Figure 5: Colors taken by the corrosion protection

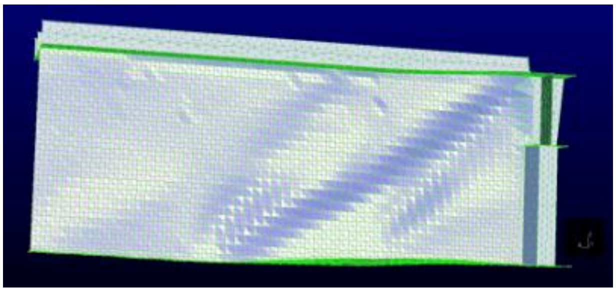

Figure 6: Transverse deformation of the web

The deformation of the downstream girder was measured using a 3D laser scanner by the company SITES. The laser record allowed to acquire 500 million points including 100 million for the end of the downstream girder. The interpretation of this survey allows the creation of a polygonal mesh with a precision of + / - 1 to 2 mm. The main results showed that the girder had a vertical displacement of the order of 210 mm and the transverse deformation of the web of the girder varied between + 18 mm and - 28 mm apart from the mean plane (Fig. 6). It can be assumed that the margins of the ultimate strength of the structure at the peak of the fire were likely very low with respect to the buckling of the downstream girder near its support on abutment. This survey also allowed CEREMA to create a mechanical model of the end of the downstream girder.

3.2 Examination of fillet welds

A first careful visual examination of thick welds beads on the downstream girder did not show cracking: this observation concerns the web-vertical stiffeners welds (in particular the stiffener at the end of the girder), the web-flange welds, and the web-longitudinal stiffeners welds.

This examination was then supplemented by the SOCOTEC Company with penetrant dye tests on weld beads at the extremity of the downstream girder, on the inside, near the tension diagonals, and with magnetic tests on different types of weld beads in areas exposed to fire. Apart from an area that has a lot of small corrosion craters over a length of 400 mm, and except for some spot areas at the junction of the webs with the flanges that need to be recharged, the welds are generally in good condition.

Moreover, the tests already performed in 1998 (penetrant dye, magnetic and U.S.) have been reproduced on the welds of the additional flanges, according to the same procedure. No defects were detected.

It should be noted that the girders of the Mathilde bridge are fully welded, and this configuration contributed to the survival of the bridge because experience shows that bolted joints can undergo serious damages in a fire. For the weld beads which have not been directly subjected to fire hoses, the high temperature of the fire may even have improved their resistance by relieving residual manufacturing stresses.

3.3 Effect of heat on steel: Measure of the Vickers hardness

This measure can be easily conducted at multiple points using a portable instrument with a diamond tip. This is a non-destructive examination intended to highlight the presence of martensite, and thus to reveal embrittlement in the tempered zones that have exceeded 725 ° C. The measurements were done by the Welding Institute of Le Havre. No evidence of embrittlement was identified. The hardness values obtained in the steel of the web and the stiffeners are quite close to that of the reference area. However, the hardness / Rm conversion according to EN ISO 18625 of June 2004 gives values that are lower of just greater than the minimum required for a steel grade E36-4 (Rm = 510 MPa according to NF A35-501 of 1973) and E460 (Rm = 590 MPa according to NF A 36 201 1975).

3.4 Effect of heat on steel: metallographic replicas

This technique has been implemented by the Welding Institute of Le Havre. It is standardized (NF A04 -154 of December 1985) and allows rapid diagnosis of steel after a fire at multiple points by implementing a lightweight portable equipment. The replica method consists of five steps:
1 . Local grinding to remove surface layers of oxides, paint, or decarburization
2 . Preparation of the area by polishing, using more and more finer abrasive paper
3 . Metallographic attack of the polished area to reveal the microstructure, by a chemical solution based on nitric acid and ethanol .
4 . Taking the impression of the microstructure by placing a film of cellulose acetate
5 . Microscopic examination

It was possible to make ten points of replicas that could be interpreted early December 2012. Nine points were chosen on site according to the curvatures of the steel plate and its surface appearance on the inside of the downstream girder (Fig. 7), because it is between the girders of the bridge that the warm air was trapped and that the temperature rose the most. One of these replicas was made in the area directly sprayed by the firefighters. Some points were localized on welds. A reference point was also taken out of the zone subjected to the fire.

Figure 7: Location of the replicas

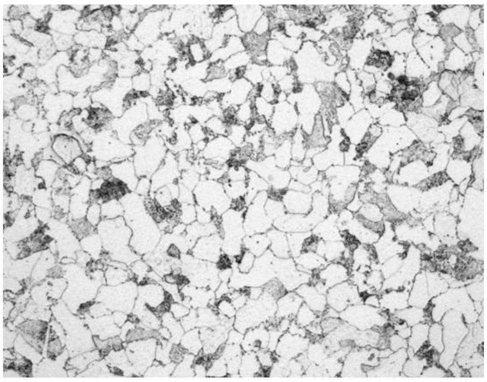

Figure 8: Observed structure of the steel on replicas

The results were very positive because the observed structure of the steel was everywhere purely ferrito-pearlitic without any trace of martensite or other structure degraded by an excessive heat. Moreover, the Welding Institute did not noticed any cracking due to creep damage or attack by liquid metals.

3.4 Effect of heat on steel : Steel samples for Charpy tests

These samples are much smaller (10 x 10 x 55 mm) than the samples taken for tensile tests. In addition they provide more relevant information on the risk of embrittlement due to tempering of the zones that have exceeded 725 °C. Therefore, SOCOTEC Company collected many specimens for Charpy tests in the highly redundant troughs of the orthotropic decks (Fig. 8) and at the ends of the longitudinal stiffeners of the web of the downstream girder (Fig.9), with the objective that these samples do not weaken the remaining structure. The samples were taken on the edge and oriented parallel to the stiffener, with a cutting a little more than 1 cm deep. These small samples are cut with a water cooled saw, so that the heat of the cut does not distort the results.

The resilience values Kv (at the temperature of - 20 °C) taken from the steel deck after the fire were between 75 and 125 J/cm2 on the normalized specimen. They were all above the average reference value KCV fixed at 50 J/cm2 and above the individual reference value fixed at 35 J/cm2, which eliminates any risk of embrittlement and crack propagation.

Figure 9: Sample taken on a deck trough

Figure 10: Sample taken on a web stiffener

3.5 Other investigations on steel samples

Others samples were taken by SOCOTEC and tested by LHEM (Laboratoire Havrais d'Essais Mécaniques) for mechanical properties. Among 17 samples, 11 had an elastic limit Re greater than the reference value of the standard NF A 35-501, Re = 355 MPa , and six samples (all coming from the troughs) had an elastic limit less than that value. Concerning the limit strength Rm, 15 samples had a value Rm greater than the reference value Rm = 510 MPa, and two samples (from the troughs) had a Rm value less than 510 MPa. It was thus found that the stiffeners had a steel grade higher than that of the troughs.

The elongation values for all 17 samples were above the reference value fixed at 22 % (for a plate thickness e such that $3 < e < 30$ mm). The values of the modulus of elasticity are generally satisfactory and close to 200 Gpa.

The carbon contents measured by the CEREMA laboratory of Nancy are relatively high but still below the limit value in the standard 0.22. The equivalent carbon of the steel is between 0.423 % and 0.462 %, which gives a high susceptibility to cold cracking. The laboratory concluded that the studies qualifying welding procedures should take into account this risk and secure precautions when welding for repair.

4. Specific investigations regarding the effects of heat on the support bearings

4.1 Expertise of damaged bearings

The expansion joints on the abutment subjected to the fire were re-opened after the fire, which seemed to show that the mobile pot bearings were functioning again. But this reopening was perhaps only due to the shortening of the deformed deck after cooling. The bearings are not accessible and the condition of the Teflon was therefore unknown. It was recommended to record the temperature and the elongations of the two girders that have not been exposed to the same fire for comparison purpose.

A comprehensive longitudinal model of the entire bridge was developed by DRIEA (a French governmental office for roads near Paris) as a bar taking into account the thermal inertia of the prestressed concrete spans over the Lacroix island. This model succeeded to explain the observed elongation with the hypothesis of pot bearings with Teflon sheets always sliding with very little friction.

4.2 Detailed inspection of the concrete supports

The examination of the concrete by the DREIA under the south bearing showed no visible cracking. This first examination made from accessible areas was completed by the inspection of the bearing from a positive inspection platform. The challenge was to ensure the resistance of the crossbeam of the abutment supporting the bearings.

The succinct hammering of the abutment face showed no degradation of concrete in depth. It seemed that the striated architectural stamping had partially protected the structural concrete that it covered. Some aggregates were observed as turning pink at the surface only. The removal of the deteriorated concrete revealed aggregates having a normal color within 1cm depth beyond the striated architectural stamping. No reinforcement steel appeared because the concrete scales remained of the order of a centimeter and were inferior to the cover depth. It could be concluded that the reinforcement had not been heated to a high temperature

SOCOTEC completed this inspection by a physico-chemical analysis of cores to determine the temperature profile that had been reached (see Fig. 11 for the location of the cores taken).

The mechanical properties of the two reinforcement samples that were taken were correct.

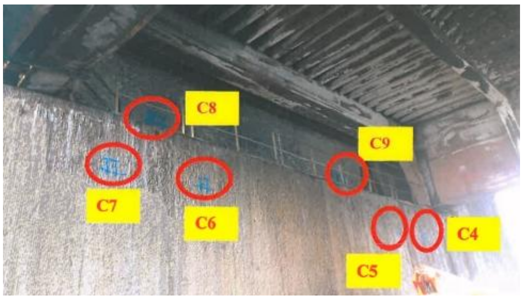

Figure 11 : Location of cores

5. Recalculation of the deformed structure

5.1 Elastic calculation with the new and very deformed geometry

From the laser topographic surveys conducted by SITES, the CEREMA (Setra) developed a mechanical model for the downstream girder end. During December 2012, a first calculation was carried out with an elastic material and large displacements, i.e. taking into account the second order effects such as the membrane effect. This calculation was conducted with Code_Aster STA.10 a general code of finite element analysis of EDF R & D which is available under GNU GPL (http://www.code-aster.org) license. It helped to explain the good performance of the bridge under its own weight with Von Mises stresses equal to 366 MPa. The deck then remains in the elastic range under its own weight G (weighted by the coefficient 1.35) and considering the effect of significant residual geometric distortions due to the fire. A horizontal concomitant effort H = 300 tons was safely considered to take account of the friction in the bearing. The figures 12 and 13 show the stresses on the extreme fibers of the most stressed shell elements. This first elastic calculation was conducted to understand the behavior of the deformed structure and to re-open the navigation under the bridge.

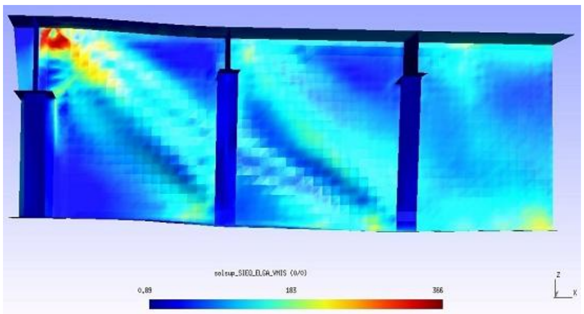

Figure 12: Elastic calculation under 1,35 G + H (scale going from 0 to 366 MPa)

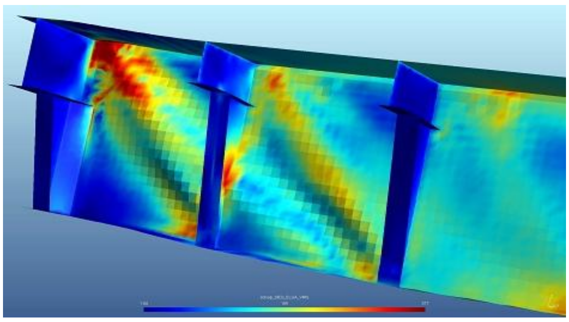

Figure 13: Plastic calculation under 2 x G (scale going from 0 to 377 MPa)

5.2 Plastic calculation with the new and very deformed geometry

The improved version of Code_Aster 11.3 was then used to show that the structure remained stable until even a load equal to 2 times its own weight (2G). The maximal Von Mises stresses reach 377 Mpa (Fig. 13). At this level of charge, the convergence of the calculation of the structure is obtained by considering both the balance of efforts due to large displacements in the deformed geometry and the plastic behavior of the material. This safety reserve allows a small engine to access on the bridge for repair work, if the company validates these results.

6. The decision taken and the repair principle

A replacement of the damaged part of the structure respecting its initial geometry was decided. Indeed, a good overall design of the existing structure has made this option more realistic than a full replacement. It generally makes little change to the orthotropic deck, but a simple overweight to meet some minimum thickness requirements.

Furthermore, a removal of the bridge through the waterway was decided because it offers many advantages. The bridge is transported to a dock distant from the site, to be cut so that the damaged parts are replaced with new parts. This principle has several advantages:

- Very little interference to navigation except during the two days of operation for the removal and the reinstallation of the entire span,
- This method has already been chosen for the construction of the bridge, and therefore it is probably the most economical one,
- Less risk than a prop that deeply modifies the mechanical functioning of the bridge in the interim phase,
- Simplicity of the ballast of the prestressed concrete cantilever span,
- Hazards reduction for repair works because the constraints due to work over the Seine river are avoided, with also, as a consequence, a better quality of execution,
- No nuisance at the bridge site near the city, especially during the renovation of the corrosion protection containing red lead. The paint stripping in the city over the Seine river would require the implementation of a scaffold engaging the navigation clearance and a containment to ensure both safety conditions and environmental protection

7. Conclusions

The implementation of a plan to bypass transit flows via A29 Motorway and the Normandy bridge has significantly reduced the transit traffic. On some secondary roads, particularly in the east of the city, the heavy weight traffic has doubled, resulting in a significant deterioration of pavements. It is the same to the west with an increase in traffic in urban areas through the Cailly valley (Maromme in particular).

Moreover, this situation with essentially only a bridge (Flaubert bridge with 2x3 lanes) to support the North-South traffic shows limits every day. Indeed when an accident occurs at the approach of this bridge, the whole agglomeration is congested very quickly. Some days (exceptional circumstances), it takes almost 2 hours for transit vehicles to cross the Seine river. It has been established that some days, there are more than 60 km of traffic jams. The traffic crossing over the Seine river decreased by 40,000 vehicles per day.

Attendance of public transport has increased such as rail, intercity (about 10%) and urban (more than 15 %, especially on own site lines). Bicycle use has grown despite a topography and an inauspicious road for practice. Walking has made its comeback for travel over short distances. A survey conducted during the spring 2013 by the Chamber for Trade and Industry shows that about 10 % of economic actors have seen their situation weaken because of accessibility issues.

Today several establishments submit briefs to the court to obtain repair for their disfavors. The Departmental Authority, although pending a judicial decision fixing the amount of damages to the bridge, conducted its rehabilitation. Re-commissioning is expected in the summer of 2014, most likely during the month of August.